Pavement Marking Durability
Statewide
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State of Vermont
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Materials and Research Section

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16. Abstract

Pavement markings provide an importance means of communication for all roadway users. These markings may consist of numerous types of materials, including standard waterborne paint, thermoplastic, epoxy and polyurea. Each one of these compositions has its own unique set of characteristics related to durability, resistance to wear from tires and shearing effects from snow plow removal, placement cost and life cycle. In an effort to assess these materials and provide placement recommendations based on roadway type, the Vermont Agency of Transportation implemented a research project to evaluate several types of durable markings in terms of retroreflectivity and resistance to wear.

One the basis of the literature search, a minimum acceptable retroreflectivity threshold of 100 mcdl was selected. Logarithmic best trend lines were extrapolated to determine when each marking material would fall below the minimum threshold and require repainting. The cost of each marking by linear foot was then divided by the number of months the applicable marking was in service to determine the cost per linear foot per month. In short, inlaid polyurea markings were found to provide the longest acceptable level of service, while thermoplastic markings appeared to the most cost-effective marking material over the life of the markings. However, the cost effectiveness modeled above presumes that there is no benefit to retroreflectivity in excess of the minimum standard

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EXECUTIVE SUMMARY

Pavement markings provide an importance means of communication for all roadway users. These markings may consist of numerous types of materials, including standard waterborne paint, thermoplastic, epoxy and polyurea. Each one of these compositions has its own unique set of characteristics related to durability, resistance to wear from tires and shearing effects from snow plow removal, placement cost and life cycle. In an effort to assess these materials and provide placement recommendations based on roadway type, the Vermont Agency of Transportation implemented a research project to evaluate several types of durable markings in terms of retroreflectivity and resistance to wear.

The project was broken down into several phases which included a synthesis of concurrent studies, data collection, data reduction and subsequent analysis, decay modeling and corresponding economic analysis. A total of 25 newly constructed pavement projects were incorporated into the study in the following manner: 19 thermoplastic projects, 5 polyurea projects and 1 epoxy paint marking project. In some cases, multiple markings were applied to one project. Data collection efforts were conducted between 2002 and 2005.

Following data reduction measures, the retroreflectivity of pavement marking were examined as a function of age, traffic volume, regional placement, seasonal application and recessing. Age and winter maintenance practices were found to have the largest correlation to the decay of retroreflectivity over time.

On the basis of the literature search, a minimum acceptable retroreflectivity threshold of 100 mcdl was selected. Logarithmic best trend lines were extrapolated to determine when each marking material would fall below the minimum threshold and require repainting. The cost of each marking by linear foot was then divided by the number of months the applicable marking was in service to determine the cost per linear foot per month. In short, inlaid polyurea markings were found provide the longest acceptable level of service while thermoplastic markings appeared to the most cost effective marking material over the life of the markings. However, the cost effectiveness modeled above presumes that there is no benefit to retroreflectivity in excess of the minimum standard.

INTRODUCTION

Pavement markings are the most widely employed traffic control devices worldwide. They are intended to promote driver safety by delineating vehicular paths along the roadway surface thereby supplying advanced warning of upcoming regulatory, warning or guidance information. Specifically, longitudinal pavement markings delineate driving lanes, segregate traffic in opposing directions and indicate where passing is permissible. These markings must also be capable of conveying information during inclement weather and evening hours when there may be little to no contribution from overhead lighting.

Markings are required to be visible at all times. The condition of the markings can be measured under standard protocols following placement. However, these markings decay over time due to several factors including wear from winter maintenance practices, insufficient temperatures characteristics, ultraviolet sunlight and fading pigments.

Several pavement marking materials are approved for use in the State of Vermont including standard waterborne paint, low volatile organic compound (VOC) paint and three durable pavement marking materials. Vermont has general and project-specific specifications with regards to material and placement associated with each of these materials, but no policy for which type of marking should be applied to a particular roadway. Considerations in terms of project specific criteria include pavement, roadway type and projected traffic stream composition. Additionally, each marking material, comprised of various elements, displays unique characteristics resulting in differing lifecycles. There are specific costs associated for each type of marking material including product cost and installation. The National Cooperative Highway Research Program, or NCHRP, reported that "the estimated total money spent on pavement markings in the year 2000 by the 50 state transportation agencies, 13 Canadian provinces and territories, U.S. counties, and U.S. cities was $1,548,616,821 on 6,148,088 centerline-km (3,818,688 centerline-mi) of highways." However, as of 2002, "only eight state agencies have deployed guidelines for the selection of materials." (NCHRP 1)

In the spring of 2002, the Vermont Research Advisory Counsel, or RAC, accepted a proposal from the Materials and Research Section to conduct an investigation concerning pavement marking durability. The principal goal of this research initiative, as stated within the problem statement, was to "determine the lifetime and life cycle costs of pavement marking materials in the State of Vermont" and "produce recommendations regarding which materials are best suited for use on different roadway types." The investigation contained several phases including a literature review, data collection and reduction, a lifecycle cost analysis and associated reporting. The following final report outlines all efforts and substantial findings. A copy of the RAC solicitation form is given in Appendix A.

BACKGROUND

Pavement markings are a critical safety feature for local roads and interstates, as they provide a visual reference for proper vehicle position within the roadway. They may also be used to enhance other traffic control devices. In order to maintain safety, these markings must be visible to the driver at all times under varying driving conditions. Three principles factors affect recognition of the markings include contrast to the underlying substrate, color and luminance. Perhaps the most critical factor that can affect visual performance, or how well a target can be seen by the eye, is the luminance of an object as compared to the luminance of the background. The greater the contrast between the two objects, the easier an object is to identify. This is especially important for nighttime visibility as there is typically little to no ambient lighting reducing the overall contrast between pavement markings and the road surface. In order to ensure adequate visibility at night, reflective elements are applied to the pavement markings. However, the reflective properties as well as the pavement marking materials decay over time requiring periodic reapplication.

Reflective properties are typically attained by drop on or spray applied glass beads. However, other new and innovative materials have been shown to increase the initial luminance of pavement markings following installation. In order to produce reflective properties, a light source, such as a headlight from a vehicle, interacts with the glass beads and pigment in the pavement marking binder to reflect a portion of the incoming light rays back towards the driver. This is a quantifiable property known as retroreflectivity. Greater retroreflectivity results in an increase in pavement marking visibility and preview distances. Many studies have shown that this is especially important for older drivers which require “more light to see delineation and are slower to react.” (NCHRP 2) Many factors can influence the initial retroreflectivity of a particular marking, including bead gradation, binder viscosity, pigment, and installation procedures. Following application, the reflective properties as well as the marking materials are subject to environmental factors often resulting in brittleness, fading pigments, binder detachment, bead fracture and bead loss. It should be noted that abrasion from traffic typically results in a loss of the marking material and glass beads, decreasing both daytime and nighttime visibility.

The most common way to evaluate the retroreflectivity of pavement markings is through the use of a retroreflectometer, an apparatus capable of quantifying nighttime luminance under daylight conditions. This machine is designed to employ 30 meter geometry in order to reproduce the entrance and observation angles of a typical driver from the driver’s eye to the marking on the road. Specifically, in order to comply with the European Committee for Standardization (CEN) standard as referenced by the associated ASTM standards, the retroreflectometer replicates an entrance angle of 88.76 degrees and an observation angle of 1.05 degrees for a driver observing the markings from 30 meters ahead of the vehicle. All measurements are reported in millicandelas per square meter per lux, or $mcd/m^2/lux$.

PROJECT SCOPE

The main objective of this research initiative was to provide recommendations for the selection of durable pavement markings for placement on newly constructed projects. The project scope was broken down into several phases and included an evaluation of several types of durable markings over time and associated lifecycle analysis. The seven phases of the project as originally stated within the project proposal are as follows:

I. Literature Review to determine what practices for evaluation of pavement markings exist in other states including research and operation activities.
II. Compilation of data taken from existing research projects, and continued collection of data from those projects.
III. Collection of additional data from newly constructed projects.
IV. Analysis and reduction of data including supplemental data collection descriptions.
V. Economic Analysis to evaluate life cycle costs over the projected pavement life.

VI. An engineering evaluation of the deterioration mechanisms of the performance factors.
VII. Compilation of data and findings in the form of a final report including conclusions, recommendations and a summary program outline.

A thorough literature search was conducted in the summer of 2002 and summarized within a brief narrative. The research focused on the objectives, findings and/or conclusions concerning field and laboratory studies as well as current pavement marking management practices of various types of pavement markings. Field testing techniques were found to consider durability, retroreflectivity, color measurements, brightness and resistance to wear. Laboratory testing covered a wide range of testing procedures from adhesion and specific gravity characteristics to viscosity measurements. A copy of the "Literature Review" is provided in Appendix B.

Following the literature search, data collection ensued on several preexisting paving projects constructed in 2001 with subsequent collection from newly constructed paving projects from 2002 through 2003. This included the establishment of random test sites and subsequent collection of retroreflectivity readings and appearance ratings. All data was compiled into appropriate spreadsheets which were then analyzed within an interim report entitled "Pavement Marking Durability" published in 2005. A copy of this report is available upon request.

The remaining sections of this report outline project selection, data collection procedures, reductions of data sets, a lifecycle cost analysis and pavement marking recommendations based on specific roadway characteristics.

PROJECT DESCRIPTION

In an effort to generate recommendations for pavement marking material selection, several types of durable pavement markings were assessed including epoxy paint, thermoplastic markings and polyurea paint. Other markings, e.g., waterborne paint, were also assessed during this evaluation period. Project selection criteria included newly constructed paving projects which incorporated the application of one of the markings referenced above. Additionally, the overall sample population included sites on Interstate, Vermont and US Routes.

When a construction project, or sample population, met the above referenced criteria within the evaluation period from 2002 to 2005, simple random sampling was utilized to select a specific project. However, as is often the case in research studies coupled with random sampling, thermoplastic markings, or typically applied markings, were selected for evaluation more often than the experimental markings. A total of 25 sites were incorporated into the study in the following manner: 19 thermoplastic projects, 5 polyurea projects and 1 epoxy paint marking project. In some cases, multiple markings were applied to one construction project. Please refer to Appendix C for a map of all sampling locations.

Data Collection Methods

All data was collected and recorded under the "Data Collection Procedures" published by the Materials and Research Section in April of 2002. In brief, a minimum of five test site locations were established throughout the length of a construction project. All test sites were selected by a random number generator and referenced by a mile marker location. Each test site consisted of a total length of 40' partitioned into 10' intervals incorporating all white and yellow edge lines as well as white skip lines and yellow centerlines. Every interval was distinguished by white marking paint along the shoulder of the driving lane and freshened as needed to mark the sampling locations. Data collection was carried out on a periodic basis at all specified locations. Efforts were made to conduct testing within 14 days of application in order to comply with ASTM D 6359-99, "Standard Specification for Minimum Retroreflectance of Newly Applied Pavement Marking Using Portable Hand-Operated Instruments" for newly applied pavement markings. Figure 1, provided below, displays a typical test site.

Figure 1 – Test Site on VT 114 in Norton-Cannon

As stated previously, both daytime and nighttime visibility is closely correlated. Therefore, data collection efforts included both the collection of retroreflectivity readings, in order to adequately assess nighttime visibility, and a visual assessment of the amount of intact marking substrate. All retroreflectivity readings were collected with an LTL 2000 Retrometer in accordance with ASTM E 1710-97, "Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer." Visual assessments were conducted in accordance with ASTM D913-03, "Standard Test Method for Evaluating Degree of Resistance to Wear of Traffic Paint." This method requires a visual comparison between the representative areas of the traffic paint stripes to photographic reference standards shown within the testing protocol. Two examples of varying film thicknesses are shown in Figures 2 and 3. These photographs were collected from test site 5 within the Cavendish Wethersfield construction project one to two years following application, respectively. All retroreflectivity and durability readings were recorded onto the appropriate field forms and then entered into project specific spreadsheets. A copy of the field form is provided in Appendix D.

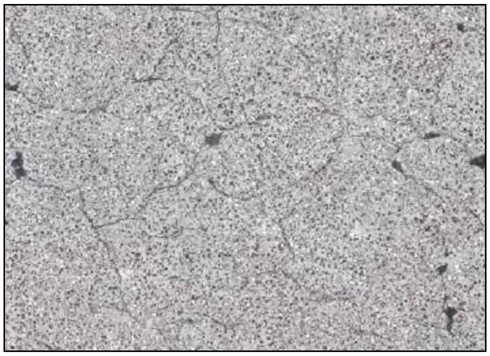

Figure 2 – 98% Intact

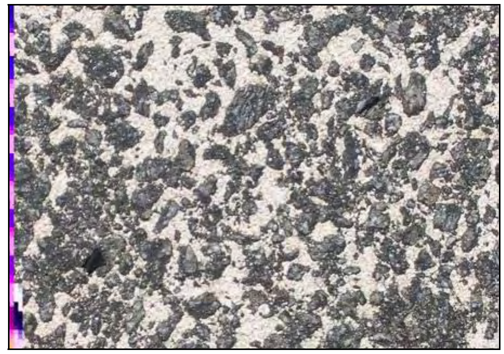

Figure 3 – 40% Intact

Data collection was carried out year round, including winter months when the ambient air temperature fell below the minimum temperature specified within the ASTM testing procedures of 40^{o}F. However, care was taken to maintain the testing equipment above the minimum specifications during travel and between test sites. A clear plexiglass enclosure that maintained temperatures between 50 and 65 degrees F was placed over the retroreflectometer. Where warranted, the pavement markings were cleaned with a mixture of water and windshield washer fluid to remove any salt, dirt or other debris and then thoroughly dried prior to data collection.

MARKING CHARACTERISTICS

Prior to performing a comparative analysis it is important to consider the unique characteristics of each marking type. These characteristics, in association with application techniques, will likely effect bond strength to the underlying pavement, resistance to abrasion and shearing effects, and brittleness during low temperatures. These parameters have been shown to have a direct correlation to retroreflectivity and wear. Application requirements and compatibility to other marking types are also important aspects when selecting a particular marking for application. For optimum performance of all markings, the pavement surface must be clean, free of dust or other particles, and dry. The following subsections provide a brief narrative of each marking type.

Thermoplastic

Thermoplastic is a solid compound containing binder, pigments and filler, such as calcium carbonate, which liquefies when heat is applied. The binder, consisting of plasticizers and resins, are proven to provide toughness, flexibility and bond strength while holding all of the components together. The glass beads supply retroreflectivity while the pigment provides color and opacity.

Thermoplastic may be composed of either hydrocarbon from petroleum derived resins or alkyd from wood derived resins. In either case, the marking material should be heated to

400^{o}F and hot applied to the underlying pavement. Poorly adherent preexisting markings must be removed prior application although new thermoplastic applications should successfully bond to worn existing thermoplastic markings. Glass spheres must be applied immediately to the marking material. In accordance with the manufacturer's specifications, the pavement and ambient air temperature must be at least 50^{o}F. In addition, while the specified thickness may vary from 30 to 125 mils, the manufacturer recommends a thickness of 90 mils and states that a materials applied thinner than specified will shorten the life expectancy of the marking and can cause premature bond and retroreflectivity failures.

Epoxy

Epoxy typically is a two-part system formulated and designed to provide a simple volumetric mixing ratio of the two components. As with all other marking materials examined in this study, it also contains a binder, in the form of an epoxy resin, pigments and filler. Specialized equipment, with complex process control systems, is required to assure proper blending of the two components. Existing pavement markings must be removed prior to application with the exception of latex water-based paint applied as temporary markings provided these markings were installed at a thickness of 10 mils or less. According to the manufacturer, the pavement and air temperature must be at least 40^{o}F. The manufacturer also recommends a dry thickness of 20 +/- 2 mils for optimum performance. As placement of the epoxy binder results in a lower mass per unit area, it may be less tolerant if applied outside of the manufacturer's specifications with consideration to ambient air temperatures and humidity.

Polyurea

Polyurea is a two component system composed of 100% polyurea coating materials containing binder, pigments and filler, which cure rapidly to hardness following application. Two manufactured brands were incorporated into this assessment. In addition, one brand supplied two different grades of polyurea pavement markings identified as "Polyurea 1A" and "Polyurea 2A." While the marking binder materials are the same, retroreflectivity is provided by a combination of reflective elements and glass beads on the "Polyurea 2A" and glass beads only on the "Polyurea 1A." The reflective elements have been shown to display a higher initial luminance. Specialized equipment is necessary for the application of the marking. Prior to application, the existing pavement marking must be removed to expose a minimum of 80 percent of the pavement surface below the old marking. However, polyurea markings may be applied over existing latex or water based temporary pavement marking paint provided the temporary paint is adequately bonded to the surface and has a maximum thickness of 7 to 8 mils. It is recommended that polyurea is applied when air and road temperatures are 40^{o}F or higher. In addition, for optimum performance, 18-20 mils should be applied to new asphalt surface.

Table 1, displayed below, contains a brief comparison of each durable pavement markings incorporated into the investigation. It is important to consider each of these parameters during the selection process as they will likely have an effect on overall performance.

Durable Marking Comparison			
Marking Material	Compatibility	Minimum Application Air and Pavement Temperature (^oF)	Application Rate (mils)
Thermoplastic	Worn Thermoplastic	50	90
Epoxy	Latex water-based paint at a maximum thickness of 10 mils	40	20 +/- 2
Polyurea	Latex or water-based paint at a maximum thickness of 7 to 8 mils	40	19 +/- 1

Table 1 – Marking Comparison

REDUCTION AND STATISTICAL ANALYSIS

The main objective of this report was to statistically compare the durability of the thermoplastic markings, or control, to experimental pavement marking applied to roadway section throughout the State of Vermont. The analysis was performed on retroreflectivity readings collected from markings applied to pavement projects constructed during 2000 through 2004. Roadway and traffic characteristics, including roadway type, AADT and average annual snowfall amount, varied between test sections and were evaluated in an attempt to estimate service life and determine possible trends in the decay of pavement markings.

Overall, the retroreflectivity readings displayed a significant amount of variability among roadways with similar roadway and traffic characteristics as well as each individual test section. The variability had a significant impact in determining an estimate for service life and patterns in retroreflective decay. In addition to roadway and traffic characteristics, variability in pavement marking durability can also be attributed to type of marking, the manufacturer of the marking material and glass beads, quality control during placement and snow removal. The following sections will present the statistical analyses performed and subsequent results of the service life and decay evaluation.

Data Reduction

As with all research investigations conducted over multiple years, some data interferences were anticipated. Prior to performing statistical analysis, each data set, or project, was examined for questionable results. For example, if salt was present on top of the pavement marking, the resulting retroreflectivity was found to be unbelievably high. Conversely, if water was present during data collection efforts, the resulting retroreflectivity results were found to be implausibly low. In addition, if newly repainted lines were encountered during any data collection event it was noted on the field form and data collection ceased for the associated project. In many cases, field observations were appended to each project file and highlighted. However, there were some instances where this information was not recorded and engineering judgment was needed to draw conclusions on erroneous data sets. This was done by assessing each individual data collection event per project. If any data was found to increase by more than three standard deviations within a data set for any given data collection event, the data was removed. Additionally, if any retroreflectivity results emulated those with known interferences such as the referenced examples above, the data was also removed.

Following the initial assessment of each project, all data was compiled into a master database. The database was sorted by each marking type and color. In order to provide a comparison between markings comprised of the same material, the number of days since installation was calculated. From this information, the number of months since application was determined and all results were inserted under the appropriate month. An average was calculated for each month and utilized to compose a graph of retroreflectivity readings over time for each marking type for a given color regardless of what time of year the marking was applied. The following graph displays the retroreflectivity readings over time in conjunction with all thermoplastic projects.

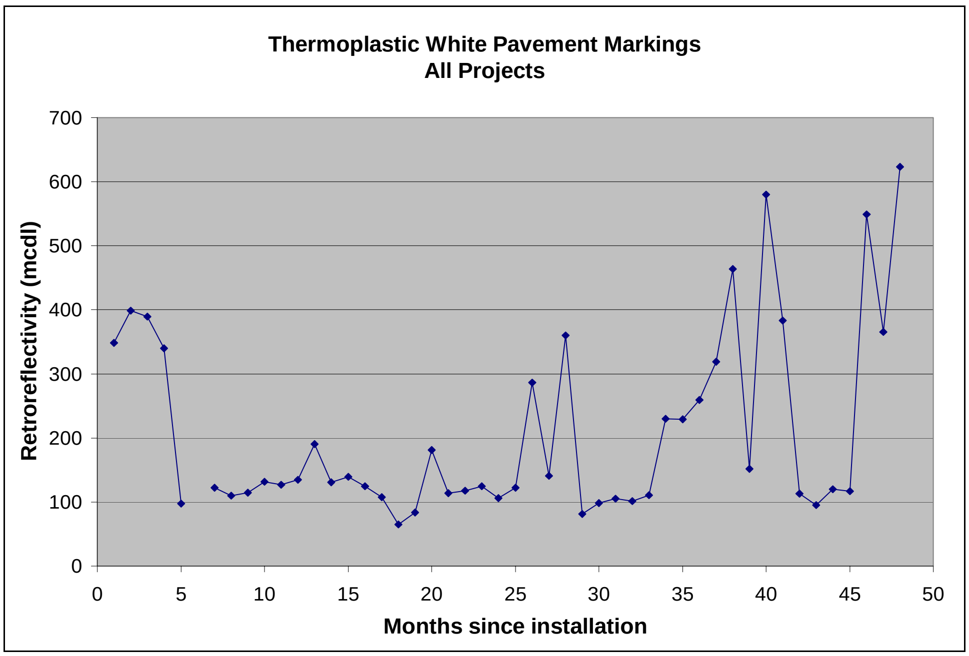

Figure 4 – Thermoplastic Markings with Interferences

In examining the graph above, it was clear that interferences still remained within the data pool as retroreflectivity readings were expected to continually decrease over time. Higher luminance readings well above the initial readings within the first 6 months of application were considered implausible. This lead to one final examination of all data sets. As the study was initiated in 2002, the initial retroreflectivity readings were not collected on projects constructed in 2001 and 2000 until one to two years following application, respectively. Additionally, the Agency typically applies standard waterborne paint over durable markings two to three years in age. Therefore, it is difficult to ascertain whether readings collected from projects constructed in 2000 were from the original markings or newly applied waterborne paint. From this information, it was decided to remove any data sets from projects constructed in 2000, eliminating nine thermoplastic projects from the study. The following graph contains all data from thermoplastic projects constructed in 2001 and 2002.

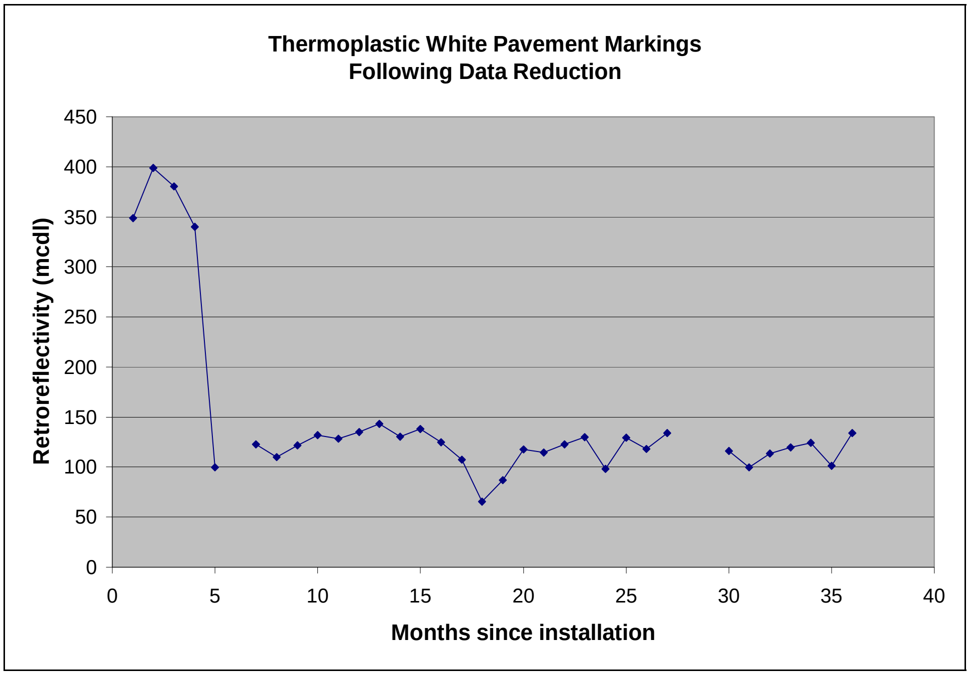

Figure 5 – Thermoplastic Markings following Data Reduction

The graph depicted above is consistent with field factors. Initially, the readings increase over the first few months as the result of tire abrasion exposing a larger portion of glass beads. The luminance readings then drop significantly during the winter months which may be attributed to shearing effects from winter maintenance practices and dirt or debris on the markings during data collection. The markings rebound during the spring and summer months climaxing in late summer and into early fall. This cyclic pattern continues over time.

The same data reduction procedure was carried out for all durable white and yellow pavement markings. Care was taken to note all omissions within the master database. As is typically the scenario for yellow pavement markings, the data displayed much more variability then its counterpart. However, previous studies have verified this relationship. Further, the color based variation appears to be independent of marking type. Rather it may be the result of inconsistent yellow pigment within the marking materials, inaccurate readings based on optical interferences or due to line position within the roadway. This will be examined more thoroughly.

Statistical Analysis

The service life of pavement markings were used to compare the durability and decay rates of various types of the marking materials to a predefined benchmark in order to evaluate and determine life cycle costs, which will be addressed later in this report. The analysis of pavement markings was performed by comparing retroreflectivity readings to the amount of time the markings displayed acceptable retroreflectivity. To date the Federal Highway Administration, or FHWA, and other federal and state authorities have not established minimum required values for the retroreflectivity of pavement markings. However, the FHWA published recommended minimum retroreflectivity values for white and yellow pavement markings by roadway type as shown in Table 2.

1998 FHWA Research-Recommended Pavement Marking Values			
Type	**Non-Frwy**	**Non-Frwy**	**Freeway**
Option 1	<= 40 mph	>= 45 mph	>= 55 mph
Option 2	<= 40 mph	>= 45 mph	>= 60 mph, >10K ADT
Option 3	<= 40 mph	45-55 mph	>= 60 mph
White	85	100	150
Yellow	55	65	100

Table 2 –FHWA Recommendations

These values were used as the standard for determining the end of useful service life.

Data Variability

The data collected reveals a significant amount of variability in the R_L values, or coefficient of retroreflective luminance, of the individual test sections. This variability exists among roadways with similar traffic streams and annual average snowfall amounts. As the variability increases, the level of statistical confidence in any trend or model decreases, therefore it is important to examine the variability of data subjected to analysis.

Figure 6 below presents the average retroreflectivity across all test sites within a newly constructed roadway section of I-91 for the entire duration of the study. The project incorporated the placement of durable thermoplastic markings in October of 2001. Readings indicated in pink were expected to display little variability during summer months where environmental conditions are relatively constant. However, the average retroreflectivity reading measured in the test section during the summer of 2002, one year subsequent to application, ranged from 70 to 135 mcdl with an average of 94 mcdl. The standard deviation of the average retroreflectivity reading was approximately 23 mcdl. This is a relatively large standard deviation displaying the significance of the variability on the data set.

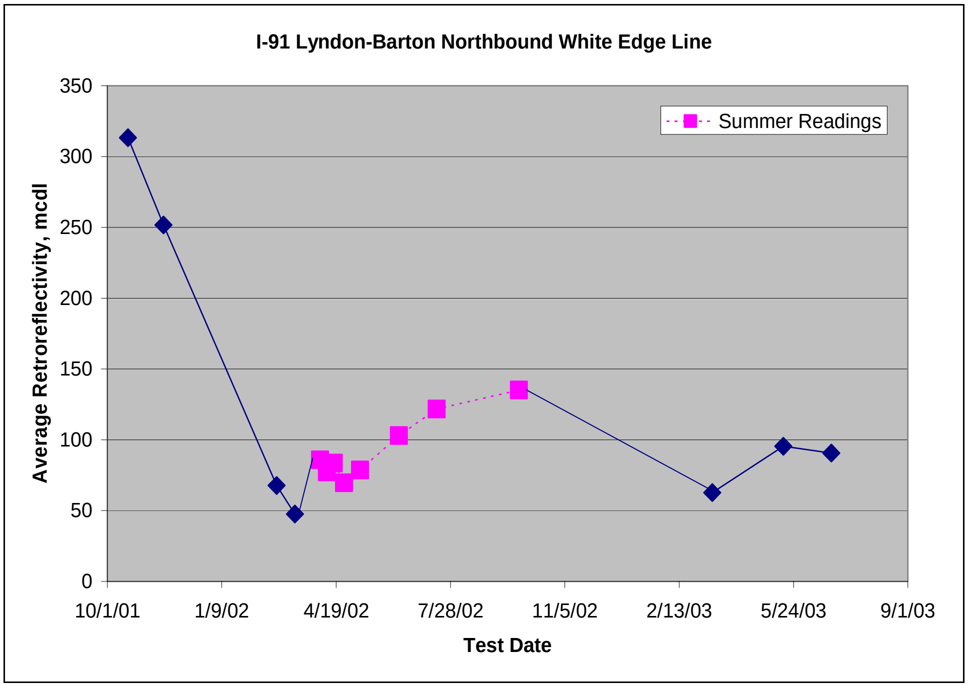

Figure 6 – White Thermoplastic Edge Line, I-91 Northbound

To further examine variability within the data sets, the average retroreflectivity result per test site was plotted in reference to mile marker location. Once again, one would expect the results to be fairly consistent for a given date across the entire project as many of the parameters, such as weather conditions, installation date and material composition, would be held constant on any single date. The data in Figure 7 displays the dissimilarity throughout the entire length of the project during a single data collection event. It is also interesting to note that the initial retroreflectivity increased on average from July to October of 2002. While the retroreflectivity recovers during the summer months, a significant loss in retroreflectivity occurs following one winter of service, over 100 mcdl on average. Additionally, all subsequent readings were found to be below the minimum recommendation from FWHA of 150 mcdl for white interstate markings. It does raise the question as to whether this minimum expectation is sustainable in snowy climates during winter months. As a final aside, it is difficult observe any patterns in reproducibility due to the dissimilarity between data collection events. This variability will resound throughout the remainder of the analysis.

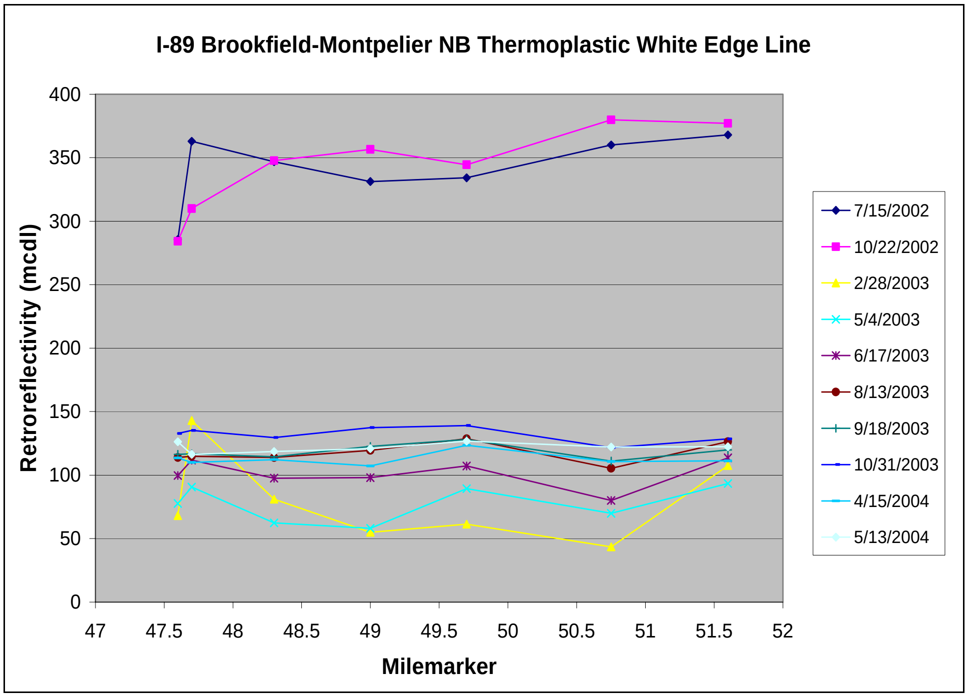

Figure 7 – White Thermoplastic Edge Line, I-89 Northbound

Yellow markings were found to less retroreflective with a higher variability when compared to white markings. Figure 8 exhibits the average retroreflectivity of white and yellow thermoplastic pavement markings applied in low AADT, or average annual daily traffic, (<3600) roadway sections.

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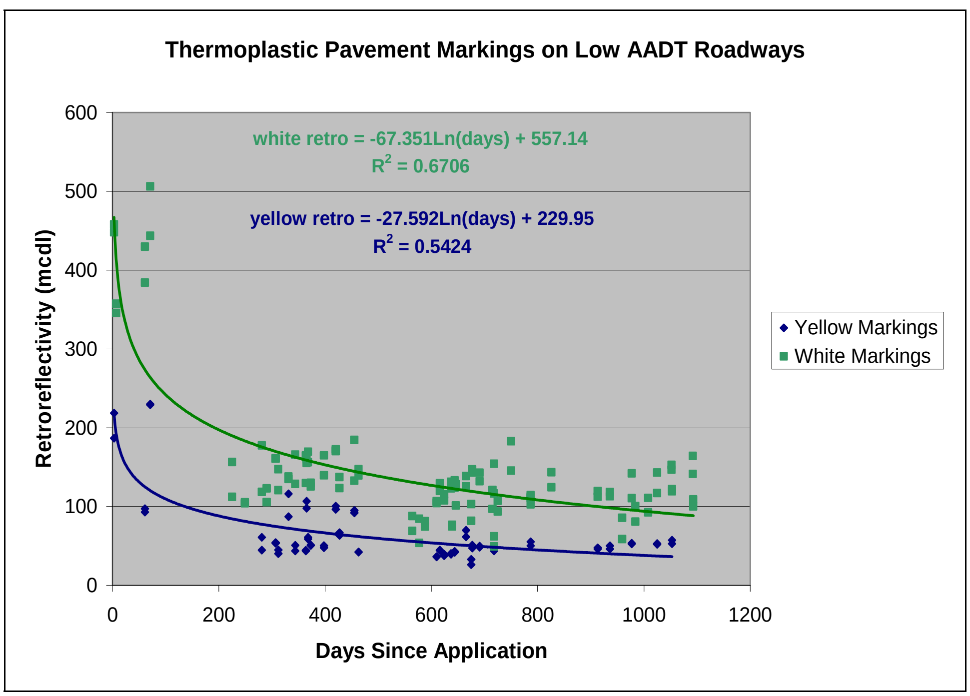

Figure 8 –Thermoplastic Pavement Markings, Low AADT

While the general downward trend over time is quite visible, the amount of variably within the first 480 days following application is considerable. In particular, the reductions associated with winter maintenance occur at a similar point in time each year, but the age of the marking may vary when that event occurs. Over time the data sets appear to become more confined. However, is it important to examine the magnitude of the readings as well. Additionally, a regression analysis was performed using the trend line function in Excel in order to provide a logarithmic equation that predicts the decay of the reflectivity as a function of elapsed time. Note than an R^2 value, or coefficient of determination, was also presented below each equation. Given as a number between 0 and 1, the closer the R^2 number is to one, the closer the fit of the data to the trend line. As you can see, the R^2 value is much greater for the white markings in comparison to the yellow markings.

The key variables affecting the overall decay relationship are time of year the markings were applied, installation methods and roadway alignment. Previous studies have shown that marking condition is often influenced by a tangent or curved roadway alignment. In addition, the majority of the readings collected from the yellow thermoplastic markings after one year of service do not meet the FHWA recommended minimum values. Since the yellow markings display the same trends as their counterpart, the white markings, but contain a greater amount of variability, only white pavement markings will be assessed throughout the remainder of the report.

In the analyses that follow, the amount of elapsed time in days following application was selected as the dependant variable based on the assumption that age is the number one factor affecting the performance of pavement markings. However, in cold climate regions, markings are subjected to plow damage. During data analysis, this relationship is examined but does not coincide within the independent variable. Since plow damage is expected to occur during each snowfall event, this remains a constant for all markings for the particular event on a specific date. Placement of the pavement markings occurred from June through November. Assuming the first snowfall event occurs in December, roughly six months would have elapsed for the June markings vs. one month for November markings. By using the number of elapsed days following application, it does not reference the time of year or any specific annual effects.

Since time of year will be not be a function of the dependant variable, this relationship was examined in the Figure 9 and 10 for thermoplastic and polyurea markings, respectively. Utilizing the date of a specific data collection event and first occurring November 1st following application, the number of elapsed days was calculated referenced around November 1st.

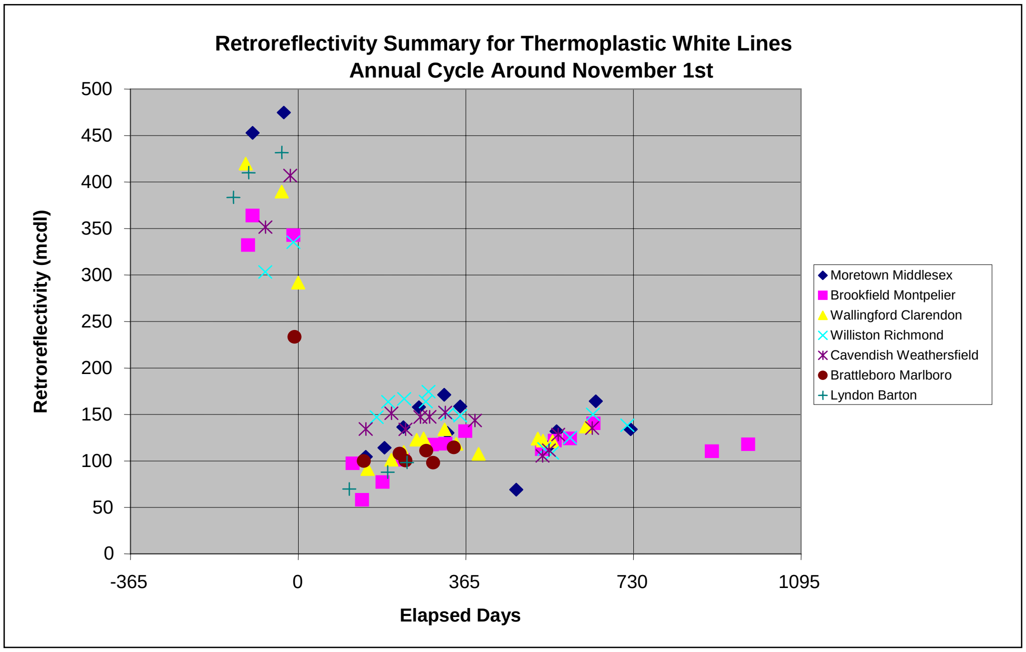

Figure 9 – White thermoplastic markings calibrated to November 1st

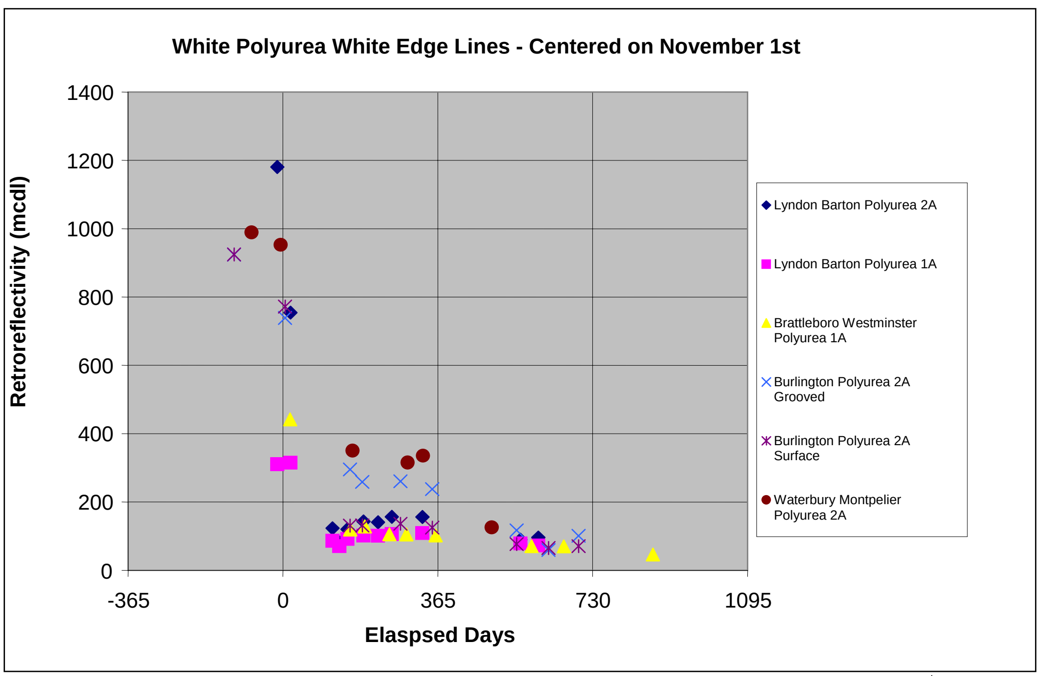

Figure 10 – White polyurea markings calibrated to November 1st

Snowfall events generally occur between November and April each year and may be assumed to be a seasonal pattern. With this in mind, the damage from snow plow events is evident for both thermoplastic and polyurea markings between November 1st and the following 150 days, roughly until April 1st. While annual damage accumulation is consistent for both markings, the subsequent response is quite different. Thermoplastic markings appear to rebound by increasing in retroreflectivity during the summer and fall months. Conversely, polyurea markings were found to plateau during the same time frame. This is projected to be caused by hardness of the polyurea markings cxpmpared with thermoplastic. This may provide more protection for the binder but may not protect any protruding glass beads from becoming dislodged or sheared. If the binder of the thermoplastic marking is less resistant to damage, it may also be less resistant to wear from vehicle tires resulting in abrasion and exposure of embedded glass beads thereby increasing the retroreflectivity of the pavement marking.

DECAY ANALYSIS

Several parameters which may effect the overall performance of the durable markings were assessed throughout the decay analysis and may be used a predictors during future applications. In the following section, the influence of the elapsed time, traffic volume, climate and snow removal will be evaluated with consideration to each durable marking. It will be important to take into account the various material characteristics of each marking, the size of each data pool and the amount of variability throughout the retroreflectivity data. In addition to these parameters, the time of year that the markings were applied will also be examined as proper application techniques are critical for optimum performance.

Age Effect

Previous studies indicate that the age of a pavement marking is the most important variable when predicting retroreflectivity. Figure 11 displays the relationship between age and retroreflectivity for all pavement markings incorporated into the investigation. Each data point on the graph represents an average reading for a particular test site during a specific data collection event. The following is a description of the sample population:

- 11 Thermoplastic Projects with 99 test sites.
- 4 Polyurea Projects with 33 test sites.
- 1 Epoxy Project with 5 test sites.

Please note that due to the small sample population for the LPM pavement markings, both surface applied and recessed markings were incorporated into the graph as shown below.

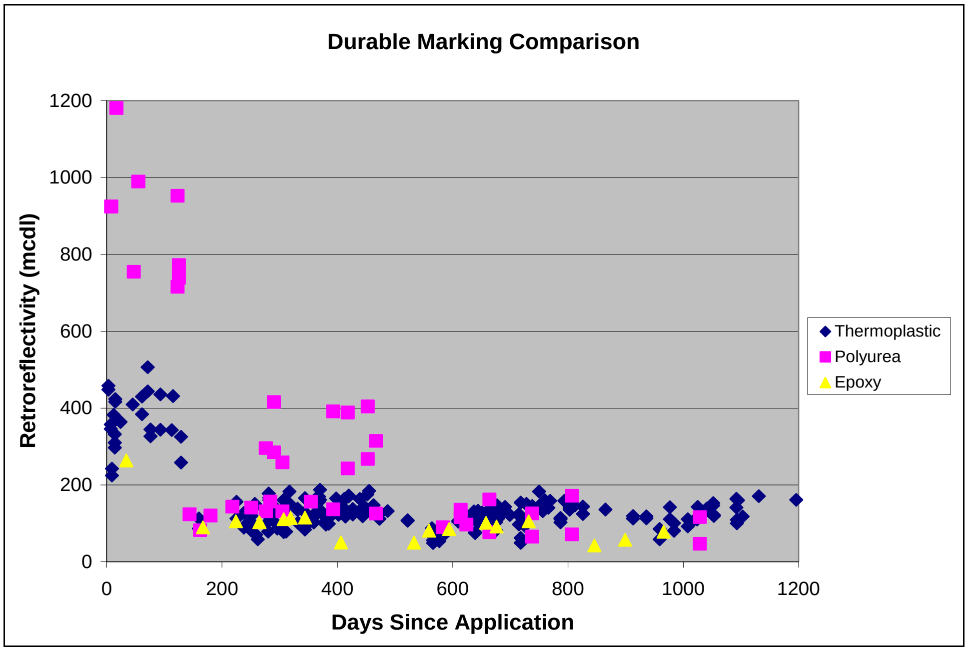

Figure 11 – Overall Comparison

As shown in Figure 11, retroreflectivity decreases in a non-linear fashion as pavement markings age. Additionally, the amount of variability in retroreflectivity for markings of the same age is quite evident. The variability decreases both in absolute value and in percentage of residual retroreflectivity. A significant loss of retroreflectivity is noted within the first 180 days following application most likely attributed to winter maintenance practices. Polyurea pavement markings display much higher luminance within the first 450 days following application. However, it was quite surprising to observe that polyurea and thermoplastic materials exhibit similar retroreflectivity following 540 days of application. As a final note, an annual cyclic pattern within thermoplastic projects is highly discernable. The decrease in early winter is followed by a recovery phase between April and June. The shape of the exposed glass bead is controlled by maintenance practices during winter months and tire abrasion during summer months.

Based upon data collection from one project, epoxy markings appear to be inferior to all other durable markings within this study. However, it is important to consider that installation was conducted on October 22, 2002 when the reported minimum and maximum ambient air conditions where 31^{o}F and 43^{o}F, respectively, on the low end of the specified minimum application temperature of 40^{o}F potentially resulting in inadequate performance. A special type of bead, known as Visibead, was also dropped onto the marking material. These are much larger in diameter as compared to the standard AASHTO Type I beads and may require additional binder thickness. However, records indicate that a standard film thickness of 20 mils +/- 2 mils was utilized. Inadequate cure conditions coupled with a minimal film thickness for the larger glass beads likely resulted in reduced bond strength and loss of glass beads due to winter maintenance practices.

Traffic Volume Effect

The distribution of the number of observations by AADT is provided in Table 3. Each data set by marking type was proportioned into two bins in terms of the number of observations, with one bin having a traffic volume equal to or less than 6,000 vehicles per day and one bin with a traffic volume greater than 6,000 vehicles per day. A scatter plot of thermoplastic and polyurea markings is displayed in Figures 12 and 13, respectively. The sample population for each marking is comprised as follows:

- 6 Thermoplastic Projects with an AADT less than or equal to 6000 and 5 projects with an AADT greater than 6000
- 1 Polyurea Project with an AADT less than or equal to 6000 and 3 projects with an AADT greater than 6000

As there was only one epoxy project examined in this study, the effect of traffic volume could not be examined.

Number of Observations by AADT			
AADT	**Number of Observations**	**Percent of Observation**	**Cumulative Percent**
1000-2000	980	13.03%	13.03%
2000-3000	1130	15.03%	28.06%
4000-5000	550	7.31%	35.37%
5000-6000	1260	16.76%	52.13%
6000-7000	1590	21.14%	73.27%
11000-12000	490	6.52%	79.79%
15000-16000	345	4.59%	84.38%
25000-26000	975	12.97%	97.34%
39000-40000	200	2.66%	100.00%
Total:	7520	100.00%	

Table 3 – Traffic Distribution

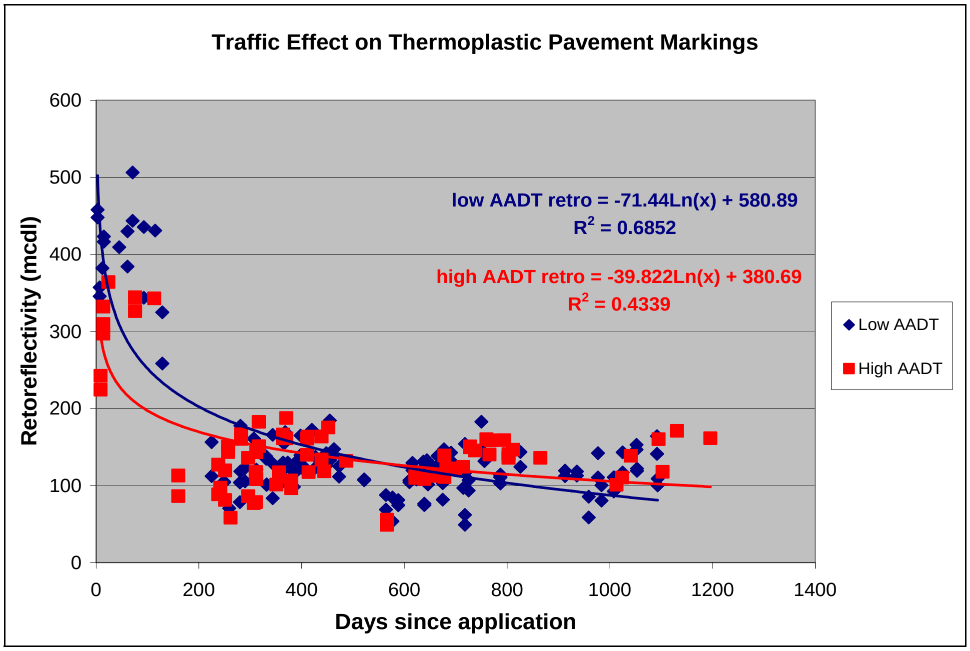

Figure 12 – Thermoplastic AADT Comparison

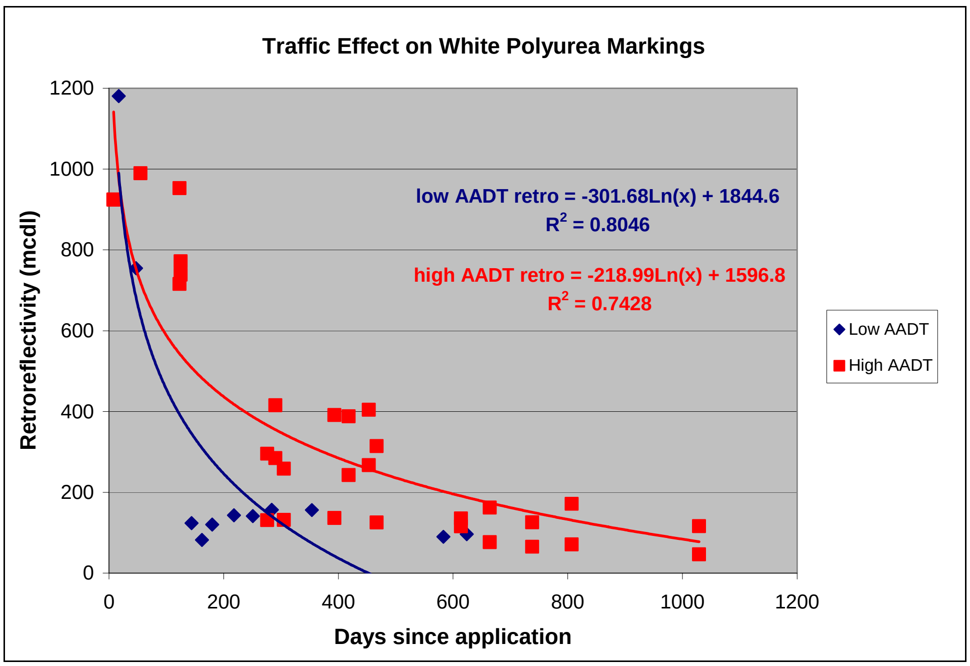

Figure 13 – Polyurea AADT Comparison

Although counterintuitive, Figures 12 and 13 depict higher rates of decay for rural applications over high traffic locations. In examining Figure 12, thermoplastic markings within a heavily traveled roadway decay more readily within the first 1.5 years of application. Following this period, markings applied in a low AADT area display greater decay with resultant low retroreflectivity. A plausible explanation for this condition relates back to condition of the glass bead at the surface. Wear rates on the beads are affected by two specific events – plowing and tire abrasion. The bead surface under plow-sheared conditions does not provide retroreflectivity. As tire abrasion removes the marking material the bead is re-exposed to incipient light at low angles. This phenomenon explains the recovery on high AADT roads. The glass bead is worn at a lower rate than the marking material that holds the bead in-place.

As shown, all of the thermoplastic marking data points are clustered together regardless of traffic volume. This may be attributed to the greater application thickness of the thermoplastic markings as compared to the other durable markings. As the markings begin to wear down, additional beads are exposed. A thicker marking should allow for an increased amount of time before the marking is worn through, assuming that the resistance to wear, or hardness, is similar for all materials. However, the polyurea retroreflectivity results as shown within the graph are from both surface applied and recessed markings. Given that the application methods vary, no conclusion will be drawn regarding the overall effect traffic volume on polyurea markings.

Regional Effect

The geographic regional effect on retroreflectivity over time is explored in Figures 14 and 15. The state was divided into three distinct areas as follows: the Champlain Valley (Region 1), the northeast/central area (Region 2) and the southern region (Region 3). The Champlain Valley is the most heavily populated region in Vermont and lies alongside Lake Champlain which moderates the weather in nearby areas. Outside heavily populated areas, the remainder of the valley is characterized by open pastures. The northeast/central area is characterized by the Northeast highlands, Green Mountains and Western New England Upland. This area is known for an increased annual snowfall amount in comparison to both Regions 1 and 3. Southern Vermont is defined by the Taconic Range extending from Massachusetts and the Western New England Upland. While each region is unique in terms of land use and population density, other concurrent studies define Vermont as a cold climate and heavy snowfall removal. The sample population is composed as follows:

- Two thermoplastic projects in Region 1, five projects in Region 2 and four projects in Region 3.
- One polyurea project in Region 1 and two projects in Region 2.

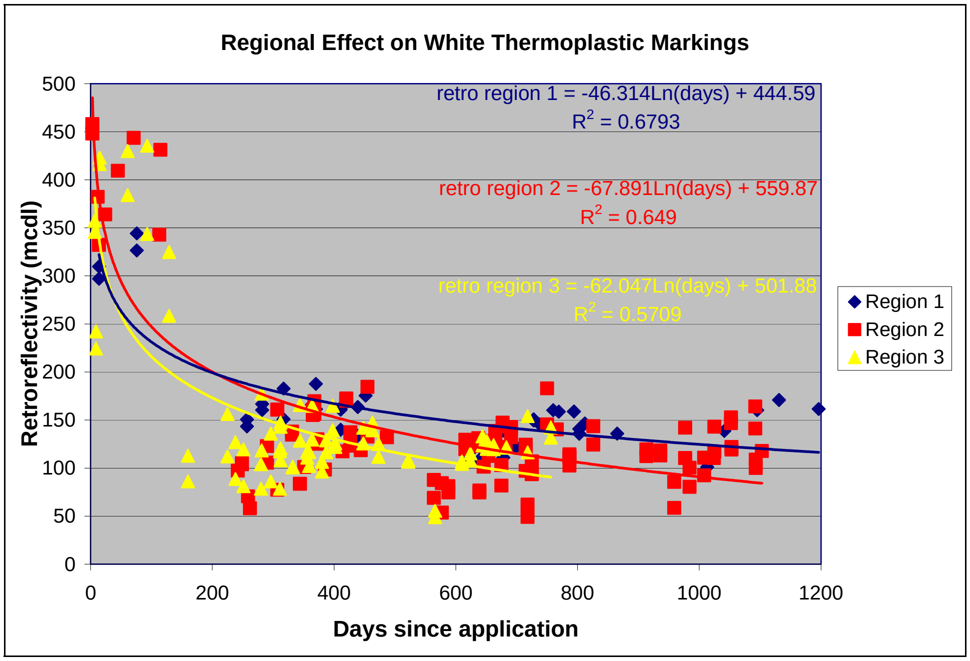

Figure 14 – Thermoplastic Regional Comparison

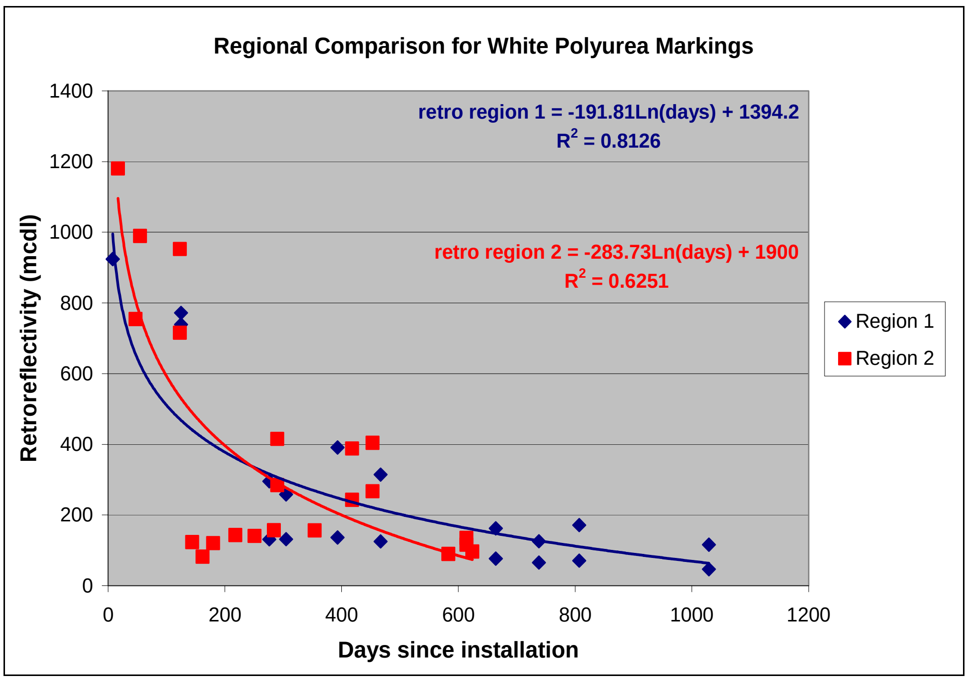

Figure 15 – Polyurea Regional Comparison

In examining Figures 14 and 15, it does appear that the location of a project within a specific region does have an effect on the overall durability and luminance of a marking. As would be expected, markings within a warmer region, as found in the Champlain Valley, appear to retain a higher level of retroreflectivity over time as was true for both the thermoplastic and polyurea markings. Then again, this area is also known for a high population density, or AADT, which typically results in a greater amount of abrasion. It may be surmised from this information that winter maintenance practices, or shearing, cause more damage than tire abrasion. Utilizing the same logic, it was surprising to note the greatest loss of retroreflectivity within the southern region of the State as this area typically receives an annual snowfall amount of 76” as compared to the northeast and central region which obtain an annual snowfall amount of 101” and 67”, respectively.

Seasonal Application Effect

Figures 16 and 17 assess the impact of late season application on the overall durability of thermoplastic and polyurea pavement markings, respectively. The date of application for each project was examined and utilized to create two bins, summer (June through August) and fall (September through November). The sample population is composed as follows:

- 7 Thermoplastic projects applied during the summer and 4 projects applied in the fall
- 2 Polyurea projects applied during the summer and 1 project applied in the fall.

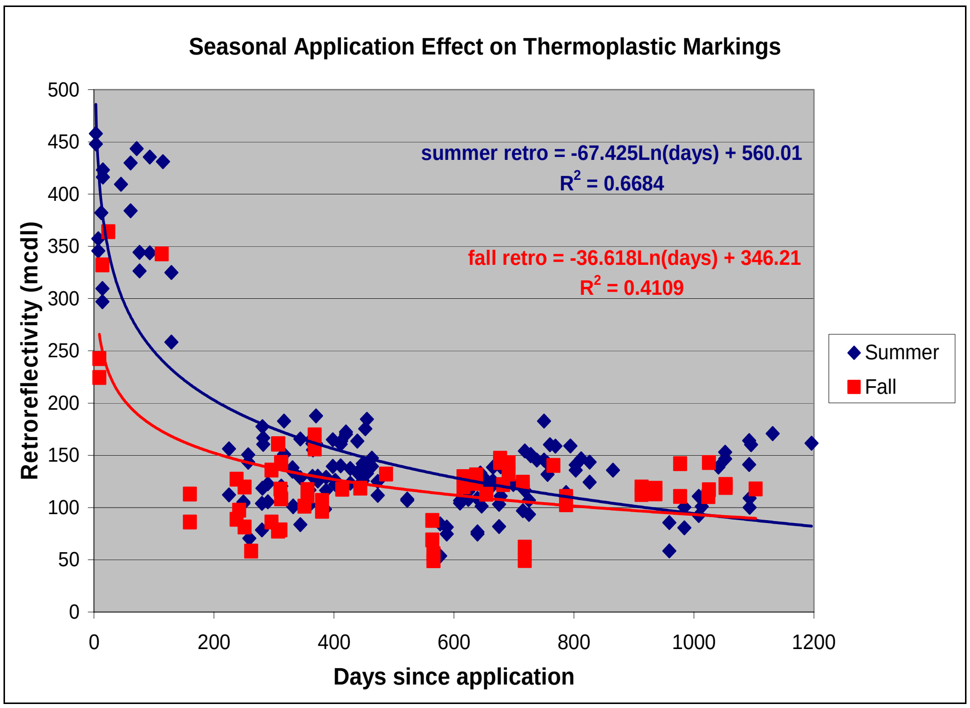

Figure 16 – Thermoplastic Seasonal Comparison

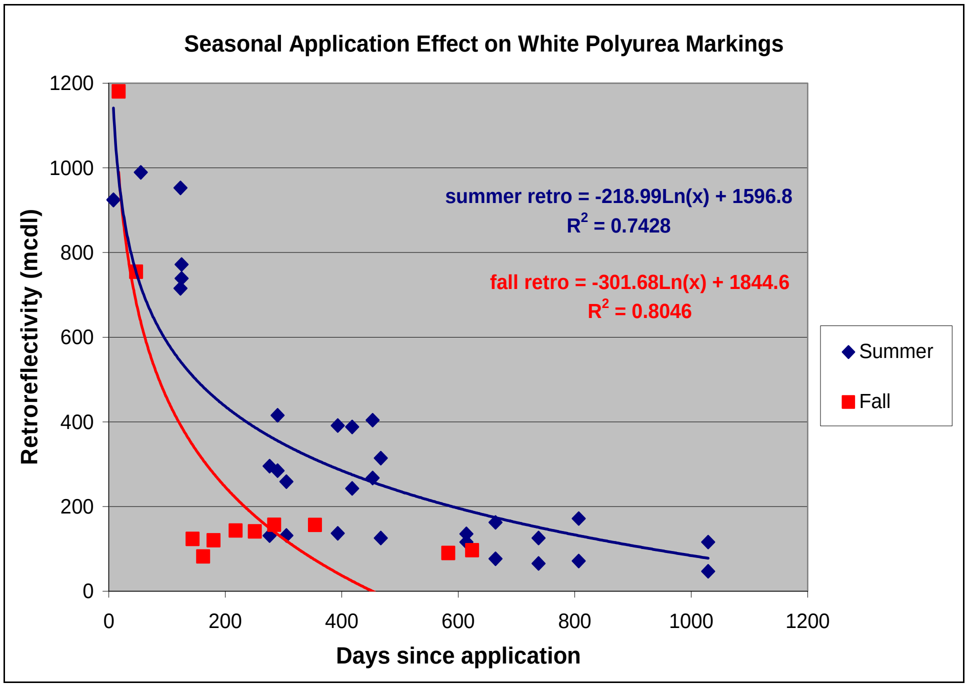

Figure 17 – Polyurea Seasonal Comparison

As shown within Figure 16 and 17, there does appear to be a correlation between seasonal placement and luminance. Within the first six months following placement, the retroreflectivity of markings applied during summer months was found to be greater as compared to markings placed during the fall. For thermoplastic markings, this trend is most evident within the first few months of application when markings applied during the summer exhibit a greater amount of reflectivity, 100 mcdl on average prior to any winter maintenance practice. After two and half years of service, the two data sets are coincident and display similar luminance. The same appears to be true for polyurea pavement markings, except the trend is less clear after one year of service. The recommended conditions for placement of the markings are dissimilar. Polyurea can be placed at a lower minimum ambient air temperature (40^{o}F) as compared to thermoplastic (50^{o}F). Therefore polyurea should be less susceptible to cure-related problems at lower temperatures, which may account for the greater effect of seasonal placement on thermoplastic markings during fall placement.

Recessing Effect

In an effort to increase the life cycle of pavement markings, the Agency began an initiative to recess polyurea pavement markings on the Interstate. The recess entails grinding the pavement where markings are to be applied to a specified minimum depth. In theory, recessed markings should be less subject to damage from winter maintenance practices, in particular plow-sheared beads should not occur significantly. However, recessed markings do not protect markings from tire abrasion. Figure 18, provided below, contains all Polyurea 2A projects incorporated into the study. The sample population contains two recessed and two surface applied projects.

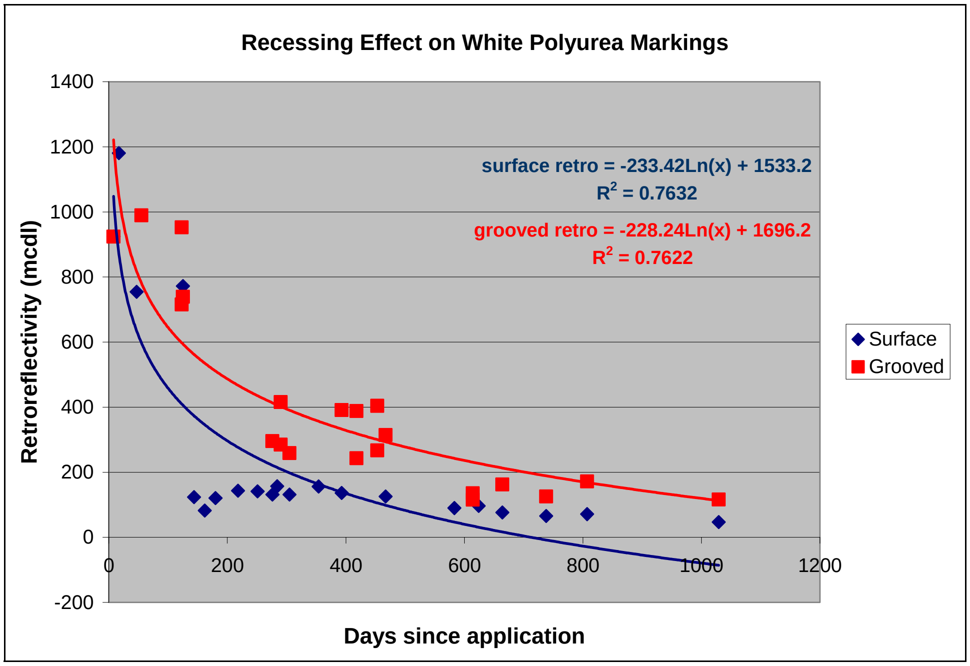

Figure 18 – Polyurea Recessing Comparison

As displayed in Figure 18, recessing does appear to aid in the retention of retroreflectivity over time. Prior to the first winter season, both recessed and surface applied markings display similar retroreflectivity. However, following the initial winter season, the overall loss of retroreflectivity of surface applied markings is much more apparent than recessed markings. Additionally, regression modeling was performed on both data sets with a resulting non-linear decay trend. Although the coefficient of determination indicates that the trend line is fairly accurate, pavement markings cannot absorb light. Negative readings cannot occur, suggesting that a boundary condition exists. The model was influenced by the great loss of reflectance following the first winter season, roughly 615 mcdl for surface applied markings and 300 mcdl for recessed markings. This loss is significant and should be considered during marking selection. In order to more accurately model the decay of the polyurea markings, each parameter was separated into two discrete bins, prior to and following 180 days of application as displayed in Figure 19.

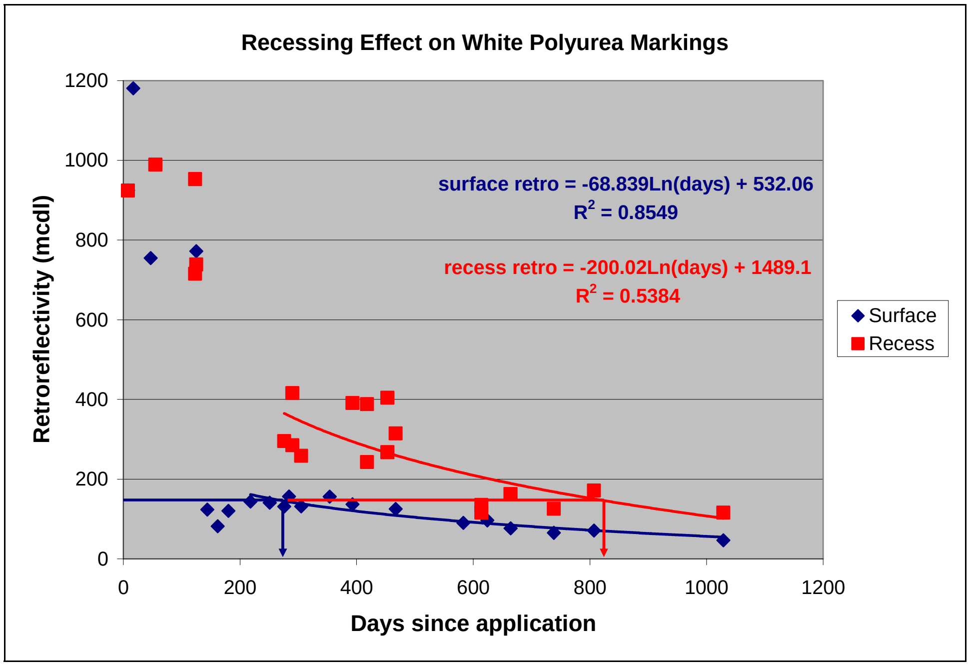

Figure 19 – Polyurea Recessing Comparison

As you can see, the new polyurea marking regression model fit from 180 days appears to be more sensible as both trend lines follow the two data sets. This further maintains the idea that pavement markings in Vermont as more susceptible to plow damage than any other variable with the exception of elapsed time. The number of elapsed days prior to meeting the FHWA recommended minimum retroreflectivity of 150 mcdl for interstates was calculated to be approximately 280 days for surface applied and 830 days for recessed markings, respectively. Seasonal rebound observed within thermoplastic markings is not evident within polyurea markings. This may be due to inherent material characteristics such as polyurea greater hardness, which means that it may not benefit as readily from tire abrasion.

Findings

As shown in concurrent ongoing pavement marking assessments, there are many parameters that impact the longevity of pavement markings. However, roadway conditions vary throughout the United States including climate, traffic volume, pavement surface and snow removal practices. Therefore it is important to examine each parameter separately to determine individual contribution to decay rates. Inferences may then be made about the combined effect and which factor appears to have the greatest impact on decay.

In Vermont, the age of a marking has shown the highest correlation to overall durability. However, all durable markings show very significant effect from winter maintenance. The essential nature of winter operations precludes obvious change in effect on markings. Winter maintenance practices certainly takes a toll, especially during the first winter following application, with an average calculated loss of approximately 100 mcdl for thermoplastic markings, 150 mcdl for epoxy markings and 300 mcdl for polyurea markings. Loss in subsequent winter seasons was lower; however an annual cyclic pattern was detected. This is especially true for thermoplastic markings and may be the result of material characteristics as well as application thickness. Additionally, a slight regional effect within Vermont was also observed but, once again, this is mostly likely the result of the average snowfall amounts within each region. Surprisingly, traffic volume was not found to have much of an influence on the overall durability of the pavement markings or it simply may be overshadowed by snow removal or may be due to the smaller range of traffic volumes in Vermont as compared to other more densely populated regions.

Construction techniques were proven to be vital for optimal performance. Retroreflectivity readings collected within the first six months of application were shown to be higher when applied during summer months as compared to fall placement. This may be caused by lower ambient air and surface temperatures during installation or could be the result of reduced pavement cure time. Cure times for bituminous pavements affect the bond strength of the markings to the underlying pavement and resulting color. Recessing pavement markings has proven to be effective in reducing the impact of plow damage. While there was a loss of retroreflectivity in both surface applied and recessed markings during the first winter after placement, the loss was much greater for surface applied markings. If these beads or any other part of the marking protrudes above the surface of the pavement it will be impacted by snow plow damage. However, once these beads or marking material is dislodged it is unlikely that any other portion of the marking would be damaged.

COST ANALYSIS

Regression modeling was performed on each type of durable marking assessed within this investigation. All models are based upon the average retroreflectivity values collected in the field for each paving project. As there was an identifiable interference with snow plow damage along with a great loss of luminance following one winter season, all polyurea markings, regardless of type and application method, were modeled in two increments, prior to and following one winter season. This appeared to provide the best fit to the data points. Conversely, while winter maintenance damage is also visible in thermoplastic and epoxy markings, the magnitude of the initial loss is much smaller allowing for one best fit non-linear trend line. Figure 20 displays each trend line along with marking type.

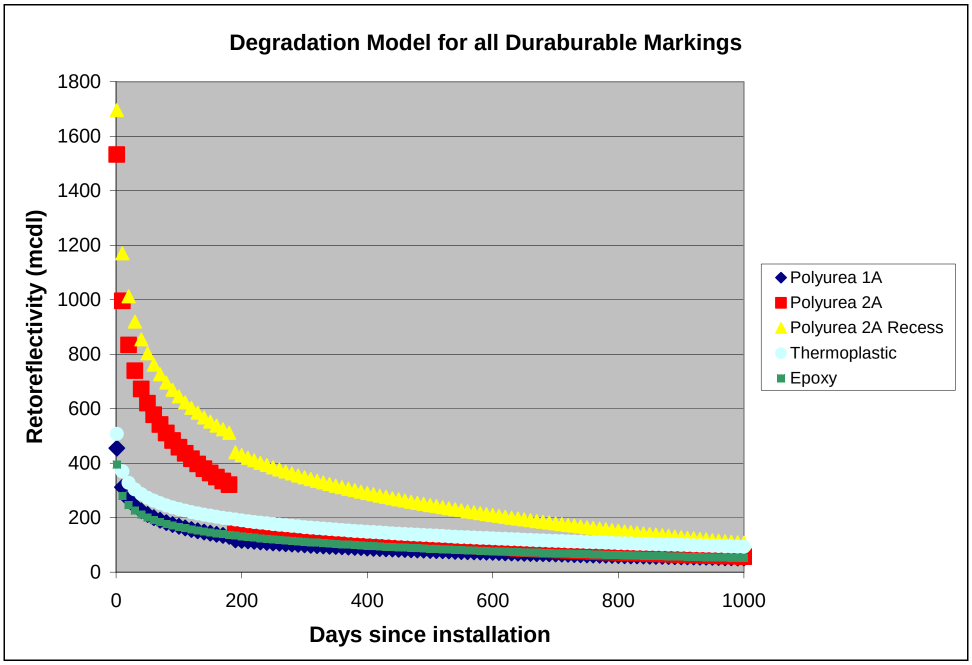

Figure 20 - Modeled Durable Marking Longevity

In addition to the decay analysis provided within the figure above, the equation of each trend line is supplied in Table 4 along with the coefficient of determination.

Pavement Marking Durability Decay Models			
Marking Type	**Applicability**	**Model**	**R^2**
Thermoplastic	-----	=-60.018*LN(elapsed days)+507.54	0.59
Epoxy	-----	=-49.648*LN(elapsed days)+394.52	0.68
Polyurea 1A	<180 days	=-49.648*LN(elapsed days)+455.24	0.87
	>180 days	=-40.065*LN(elapsed days)+328.38	0.85
Polyurea 2A	<180 days	=-233.42*LN(elapsed days)+1533.2	0.76
	>180 days	=-68.839*LN(elapsed days)+532.06	0.86
Polyurea 2A Inlaid	<180 days	=-228.24*LN(elapsed days)+1696.2	0.72
	>180 days	=-200.02*LN(elapsed days)+1489.1	0.53

Table 4 – Decay Analysis

Generally, the computed trend lines from the retroreflectivity data are precise given the amount of variably within the data sets and small sample population. As expected, the trend line for the thermoplastic marking material appears to be a weak fit to the data. This is most likely due to the detected cyclic seasonal pattern. However, the trend line appears to underestimate the long term retroreflectivity of the thermoplastic markings resulting in a conservative model. Therefore all equations were used to determine the amount of elapse time until each marking fell below a particular benchmark. As the roadway types vary from Interstates, US and Vermont Routes, a minimum acceptable value of 100 mcdl was selected for all projects and marking types. Table 5 summarizes the estimated service lives for the various types of pavement markings. Standard waterborne paint markings were assessed on a limited basis throughout the investigation. From this small data set, it appears that waterborne paint markings remain at or above the minimum acceptable reflectance of 100 mcdl for about 12 months and are much cheaper to apply than any durable markings.

Pavement Marking Durability Cost Analysis						
	Elapsed Time		Historic Records		Industry Comparison	
Marking Type	Days	Months	Cost	Cost/Month	Cost	Cost/Month
Thermoplastic	889	29	$0.46/LF	**$0.02**	$0.48/LF	**$0.02**
Epoxy	377	12	$0.26/LF	**$0.02**	-----	**-----**
Polyurea 1A	299	10	$0.68/LF	**$0.07**	$0.75/LF	**$0.08**
Polyurea 2A	532	17	$0.93/LF	**$0.05**	$1.00/LF	**$0.06**
Polyurea 2A Recessed	1038	34	$1.34/LF	**$0.04**	$1.42/LF	**$0.04**
Waterborne	-----	12*	-----	**-----**	$0.06/LF	**$0.01**

*Estimated

Table 5 – Computed Service Lives

In addition to a service life estimate, the cost for the placement of each marking by linear foot was configured from historical bid information. Due to the recent application of polyurea and epoxy markings, historical information is limited. Therefore, a private contractor was also contacted to attain current pricing. The costs reflected within Table 5 include labor, materials and overhead.

The results from the Table 5 are somewhat surprising and should be given some additional consideration. While all polyurea markings were expected to display a greater amount of reflectance over time as compared to thermoplastic, this was not found to be the case. Surface applied polyurea markings decay more readily than expected. This is counterintuitive given the hardness of the material and differing glass beads. However, the optimum application thickness is only 19 dry mils which may be inadequate considering winter maintenance practices in Vermont. Surface applied epoxy markings were found to display a lowest initial retroreflectivity and quickly decayed over time. However, the ambient air temperature during placement may not have been within the manufacturer’s specifications as they were applied during October. Thermoplastic and recessed polyurea markings were found to display the best long term retroreflectivity. Waterborne markings appear to be the most cost effective but would require annual restriping.

Not only is it important to examine the amount of time elapsed to reach a minimum retroreflectivity, but it’s also valuable to consider the initial increased reflectance provided by polyurea markings, specifically Polyurea 2A. Higher initial retroreflectivity will increase nighttime visibly as the contrast between the road surface and pavement markings will be greater. This increased luminance would prove beneficial during storm events and for older drivers. The cost effectiveness modeled above presumes that there is no benefit to retroreflectivity in excess of the minimum standard. This is a key policy consideration, as cost effectiveness measured against a luminance-time parameter would substantially change the benefits associated with high luminance markings.

SUMMARY:

In an effort to determine the lifetime and life cycle costs of various durable pavement markings, the Vermont Agency of Transportation implemented a research program in order to produce recommendation regarding which materials are best suited for use on different roadway types. To date, over 24 newly constructed pavement projects have been incorporated into the investigation.

The retroreflectivity values from roadways with similar AADT and regional environments displayed a significant amount of variably. This variability is most likely attributed to several factors including application methods by different striping crews, inherent variability in the test device, and/or environmental conditions during data collection. However, many studies have discovered similar variation and trends which indicate that prediction modeling may provide a good general view but may not be applicable for a specific day or project.

Data reduction measures were carried out on all data sets. These included the removal of any readings collected over wet pavements thereby minimizing retroreflectivity or over salt residual which has shown to greatly increase the reflectance. Additionally, data collection commenced in the summer of 2002 which included projects constructed in 2000. Due to the current marking program practices, it was difficult to ascertain whether readings were collected on preexisting or newly freshened pavement markings. Therefore, all pavement projects constructed in 2000 were removed from overall data set.

Corollary statistics were created in order to determine which variables appeared to greatly effect the decay of the pavement markings. Age was found to be the most reliable variable in determining retroreflectivity and was subsequently used to model the decay of the pavement markings. In addition, a large drop in luminance was observed during the first winter following placement most likely caused by snow plow damage. Interestingly, traffic volume and regional placement did not appear to control the decay of the markings. Application techniques such as recessing and time of placement did prove to be important for optimum performance. Proper application in accordance with the manufacturer’s recommendations is advised.

The retroreflectivity of each marking was modeled in a logarithmic trend line as a function of time. Due to the initial increase and significant loss of retroreflectivity following one winter season, all polyurea markings were modeled in two time durations, prior to and following 180 days after application. The time to a minimum acceptable retroreflectivity, or 100 mcdl, was calculated along with the cost per month of each marking.

So the question remains, what is important to you? A compulsory marking protocol by roadway type is not recommended. Rather, an examination on a project by project basis

is advised recognizing that safety has both construction and post-construction components for the marking selected. It is important to consider the projected outcome. Is a first-cost effective marking that may not provide the long term benefits a good selection? Or could an increased reflectance be vital in a demographic comprised of older citizens? Maybe the longevity of a marking is important in areas that are further away from Operation centers. In any case, due to the smaller epoxy and polyurea data sets, additional data collection is recommended in order to verify all findings within the report.

References

Migletz, James, and Jerry Graham. "Long-Term Pavement Marking Practices." *National Cooperative Highway Research Program* Synthesis 306 (2002): 1-4.

Appendix A

VERMONT AGENCY OF TRANSPORTATION (VAOT)
RESEARCH ADVISORY COUNCIL (RAC)
RESEARCH, DEVELOPMENT AND TECHNOLOGY TRANSFER (RD&T)
FY2003 PROJECT SOLICITATION

PROJECT TITLE:
Pavement Marking Durability Evaluation

Submitting Individuals: C. Graham and T. Gilman | Date: April 5, 2002 | Phone: 2561

Division/Section/Unit: Technical Services/Materials and Research/Research and Testing

Type of Activity (Mark most appropriate item):
✓ *Applied Research* (To answer a question or solve a problem)
✓ *Basic Research* (To increase knowledge)
___ *Development* (Translation of research into a prototype use)
___ *Technology Transfer* (Leads to adoption of a new technology)

Project Goal(s):
The first goal of this project is to determine the lifetime and life cycle costs of pavement marking materials in the State of Vermont. The second goal is to produce recommendations regarding which materials are best suited for use on different roadway types (i.e. Interstate, State and Town Highways).

Brief Description of Project (Attach additional sheets if necessary):
Pavement markings are an important part of any construction project by contributing to the safety of the roadway. Many materials are available for use in the State of Vermont, without any policy as to which markings should be used dependent on the type of roadway. This research project is intended to make recommendations for the development of such a policy, and includes a field study with data collection to determine the life cycle cost of materials used, and an engineering study into the mechanisms behind the change of factors that affect the performance of a material. The study can be divided into the following phases: (See attached scope of work)

Phase I: Literature Review to determine what practices for evaluation of pavement markings exist in other states including research and operation activities.
Phase II: Compilation of data taken from existing research projects, and continued collection of data from those projects.
Phase III: Collection of additional data from newly constructed projects.
Phase IV: Analysis and reduction of data including supplemental data collection descriptions.
Phase V: Economic Analysis to evaluate life cycle costs over the projected pavement life.
Phase VI: An engineering evaluation of the deterioration mechanisms of the performance factors.
Phase VII: Compilation of data and findings in the form of a final report including conclusions, recommendations and a summary program outline.

Project Deliverable(s):
Each of these phases will have a workplan outlining research procedures and Interim Reports will be provided after Phase II, Phase IV, and a Final Report after Phase VII.

Scope of Work by Phase
04/01/02

Phase I: Literature Review FY02

A literature review will be performed by the research staff and include research performed on the state, regional and national levels. Collection and synthesis of this information will be tabulated and documented in a summary and bibliography. This information will expand the researcher's knowledge of pavement markings, testing procedures, current research, current operation practices and new technologies. Identification and proposal of test methods will also occur in this phase.

Upon completion of this phase a stakeholders meeting will be arranged with interested members of the Agency of Transportation to discuss the outcomes of this study.

Phase II: Compilation of data taken from existing research projects and continued collection of data from those projects. FY02-05

In the year 2001 data has been collected on 3 construction projects including 6 different materials. Data has been collected on the Lyndon-Barton Project #IM 091-3(10), 3M Stamark™ Liquid Pavement Marking series 1000 & 1200 and Per Spec Thermoplastic were used. Data has also been collected on the Statewide Project #IMG-MARK (101) where 40 mils Thermoplastic and Standard Waterborne paint was used. Finally data has been collected on the Middlesex-Bolton Project #AC IM 089-2(26) where Snowplowable Raised Pavement Markings were used. The workplans associated with each of these projects are 2001-R-3, 2001-R-1, and 2001-R-6 respectively. This project will increase the frequency of testing and the types of tests performed at these locations. Currently 5 retroreflectivity readings are taken monthly at 5 test sites per line per material. The same number of readings will be taken on a biweekly basis. We will also include additional tests that will be performed in the lab on material sampled from the sites. The additional tests in the field will include but are not limited to a high-resolution digital photograph, a subjective appearance rating, and day/night reading comparisons (See attached Data Collection Procedure and Record Form).

An interim report will be completed at this time to mark progress.

Phase III: Collection of additional data from newly constructed sites FY02-05

In the year 2002 five resurfacing projects are expected to be constructed, those projects will be evaluated to determine their suitability for involvement in this study. Criteria of material type, roadway use, and surfacing material will be used to determine suitability. Test sites will be located on each project using a random selection method for test location (see attached spreadsheet). Data will be collected and recorded in the same manner as *Phase II* (see attached Data Collection Procedure and Record Form).

Phase IV: Analysis and Reduction of Data FY03-05

An analysis will be performed on the data to evaluate statistical validity and conformity. Additional data collection will be performed if deemed necessary. Then an analysis of the results will be performed to establish the lifetime of each material tested. The lifetimes will be either observed or projected based on threshold values and regression modeling techniques. The final analytical portion of this phase will be to find trends to investigate in *Phase VI,* the engineering evaluation.

An interim report will be completed at this time establishing product life, product performance tables and to address issues that will be investigated in Phase VI.

Phase V: Economic Analysis FY03-05

The lifecycle cost of each material will be determined in this phase. Factors to determine the life cycle cost will include but are not limited to application costs, overcoating material options, overcoating costs, roadway repaving time frames, and current and future economic trends.

Phase VI: An Engineering Evaluation of the deterioration mechanisms of the performance factors FY04-05.

Retroreflectivity is expected to vary over time, causes of this variation are expected to be snowplow abrasion, tire wear and environmental degradation of the material. In this phase those causes will be explored from an engineering perspective including investigating the chemical and physical changes occurring within the material. The complete scope of work for this phase will not be known until the completion of *Phase IV*.

Phase VII: Compilation of data and findings to form conclusions and recommendations FY05

The final report for this project will be developed in this phase. This report will be directed toward three different audiences, our peers in research, designers, and the general public. An executive summary will let the general public see the full project scope at a glance, a forward will direct designers to the pertinent design information and the full report will detail the research methods used.

Estimated Project Duration/Phasing: Data collection will continue for a period of three years on newly constructed projects.
Estimated Cost: Total $110,000 Yearly Breakdown: $ FY02: $20,000; FY03: $30,000; FY04: $30,000; FY05: $30,000
Funding Other Than SPR (Matching Source(s) / Amount(s): None
How the Agency.s .Vision/Mission is supported (Area(s) addressed): This project will help support and maintain Vermont's transportation systems and promote efficient operations in both design and maintenance of pavement markings. This project will also enhance safety on a statewide level.
Describe the urgency of this project: Currently there is no design guidance policy for selection of pavement marking material type on projects, and there is a need for such a policy. This project will produce a policy and compare the performance of material types which will be useful to design and maintenance.
What will happen if this project is not approved: The state will continue using materials that may not be the best alternative for a particular roadway and safety concerns will continue to be an issue.

Appendix B

Pavement Marking Durability Evaluation L. Ashworth
Phase I: Literature Review May 23, 2002

Pavement markings are an important component of any highway construction project, as they provide safe delineation on any roadways. There are many different types of pavement markings available for use in the State of Vermont as well as many different products of each material type. Currently there is no established policy in the State of Vermont, which specifies materials based upon classification of roadway, and therefore no criteria to base a decision on. The overall goal of this research project is to investigate material qualities and performance to contribute to such a policy. This portion of the research project is a review of available literature on the subject.

OBJECTIVES

One of the objectives of this literature review is to expand the researchers' knowledge of pavement markings, testing procedures, current research, current operation practices and new technologies. Another objective is to compile research methods, testing procedures and conclusions from current research for the benefit of the reader.

This narrative report summarizes the literature reviewed including the objectives and the findings or conclusions that were made. The objectives of the field studies, the materials tested, the tests used, the sampling procedures and how the results are presented, are included in the attached worksheet titled Report Table.

INTRODUCTION

Three major groups of studies are summarized in this report, Field Studies, Laboratory Studies and Pavement Marking Management Studies. Field testing techniques addressed include durability, retroreflectivity, color measurements, brightness evaluation, removability, and discernability. A complete list of laboratory testing techniques is included in the attached table, some examples are adhesion, specific gravity, flowability, and viscosity. Materials tested in these reports include thermoplastics, epoxies, paints, tapes, and polyesters. See the glossary included in this report for a description of material types.

FIELD STUDIES

NTPEP Reports (1996-1998)

These reports (2,3,4) present a collection of field data taken in four locations across the country. Durability, retroreflectivity readings, and brightness evaluations were collected on all the liquid markings, and removability and discernability ratings were given to the tapes. All the materials were placed on the same standard NTPEP Test Deck, which includes both AC and PCC surfaces, located in four different climatic regions of the United States. The four regions are the northeast, for a cold-humid climate, the southeast for a hot-humid climate, the northwest for a cold-dry climate and the southwest for a hot-dry climate.

These reports contain the most extensive list of laboratory tests, which is included in the following table. No conclusions made from the data are included in the reports; the data is simply presented for interpretation by the reader.

Las Vegas Test Decks (2001)

This study (10) addresses three objectives, the first is to evaluate the performance of various materials, the second is to compare the materials performance on asphalt versus concrete and the third is to compare results on a NTPEP Test Deck versus an Intersection Test Deck designed for this study.

The NTPEP Test Deck was constructed on both an AC and a PCC pavement near the same location. The Intersection Test Decks were constructed in six intersections on AC pavement and were marked with experimental stop bars and pedestrian crosswalks. Four material types were evaluated; paints, tapes, preformed thermoplastic and thermoplastics. All the materials were tested for durability, retroreflectivity and color.

Conclusions made about the durability of the materials included that the paints performed the worst on the Intersection Test Deck, but performed comparably to all the other materials on the NTPEP Deck, illustrating that the NTPEP Test Deck may not accurately simulate an intersection situation. The retroreflectivity results yield several conclusions. Overall the difference in readings between materials was more pronounced on the Intersection Test Deck than the NTPEP Test Deck, and there was no consistency found between the performance of the individual materials between the test decks. The materials on the PCC pavement had relatively higher readings than the materials on the AC pavement, probably due to the asphalt in the pavement dirtying the material. Color measurements were taken, but they could not be compared across material types because the value varies with thickness and texture. Only subjective evaluations were taken about color.

Rhode Island NETC Test (1995)

This study (13) evaluates five different application procedures of thermoplastic and tape in three different open grade friction course roadway sections according to durability and retroreflectivity. The test segments were set up with experimental skip lines on an exit ramp, a tangent section and a curved section. The materials tested were; fully recessed thermoplastic (FRT), semi-recessed thermoplastic (SRT), tapered recessed thermoplastic (TRT), non-recessed thermoplastic (NRT), and permanent inlaid tape.

Overall the recessed thermoplastic markings had slightly higher durability values than the non-recessed thermoplastic markings, and significantly higher durability values than the inlaid tapes. The largest difference in recessed and non-recessed thermoplastic durability values occurred on the exit ramp. The retroreflectivity values reduced significantly for all the materials, and only the tapered and non-recessed thermoplastic retained a retroreflectivity value above 100 mcd/m^2/lux. Wet night retroreflectivity values were also collected and they showed that the more the marking was recessed the lower the retroreflectivity, probably due to the increased thickness of the water film.

This report also includes cost and cost effectiveness data.

1999 Migletz Report

This study (12) evaluates data collected from field surveys which took place with 32 states highway and local agencies. Six types of pavement markings (epoxy, polyester, solvent borne paint, water borne paint, tape and thermoplastic) were evaluated in 1994 and 1995 using a Retrolux 1500 retroreflectometer. Retroreflectivity values were taken of both the line and the surrounding pavement, giving a contrast ratio as well as a retroreflectivity value.

This report provided a few general conclusions. The color of the marking greatly affects the retroreflectivity, white being the higher of the two. Durable markings generally have higher retroreflectivity values than paints. States with relatively severe winter climates see a large drop in values over the winter months.

2001 Migletz Report

This report (11) evaluates data from field surveys taken in 19 states on epoxies, polyester, poly methyl methacrylate, thermoplastic, preformed tapes, and raised retroreflective pavement markings.

The objective of this report was to determine the service life of the pavement markings based on both time and cumulative traffic passes. This report produced equations through regression modeling. The modeling was performed separately for each marking at each site, because a correlation between the markings at different sites could not be found. The variations in service life from one site to another within the same product were attributed to roadway type, regions of the country, marking specifications, and installation practices.

Michigan Field Study (1997)

This is a four-year study (17) with three test areas in the state of Michigan. Retroreflectivity readings were taken over the four years at 70 different locations on three materials, polyester, thermoplastic and water-based paint.

Conclusions made from the study are as follows. The type of pavement surface had little effect on the performance, yellow paint had lower retroreflectivity results than the white paint. Snowplow wear seems to be the largest factor leading to degradation of the lane lines.

LABORATORY STUDIES

Glass Sphere Loading Determination (2002)

A study was conducted in Michigan (15) to develop methods of determining the glass sphere content of recently placed materials. Two techniques are developed first a pyrolysis, where the sample is heated at 500°C for 5 hours and the change in weight monitored; and second, macroscopic photography with digital analysis.

The Pyrolysis method accurately determines the amount of glass spheres contained within the sample, but does not determine the amount of glass spheres that are visible and contribute to the retroreflectivity of the material. 5 white and 5 yellow samples of pavement markings were analyzed with a known quantity of glass beads and results of the pyrolysis method varied between 6.3 and 0.8 percent error.

The digital analysis is capable of measuring the glass spheres that are exposed. Four panels were assessed by both methods with a correlation coefficient of $R=0.93$ which indicates that the image analysis can be applied to assess the glass content of pavement markings. Both of these tests are conducted on sheet metal panels taken from the roadway.

PAVEMENT MARKING MANAGEMENT SYSTEMS

Missouri's Phase I (2000)

An initial investigation into the effectiveness of Missouri's current pavement marking procedures and the feasibility of producing an automated customized Pavement Marking Management System (PMMS) (6). The objectives of the PMMS are to provide; a system to track the markings' performance, material selection based on valid data, better quality assurance, service life estimates and life cycle costs of materials, and a process to evaluate new materials. The consultant hired to conduct this research came up with some recommendations necessary to produce an effective program. They include providing a centralized location for the PMMS, defining who will have access to the system, and considering the differing needs of each district. The report also gives recommendations on the pavement markings and planning.

Iowa's Synthesis of Research (2001)

Iowa is also considering a program to evaluate pavement markings that would include maintaining a database of performance and cost information. This report (7) summarizes a collection of current research noting the NTPEP Research as one project to keep track of. The final recommendation of the report is not to develop a test deck until NTPEP releases all findings of their research and Iowa can focus on testing the materials that perform well for NTPEP.

South Carolina's Multicriteria Dynamic Segmentation in GIS (2001)

In order to accurately account for roadway conditions without storing large amounts of data on geographic information systems multicriteria dynamic segmentation is necessary. This paper (16) introduces this approach to more effectively manage the data for South Carolina's Pavement Marking Management System.

Minnesota's Pavement Marking Management System

No literature was available on Minnesota's program, so the Pavement Marking Section of the Office of Traffic Engineering was contacted and the information was provided through email by Jon Jackels of the MnDOT on May 24, 2002, which is attached here.

"Mn/DOT has adopted an aggressive goal of providing adequate pavement markings on all highways 365 days per year. To help achieve this goal we have adopted a pavement marking policy that uses many long term durable markings, primarily epoxy and polypreformed tape.

The material specifications are performance based and we have been tracking the performance of these products since the early 90s. We are continuing this program, however, we have begun to review, update and revise these specifications and requirements. The specifications also include provisions for monitoring our qualified products through our materials lab.

Two years ago we began to coordinate the maintenance of pavement markings on a statewide basis. Before this time each district managed their own pavement marking maintenance program with assistance from the Office of Traffic Engineering. During this time we developed a pavement marking management system that tracked costs and quality of all pavement markings installed by maintenance forces.

We have just begun an update of all of these pavement marking management tools. First, the central maintenance striping business has implemented new software that incorporates our statewide accounting systems to track all costs for materials, labor and equipment for all maintenance striping activities. Second we have just started to revise our old management system to incorporate improved statewide inventory and this new cost data. Third, we will be beginning to develop improved predictive models for all of our pavement marking materials for both construction and maintenance activities. It is our hope that this improved system will be in place for the 2003 striping season."

OTHERS

Environmental considerations (1997)

An NCHRP Report (5) addressing the environmental impacts and considerations of pavement markings in anticipation of the 1998 USEPA Regulations limiting volatile organic compound levels of marking materials. The report gives methodologies for assessing the performance of pavement markings in terms of both engineering and environmental performance.

Retroreflectometer Comparisons (2001)

This report (7) was prepared for South Carolina DOT in anticipation of developing a pavement marking management system. The primary task was to evaluate the effectiveness of retroreflectometers, a review of some research on retroreflectivity and a summary of a survey of states is also included.

Three handheld retroreflectometers, the Mirolux MP-30, the Delta LTL2000 and the Mirolux MX-30 and one mobile retroreflectometer, the Laserlux, were evaluated. Major considerations identified for the comparison are cost, calibration procedures, effects of temperature and humidity, effects of ambient light, and repeatability and reproducibility of results. Visual and statistical comparisons of the retroreflectometer data were made.

GLOSSARY

Retroreflection - Reflection wherein the reflected rays of radiation return along paths parallel to those of their corresponding incident rays.

Water-Based Paints - Paint in which the vehicle or binder is dissolved in water or in which the vehicle or binder is dispersed as an emulsion; and example of the dispersion type is latex paint.

> Acrylic -
> **(Acrylic resin)** - A thermoplastic synthetic organic polymer made by the polymerization of acrylic derivatives such as acrylic acid, methacrylic acid, ethyl acrylate, and methyl acrylate; used for adhesives, protective coatings and finishes.
>
> Alkyd-
> **(Alkyd resin)** - A class of adhesive resins made from unsaturated acids and glycerol.
>
> **Latex paint** - A paint consisting of a water suspension or emulsion of latex combined with pigments and additives such as binders and suspending agents.

Solvent-Based Paint - Paint in which the vehicle or binder is dissolved in a solvent or in which the vehicle or binder is dispersed as an emulsion. ???

Epoxy - A two component (two parts resin to one part curing agent) 100% soilds epoxy material, glass beads are applied to the material as it cures.
(epoxy resin) - A polyether resin formed originally by the polymerization of bisphenol A and epichlorohydrin, having high strength and low shrinkage during curing; used as a coating, adhesive, casting or foam.

Thermoplastic - **(AASHTO M-249)** Thermoplastic material which is homogeneously composed of pigment, filler, resins (hydrocarbon or alkyd) and glass reflectorizing spheres.
(thermoplastic resin) - A material with a linear macromolecular structure that will repeatedly soften when heated and harden when cooled; for example, styrene, acrylics, cellulosics, polyethylenes, vinyls, nylons, and fluorocarbons.

> **Hydrocarbon** - refering to the binder. Hydrocarbon thermoplastic is made from petroleum derived resins.
>
> **Alkyd** - refering to the binder. Alkyd thermoplastic contains a naturally occurring resin that is resistant to petroleum products. It is more heat sensative than the hydrocarbon thermoplastic.
>
> **Polymethyl methacrylate** - A thermoplastic polymer derived from methyl methacrylate, $CH_2=C(CH_3)COOCH_3$; transparent solid with excellent optical qualities and water resistance; used for aircraft domes, lighting fixtures, optical instruments and surgical appliances.

Polyester –
(polyester resin) – A thermosetting or thermoplastic synthetic resin made by esterification of polybasic organic acids with polyhydric acids; examples are Dacron and Mylar; the resin has high strength and excellent resistance to moisture and chemical s when cured.

Preformed Thermoplastic – A thermoplastic that consists of aggregates, pigments, binders and reflective glass beads. This composition enables the letters to be preformed, allows reasonable handling at normal temperatures and enables the product to liquefy and fuse together with the road surface when heated with a simple propane torch.

Liquid Pavement Markings – A two component, 100 percent soilds polyurea coating material with glass beads and possibly additional reflective elements.
(Polyurea) - Polyurea is a term which has been used for the last 15 or so years to describe a chemical technology based on two component reacted materials. One component is usually an amine blend and the other component is an isocyanate mixture. The combining of the two components results in very rapid reactions which produce extended chain polymer structures generally in a membranous form. While many of the products based on polyurea technology are used as coatings like paint, the need for specialized plural component metering/dispensing equipment make the similarities to paint very minor.

Permanent Tapes – Consists of polymeric materials, pigments, and glass beads on the surface of pre-applied, pressure sensitive adhesives.

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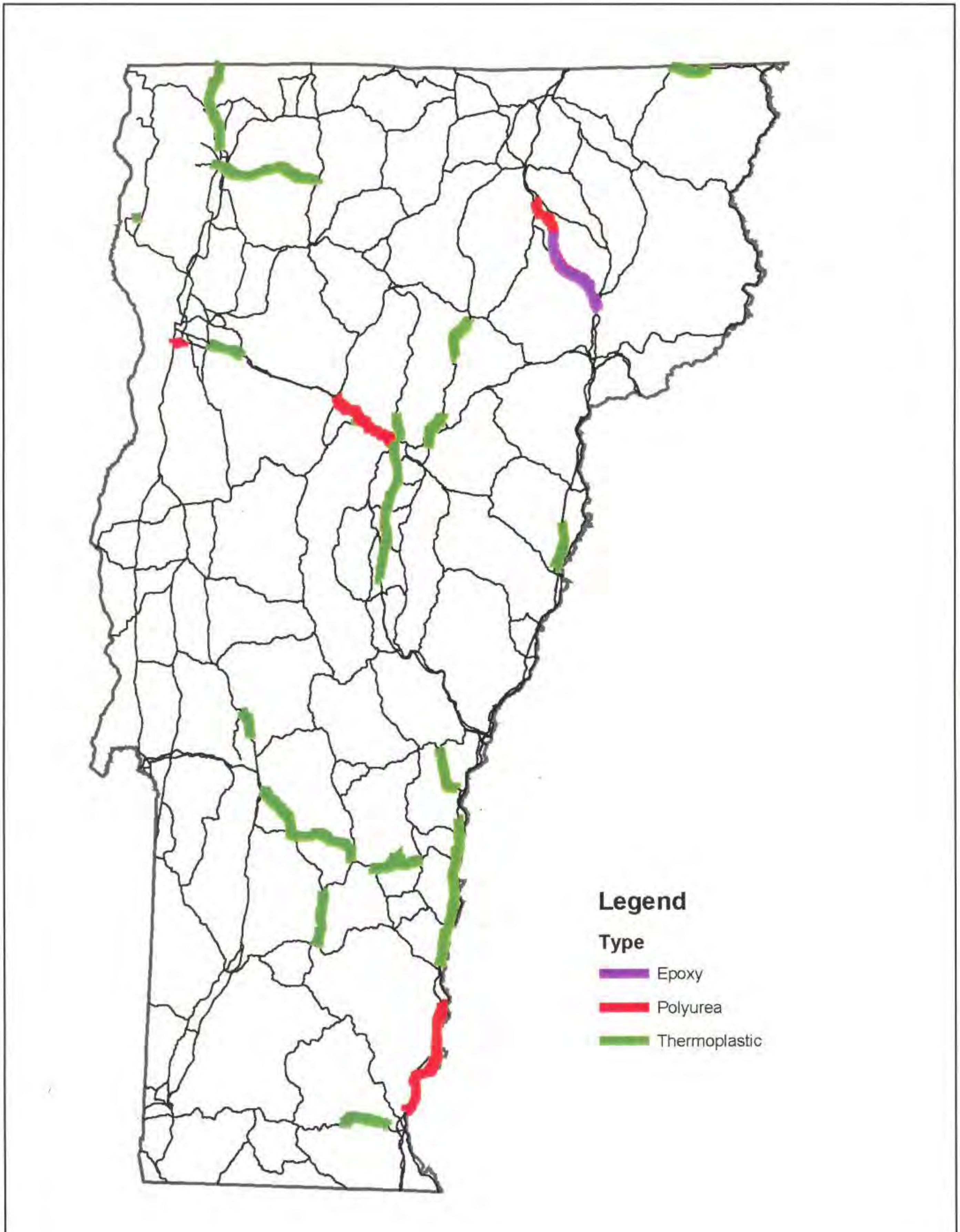
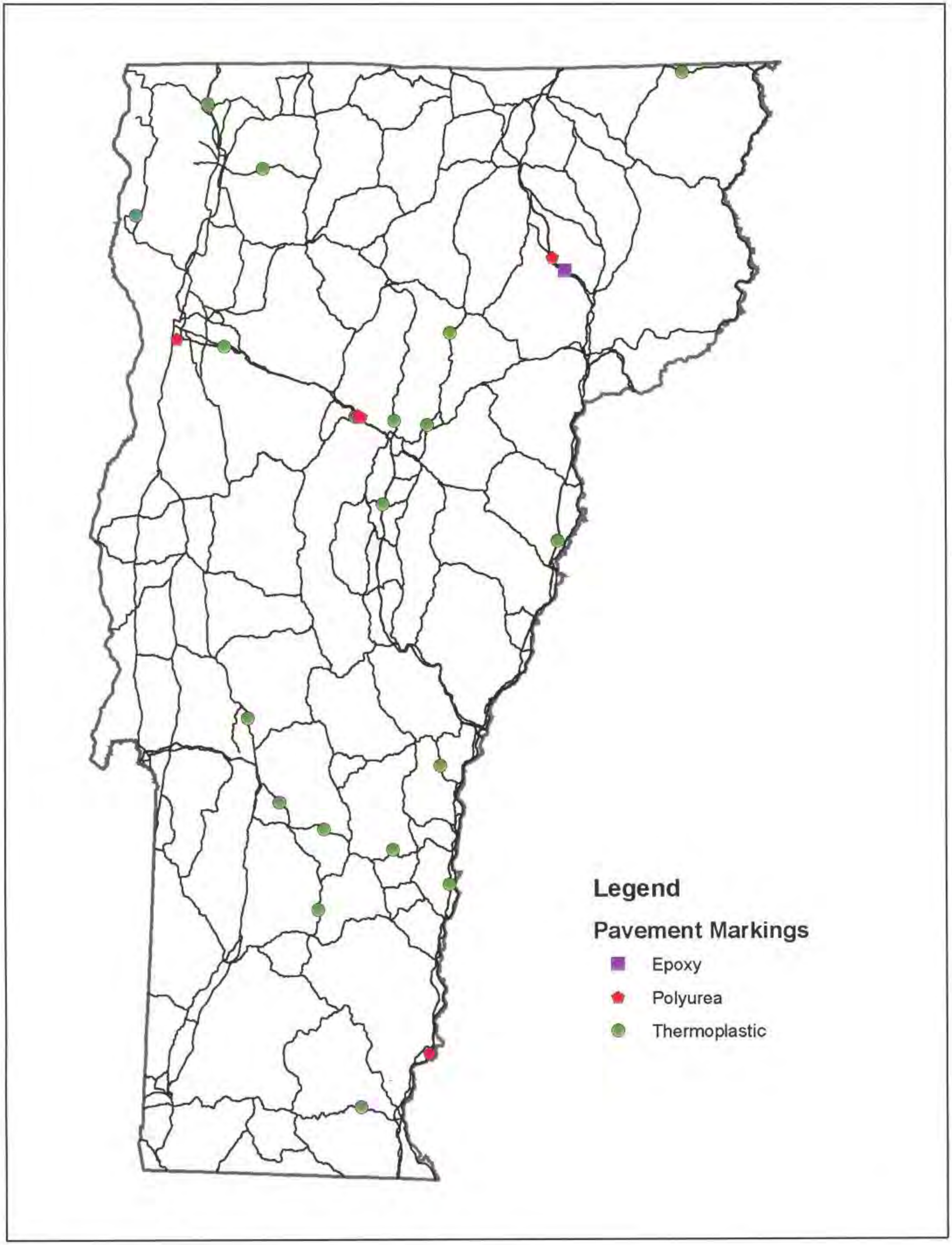
Appendix C


Legend
Type
Epoxy
Polyurea
Thermoplastic


Legend
Pavement Markings
Epoxy
Polyurea
Thermoplastic

Appendix D

Data Collection Record Form

Two Lane Road

Project: ____________________
Route: ____
Test Site 1 : MM________
Date: ____________
Initials: ____________

Weather Conditions: ________________
Temperature: ________
Pavement Temp: ________
Line Temp: ________

Material Type: ________________

Retroreflectivity Readings

Reading	WhiteEdge	Yellow	Yellow	White Edge
1				
2				
3				
4				
5				

Appearance Rating

0-not visible, 3-poor, 5-fair, 7-good, 10-perfect condition

Rating:

Digital Photograph

Notes