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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

LIFE CYCLE AND ECONOMIC EFFICIENCY ANALYSIS: DURABLE PAVEMENT MARKINGS

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16. Abstract

This project examined the life cycle and economic efficiency of two pavement marking materials — inlaid tape and thermoplastic — to find the most economical product for specific traffic and weather conditions. Six locations in the state of Maryland were selected for data collection based on the amount of traffic and snowfall they receive, and the data was collected for one year. While one year of data yielded reliable and consistent results for a recent study of the life cycle of waterborne paint, the regressions for the durable materials in this study were unreliable and cannot be recommended. To ensure reliability and consistency in the estimation of the retroreflectivity of inlaid tape and thermoplastic, we suggest that future studies include more extensive data.

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EXECUTIVE SUMMARY

This project attempted to estimate the life cycle and economic efficiency of inlaid tape and thermoplastic. The two durable pavement marking materials were tested under a variety of weather and traffic conditions to find the best-performing product for specific environments. We selected six locations in Maryland as the study sites, and the data was collected for one year.

The materials' retroreflectivity was estimated using four basic regression equations: linear, linear with quadratic, natural log, and natural log with quadratic. The input variables for these equations were cumulative traffic amount, cumulative precipitation, and cumulative snowfall.

The results showed that one year of data does not provide enough information to clearly estimate the future performance of inlaid tape and thermoplastic. Although the curves of the regression analysis show reasonable performance in the first year, the retroreflectivity values estimated after the one year period vary greatly depending on which regression equation is used.

In order to estimate the life cycle of the durable materials, we needed to test the retroreflectivity equations under various traffic scenarios (i.e., amounts and road design speeds), weather conditions, and threshold values. The traffic and snowfall amounts were specified into three typical categories (high, medium, and low), and the nine combinations of those categories were generated as different conditions for the estimation of the life cycles.

Because the proper regression could not be guaranteed, we could not produce a reliable life cycle estimation. This, consequently, prevented a conventional economic analysis, which requires the distribution of installation costs throughout the life cycles.

A similar study of waterborne paint pavement markings found reliable and proper estimates of retroreflectivity with only one year's worth of data. We used the life cycle of waterborne paint from that study and the difference between the installation costs of waterborne paint, thermoplastic, and inlaid tape to estimate the cost-equivalent life cycles of the durable materials.

A durable material's cost-equivalent life cycle is the lifespan that matches the economic performance of waterborne paint. Because the installation cost of inlaid tape is 40 times more expensive than waterborne paint, we would expect it to last 40 times longer than waterborne paint. Thermoplastic's installation costs are 10 times more expensive than waterborne paint, so we would expect it to last 10 times longer. Waterborne paint appears to be the most economical product under most conditions, but it is only estimated to last 5-13 months on roads with speeds higher than 55 mph (89 km/hr), heavy traffic, and heavy snow. More data is needed to definitively state whether inlaid tape or thermoplastic should be used in these situations.

We also performed a sensitivity analysis. We increased and decreased the estimation of the life cycles and installation costs in order to minimize the errors and provide decision makers with more flexibility. Obviously, waterborne paint becomes more competitive when its life cycle is increased and installation costs are decreased, and the inverse makes the durable materials more competitive.

This project strongly suggests that additional data collection and analysis are needed to generate a reliable and consistent estimation of the future retroreflectivity of inlaid tape and thermoplastic. As mentioned before, the regression analysis is inaccurate and cannot be recommended with only one year of data.

INTRODUCTION

The Maryland State Highway Administration (SHA) uses different pavement marking materials for roads throughout the state. However, there is no guideline that indicates the best-performing and most cost-effective product for specific locations, traffic amounts, and weather conditions. As a result, there is no guarantee of performance.

Objective

SHA is currently evaluating the long-term durability and retroreflectivity of two durable pavement marking materials — thermoplastic and inlaid tape — using existing SHA specifications and procedures.

The objectives of this project are to ensure proper procedure and evaluate the effect of various inputs (traffic volume, snow, rain, etc.) on the desired outputs (durability and retroreflectivity) for the pavement markings. From this analysis, we will be able to provide general equations for the estimation of retroreflectivity and durability. Those estimated regression equations will then be used to estimate the life cycles of the different pavement marking materials under different traffic and weather conditions. The most economical material will be suggested by an economic analysis that uses the estimated life cycles and the installation costs of the materials.

Scope

The study sites and data collection methods for this project were established at monthly meetings of the project teams from the SHA and Morgan State University. The state of Maryland was divided into three regions — western, central, and eastern — based on weather characteristics. In order to generate more consistent data, we selected sites with varying traffic amounts from a list of planned resurfacing projects in the regions. We ultimately selected four locations in the central zone, one in the eastern region, and one in the western area. It was recommended that we use more than one location in the western and eastern regions, but we could only find one in each area that satisfied the conditions required for this project.

The selected sites are shown in Figure 1 and Table 1. Both straight and curved sections were used in half-mile segments at each of the study locations to account for any geometric issues that might possibly affect retroreflectivity. Thermoplastic and inlaid tape were installed at each location so their performance could be directly compared under the same conditions. Interstate 68 was added as a test location in western Maryland after markings were obliterated. Only inlaid tape was installed on I-68.

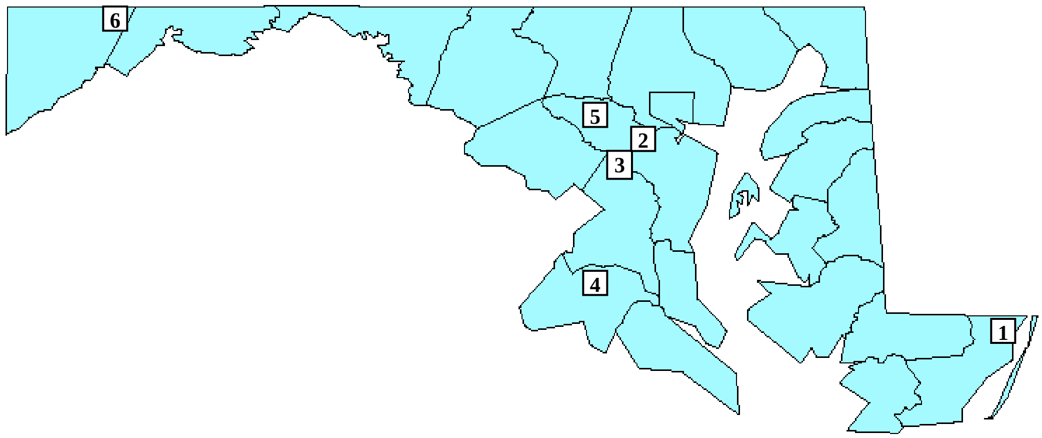

Figure 1. Six Locations for the Research

REGION	LEGEND	COUNTY	ROUTE	RANGE	MP from:	MP to:	AADT	LANES
Eastern	1	WORCESTER	MD 611	Low AADT	4.49	8.51	10,725	2
Central	2	HOWARD	MD 175	High AADT	1.54	2.03	44,750	4
	3	HOWARD	MD 216	Mid AADT	0.87	1.55	21,825	4
	4	CHARLES	MD 5	Mid AADT	10.44	13.65	23,875	4
	5	HOWARD	MD 32	Mid AADT	19.08	20.19	28,125	4
Western	6	GARRETT	I 68 West-bound	Low AADT	6	7	11,675	4

Note: MP=mile point; AADT=annual average daily traffic.

Table 1. Specific Information on the Six Locations

LITERATURE REVIEW

Pavement Marking Materials

The three ways pavement marking materials can be categorized — temporary, durable, and conventional — are summarized in Table 2 (Montebello et al., 2000).

Category	Products	Estimated Cost per Ft.	Estimated Life	Advantages	Disadvantages
Conventional Products	Latex	$0.03-0.05	9-36 months	- Inexpensive - Quick drying - Longer life on low-volume - Easy clean-up - No hazardous waste products	- Short life on high-volume - Damage by sands - Bead required - Not good for concrete - Warm weather required
	Alkyd	$0.03-0.05	9-36 months	- Inexpensive - Quick drying - Works in cold temperature	- Short life on high-volume - Damage by sands - Bead required - Not good for concrete - Highly flammable - Bad smell
Durable Products	Mid-Durable Paint	$0.08-0.10	9-36 months	- Inexpensive - Quick drying - Longer life on low-volume - Easy clean-up - No hazardous waste products	- Short life on high-volume - Damage by sands - Bead required - Not good for concrete - Warm weather required
	Epoxy	$0.20-0.30	4 years	- Longer life on low- and high- volume - More retroreflectivity	- Slow-drying - Coning and flagging required - Heavy bead required - High initial expense - Damage by sands
	Tape	$1.50-2.65	4– 8 years	- Highly retroreflective - Long life on low- and high- volume - No beads needed	- High initial expense - Best for newly surfaced roads - Weak for snowplow
	Preformed Thermoplastic	NA	3–6 years	- Highly retroreflective - Long life on low- and high- volume - No beads needed - Any temperature for application	- Only used for symbols - Damage from sands - Weak for snowplow
Temporary Products	Temporary Tape	$1.10-1.50	Length of construction	- Easy application and removal - Last the life of construction - Does not damage new pavement	- Only for construction zones

Table 2. Pavement Marking Materials (Source: Montebello et al., 2000)

Conventional pavement materials, which include latex (waterborne) and alkyd (solvent-based) paint, are typically inexpensive and have a relatively short lifespan.

Durable materials, in contrast, are more expensive but have a longer life expectancy. Thermoplastic and tape, the products examined in the present study, are in this particular category, as are mid-durable paint and epoxy.

Thermoplastic has been used successfully in warmer climates for a number of years. It is made up of glass beads, pigment, binders, and fillers. The glass beads and pigment give the material its retroreflectivity. Inert substances work as fillers that provide bulk, and a mixture of plasticizer and resin hold the components together (Montebello et al., 2000).

Inlaid tape is resistant to snowplow damage. The tape is rolled into hot, freshly compacted asphalt and pressed into the surface with a finishing roller (Montebello et al., 2000).

Retroreflectivity

When deciding which pavement marking material to use, one must consider its visibility during the day and night. Retroreflectivity refers to the portion of incident light from a vehicle's headlights that is reflected back toward the driver.

Glass or ceramic beads are added to the surface of marking materials to make them retroreflective (Migletz et al, 1999). Figure 2 illustrates how light travels through the beads. These tiny spherical balls must be transparent and act like lenses. They can also be treated or untreated. Treated glass beads have a coating on their surface that enables the bead to sink into the paint, while the untreated beads float on the surface. Having a portion of the beads on the surface and in the paint allow for continued retroreflectivity as the paint wears. The same results can be achieved by using pre-mixed paints and adding untreated beads. The proper application of beads is crucial to creating the marking's retroreflectivity (Montebello et al., 2000).

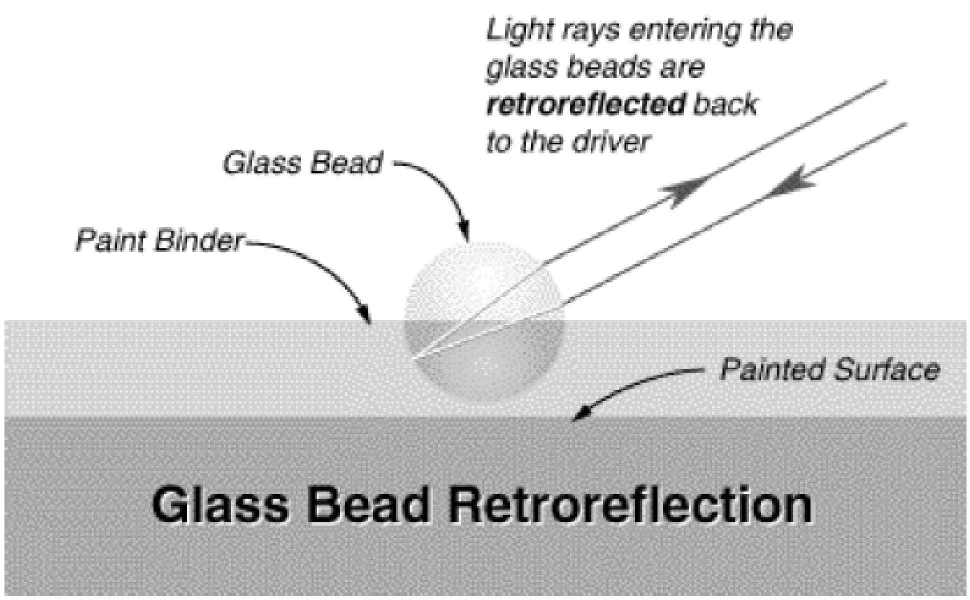

Figure 2. Glass Bead Retroreflection

Service Life of the Pavement Markings

Recent research concluded that the life cycle of a pavement marking is related to its traffic exposure, and the retroreflectivity can be expressed as a logarithmic regression equation (Abboud et al., 2002). However, this data was collected from locations that do not receive snow.

Another project detailed the threshold retroreflectivity values that define the end of a pavement marking's service life, and the results can be seen in Table 3 (Migletz et al., 2001). As shown in Table 4, the project also illustrated how a product's life cycle (elapsed months) can be affected by the type of roadway on which it is placed (cumulated traffic passages).

Color of Marking	Threshold retroreflectivity values (mcd/m^2/lux)		
	Non-Freeway ≤ 40 mph (64 km/hr)	Non-Freeway ≥ 45 mph (72 km/hr)	Non-Freeway ≥ 55 mph (89 km/hr)
White	85	100	150
Yellow	55	65	100

Table 3. Threshold Retroreflectivity Values Used to Define the End of Pavement Marking Service Life (Source: Migletz et al., 2001)

Roadway Type and Material	Number of Pavement Marking Lines	Service Life	
		Average Cumulative Trips (million vehicles)	Elapsed Months
Freeway:			
Polyester	1	11.1	39.7
Profiled tape	3	6.9	25.8
Thermoplastic	7	6.1	24.7
Profiled Thermoplastic	4	5.3	23.5
Epoxy	7	4.7	23.2
Profiled poly methyl methacrylate	3	6.2	21.1
Poly methyl methacrylate	3	3.0	15.6
Non-Freeway ≤ 64 km/hr:			
Profiled Thermoplastic	1	11.4	50.7
Epoxy	2	3.6	43.6
Profiled polyester	1	4.7	39.6
Profiled tape	1	3.5	19.6
Non-Freeway ≥ 72 km/hr:			
Polyester	1	9.1	47.9
Epoxy	6	8.9	44.1
Profiled tape	3	5.1	38.9
Thermoplastic	3	4.5	33.8
Profiled poly methyl methacrylate	2	6.5	31.0
Profiled Thermoplastic	3	3.9	23.0
Poly methyl methacrylate	1	4.8	20.5

Table 4. Estimated Service Life of Yellow Lines by Roadway Type and Pavement Marking Material (Source: Migletz et al., 2001)

METHODOLOGY

Data Selection

The three inputs used in this analysis are cumulated annual average daily traffic (AADT) per lane, cumulated precipitation, and cumulated snowfall. Many other studies use cumulated AADT, but we believe that cumulated AADT per lane better represents the chance of exposure to traffic. We only focus on cumulated precipitation and cumulated snowfall because we assume that other weather-related inputs will have little or no effect on retroreflectivity.

Retroreflectivity is considered the only output of the relationship, but it will allow us to determine life cycle and economic efficiency.

Data Collection

Retroreflectivity Data Collection Methods

SHA collected retroreflectivity data at the six locations six or seven times a year for the following marking types: white edge (WE); white skip (WS); yellow center (YC); yellow edge (YE); and yellow skip (YS). In addition to retroreflectivity, the SHA recorded the number of lanes and annual average daily traffic for each test site. Morgan State University collected the daily precipitation and snowfall amounts from each site's nearest weather station. The collection schedule can be seen in Table 5. Data was collected more frequently in the winter because the previous waterborne paint study found that snow can be an important factor in the deterioration of a pavement marking's retroreflectivity.

	Route	MD 5	MD 32	MD 175	MD 216	MD 611	I 68
	Date Striped	12/10/2006	06/21/2006	08/01/2006	09/18/2006	11/28/2006	06/26/2007
2006	Jun		23				
	Jul		28				
	Aug		30	4			
	Sep		28	13	26		
	Oct			10	25		
	Nov			15	27		
	Dec		6				
2007	Jan	29	9	17	30	4	
	Feb	27				22	
	Mar	26	9	15	22	29	
	Apr						
	May	22	7	15	18	31	
	Jun				19		
	Jul	25		19		31	
	Aug				15		
	Sep	25				7	28
	Oct						31
	Nov					1	30
	Dec	12					
2008	Jan						
	Feb						
	Mar						17
	Apr						23

Table 5. Retroreflectivity Data Collection Schedules

As shown in Figure 3, the retroreflectivity data was measured at the exact same five mile points and at each mile point.

Figure 3. Photo of Test Site with Spot Markings

Retroreflectivity Measuring Equipment

Retroreflectivity was measured with the LTL-X retrometer (Figure 4). Produced by Delta Company in Denmark, the LTL-X retrometer is a portable field instrument that measures retroreflection in terms of $R_{L,}$ the coefficient of retroreflected luminance, according to international agreements. The road is illuminated at an angle of 1.24°, and the reflected light is measured at an angle of 2.29° that corresponds to an observation distance of 100 feet (30 m). (These measurements mimic a driver's visibility field under normal conditions.)

Figure 4. Retroreflectivity Measuring Equipment (LTL-X)

The instrument’s illumination field is approximately 80 inches x 18 inches (200 mm x 45 mm), and the observation field is about 244 inches x 24 inches (610 mm x 60 mm). The tower of the LTL-X contains the illumination and observation system and the control electronics. An optical system at the bottom of the tower directs a beam of light toward the road surface through a dust-protection window. A polymer shielding covers the measuring area for normal operation.

The LTL-X is controlled by multiple microprocessors, and it is operated with an extractable keyboard located at the top of the retrometer. With the push of a button, it executes the measurement and displays the result in plain text. The result is automatically transferred to the internal memory. The measurement — along with its corresponding time, date, and other information — can be printed using the built-in printer.

Data Entry

The retroreflectivity data collected by SHA was handwritten, and the data needed to be entered into an electronic file for analysis. The Morgan State University project team entered the retroreflectivity data and the weather-related information into the electronic file on a monthly basis for one year.

Regression Analysis

Regression analysis is the main method for estimating the relationship between the output (retroreflectivity) and inputs in this study. It involves a single dependent variable or response, Y, which is uncontrolled in this experiment. The response depends on one or more independent or regressor variables that are measured with negligible error and controlled. The relationship fit to a set of experimental data is characterized by a prediction equation called a regression equation. It is called single variable regression if there is only one regressor, or a multi-variable regression if there are more than two regressors.

The smaller the variability of the residual values around the regression line relative to the overall variability, the better our prediction. For example, if there is no relationship between the *x* and *Y* variables, then the ratio of the residual variability of the *Y* variable to the original variance is equal to 1.0. If *X* and *Y* are perfectly related, then there is no residual variance and the ratio of variance is zero. In most cases, the ratio would fall somewhere between 0 and 1.0. One minus this ratio is referred to as R-square or the coefficient of determination. This value is immediately interpretable in the following manner. If we have an R-square of 0.4, then we know that the variability of the *Y* values around the regression line is 1-0.4 times the original variance. In other words, we have explained 40 percent of the original variability and are left with 60 percent residual variability. Ideally, we would like to explain most, if not all, of the original variability. The R-square value is an indicator of how well the model fits the data (i.e., an R-square close to 1.0 indicates that we have accounted for almost all of the variability with the variables specified in the model).

The adjusted R-square attempts to yield a more honest value to estimate the R-square for the population. The value of R-square was .4892, while the value of adjusted R-square was 0.4788. Adjusted R-square is computed using the formula 1 - ((1 - Rsq) ((N - 1) / (N - k - 1)). From this formula, you can see that when the number of observations is small and the number of predictors is large, there will be a much greater difference between R-square and adjusted R-square (because the ratio of (N - 1) / (N - k - 1) will be much greater than 1). By contrast, when the number of observations is very large compared to the number of predictors, the value of R-square and adjusted R-square will be much closer because the ratio of (N - 1)/ (N - k - 1) will approach 1.

This project uses the following four basic regression equations:

- Linear : $Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4$ (1)
- Linear with quadratic: $Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 (X_1)^2 + b_6 (X_2)^2 + b_7 (X_3)^2 + b_8 (X_4)^2$ (2)
- Natural log: $Ln(Y) = a + b_1 Ln(X_1) + b_2 Ln(X_2) + b_3 Ln(X_3) + b_4 Ln(X_4)$ (3)
- Natural log with quadratic: $Ln(Y) = a + b_1 Ln(X_1) + b_2 Ln(X_2) + b_3 Ln(X_3) + b_4 Ln(X_4) + b_5 Ln((X_1)^2) + b_6 Ln((X_2)^2) + b_7 Ln((X_3)^2) + b_8 Ln((X_4)^2)$ (4)

where:

Y = retroreflectivity;
a = intercept;

b_i = coefficient;
X_1 = number of days;
X_2 = cumulative traffic amounts (AADT/lane);
X_3 = cumulative precipitation; and
X_4 = cumulative snowfall.

Since the correct function for the estimation is not known, those four basic functions are examined and the function that best fits the data will be used for the estimation.

Analysis Process

The analysis process for this project is summarized in Figure 5.

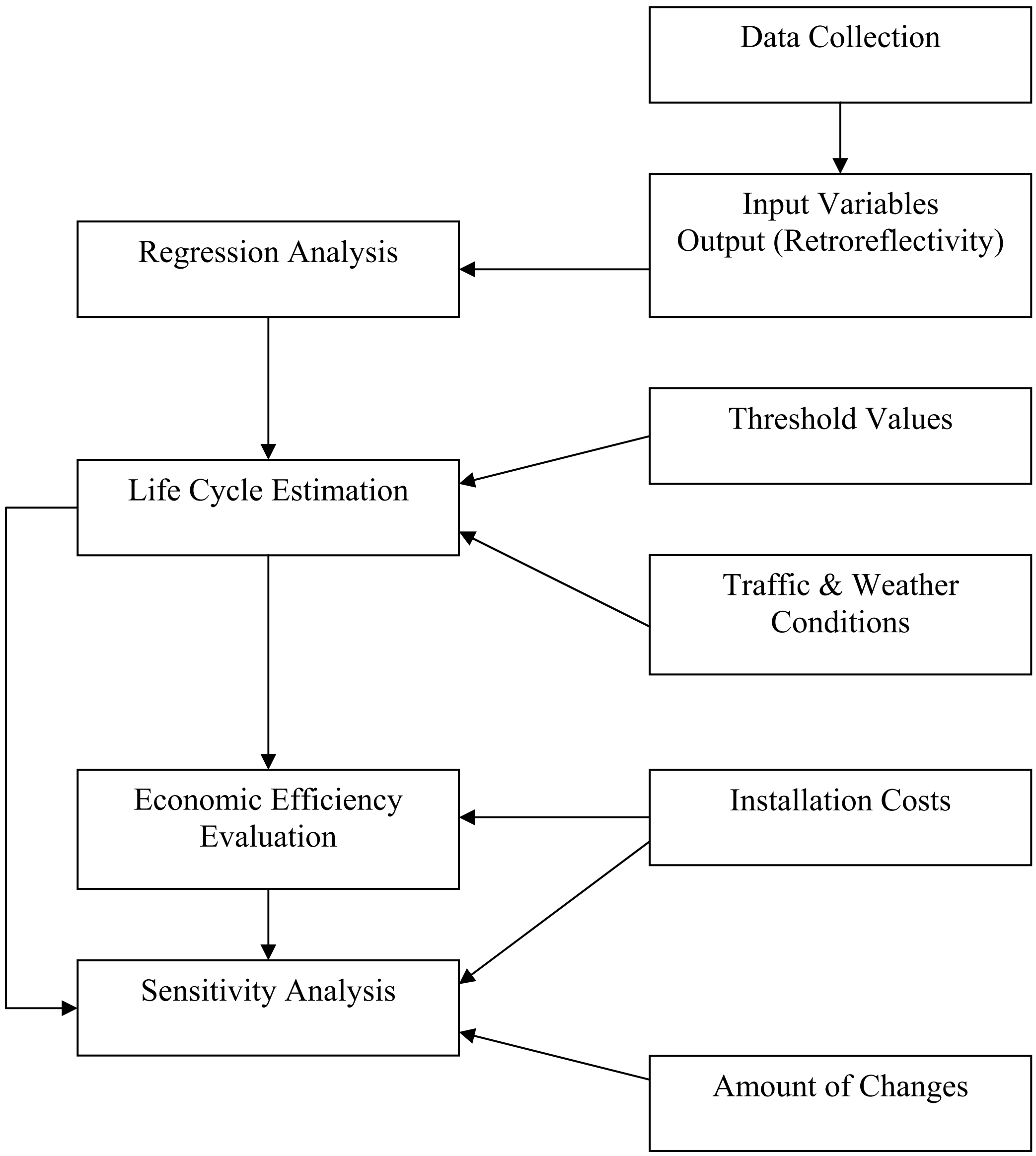

Figure 5. Flow Chart for the Analysis

Life Cycle Estimation for the Different Materials

The proper regression equation and the threshold values in Table 3 will allow us to estimate the life cycles of the pavement marking materials. The three input variables used to estimate retroreflectivity are all dependent on the number of days. In order to find the relationship between retroreflectivity and number of days, we fixed the unit values for those variables as typical low, medium, and high.

The typical low, medium, and high values for daily traffic — 1500 AADT per lane, 3000 AADT per lane, and 6000 AADT per lane, respectively — are based on the traffic amounts at the study locations.

The values for the snowfall are based on the two-year average of the study locations. The typical annual high snowfall amount, 88 inches per year, is based on the western area. The central region was the basis for the medium amount (20 inches per year), and the eastern area is the basis for the low amount (13 inches per year). The annual precipitation — 30 inches per year —was similar throughout the regions. Table 6 shows the life cycles of the pavement marking materials based on the nine combinations.

Snow Traffic	Low snow (Eastern)	Medium snow (Central)	High snow (Western)
Low traffic	1500 AADT/lane 13 inches/year	1500 AADT/lane 22 inches/year	1500 AADT/lane 88 inches/year
Medium traffic	3000 AADT/lane 13 inches/year	3000 AADT/lane 22 inches/year	3000 AADT/lane 88 inches/year
High traffic	6000 AADT/lane 13 inches/year	6000 AADT/lane 22 inches/year	6000 AADT/lane 88 inches/year

Annual precipitation is assumed to be 30 inches per year for all nine combinations.

Table 6. Nine Typical Combinations for Life Cycle Analysis

Cost Estimation for the Different Materials

In order to estimate economic efficiency, we need to know how much it costs to install each product. The estimation of installation costs should incorporate all components of the application, including material, labor, equipment, overhead, congestion, and safety. Because the state of Maryland does not keep detailed records of these costs in this format, this study uses estimates from national studies and typical costs in Maryland (Table 7).

Material	Installation Costs ($/ft.)
Waterborne Paint	$0.05/ft.
Thermoplastic	$0.50/ft.
Inlaid Tape	$2.00/ft.

Table 7. Typical Installation Costs for the Different Pavement Marking Materials

Economic Efficiency Estimation for the Different Materials

Because installation costs only occur once in a material’s life cycle, the costs must be distributed throughout the life cycle. This distribution is done using a conversion method from present value to annual value with the assumed interest rate. The annual cost of the pavement marking material will show its economic efficiency, but this estimation is not definite.

Sensitivity Analysis

A sensitivity analysis, which examines how uncertainty and changes in life cycle and installation costs influence economic efficiency, can give decision makers a more complete picture and help overcome errors in the economic efficiency estimation and material choice.

RESEARCH FINDINGS

Difficulties in the Regression Analysis

The biggest challenge in this regression analysis is the fact that the estimation required is outside of the data range. Data was collected for a one year period in which the maximum cumulative snowfall was less than 88 inches and the maximum cumulative traffic per lane was less than 3 million cars. However, the materials that we examined are known to last for at least 3 years and possibly more than five. This would require us to forecast performance, resulting in too many uncertainties in the analysis.

The shape of the function with the one year data collection also concerns us. As shown in Figure 6, unlike waterborne paint, the durable materials' retroreflectivity does not change much in the first year. In fact, the retroreflectivity tends to increase in the first few months after application. Because one year is relatively short compared to the long life cycle of these materials, it is difficult to predict performance with only one year of data.

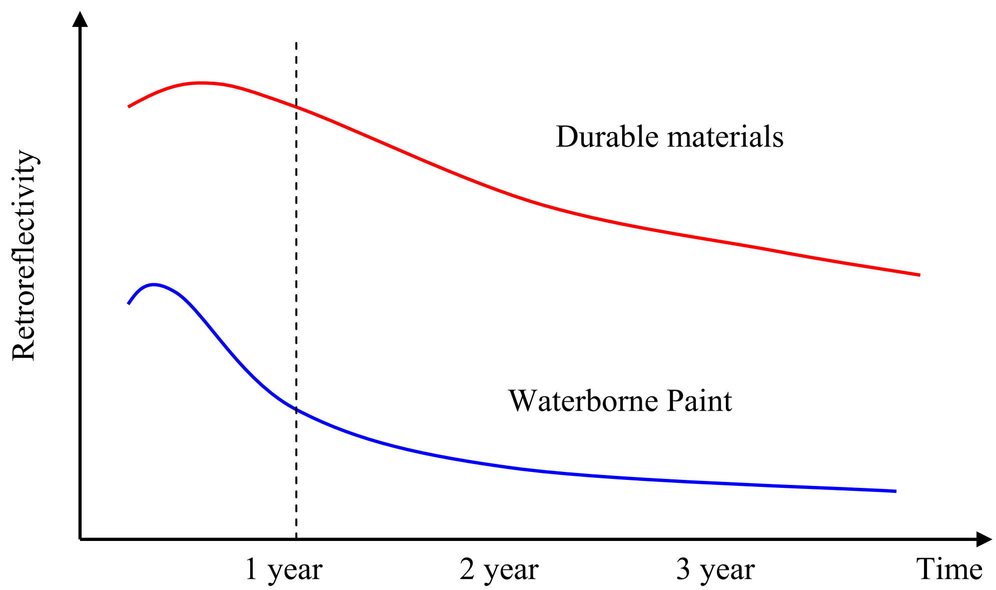

Figure 6. Typical Retroreflectivity Curves for the Different Pavement Marking Materials

Because the first year's data for the durable materials does not clearly show a tendency of diminishing retroreflectivity, the regression analysis yields totally different scenarios with each basic function (Figure 7).

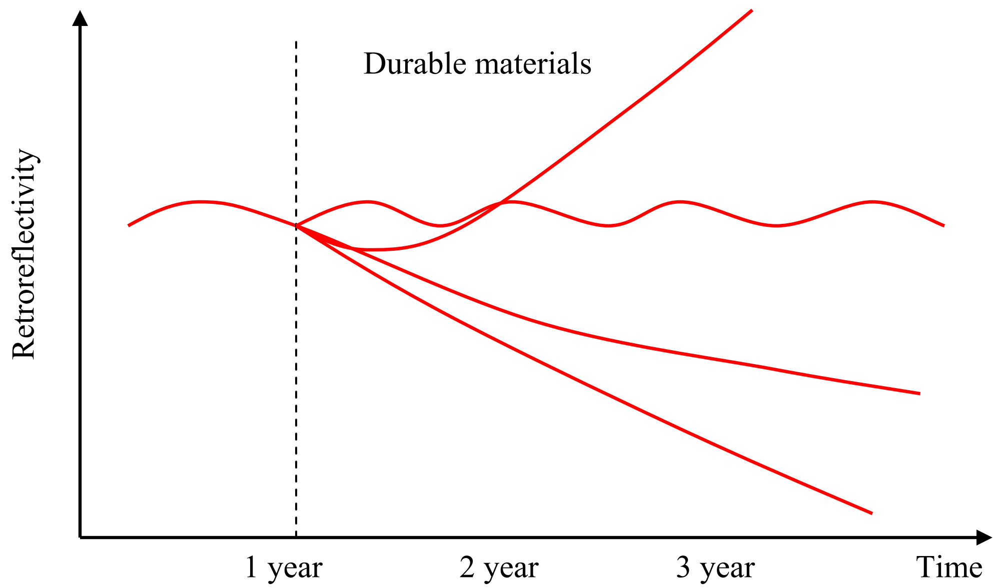

Figure 7. Potential Results of the Regression Analysis with Different Basic Equations for the Durable Materials with One Year of Data

The life cycle estimation is very sensitive because the durable materials' retroreflectivity values (about 300- 800 mcd/m^2/lux) are much higher than the threshold values (80-150 mcd/m^2/lux). This sensitivity is further illustrated in Figure 8, which compares the life cycle estimation of waterborne paint and the durable materials. After one year, the durable materials' retroreflectivity is far from the threshold value, while the retroreflectivity value of the waterborne paint is relatively close to the threshold value. Because of this characteristic, the durable materials' life cycle can differ by a few years, while waterborne paint's life cycle can only vary within a few months.

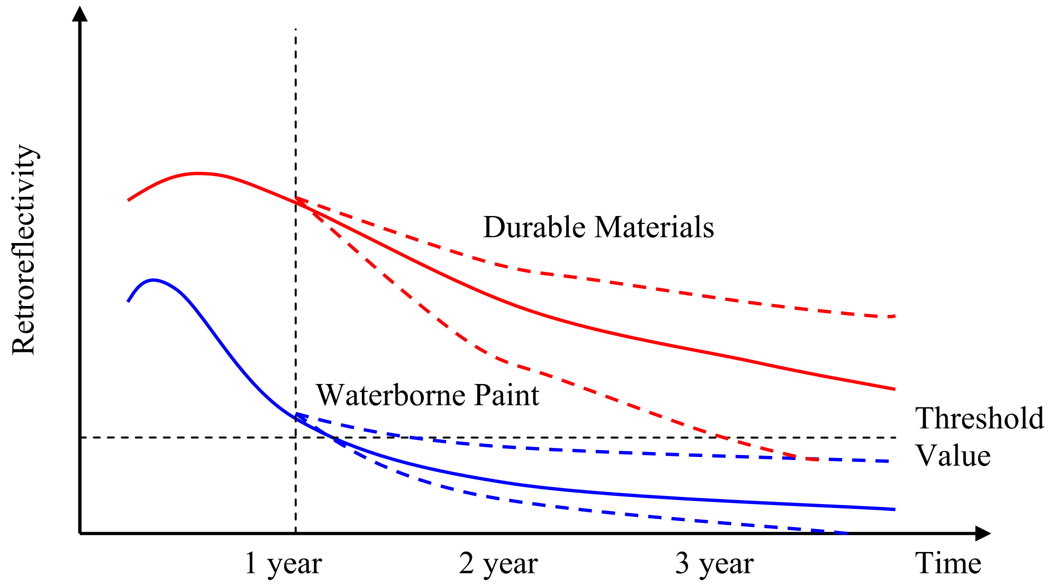

Figure 8. Different Life Cycles with Different Estimation Curves

Regression Analysis

Tables 8 and 9 show the regression results for inlaid tape and thermoplastic. The regression analysis was pursued with the three variables (precipitation, snowfall, and traffic amount) and the marking types (white edge, white skip, yellow center, and yellow edge). The locations were also added to compensate for differences in the initial retroreflectivity.

	Linear	Linear Quadratic	Log	Log Quadratic
Number of Observations	1087	1087	1087	1087
F-Value	189.26 <.0001	170.37 <.0001	163.2 <.0001	149.9 <.0001
Adjusted R-square	0.656	0.6859	0.6216	0.6575
Intercept	680.73303*** (12.97846)	678.56572*** (12.88154)	6.57321*** (0.0467)	6.66737*** (0.15701)
Tottraff	31.23818** (12.6348)	170.49495*** (43.20208)	0.06253*** (0.01842)	0.19877*** (0.06754)
Totprep	0.95033 (0.93359)	-3.44422 (2.56734)	-0.01087 (0.0134)	-0.00199 (0.0272)
Totsnow	-12.07561*** (0.85323)	3.17991 (2.34326)	-0.07324*** (0.00542)	-0.06342*** (0.01145)
Tottraffsq	N/A	-30.16648*** (7.3001)	N/A	0.04326*** (0.0075)
Totprepsq	N/A	-0.03249 (0.03747)	N/A	-0.00619 (0.00842)
totsnowsq	N/A	-0.5712*** (0.09574)	N/A	-0.03355*** (0.00672)
WS	-27.07105*** (9.90235)	-27.07105*** (9.46264)	-0.04532** (0.01939)	-0.04532** (0.01845)
YE	-318.01379*** (9.56959)	-318.01379*** (9.14466)	-0.57737*** (0.01874)	-0.57737*** (0.01783)
YC	-134.87143*** (23.85551)	-134.87143*** (22.79624)	-0.24388*** (0.04672)	-0.24388*** (0.04445)
I68	68.22639*** (16.79956)	150.71256*** (24.75054)	-0.09503*** (0.02904)	0.08858 (0.06018)
MD175	124.29024*** (14.7665)	99.56547*** (16.62666)	0.18949*** (0.02296)	0.14882*** (0.04111)
MD216	70.54908*** (11.0293)	34.76084*** (11.86466)	0.10775*** (0.02174)	0.17191*** (0.02435)
MD5	132.84523*** (16.72725)	29.27921 (19.21248)	0.22919*** (0.029)	0.27484*** (0.04334)
MD611	-121.22096*** (17.55066)	-165.74619*** (18.40197)	-0.17352*** (0.03297)	-0.20511*** (0.04201)

Numbers in the table are based on white edge and MD 32, which are basic case. Parameter values with an * are significant at the 10% level, ** at the 5% level, and *** at the 1% level.

Table 8. Regression Results for Inlaid Tape

	Linear	Linear Quadratic	Log	Log Quadratic
Number of Observations	1090	1090	1090	1090
F-Value	136.01 <.0001	136.01 <.0001	157.72 <.0001	122.27 <.0001
Adjusted R-square	0.6161	0.6171	0.59	0.5914
Intercept	311.055*** (7.67744)	311.78269*** (8.26537)	5.71766*** (0.05694)	5.26577*** (0.19944)
Tottraff	-42.05272*** (8.64858)	-11.88891 (26.75289)	0.0044 (0.02242)	-0.19953** (0.08742)
Totprep	3.63703*** (0.5727)	0.04639** (0.0236)	0.01829 (0.01627)	0.09367*** (0.03428)
Totsnow	-2.35335*** (0.84549)	-0.5826 (0.36044)	-0.026*** (0.00751)	-0.00974 (0.01398)
Tottraffsq	N/A	N/A	N/A	-0.01842* (0.00996)
Totprepsq	N/A	N/A	N/A	0.02672** (0.01067)
totsnowsq	N/A	N/A	N/A	-0.01115 (0.00959)
WS	-18.67889*** (6.11157)	-18.47398*** (6.11073)	-0.02653 (0.02412)	-0.02599 (0.0241)
YE	-165.299*** (5.33384)	-164.889*** (5.35993)	-0.64063*** (0.02102)	-0.63955*** (0.0211)
YC	-181.1268*** (8.47334)	-181.811*** (8.57591)	-0.68088*** (0.0333)	-0.68425*** (0.03363)
I68	0 0	0 0	0 0	0 0
MD175	-11.3297 (9.1739)	-12.73312 (10.38149)	-0.13415*** (0.02798)	-0.02419 (0.05237)
MD216	64.50386*** (7.04653)	70.14463*** (7.50928)	0.21311*** (0.02684)	0.19303*** (0.0316)
MD5	48.70753*** (9.38648)	45.45783*** (11.2188)	0.11779*** (0.03147)	0.19859*** (0.05025)
MD611	64.563*** (9.78702)	58.2898*** (11.31448)	0.12542*** (0.03656)	0.17626*** (0.05026)

Numbers in the table are based on white edge and MD 32, which are basic case. Parameter values with an * are significant at the 10% level, ** at the 5% level and, *** at the 1% level.

Table 9. Regression Results for Thermoplastic

Because of these efforts, the estimated regression equations have relatively high adjusted R-square values, indicating the correctness of the estimation. While the regression equations are good for estimating performance (retroreflectivity) during the period of data collection, they do not accurately predict performance for the reasons discussed at the beginning of this section.

Figures 9-17 show the estimated retroreflectivity curves for inlaid tape for the nine different traffic and snowfall combinations. The estimations and the shapes of the curves for the first year look similar regardless of the basic equation, but, as explained, the estimations after one year vary greatly because of the small changes in retroreflectivity in the first year. In order to draw regression curves, it is assumed that the markings are installed in July, and the annual precipitation and traffic are distributed evenly throughout the year. Annual snowfall was distributed throughout December, January, and February, which is why some curves show big changes in months 6-8 and 18-20.

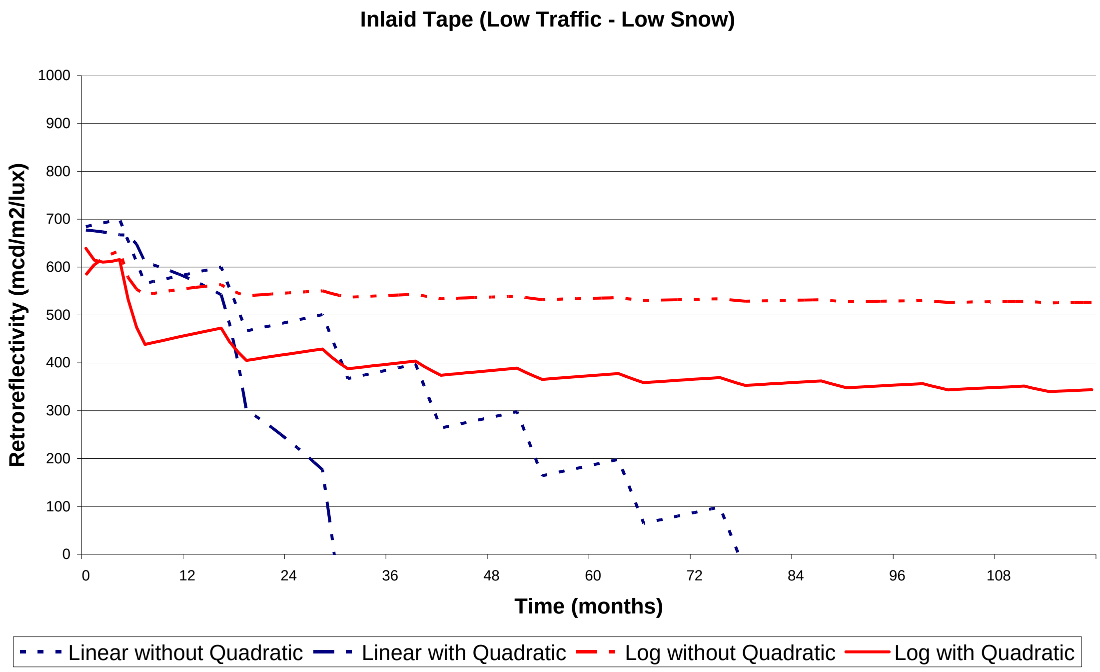

Figure 9. Regression Curves for Inlaid Tape (Low Traffic & Low Snow)

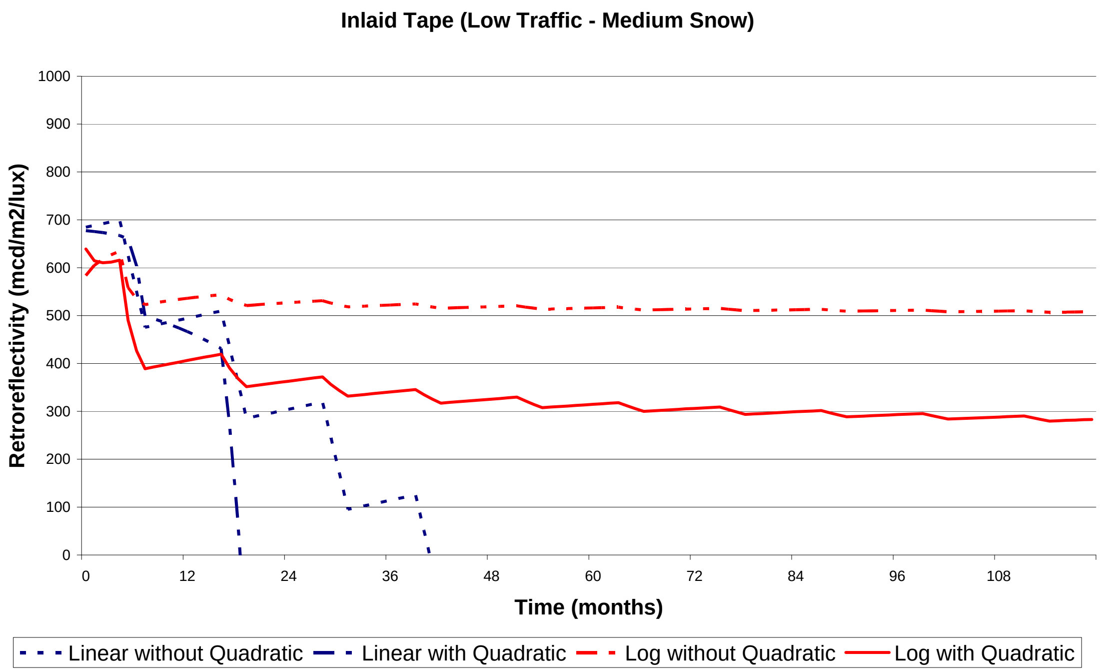

Figure 10. Regression Curves for Inlaid Tape (Low Traffic & Medium Snow)

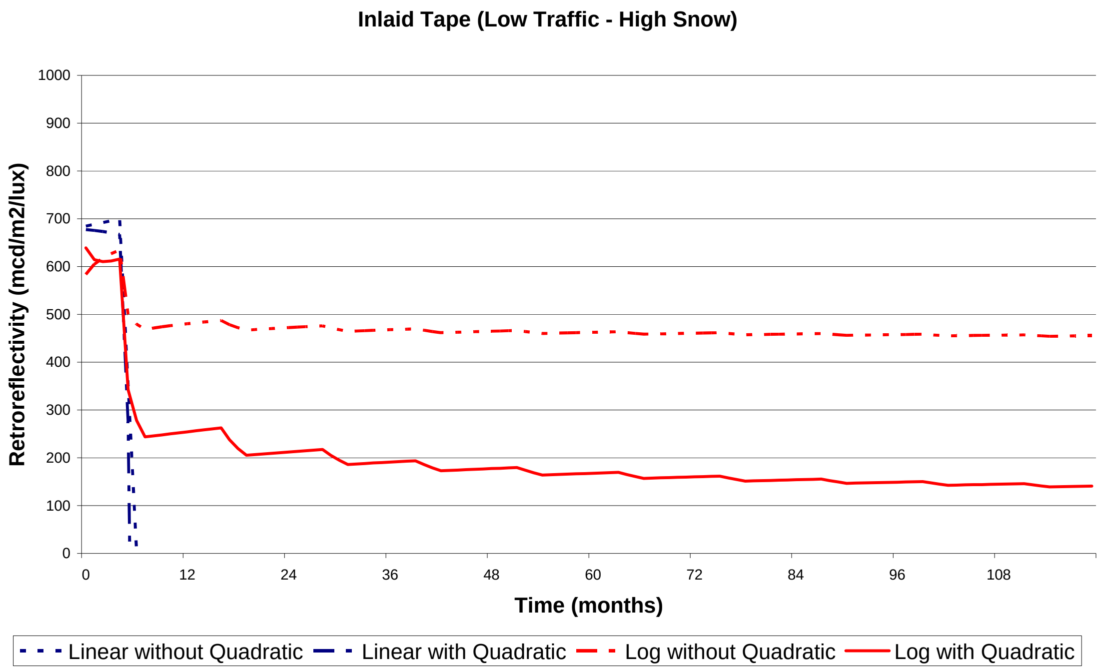

Figure 11. Regression Curves for Inlaid Tape (Low Traffic & High Snow)

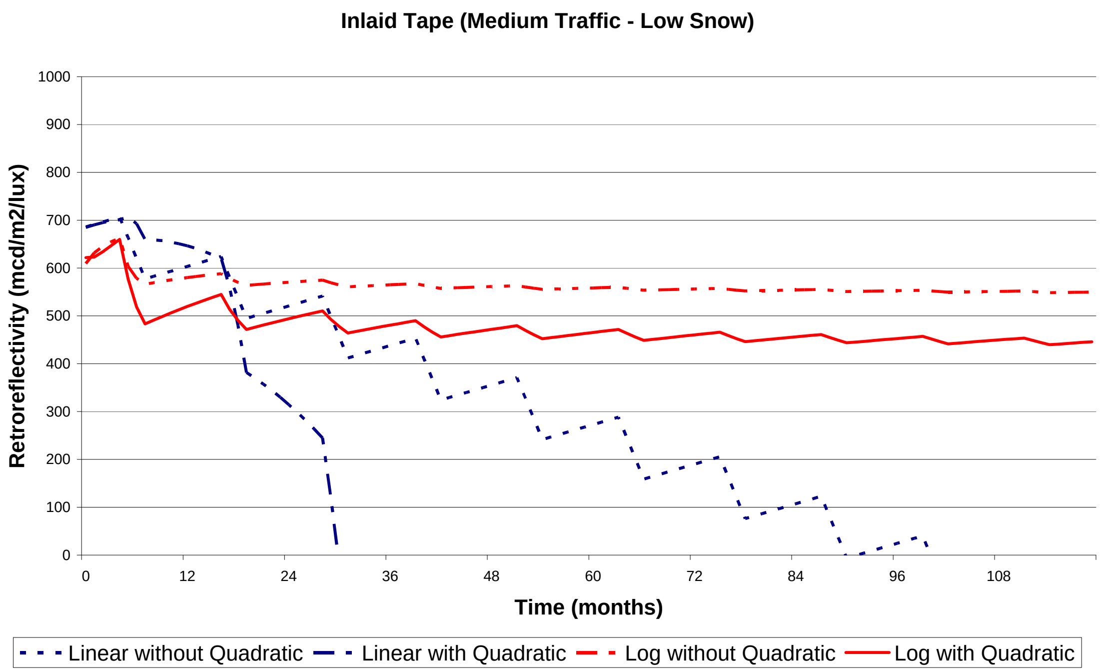

Figure 12. Regression Curves for Inlaid Tape (Medium Traffic & Low Snow)

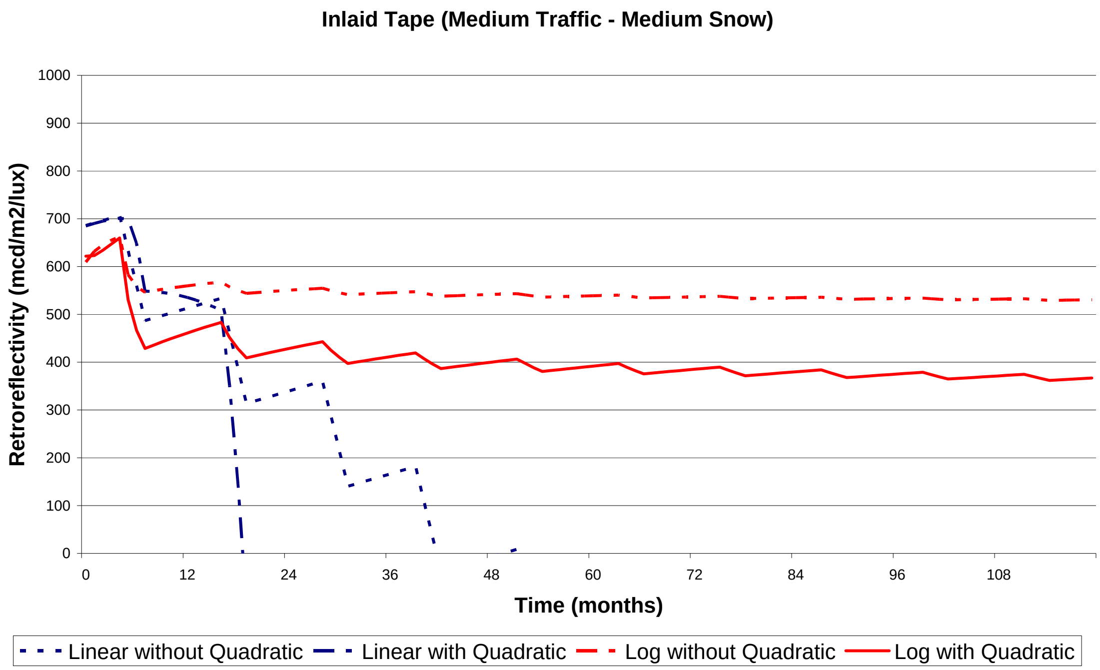

Figure 13. Regression Curves for Inlaid Tape (Medium Traffic & Medium Snow)

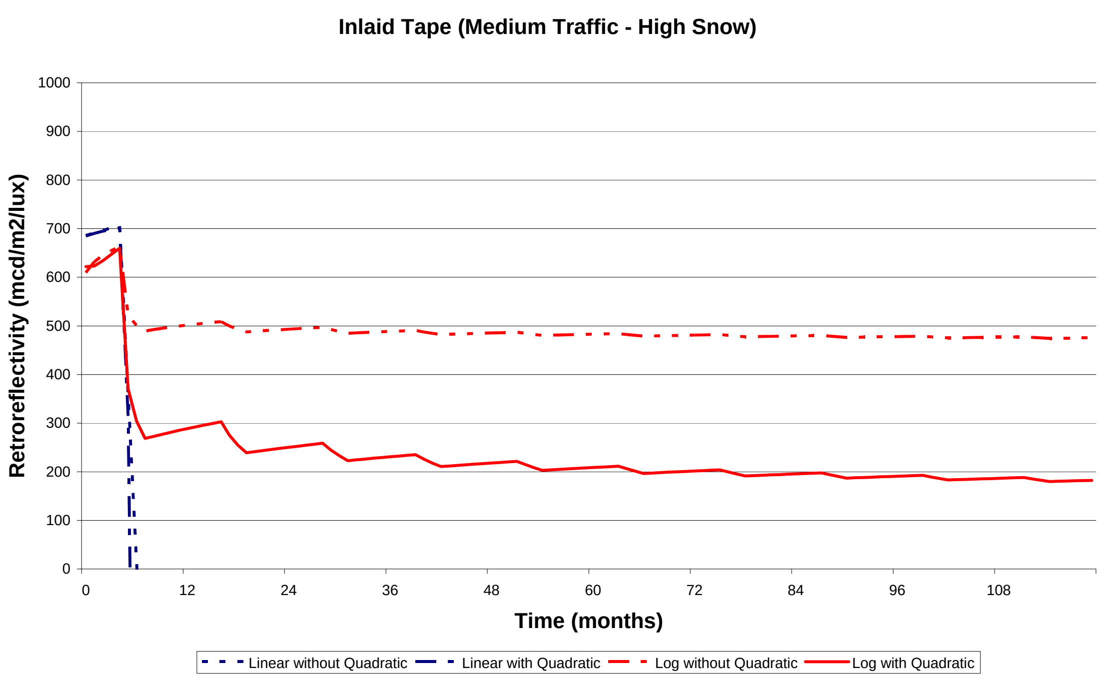

Figure 14. Regression Curves for Inlaid Tape (Medium Traffic & High Snow)

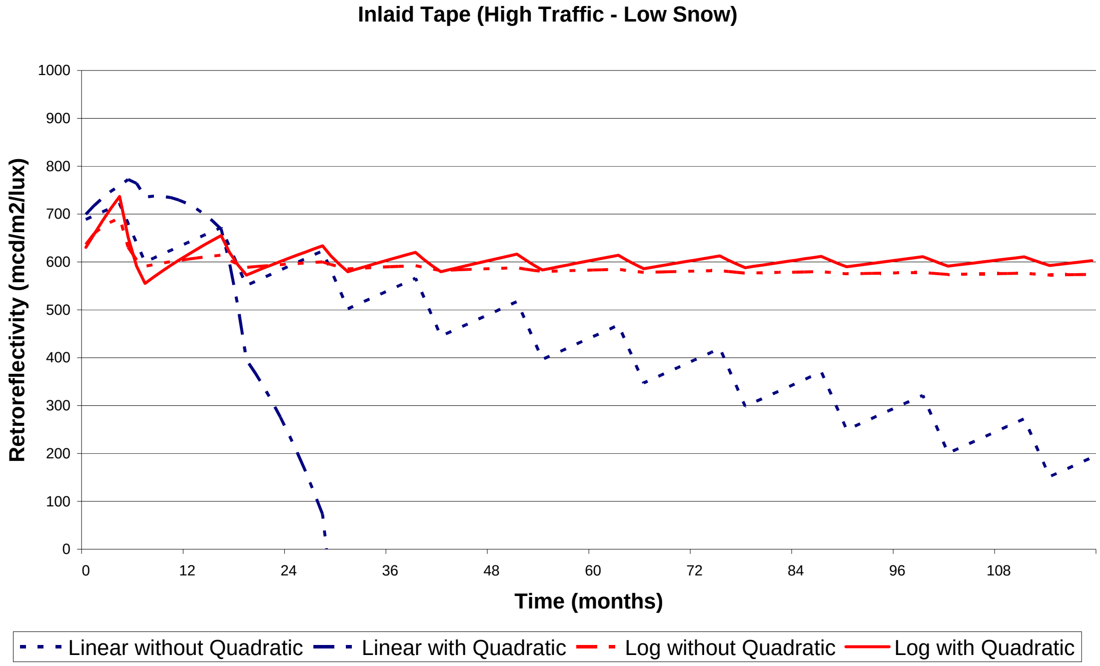

Figure 15. Regression Curves for Inlaid Tape (High Traffic & Low Snow)

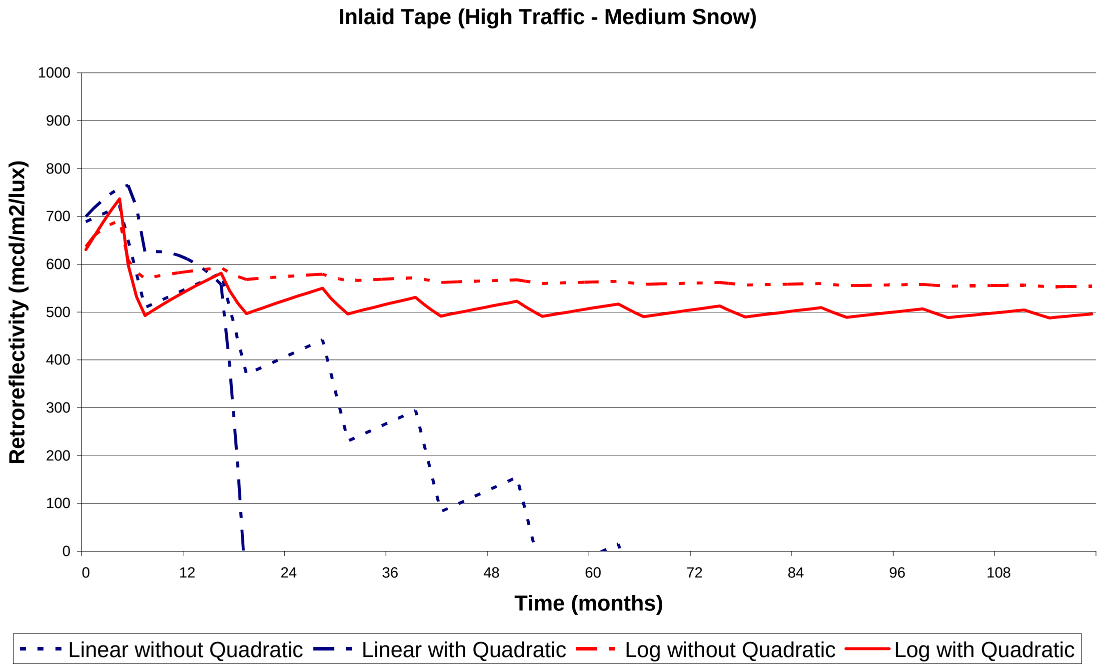

Figure 16. Regression Curves for Inlaid Tape (High Traffic & Medium Snow)

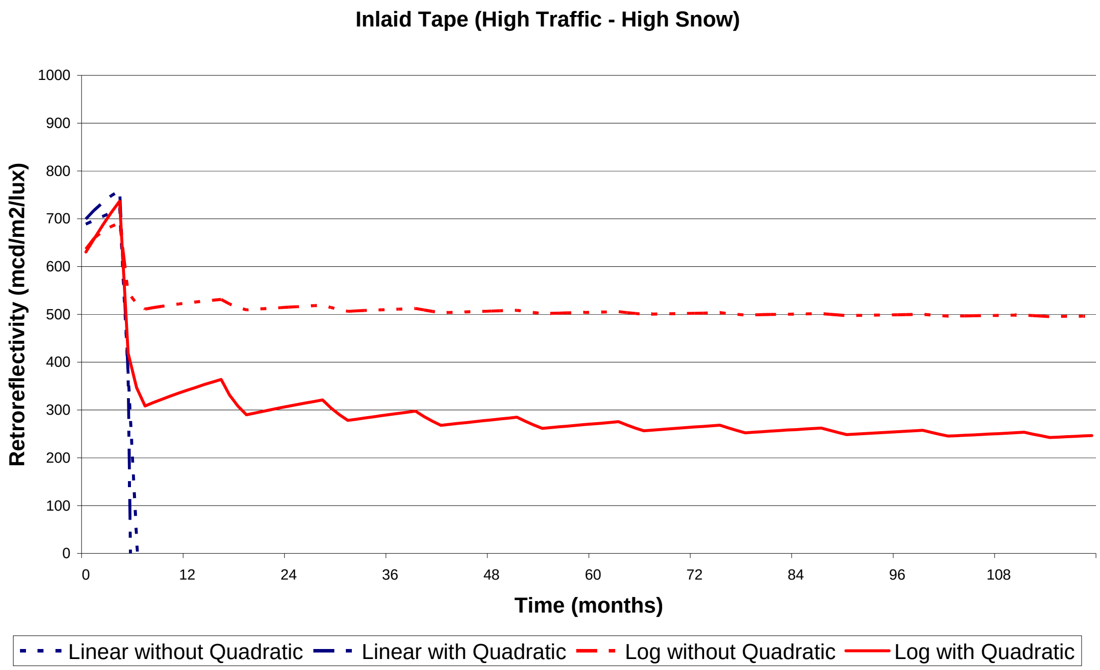

Figure 17. Regression Curves for Inlaid Tape (High Traffic & High Snow)

Figures 18-26 show similar curves for thermoplastic: After the first year, each basic equation produces different estimation curves.

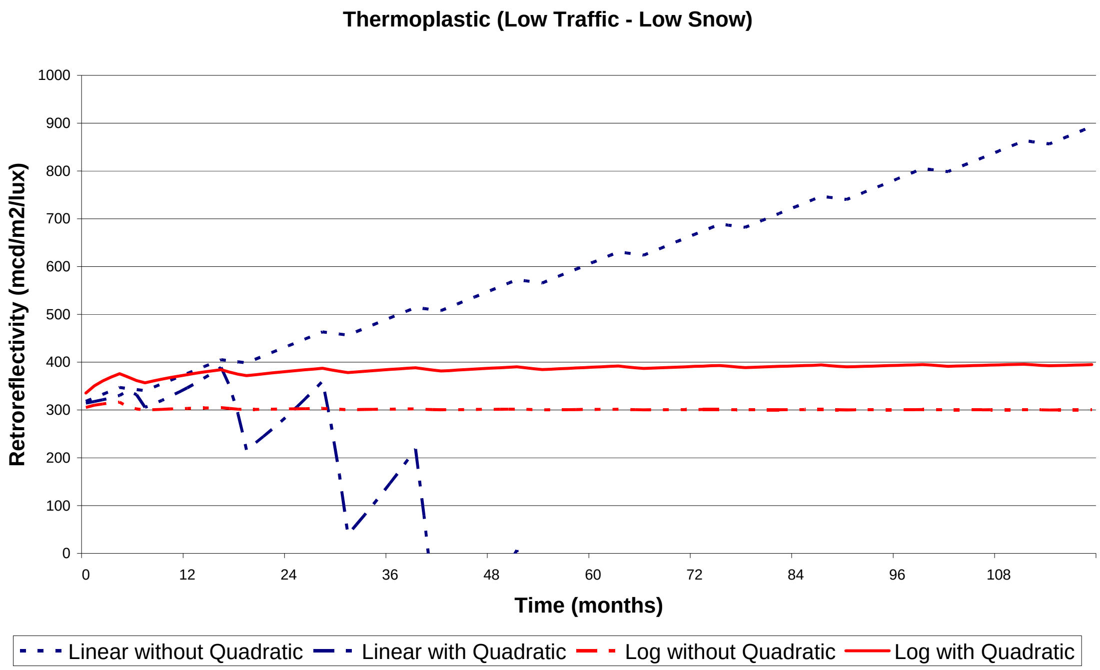

Figure 18. Regression Curves for Thermoplastic (Low Traffic & Low Snow)

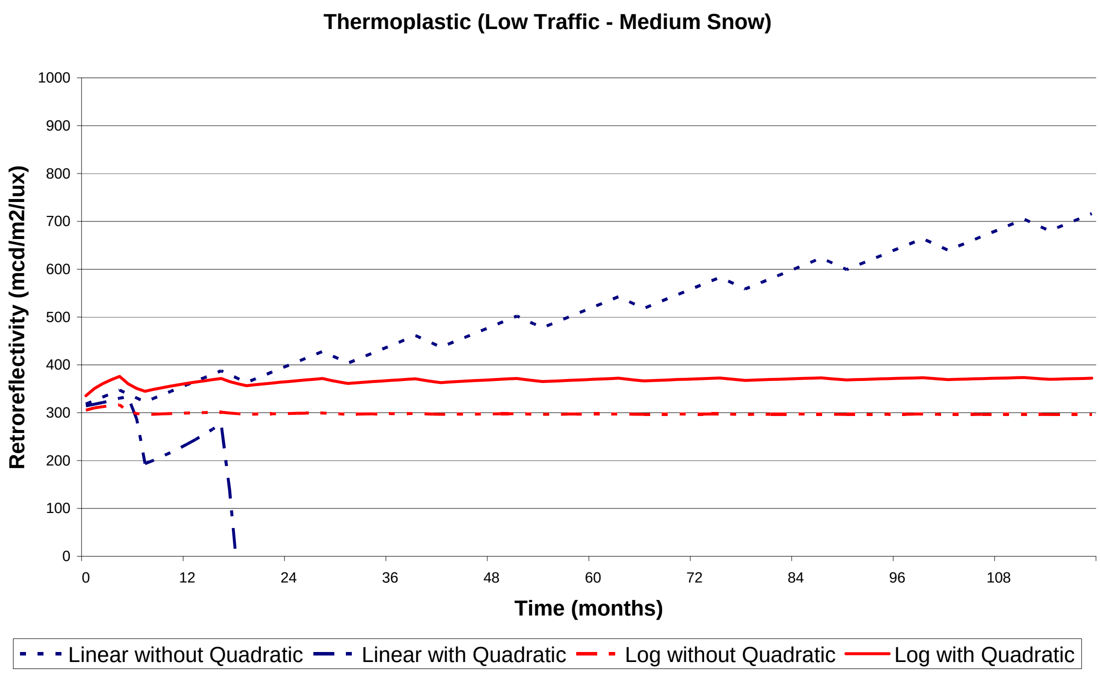

Figure 19. Regression Curves for Thermoplastic (Low Traffic & Medium Snow)

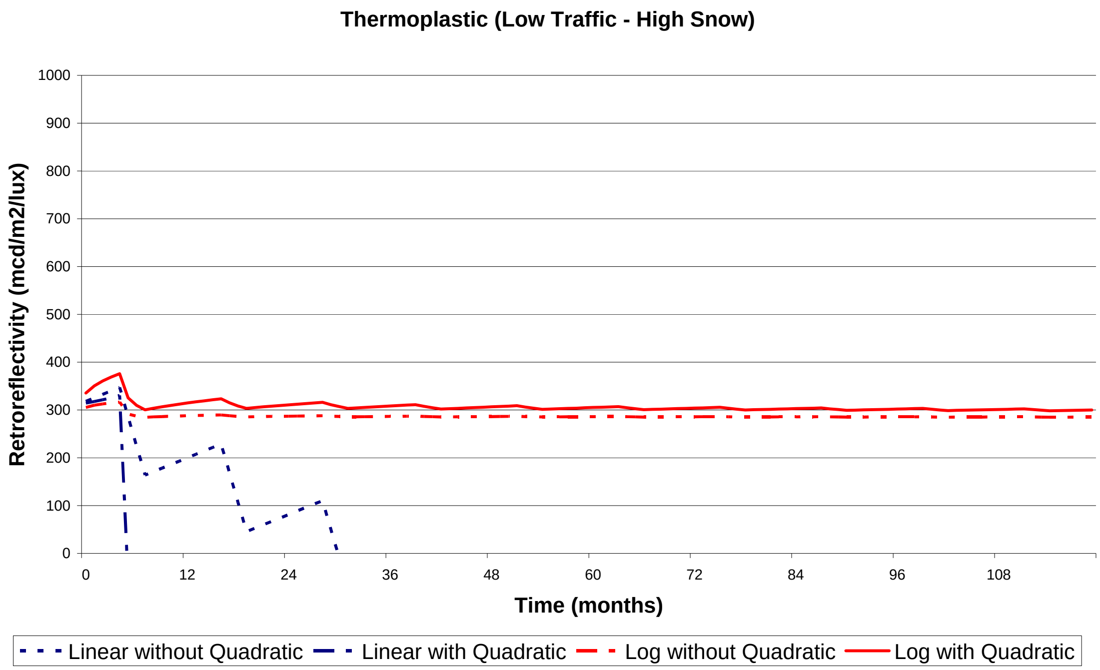

Figure 20. Regression Curves for Thermoplastic (Low Traffic & High Snow)

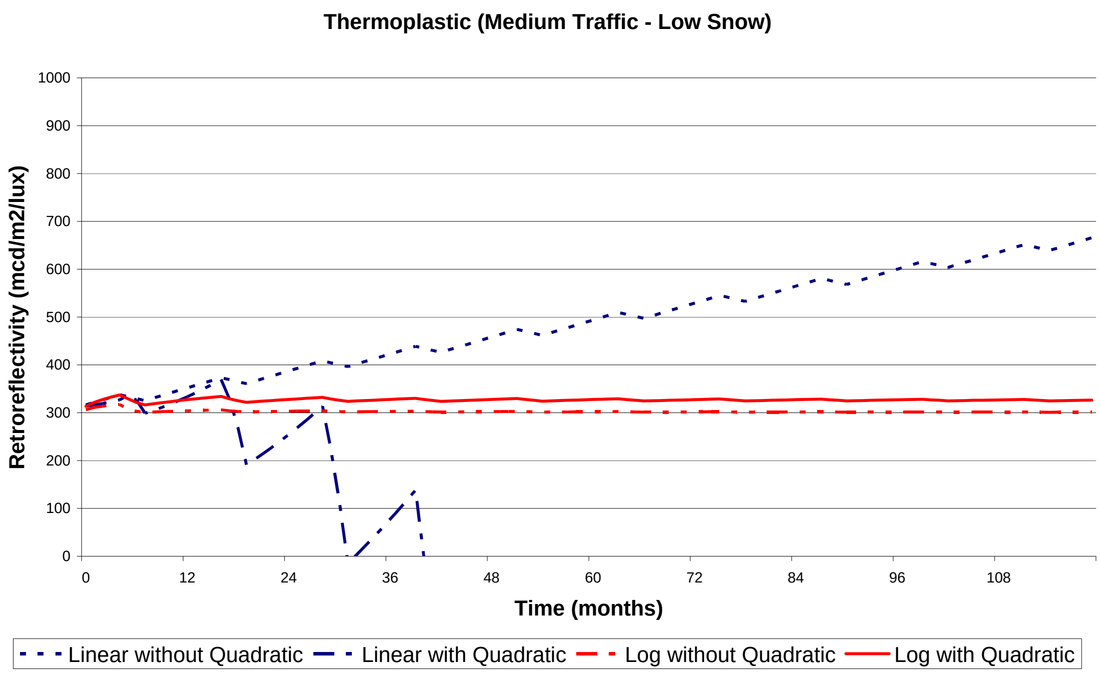

Figure 21. Regression Curves for Thermoplastic (Medium Traffic & Low Snow)

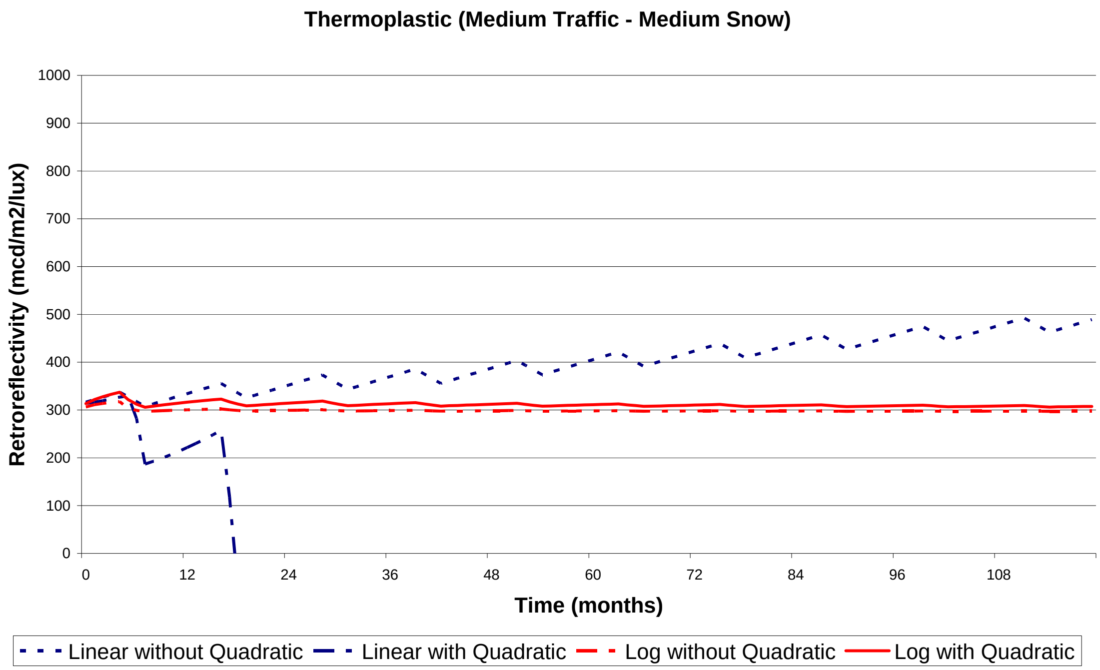

Figure 22. Regression Curves for Thermoplastic (Medium Traffic & Medium Snow)

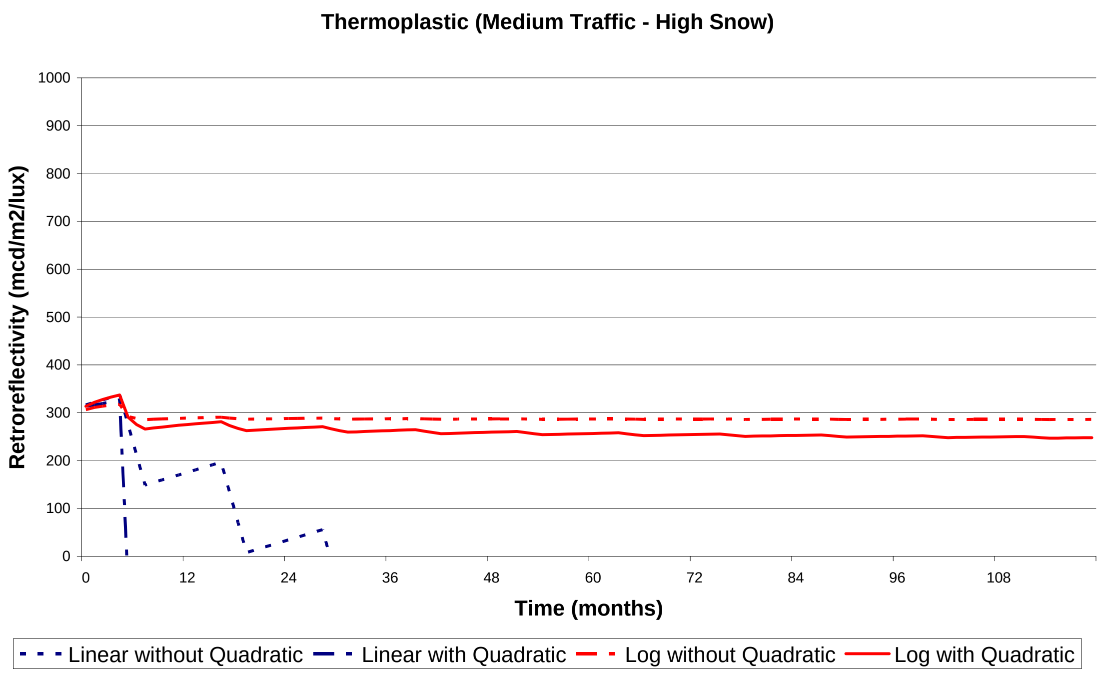

Figure 23. Regression Curves for Thermoplastic (Medium Traffic & High Snow)

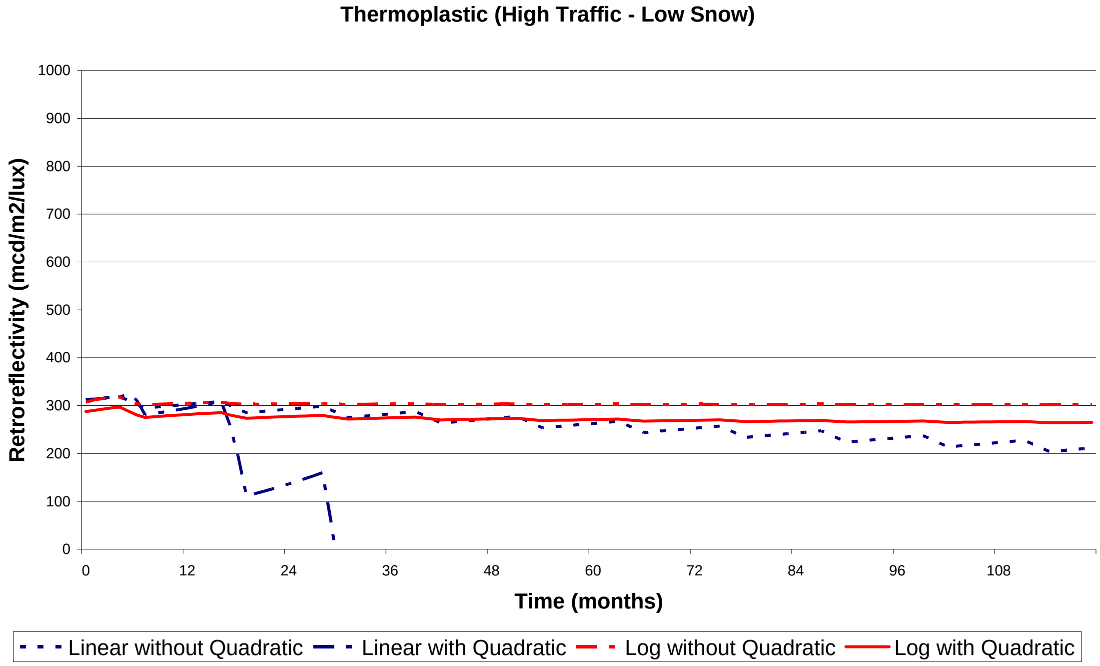

Figure 24. Regression Curves for Thermoplastic (High Traffic & Low Snow)

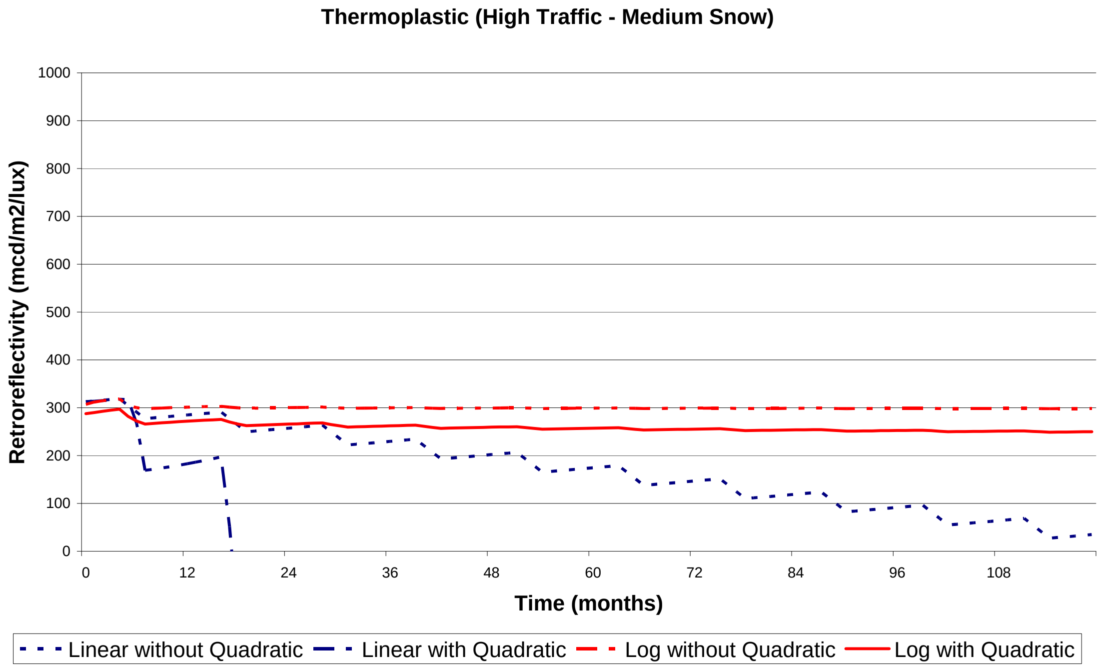

Figure 25. Regression Curves for Thermoplastic (High Traffic & Medium Snow)

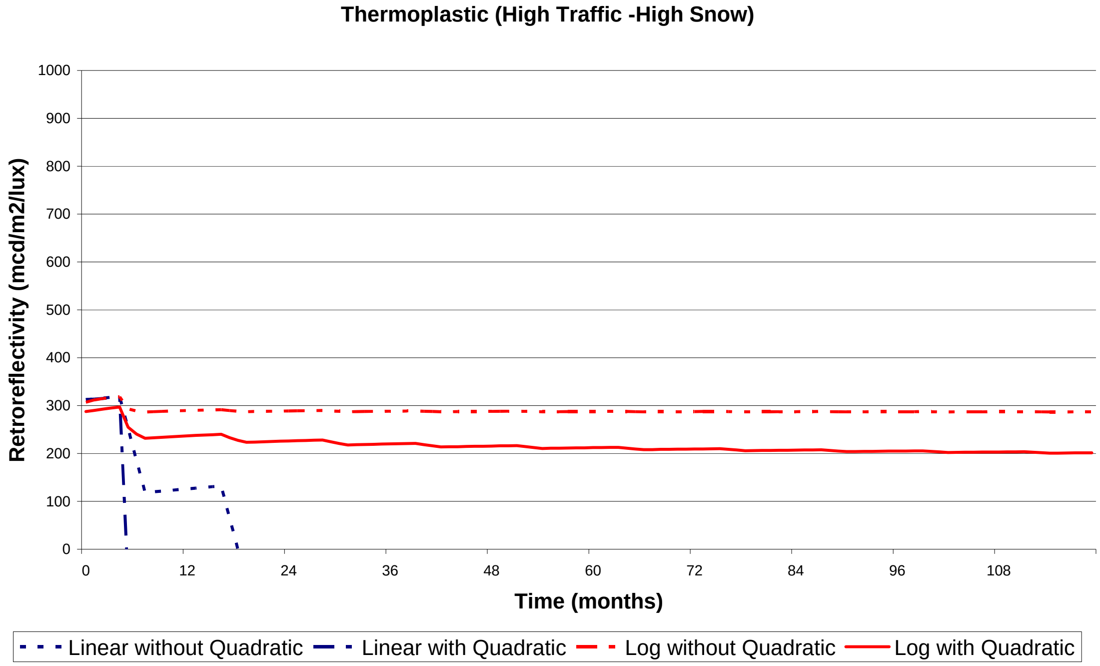

Figure 26. Regression Curves for Thermoplastic (High Traffic & High Snow)

Life Cycle Estimation

In order to draw the regression curves in Figures 9-26, we estimated the retroreflectivity with the assumed traffic and weather conditions for each basic regression equation. Once retroreflectivity was estimated for each condition, the life cycles could be found using threshold values.

In Table 10, the estimated life cycles for the three pavement marking materials are shown for each condition and regression equation. The life cycles of waterborne paint were estimated from previous studies (Lee, 2007; Lee, et al., 2008). Natural log with quadratic was found to be the best basic equation for waterborne paint, and the results from the two different versions of the equation were averaged and used for estimating the life cycles of waterborne paint.

Condition	Regression Equations	Life Cycle of Pavement Marking Materials (months)		
		Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	Linear	64, 65, 66	N/A	13, 24, 40
	Linear with Quadratic	30, 30, 30	32, 32, 32	
	Natural Log (LN)	> 10 years	N/A	
	LN with Quadratic	>10 years	N/A	
Low Traffic & Medium Snow	Linear	30, 30, 40	N/A	12, 23, 33
	Linear with Quadratic	18, 18, 18	17, 18, 18	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
Low Traffic & High Snow	Linear	5, 5, 5	17, 18, 19	11, 20, 28
	Linear with Quadratic	6, 6, 6	5, 5, 5	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
Medium Traffic & Low Snow	Linear	76, 77, 78	N/A	7, 16, 30
	Linear with Quadratic	29, 30, 30	30, 31, 31	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
Medium Traffic & Medium Snow	Linear	30, 40, 40	N/A	7, 15, 27
	Linear with Quadratic	18, 19, 19	17, 18, 18	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
Medium Traffic & High Snow	Linear	6, 6, 6	17, 18, 18	7, 13, 18
	Linear with Quadratic	6, 6, 6	5, 5, 5	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
High Traffic & Low Snow	Linear	> 10 years	> 10 years	6, 12, 14
	Linear with Quadratic	27, 28, 29	19, 29, 29	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
High Traffic & Medium Snow	Linear	42, 43, 43	66, 89, 101	5, 10, 14
	Linear with Quadratic	19, 19, 19	17, 17, 17	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	
High Traffic & High Snow	Linear	6, 6, 6	7, 17, 17	5, 9, 12
	Linear with Quadratic	6, 6, 6	5, 5, 5	
	Natural Log (LN)	> 10 years	> 10 years	
	LN with Quadratic	> 10 years	> 10 years	

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 10. Estimated Life Cycle of the Different Pavement Marking Materials (White)

In Table 11, for each case, the three different life cycles are estimated based on three different design speeds in Table 3. Again, unlike waterborne paint, the life cycles for the durable materials are very inconsistent and reflect the curves in Figures 9-26. It is almost impossible to say which of the four basic equations can best estimate the results.

Condition	Cost-Equivalent Life Cycles Based on Waterborne Paint (months)		
	Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	520, 960, 1600	130, 240, 400	13, 24, 40
Low Traffic & Medium Snow	480, 920, 1320	120, 230, 330	12, 23, 33
Low Traffic & High Snow	440, 800, 1120	110, 200, 280	11, 20, 28
Medium Traffic & Low Snow	280, 640, 1200	70, 160, 300	7, 16, 30
Medium Traffic & Medium Snow	280, 600, 1080	70, 150, 270	7, 15, 27
Medium Traffic & High Snow	280, 520, 720	70, 130, 180	7, 13, 18
High Traffic & Low Snow	240, 520, 560	60, 120, 140	6, 12, 14
High Traffic & Medium Snow	200, 400, 560	50, 100, 140	5, 10, 14
High Traffic & High Snow	200, 360, 480	50, 90, 120	5, 9, 12

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 11. Cost-Equivalent Life Cycles of Durable Materials Based on Waterborne Paint (White)

The life cycles of the waterborne paint for the nine different conditions show very consistent results. Depending on traffic and weather conditions, it can be effective for one to three years (Table 10). Obviously, when the design speed of the road is higher, a higher threshold value is required and the life cycle of waterborne paint becomes shorter. The life cycle also declines with more traffic and snowfall.

If the design speed of a road is higher than 55 mph (89 km/hr), which requires a threshold value higher than 150 mcd/m^2/lux, waterborne paint will not last more than 13 months under any conditions. In severe conditions on a road of that speed, it will only stay above 150 mcd/m^2/lux for five months. Since a July installation was assumed, the retroreflectivity would fall under the threshold value after one month of snow and not meet the standard in the middle of winter. In milder conditions, waterborne paint can be effective on 55 mph (89 km/hour) roads for up to six months, which means that it can continue to be effective after the winter is over.

Waterborne paint can be effective and remain above the threshold value for more than three years if a road's design speed is below 55 mph (89 km/hr) and it receives low traffic and snowfall.

Economic Efficiency Analysis

Economic efficiency is typically determined by annual costs. The annual cost is found through the even distribution of the installation costs throughout the estimated life cycle. However, we cannot use that conventional method in this research because of the difficulty in estimating the life cycles of the durable materials. As a result, we used the cost-equivalent life cycles of waterborne paint.

As shown in the Table 7, the assumed installation costs for waterborne paint, thermoplastic, and inlaid tape are \$0.05/ft., \$0.50/ft., and \$2.00/ft., respectively. In other words, thermoplastic must last 10 times longer than waterborne paint to be considered cost-effective. Furthermore, inlaid tape must last 40 times longer than waterborne paint and four times the life cycle of thermoplastic to be considered cost-effective.

The cost-equivalent life cycles of the durable materials shown in Table 11 are based on the reasonable life cycles and installation costs of waterborne paint that are detailed in Table 7. According to Table 11, inlaid tape and thermoplastic must last in severe traffic and weather conditions for 200 months and 50 months, respectively, to be considered more cost-effective than waterborne paint. Because we can hardly expect those materials to last that long, waterborne paint is mathematically cost-effective in almost any condition.

However, waterborne paint may not be effective in every condition. Its retroreflectivity lasts less than one year on high speed roads (55 mph), and 45 mph roads that receive medium traffic and high snow. Waterborne paint should also not be used if its retroreflectivity will fall under the threshold in the winter due to the impracticality of a winter installation. For that reason, we recommend that durable materials be used in places where waterborne paint's life cycle would be less than 7 months.

A definitive answer to the question of whether inlaid tape or thermoplastic is more economical can be answered once the materials' life cycles are estimated with more than a year's worth of data.

Sensitivity Analysis

We performed a sensitivity analysis to minimize the errors and uncertainties in the estimation, which included increasing and decreasing the life cycles and installation costs to include the effects of those changes. Because the life cycles of the durable materials are not estimated, the changes in life cycles of waterborne paint are shown as examples in Tables 12-15.

Condition	Cost-Equivalent Life Cycles Based on Waterborne Paint (months)		
	Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	680, 1240, 2080	170, 310, 520	17, 31, 52
Low Traffic & Medium Snow	640, 1200, 1720	160, 300, 430	16, 30, 43
Low Traffic & High Snow	560, 1040, 1440	140, 260, 360	14, 26, 36
Medium Traffic & Low Snow	360, 840, 1560	90, 210, 390	9, 21, 39
Medium Traffic & Medium Snow	360, 800, 1400	90, 200, 350	9, 20, 35
Medium Traffic & High Snow	360, 680, 920	90, 170, 230	9, 17, 23
High Traffic & Low Snow	320, 640, 720	80, 160, 180	8, 16, 18
High Traffic & Medium Snow	280, 520, 720	70, 130, 180	7, 13, 18
High Traffic & High Snow	280, 480, 640	70, 120, 160	7, 12, 16

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 12. Sensitivity Analysis (30% Higher Life Cycle of Waterborne Paint)

Condition	Cost-Equivalent Life Cycles Based on Waterborne Paint (months)		
	Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	360, 680, 1120	90, 170, 280	9, 17, 28
Low Traffic & Medium Snow	320, 640, 920	80, 160, 230	8, 16, 23
Low Traffic & High Snow	320, 560, 800	80, 140, 200	8, 14, 20
Medium Traffic & Low Snow	200, 440, 840	50, 110, 210	5, 11, 21
Medium Traffic & Medium Snow	200, 440, 760	50, 110, 190	5, 11, 19
Medium Traffic & High Snow	200, 360, 760	50, 90, 190	5, 9, 19
High Traffic & Low Snow	160, 320, 400	40, 80, 100	4, 8, 10
High Traffic & Medium Snow	160, 280, 400	40, 70, 100	4, 7, 10
High Traffic & High Snow	160, 240, 320	40, 60,80	4, 6, 8

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 13. Sensitivity Analysis (30% Lower Life Cycles of Waterborne Paint)

Condition	Cost-Equivalent Life Cycles Based on Waterborne Paint (months)		
	Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	400, 738, 1231	100, 185, 308	13, 24, 40
Low Traffic & Medium Snow	369, 708, 1015	92, 177, 254	12, 23, 33
Low Traffic & High Snow	338, 615, 862	85, 154, 215	11, 20, 28
Medium Traffic & Low Snow	215, 492, 923	54, 123, 230	7, 16, 30
Medium Traffic & Medium Snow	215, 462, 831	54, 115, 208	7, 15, 27
Medium Traffic & High Snow	215, 400, 554	54, 100, 138	7, 13, 18
High Traffic & Low Snow	185, 369, 431	46, 92, 108	6, 12, 14
High Traffic & Medium Snow	154, 308, 431	38, 77, 108	5, 10, 14
High Traffic & High Snow	154, 277, 369	38, 69, 92	5, 9, 12

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 14. Sensitivity Analysis (30% Higher Installation Costs of Waterborne Paint)

Condition	Cost-Equivalent Life Cycles Based on Waterborne Paint (months)		
	Inlaid Tape	Thermoplastic	Waterborne Paint
Low Traffic & Low Snow	743, 1371, 2286	186, 343, 571	13, 24, 40
Low Traffic & Medium Snow	686, 1314, 1886	171, 329, 471	12, 23, 33
Low Traffic & High Snow	629, 1143, 1600	157, 286, 400	11, 20, 28
Medium Traffic & Low Snow	400, 914, 1714	100, 229, 428	7, 16, 30
Medium Traffic & Medium Snow	400, 857, 1543	100, 214, 386	7, 15, 27
Medium Traffic & High Snow	400, 743, 1029	100, 186, 257	7, 13, 18
High Traffic & Low Snow	343, 686, 800	86, 172, 200	6, 12, 14
High Traffic & Medium Snow	286, 572, 800	71, 142, 200	5, 10, 14
High Traffic & High Snow	286, 514, 686	71, 129, 172	5, 9, 12

Life cycles are based on the thresholds of 150, 100, and 85 mcd/m^2/lux, respectively.

Table 15. Sensitivity Analysis (30% Lower Installation Costs of Waterborne Paint)

When the life cycle of waterborne paint is longer, the cost-equivalent life cycles of the durable materials becomes longer as well (Table 12). In other words, if the life cycle of waterborne paint becomes longer without changes in installation costs, then the life cycles of the durable materials should become longer to be competitive with waterborne paint. It should also be noted that the number of months that should be increased for the durable materials is much higher than that for waterborne paint. If the life cycle of waterborne paint becomes two months longer, then thermoplastic's should be 20 months longer and inlaid tape's should be 80 months longer to maintain the competitiveness. On the other hand, if the life cycle of waterborne paint is decreased, then those of durable materials can be much shorter and remain competitive (Table 13).

A similar rule is applied to the sensitivity analysis of the installation costs. If the installation costs of waterborne paint are higher, then the cost-equivalent life cycles of the durable materials can be shorter if their installation costs remain the same (Table 14). The ratio between the installation costs of waterborne paint and the durable materials decides the ratio between the cost-equivalent life cycles of the different materials. If waterborne paint's installation cost decreases and the durable materials' costs do not change, then the resulting high life cycle ratio increases the durable materials' cost-equivalent life cycles and makes them more competitive (Table 15).

An extensive sensitivity analysis can be pursued once the life cycles of the durable materials are estimated with more detailed data.

CONCLUSIONS

The future performance and life cycle of inlaid tape and thermoplastic cannot be properly estimated with only one year of data. There was not much decline in the retroreflectivity of the durable materials during the study period, and their retroreflectivity tends to increase in the first few months because of revealed beads. This fluctuation in retroreflectivity makes it extremely difficult to forecast performance. As shown in Figure 7, the forecasted retroreflectivity values vary greatly depending on which basic equation is used. While the retroreflectivity of waterborne paint also fluctuates during the first few months, it changes enough throughout the rest of the year to provide for reliable and proper estimates of future performance.

Even if we were able to select the right estimation function, there can be big differences in the life cycle estimations because the retroreflectivity of the durable materials is much higher than the threshold values that decide the life cycles of the materials. Because of these big differences, small errors in the estimation can result in big variations in the life cycles (Figure 8). In comparison, waterborne paint's first year retroreflectivity is very close to its threshold values, which means that there are fewer errors in its life cycle estimation.

The aforementioned problems also made it difficult to estimate retroreflectivity for the durable materials. Although the curves in Figures 9-26 show reasonable performance during the study period, each basic regression equation produces dramatically different retroreflectivity estimates after the first year.

The life cycle of a material is defined as the period at which the retroreflectivity falls below the threshold value. Economic efficiency is based on the even distribution of installation costs throughout the life cycle. Our unreliable retroreflectivity estimates prevented a proper estimate of the durable materials' life cycle and economic efficiency. Instead, this study's economic analysis used waterborne paint's more reliable life cycles, and compared the three materials' performance under various traffic and weather conditions.

The cost-equivalent life cycles of inlaid tape and thermoplastic were based on the life cycle of waterborne paint. The cost-equivalent life cycles of the durable materials were estimated using the ratio between the installation costs of the different materials. As shown in Table 11, the installation costs of inlaid tape and thermoplastic dictate that their cost-equivalent life cycles must be, respectively, 40 times and 10 times longer than that of waterborne paint.

Those high cost-equivalent life cycles suggest that waterborne paint is the most economical product for most conditions. However, waterborne paint will only last 5-7 months and not longer than a year on roads with high design speed (55 mph or higher), high traffic, and heavy snow. We would recommend the use of inlaid tape or thermoplastic in those conditions, but a definitive answer requires more data.

The sensitivity analysis showed that waterborne paint becomes more competitive when its life cycle is increased and its installation cost is decreased, and the inverse makes the durable materials more competitive.

This research establishes that data must be collected for more than a year in order to generate reliable and consistent estimates of future retroreflectivity. We should also note that an accurate economic efficiency analysis is dependent on the proper estimation of installation costs. This study used nationwide estimated installation costs, but a good estimate of installation costs should include prices related to materials, labor, equipment, congestion, and safety.

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