Martin O'Malley, *Governor*
Anthony G. Brown, *Lt. Governor*

John D. Porcari, *Secretary*
Neil J. Pedersen, *Administrator*

STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

DURABILITY STUDY:
WATERBORNE PAINT PAVEMENT MARKINGS

DR. YOUNG –JAE LEE, PH.D.

DEPARTMENT OF TRANSPORTATION AND URBAN INFRASTRUCTURE STUDIES MORGAN STATE UNIVERSITY

SP508B49
FINAL REPORT

November 2008

i

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Maryland State Highway Administration. This report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

1. Report No. MD-08-SP508B49	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Durability Study: Waterborne Paint Pavement Markings		5. Report Date *November 2008*
		6. Performing Organization Code
7. Author/s Dr. Young-Jae Lee		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Transportation and Urban Infrastructure Studies Morgan State University Baltimore, MD 21251		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. *SP508B49*
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore MD 21202		13. Type of Report and Period Covered *Final Report*
		14. Sponsoring Agency Code (7120) STMD - MDOT/SHA

15. Supplementary Notes

16. Abstract

In this research, the relationship between retroreflectivity and various inputs that possibly affect retroreflectivity were analyzed for different traffic volumes and weather conditions from eight locations throughout the state of Maryland. Inputs considered in this research were Number of Days Exposed, Cumulated Traffic Exposed, Cumulated Precipitation, and Cumulated Snowfall. First, the relationship between retroreflectivity and the Number of Days Exposed was analyzed for each location. The retroreflectivity and input data were then aggregated and analyzed for each pavement marking type, and a total analysis was completed. Single variable regression analysis was used to find the relationship between retroreflectivity and input variables. After single variable regression analysis, multivariable regression analysis was conducted using the multiple inputs as well. Finally, the durability and life cycle of the white and yellow waterborne paint pavement markings were estimated using the regression equations and thresholds of each paint type for different speed limits.

17. Key Words Pavement, Markings, Waterborne paint, Retroreflectivity	18. Distribution Statement: No restrictions This document is available from the Research Division upon request.		
19. Security Classification (of this report) *None*	20. Security Classification (of this page) *None*	21. No. Of Pages 105	22. Price

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

EXECUTIVE SUMMARY

The Maryland State Highway Administration (SHA) has been evaluating the long-term durability and retroreflectivity of waterborne paint pavement marking materials using existing SHA specifications and procedures. The objectives of this research are to ensure proper procedure; and to evaluate the effect of various inputs (traffic volume, snow, and rain) on the desired outputs (durability and retroreflectivity) for pavement markings.

In order to perform this research, meetings between the project teams from Morgan State University and SHA were held about once a month to select locations and establish data collection methods. For purposes of this research, the state of Maryland was divided into three geographic regions — western, central, and eastern. These divisions were made because of the different characteristics of the regions in terms of the weather, topography, and traffic volumes and attributes. In each region three locations were selected as study sites in terms of the traffic volumes (low, medium, and high). However, only two sites in the western area were selected for this project due to the difficulty of finding three locations that satisfied the conditions required for the project. To generate more consistent data, test sections of flat and straight areas over a half mile were chosen. Physical site investigation was conducted to find reasonable sites. In order to generate more consistent data, the sites were selected from planned resurfacing and repainting projects in the target areas, and pavement materials were applied under standardized conditions.

In this research, the relationship between retroreflectivity and various inputs that possibly affect retroreflectivity were analyzed for different traffic volumes and weather conditions from eight locations throughout the state of Maryland. Inputs considered in this research were Number of Days Exposed, Cumulated Traffic Exposed, Cumulated Precipitation, and Cumulated Snowfall.

First, the relationship between retroreflectivity and the Number of Days Exposed was analyzed for each location. Next, the retroreflectivity and input data were aggregated and analyzed for each pavement marking type — White Edge (WE), White Skip (WS), Yellow Center (YC), Yellow Edge (YE), and Yellow Skip (YS) — and a total analysis was completed. The single variable regression analysis was used to find the relationship between retroreflectivity and input variables. After single variable regression analysis, multivariable regression analysis was conducted using the multiple inputs as well. Finally, the durability and life cycle of the white and yellow waterborne paint pavement markings were estimated using the regression equations and thresholds of each paint type for different speed limits.

I. INTRODUCTION

I.1 Problem Statement

The Maryland State Highway Administration (SHA), in its continuing efforts to provide superior guidance to motorists by clearly defining traffic lanes during day and night, continues to investigate and research pavement marking products that are dependable, durable, and effective. Evaluations are necessary to determine whether new pavement marking products (or existing products from new manufacturers) are suitable for use on Maryland highways, and also to ensure fairness and consistency across the state in evaluation of these products.

I.2 Objective

SHA is currently evaluating the long-term durability and retroreflectivity of waterborne paint pavement marking materials using existing SHA specifications and procedures. The objectives of this project are to ensure proper procedure; and to evaluate the effect of various inputs (traffic volume, snow, rain, etc) on the desired outputs (durability and retroreflectivity) for pavement markings. From this analysis, general equations to estimate the retroreflectivity and durability will be provided from the inputs collected.

I.3 Preliminary Analysis

The data for the research was originally collected in October 2004, prior to the start date of current research. The data collection was pursued at the existing markings at each site before application, which have a minimum retroreflectivity value of 100 millicandelas/meter^2/lux (mcd). Data readings were collected every one or two months for the high AADT (Annual Average Daily Traffic) locations, and every three months for the low AADT locations.

The study locations were selected from the each of the seven districts, two locations with existing markings: a high traffic volume site (40,000 AADT minimum) and a low traffic volume site (10,000 AADT maximum). At each location, five mile points were selected. At each mile point, the retroreflectivities of the five spots were measured. However, because data collection and site selection did not produce meaningful results, it became necessary to conduct a second phase research. This second phase research was coordinated by the research team from the very beginning stage of the research to ensure consistent application of materials and data collection.

I.4 Main Analysis

As the second phase study, the project meetings were held once a month to select locations and establish data collection methods with Morgan State University and the SHA project team. In the second phase research, the state of Maryland was divided into three regions: western, central, and eastern. These distinctions were made because of the

regions' different characteristics in terms of the weather, topography, and traffic amounts and attributes. In each region, three test locations were selected as study sites in terms of the traffic volume (low, medium, and high). However, only two sites in the western area were selected for this project due to the difficulty of finding three locations that satisfied the conditions required for the project. For site selection, in order to generate more consistent data, flat and straight roadway area sections on half- mile segments were chosen. Extensive physical investigations of possible sites were conducted in order to find reasonable sites. Also, in order to generate more consistent data, the sites were selected from planned resurfacing and repainting projects in the areas. The selected sites are shown in Figure 1 and Table 1.
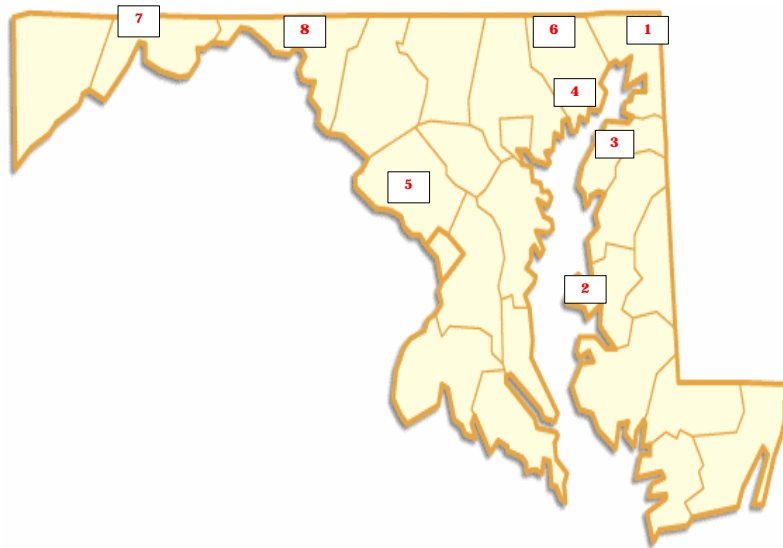
Figure 1. Eight Locations for the Research

Table 1. Specific Information of the Eight Locations

REGION	LEGEND	COUNTY	ROUTE	RANGE	MP-from:	MP-to:	AADT	LANES
Eastern	1	CECIL	MD 273	High AADT	12.36	14.96	10,300	2
	2	TALBOT	MD 33	Mid AADAT	10.82	13.02	6,550	2
	3	KENT	MD 297	Low AADT	0.00	3.59	2,375	2
Central	4	HARFORD	US 40	High AADT	6.85	9.93	21,500	4
	5	MONTGOMERY	MD 117	Mid AADAT	5.23	6.20	5,825	2
	6	HARFORD	MD 165	Low AADT	13.12	13.52	6,450	2
Western	7	ALLEGANY	MD 53	High AADT	0.63	3.03	14,575	2
	8	WASHINGTON	US 40ALT	Mid AADAT	2.53	6.21	6,175	2

Instead of bimonthly or quarterly measurements, the data were collected monthly at the eight locations. The data collection was pursued by SHA. In order to provide more consistent data, for each location, the retroflectivity readings were taken at the exact same five-mile points and at each mile-point, exact same five spots were selected. Some inconsistencies were found in the data during the winter period. As a result, the paint markings were cleaned and measured again after the measurements of the retroreflectivity. This was done so that the dust effect during the winter could be analyzed separately.

II. LITERATURE REVIEW

In this chapter, important background information for this research is presented.

II.1 Pavement Marking Materials

The pavement marking materials are categorized as conventional products and durable products. Conventional pavement marking materials are latex (waterborne) and alkyd (solvent based) paints. These products are typically inexpensive and may have a relatively short life span. Durable pavement marking materials have a longer life expectancy than conventional pavement marking materials. This category includes mid-durable paint, thermosets (epoxy and polyester), thermoplastics, and tape (poly perform). These products are more expensive than conventional pavement marking materials, but last longer. In addition to above durable pavement marking materials, there is a temporary products and temporary tape is in this category. Table 2 shows the summary of the pavement marking materials (Montebello and Schroeder 2000).

II.2 Waterborne Paint (Latex)

Waterborne paint has become increasingly popular as a pavement marking material due to its low cost and the ease of cleaning up and disposing of leftover paint. It typically costs between \$0.03 and \$0.05 per linear foot installed. Waterborne paint is also more environmentally friendly because waterborne paint does not contain lead, other heavy metals, or volatile organic compounds that are hazardous to the environment and to those applying it. Because latex is more environmentally friendly than alkyd paints and it is comparable in costs, it is likely that latex will be promoted for use by striping companies.

When applied, waterborne paints should have initial retroreflectivity readings of at least 275 mcd/m^2/lux for white, and at least 180 mcd/m^2/lux for yellow (250 mcd/m^2/lux for white, and at least 150 mcd/m^2/lux for yellow in Maryland).

The drawback of using latex paint is that it is not as long lasting as a durable material. Studies show that the waterborne paint is generally good for no more than a year in high volume areas (AADT of 10,000 or more), and probably should be replaced after nine months. In some areas with low traffic volume, markings may last as long as three years (Montebello and Schroeder 2000).

II.3 Retroreflectivity

Two important components must be evaluated when deciding which pavement marking material to use. The first component is whether the line or the marking that is put on the pavement is visible during the day. The second component is the retroreflectivity, which is the part visible at night when headlights reflect off of the line. Both components are necessary for the marking to be useful to drivers. Typically, beads are dropped on top of the material that is used to give the line marking its retroreflectivity.

Table 2. Pavement Marking Materials (Source: Montebello and Schroeder 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

Retroreflectivity is the portion of incident light from a vehicle's headlights reflected back toward the eye of the driver of the vehicle. Retroreflectivity is provided in pavement marking materials by glass or ceramic beads that are partially embedded in the surface of the material (Migletz, et al. 1999).

II. 4 Glass Beads

Glass beads are tiny spherical balls that are used to make pavement marking materials retroreflective. The beads must be transparent and round to act like lenses. Light, as it enters a bead, is refracted, or focused down through the bead, and reflects back toward the path of entry as shown in Figure 2 (Pavement Marking Studies Near Completion 1996).
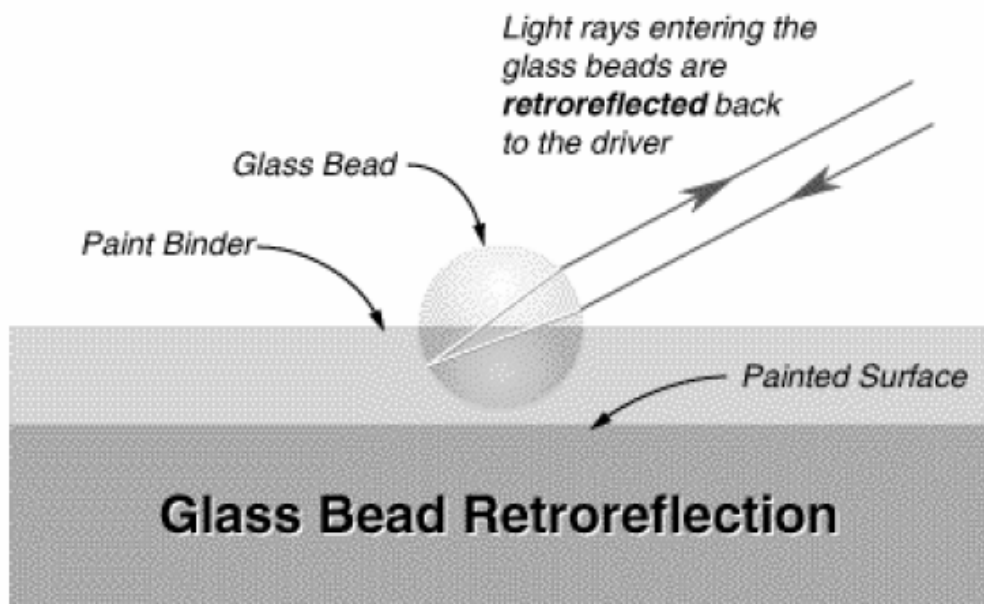
Figure 2. Glass Bead Retroreflection

Glass beads are dropped on top of freshly applied conventional paints and durable materials such as epoxies. In some cases, portions of beads are mixed in with paint before it is applied (pre-mixed paint).

Glass beads 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 continued retroreflectivity as the paint wears. The same results can be achieved by using the pre-mixed paints and dropping in untreated beads. The proper application of beads is key to creating the marking's retroreflectivity (Montebello and Schroeder 2000).

II. 5 Retroreflectivity Measuring Equipment

Retroreflectivity is measured by the LTL-X, a product by the Delta Company in Denmark. The LTL-X retrometer is a portable field instrument intended for measuring the retroreflection properties of road markings in car headlight illumination. The value R1 (coefficient of retroreflected luminance) is used. R1 is a measure of the lightness of the road marking as seen by drivers of motorized vehicles in car headlight illumination. The road is illuminated at an angle of 1.24°, and the reflected light, measured at an angle of 2.29°, corresponds to an observation distance of 30 meters (100 ft). This is relevant for a motorist's viewing situation under normal conditions.

The LTL-X measures the retroreflectivity and calculated R1 according to international agreements. Results are presented in plain text on a large graphic display. The instrument's illumination field is approximately 200 mm x 45 mm (7.9 inches x 1.8 inches), and the observation field is about 610 mm x 60 mm (24.1 inches x 2.4 inches). The tower of the LTL-X contains the illumination and observation system and the control electronics. With a mirror, 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. The result is automatically transferred to the internal memory. The measurement — along with its corresponding time, date, and other data — can be printed using the built-in printer.

Figure 3. Retroreflectivity Measuring Equipment (LTL-X)

II. 6 Service Life of the Pavement Markings

Recent research shows that the life cycle of the pavement markings is relevant to the traffic exposure, and the retroreflectivity can be expressed as a logarithmic regression equation (Abboud and Bowman 2002). However, the data was only collected from locations that do not have snow in winter.

Other research has also shown the life cycle of the pavement markings (Migletz, etc 2001). In that research, threshold retroreflectivity values were defined as shown in Table 3. Table 3 also shows how the life cycle of pavement markings vary depending on

the materials and roadway types. They are represented by cumulated traffic passages (CTP) and elapsed months as shown in Table 4.

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

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

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

Roadway Type and Material	Number of Pavement Marking Lines	Service Life	
		Average CTP (million vehicles)	Elapsed Months
Freeway:			
Polyester	1	11.1	39.7
Profiled tape	3	6.9	25.8
Thermoplastic	7	6.1	24.7
Profiled thermoplastic	4	5.3	23.5
Epoxy	7	4.7	23.2
Profiled poly methyl methacrylate	3	6.2	21.1
Poly methyl methacrylate	3	3.0	15.6
Non-Freeway ≤ 64 km/hr (40 mph):			
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 (45 mph):			
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

III. EXPERIENCE FROM THE PRELIMINARY STUDY

As mentioned previously, the data was collected before the initial research began. Because of potential false in-site selection and data collection, first phase analysis was conducted with limited data.

III.1 Analysis

From the total 14 sites, the data from 12 sites were provided. Since data had been collected for about six months, the collected data was not enough to generate meaningful results in terms of durability of the paint markings. However, it would be beneficial to provide valuable recommendations for the second phase study in terms of site selection and data collection methods.

Among those 12 sites in six districts, only District 2 provided complete data for the last six months. As a result, data for District 2 will be presented and analyzed as an example in this report. Figures 4-6 show the retroreflectivities of the White Edge (WE), White Skip (WS), and Yellow Edge (YE) of the high AADT area in the District 2 for six months. As mentioned, five-mile points were selected at each location. For the each mile point, five spots were selected. In the figures, each point, such as WE1, represents each mile point, which is the average of the five spots in the mile point. Also, the average of the five mile points is also plotted. As seen and discussed earlier, the average and other five-mile points show inconsistent results because of inconsistent data collection methods.

Figure 7 shows the average retroreflectivity numbers of the five mile points for the WE, WS, and YE. Although retroflectivities for the three cases are expected to decline over the periods, white edge and white skip have a similar V shapes. However, yellow edge shows the opposite shape. Since there are only three observations, it is premature to make any significant conclusions. However, it can be expected that because of snow effects during winter, different timings of the exposed beads, depreciation of the paint markings and/or combination of those made different shapes of the retroreflectivity changes for the different types of pavement markings.

Figures 8-10 show the retroreflectivities of WE, WS, and YE of the low AADT area in the District 2 for six months. The shapes of the plotted results are very similar to the ones for the high AADT case.
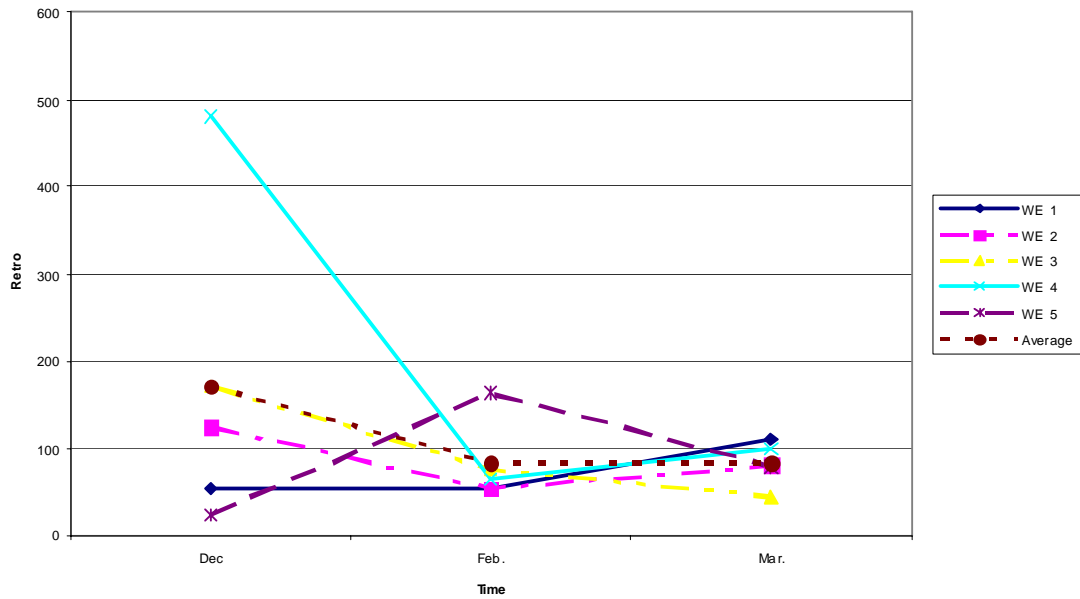
Figure 4. Retroreflectivity of the White Edge markings at District 2 High AADT
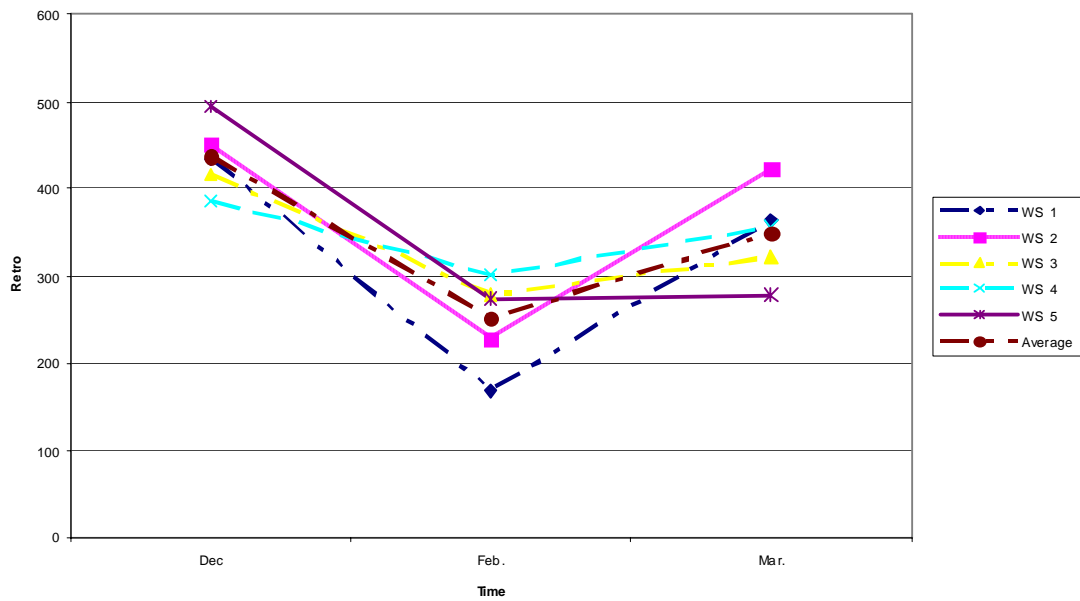
Figure 5. Retroreflectivity of the White Skip markings at District 2 High AADT
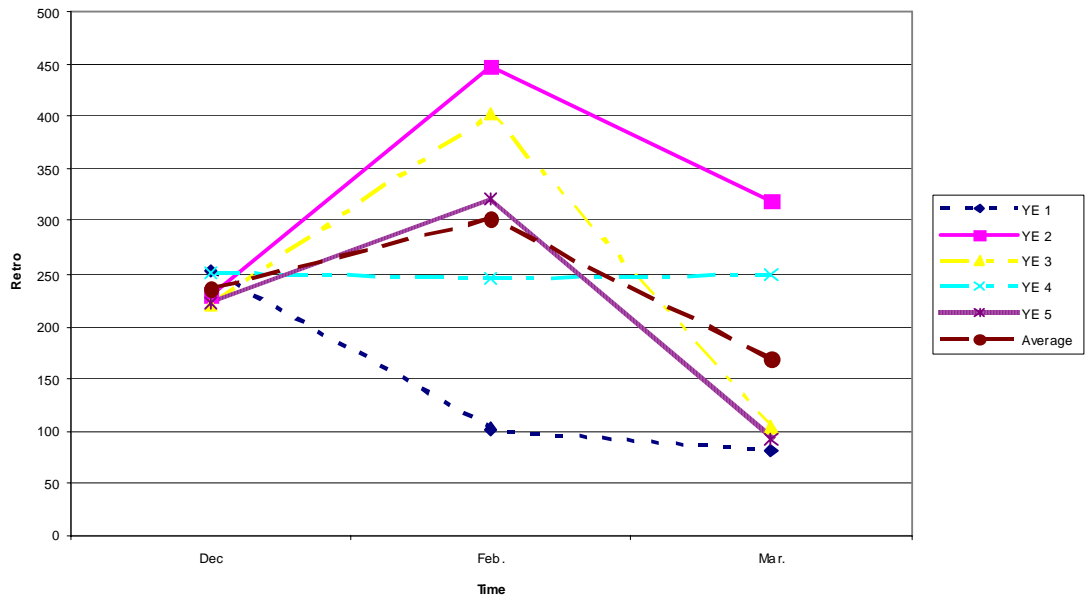
Figure 6. Retroreflectivity of the Yellow Edge markings at District 2 High AADT
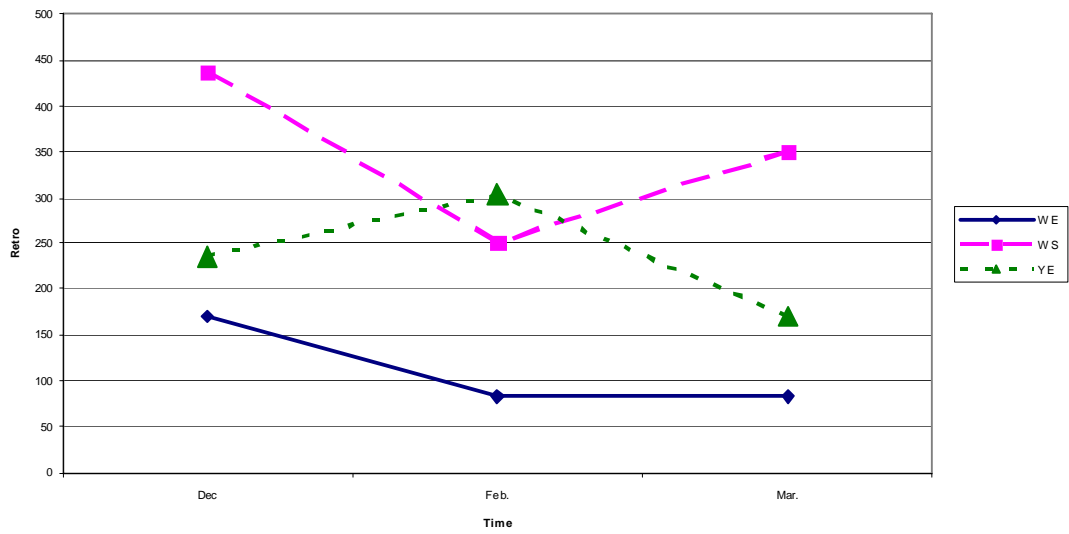
Figure 7. Overall retroreflectivity at District 2 High AADT
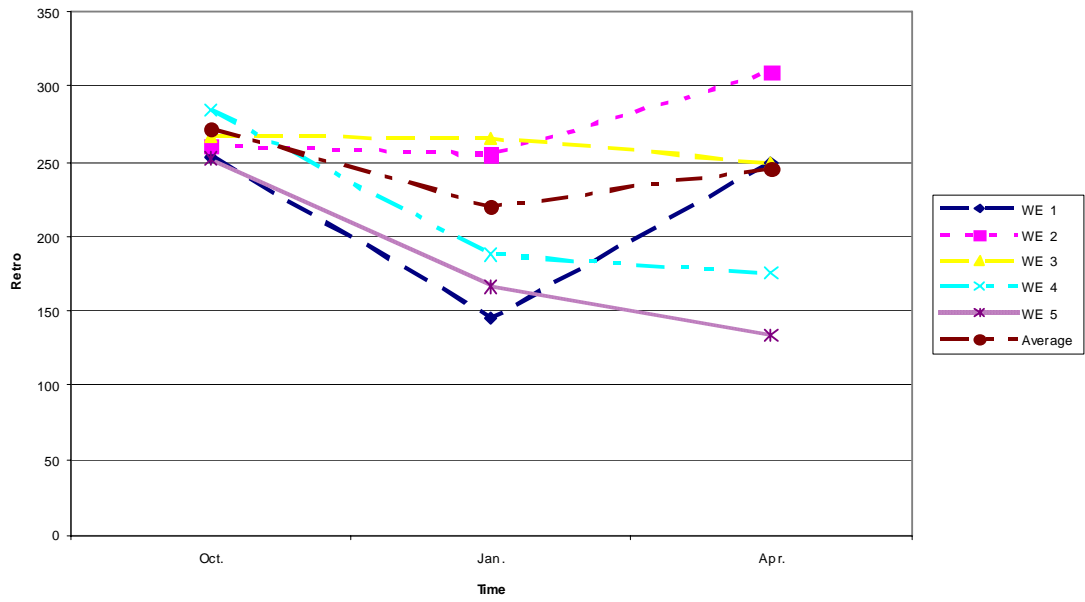
Figure 8. Retroreflectivity of the White Edge markings at District 2 Low AADT
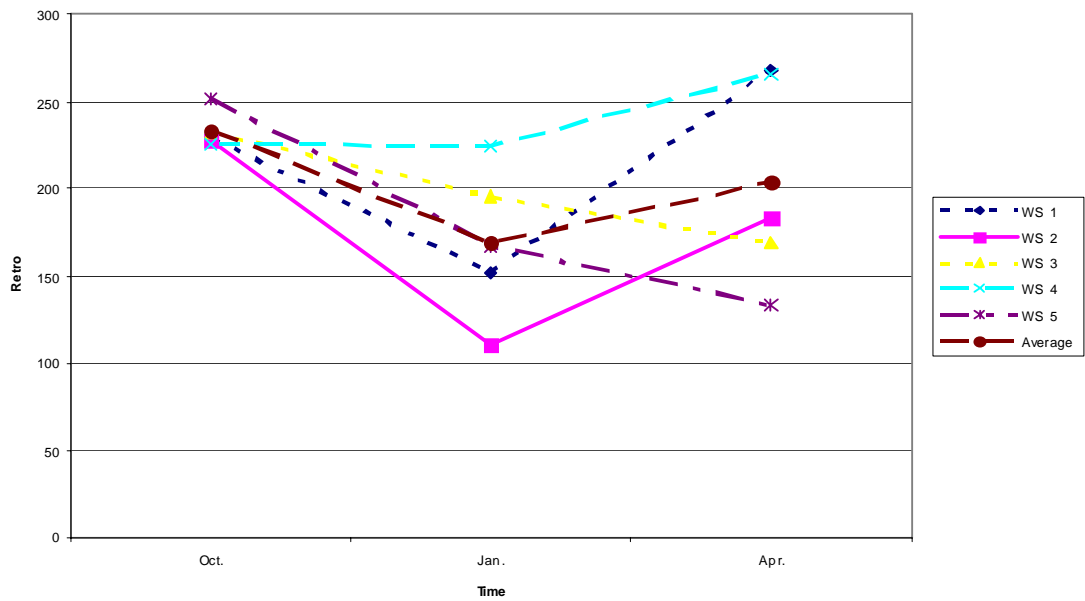
Figure 9. Retroreflectivity of the White Skip markings at District 2 Low AADT
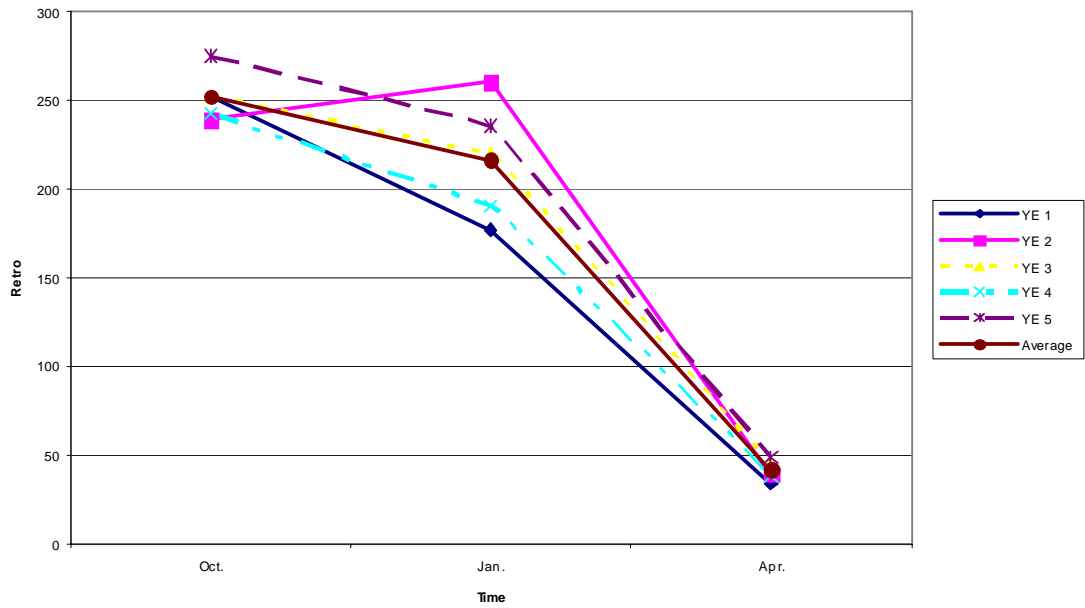
Figure 10. Retroreflectivity of the Yellow Edge markings at District 2 Low AADT
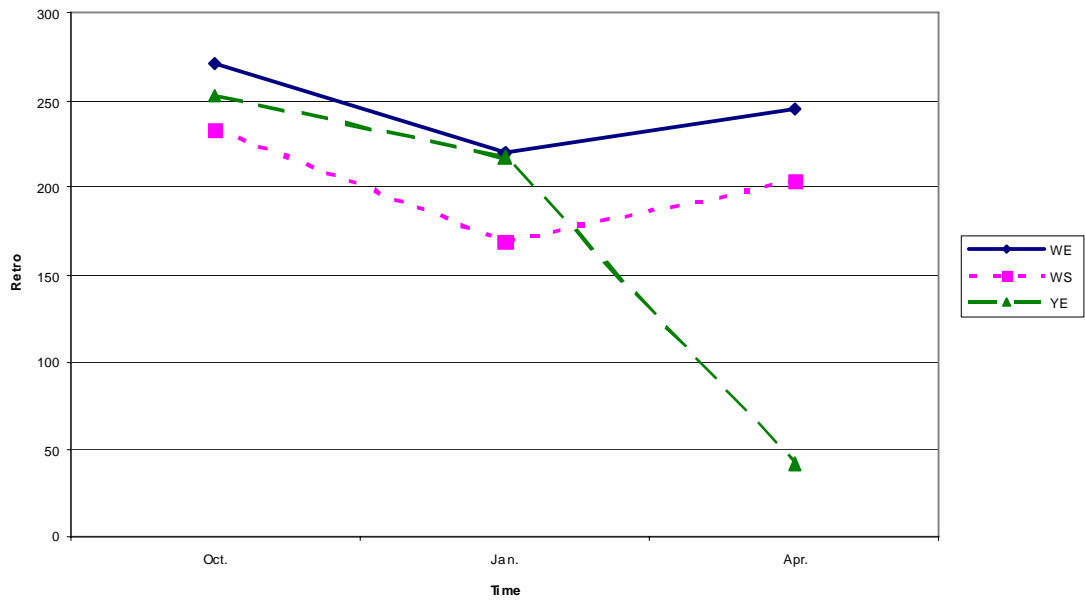
Figure 11. Overall retroreflectivity at District 2 Low AADT

III.2 Experience from the Preliminary Study and Recommendation for the Main Study

The figures from the first phase study showed inconsistency in the retroreflectivity due to site selection, data collection methods, and collected data from the first phase study. It was then recommended that a second phase study be pursued in order to make the output more consistent. The following corrections were recommended.

For the site selection,
- Rather than select sites from each district, the state of Maryland should be divided into regions — western, central, and eastern. This is due to the different weather, topography, and traffic amounts and attributes in each region.
- Instead of choosing two locations in each district in terms of AADT (high and low), three locations in each region should be selected in terms of the traffic amount.
- Since AADT is average annual daily traffic for the direction, the primary criteria for selecting three locations became traffic volume per lane, a reasonable measure to classify the locations.
- In order to generate more consistent data, the selected sites will be flat and straight over a half mile section.
- In order to generate more consistent data, the sites will be selected from the planned resurfaced and repainting projects.

For the data collection,
- Instead of taking bimonthly or quarterly measurements, the data will be collected monthly for the nine locations.
- In order to provide more consistent area, for each location, the retroflectivity will be measured at the exact same five mile points and at each mile point, exact same five spots will be selected.
- Due to inconsistencies in the data during the winter period, the paint markings should be cleaned and measured again after the measurements of the retroreflectivity. This will allow for separate analysis of the dust effect during the winter.

IV. METHODOLOGY

The study tests and evaluates the durability and retroreflectivity of waterborne paint. Application data includes: paint; bead application rates; no-track times; ambient weather conditions; and retroreflectivity measurements from LTL-X, a 30-meter retroreflectometer. An initial nighttime drive-through inspection of each site was conducted shortly after the striping was completed. Durability and retroreflectivity inspections (as well as follow-up drive-through inspections) were conducted monthly on the high and low traffic volume roadways for a period of one year. Statistical analysis was performed on the collected data to determine the effect of weather and traffic on pavement markings. Using regression analysis and sensitivity analysis, the effect of the inputs (traffic volume, snow, rain, etc.) on the output (retroreflectivity, etc.) was evaluated. Project development meetings were held at least once per month to develop the project.

IV.1 Retroreflectivity Data Collection Methods

The retroreflectivity data was collected monthly from the eight study locations about every 30 days. For each location, the retroreflectivity was measured at the exact same five mile points and each mile point in order to obtain the most consistent data. The exact same five points are selected as shown in Figure 12. Because inconsistencies were found in the data during the winter period, the paint markings were cleaned and measured again after the measurements of the retroreflectivity so that the dust effect during the winter could be analyzed separately.

Figure 12. Photos of Test Sites with Spot Markings

From the five mile points of each test site, only two mile points (total of 10 spots) were selected for the extra measurements after cleaning up. Those two mile points were first and third mile points among five mile points. Consistent cleaning methods were developed and applied in order to get consistent data along the sites. Retroreflectivity data was collected for each lane including White Edge (WE), White Skip (WS), Yellow Center (YC), Yellow Edge (YE), and Yellow Skip (YS).

IV.2 Data Selection

Other data for the statistical analysis was collected in addition to the retroreflectivity data collected by SHA. For each test site, the number of lanes, AADT (Average annual daily traffic), and weather-related data (temperature, humidity, and precipitation, and snow amount) were collected for the analysis. The weather information for those eight sites was collected on a daily basis by the Morgan State University (MSU) project team.

IV.3 Data Entry

The retroreflectivity data collected by SHA was handwritten on paper. Consequently, that information needed to be entered into an electronic file for analysis along with other data. For one year, the MSU project team conducted data entry as the statistics were provided. Weather-related data was also entered into the electronic file for analysis. Table 5 is an example of data entered (MD273, May 2006).

IV.4 Inputs and Outputs for the Analysis

Collected data was used for analysis. Among collected data, some information was used as main inputs, and the retroreflectivity was used as outputs for the analysis. The first input was Number of Days Exposed. Number of Days Exposed, one of the major inputs for the analysis, can potentially represent the chance of exposure to traffic, precipitation, and snow amounts.

Cumulated AADT/Lane was used for the potential exposure to traffic. Many other studies used Cumulated AADT; however, it is believed that AADT/lane is a more proper input for the analysis. Since the chance of exposure to the traffic is the main idea as an input, AADT/lane is better than AADT in terms of representing the chance of exposure to traffic.

The study used the weather-related inputs Cumulated Precipitation and Cumulated Snowfall Amounts. Other weather related inputs are assumed to have little or no effects on the outputs.

Outputs were shown in two different ways: absolute value of retroreflectivity, and percentage of initial retroreflectivity. The relationship between these two kinds of retroreflectivity and major inputs were analyzed.

Table 5. Example of Entered Data

Mile Point	Readings	MD 273					
		5/24/2006					
		DIRTY			CLEAN		
		WE	YS	WE	WE	YS	WE
MP1	1	95	291	252	97	303	263
	2	131	209	204	121	233	207
	3	187	159	274	116	161	268
	4	154	161	305	97	174	282
	5	129	196	287	66	196	276
	MP1 AVG	139.2	203.2	264.4	99.4	213.4	259.2
MP2	1	60	277	164			
	2	59	280	158			
	3	60	324	179			
	4	89	283	155			
	5	68	259	186			
	MP2 AVG	67.2	284.6	168.4			
MP3	1	257	93	208	182	112	215
	2	286	107	264	150	93	239
	3	179	127	208	151	118	203
	4	122	129	248	152	128	254
	5	224	105	304	98	117	269
	MP3 AVG	213.6	112.2	246.4	146.6	113.6	236
MP4	1	112	207	248			
	2	146	134	227			
	3	188	279	233			
	4	113	191	247			
	5	169	197	183			
	MP4 AVG	145.6	201.6	227.6			
MP5	1	178	165	195			
	2	113	308	191			
	3	92	198	173			
	4	82	279	190			
	5	69	310	169			
	MP5 AVG	106.8	252	183.6			
	Total AVG	134.48	210.72	218.08	123	163.5	247.6
	Night Vision						

IV.5 Analysis Process

Regression analysis presented the relationship between inputs and outputs. First, the analysis by location was conducted. Each location had different weather and traffic characteristics, and they were neutralized if the analysis was pursued by each location. Then, all data was aggregated and analyzed together: retroreflectivity data of all kinds of pavement markings from all eight sites. Two kinds of retroreflectivity data (absolute number and percentage of initial retroreflectivity) were compared with each major input. The major inputs included Number of Days, Cumulated AADT/Lane (traffic exposure), Cumulative Precipitation, and Cumulative Snowfall.

Two kinds of retroreflectivity are absolute number of retroreflectivity values and percentages to initial retroreflectivities. Two kinds of retroreflectivity are used because of the different value of initial retroreflectivity of different pavement markings from different locations. Although there were efforts to create the same degree of retroreflectivity for different locations with the same guidelines for application, the initial value of retroreflectivities of the assorted locations were different. Therefore, percentages to the initial retroreflectivity were used to provide the same condition at all locations. Then, retroreflectivity data for each pavement markings — WE, WS, YC, YS, etc — were compared with each major input. For both cases, single variable regression analysis was pursued and the relative importance of inputs was evaluated. Multivariable regression analysis was then conducted as well with multiple inputs.

IV.6 Regression Analysis

Regression analysis was used in this study to estimate the relationship between output (retroreflectivity) and inputs. In regression analysis, there is a single dependent variable or response Y, which is uncontrolled in this experiment. This response depends on one or more independent or regressor variables, $x_1, x_2... x_k$, that are measured with negligible error and are often controlled in the experiment. The relationship fit to a set of experimental data is characterized by a prediction equation called a regression equation. If there is only one regressor, it is called single variable regression. It is called multivariable regression if there are two or more regressors.

The smaller the variability of the residual values around the regression line relative to the overall variability, the better our prediction is. 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, there is no residual variance and the ratio of variance is 0.0. In most cases, the ratio would fall somewhere between 0.0 and 1.0. *R-square,* or the *coefficient of determination,* refers to 1.0 minus the aforementioned ratio. This value is immediately interpretable in the following manner. For an *R-square* of 0.4, 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% of the original variability and are left with 60% 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 (e.g., 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-squared* for the population. The value of *R-square* was .4892, while the value of adjusted *R-square* was .4788. Adjusted *R-squared* is computed using the formula 1 - ((1 - Rsq) ((N - 1) / (N - k - 1)). You can see from this formula 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, the value of *R-square* and adjusted *R-square* will be much closer when the number of observations is very large as compared to the number of predictors. This is because the ratio of (N-1)/ (N-k-1) will approach 1.

V. ANALYSIS BY LOCATION

In this chapter, analyses for eight locations are individually discussed. Since each location has different characteristics, such as weather and traffic, the relationship between inputs and outputs for each location may vary. In each location, all the collected data are grouped to show the general relationship between retroreflectivity and number of days. In this chapter, retroreflectivity is compared with the number of days. As all other inputs — Cumulated Traffic, Cumulated Precipitation, and Cumulated Snowfall — are all linearly dependent to the number of days in a single location, it is not necessary to show the relationship between retroreflectivity and other inputs. Then, pavement markings are analyzed individually as well.

Two kinds of retroreflectivities are used for the analysis: retroreflectivity value and retroreflectivity percentage. Retroreflectivity value is measured at the sites. Retroreflectivity percentage is based on an initial retroreflectivity value of 100 percent. Since all the pavement markings have different initial retroreflectivity, retroreflectivity percentage equalizes the starting points of all the pavement markings.

Each location has 5-mile points and each mile point has five spots for the measurement. In this chapter, overall regression analysis uses retroreflectivity of each mile point, which is the average of five spots of each mile point to neutralize the measurement error. Analysis for each pavement marking uses average of five mile points, which is average of 25 spots, in order to show trend line for each pavement marking.

V.1 MD 273

The first location studied is Mile Point 12.36 to Mile Point 14.96 of MD 273 (shown in Figure 1). It has AADT of 10,300 vehicles per day, which is relatively high traffic volume in this study. It is in Cecil County. It is also in the eastern region, which has less snow than the central and western regions. As shown in Figures 13 and 14, there is a good relationship between retroreflectivity and Number of Days Exposed. For this particular location, retroreflectivity value shows a stronger relationship with Number of Days Exposed than retroreflectivity percentage.

Figures 15 and 16 show the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Skip) are found. As mentioned, each pavement marking includes five mile points and each mile point consists of five spots. In these figures, each measurement is the average value of those 25 spots in order to show trend line more effectively. Except for some irregular jumpiness, the trend lines seen in Figure 15 and 16 show general relation of downward trend.

Figure 13. Overall Regression Analysis for MD 273 (Retroreflectivity Value and Number of Days)

Figure 14. Overall Regression Analysis for MD 273 (Retroreflectivity Percentage and Number of Days)

Figure 15. Trend Lines of Each Pavement Marking for MD 273 (Retroreflectivity Value and Number of Days)

Figure 16. Trend Lines of Each Pavement Marking for MD 273 (Retroreflectivity Percentage and Number of Days)

V.2 MD 33

The second location studied is Mile Point 10.82 to Mile Point 13.02 of MD 33, as detailed in Figure 1. This location has AADT of 6,550 vehicles per day, which is medium traffic volume in this study. It is in Talbot County and in the eastern region, which has less snow than central and western regions. As shown in Figures 17 and 18, there is a good relationship between retroreflectivity and Number of Days Exposed. However, their *R square* values are not as high as other locations because of the very high retroreflectivity at the second month measurement. Besides that sudden jump of retroreflectivity at the second month, the relationship between retroreflectivity and the Number of Days Exposed is good. In this particular location, retroreflectivity value shows a stronger relationship with Number of Days Exposed than retroreflectivity percentage.

Figures 19 and 20 illustrate the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Center) are found. The trend lines show general relation of downward trend except for the jump at the second month.

Figure 17. Overall Regression Analysis for MD 33 (Retroreflectivity Value and Number of Days)

Figure 18. Overall Regression Analysis for MD 33 (Retroreflectivity Percentage and Number of Days)

Figure 19. Trend Lines of Each Pavement Marking for MD 33 (Retroreflectivity Value and Number of Days)

Figure 20. Trend Lines of Each Pavement Marking for MD 33 (Retroreflectivity Percentage and Number of Days)

V.3 MD 297

The third location studied is Mile Point 0.00 to Mile Point 3.59 of MD 297 (Figure 1). The third location has AADT of 2,357 vehicles per day, a low traffic volume for this study. It is in Kent County, and it is in Eastern region. The eastern region has less snow than the central and western regions.

Figures 21 and 22 show a weaker relationship between retroreflectivity and Number of Days Exposed than other locations with spread retroreflectivities. However, the graphs still show the downward trends of retroreflectivity along the Number of Days Exposed. The regression analysis does not show a strong correlation due to the different ratio of depreciation of each pavement marking as seen in Figures 23 and 24. In this particular location, retroreflectivity value shows a stronger relationship with Number of Days Exposed than retroreflectivity percentage.

Figures 23 and 24 also show the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, two pavement markings (one White Edges and one Yellow Center) are found. As mentioned earlier, each pavement marking includes five mile points and each mile point consists of five spots. In these figures, each measurement is average value of those 25 spots in order to show trend line more effectively. According to Figures 23 and 24, the trend lines show general relation of downward trend although their degrees of depreciation are different. After a few months, there were big drops in retroreflectivity for both pavement markings. It is assumed that this was due to snowplows.

Figure 21. Overall Regression Analysis for MD 297 (Retroreflectivity Value and Number of Days)

Figure 22. Overall Regression Analysis for MD 297 (Retroreflectivity Percentage and Number of Days)

Figure 23. Trend Lines of Each Pavement Marking for MD 297 (Retroreflectivity Value and Number of Days)

Figure 24. Trend Lines of Each Pavement Marking for MD 297 (Retroreflectivity Percentage and Number of Days)

V.4 US 40

The fourth location in study was Mile Point 6.85 to Mile Point 9.93 of MD 40 (Figure 1). This location in Harford County has an AADT of 21,500 vehicles per day, a high traffic volume. This location is also in the central region, which has medium characteristics in terms of the weather between the eastern and western regions. As illustrated in Figures 25 and 26, there is a moderately good downward relationship between retroreflectivity and Number of Days Exposed than other locations. However, the retroreflectivities are widely spread, and the graphs still show the downward trends of retroreflectivity along the Number of Days Exposed. In this particular location, retroreflectivity percentage shows a stronger relationship with Number of Days Exposed than retroreflectivity value.

Figures 27 and 28 show the trend in retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (one White Edges, one White Skip, and one Yellow Edge) are found. As mentioned, each pavement marking includes 5-mile points and each mile point consists of five spots. To show the trend more effectively, each measurement is the average value of those 25 spots. According to Figures 27 and 28, the trend lines show general relation of downward trend, and Yellow Edge shows a different trend compared to the other two pavement markings.

Figure 25. Overall Regression Analysis for US 40 (Retroreflectivity Value and Number of Days)

Figure 26. Overall Regression Analysis for US 40 (Retroreflectivity Percentage and Number of Days)
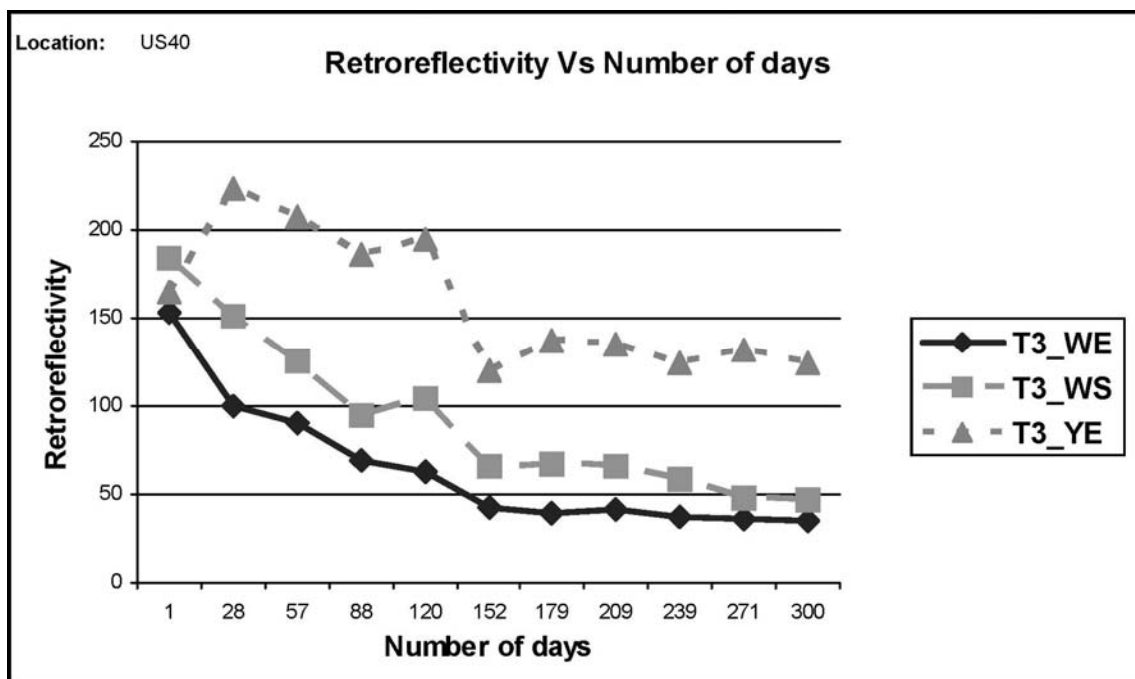
Figure 27. Trend Lines of Each Pavement Marking for US 40 (Retroreflectivity Value and Number of Days)
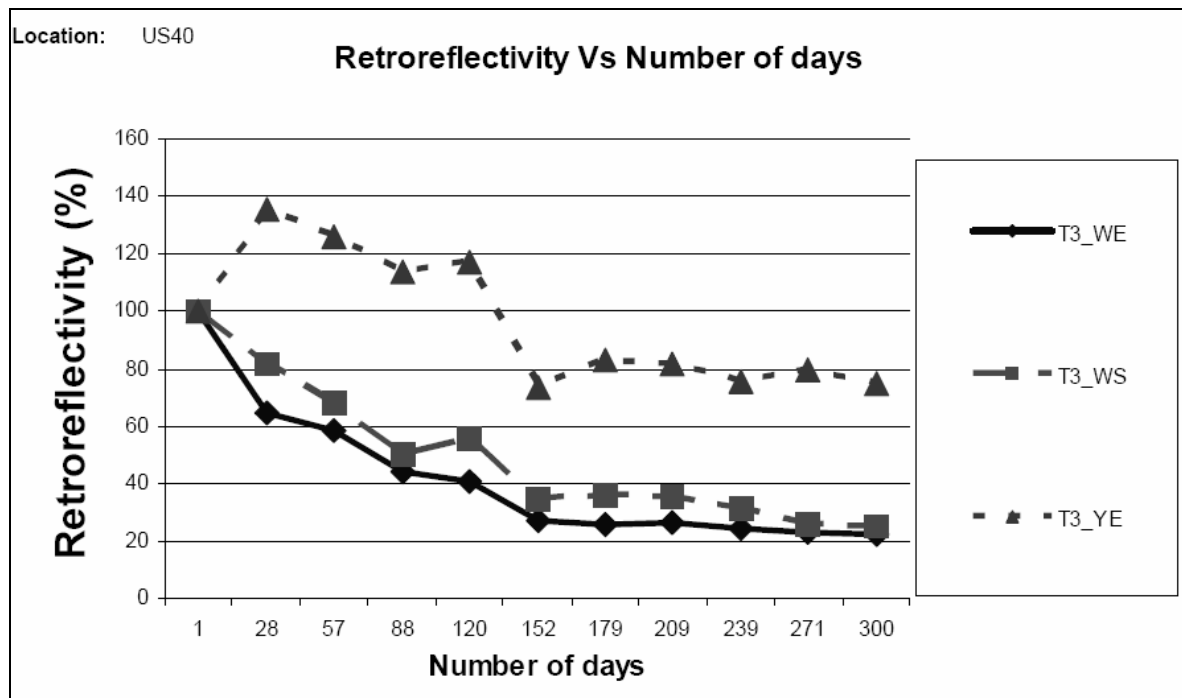
Figure 28. Trend Lines of Each Pavement Marking for US 40 (Retroreflectivity Percentage and Number of Days)

V.5 MD 117

The fifth study location is Mile Point 5.23 to Mile Point 6.20 of MD 117 (Figure 1). It has AADT of 5,825 vehicles per day, a low traffic volume. It is in Montgomery County, and this is in the central region, which has medium characteristics in terms of weather between eastern and western regions. As shown in Figures 29 and 30, a weaker relationship exists between retroreflectivity and Number of Days Exposed than other locations with spread retroreflectivities. In this particular location, the retroreflectivity percentage shows a stronger relationship with Number of Days Exposed than retroreflectivity value.

Figures 31 and 32 show a trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Center) are found. As seen in Figures 31 and 32, the trend lines show very lumpy trend although there is a slight downward trend along the Number of Days Exposed.
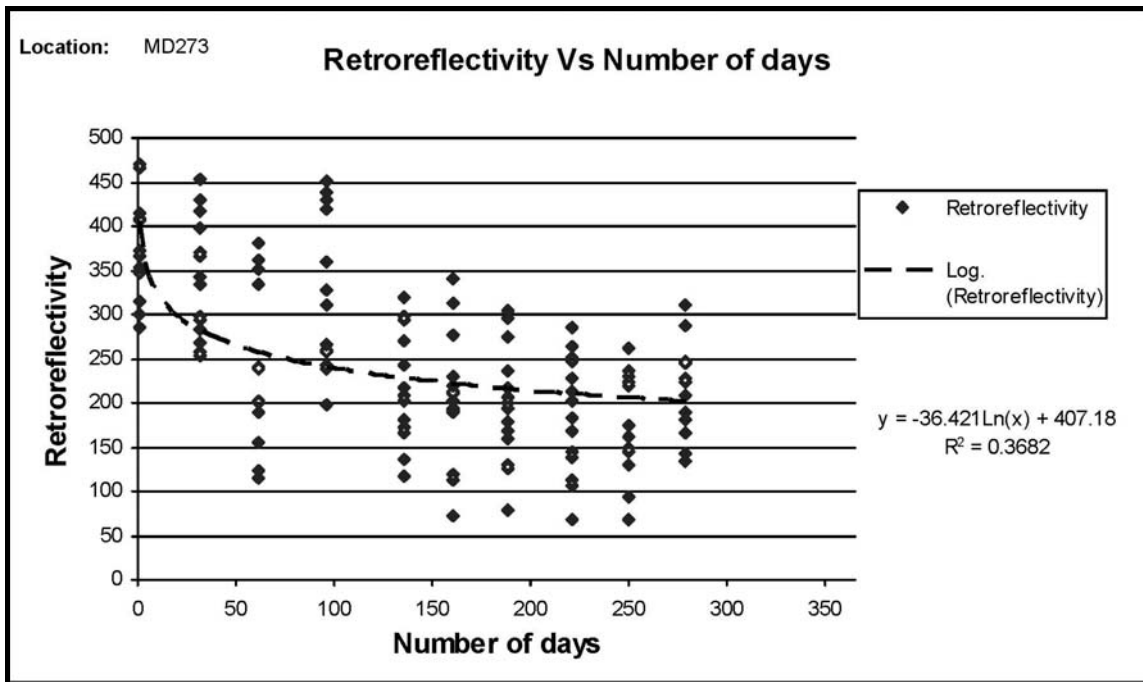
Figure 29. Overall Regression Analysis for MD 117 (Retroreflectivity Value and Number of Days)
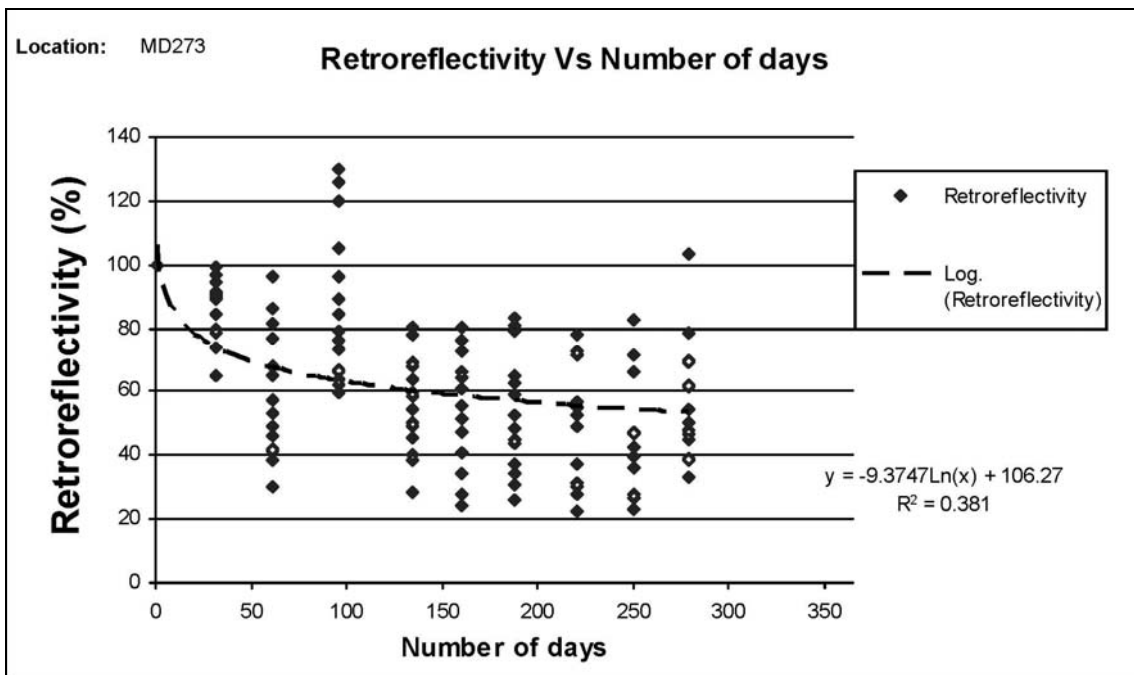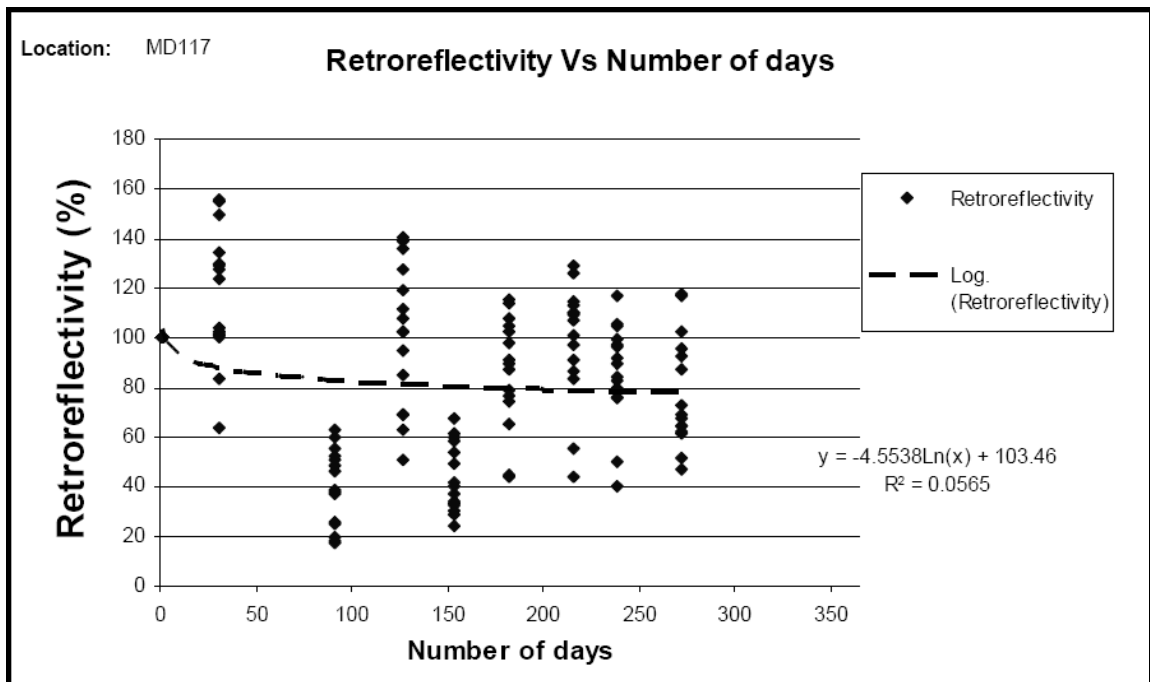

Figure 30. Overall Regression Analysis for MD 117 (Retroreflectivity Percentage and Number of Days)
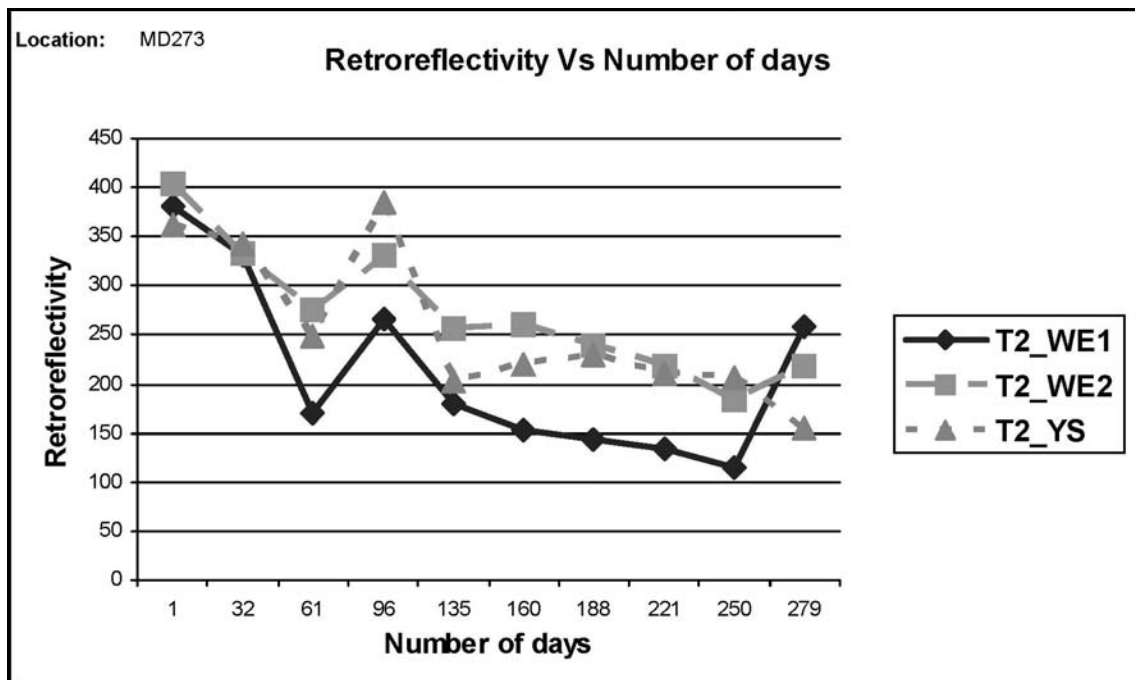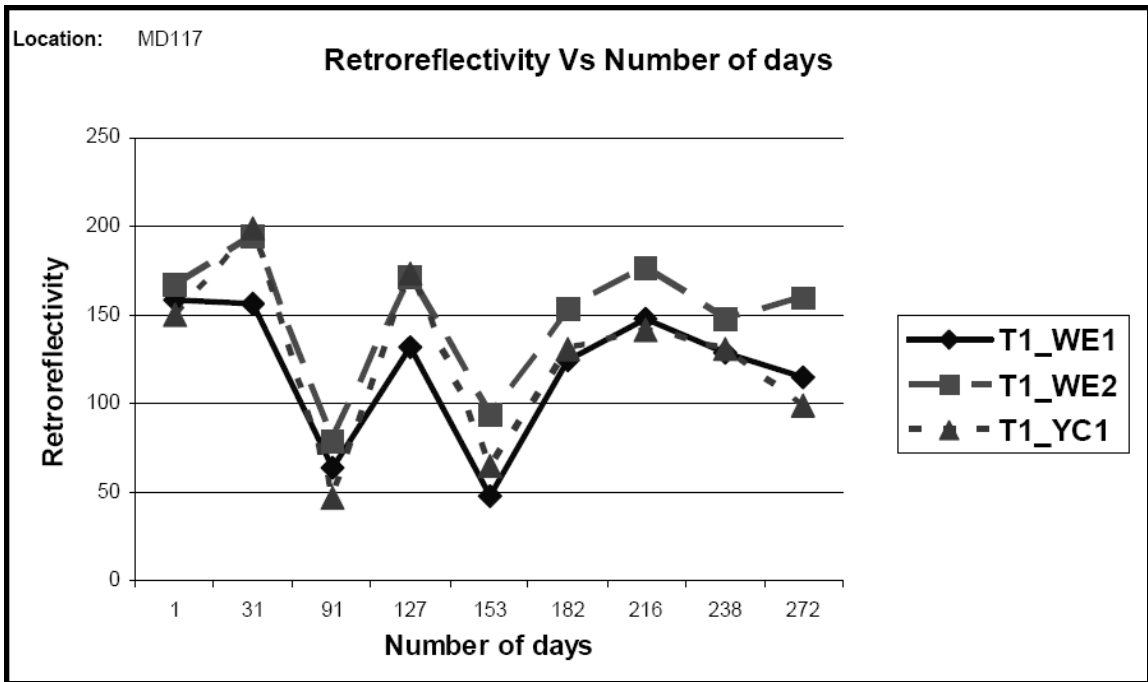
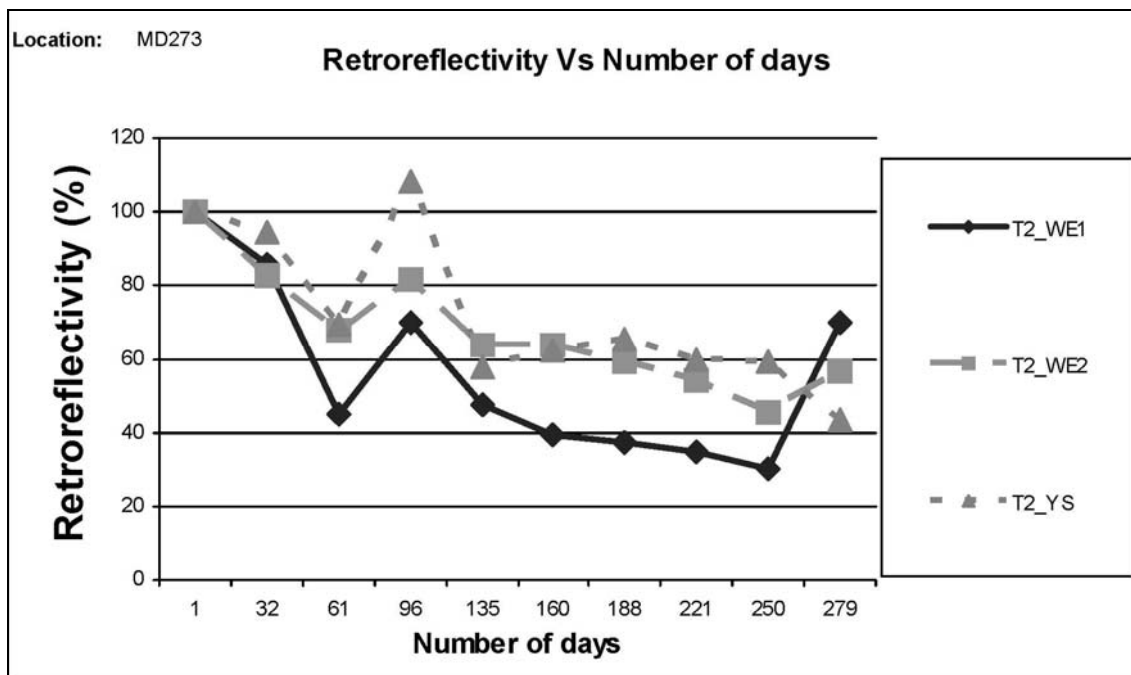**Figure 31. Trend Lines of Each Pavement Marking for MD 117 (Retroreflectivity Value and Number of Days)**
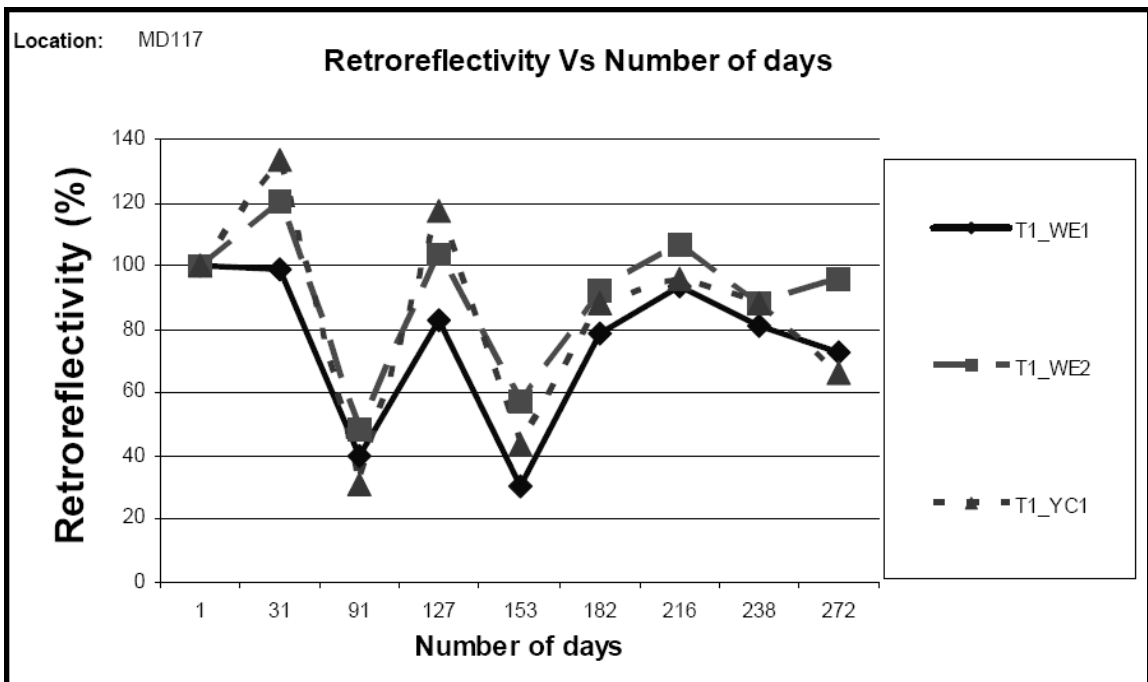
Figure 32. Trend Lines of Each Pavement Marking for MD 117 (Retroreflectivity Percentage and Number of Days)

V.6 MD 165

The sixth location studied is Mile Point 13.12 to Mile Point 13.52 of MD 165 (Figure 1). It has AADT of 6,450 vehicles per day, a medium traffic volume. It is in Harford County, and it is in Central region, which has medium characteristics in terms of weather between eastern and western regions. As shown in Figures 33 and 34, there is a weaker relationship between retroreflectivity and Number of Days Exposed than other locations with spread retroreflectivities. In this particular location, retroreflectivity value shows a stronger relationship with Number of Days Exposed than retroreflectivity percentage.

Figures 35 and 36 track the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Center) are found. According to Figures 33 and 34, the trend lines show general relation of downward.
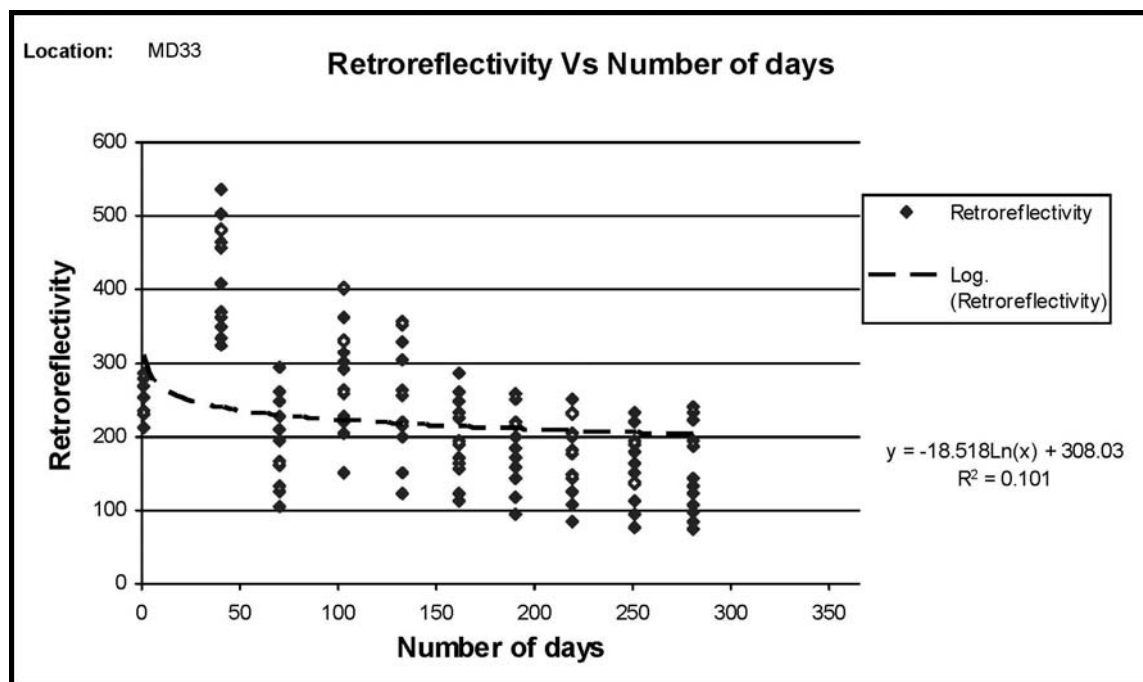

Figure 33. Overall Regression Analysis for MD 165 (Retroreflectivity Value and Number of Days)
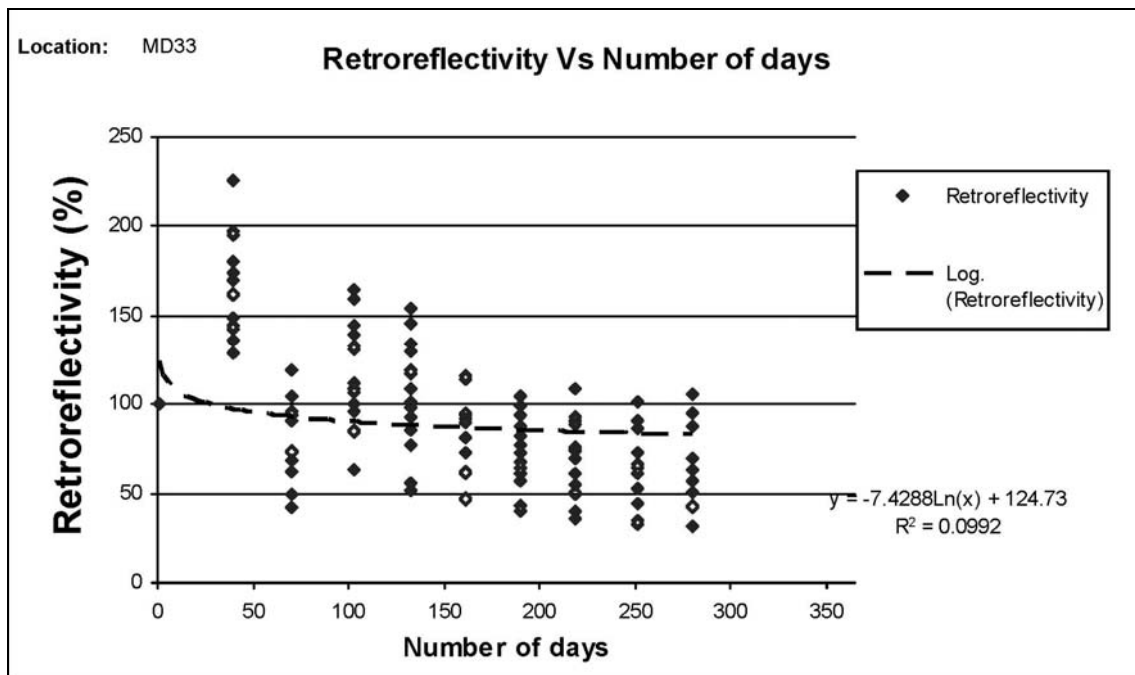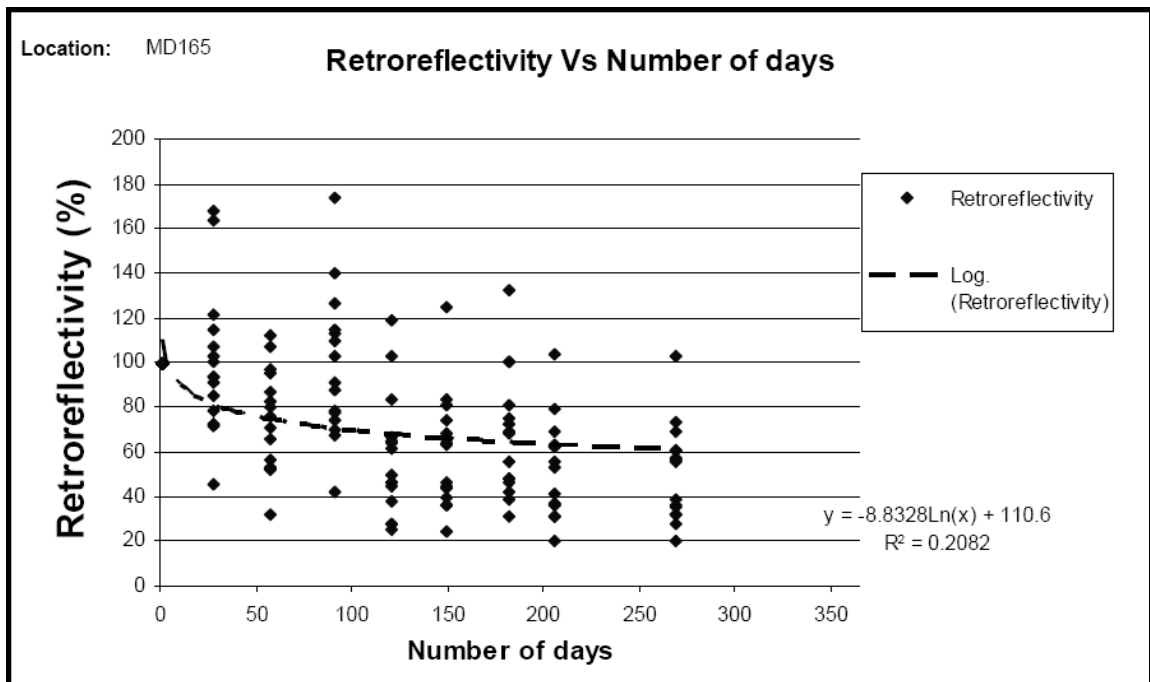
Figure 34. Overall Regression Analysis for MD 165 (Retroreflectivity Percentage and Number of Days)
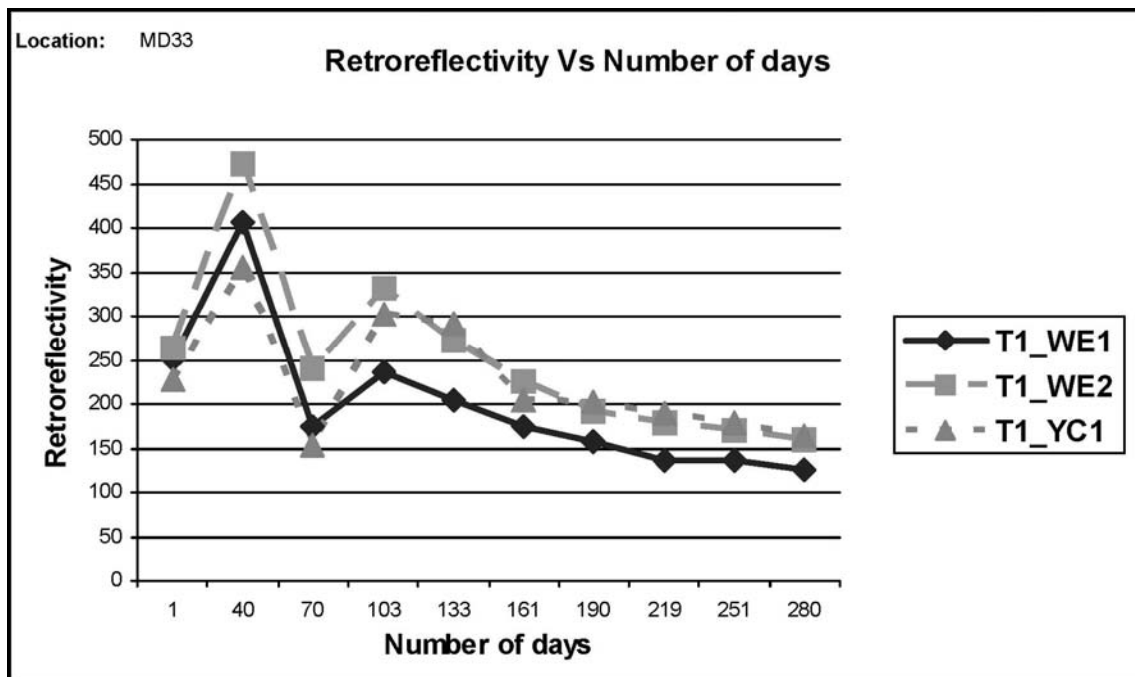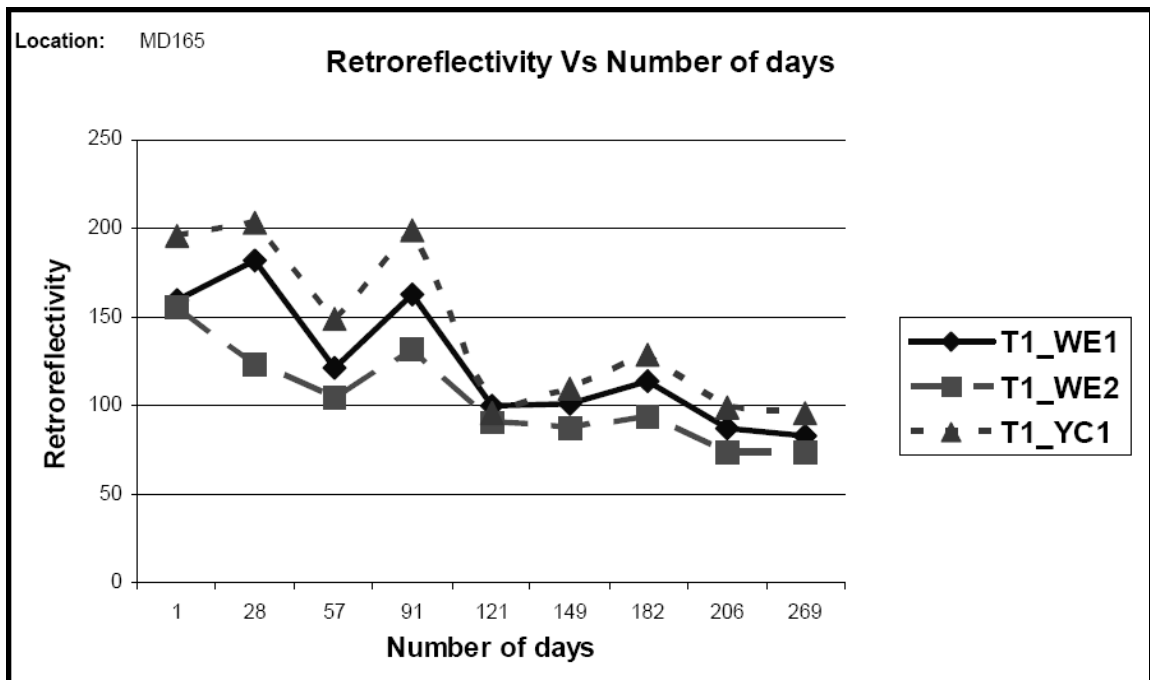

Figure 35. Trend Lines of Each Pavement Marking for MD 165 (Retroreflectivity Value and Number of Days)
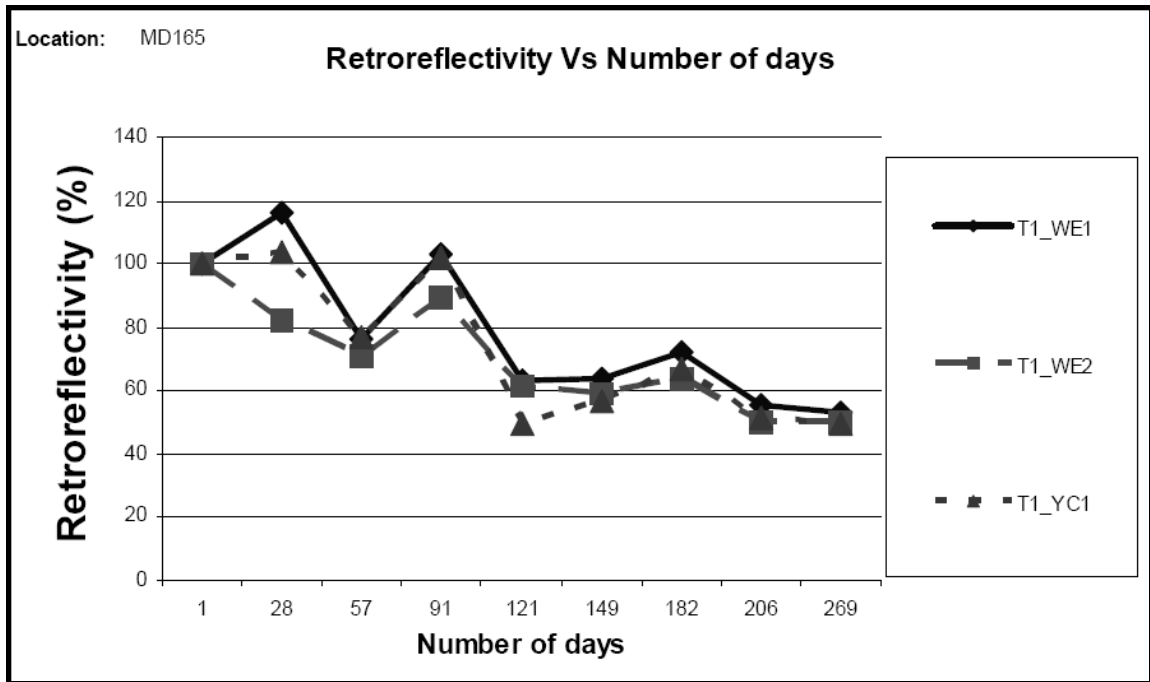
Figure 36. Trend Lines of Each Pavement Marking for MD 165 (Retroreflectivity Percentage and Number of Days)

V.7 MD 53

The seventh location studied is Mile Point 0.63 to Mile Point 3.03 of MD 53 (Figure 1). It has AADT of 14,575 vehicles per day, which is a relatively high traffic volume in this study. It is in Allegany County and the western region. As a site in the western region, this location receives more snowfall than central and eastern regions. As shown in Figures 37 and 38, there is a substantial relationship between retroreflectivity and Number of Days Exposed. In this location, retroreflectivity value has a stronger relationship than retroreflectivity percentage.

Figures 39 and 40 present the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Center) are found. According to Figures 39 and 40, except some irregular jumpiness, the trend lines show a general relation of downward trend. They also show a big drop of retroreflectivity in the first couple of months when snowplows were operating.
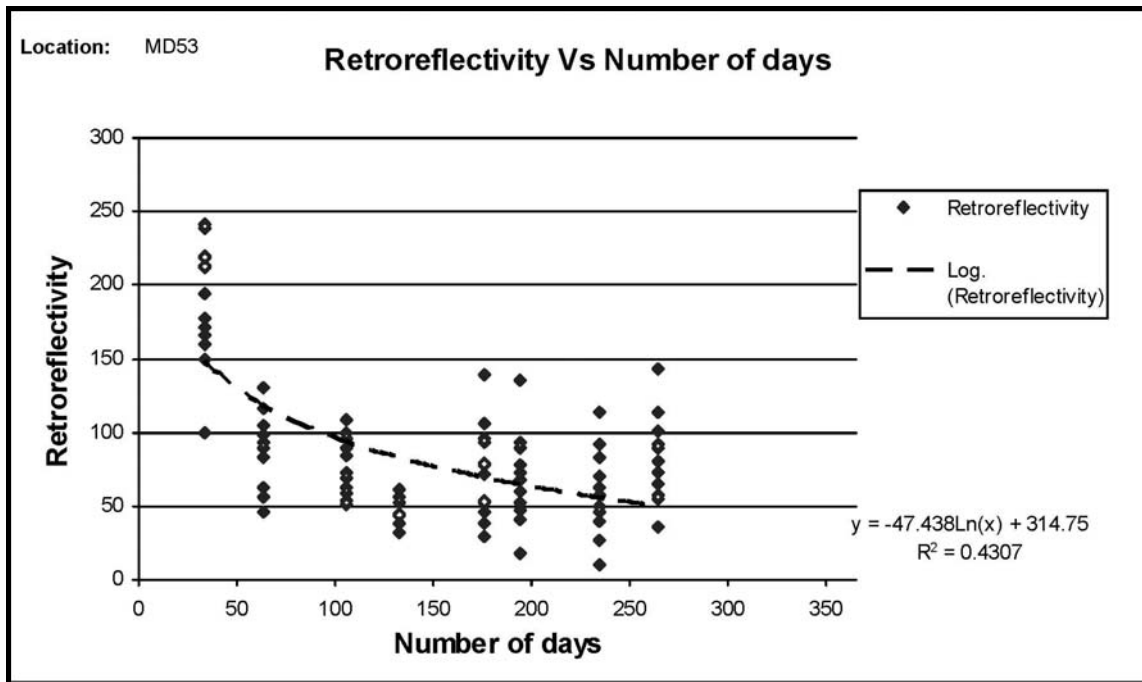
Figure 37. Overall Regression Analysis for MD 53 (Retroreflectivity Value and Number of Days)
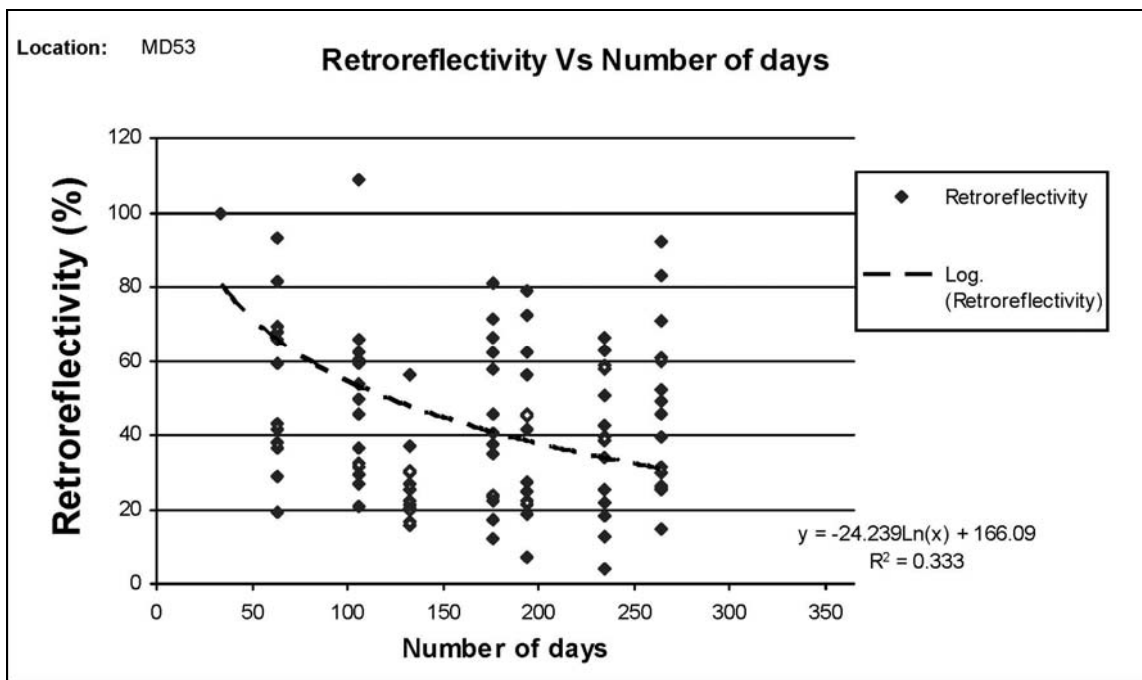
Figure 38. Overall Regression Analysis for MD 53 (Retroreflectivity Percentage and Number of Days)
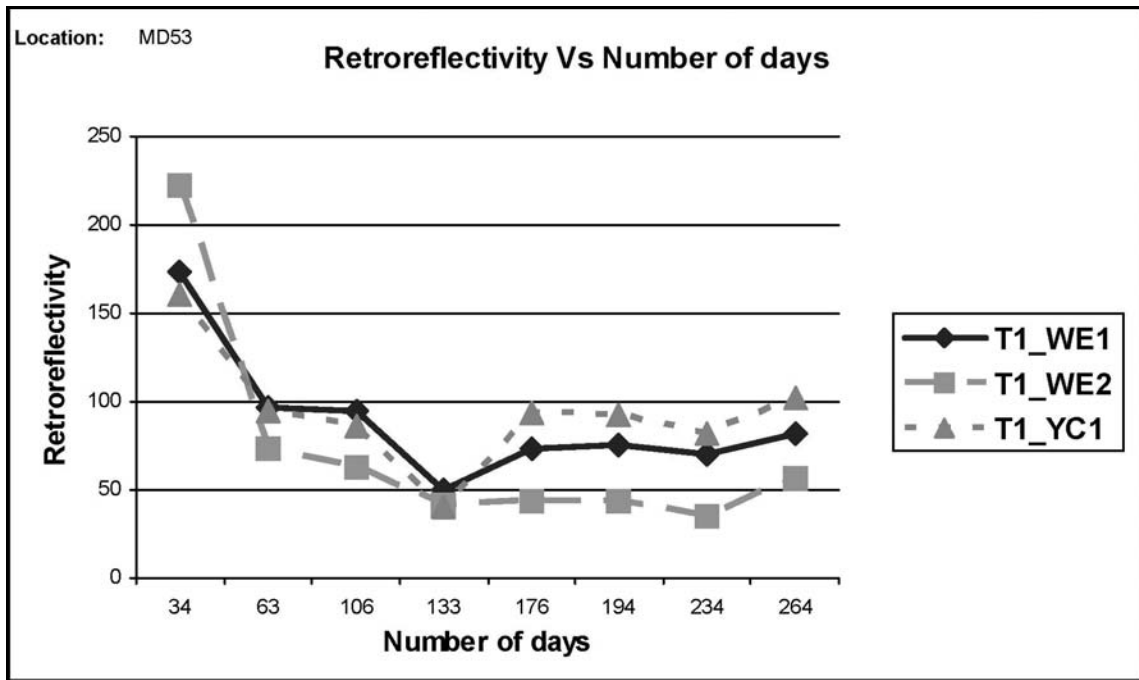
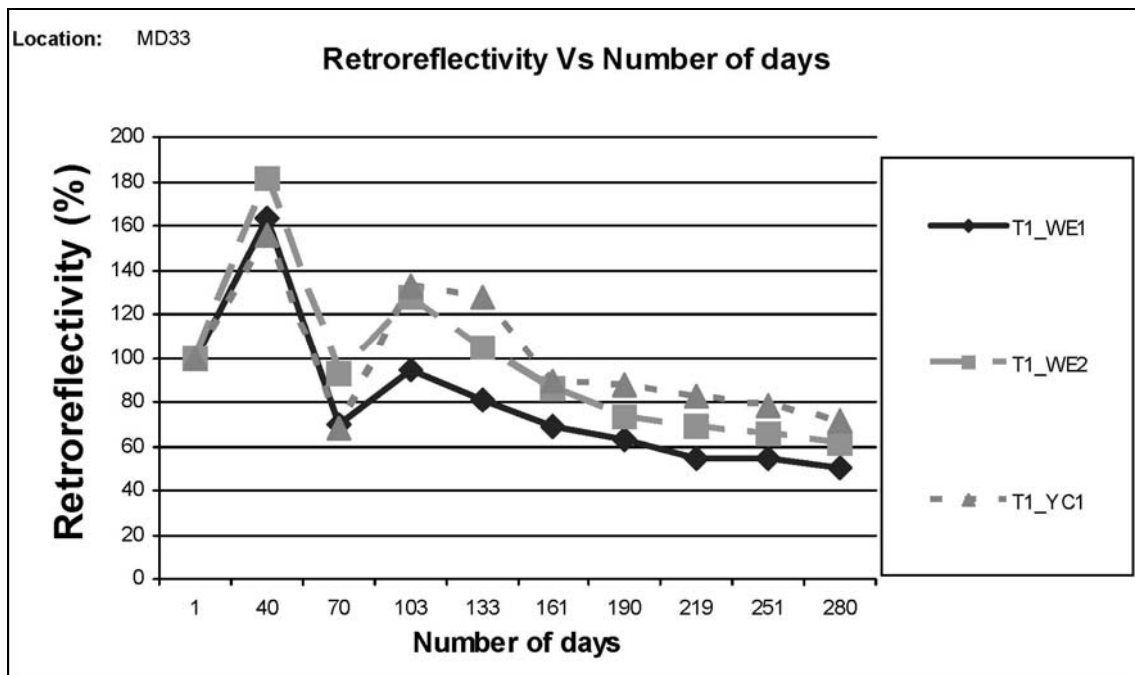**Figure 39. Trend Lines of Each Pavement Marking for MD 53 (Retroreflectivity Value and Number of Days)**
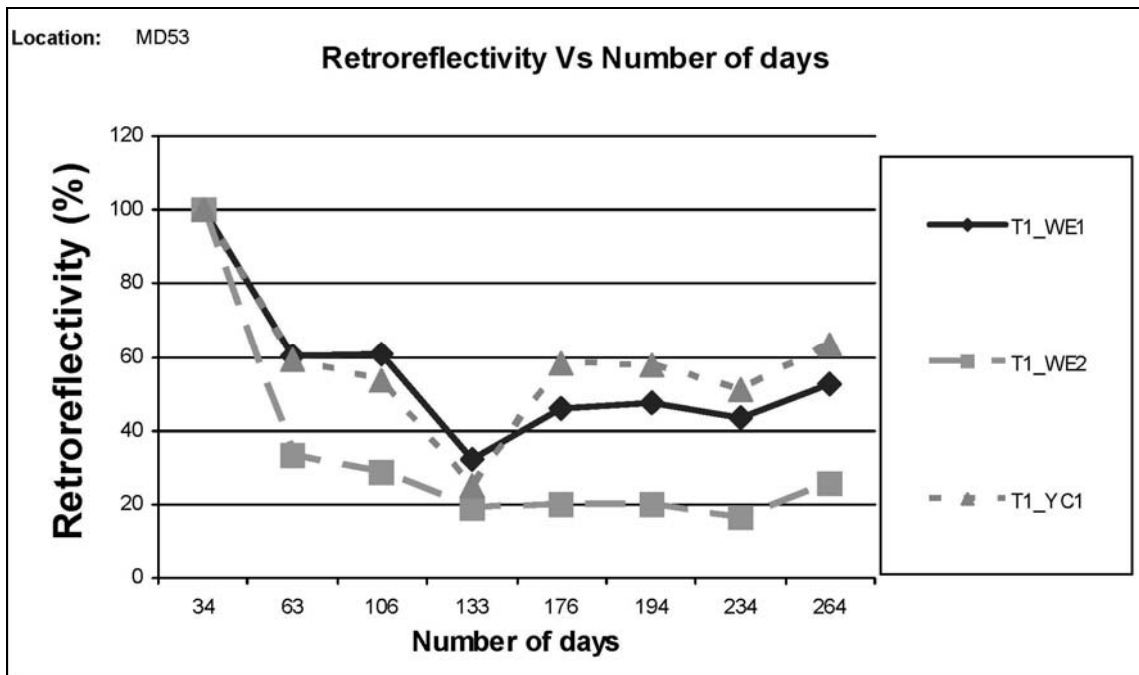
Figure 40. Trend Lines of Each Pavement Marking for MD 53 (Retroreflectivity Percentage and Number of Days)

V.8 US 40 ALT

The final location studied was Mile Point 2.53 to Mile Point 6.21 of MD 40 ALT (Figure 1). It has AADT of 6,175 vehicles per day, a medium traffic volume. It is in Washington County and the western region, which has more snowfall than central and eastern regions. As seen in Figures 41 and 42, although they still show some downward trend, there is a weaker relationship between retroreflectivity and Number of Days Exposed than other locations with spread retroreflectivities. In this location, retroreflectivity percentage shows stronger relationship than retroreflectivity value.

Figures 43 and 44 show the trend of retroreflectivity along the Number of Days Exposed for each pavement marking. In this particular area, three pavement markings (two White Edges and one Yellow Center) are found. According to Figures 43 and 44, the trend lines show general relation of downward trend. However, some lumpiness of retroreflectivity exists.
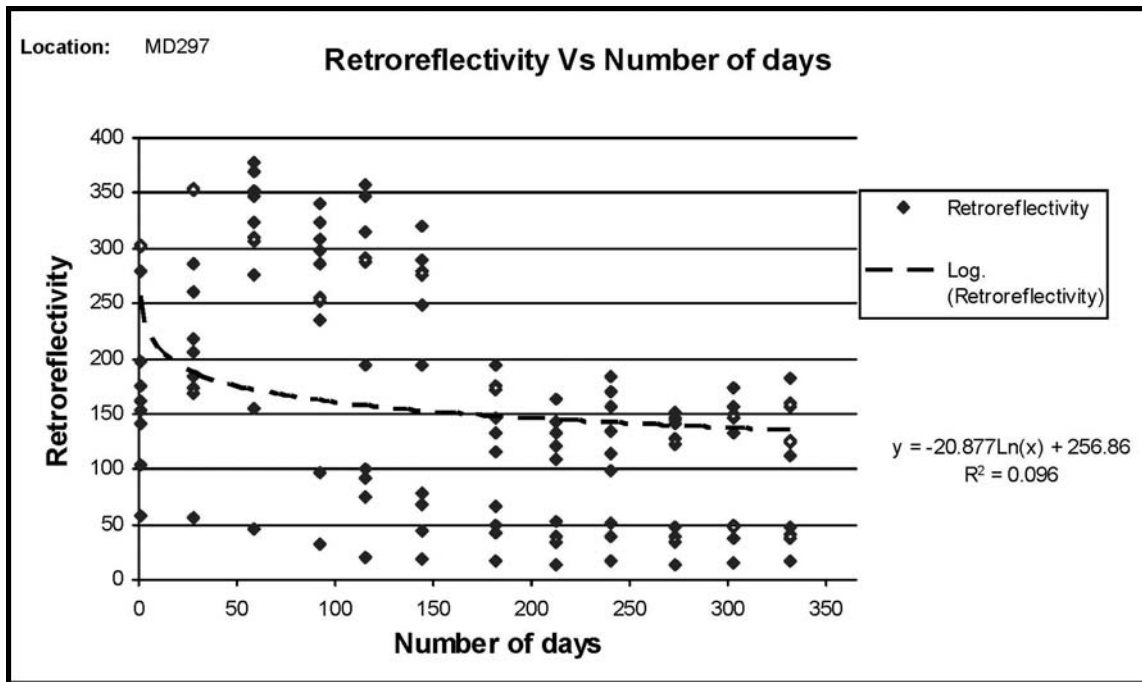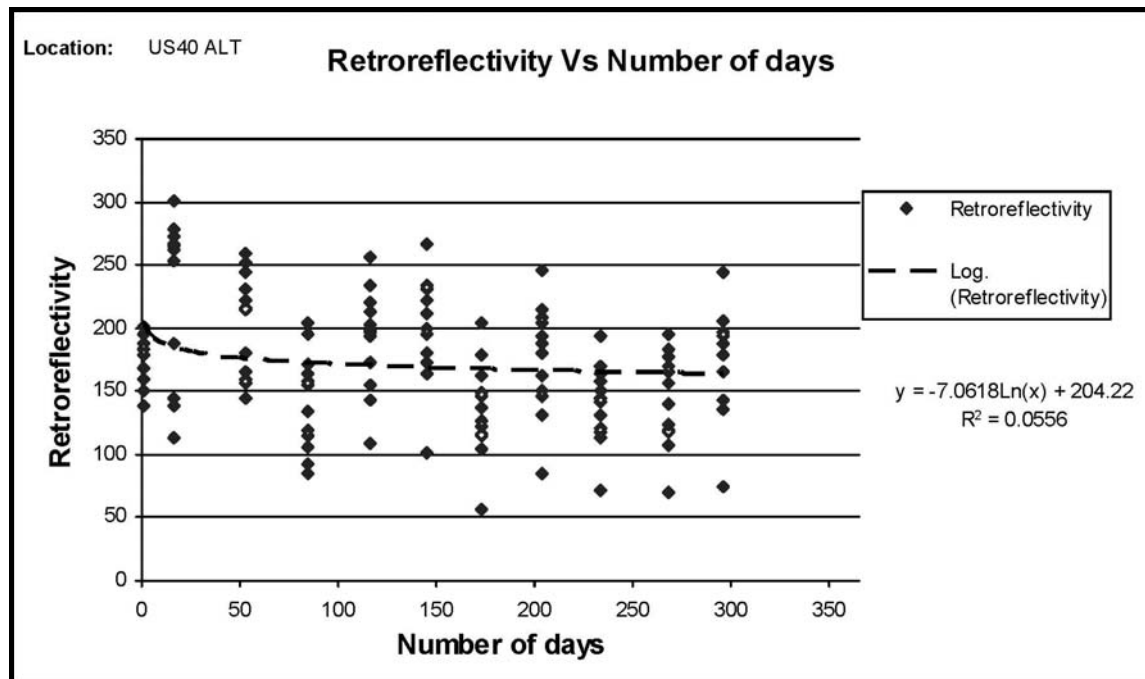

Figure 41. Overall Regression Analysis for US 40 ALT (Retroreflectivity Value and Number of Days)
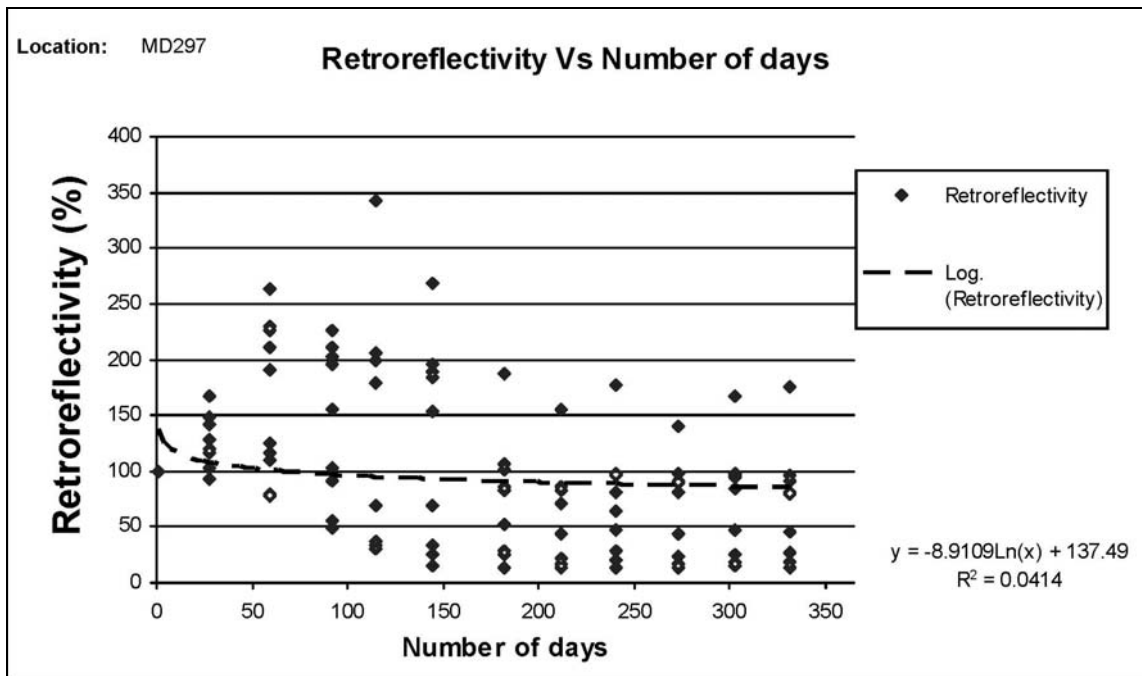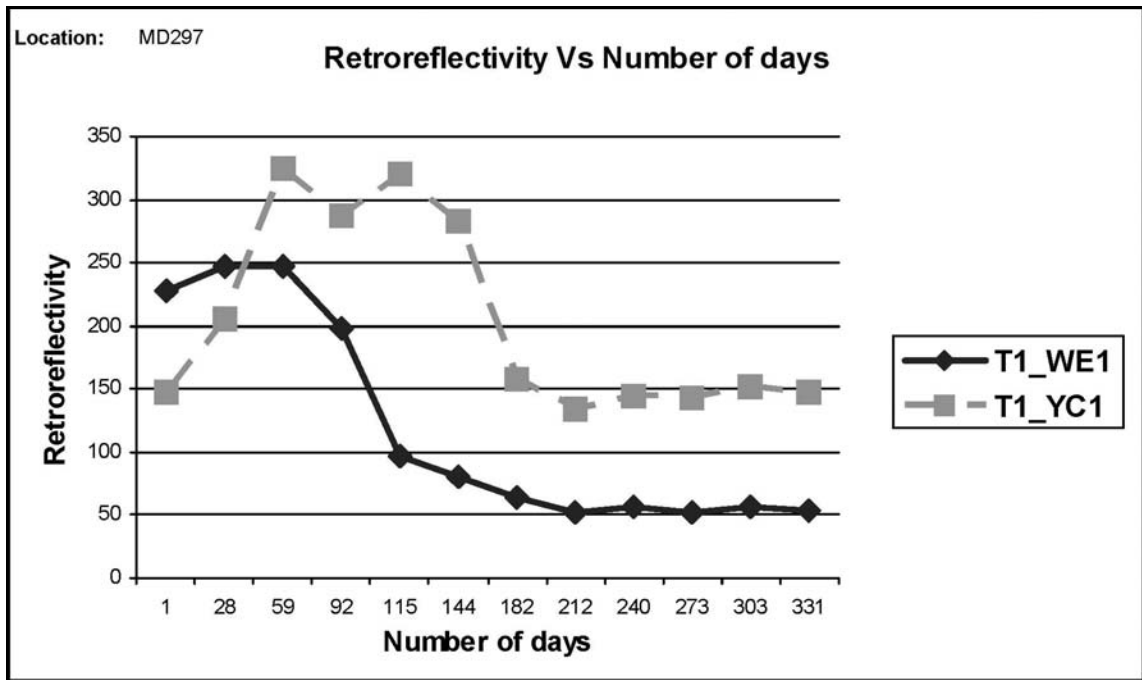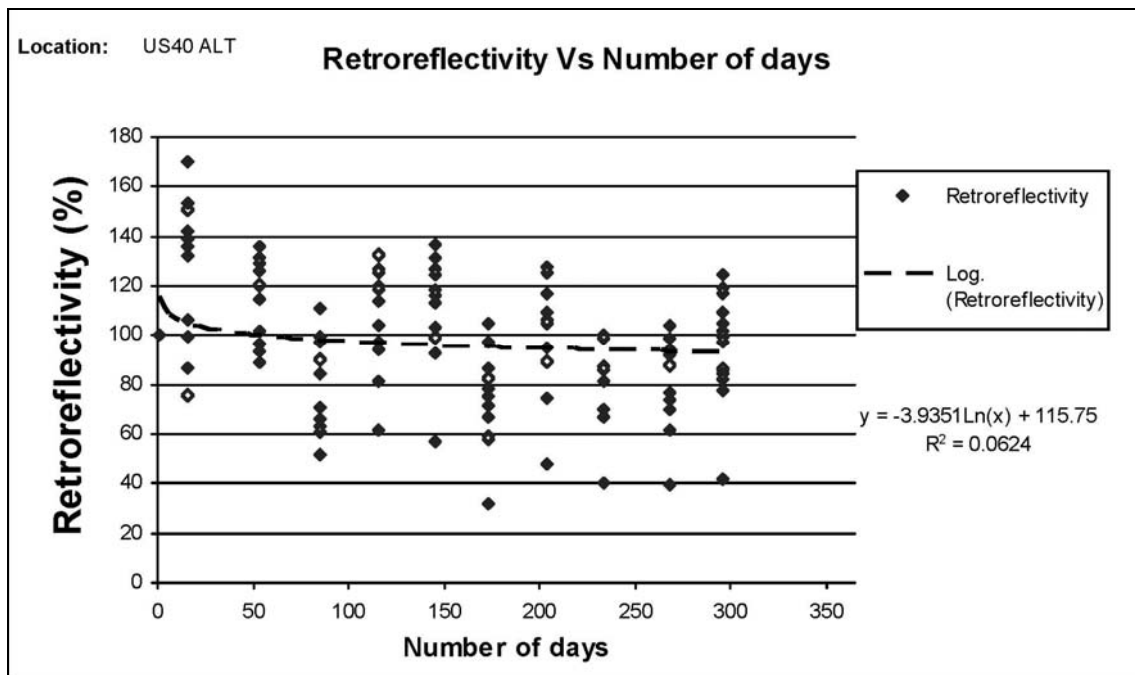
Figure 42. Overall Regression Analysis for US 40 ALT (Retroreflectivity Percentage and Number of Days)
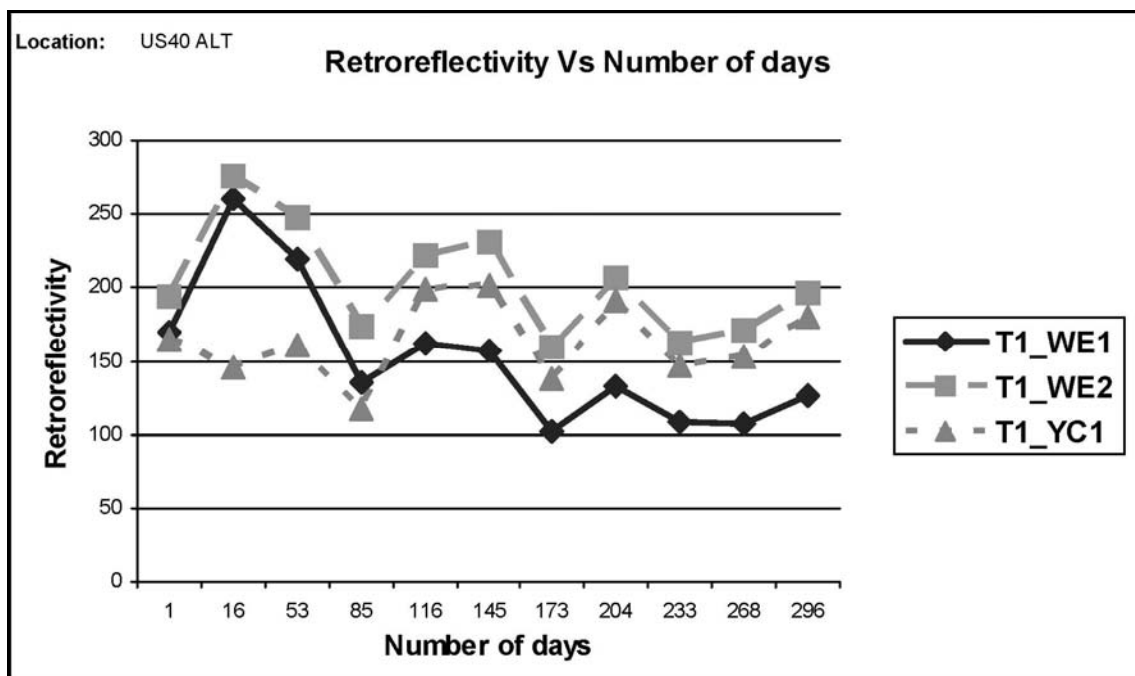
Figure 43. Trend Lines of Each Pavement Marking for US 40 ALT (Retroreflectivity Value and Number of Days)
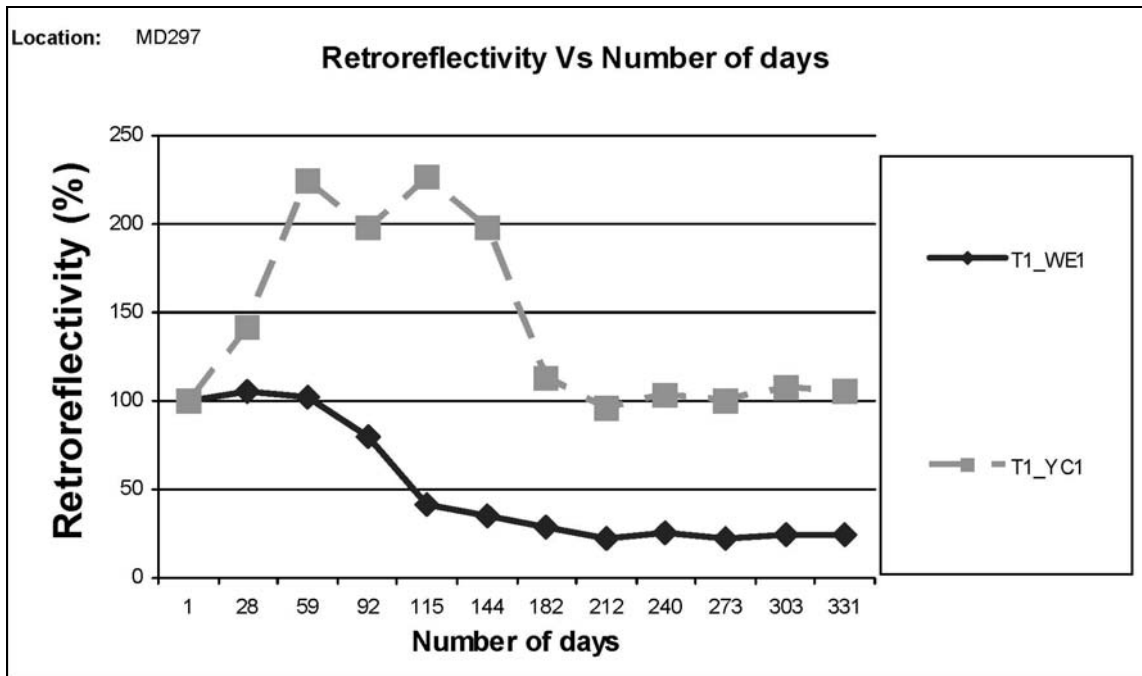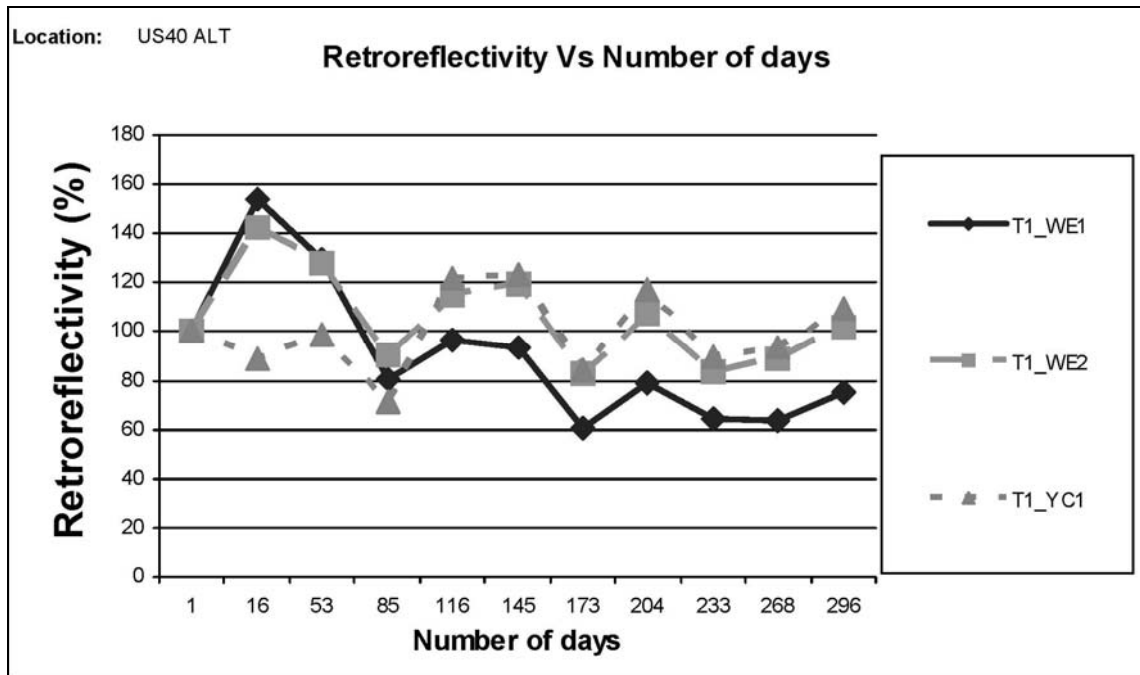
Figure 44. Trend Lines of Each Pavement Marking for US 40 ALT (Retroreflectivity Percentage and Number of Days)

VI. SINGLE VARIABLE REGRESSION ANALYSIS

In this chapter, data from the different pavement marking types from the eight locations were aggregated and analyzed. This was done to find the relationship between the two kinds of retroreflectivities and major inputs for changed retroreflectivity through graphical and regression analysis. Two kinds of outputs are retroreflectivity values and retroreflectivity percentages to initial retroreflectivity values. Major inputs to change retroreflectivity were number of days, cumulated traffic amount, cumulated precipitation, and cumulated snow amounts. Then, regression analyses were pursued for five individual pavement marking types — White Edge (WE), White Skip (WS), Yellow Center (YC), Yellow Edge (YE), and Yellow Skip (YS). Data for each type of pavement markings were aggregated from the eight locations and analyzed with two kinds of outputs and four kinds of major inputs.

VI.1 Overall Single Variable Regression Analysis

The data was collected from all eight sites and five different pavement markings. The composition of the pavement markings depended on the location. Depending on the location, the composition of the pavement markings varied. In this section, all the data was aggregated and analyzed as single variable regression analysis. The analysis includes two kinds of output, absolute value of retroreflectivity measured, initial retroreflectivity, and major inputs. The major inputs were Number of Days Exposed, Cumulated Traffic per Lane (exposure to traffic), Cumulated Precipitation, and Cumulated Snow Amounts.

VI.1.1 Relationship between Retroreflectivity Value and Other Inputs

The retroreflectivity value of all kinds of pavement marking from the eight sites were compared with four major inputs and plotted.

Since cumulated inputs are related to the time factor (number of days), all four relationships are not irrelevant and show similar forms. Figure 45 shows the relationship between retroreflectivity value and Number of Days. Figure 46 illustrates the relationship between retroreflectivity value and Cumulated Traffic. Figure 47 presents the relationship between retroreflectivity value and Cumulated Precipitation. Figure 48 shows the relationship between retroreflectivity value and Cumulated Snow Amount. The regression equations and *R square* values are also presented in the figures.

The same shape of relationship can be seen in Figures 45-48, and this can be shown in a logarithm equation. Since the analysis was used with aggregated data from different markings and locations, the relationship between retroreflectivity values and inputs was inconsistent. Among those relationships, the relationship between retroreflectivity and Cumulated Snowfall is the most consistent one in terms of *R square* analysis. The next correlated input to the retroreflectivity is Number of Days Exposed. Cumulated traffic and Cumulated Precipitation are not very related to retroreflectivity. Even if snowfall and number of days are more related to the retroreflectivity, the relationships with the

four major inputs are not very close. However, general downward trend of retroreflectivity exists. Table 6 shows the regression equations and *R square* values from the four relationships.
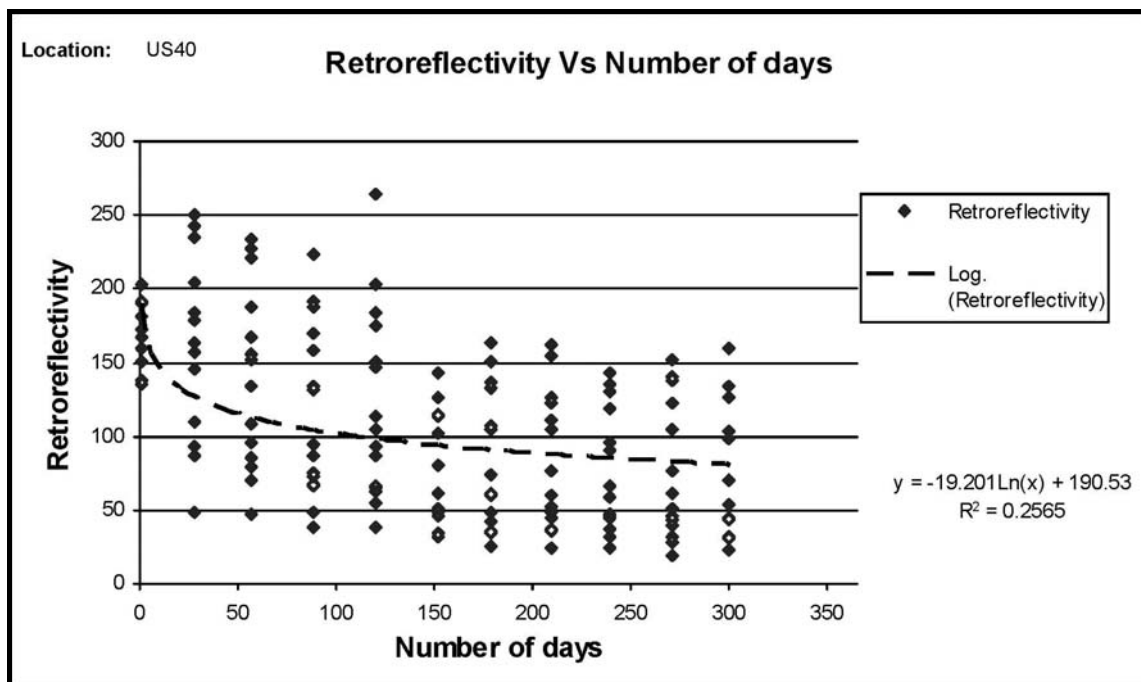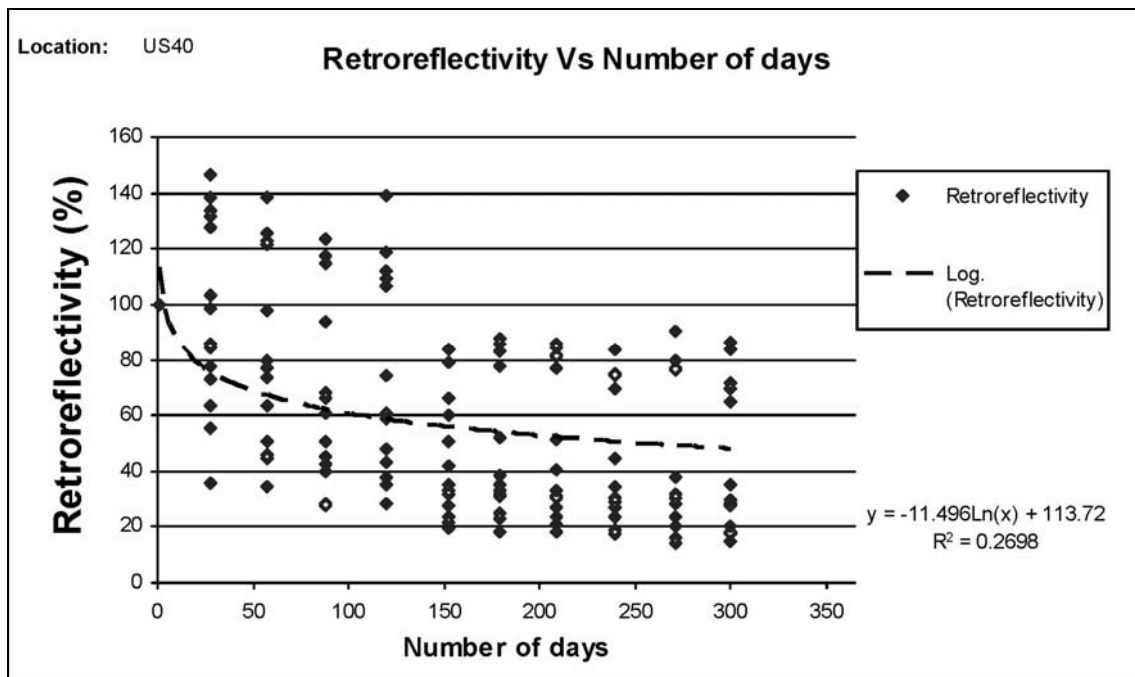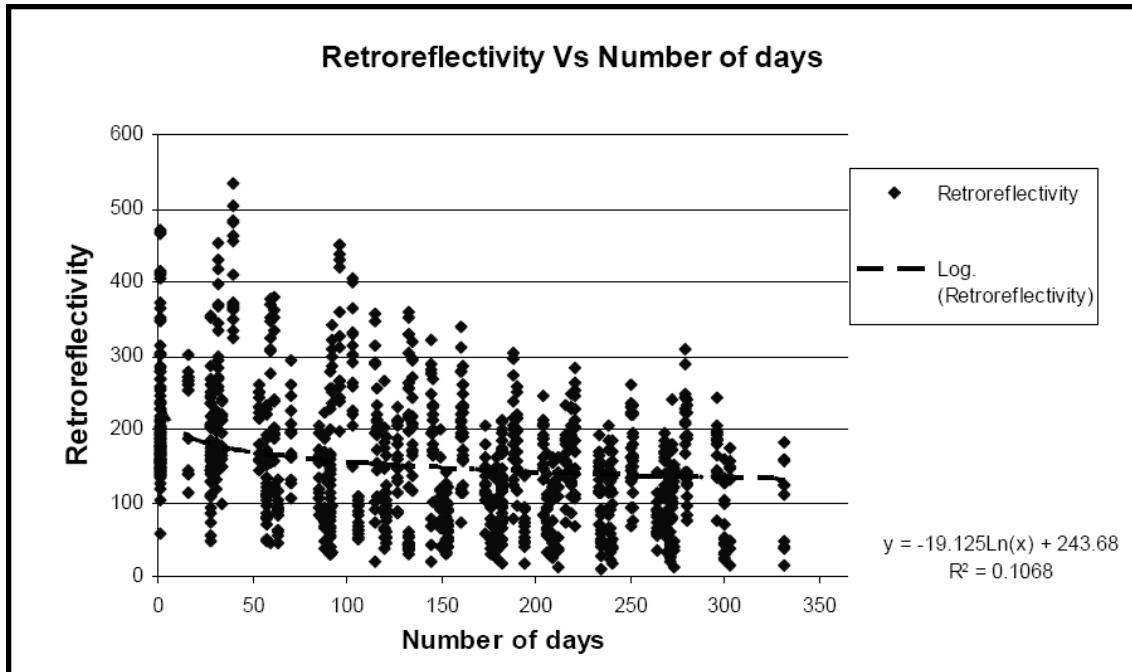

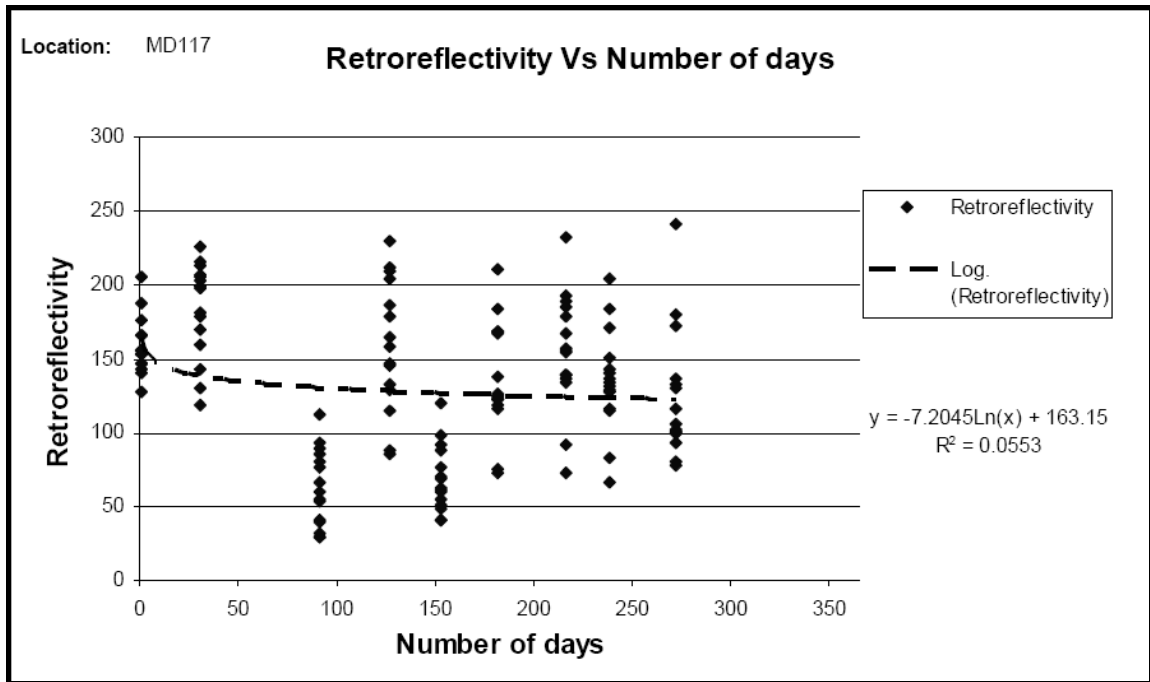**Figure 45. Overall Regression Analysis with Retroreflectivity Value and Number of Days**
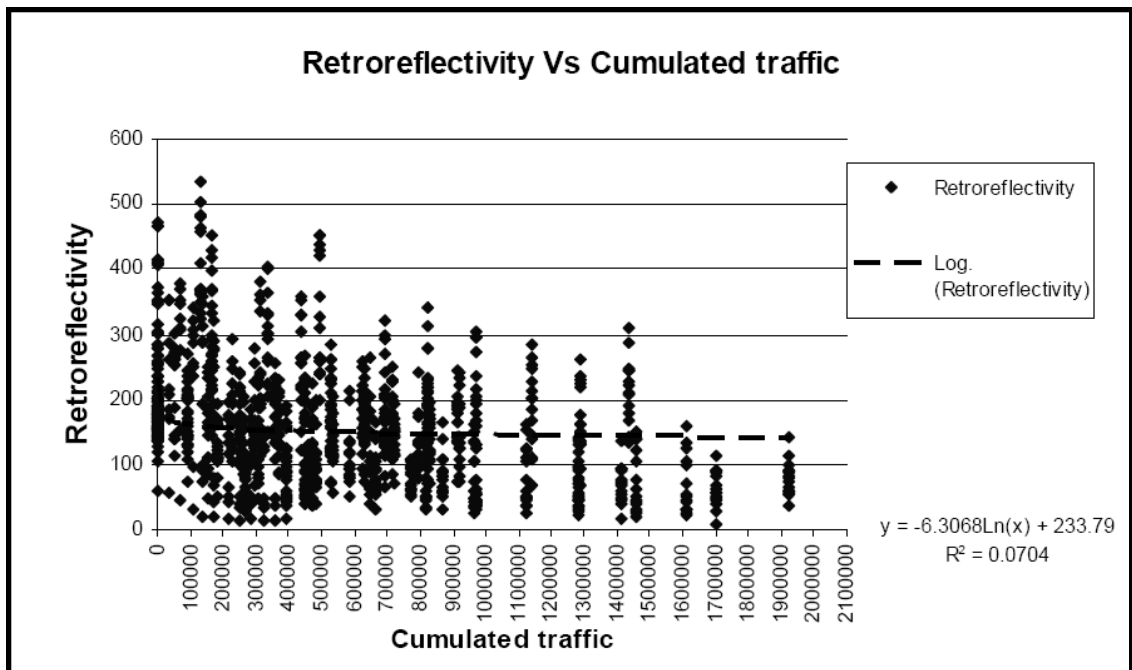
Figure 46. Overall Regression Analysis with Retroreflectivity Value and Cumulated Traffic per Lane
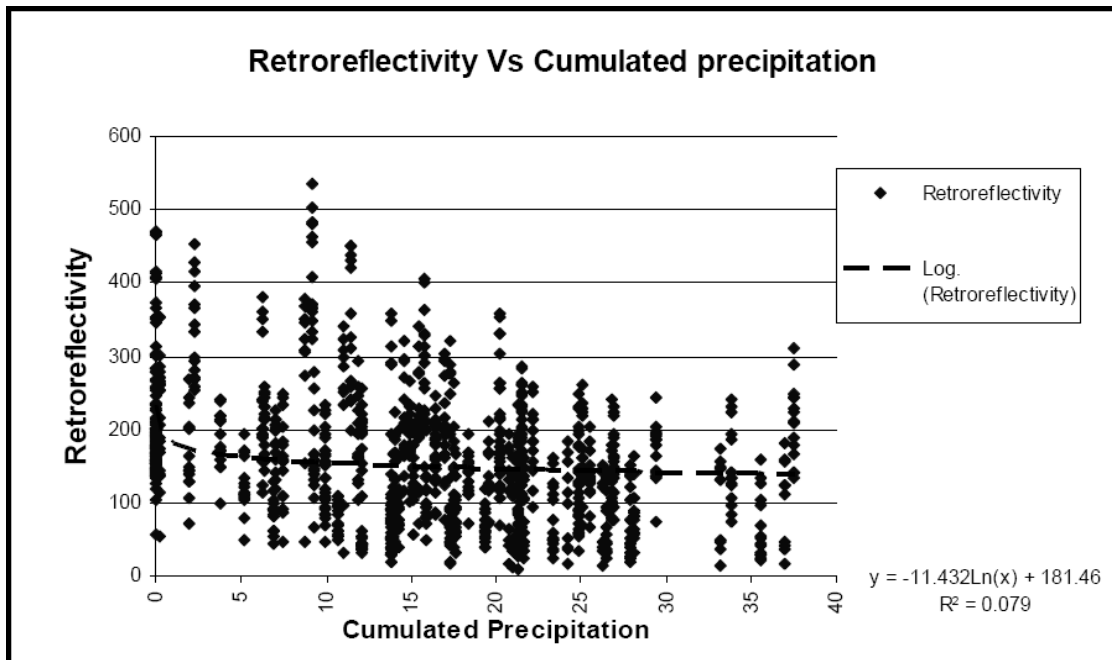
Figure 47. Overall Regression Analysis with Retroreflectivity Value and Cumulated Precipitation
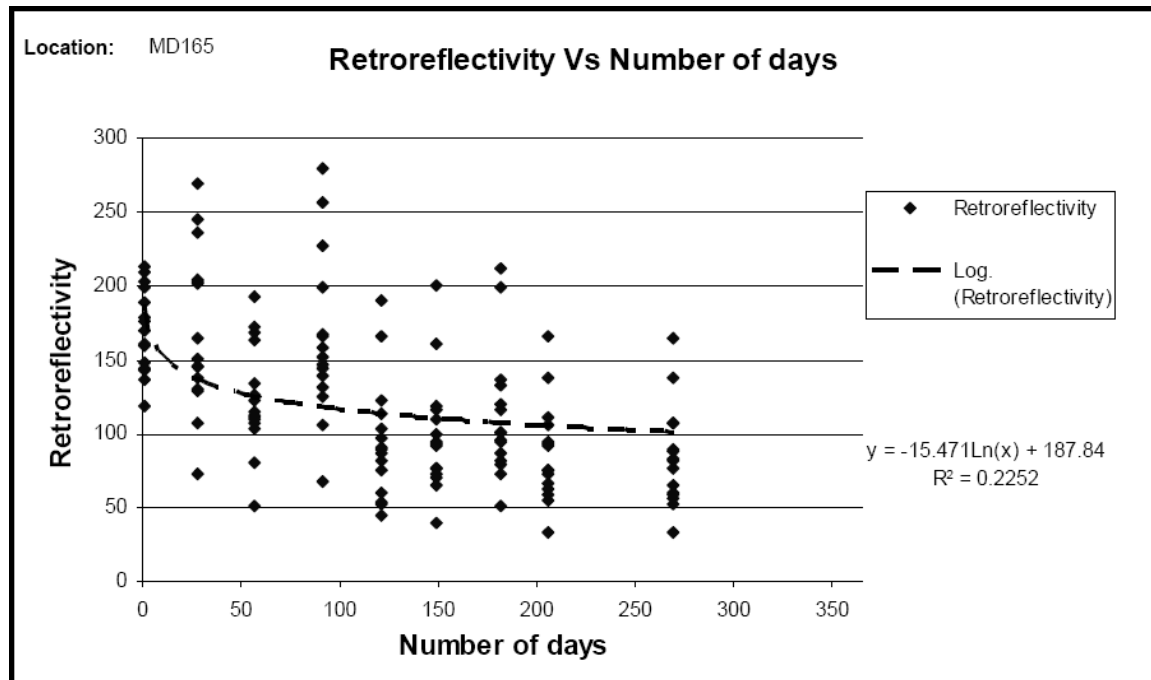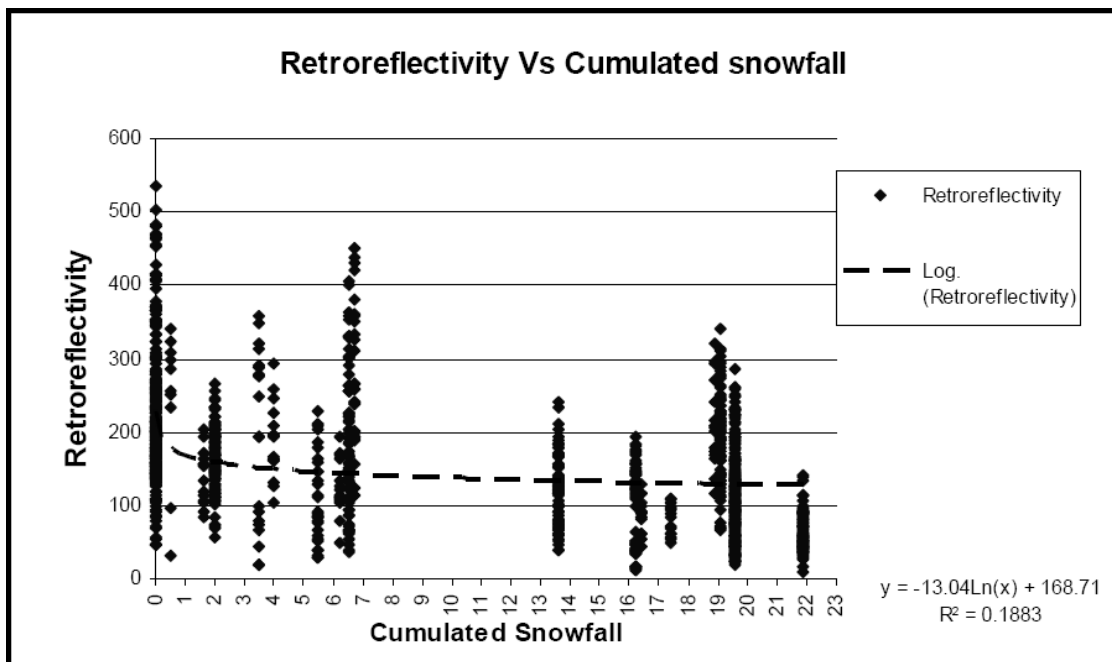

Figure 48. Overall Regression Analysis with Retroreflectivity Value and Cumulated Snowfall

Table 6. Regression Equations and R Square Values of Retroreflectivity Value

Analysis

Variable	Regression equation	R^2	Ranking
Number of Days	y = -19.125 Ln (x) + 243.68	0.1068	2
Cumulated Traffic	y = -6.3068 Ln (x) + 233.79	0.0704	4
Cumulated Precipitation	y = -11.432 Ln (x) + 181.46	0.079	3
Cumulated Snowfall	y = -13.04 Ln (x) + 168.71	0.1883	1

VI.1.2 Relationship between Retroreflectivity Percentages and Other Inputs

In this section, the percentages of the initial retroreflectivity readings were compared with four major inputs — Number of Days, Cumulated Traffic, Cumulated Precipitation, Cumulated Snow Amounts — and then plotted. Just like the previous case of retroreflectivity values, all four relationships are relevant and show similar forms because cumulated inputs are related to the time factor (Number of Days).

Figure 49 shows the relationship between retroreflectivity percentage and Number of Days. Figure 50 shows the relationship between retroreflectivity percentage and cumulated traffic. Figure 51 shows the relationship between retroreflectivity percentage and cumulated precipitation. Figure 52 shows the relationship between retroreflectivity percentage and cumulated snow amount. The regression equations and *R square* values are also presented in the figures.

Figures 49-52 show the same shape of relationship, and can be presented as a logarithm equation. Since these analyses use aggregated data from different markings and locations, the relationship between retroreflectivity values and inputs are not very consistent. They are also very similar to Figures 45-48, which use retroreflectivity value.

Among those relationships, just as in retroreflectivity value analysis, the relationship between retroreflectivity and Cumulated Snowfall is the most consistent in terms of *R square* analysis. The next correlated input to the retroreflectivity is Number of Days Exposed. Cumulated Traffic and Cumulated Precipitation are not very related to retroreflectivity. Even if snowfall and number of days are more related to the retroreflectivity, all relationships with the four major inputs were not very close despite the existence of the general downward trend of retroreflectivity. Table 7 shows the regression equations and R square values from the four relationships.
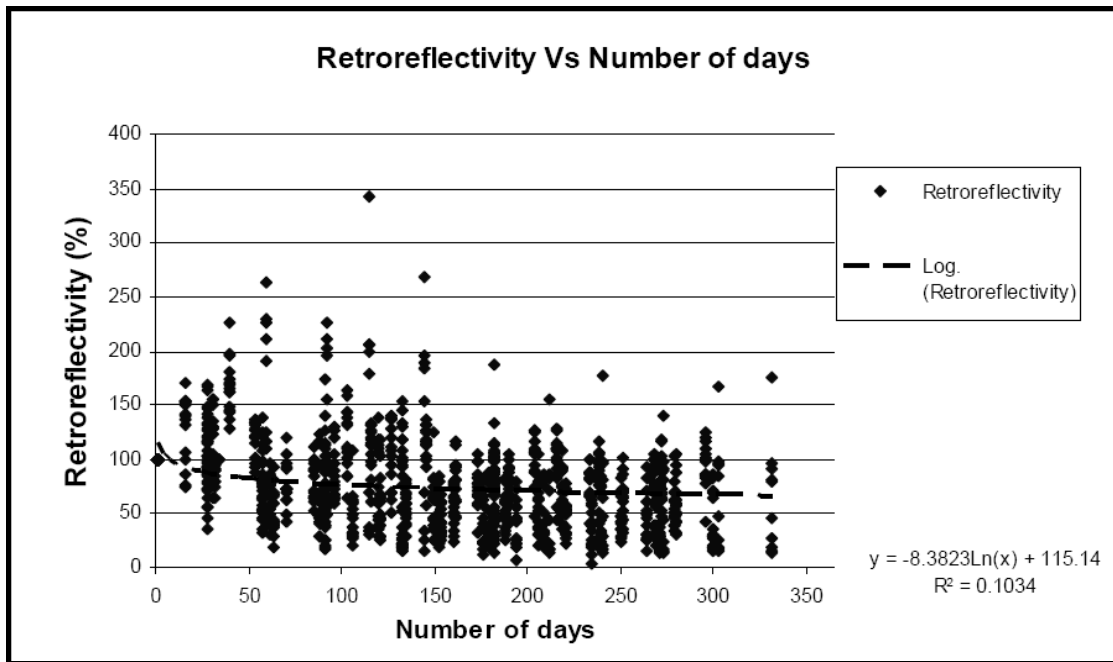
Figure 49. Overall Regression Analysis with Retroreflectivity Percentage and Number of Days
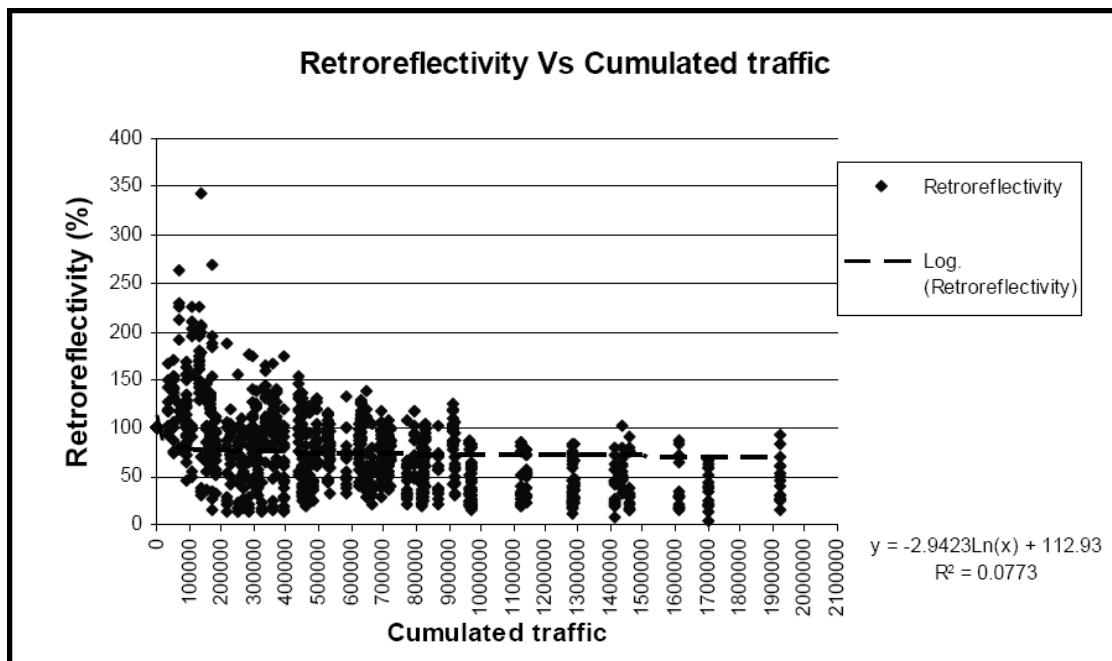
Figure 50. Overall Regression Analysis with Retroreflectivity Percentage and Cumulated Traffic per Lane
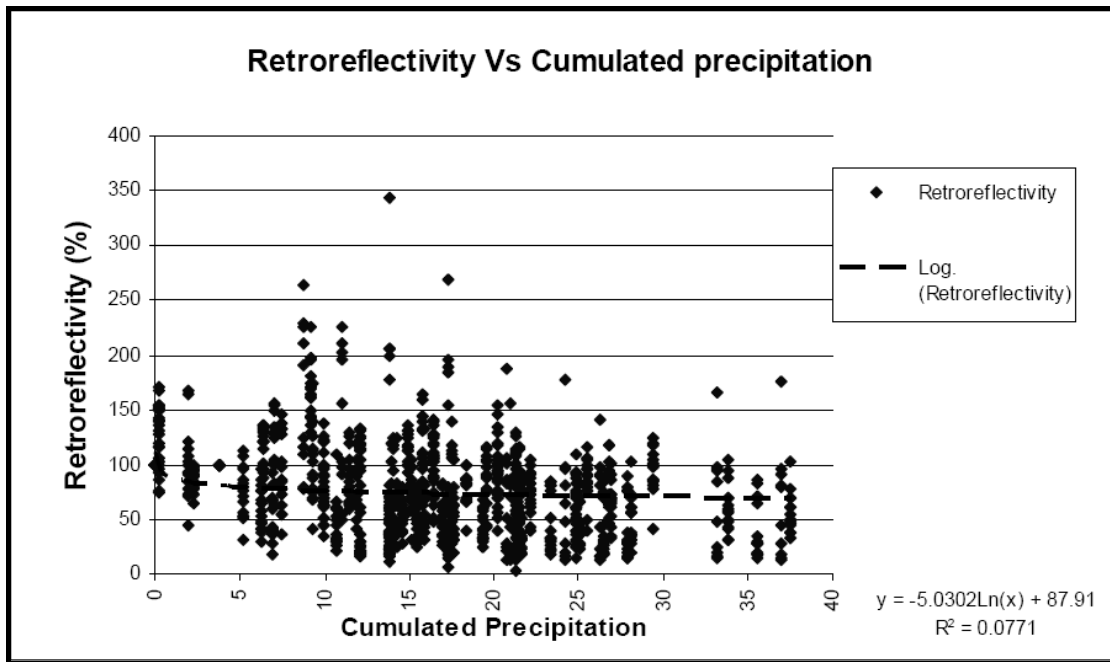
Figure 51. Overall Regression Analysis with Retroreflectivity Percentage and Cumulated Precipitation
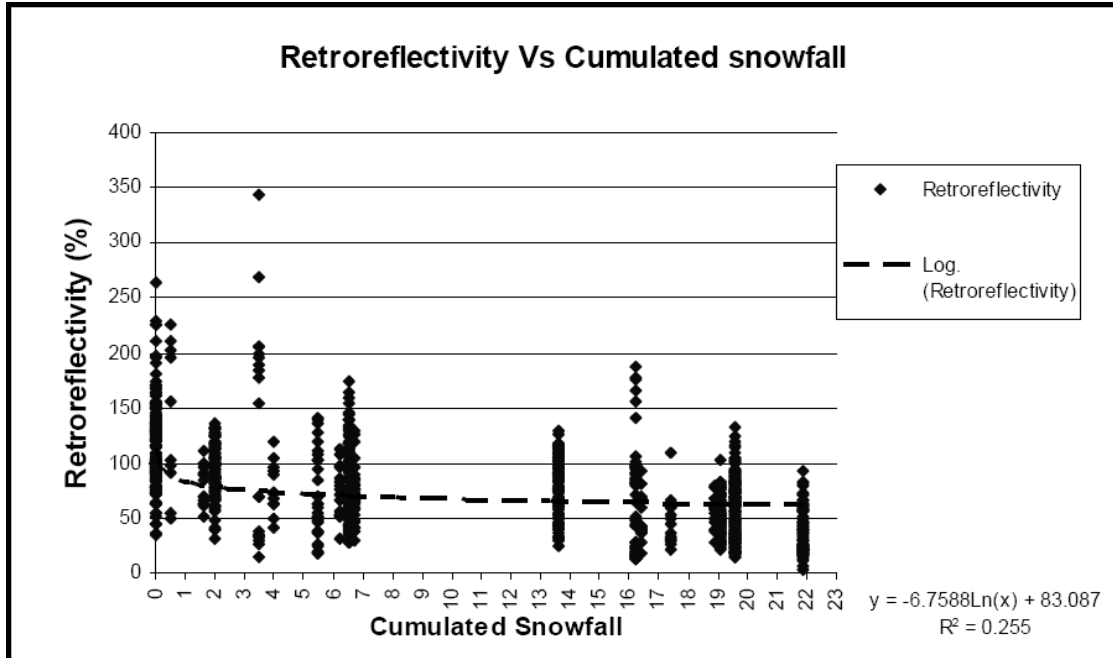
Figure 52. Overall Regression Analysis with Retroreflectivity Percentage and Cumulated Snowfall

Table 7. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis

Variable	Regression equation	R^2	Ranking
Number of Days	y = -8.3823 Ln (x) + 115.14	0.1034	2
Cumulated Traffic	y = -2.9423 Ln (x) + 112.93	0.0773	3
Cumulated Precipitation	y = -5.03 Ln (x) + 87.91	0.0771	4
Cumulated Snowfall	y = -6.7588 Ln (x) + 83.087	0.255	1

VI.2 Single Variable Regression Analysis for Each Pavement Marking

Each location can have a maximum of five different kinds of pavement markings. These pavement markings are White Edge (WE), White Skip (WS), Yellow Center (YC), Yellow Edge (YE), and Yellow Skip (YS). Analysis for each pavement marking is necessary because they can have different initial retroreflectivity, pavement marking material, and traffic exposure. In this section, a regression analyses for each pavement marking is presented with the four different inputs that have been discussed. Analyses for two different outputs — retroreflectivity values and retroreflectivity percentages to initial retroreflectivities — are presented as in the previous section.

VI.2.1 White Edge (WE) Pavement Marking

White Edge (WE) pavement marking is the most popular pavement marking in this study. All eight locations have WE pavement markings. Among those eight locations, six locations — MD 117, MD 165, MD 273, MD 33, MD 53, and US 40 ALT — have two. Fourteen WE pavement markings were used in this study. Only MD 297 and US 40 had one White Edge pavement marking.

VI.2.1.1 Relationship between Retroreflectivity Value and Other Inputs

As WE pavement markings were the most popular among various pavement markings and in similar locations, the results in Figures 53-56 are very similar to those in Figures 45-48. Table 8 illustrates how retroreflectivity values of WE pavement markings are more correlated with Number of Days Exposed and Cumulated Snowfall than Cumulated Traffic and Cumulated Precipitation. Because the data for the WE pavement markings are collected from various locations, the results are widely spread and correlations are not very strong.
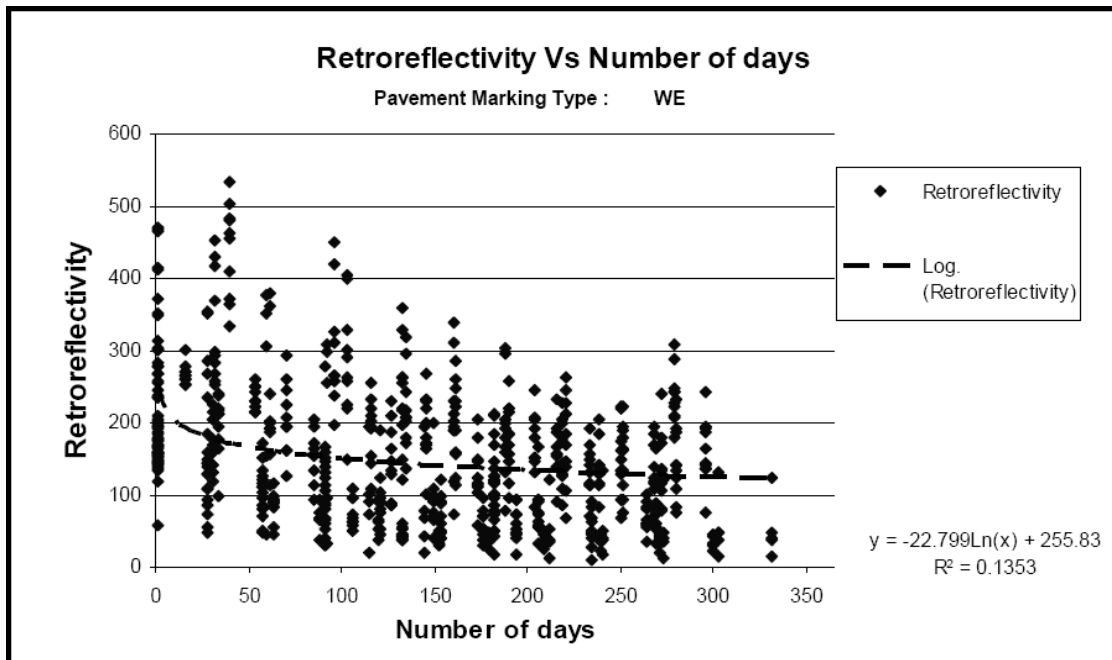
Figure 53. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Value and Number of Days
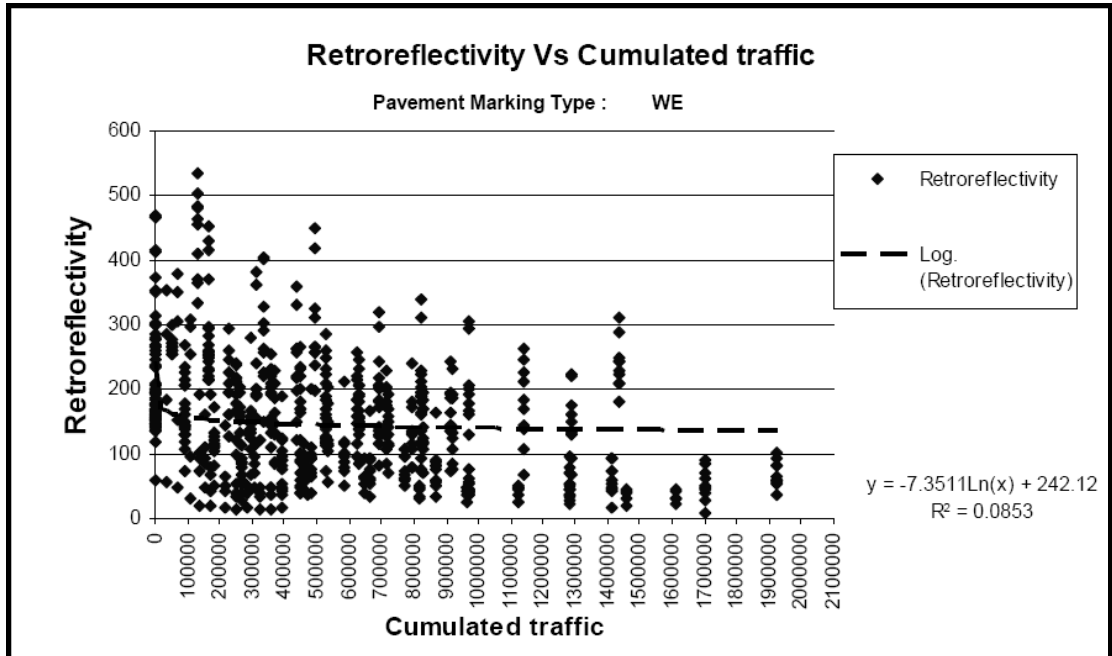
Figure 54. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Value and Cumulated Traffic per Lane

Figure 55. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Value and Cumulated Precipitation
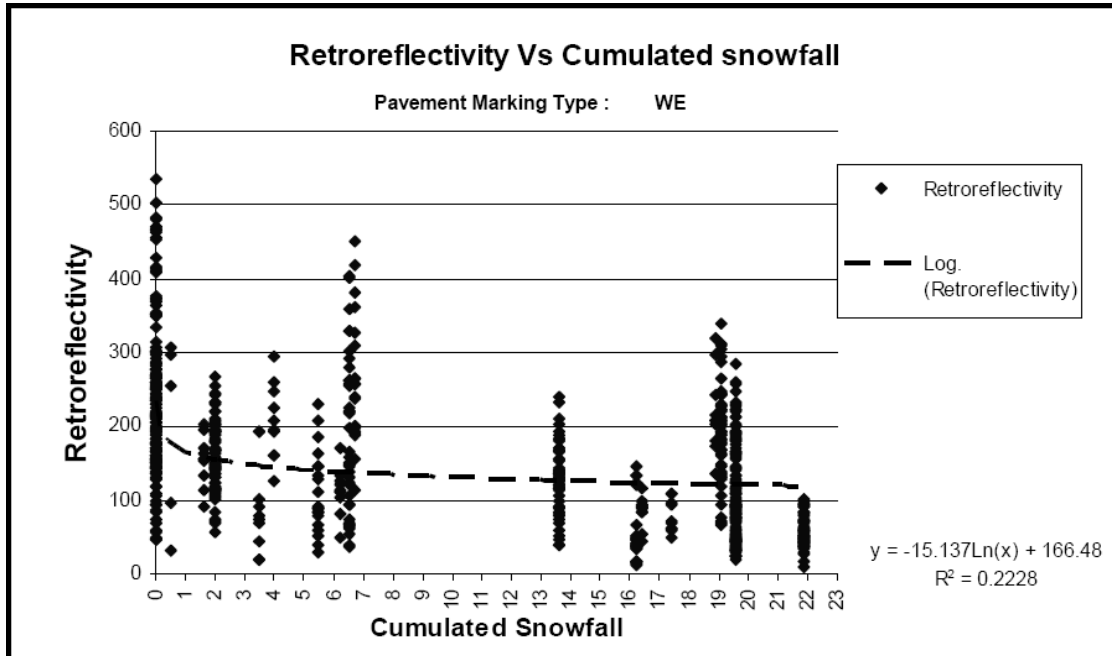
Figure 56. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Value and Cumulated Snowfall

Table 8. Regression Equations and R Square Values of Retroreflectivity Value Analysis of White Edge Pavement Markings (WE)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -22.799 Ln (x) + 255.83	0.1353	2
Cumulated Traffic	y = -7.3511 Ln (x) + 242.12	0.0853	4
Cumulated Precipitation	y = -14.066 Ln (x) + 182.35	0.1064	3
Cumulated Snowfall	y = -15.137 Ln (x) + 166.48	0.2228	1

VI.2.1.2 Relationship between Retroreflectivity Percentage and Other Inputs

The relationships between retroreflectivity percentage and various inputs were analyzed for White Edge pavement markings similar to the previous analysis. The results in Figures 57-60 were not very different from the analysis with retroreflectivity value. Number of Days Exposed was the input that made the most impact on retroreflectivity percentage, as it did for the retroreflectivity value (Table 9).

Figure 57. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Percentage and Number of Days

Figure 58. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Percentage and Cumulated Traffic per Lane

Figure 59. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Percentage and Cumulated Precipitation

Figure 60. Regression Analysis of White Edge Pavement Markings (WE) with Retroreflectivity Percentage and Cumulated Snowfall

Table 9. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis of White Edge Pavement Markings (WE)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -10.11 Ln (x) + 116.00	0.1817	2
Cumulated Traffic	y = -3.3137 Ln (x) + 110.56	0.1184	4
Cumulated Precipitation	y = -06.359 Ln (x) + 083.65	0.1486	3
Cumulated Snowfall	y = -7.361 Ln (x) + 76.889	0.3601	1

VI.2.2 White Skip (WS) Pavement Marking

The White Skip (WS) pavement marking is found at only one location, US 40. Since the data was collected from only one location, the results were highly converged.

<u>**VI.2.2.1 Relationship between Retroreflectivity Value and Other Inputs**</u>
As mentioned, the relationships between retroreflectivity value and inputs for WS pavement marking were very strong (see Figure 61-64). While the WS pavement markings provide a strong relationship, it is also due to the limited number of data used for the analysis. For White Skip pavement marking, Cumulated Snowfall and Number of Days Exposed made stronger relationships with retroreflectivity value than other inputs, such as Cumulated Traffic Exposed and Cumulated Precipitation. This can be seen in Table 10.

Figure 61. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Value and Number of Days

Figure 62. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Value and Cumulated Traffic per Lane

Figure 63. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Value and Cumulated Precipitation

Figure 64. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Value and Cumulated Snowfall

Table 10. Regression Equations and R Square Values of Retroreflectivity Value Analysis of White Skip Pavement Markings (WS)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -25.388 Ln (x) + 205.03	0.6561	1
Cumulated Traffic	y = -8.6541 Ln (x) + 198.13	0.4825	4
Cumulated Precipitation	y = -15.699 Ln (x) + 127.22	0.5	3
Cumulated Snowfall	y = -12.011 Ln (x) + 100.51	0.6445	2

VI.2.2.2 Relationship between Retroreflectivity Percentage and Other Inputs

Just as in other analysis in this study, retroreflectivity percentage to initial retroreflectivity values was used in this section rather than retroflectivity value. The results show that number of days exposed and Cumulated Snowfall made stronger relationships with retroreflectivity percentages. For US 40, the relationship with retroreflectivity percentage was stronger than retroreflectivity value (see Figures 65- 68 and Table 11).

Figure 65. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Percentage and Number of Days

Figure 66. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Percentage and Cumulated Traffic per Lane

Figure 67. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Percentage and Cumulated Precipitation

Figure 68. Regression Analysis of White Skip Pavement Markings (WS) with Retroreflectivity Percentage and Cumulated Snowfall

Table 11. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis of White Skip Pavement Markings (WS)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -13.887 Ln (x) + 111.33	0.7126	1
Cumulated Traffic	y = -4.7394 Ln (x) + 107.61	0.5250	4
Cumulated Precipitation	y = -8.595 Ln (x) + 68.77	0.5438	3
Cumulated Snowfall	y = -6.566 Ln (x) + 54.141	0.6989	2

VI.2.3 Yellow Center (YC) Pavement Marking

Yellow Center (YC) pavement markings were found in six locations: MD 117, MD 165, MD 297, MD 33, MD 53, and US 40 ALT. After White Edge, these were the second most found pavement markings in this study.

VI.2.3.1 Relationship between Retroreflectivity Value and Other Inputs

Since those six locations were spread throughout the region — including western, central and eastern Maryland — the relationships between retroreflectivity and inputs are not strong as shown in Figures 69-72. As illustrated in Table 12, only Cumulated Snowfall has a reasonable relationship with retroreflectivity value. All others have very weak relationship.

Figure 69. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Value and Number of Days

Figure 70. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Value and Cumulated Traffic per Lane
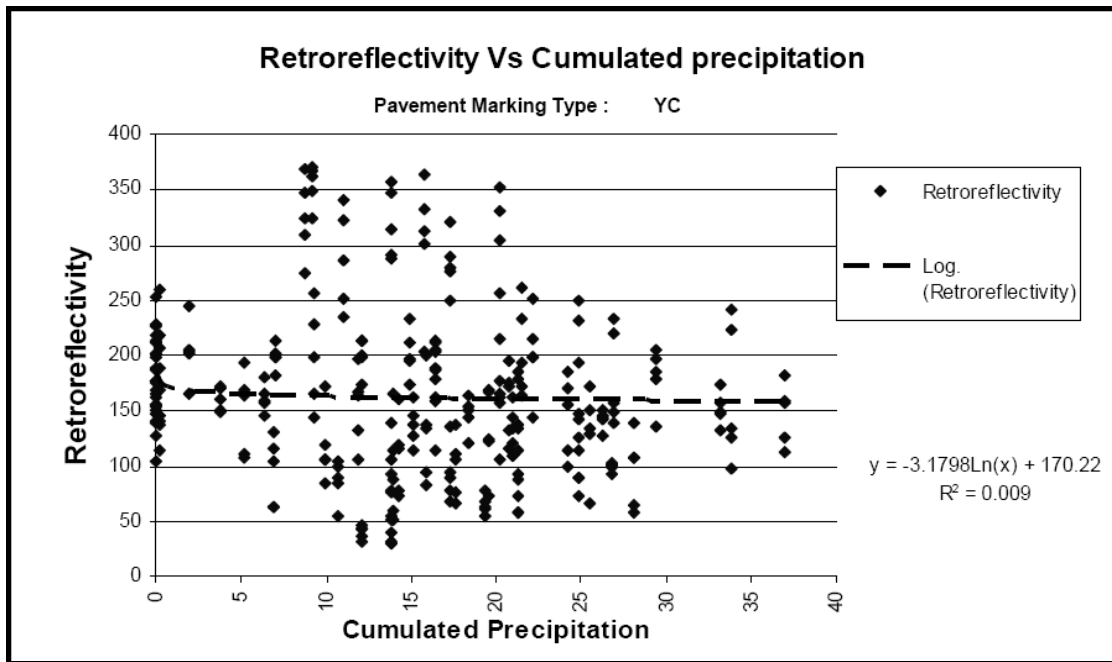
Figure 71. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Value and Cumulated Precipitation
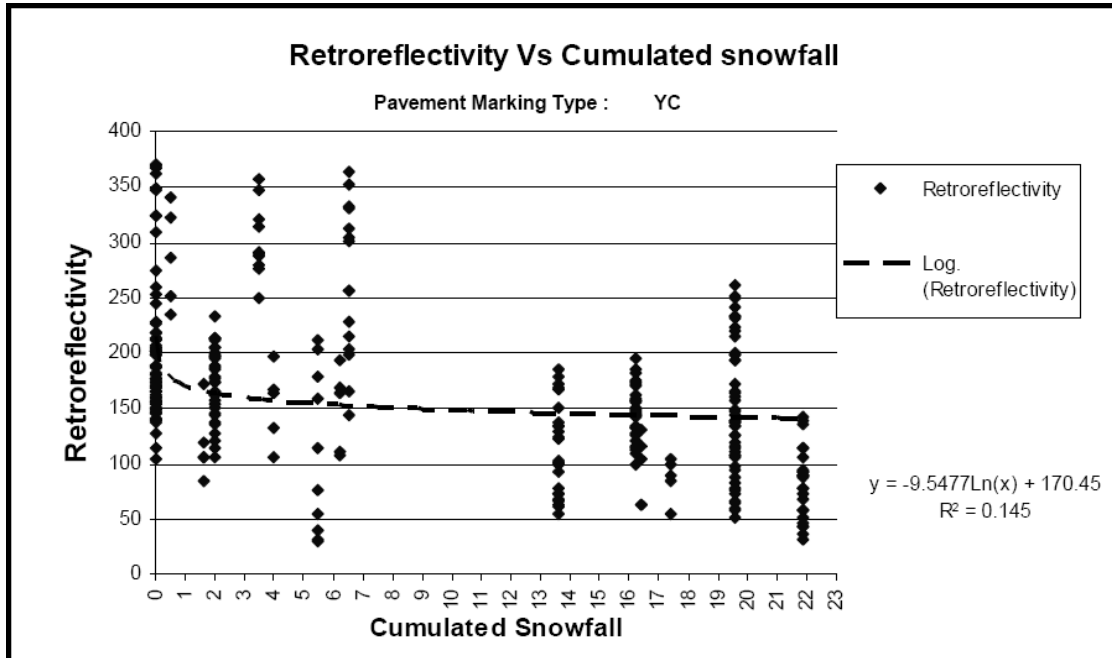
Figure 72. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Value and Cumulated Snowfall

Table 12. Regression Equations and R Square Values of Retroreflectivity Value Analysis of Yellow Center Pavement Markings (YC)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -8.1483 Ln (x) + 200.32	0.0282	2
Cumulated Traffic	y = -3.1961 Ln (x) + 201.55	0.0254	3
Cumulated Precipitation	y = -3.1798 Ln (x) + 170.22	0.0090	4
Cumulated Snowfall	y = -9.5477 Ln (x) + 170.45	0.145	1

VI.2.3.2 Relationship between Retroreflectivity Percentage and Other Inputs

For YC pavement markings, the relationships between retroreflectivity percentage and inputs were conducted as well. Just as with retroreflectivity value, other than Cumulated Snowfall, the retroflectivity percentages were not affected by other inputs (see Figures 73 -76 and Table 13). In this case, retroreflectivity value had a stronger relationship with inputs than retroreflectivity percentages.
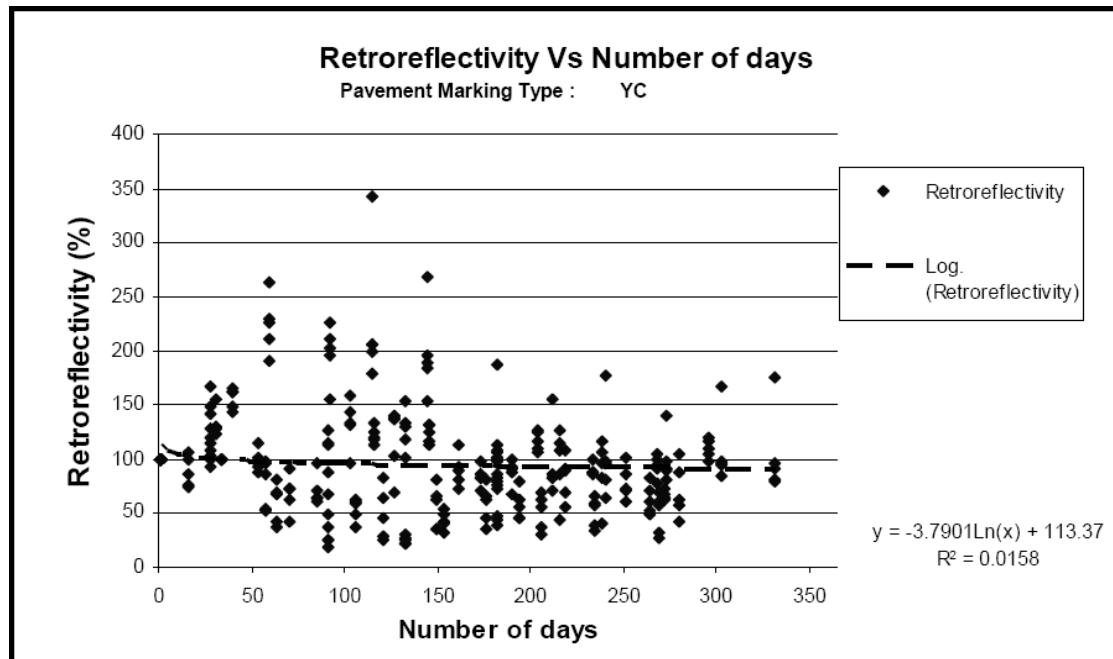
Figure 73. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Percentage and Number of Days
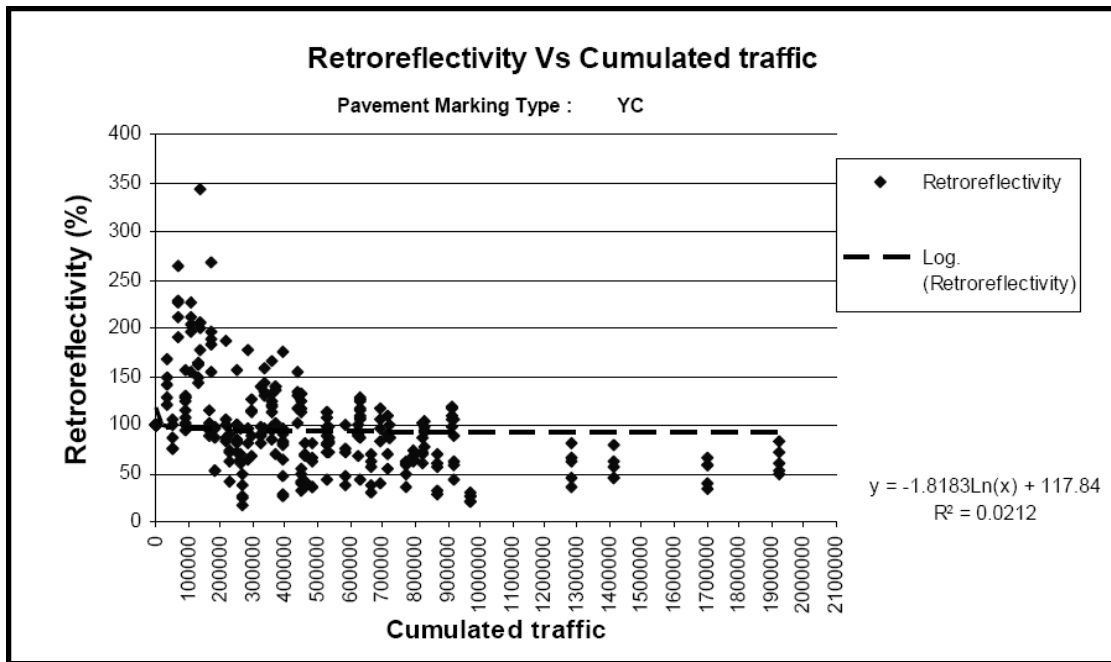
Figure 74. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Percentage and Cumulated Traffic per Lane
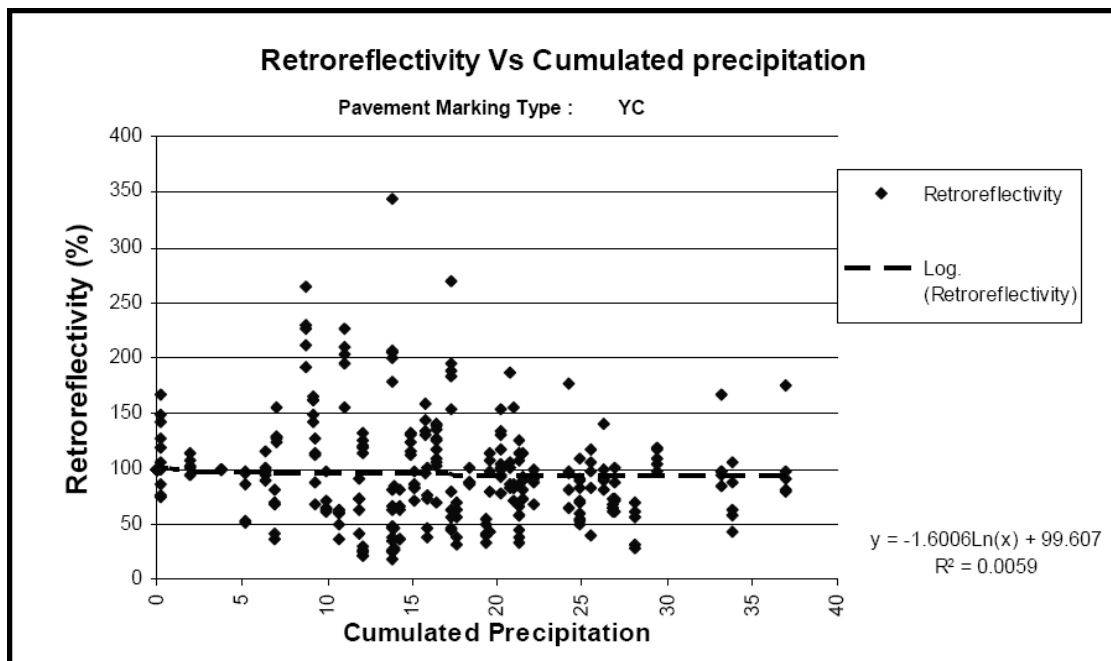
Figure 75. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Percentage and Cumulated Precipitation
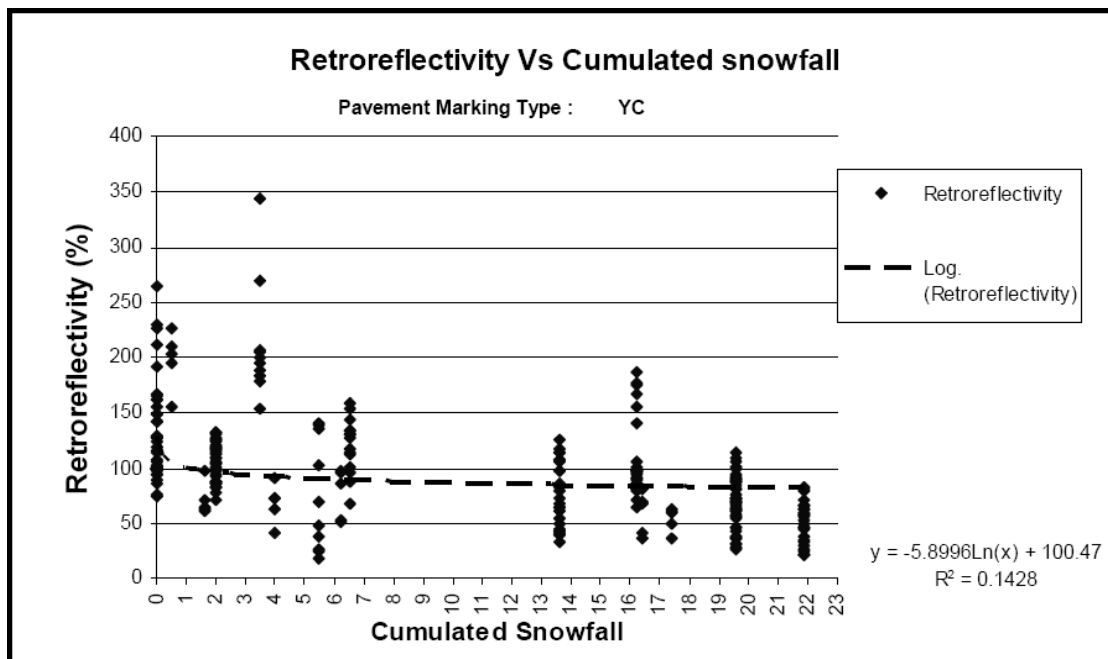
Figure 76. Regression Analysis of Yellow Center Pavement Markings (YC) with Retroreflectivity Percentage and Cumulated Snowfall

Table 13. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis of Yellow Center Pavement Markings (YC)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -3.7901 Ln (x) + 113.37	0.0158	3
Cumulated Traffic	y = -1.8183 Ln (x) + 117.84	0.0212	2
Cumulated Precipitation	y = -1.6006 Ln (x) + 99.607	0.0059	4
Cumulated Snowfall	y = -5.8996 Ln (x) + 100.47	0.1428	1

VI.2.4 Yellow Edge (YE) Pavement Marking

The Yellow Edge pavement marking was found at one location, US 40. Since the data was collected from one location, the results were much more converged than White Edge pavement marking cases and Yellow Center pavement marking cases, which have data from many locations.

VI.2.4.1 Relationship between Retroreflectivity Value and Other Inputs

As mentioned, the relationships between retroreflectivity value and inputs for Yellow Edge pavement marking are relatively strong (see Figure 77-80) because of the limited number of data used for the analysis. For Yellow Edge pavement marking, Cumulated Snowfall and Number of Days Exposed made a stronger relationship with

retroreflectivity value than other inputs such as cumulated traffic exposed and cumulated precipitation (Table 14).
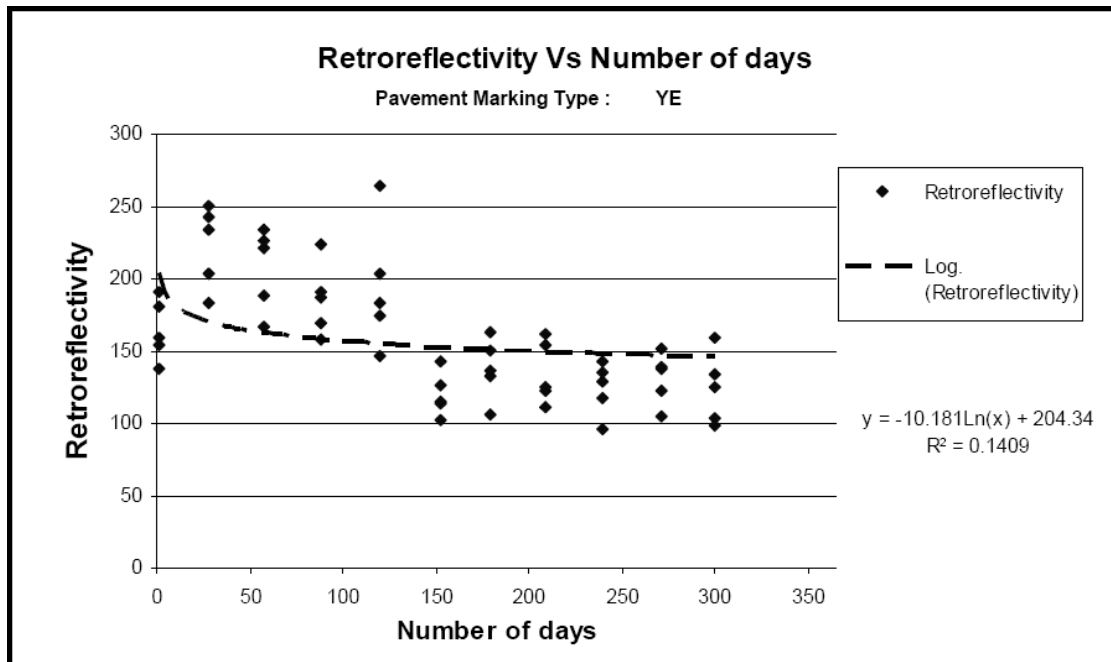
Figure 77. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Value and Number of Days
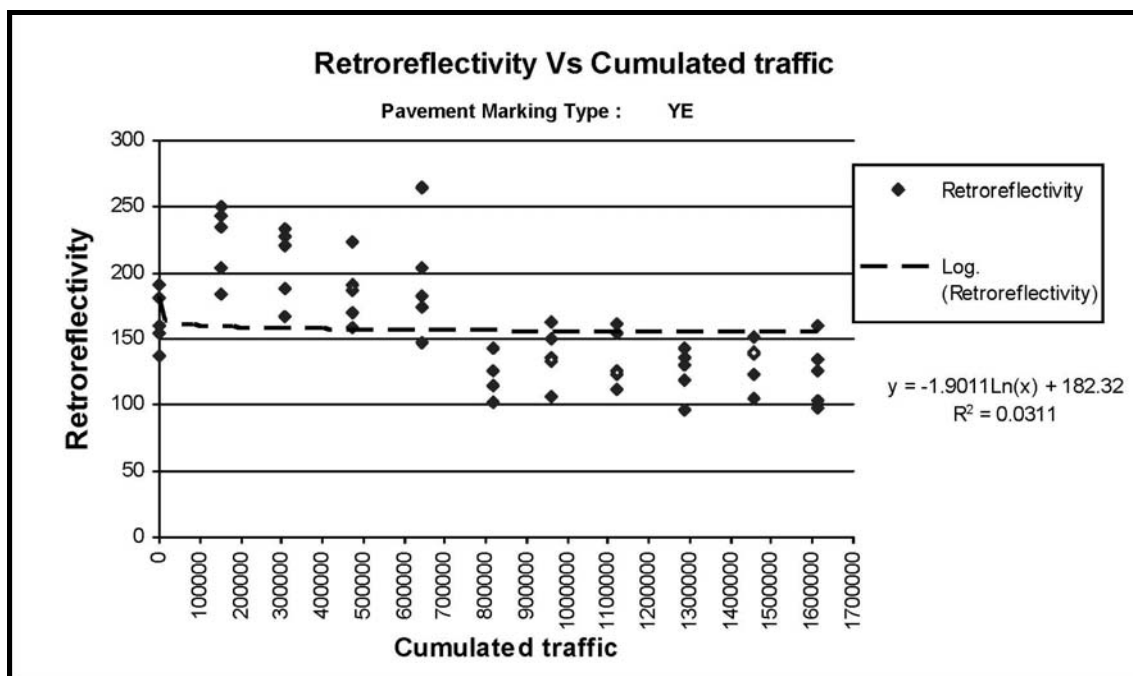
Figure 78. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Value and Cumulated Traffic per Lane
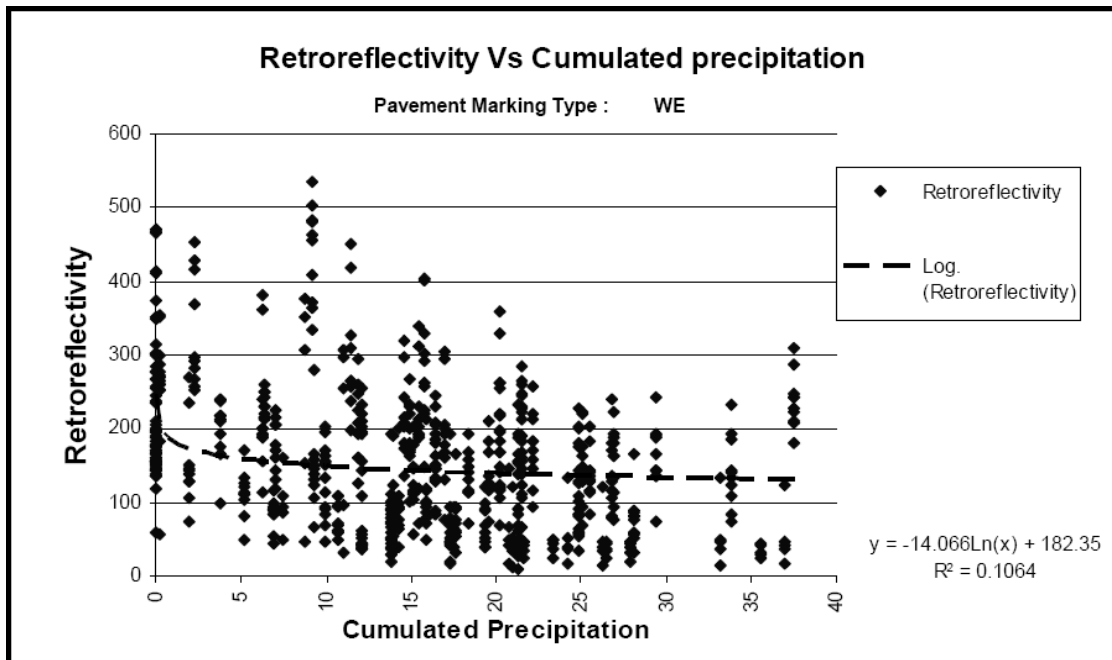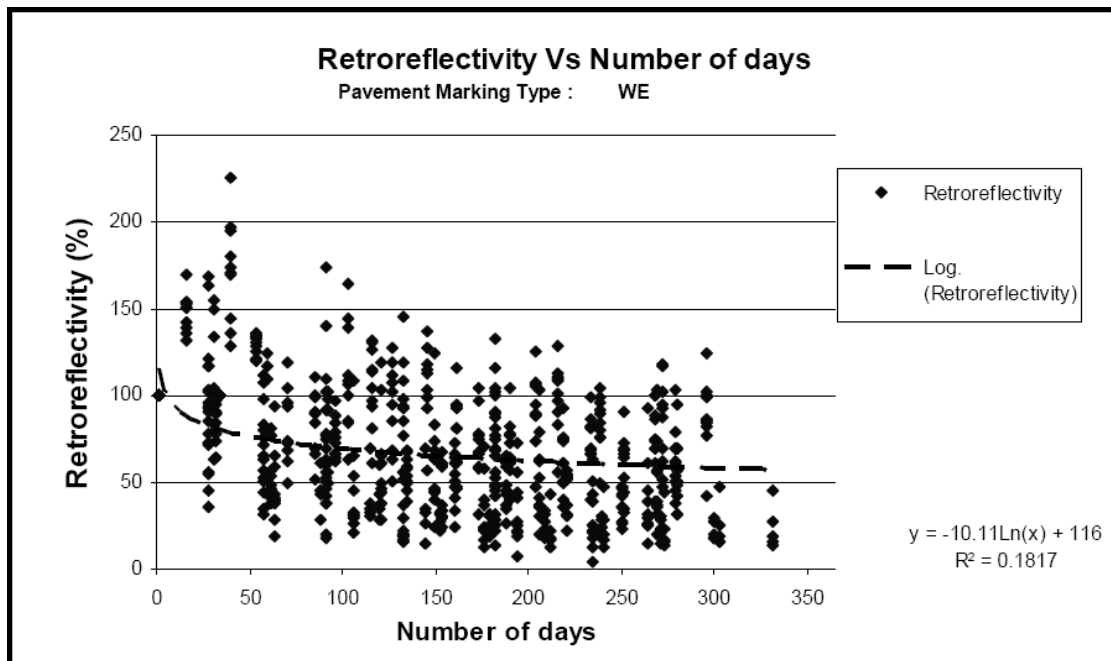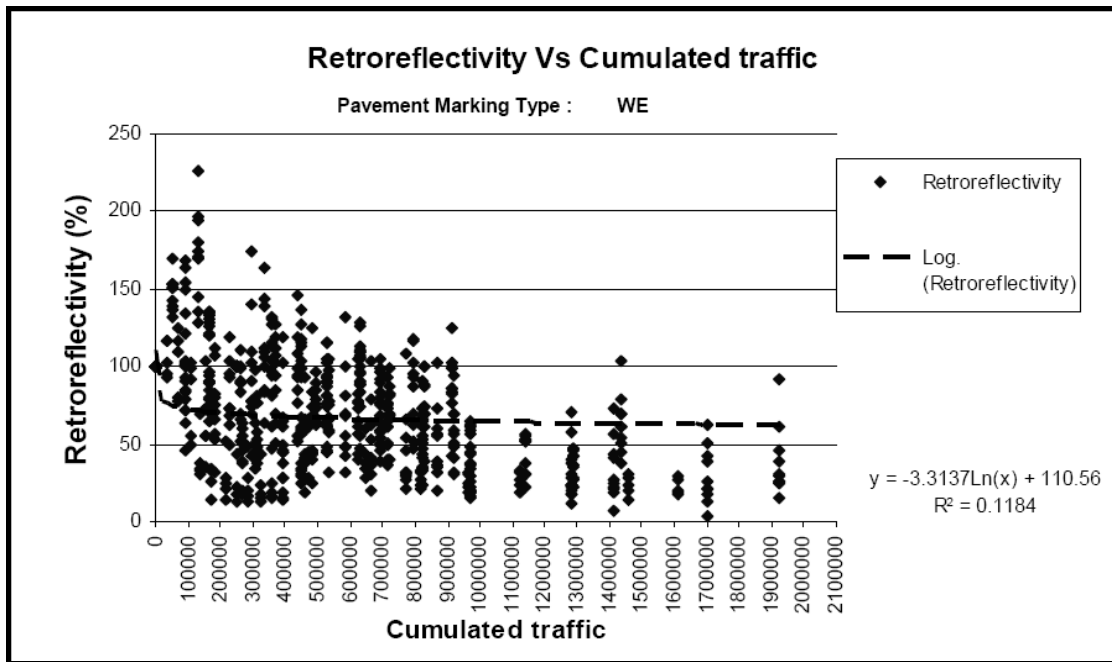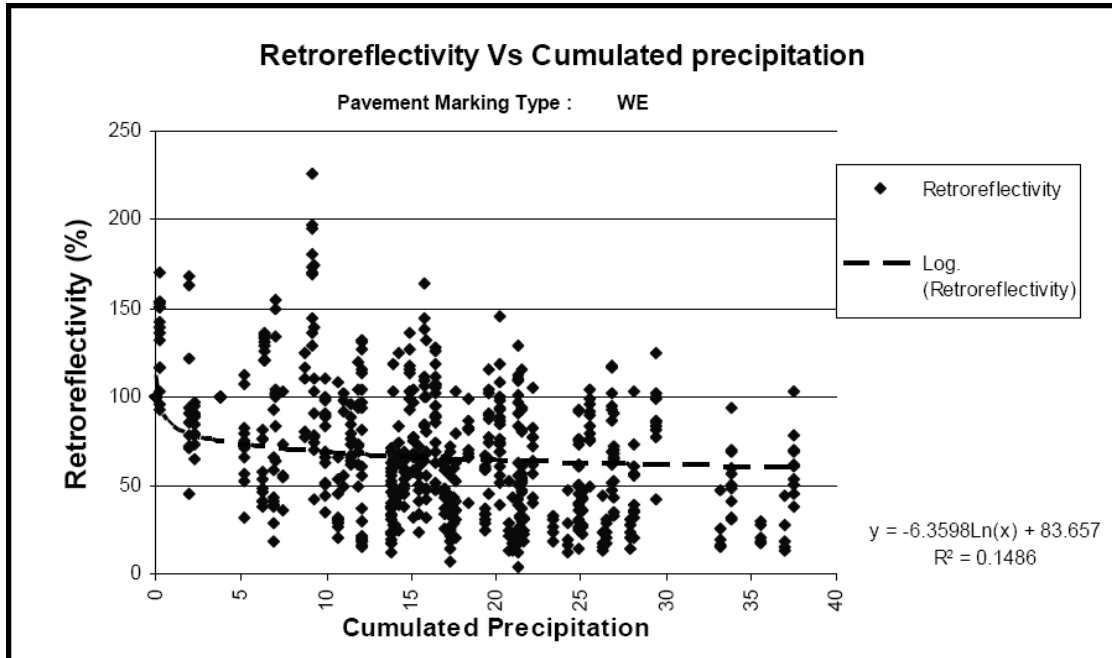
67
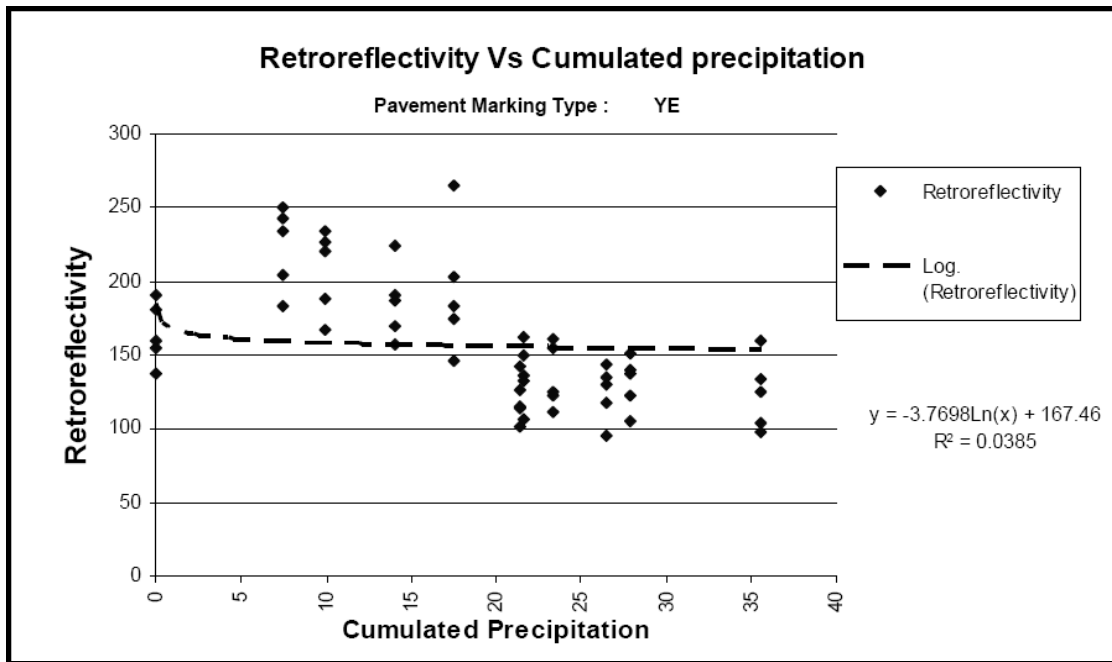
Figure 79. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Value and Cumulated Precipitation
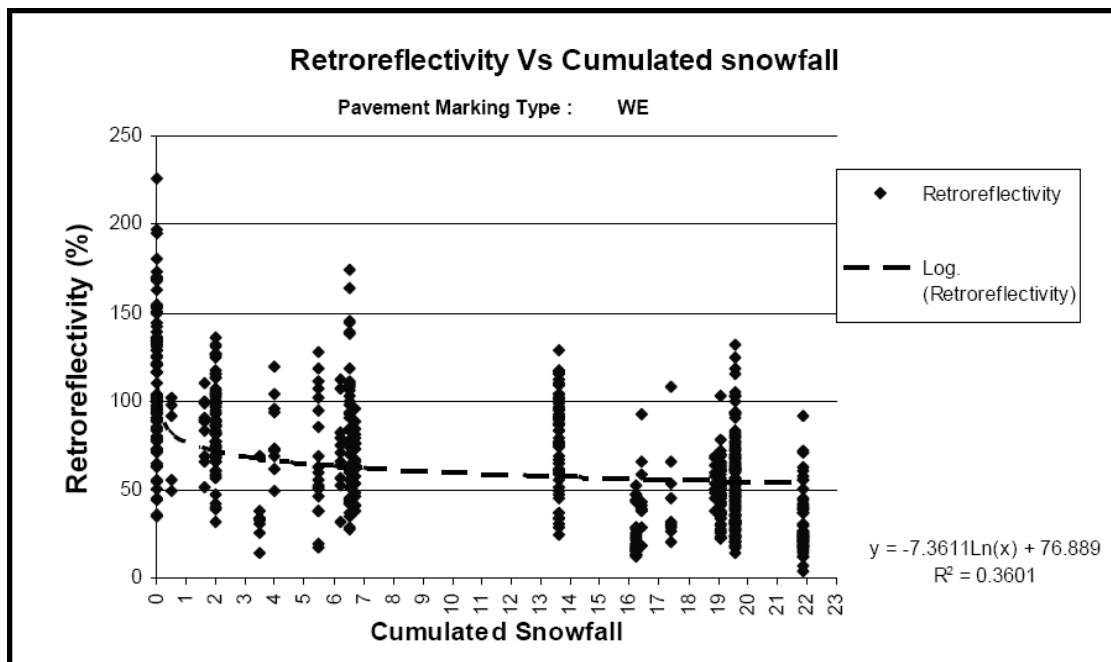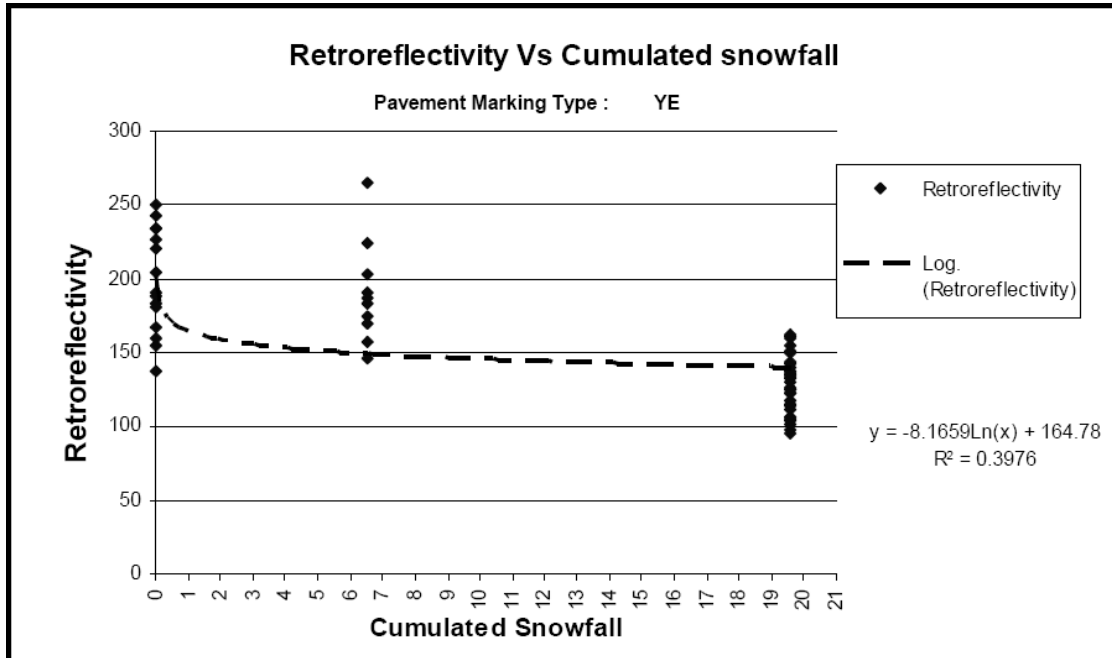

Figure 80. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Value and Cumulated Snowfall

Table 14. Regression Equations and R Square Values of Retroreflectivity Value Analysis of Yellow Edge Pavement Markings (YE)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -10.181 Ln (x) + 204.34	0.1409	2
Cumulated Traffic	y = -1.9011 Ln (x) + 182.32	0.0311	4
Cumulated Precipitation	y = -3.7698 Ln (x) + 167.46	0.0385	3
Cumulated Snowfall	y = -8.1659 Ln (x) + 164.78	0.3976	1

VI.2.4.2 Relationship between Retroreflectivity Percentage and Other Inputs

Relationships between retroreflectivity percentages and inputs were conducted as well. All relationships were similar to the relationships between retroreflectivity and inputs (Figures 81-84). For Yellow Edge pavement markings, relationships for retroreflectivity percentage are stronger than relationships for retroreflectivity value. This is shown in Table 15.
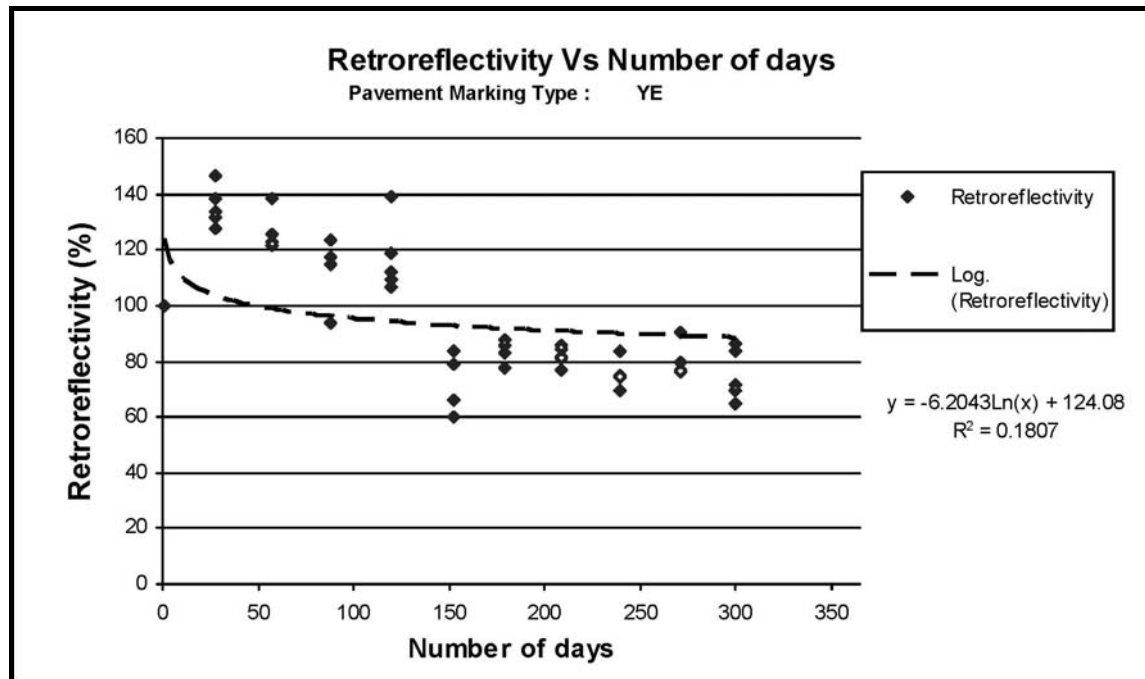
Figure 81. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Percentage and Number of Days
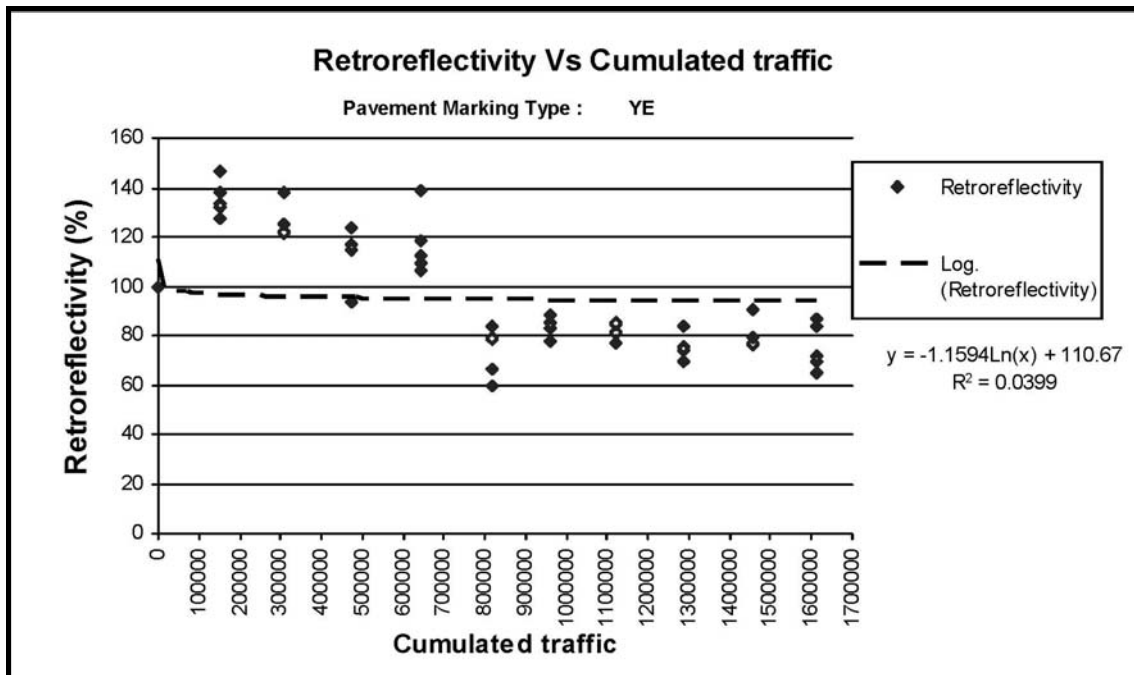
Figure 82. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Percentage and Cumulated Traffic per Lane
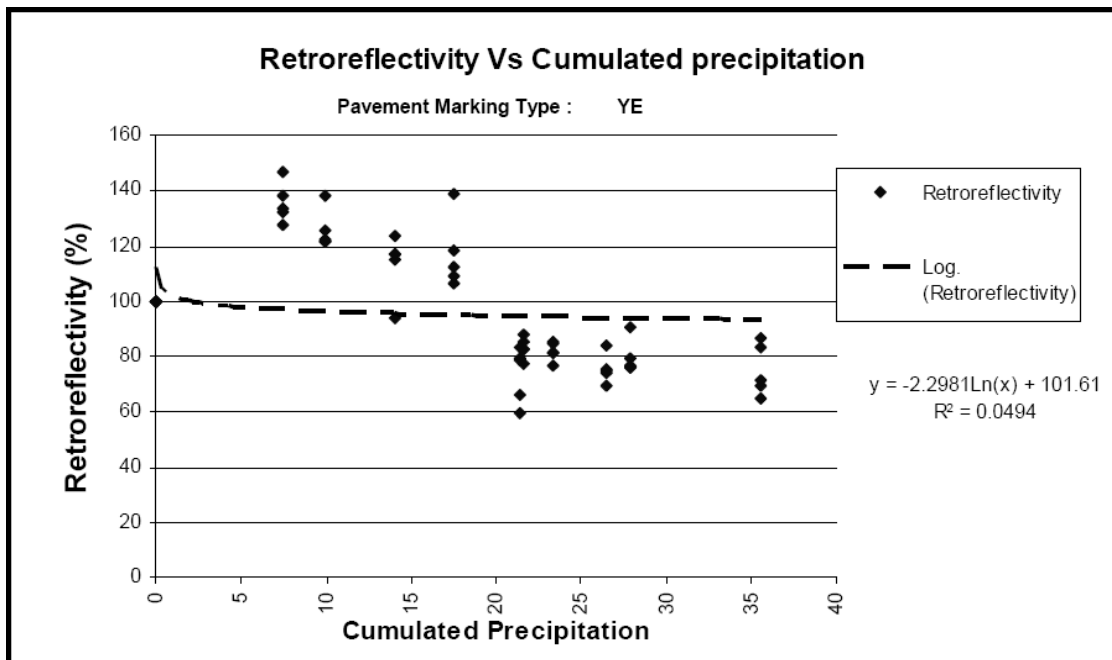
Figure 83. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Percentage and Cumulated Precipitation
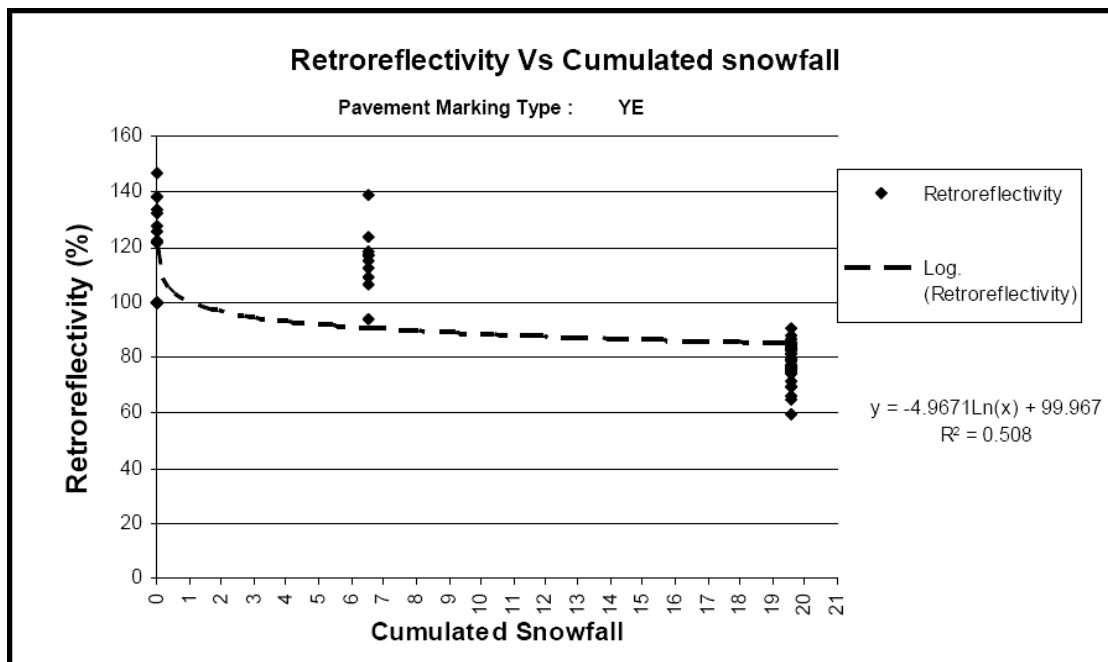
Figure 84. Regression Analysis of Yellow Edge Pavement Markings (YE) with Retroreflectivity Percentage and Cumulated Snowfall

Table 15. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis of Yellow Edge Pavement Markings (YE)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -6.2043 Ln (x) + 124.08	0.1807	2
Cumulated Traffic	y = -1.1594 Ln (x) + 110.67	0.0399	4
Cumulated Precipitation	y = -2.2981 Ln (x) + 101.61	0.0494	3
Cumulated Snowfall	y = -4.967 Ln (x) + 99.967	0.5080	1

VI.2.5 Yellow Skip (YS) Pavement Marking

Yellow Skip pavement marking was found only at MD 273. Since it was found at one location, the relationships between retroreflectivity and inputs for Yellow Skip pavement marking are stronger than those for other pavement markings that were in many locations.

VI.2.5.1 Relationship between Retroreflectivity Value and Other Inputs

As shown in Figures 85-88, the relationships between retroreflectivity value and inputs for Yellow Skip pavement markings were generally stronger than those for the other pavement markings that were found in many locations. Unlike other pavement markings or locations, retroreflectivities for Yellow Skip pavement marking and MD 273 in the eastern region had the strongest relationship with the Cumulated Snowfall and Number of Days (see Table 16).
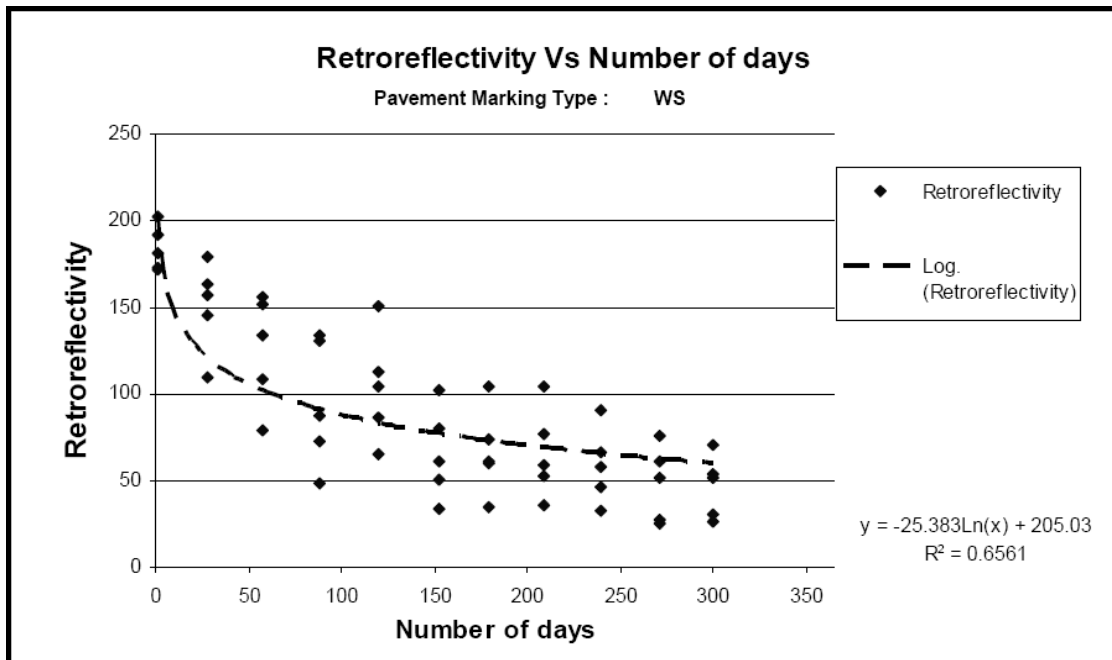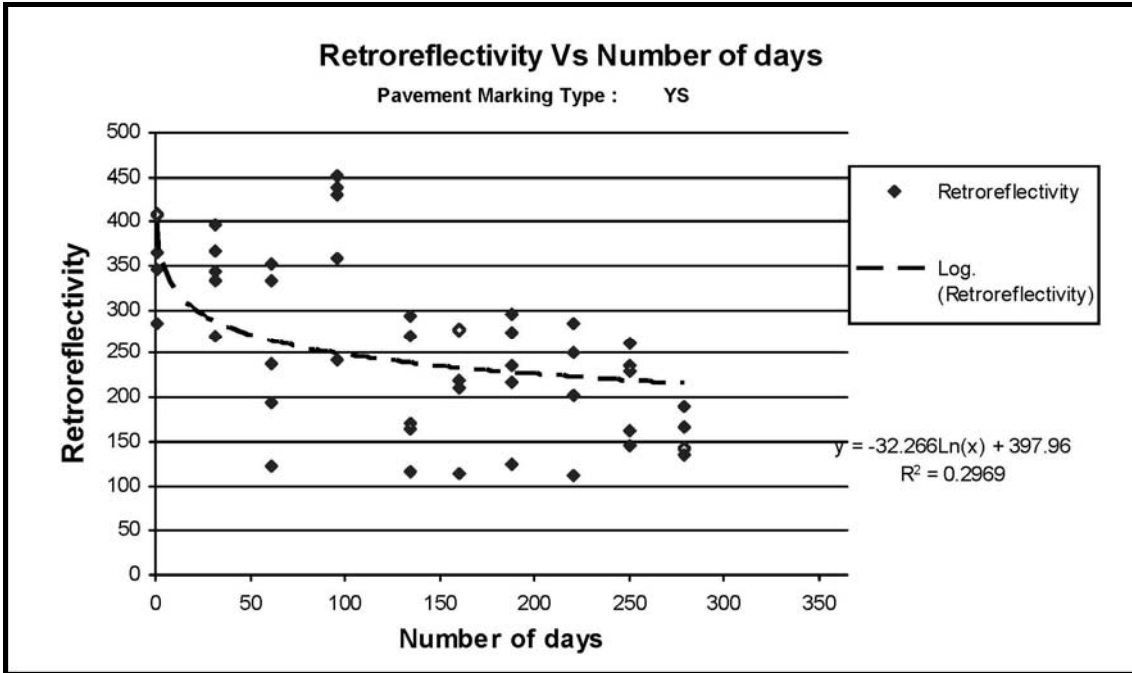
Figure 85. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Value and Number of Days
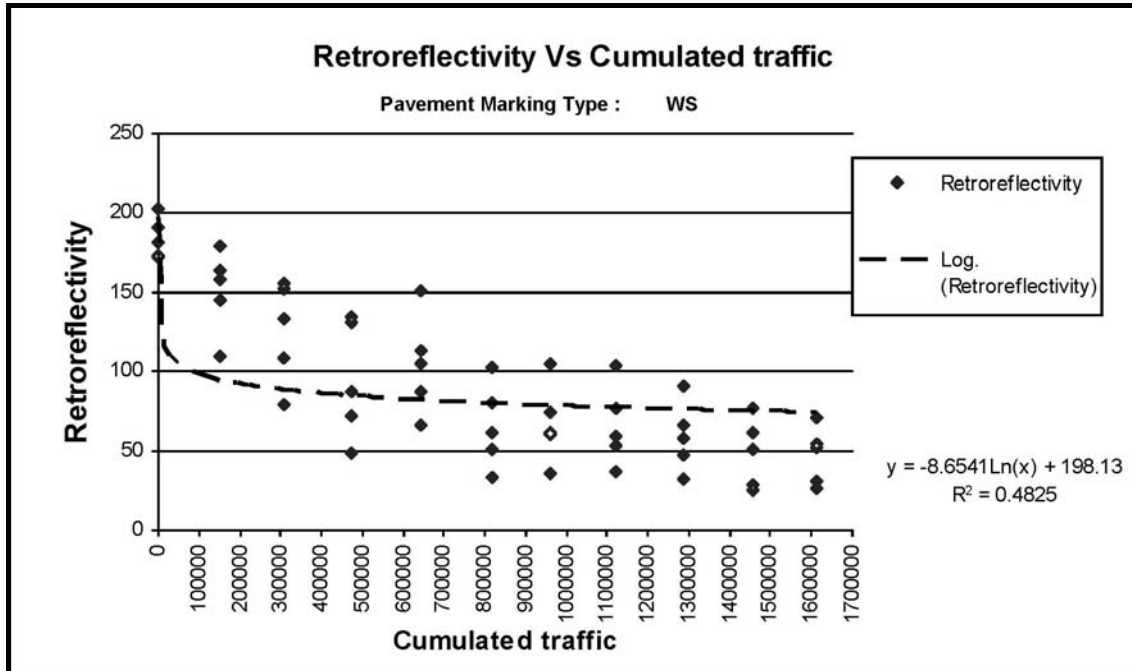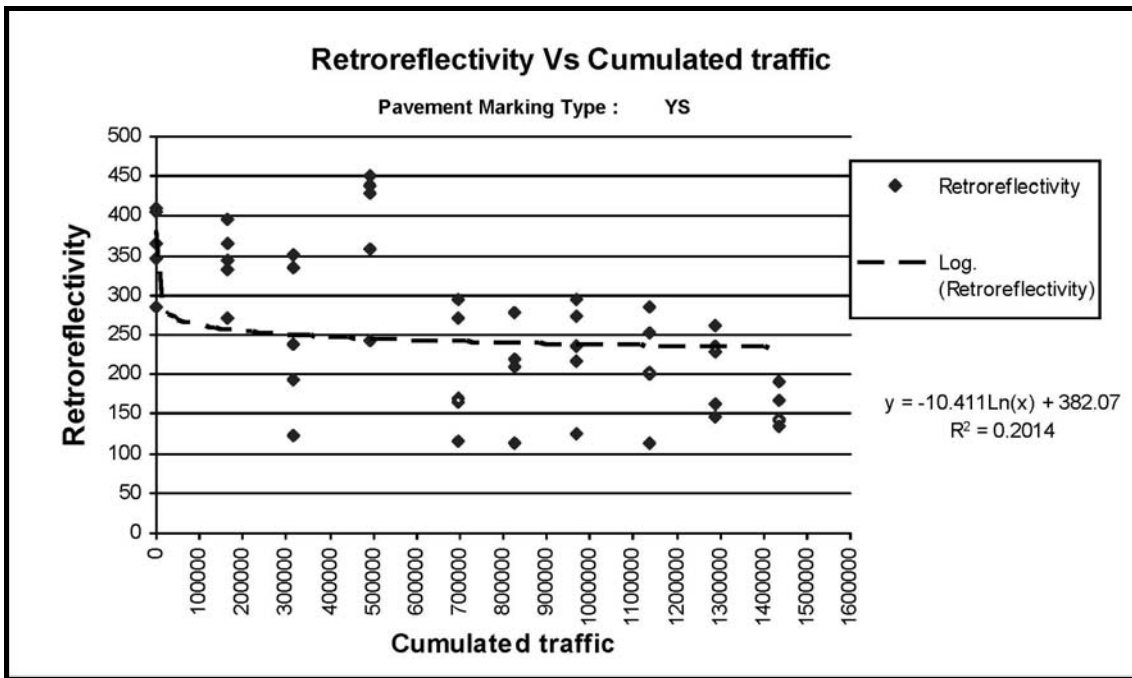

Figure 86. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Value and Cumulated Traffic per Lane
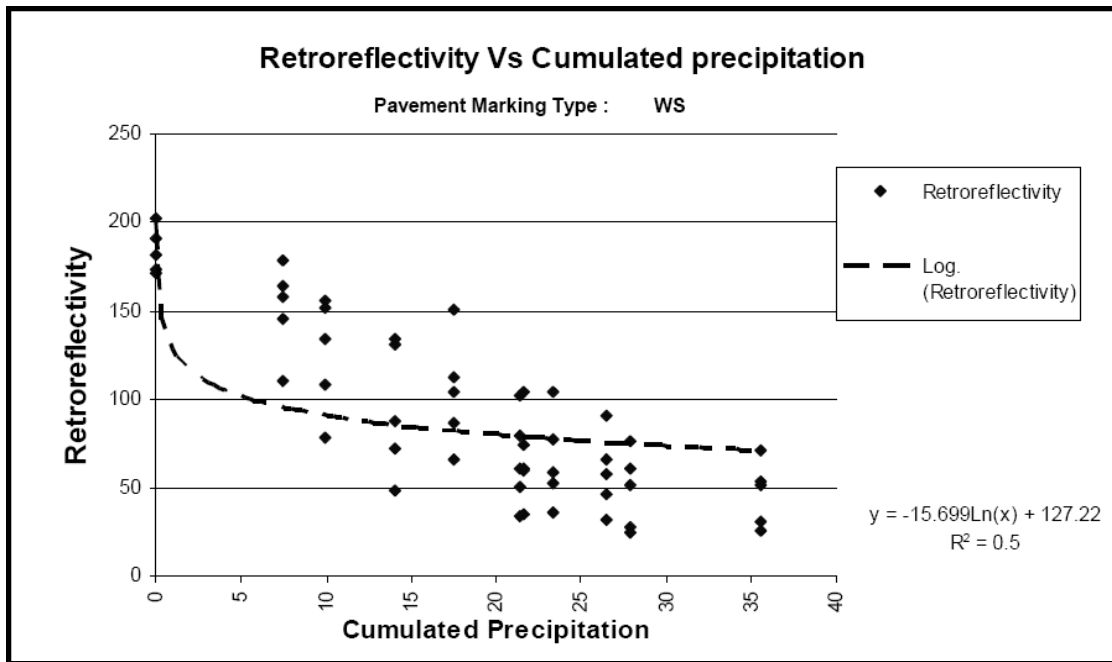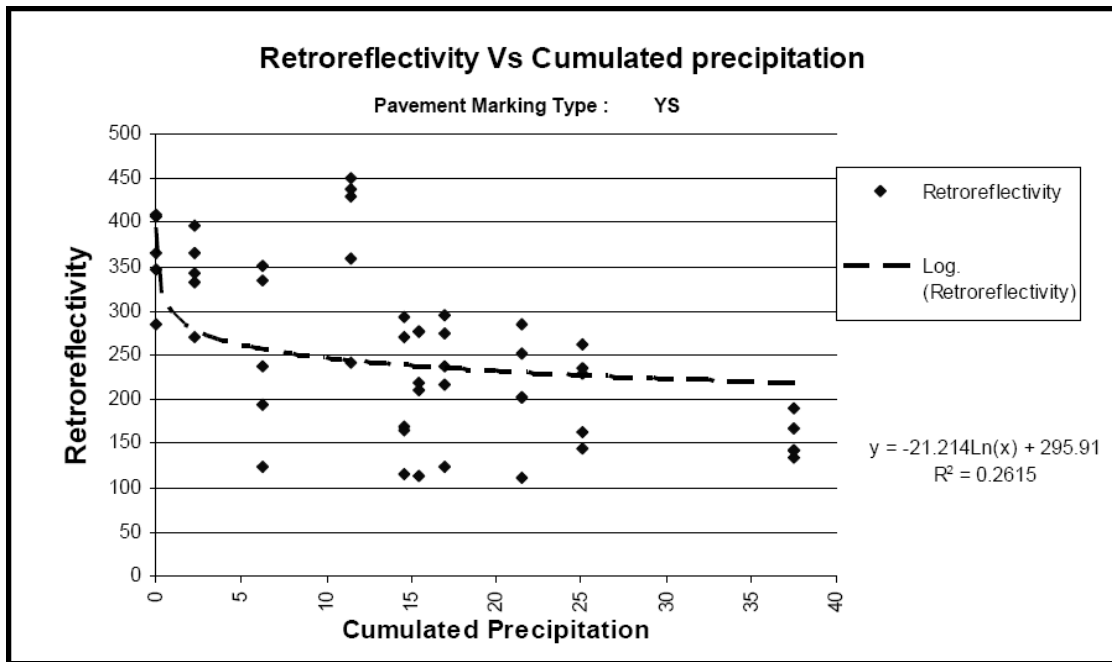
Figure 87. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Value and Cumulated Precipitation
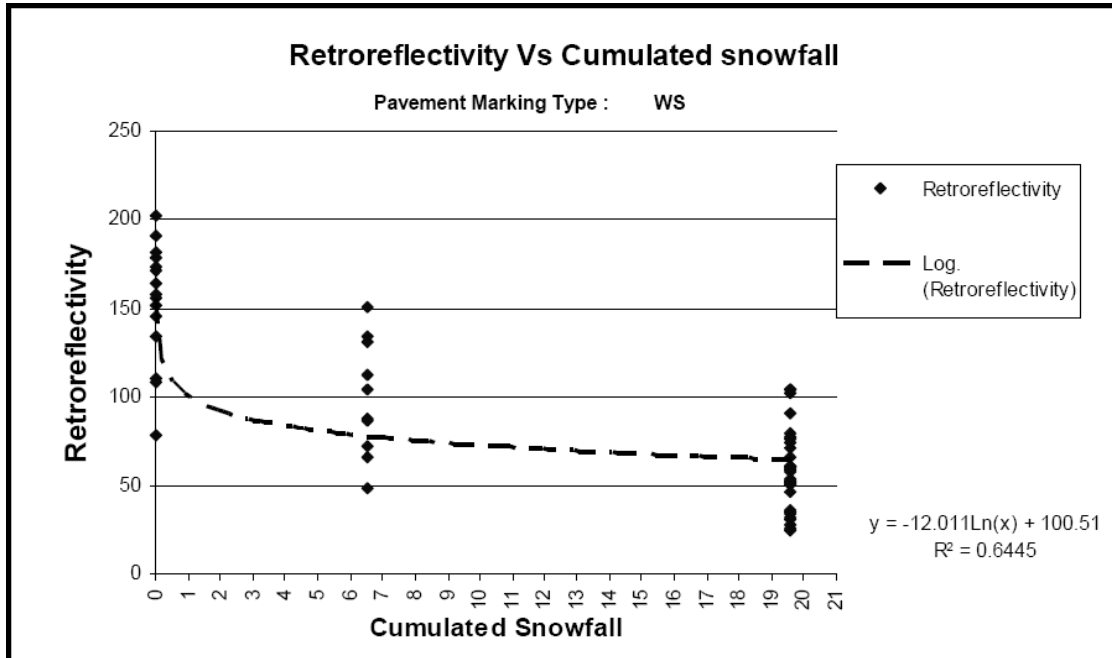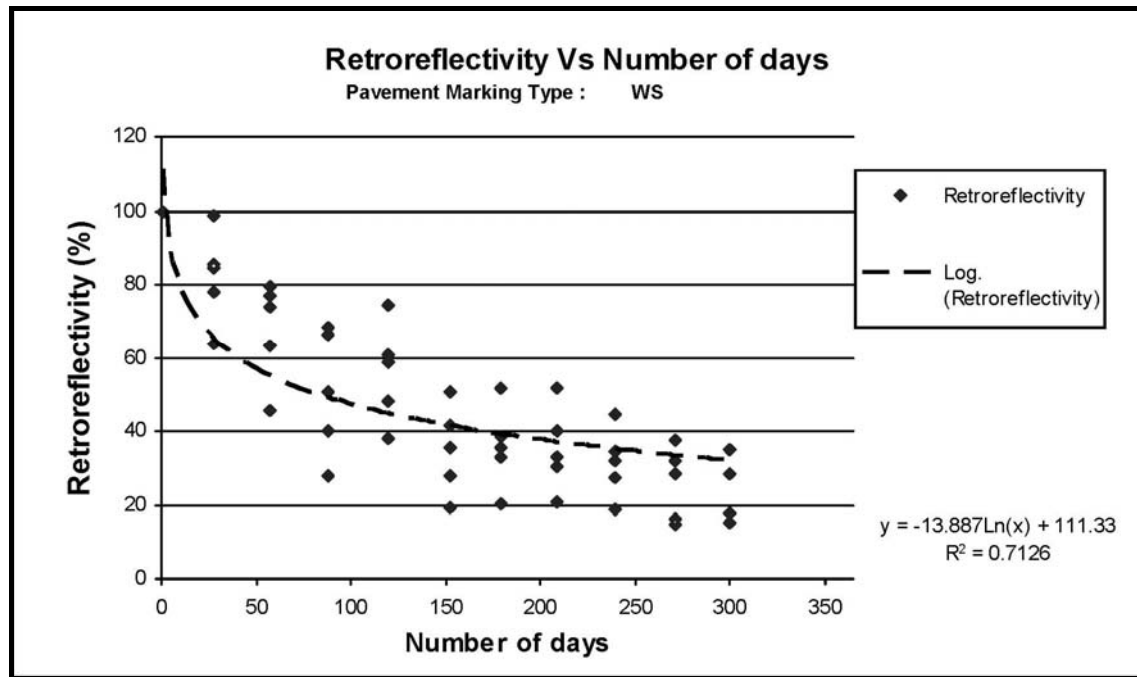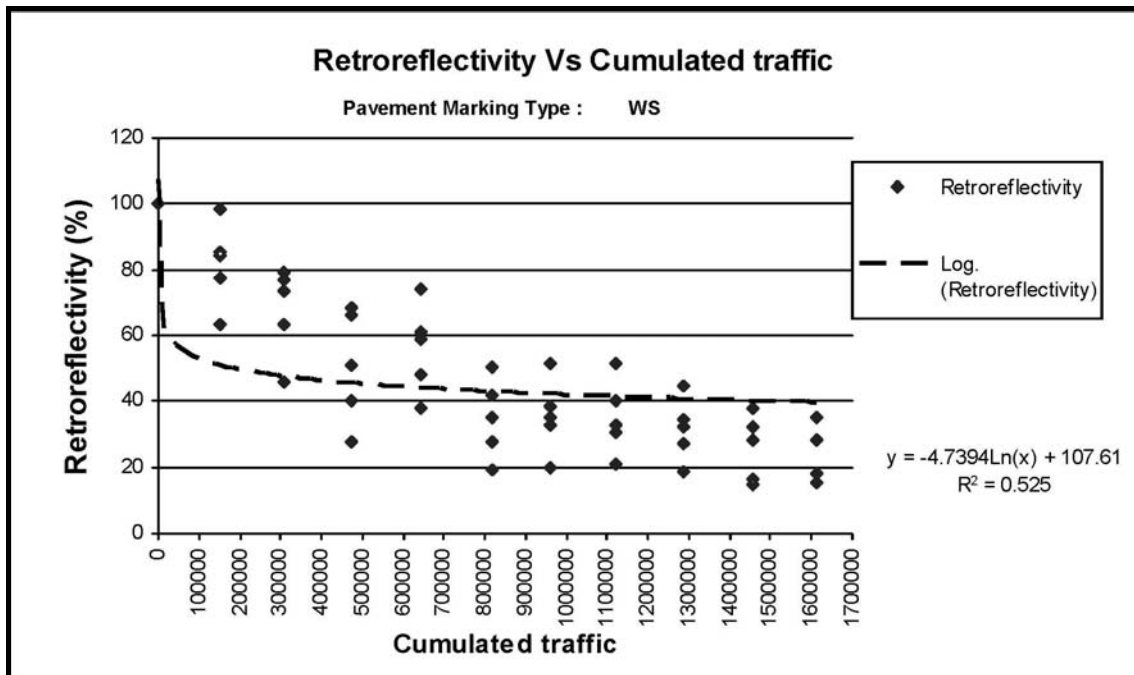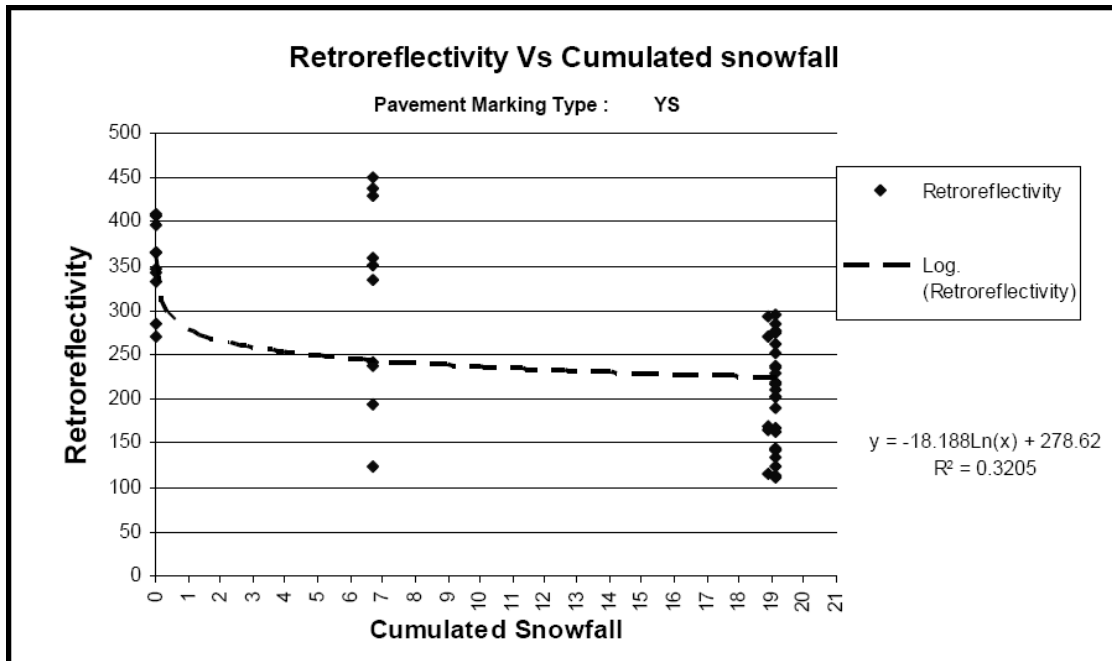

Figure 88. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Value and Cumulated Snowfall

Table 16. Regression Equations and R Square Values of Retroreflectivity Value Analysis of Yellow Skip Pavement Markings (YS)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -32.266 Ln (x) + 397.96	0.2969	2
Cumulated Traffic	y = -10.411 Ln (x) + 382.07	0.2014	4
Cumulated Precipitation	y = -21.214 Ln (x) + 295.91	0.2615	3
Cumulated Snowfall	y = -18.188 Ln (x) + 278.62	0.3205	1

VI.2.5.2 Relationship between Retroreflectivity Percentage and Other Inputs

For Yellow Skip pavement marking, the regression analysis was conducted with retroreflectivity percentages and inputs (see Figures 89-92). The general shapes of relationships are very similar to the analysis with retroreflectivity value.
As shown in Table 17, a relationship with retroreflectivity percentages was weaker than those with retroreflectivity values.
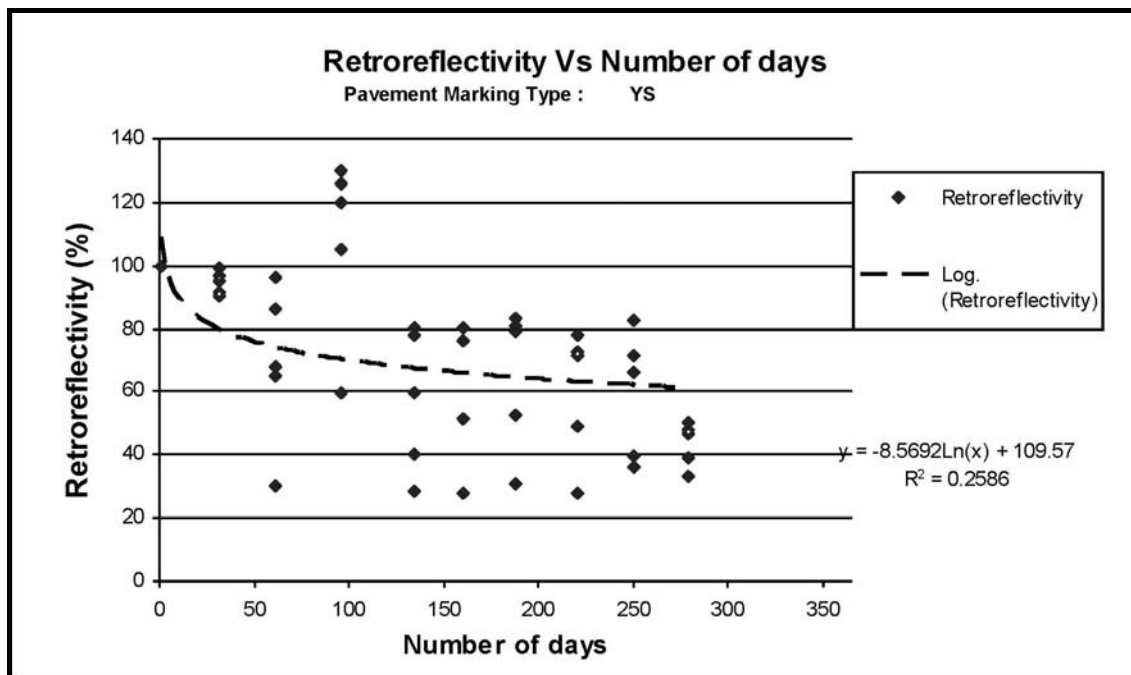
Figure 89. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Percentage and Number of Days
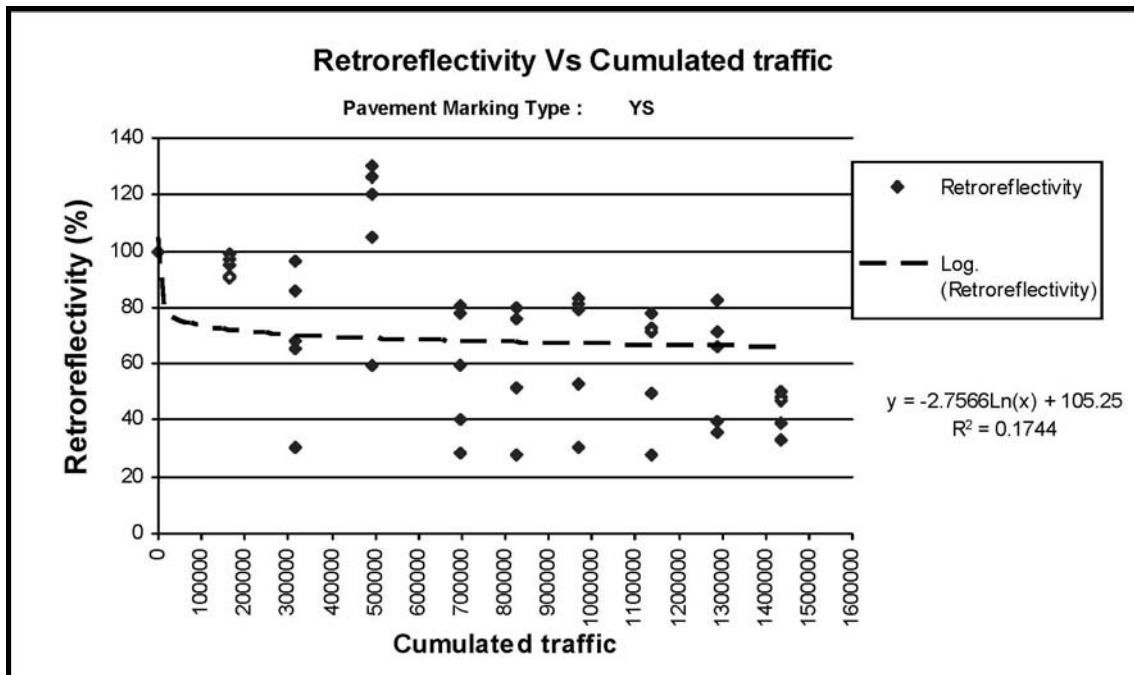
Figure 90. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Percentage and Cumulated traffic per Lane
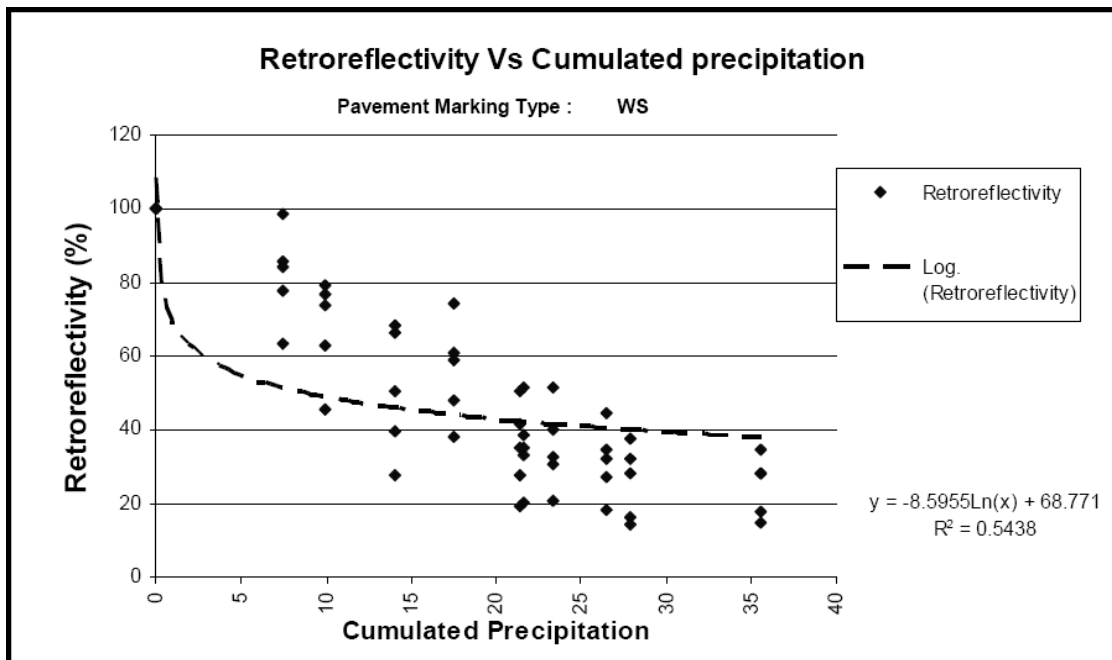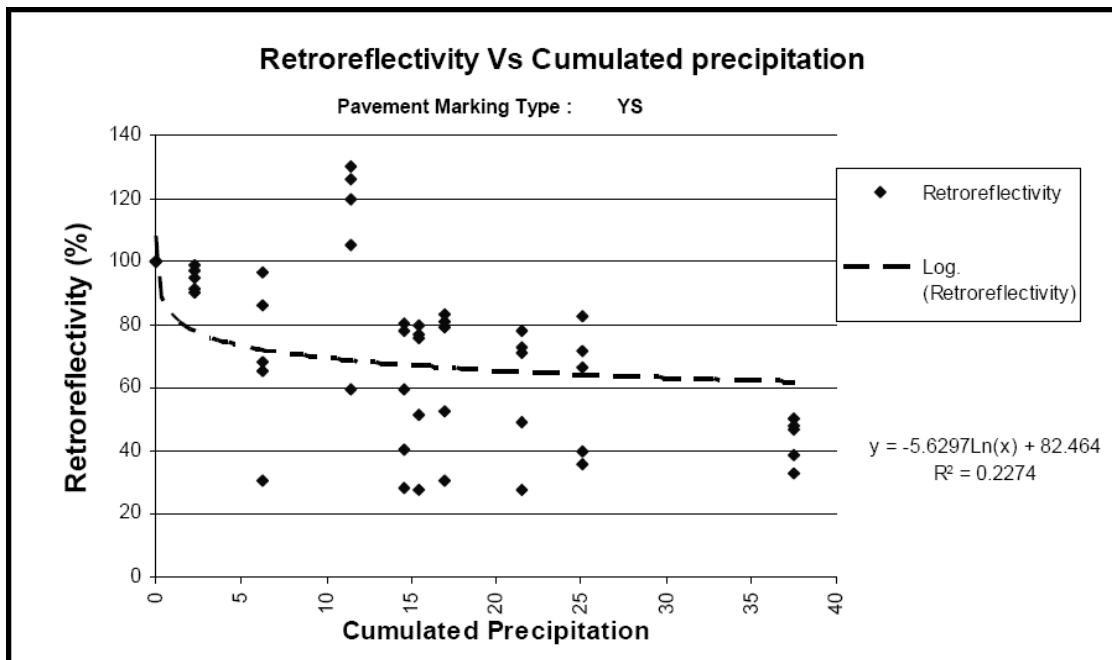

Figure 91. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Percentage and Cumulated Precipitation
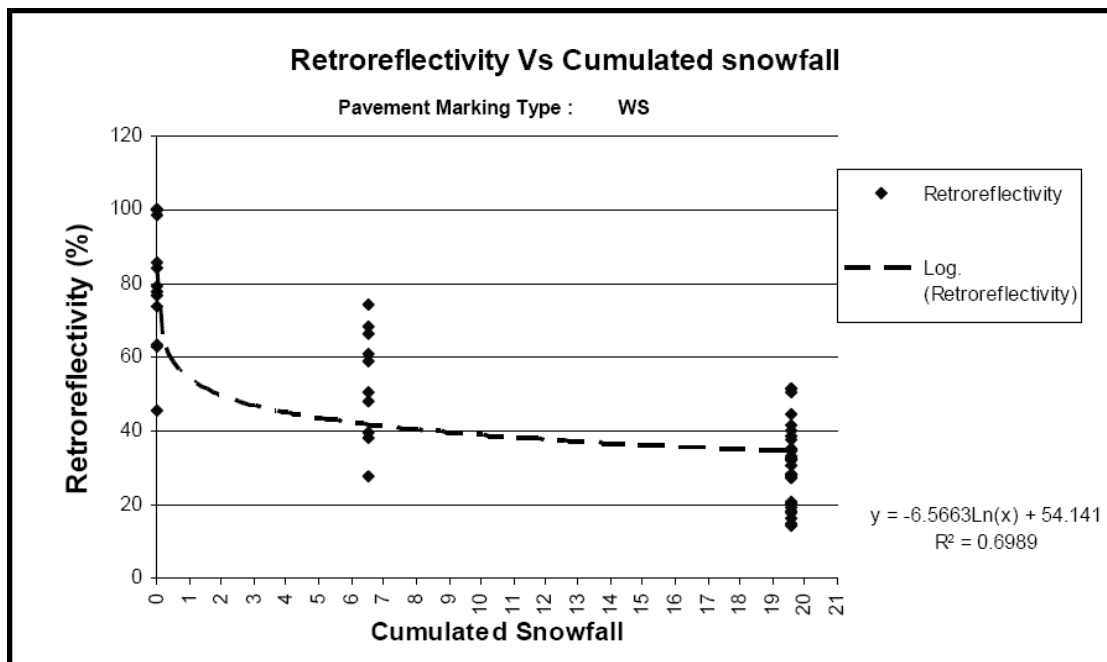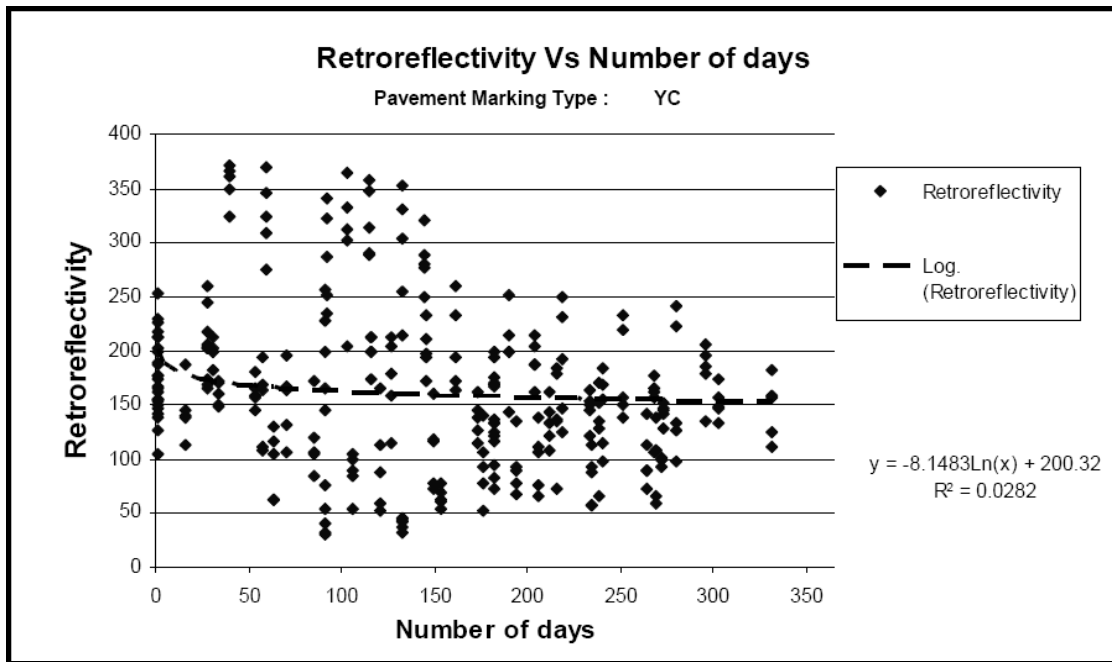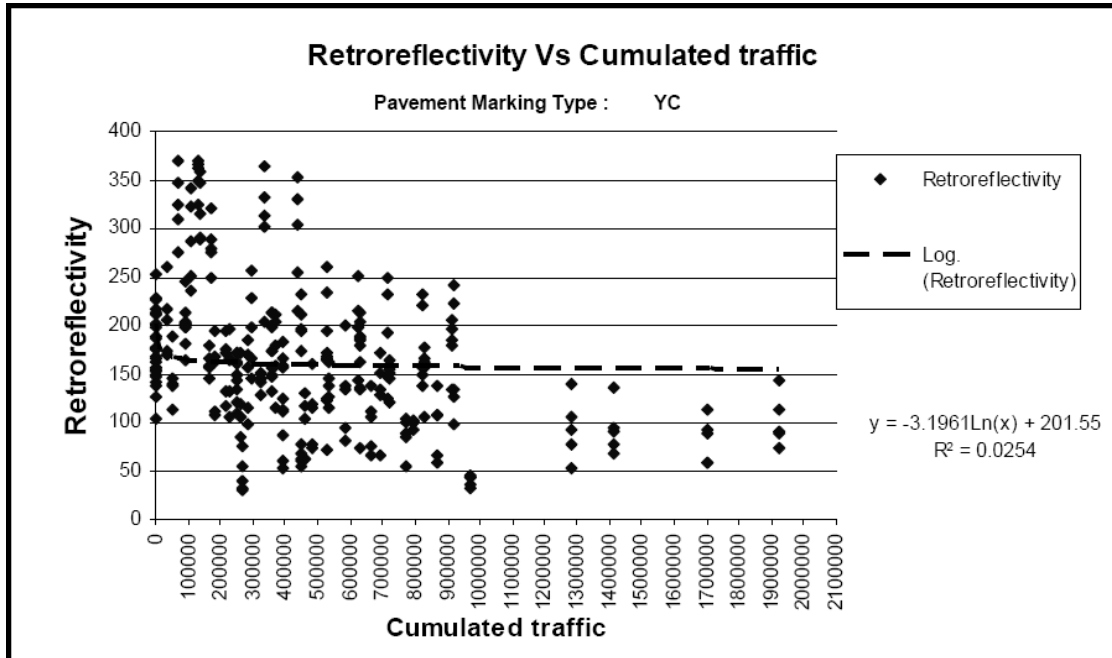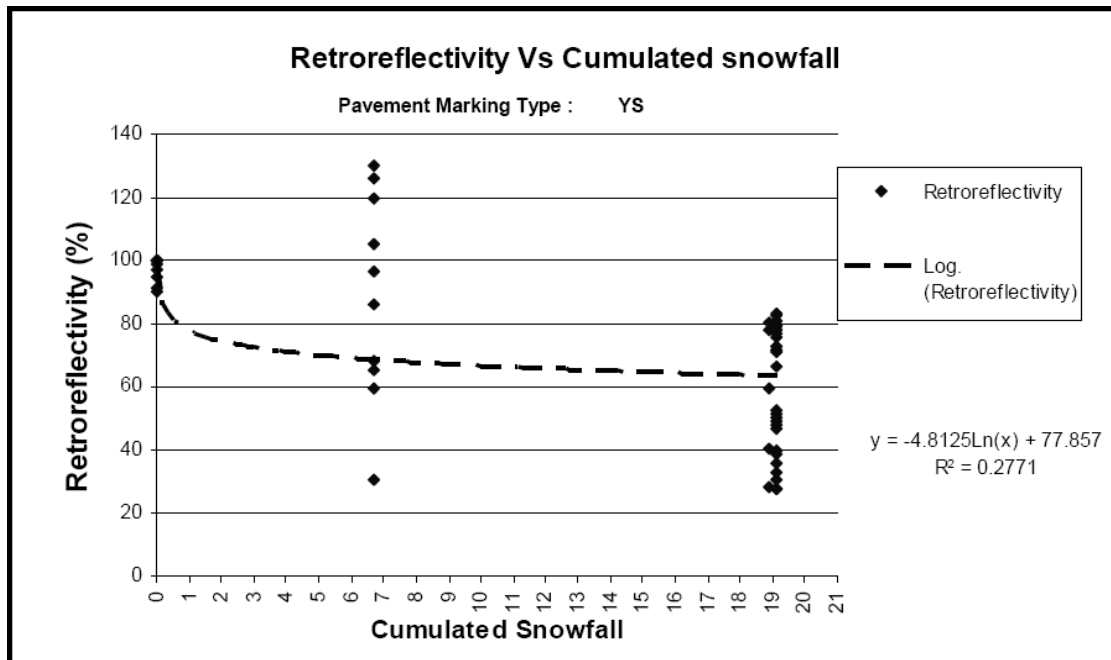
Figure 92. Regression Analysis of Yellow Skip Pavement Markings (YS) with Retroreflectivity Percentage and Cumulated Snowfall

Table 17. Regression Equations and R Square Values of Retroreflectivity Percentage Analysis of Yellow Skip Pavement Markings (YS)

Variable	Regression equation	R^2	Ranking
Number of Days	y = -8.5692 Ln (x) + 109.57	0.2586	2
Cumulated Traffic	y = -2.7566 Ln (x) + 105.25	0.1744	4
Cumulated Precipitation	y = -5.6297 Ln (x) + 082.46	0.2274	3
Cumulated Snowfall	y = -4.8125 Ln (x) + 77.857	0.2771	1

VII. MULTIVARIABLE REGRESSION ANALYSIS

In Chapters V and VI, the retroreflectivity analysis by location and pavement marking types, as well as for overall aggregated data, were done with single variable regression analysis. As shown in those chapters, the correlation between retroreflectivity and inputs by location was generally strong. However, that is because each site has similar conditions in terms of traffic volume and weather condition. That status is also applied to the analysis for each pavement marking with less number of locations and because of the amount of data used. If the number of analyzed data is smaller, the tendency is for the correlation to be stronger.

However, the correlations for the pavement marking types with many locations and analysis with overall aggregate data were not very strong with single variable regression analysis. Although all inputs show the downward relationship with retroreflectivity, only the Number of Days Exposed and Cumulated Snowfall shows reasonable correlation with retroreflectivity. So, in this chapter, multivariable regression analysis was conducted using the results of previous single variable regression analysis. The four kinds of two variable regression analysis were broken into combinations of two weather related inputs (Cumulated Precipitation and Cumulated Snowfall) and two other inputs (Number of Days Exposed and Cumulated Traffic per Lane) are conducted, as well as multivariable regression with all four inputs.

Multivariable regression analysis in this chapter was done in two ways, linear and natural logarithm. Although logarithm is also considered as a linear function in regression analysis, it was used as a natural logarithm regression analysis. Figures 93-97 and Table 18 show the process of multivariable regression analysis. Overall *R square* values in these multivariable analyses become higher than those in single variable regression analyses. As illustrated in Table 18, the *R square* value was highest when all four inputs and Number of Days and Cumulated Snowfall — the two most important inputs from the single variable regression analysis — were used. The *R Square* value was the second highest input.

It was revealed that when all four inputs are used for regression analysis, the coefficient for Cumulated Traffic is zero. The zero coefficient for Cumulated Traffic means that the amount of traffic did not play a major role in estimating retroreflectivity of the pavement markings. However, the Number of Days Exposed includes the Cumulated Traffic Exposed as a component.

Figure 93. Multivariable Linear Regression Analysis with Number of Days Exposed and Cumulated Precipitation

Figure 94. Multivariable Linear Regression Analysis with Number of Days Exposed and Cumulated Snowfall

Figure 95 panel

Equation Parameters

R Square	0.1291
Adjusted R Square	0.1251
Standard Error	75.5432
F - Statistic	32.7502

12.91% of the change in Dependent can be explained by the change in the 2 Independent Variables
Adjusted for Sample Size bias
to +/- on result of Regression Equation
Therefore analysis IS Significant

1.21483	Durbin-Watson Statistic	Critical D-W Values: Lower (Dl)=1.63; Upper (Du)=1.72
	Therefore Positive Autocorrelation detected at 95% Confidence	
3.01604	Critical F-Statistic at 95% Confidence	(Significance holds to 99.9% Level of Confidence)

Multiple Regression Equation

	Coefficients	Standard Error
Intercept	178.604	6.777
Cum_traffic	0.000	0.000
Cum_precipitation	-1.481	0.542

Independent Analysis

R Squared	Gradient	Intercept
11.44%	0.00	171.37
11.17%	-2.69	174.54

Auto Correlation (Dl=1.65, Du=1.69, DW-Stat)

0.36	
0.38	

Tests for Multicolinearity between Independent Variables — Independent R-Square Matrix

100%	57%	Cum_traffic
57%	100%	Cum_precipitation

Dependent = $0.00 \cdot Cum\_traffic + -1.48 \cdot Cum\_precipitation + 178.60$ (+/- 75.54)

Actual versus Predicted Dependent

$y = 0.062x + 130.23$
$R^2 = 0.0137$

Step 2 - Forecasting — Trend R-Squared Matrix

Independent Variable	3rd Ord Polynomial	2nd Ord Polynomia	Exponential	Linear	Choose Method
Cum_traffic	2%	2%	####	2%	Exponential
Cum_precipitation	1%	1%	####	0%	Exponential
					Exponential
					Exponential

Number of Periods to Forecast: 10

Figure 95. Multivariable Linear Regression Analysis with Cumulative Traffic Exposed and Cumulated Precipitation

---

Figure 96 panel

Equation Parameters

R Square	0.1566
Adjusted R Square	0.1528
Standard Error	74.3404
F - Statistic	41.0276

15.66% of the change in Dependent can be explained by the change in the 2 Independent Variables
Adjusted for Sample Size bias
to +/- on result of Regression Equation
Therefore analysis IS Significant

1.44456	Durbin-Watson Statistic	Critical D-W Values: Lower (Dl)=1.63; Upper (Du)=1.72
	Therefore Positive Autocorrelation detected at 95% Confidence	
3.01604	Critical F-Statistic at 95% Confidence	(Significance holds to 100.0% Level of Confidence)

Multiple Regression Equation

	Coefficients	Standard Error
Intercept	173.635	6.157
Cum_traffic	0.000	0.000
cum_snowfall	-2.585	0.550

Independent Analysis

R Squared	Gradient	Intercept
11.44%	0.00	171.37
14.35%	-3.55	164.70

Auto Correlation (Dl=1.65, Du=1.69, DW-Stat)

0.36	
0.35	

Tests for Multicolinearity between Independent Variables — Independent R-Square Matrix

100%	45%	Cum_traffic
45%	100%	cum_snowfall

Dependent = $0.00 \cdot Cum\_traffic + -2.59 \cdot cum\_snowfall + 173.63$ (+/- 74.34)

Actual versus Predicted Dependent

$y = 0.1963x + 107.99$
$R^2 = 0.1312$

Step 2 - Forecasting — Trend R-Squared Matrix

Independent Variable	3rd Ord Polynomial	2nd Ord Polynomia	Exponential	Linear	Choose Method
Cum_traffic	2%	2%	####	2%	Exponential
cum_snowfall	2%	2%	####	17%	Exponential
					Exponential
					Exponential

Number of Periods to Forecast: 10

Figure 96. Multivariable Linear Regression Analysis with Cumulative Traffic Exposed and Cumulated Snow

Figure 97. Multivariable Linear Regression Analysis with All Four Inputs

Table 18. Multivariable Linear Regression Equations, R Square Values, Adjusted R Square Values, and Their Rankings

Variables	Regression equation	R^2	Adjusted R^2	Ranking
Number of Days & Cumulated Precipitation	y = -0.28 (ND) – 0.54 (CP) + 183.18	0.1341	0.1302	4
Number of Days & Cumulated Snow	y = -0.22 (ND) – 2.49 (CS) + 188.11	0.1880	0.1843	2
Cumulated Traffic & Cumulated Precipitation	y = -0 (CT) – 1.48 (CP) + 178.60	0.1291	0.1251	5
Cumulated Traffic & Cumulated Snow	y = -0 (CT) – 2.59 (CS) + 173.63	0.1566	0.1528	3
All Inputs	y = -0.18 (ND) – 1.32 (CP) + 0 (CT) – 3.16 (CS) + 189.68	0.1977	0.1904	1

The multivariable regression analysis assuming natural logarithm function was also done by using the same method used with linear function. As shown in Figures 98-102 and Table 19, the logarithm regression analysis was better than those by the linear regression analysis. However, the rankings of correlation with retroreflectivity and inputs for logarithm are the same as those with linear regression analysis. Again, regression using all inputs has the best correlation with retroreflectivity. Number of

Days Exposed and the Cumulated Snowfall is the second best for this logarithm regression analysis.

Notably, unlike other inputs which act negatively for retroreflectivity, Cumulated Traffic Exposed works positively for retroreflectivity, which can not be true. However, from the linear regression analysis, which has no impact from Cumulated Traffic, and from this positive impact by the Cumulated Traffic for the logarithm regression analysis, it can be assumed that the impact by the Cumulated Traffic Exposed is minimal if there is Number of Days Exposed input in the analysis. For these reasons, it can be inferred that logarithm multi regression analysis with the Number of Days Exposed and Cumulated Snowfall is the best choice to estimate the retroreflectivity of the waterborne paint pavement markings.
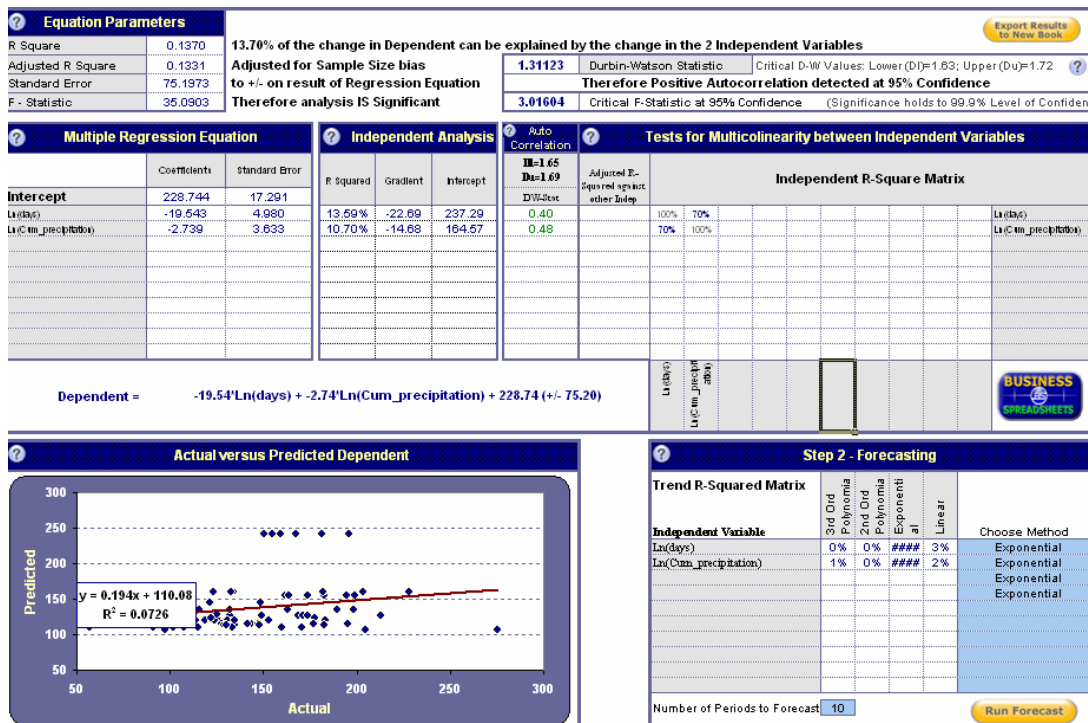
Figure 98. Multivariable Logarithm Regression Analysis with Number of Days Exposed and Cumulated Precipitation

Figure 99. Multivariable Logarithm Regression Analysis with Number of Days Exposed and Cumulated Snow

Figure 100. Multivariable Logarithm Regression Analysis with Cumulated Traffic Exposed and Cumulated Precipitation

Equation Parameters

R Square	0.1849	18.49% of the change in Dependent can be explained by the change in the 2 Independent Variables
Adjusted R Square	0.1812	Adjusted for Sample Size bias
Standard Error	73.0828	to +/- on result of Regression Equation
F - Statistic	50.1230	Therefore analysis IS Significant

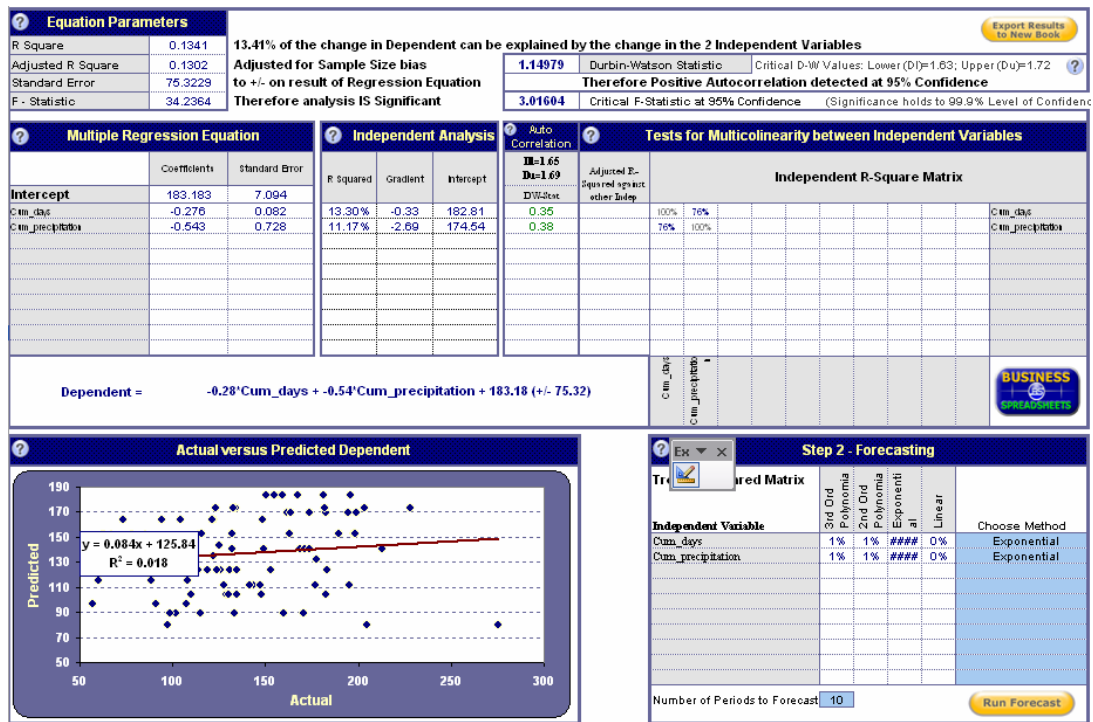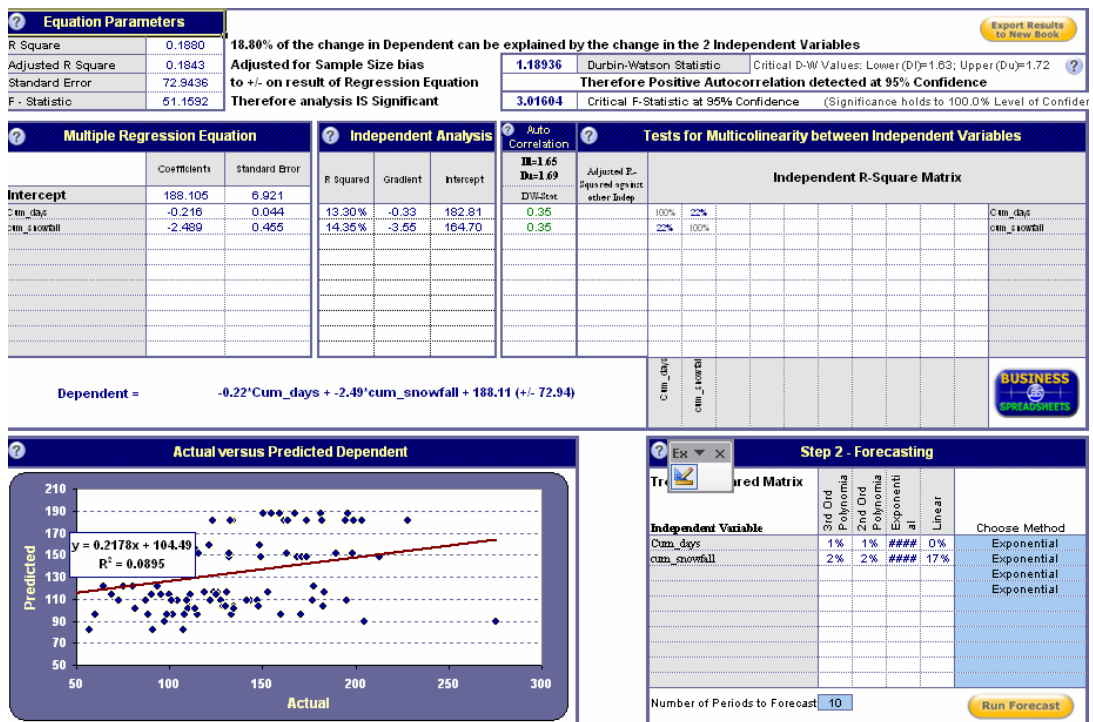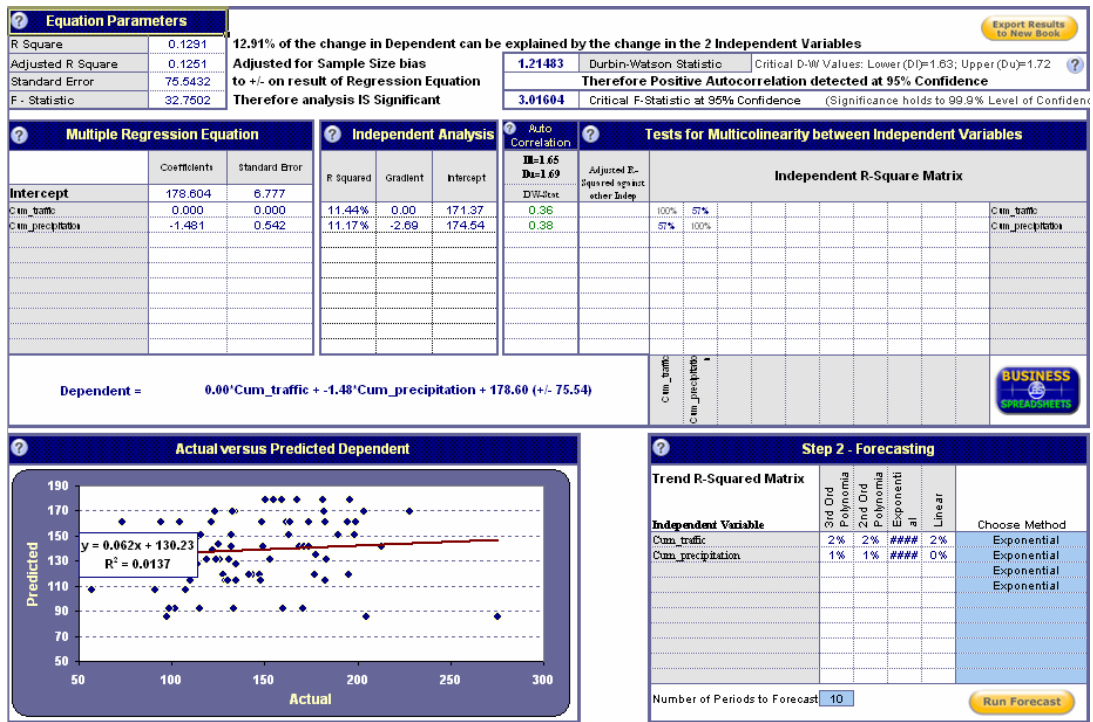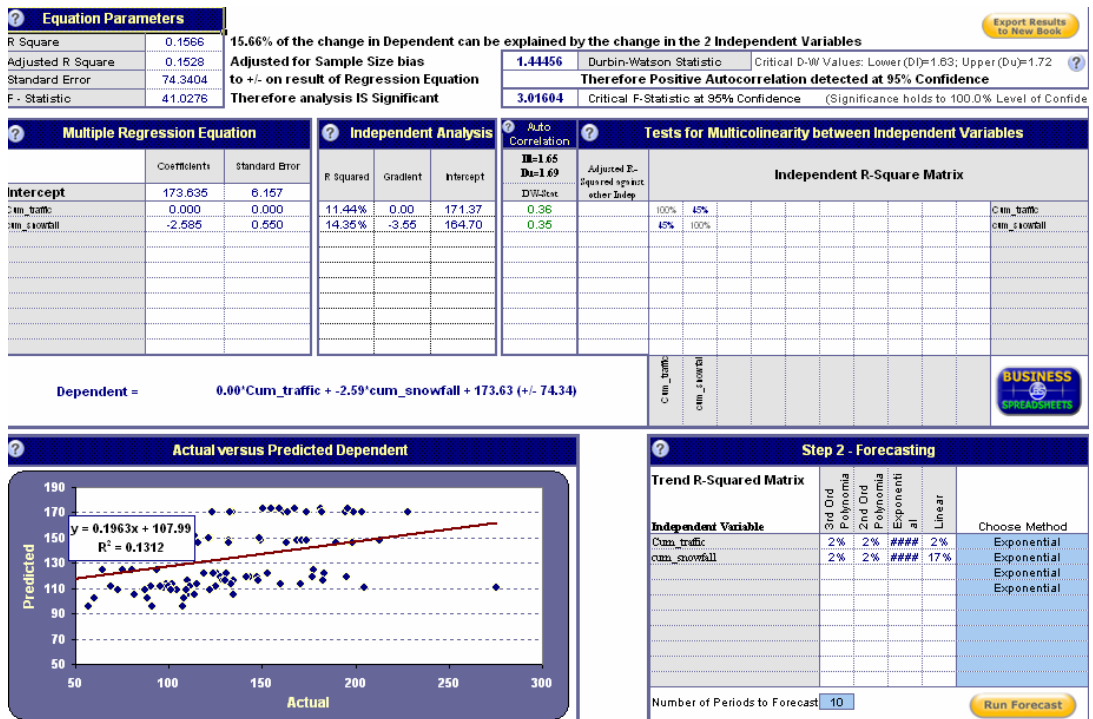|		
1.35772	Durbin-Watson Statistic	Critical D-W Values: Lower (Dl)=1.63; Upper (Du)=1.72
	Therefore Positive Autocorrelation detected at 95% Confidence	
3.01604	Critical F-Statistic at 95% Confidence	(Significance holds to 100.0% Level of Confide

Multiple Regression Equation / **Independent Analysis** / Auto Correlation / **Tests for Multicolinearity between Independent Variables**

	Coefficients	Standard Error	R Squared	Gradient	Intercept	Dl=1.65 Du=1.69 DW-Stat	Adjusted R-Squared against other Indep	Independent R-Square Matrix			
Intercept	179.819	16.178									
Ln(Cum_traffic)	-3.831	1.288	9.27%	-8.07	231.68	0.49		100%	22%		Ln(Cum_traffic)
Ln(cum_snowfall)	-8.302	1.174	16.85%	-9.93	132.80	0.34		22%	100%		Ln(cum_snowfall)

Dependent = -3.83'Ln(Cum_traffic) + -8.30'Ln(cum_snowfall) + 179.82 (+/- 73.08)

Actual versus Predicted Dependent

y = 0.2687x + 88.291
$R^2 = 0.1469$

Step 2 - Forecasting

Trend R-Squared Matrix

Independent Variable	3rd Ord Polynomial	2nd Ord Polynomial	Exponential	Linear	Choose Method
Ln(Cum_traffic)	0%	0%	####	5%	Exponential
Ln(cum_snowfall)	6%	6%	####	11%	Exponential
					Exponential
					Exponential

Number of Periods to Forecast 10   Run Forecast

Figure 101. Multivariable Logarithm Regression Analysis with Cumulated Traffic Exposed and Cumulated Snowfall

---

Equation Parameters

R Square	0.2324	23.24% of the change in Dependent can be explained by the change in the 4 Independent Variables
Adjusted R Square	0.2254	Adjusted for Sample Size bias
Standard Error	71.0804	to +/- on result of Regression Equation
F - Statistic	33.3072	Therefore analysis IS Significant

1.12532	Durbin-Watson Statistic	Critical D-W Values: Lower (Dl)=1.59; Upper (Du)=1.76
	Therefore Positive Autocorrelation detected at 95% Confidence	
2.39203	Critical F-Statistic at 95% Confidence	(Significance holds to 100.0% Level of Confide

Multiple Regression Equation / **Independent Analysis** / Auto Correlation / **Tests for Multicolinearity between Independent Variables**

	Coefficients	Standard Error	R Squared	Gradient	Intercept	Dl=1.65 Du=1.69 DW-Stat	Adjusted R-Squared against other Indep	Independent R-Square Matrix				
Intercept	156.229	19.747										
Ln(days)	-33.031	7.896	13.59%	-22.69	237.29	0.40	99.02%	100%	70%	87%	21%	Ln(days)
Ln(Cum_precipitation)	-4.249	3.463	10.70%	-14.68	164.57	0.48	99.57%	70%	100%	65%	15%	Ln(Cum_precipitation)
Ln(Cum_traffic)	11.264	3.163	9.27%	-8.07	231.68	0.49	98.97%	87%	65%	100%	22%	Ln(Cum_traffic)
Ln(cum_snowfall)	-7.826	1.146	16.85%	-9.93	132.80	0.34	93.65%	21%	15%	22%	100%	Ln(cum_snowfall)

Dependent = -33.03'Ln(days) + -4.25'Ln(Cum_precipitation) + 11.26'Ln(Cum_traffic) + -7.83'Ln(cum_snowfall) + 156.23 (+/- 71.08)

Actual versus Predicted Dependent

y = 0.3025x + 84.229
$R^2 = 0.125$

Step 2 - Forecasting

Trend R-Squared Matrix

Independent Variable	3rd Ord Polynomial	2nd Ord Polynomial	Exponential	Linear	Choose Method
Ln(days)	0%	0%	####	3%	Exponential
Ln(Cum_precipitation)	1%	0%	####	2%	Exponential
Ln(Cum_traffic)	0%	0%	####	5%	Exponential
Ln(cum_snowfall)	6%	6%	####	11%	Exponential

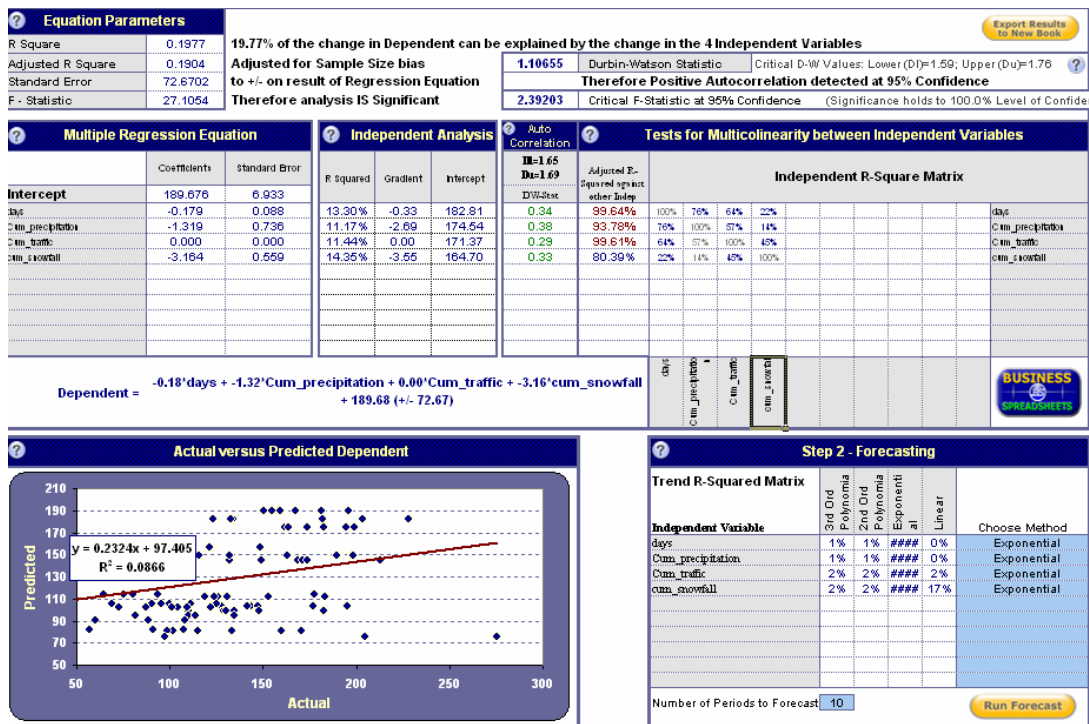Number of Periods to Forecast 10   Run Forecast

Figure 102. Multivariable Logarithm Regression Analysis with All Four Inputs

Table 19. Multivariable Logarithm Regression Equations, R Square Values, Adjusted R Square Values, and Their Rankings

Variables	Regression equation	R^2	Adjusted R^2	Ranking
Number of Days & Cumulated Precipitation	y = -19.54 Ln(ND) – 2.74 Ln(CP) + 228.74	0.1370	0.1331	4
Number of Days & Cumulated Snow	y = -14.00 Ln(ND) – 7.39 Ln(CS) + 197.41	0.2093	0.2057	2
Cumulated Traffic & Cumulated Precipitation	y = -3.07 Ln(CT) – 10.49 Ln(CP)+193.08	0.1116	0.1076	5
Cumulated Traffic & Cumulated Snow	y = -3.83 Ln(CT) – 8.30 Ln(CS) + 179.82	0.1849	0.1812	3
All Inputs	y = -33.03 Ln(ND) – 4.25 Ln(CP) + 11.26 Ln(CT) – 7.83 Ln(CS) + 156.23	0.2324	0.2254	1

VIII. Durability and Life Cycle Analysis

In Chapter 6, single variable regression analysis was conducted, and multivariable regression analysis was done in Chapter 7. Using the estimated regression equations in this chapter, the durability and the life cycle of the waterborne paint pavement markings were analyzed. A regression equation with more variables can estimate the results better due to the nature of regression analysis, even though more variables can make the equation complicated. Because of this, multivariable logarithm regression analysis with Number of Days Exposed and Cumulated Snowfall was used to estimate the durability and life cycle of the waterborne paint pavement markings.

Although the regression analysis was conducted with all the data inclusive of data from white paint pavement markings and yellow paint pavement markings in Chapter 7, multivariable regression for white paint pavement markings and yellow paint pavement markings were conducted separately in this chapter. The life cycle analyses were pursued separately because the threshold for the white paint pavement markings and yellow paint pavement markings may be different according to the recent study (Migletz, etc 2001).
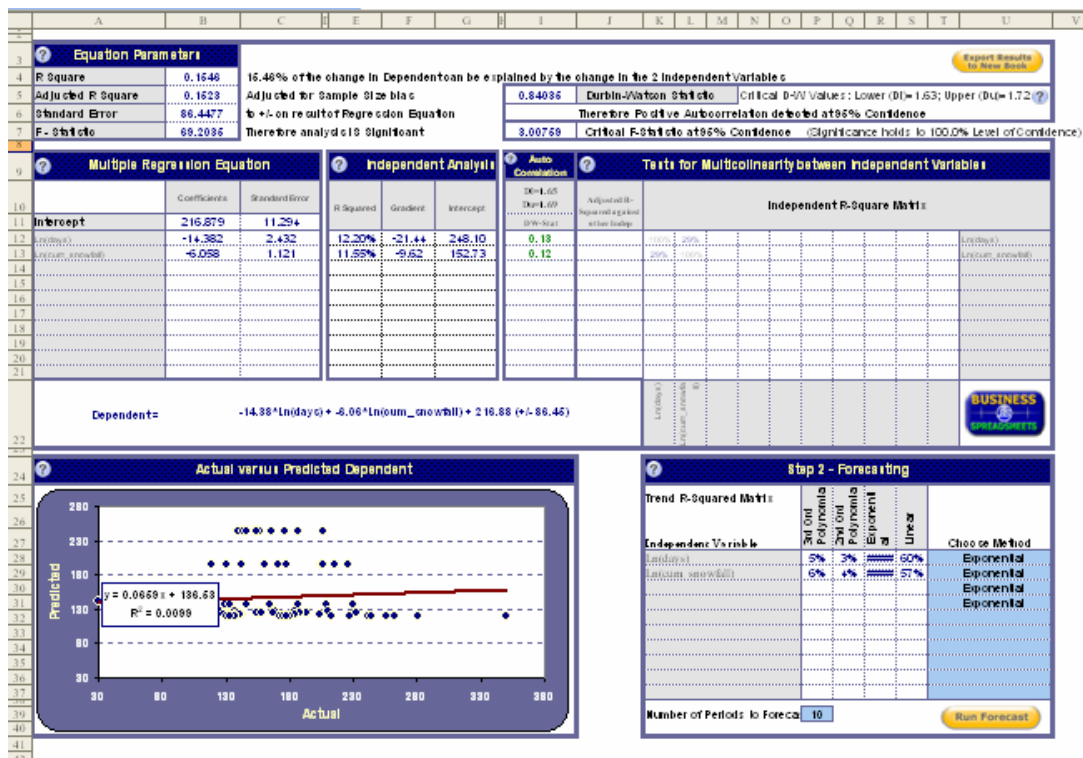
Figure 103. Multivariable Logarithm Regression Analysis with Number of Days Exposed and Cumulated Snowfall for White Paint Pavement Markings

Figure 103 shows the results of the multi variable logarithm regression analysis for white paint pavement markings using Number of Days Exposed and Cumulated

Snowfall variables. The estimated regression equation is **Y= -14.38*Ln (days) + -6.06*Ln (cum_snowfall) + 216.88.**

Figure 104 shows the results of the multi variable logarithm regression analysis for yellow paint pavement markings using Number of Days Exposed and Cumulated Snowfall as variables. The estimated regression equation is **Y = -2.93*Ln (days) + -9.19*Ln (cum_snowfall) + 183.62.**
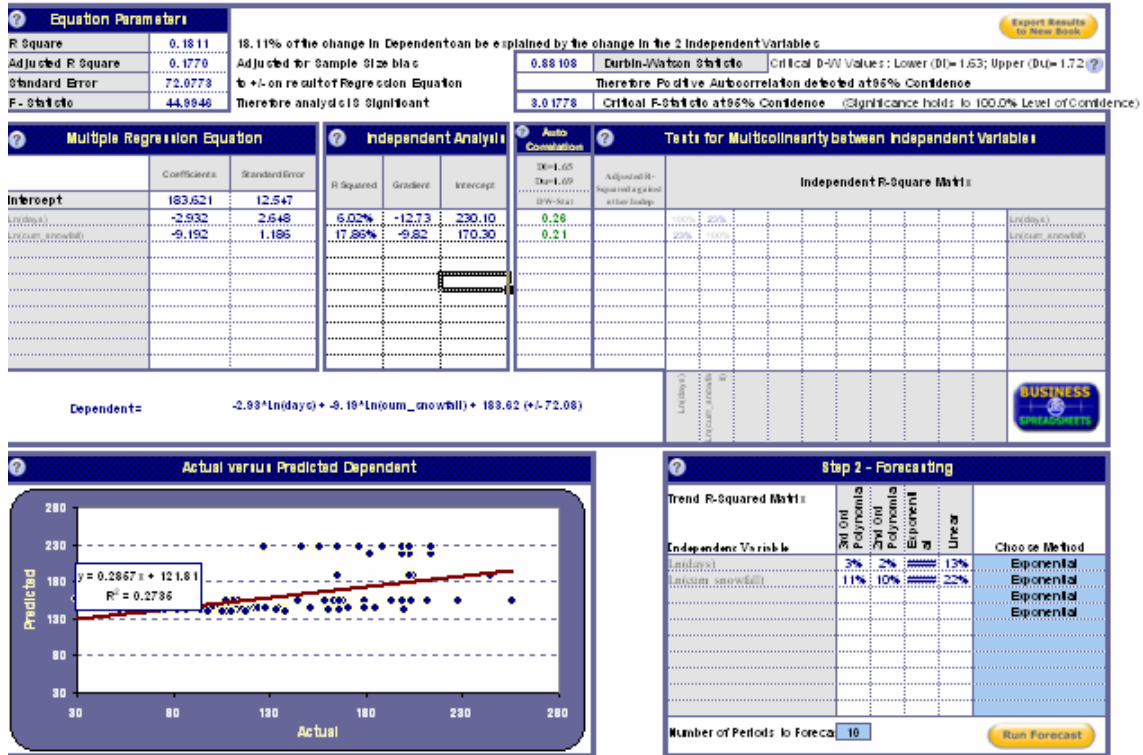
Figure 104. Multivariable Linear Regression Analysis with Number of Days Exposed and Cumulated Snowfall for White Pavement Markings

Figure 105 shows the life cycle figure for the white paint pavement markings using the estimated regression analysis Y= -14.38*Ln (days) + -6.06*Ln (cum_snowfall) + 216.88. This is based on threshold retroreflectivities in Table 3.

Threshold retroreflectivity values are the minimum retroreflectivities that determine the life of the pavement markings. As shown in Table 3, they vary depending on the speed limits of the roads. In Figure 105, there are three curves that represent the combination of Number of Days Exposed and Cumulated Snowfall to reach the threshold retroreflectivity values for three non-freeways. The speed limits of these three non-freeways are 64 km/hr (40 mph), 72 km/hr (45 mph), and 89 km/h (55 mph); and their threshold retroreflectivity values are 85, 100, and 150 mcd/m^2/lux, respectively. For example, threshold retroreflectivity value of 85 mcd/m^2/lux for non-freeway with the

speed limit of 64 km/hr can be reached with the many different combinations of Number of Days Exposed and Cumulated Snowfall as shown in the curve R-85. According to the Figure 105, a non-freeway with a 72 km/hr (45 mph) speed limit reaches the threshold retroreflectivity of 100 mcd/m^2/lux with the following combinations: 30 inches Cumulated Snowfall and about 800 days exposed; 50 inches Cumulated Snowfall and about 650 days exposed; and 70 inches of Cumulated Snowfall and about 600 days exposed.
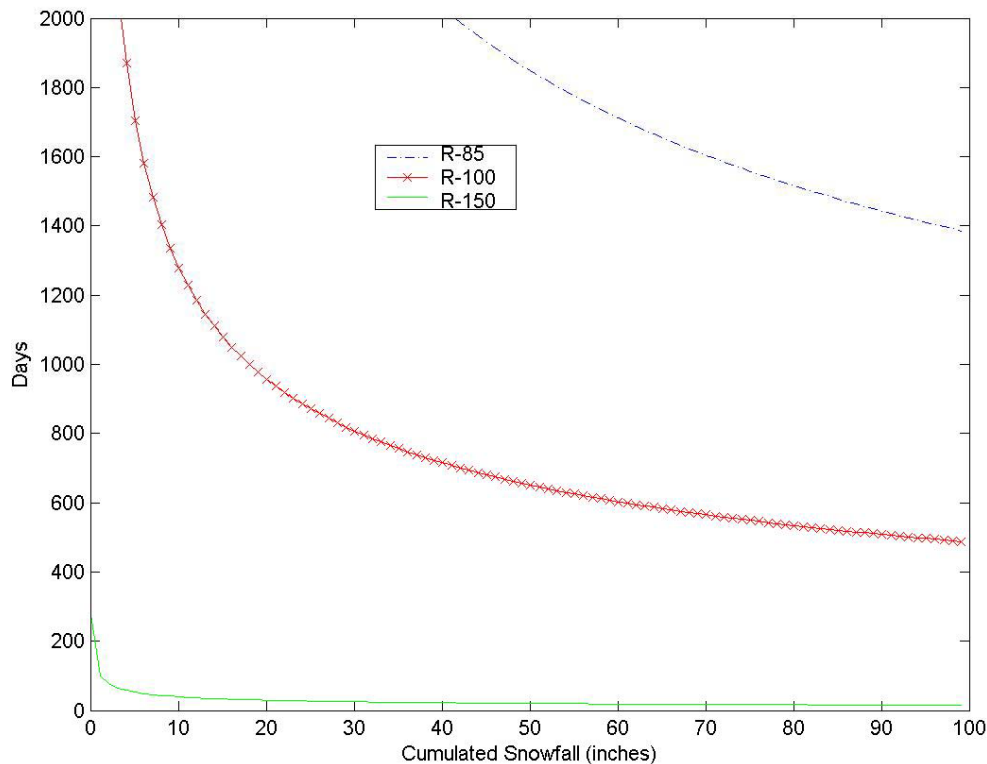
Figure 105. Estimated Life Cycle of White Waterborne Paint Pavement Markings with Different Retroreflectivity Threshold Values

The same life cycle analysis for yellow paint pavement markings has been conducted in Figure 106 using the estimated regression equation of Y = -2.93*Ln(days) + -9.19*Ln(cum_snowfall) + 183.62. As in the previous analysis, Figure 106 shows the life cycles of three different types of roads in Table 3: non-freeways with the speed limits of 64 km/hr (40 mph), 72 km/hr (45 mph), and 89 km/hr (55 mph). Their threshold retroreflectivity values are 55, 65, and 100 mcd/m^2/lux, respectively.

Unlike common experiences, in this research, the initial retroreflectivity values of the yellow paint were higher, and yellow waterborne paint pavement markings stayed effective longer than white waterborne paint pavement markings did. This is because threshold retroreflectivity values of yellow paint are set lower than those of white waterborne paint pavement markings.

In general, the Figures 105 and 106 show that the waterborne paint can last relatively longer and have a longer life cycle in an area with less snowfall and a low speed limit. However, waterborne paint may not be a good option in an area with more snowfall and higher speed limit.
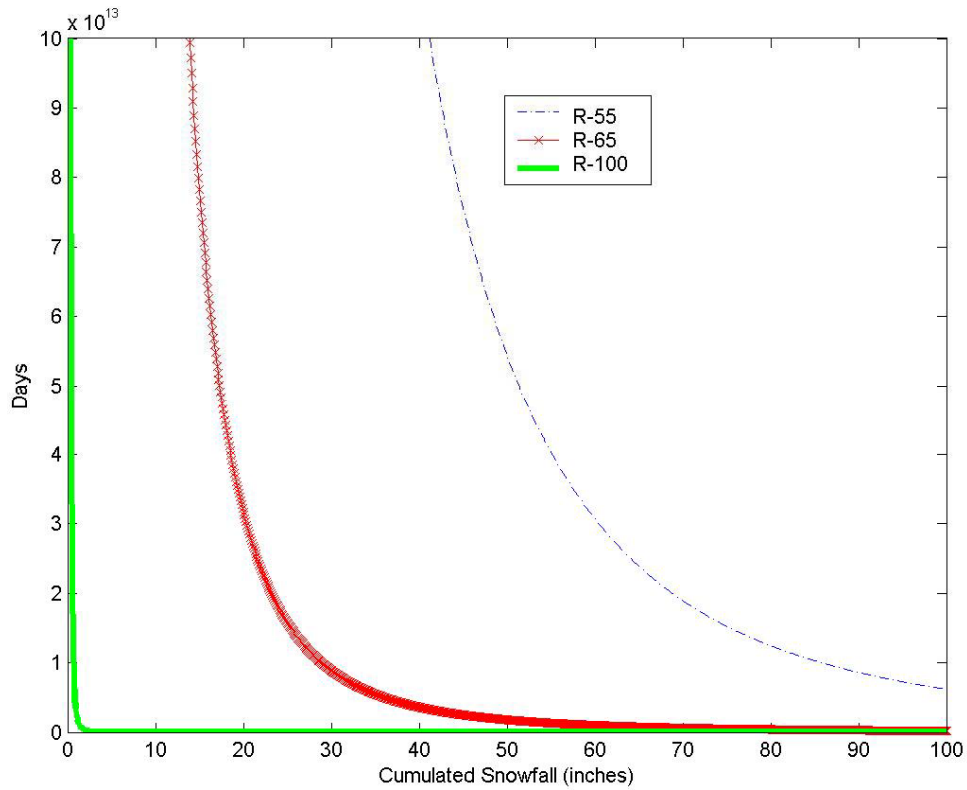
Figure 106. Estimated Life Cycle of Yellow Waterborne Paint Pavement Markings with Different Retroreflectivity Threshold Values

From the regression equations, the research shows that yellow waterborne paint pavement markings last more than many years for most roads with speed limits up to 89 km/hr (55mph) and the reasonable snow amounts in the state of Maryland. However, white waterborne paint pavement markings can last more than a year for roads with speed limits less than 72 km/hr (45 mph), or roads with higher speed limits and almost no snowfall.

IX. CONCLUSION

In this research, the relationship between retroreflectivity and various inputs that may affect the retroreflectivity — Number of Days Exposed, Cumulated Traffic Exposed, Cumulated Precipitation, and Cumulated Snowfall — were collected and analyzed from eight locations throughout the state of Maryland. The eight locations had different traffic amounts and weather conditions, were analyzed.

First, the relationship between retroreflectivity and the Number of Days Exposed was analyzed for each location. Since the precipitation, snowfall, and traffic amount depend on the number of days for the same location, it is good enough to find the relationship with the Number of Days Exposed. Then, the retroreflectivity and input data were aggregated and analyzed for each pavement marking type —White Edge (WE), White Skip (WS), Yellow Center (YC), Yellow Edge (YE) and Yellow Skip (YS) — as well as total analysis. The single variable regression analysis was used to find the relationship between retroreflectivity and input variables. After single variable regression analysis, multivariable regression analysis was conducted using the multiple inputs as well.

Finally, the durability and life cycle of the white and yellow waterborne paint pavement markings were estimated using the regression equations and thresholds of each paint type for different speed limits.

Summaries of the analysis are as follows:

Single variable regression analysis by location
- In general, retroreflectivity decreases with time passed.
- At each location, the correlation between retroreflectivity values and the Number of Days Exposed was relatively strong because each location has the same conditions in terms of the weather and traffic.
- In most locations, snowfall amounts affect retroreflectivity the most.
- However, some lumpiness was also found in some locations because of the characteristics of the retroreflectivity of the waterborne paint, which has beads on it, and retroreflectivity is highly related to the beads.
- Also, the correlation between retroreflectivity percentage to initial retroreflectivity value and the Number of Days Exposed was analyzed. The results were not different from those with retroreflectivity value, and neither is explicitly stronger than the other.

Single variable regression analysis by pavement marking type
- Single variable regression analysis was conducted to find the relationship between retroreflectivity and the following inputs: Number of Days Exposed, Cumulated Traffic Exposed per Lane, Cumulated Precipitation, and Cumulated Snowfall.
- Retroreflectivity generally decreases with time passed, traffic exposed, more precipitation, and more snowfall.

- Logarithm function made the best correlation between retroreflectivity and inputs.
- Stronger correlations between retroreflectivity and inputs were found in the pavement marking types, such as White Skip (WS), Yellow Edge (YE) and Yellow Skip (YS), which were found at only one location each.
- Weaker correlations between retroreflectivity and inputs were found in the popular pavement markings such as White Edge (WE) and Yellow Center (YC), which were found at all eight locations and six locations.

Single Variable Regression Analysis with aggregated data
- Aggregated data of all the pavement markings from all eight locations were analyzed in two ways, retroreflectivity values and retroreflectivity percentage to the initial retroreflectivity values.
- Correlations between retroreflectivity and inputs were not very strong. However, they show general downward trends of retroreflectivity with time passed, traffic exposed, more precipitation, and more snowfall.
- Logarithm function provides the best correlation between retroreflectivity and inputs.
- Cumulated Snowfall and Number of Days Exposed were the major inputs to have stronger correlation with retroreflectivity.
- Because Number of Days Exposed includes weather inputs and traffic inputs, it has a stronger relationship with retroreflectivity than other individual inputs next to Cumulated Snowfall.
- Both retroreflectivity value and retroreflectivity percentage were used as output for the analysis. However, neither one was better than the other for sure.

Multivariable regression analysis with aggregated data
- Two kinds of multivariable regression analysis, linear and logarithm, were conducted.
- Logarithm regression analysis made better correlation than linear regression analysis.
- Five ways of analysis — which include four kinds of two variable regression and multivariable using all four inputs — were conducted to find which regression provides the best correlation.
- Obviously, multivariable logarithm regression analysis using all four inputs made the best estimation of the retroreflectivity.
- In this case, Cumulated Traffic worked against other inputs. This is mathematically possible, but not realistic.
- The second best results came from the regression analysis with Number of Days Exposed and Cumulated Snowfall, the two most important inputs for the single variable regression analysis.

Durability and Life cycle analysis
- Durability and life cycle analyses were conducted for white paint pavement markings and yellow pavement markings separately.

- Multivariable logarithm regression analysis with Number of Days Exposed and Cumulated Snowfall was used to estimate the durability and life cycle of the waterborne paint pavement markings.
- For each pavement marking type, three different thresholds were used. These thresholds were based on speed limits of the roads.
- In this analysis, initial retroreflectivity values of yellow waterborne paint pavement markings were relatively higher than conventional initial values of yellow pavement markings, which is usually much lower than initial retroreflectivity values of white pavement markings.
- In this research, yellow waterborne paint pavement markings stayed effective longer than white waterborne paint pavement markings did because lower threshold retroreflectivity values of the yellow pavement markings than those of white waterborne paint pavement markings and relatively higher initial retroreflectivity of the yellow paint in this particular research.
- Waterborne paint pavement markings can last relatively long and have a longer life cycle in an area with less snowfall and a lower speed limit.
- Waterborne paint pavement markings may not be a good option in an area with more snowfall and a higher speed limit.
- From the regression equations, the research shows that yellow waterborne paint pavement markings last more than many years on most roads with speed limits up to 89 km/hr (55 mph) and the reasonable snow amounts in the state of Maryland.
- White waterborne paint pavement markings can last more than a year on roads with speed limits less than 72 km/hr (45 mph), or higher speed limits with almost no snowfall.

Overall
- In general, retroreflectivity decreases with time passed, more traffic, more precipitation, and more snowfall.
- Among the inputs, retroreflectivity is most affected by the Number of Days Exposed and Cumulated Snowfall Amount.
- Other research shows that Cumulated Traffic was the main factor to reduce retroreflectivity. However, in this research, although Cumulated Traffic Exposed provides correlation with retroreflectivity, it is not very strong compared to Number of Days Exposed. This is because Number of Days Exposed contains not only Cumulated Traffic Exposed, but also weather related inputs, such as Cumulated Snowfall and Cumulated Precipitation.
- Multivariable logarithm regression analysis including the Number of Days Exposed and Cumulated Snowfall provides the best estimation of retroreflectivity among all the regression analysis.
- Although the relationships between retroreflectivity and inputs are induced, the correlation was not very strong due to the nature of the empirical study.
- Retroreflectivity, which depends greatly on the beads in waterborne paint, may not match with visual damages. However, it can be an advantage of waterborne paint — which can provide a certain level of retroreflectivity throughout the life cycle of the waterborne paint — if the application is properly done.

- For some spots, after measuring the retroreflectivity as is, pavement markings were cleaned and then measured again to compare the changes in retroreflectivity. The results were not consistent and did not show any consistency in terms of changes in retroreflectivity.
- Yellow waterborne paint pavement markings lasted effectively longer than white waterborne paint pavement markings in this analysis because threshold retroreflectivity values of the yellow pavement markings are lower than those of white waterborne paint pavement markings.
- From the regression equations, the research shows that yellow waterborne paint pavement markings last more than many years for most roads with speed limits up to 89 km/hr (55 mph) and the reasonable snow amounts in the state of Maryland.
- White waterborne paint pavement markings can last more than a year for roads with speed limits less than 72 km/hr (45 mph), or higher speed limit and almost no snowfall.

Future proposed research
- Retroreflectivity is more effective during the night time, so it may be necessary to consider other elements, such as visibility, to find the damage and wear of pavement markings during the day time.
- There was not enough data to check the relationship between retroreflectivity and inputs by pavement marking type. More data is needed to find the proper correlation between retroreflectivity and inputs for each pavement marking type. In order to learn how snowplows damage the specific pavement marking types, it is necessary to collect more data.

REFERENCES

1.   Migletz, J., J. Graham, K. Bauer, and D. Harwood. Field Surveys of Pavement Marking Retroreflectivity. *Transportation Research Record 1657.* Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 71-78.

2.   Pavement Markings Study Nears Completion. *Better Roads*, Vol. 66, No. 4. April 1996.

3.   Migletz, J., J. Graham, K. Bauer, and D. Harwood. Service Life of Durable Pavement Markings. Paper 010-447. *Transportation Research Board 80th Anual Meeting Preprint CD-ROM.* Transportation Research Board, National Research Council, Washington, D.C., Jan. 2001.

4.   Montebello, David and Jacqueline Schroeder, *Cost of Pavement Marking Materials, Final Report*, Minnesota Local Road Research Board, March 2000.

5.   Abboud, Nasser and Brian Nowman, Cost- and Longevity-Based Scheduling of Paint and Thermoplastic Striping, *Transportation research Record 1794.* Transportation Research Board, National Research Council, Washington, D.C., 2002, pp. 55-62.