Evaluation of Profiled Pavement Markings

By

Dr. Jay K. Lindly and Mr. Ravindra K. Wijesundera
Department of Civil and Environmental Engineering
The University of Alabama
Tuscaloosa, Alabama

Prepared by

UTCA

University Transportation Center for Alabama
The University of Alabama, The University of Alabama in Birmingham
and The University of Alabama at Huntsville

UTCA Report Number 01465
November 13, 2003

Technical Report Documentation Page

1. Report No FHWA/CA/OR-	**2. Government Accession No.**	**3. Recipient Catalog No.**
4. Title and Subtitle Evaluation of Profiled Pavement Markings	**5. Report Date** November 2003 **6. Performing Organization Code**	
7. Authors Dr. Jay K. Lindly and Mr. Ravindra K. Wijesundera	**8. Performing Organization Report No.** UTCA Final Report 01465	
9. Performing Organization Name and Address The University Transportation Center for Alabama The University of Alabama Box 870205 Tuscaloosa, AL 35487	**10. Work Unit No.** **11. Contract or Grant No.** Alabama DOT Research Project No. 930-506	
12. Sponsoring Agency Name and Address Alabama Department of Transportation 1409 Coliseum Boulevard Montgomery, AL 36130	**13. Type of Report and Period Covered.** Final Report: August 13, 2001 – August 13, 2003 **14. Sponsoring Agency Code**	
15. Supplementary Notes		

16. Abstract

This study evaluated flat thermoplastic markings (FTM) and profiled pavement markings (PPM) installed on highways maintained by the Alabama Department of Transportation. The primary objectives of this evaluation were to compare service life, life-cycle costs, crash rates, and wet-night visibility (measured by wet retroreflectivity) of the two marking types. Nighttime dry and wet retroreflectivity of sixteen one-mile segments of FTM and twenty-one, one-mile segments of PPM were measured using a mobile retroreflectometer.

The average dry retroreflectivity of new FTM and PPM tested by this study were 320 and 242 mcd/m2/lux, respectively. In addition, both FTM and PPM were found to lose dry retroreflectivity at similar rates with respect to CTP. As a result, under similar ADT levels, FTM consistently provides a higher dry retroreflectivity than PPM of the same age. On average, FTM was found to last six or more months longer than PPM.

The average wet retroreflectivity of PPM at the end of its service life was found to be as high as the average wet retroreflectivity of FTM at the beginning of its life. However, crash data analysis did not indicate that the higher retroreflectivity of PPM resulted in a lower crash rate than FTM. The life cycle cost analysis showed that for a five-year marking service life and an eight year life cycle, the cost per mile of marking was $1,355 for FTM and $4,240 for PPM. Overall, the study found that economics, marking service life, and crash data do not justify widespread use of PPM in preference to FTM.

17. Key Words Pavement markings, safety, pavement edge lines, profiled pavement markings, flat thermoplastic markings, retroreflectivity		**18. Distribution Statement**	
19. Security Class (of this report) Unclassified	**20. Security Class (of this page)** Unclassified	**21. No. of Pages**	**22. Price**

Contents

Tables

Figures

Number Page

Executive Summary

This study evaluated flat thermoplastic markings (FTM) and profiled pavement markings (PPM) installed on highways maintained by the Alabama Department of Transportation. The primary objectives of this evaluation were to compare service life, life-cycle costs, crash rates, and wet-night visibility (measured by wet retroreflectivity) of the two marking types. Nighttime dry and wet retroreflectivity of sixteen one-mile segments of FTM and twenty-one, one-mile segments of PPM were measured using a mobile retroreflectometer.

The average dry retroreflectivity of new FTM and PPM tested by this study were 320 and 242 mcd/m^2/lux, respectively. In addition, both FTM and PPM were found to lose dry retroreflectivity at similar rates with respect to cumulative traffic passes (CTP). As a result, under similar average daily traffic (ADT) levels, FTM consistently provides a higher dry retroreflectivity than PPM of the same age. On average, FTM was found to last six or more months longer than PPM.

The average wet retroreflectivity of PPM at the end of its service life was found to be as high as the average wet retroreflectivity of FTM at the beginning of its life. However, crash data analysis did not indicate that the higher retroreflectivity of PPM resulted in a lower crash rate than FTM. The life cycle cost analysis showed that for a five-year marking service life and an eight year life cycle, the cost per mile of marking was $1,355 for FTM and $4,240 for PPM. Overall, the study found that economics, marking service life, and crash data do not justify widespread use of PPM in preference to FTM.

Section 1
Introduction

This study was conducted by the University Transportation Center for Alabama (UTCA) to evaluate two types of pavement markings as they are used by the Alabama Department of Transportation (ALDOT): flat thermoplastic markings (FTM), and profiled pavement markings (PPM). The primary objectives of this evaluation were to compare service life, life-cycle costs, crash rates, and wet-night visibility (measured by wet retroreflectivity) of the two marking types. Retroreflectivity is the ability of a pavement marking to reflect light back to its source of emission, which enables drivers to see markings at night. The service life is the duration of time a marking can retain its retroreflectivity value above a minimum threshold value. An underlying assumption of this study is that higher retroreflectivity is beneficial to drivers.

There were several other study objectives:
- Obtain photo or video documentation of PPM sites
- Evaluate ALDOT's test sections of 'rumble stripes,' which are rumble stripes placed immediately adjacent to the outside lane with a paint or thermoplastic edge line in the inside 6 inches of the rumble stripes.
- Establish a correlation between wet and dry FTM markings and between wet and dry PPM markings.

1.1 Problem Statement

In 1999, ALDOT began applying PPM to certain state-maintained roads because the ridge and valley structure of PPM promises higher wet visibility than FTM. However, PPM is three to four times more expensive than FTM (see Section 2.1 for details). To help decide which marking type should be used and the appropriate circumstances under which it should be used, ALDOT contracted UTCA to compare FTM and PPM in three ways:
- Longevity, as measured by service life
- Benefits to drivers under wet night conditions, as measured by wet retroreflectivity and crash rates
- Economics, as measured by life cycle costs

Another major reason for this study is that the Federal Highway Administration (FHWA) may require state highway agencies to replace a marking when its retroreflectivity falls below a minimum threshold value. This anticipated requirement is due to section 406(a) of the 1993 Department of Transportation Appropriations Act, which requires the Manual on Uniform Traffic Control Devices (MUTCD) to specify minimum retroreflectivity values for in-service pavement markings (FHWA 1998). As a result, ALDOT wants to develop an appropriate plan to measure retroreflectivity of pavement markings that are installed on nearly 11,000 miles of state-maintained highways in Alabama on a yearly cycle. The experience gained from tests reported in this report would help ALDOT to prepare a plan and to be ready for impending MUTCD requirements.

The performance of pavement markings under wet and rainy conditions has been of interest to researchers for the past two decades. However, those researchers faced two noteworthy obstacles: unavailability of instruments to measure markings when raining and absence of a well-defined testing methodology. As a result of these obstacles, researchers could not perform satisfactory wet tests. The FHWA's desire to perform wet tests was emphasized in its report (FHWA 2000), which concluded, "There is a need for more widespread measurement of pavement marking retroreflectivity under wet-pavement condition and for determining the visibility of markings under those conditions." Therefore, the study conducted by UTCA addressed an important area of interest to the FHWA.

1.2 Scope of Study

The two main colors of longitudinal pavement markings are yellow and white. Yellow lines usually separate traffic traveling in opposite directions, such as the centerlines of 2-lane roads and the inside edge lines of divided highways. White longitudinal pavement markings usually separate traffic flows in the same direction (lane lines) or mark the right edge of pavement. Lane lines are made of broken white lines, whereas edge lines are continuous. This study needed to decide whether to evaluate all these markings, or only a selected type(s) of line(s). After a consultation with representatives from ALDOT and Precision Scan (a commercial pavement marking testing company), this study was limited to evaluation of white edge lines only. The main problem with testing centerlines and yellow edge lines is the length of time needed to perform tests at one location. After testing right edge lines and lane lines, the laser scanner of the mobile retroreflectometer (the device that measures retroreflectivity) must be shifted from one side of the vehicle to the other side to measure centerlines and left edge lines. Before further testing can be done at that site, the laser scanner must be recalibrated. Recalibration takes about one hour to complete and would add too much time to the testing program. To test lane lines, multi-lane highways had to be selected. However, the majority of roads in Alabama are two-lane roads. Therefore, the research team felt that testing adequate numbers of multi-lane roads (along with the necessary numbers of two-lane roads) would be too time consuming and as a result, only edge lines were tested.

Retroreflectometers cannot be used during rain or on wet pavements when water splashes onto the equipment. As a result, wet tests were performed by artificially wetting a narrow strip of pavement around the edge line, which would not cause the test vehicle tires to splash water onto the laser scanner. Among the other factors that defined the scope of work are the number of sample sites to be tested, different characteristics these sites represented, and how often and how many times these markings should be tested. The site selection and test procedure are discussed in detail under the Methodology section of this report.

1.3 Organization of Report

This report consists of ten sections. Section One gives an introduction to the study and defines the scope of this study. Section Two presents the review of relevant literature, and Section Three explains the test methodology. Section Four describes development of dry and wet retroreflectivity decay curves for FTM and PPM. Service life estimation for PPM and FTM is given in Section Five. The results of correlation analyses between dry and wet retroreflectivity are presented in Section Six. Section Seven presents methodology and results of crash data analysis. Life cycle cost analysis is presented in Section Eight. Section Nine presents a brief look at the retroreflectivity testing done on ALDOT's two short test sections of rumble stripes. Section ten summarizes conclusions and recommendations of this study.

Section 2
Review of the Literature

An extensive literature search was conducted to gather information on thermoplastic pavement markings, test standards, retroreflectivity decay analysis, service life estimation, and current national interests in pavement marking research. Since most of the existing pavement marking evaluation methodologies and retroreflectivity measurement devices were developed within the last ten years, the literature review mainly focused on studies carried out during that period. The main sources of literature were Transportation Research Records, FHWA publications, ITE Journals, ASTM standards, and the worldwide web.

2.1 Thermoplastic Pavement Markings

Thermoplastic pavement markings are a compound of glass spheres, pigments, fillers, and binders. Glass spheres, also known as glass beads, provide retroreflectivity; pigments provide color; fillers such as calcium carbonate provide bulk; and binders may be plasticizers or resins that hold the other materials in the marking while providing toughness. Figure 2-1 (Schertz 2002) shows the phenomena of retroreflection by glass beads and constituent materials of a typical pavement marking.

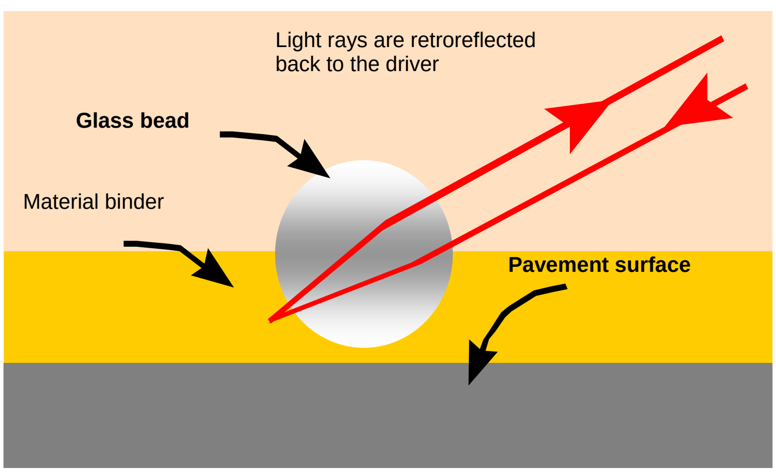


Figure 2-1. Retroreflection from glass beads (Schertz 2002)

According to FHWA (2000), both FTM and PPM are termed all-weather pavement markings. These markings should be visible at night during a rainfall of up to 0.25 inches per hour. Longitudinal thermoplastic markings are commonly found in widths of 4 inches and

6 inches. According to a study by Iowa State University (ISU), the average thickness of new FTM used in the USA is around 90 mils (ISU 2001), and ALDOT (2000) requires new PPM to be 160 mils thick. ALDOT project letting information (ALDOT 2002) indicates that the average costs for installing one mile of edge line of FTM and PPM in 2002 were $1,230 and $4,130, respectively.

2.2 Department of Transportation Appropriations Act 1993

Section 406(a) of the 1993 Department of Transportation Appropriations Act requires the MUTCD (FHWA 1998) to specify minimum threshold retroreflectivity to be maintained by pavement markings and signs. The objective of this act is to enhance nighttime visibility for drivers. So far, no such criteria have been established. However, the FHWA is evaluating the potential threshold retroreflectivity values suggested by a study it sponsored (FHWA 2000). As a result, FHWA may require states to replace a pavement marking once its retroreflectivity falls below the minimum value.

2.3 FHWA Study

After the 1993 Department of Transportation Appropriations Act, the FHWA sponsored a study that evaluated a variety of all-weather pavement markings installed in 19 states comprising 85 test locations (FHWA 2000). Dry retroreflectivity was measured using four Laserlux retroreflectometers at six-month intervals over a period of nearly four years. In October 2000, the FHWA published service life estimations based on dry retroreflectivity, safety, and life-cycle cost information for those pavement markings. The report presented potential minimum threshold retroreflectivity values (reproduced in Table 2-1) to define the end of service life of pavement markings. Most of these values are based upon recommendations made by Zwahlen and Schnell (2000) who used a computer model named CARVE (Computer-Aided Roadmarking Visibility Evaluator) to determine those values.

Table 2-1. Threshold dry retroreflectivity values suggested by FHWA to define end of pavement marking service life (FHWA 2000)

Material	Roadway type/speed classification		
	Non-freeway ≤ 40 mph	**Non-freeway ≥ 45 mph**	**Freeway ≥ 55 mph**
White	85	100	150
White with lighting or RRPM	30	35	70
Yellow	55	65	100
Yellow with lighting or RRPM	30	35	70

RRPM – Raised retroreflective pavement markers
Retroreflectivity is in mcd/m^2/lux.

The values given in Table 2-1 were used to establish the service lives of pavement markings in terms of age of markings and cumulative traffic passages (CTP). CTP is the number of vehicles that have traveled on a road (both directions) or on a lane (one direction) from the installation of a pavement marking to the date when retroreflectivity falls below the minimum threshold value. Table 2-2 reproduces the service life values established by this study for thermoplastic markings. The values given in Table 2-2 indicate that in general, FTM has a longer service life than PPM. However, there is a wide variation among individual sites tested because of the differences in average daily traffic (ADT).

Table 2-2. Estimated service life for FTM and PPM edge lines based on dry retroreflectivity for sites without roadway lighting or RRPM by FHWA (2000)

Roadway type	Material	Number of pavement markings in tests series	Service life in:		
			CTP (million vehicles)	Elapsed months	
			Average	Average	Range
Freeway ≥ 55 mph	FTM	14	7.5	22.6	7.4-49.7
	PPM	7	6.5	18.4	4.7-35.6
Non-freeway ≤ 40 mph	FTM	N/A	N/A	N/A	N/A
	PPM	1	25.1	55.7	-
Non-freeway ≥ 45 mph	FTM	5	6.0	36.6	26.5-49.1
	PPM	6	3.7	24.9	23.8-26.2

RRPM – Raised retroreflective pavement markers

The FHWA report also gives details of a small-scale retroreflectivity test under wet pavement conditions. It used a saturated paint roller to wet an approximately three foot-long segment of markings, and one minute later, measured retroreflectivity using a stationary Laserlux retroreflectometer. A comparison of results of dry tests with wet tests indicated wet retroreflectivity to be around 42 to 52 percent of dry retroreflectivity. However, the FHWA report does not give comparative values for FTM and PPM separately. These wet tests were performed before the publication of American Society for Testing and Materials (ASTM) guidelines for testing markings under wet pavement conditions (ASTM E 2177) (ASTM 2002). It is important to note one of the conclusions of the FHWA report: “There is a need for more widespread measurement of pavement marking retroreflectivity under wet-pavement condition and for determining the visibility of pavement markings under those conditions.” Therefore, the large-scale wet tests conducted in Alabama were consistent with the current FHWA interests in pavement marking research.

2.4 ASTM Standards

The American Society for Testing and Materials (ASTM) outlines three methods for testing pavement markings:

- Standard Test Method for Measuring Retroreflectivity of Pavement Markings in a Standard Condition of Continuous Wetting (ASTM E 2176) (ASTM 2002)
- Standard Test Method for Measuring Retroreflectivity of Pavement Markings in a Standard Condition of Wetness (ASTM E 2177) (ASTM 2002)
- Standard Specification for Minimum Retroreflectance of Newly Applied Pavement Makings Using Hand-Operated Instruments (ASTM D 6359) (ASTM 1998)

Since tests in Alabama were conducted under wet pavement conditions, the test procedure specified by ASTM E 2177 was studied in detail. ASTM E 2177 describes a method for measuring retroreflectivity of pavement markings under a condition of standard wetness using a hand-held or mobile retroreflectometer. The wet conditions in the standard usually exist after a rainfall is complete but while the pavement marking is still wet. ASTM E 2177 suggests using a hand sprayer for a period of 30 seconds or a bucket filled with 2 to 5 liters of water to wet the markings to be tested. The retroreflectivity is measured 45 ± 5 seconds after wetting the markings. This period of waiting allows water to drain off, yet markings are still in a wet condition.

2.5 Evaluation of Retroreflectometers

The development of retroreflectometer technology has had a major effect on pavement marking studies. At present, there are two types of retroreflectometers: hand-held and mobile retroreflectometers. In January 2000, the Highway Innovative Technology Evaluation Center (HITEC) published results of an evaluation of six commercial retroreflectometers (HITEC 2001). This report stated that the Laserlux device (a mobile retroreflectometer) had a precision of 15 percent. That means Laserlux is capable of measuring a pavement marking with a true value of 100 mcd/m^2/lux within the range of 85 to 115 mcd/m^2/lux. The HITEC study results indicate that hand-held retroreflectometers recorded higher precision than mobile retroreflectometers. However, hand-held devices require more time to take readings, and they are sample-based measuring devices, whereas mobile retroreflectometers are capable of continuous testing. None of these retroreflectometers can be used to measure retroreflectivity during rainfall.

2.6 Auburn Study

Bowman and Abboud (2001) of Auburn University published a study that evaluated paint and flat thermoplastic markings in Alabama. While the main objective of this research was to determine the service life of pavement markings based on crash records, it also established a correlation between retroreflectivity decay and exposure of markings to vehicle travel. Bowman et al. used data collected from markings that were more than one month old to develop decay models. They cited a National Transportation Product Evaluation Program study (1997) that found newly applied markings to have a low retroreflectivity during the first 30 days after installation because it takes some time for the glass beads to be exposed and give the markings maximum retroreflectivity. Bowman et al. developed the following model for decay of white thermoplastic edge lines.

$$retroreflectivity = -70.8 \times \ln(vehicle\ \ exposure) + 640 \quad (R^2 = 0.58)......................(Equation\ 2.1)$$

Where vehicle exposure = (ADT per lane × age of markings × 30.4) /1,000

Bowman et al. used equation 2.1 to estimate the service life of pavement markings based on a minimum threshold retroreflectivity value of 150 mcd/m^2/lux. Table 2-3 reproduces the estimated service life of dry flat thermoplastic pavement markings on two-lane roads.

Table 2-3. Expected service life in months according to ADT levels (Bowman *et al*. 2001)

Low ADT (<2,500)	Mid ADT (2,500 to 5,000)	High ADT (> 5,000)
53	18	10.5

While there are some similarities between the study by Bowman et al. (2001) and the research presented in this report, some significant contrasts are listed below:

- Bowman et al. did not evaluate PPM, nor did they measure retroreflectivity under wet pavement conditions.
- Bowman et al. used a hand-held retroreflectometer for data collection, whereas the UTCA study utilized a mobile retroreflectometer. The former study measured pavement markings at one to three mile intervals, whereas the UTCA study collection data continuously on one-mile segments.
- While the UTCA study used an ASTM accepted 30-meter (98 feet) geometry retroreflectometer, Bowman et al. used a 15-meter (49-feet) geometry device. The readings from these two devices are not comparable because the former simulates a situation where a driver observes markings a distance of 15 meters (49 feet) ahead, while the latter simulates a detection distance of 30 meters (98 feet).

2.7 Other Studies

Schnell and Lee (2003) evaluated the visibility of pavement markings under wet weather conditions. This study used drivers of different age groups to evaluate the visibility of pavement markings under dry and wet conditions. Similar to the UTCA study, Schnell et al. also used a water truck to wet pavement markings. Schnell et al. found marking type to significantly affect the visibility under wet pavement conditions. However, they did not correlate the visibility as determined by their human subjects with retroreflectivity of pavement markings determined by retroreflectometers.

In 1999, Lee, Maleck, and Taylor (1999) published findings of a four-year study on different types of pavement marking installed at 50 sites on state and inter-state highways in Michigan. Lee et al. established models to predict retroreflectivity decay in terms of age of markings. These models predict dry retroreflectivity of new thermoplastic pavement markings to be 255 mcd/m^2/lux. Using a minimum threshold retroreflectivity value of 100 mcd/m^2/lux, the study estimated service life of thermoplastic markings as fourteen months. This study identified snowplowing operations to have a significant impact on degradation of retroreflectivity. Traffic variables such as ADT, speed limit, and commercial traffic did not show a significant correlation with retroreflectivity degradation.

2.8 Discussion

This literature review found that the 1993 Department of Transportation Appropriations Act that requires the MUTCD to specify minimum retroreflectivity values for pavement markings had a significant influence in shaping recent studies on pavement markings. As a result of this act, the FHWA may require state agencies to measure retroreflectivity of pavement markings periodically and to replace or refurbish them when their values fall below minimum threshold values. So far, these threshold values have not been specified in the MUTCD.

Another area of interest to FHWA is the evaluation of pavement markings under wet-night conditions. The recently-promulgated ASTM standard E 2177 can be seen as providing important guidelines for these wet night evaluations. However, the method specified by ASTM is primarily suited for small-scale testing of pavement markings because it describes wetting markings with water from buckets or hand-held sprayers. Therefore, the research described by this report deviated from ASTM E 2177 and devised a method for continuous testing markings using a mobile retroreflectometer. This method is discussed in the next chapter.

When the research described by this report is compared with other recent studies that were reviewed in this chapter, the following observations can be made. This report describes the first large-scale retroreflectivity test under wet-night conditions using a mobile retroreflectometer. This is also the first known detailed study conducted after ASTM specified a methodology to test pavement markings under wet-night condition (ASTM E 2177). Finally, this literature review did not find any recent study that compared FTM and PPM. Therefore, this study opens several new fronts in pavement marking research and is consistent with the state-of-the-art of FHWA pavement marking research interests.

Section 3
Methodology

This section explains the steps involved in planning and conducting data collection. Sequentially, it describes selection of test sites, equipment used, dry and wet retroreflectivity tests, and observations made during tests.

3.1 Site Selection

In February 1999, ALDOT first began using PPM instead of FTM on selected highways. To select test sites, ALDOT division offices were requested to provide details of thermoplastic pavement marking projects conducted since February 1999. Typical details requested from ALDOT were type of marking (i.e., FTM or PPM), route number, beginning and ending mileposts (of pavement marking projects), date of completion of projects, types of road pavements, and unit costs for installing markings. Table 3-1 summarizes pavement marking projects completed during the relevant period by types of markings and year of completion for each ALDOT division. Details of 103 FTM and 114 PPM projects were provided by ALDOT.

Table 3-1. Summary of pavement marking project database

ALDOT Division	Type of marking	Year of completion			Total sites
		1999	2000	2001	
1	FTM	5	4	1	10
	PPM	1	1	11	13
2	FTM	7	9	4	20
	PPM	3	6	10	19
3	FTM	4	1	3	8
	PPM	5	7	11	23
4	FTM	4	17	9	30
	PPM	1	0	0	1
5	FTM	2	10	1	13
	PPM	0	4	7	11
6	FTM	1	2	1	4
	PPM	3	2	3	8
7	FTM	3	0	0	3
	PPM	5	12	0	17
8	FTM	2	0	2	4
	PPM	0	4	5	9
9	FTM	5	3	3	11
	PPM	0	9	4	13
Total		51	91	75	217

3.1.1 Site Selection Criteria

After obtaining details about candidate sites, the next task was to outline criteria for selecting a sample of sites for testing. The following facts were considered when selecting test sites:

- There was a need to test both FTM and PPM.
- The length of a project must be sufficient to provide a one-mile long test section.
- The numbers of test sites must be sufficient for statistically valid results.
- The sites must be selected from different regions of the state to represent geographic variations.
- There was a need to minimize travel time between sites.
- The surveys must be performed within the allocated budget.

Two external professionals were consulted in the process of site selection. One professional was from the Precision Scan Company, which was contracted to perform retroreflectivity tests. The second was a University of Alabama statistician. The productivity rates of the Laserlux retroreflectometer (explained in more detail in Section 3.3.1), the effects of environmental conditions on testing, and the cost of surveys were provided by Precision Scan Company. The statistician determined the minimum number of sites to be tested and the average length of sites. The number of test sites was based upon the geographic locations of the available test sites, the distances between test sites, the ADT of test sites, the number of times each site was to be tested, and the need to complete one series of tests in four to five days. After these considerations, forty sites were selected for testing: twenty-one of those sites had PPM and nineteen had FTM.

The length of a test site was set as one mile. Only one of the edge lines was tested at each site. The approximate locations of selected test sites are shown in Figure 3-1. These sites were located in six of the nine ALDOT divisions. This research did not test markings in the other three ALDOT divisions due to the high daily rental rate of the Laserlux device and the additional time it would have taken to drive to those divisions and conduct testing of additional sites.

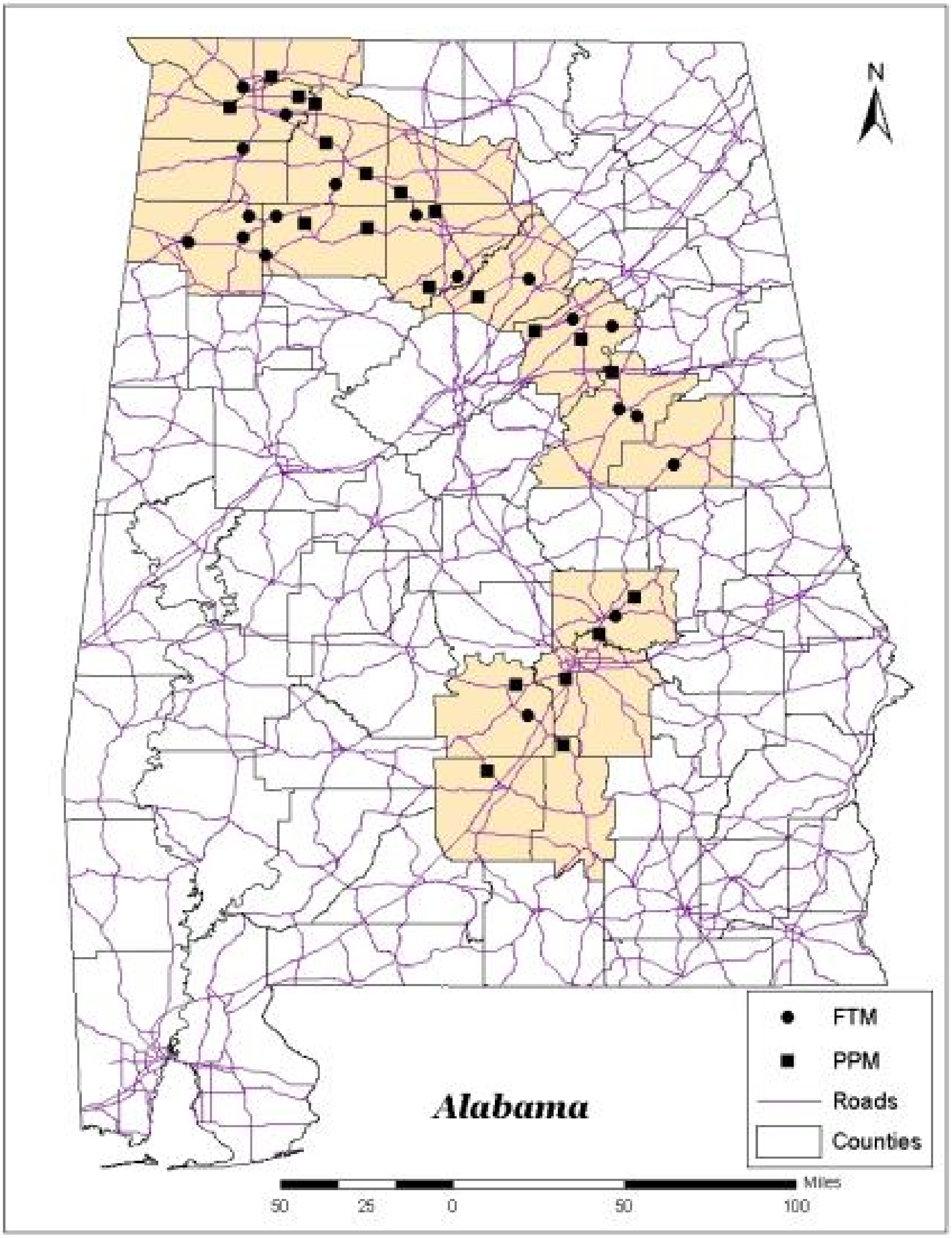


Figure 3-1. Pavement marking test sites

3.2 Pre-Survey Site Inspection

The selected sites were inspected three months before the first retroreflectivity test. This survey was used to gather additional information on test sites such as number of lanes, presence of streetlights, roadside development (i.e., rural or urban), speed limit, and thickness of markings. Table 3-2 presents a summary of selected information from field inspections.

Table 3-2. Classification of test sites by physical and operating characteristics

Type of marking	Total sites	Number of lanes		Type of development		Street lighting/RRPM		Speed limit (mph)			
		Two	Four	Urban	Rural	Present	Absent	45	55	65	70
FTM	19	15	4	2	17	0	19	5	11	3	0
PPM	21	14	7	4	17	3	18	2	12	5	2
Total	40	29	11	6	34	3	37	7	23	8	2

RRPM – Raised retroreflective pavement markers

According to Table 3-2, twenty-nine sites were located on two-lane roads, and eleven sites were on multilane roads. There were six sites in urban areas and thirty-four in rural areas. Two test sites were located on interstate highways (i.e., speed limit 70 mph). The majority of test sites were located in two-lane rural roads, as most ALDOT roads belonged to this category, and the test team wanted to minimize interference from regular traffic, which is more frequent on urban roads. During the field inspections, photos of test sites and markings were taken. Typical FTM and PPM are shown in Figures 3-2 and 3-3, respectively.

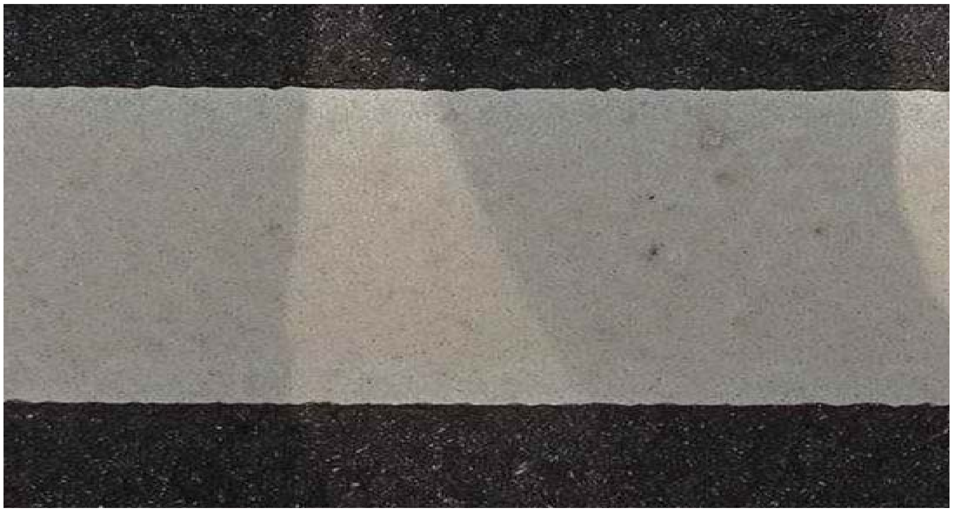


Figure 3-2. Flat thermoplastic marking

Figure 3-3. Profiled pavement marking

3.3 Resources for Surveys

The dry tests were performed without any traffic control. Therefore, the only vehicle needed for dry tests was the Laserlux van. However for wet tests, a thousand-gallon water truck was used to wet the markings, and an attenuator truck was used to provide protection for the Laserlux van. A typical wet test train consisting of water truck, mobile retroreflectometer, and attenuator truck is shown in Figure 3-4.

Figure 3-4. Wet test train of water truck, Laserlux, and attenuator truck

3.3.1 Laserlux Mobile Retroreflectometer

A product of Roadware Corporation, Potters Industries, and Advanced Retro Technology, the Laserlux retroreflectometer has been designed according to the European Committee for Standardization specification EN 1436. It uses 30-meter (98-feet) geometry, which simulates the condition when a driver detects a pavement marking 30 meters (98 feet) beyond the headlights during nighttime. Figure 3-5 illustrates the 30-meter (98-feet) geometry. Since mobile retroreflectometers make use of a specific wavelength of laser light and a narrow-band filter to block reception of all other wavelengths of light, they can measure nighttime retroreflectivity during daytime (Rennilson 1987). The main components of Laserlux retroreflectometer include an externally mounted laser scanner that measures marking retroreflectivity and an in-vehicle computer system that controls data collection and stores measured readings.

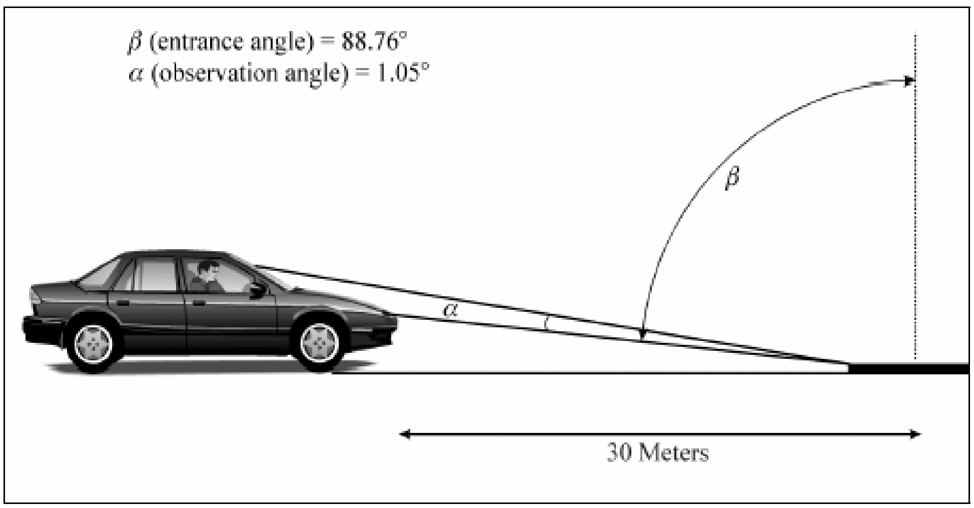


Figure 3-5. Illustration of 30-meter (98-feet) geometry [10]

A mobile retroreflectometer was used for this research instead of a hand-held retroreflectometer because the latter measures markings while stationary. As a result, a hand-held device cannot be effectively used to measure a one-mile segment continuously. The Laserlux measures retroreflectivity continuously while moving at normal traffic speeds and can collect up to 1,152 readings per minute or close to 70,000 readings per hour (HITEC 2001). Another advantage of the Laserlux is that it needs little or no traffic control while testing dry markings. Some of the characteristics of the Laserlux mobile retroreflectometer as listed by the HITEC evaluation report are reproduced in Table 3-3 (HITEC 2001).

Table 3-3. Characteristics of Laserlux mobile retroreflectometer (HITEC 2001)

Width of area measured	42 inches wide
Operating temperature	32°F - 120°F
Range of measurements	Minimum: 20 – 30 mcd/m^2/lux Maximum: 800 mcd/m^2/lux
Maximum vehicle speed while measuring	55 mph (90 km/hr)
Frequency of data acquisition	1,152 readings per minute
Cost	Laserlux unit $ 149,000 (Year 2000) plus cost of van and modifications

3.3.2 Water Truck

The wet retroreflectivity measurements were collected by artificially wetting the pavement markings. This was done by using a thousand-gallon water truck specially modified for this study. A nozzle attached to the water tank was used to spray a steady stream of water onto the markings. The nozzle was mounted not more than three to five inches above the pavement to prevent splashing of water. The nozzle and the Laserlux were provided by Precision Scan Company. Precision Scan has applied for a patent for the nozzle.

3.4 Retroreflectivity Tests

All test sites were selected such that they began and ended at a milepost. First, a test location was tested dry, then tested again after markings had been artificially wetted. In each test run, the Laserlux measured the pavement marking continuously, and the onboard computer stored average retroreflectivity for 100-foot sections measured from the beginning milepost. As a result, there were fifty-three readings for each one-mile test section. The mean retroreflectivity of each site was determined by averaging the fifty-three readings.

Sometimes the markings were missing from short segments of the test section due to wearing or due to the presence of access roads. Such situations were handled by a facility available in the computer system, which allowed defining a minimum threshold retroreflectivity value to accept a scanned reading. If a scan resulted in a value that was less than the specified minimum threshold, such a reading was discarded. The minimum threshold values for dry and wet tests were set as 25 and 5 mcd/m^2/lux, respectively.

3.4.1 Dry Retroreflectivity Tests

The only vehicle involved in dry testing was the Laserlux van. Before the start of a test run, the Laserlux technical crew entered the site number, marking type, beginning milepost, and ending milepost into the computer. The retroreflectivity data was then collected by the Laserlux while traveling at a speed of 45 mph. Usually, the Laserlux van started its test run about 500 feet outside the beginning milepost and accelerated to the desired speed before it entered a test section. On average, four minutes were required to prepare and conduct one dry test run at a one-mile site.

3.4.2 Wet Retroreflectivity Tests

The wet test was performed upon completion of the dry test. Both the water truck and the Laserlux were driven at 35 mph. This speed was 10 mph less than the speed at which dry tests were performed. However, driving the water truck containing 1,000 gallons of water at 45 mph was considered risky, and a lower test speed was selected. The researchers considered the variable speeds acceptable, as The Highway Innovative Technology Evaluation Center had used variable speeds in its field studies when testing the Laserlux (HITEC 2000). A wet test run on a one-mile site required around seven minutes after the Laserlux van returned from performing the dry test.

3.4.2.1 Variation of discharge of water: The amount of water used per test varied slightly along the length of a test site and from one site to another because water was sprayed onto the markings under gravity. Since it was impractical to refill the water truck at the completion of each site, refilling was done when the water level dropped to approximately 400 gallons. Therefore, the volume of water stored in the truck tank at any time during testing ranged from 400 to 1,000 gallons.

A limited test was performed to determine the rate of discharge of water when the tank was filled with 1,000, 700, and 400 gallons. The time taken to fill a 4.5-gallon bucket was measured using a stopwatch. Table 3-4 shows results of these tests and estimated volumes of water sprayed on one-mile test sections. These estimations are based on the assumption that the water truck traveled at a speed of 35 mph. According to Table 3-4, the maximum difference in the rate of water application for a different one-mile test segment is 33 gallons, or about 0.6 gallons per 100-foot segment. Based on those results, the researchers deemed the effect of the variation of discharge of water on wet readings to be insignificant.

Table 3-4. Variation of discharge with volume of water in tank

Volume in tank (gallons)	Volume collected (gallons)	Time taken (seconds)	Discharge in gallons per mile
1,000	4.5	3.38	137
700	4.5	3.80	123
400	4.5	4.51	104

3.4.2.2 Comparison of UTCA wet tests with ASTM E 2177: ASTM E 2177 suggests pouring two to five liters of water over the area of marking to be measured and waiting 45 ± 5 seconds before measuring retroreflectivity, but ASTM does not mention the length of markings over which water should be poured. As a result, an exact comparison of amounts of water used by the UTCA test and the ASTM test could not be performed. However, it appears that the ASTM method uses more water than the UTCA test method. The following practical considerations prevented the UTCA tests from using a higher volume of water:

- The need to prevent splashing of water onto the laser scanner
- Difficulties in refilling the water truck on a more frequent basis

This study also deviated from the ASTM specification when selecting the waiting period for measuring retroreflectivity after wetting pavement markings. The Laserlux van waited for 35 seconds instead of the ASTM recommended time gap of 45 ± 5 seconds. A shorter time gap was employed to minimize the interference from other traffic.

To investigate whether the ASTM method and the UTCA method for large-scale wet tests produced similar results, one FTM site and one PPM site were tested using both methods. The FTM test site was 2,600 feet long, and the PPM test site was 1,800 feet long. An LTL 2000 hand-held retroreflectometer was used to collect data according to the ASTM methodology, whereas a Laserlux mobile retroreflectometer was used to collect data according to the UTCA methodology. The reason for employing two devices was that the ASTM method was devised mainly to collect data using a hand-held retroreflectometer, whereas the UTCA method was devised to collect data using a mobile retroreflectometer. The LTL 2000 collected readings at 200-foot intervals and the Laserlux collected data continuously and output average readings for 100-foot segments.

The test results from the LTL 2000 device that followed the ASTM guidelines and the results from the Laserlux device that followed the UTCA test procedure are given in Tables A-1 and B-1 of Appendix 1. A two-tailed, two-sample student t-test was used to test the null hypothesis that the difference of means of data from two test methods is equal to zero, with a rejection threshold of $p = 0.05$. The comparison of the two wet test methods was based on the assumption that the ASTM method, which utilizes more water and a longer waiting period (45 seconds) and the UTCA method, which utilizes less water and a shorter waiting period (35 seconds) produce the same wet condition retroreflectivity readings. According to Tables C-1 and D-1 of Appendix 1, the tests rejected the null hypothesis. Therefore, the UTCA method and the ASTM method do not appear to produce the same wet condition readings. Two factors that may explain the differences in data follow:

- The experts from the Precision Scan Company stated that the LTL 2000 and the Laserlux have previously been shown to differ from each other by as much as 15%. This variation may have contributed to the differences of the readings collected by the two methods.
- The relatively small number of measurements taken with the LTL 2000 device may not have adequately represented the retroreflectivity of the test segment, unlike the continuous data taken with the Laserlux device. Manual pouring of water, waiting longer before taking readings, and time taken to walk from one test position to another did not allow measuring the markings at shorter intervals with the LTL 2000 device.

3.5 Notes on Three Surveys

Each of the selected locations was tested three times over a period of twelve months. The average dry and wet retroreflectivity values measured at FTM and PPM sites during the three field tests are given in Tables E-1 and F-1 of Appendix 1. Some of the noteworthy events reported during field tests are presented below.

3.5.1 Test One

Forty sites were tested on March 22, 2002 and from March 25, 2002 to March 27, 2002. Test site 210 (an FTM site) was noticed to have been refurbished recently with new retroreflective glass beads; however, the researchers judged that this event did not disqualify the site from the test series. Test sites 107 and 602 were removed from further tests as they were determined to consist of paint markings instead of thermoplastic markings. Table 3-5 shows the values obtained from these two test sites. As a result, the number of FTM sites was reduced from nineteen to seventeen.

Table 3-5. Retroreflectivity values of test sites 107 and 602

Site	Retroreflectivity	
	Dry	Wet
107	57	16
602	42	14

3.5.2 Test Two

Twenty-one sites were tested on September 15, 2002 and September 16, 2002, which was six months after the first tests. Thereafter, tests had to be postponed due to bad weather on the following days. The remaining sites were tested from November 15, 2002 to November 17, 2002. However, test site 205, an FTM site, could not be tested because its markings had been removed for a pavement overlay. In addition, tests at site 653 (a PPM site) were conducted only on a half-mile segment because a new marking had been installed on the remaining portion. Test site 209 (an FTM site) had been refurbished with new retroreflective glass beads after it was tested in March 2002; however, this site was retained for future tests.

3.5.3 Test Three

Test series three was conducted from March 24, 2003 to March 27, 2003. A total of thirty-seven sites were tested, and for some sites, the time gap between the second and third tests was six months, while for others it was not quite five months. At the completion of three rounds of testing, three complete sets of data had been collected from twenty-one PPM sites and sixteen FTM sites.

3.6 Sources of Variation

The data collection process was planned and conducted to minimize personal, technical, and random errors. This study identified the following potential sources of variation:

- As documented by HITEC (2001), the precision of Laserlux measurements is within 15 percent. Therefore, retroreflectivity values obtained at a test site can vary by at most 15 percent from its true value. In addition, the magnitude of variation from the “true” value might change when the same site is tested at different time periods.
- Dust and dirt gathered on pavement markings at the time of testing was considered to be another reason for inconsistent retroreflectivity readings. It is possible that there was more dirt on a marking during one test and less dirt during a subsequent test, as rain may have washed away dirt from the marking.
- The variation of water sprayed onto markings at different sites was discussed earlier. However, the magnitude of effect of the variation of water on test results was not quantified.
- The deviations of speeds of the Laserlux van and the water truck from desired speeds during wet tests were suspected to be another potential source of variation. To determine the actual speeds of the water truck and the Laserlux, speeds of both vehicles were recorded at ten test locations. The average speed of the water truck and the Laserlux van were found to be 34.6 ± 2.0 mph, and 34.9 ± 1.0mph, respectively. These values are acceptable since the desired speed was 35 mph.
- In test sections with sharp horizontal curves, there were difficulties in maintaining the spray nozzle directly over the markings. In addition, when curves sloped towards the travel lane, some of the water flowed in the direction of the travel lane instead of towards the pavement markings.
- Another possible source of variation was the change in the projection angle of the laser scanner when measuring markings on horizontal curves. This variation is likely to affect PPM readings more than FTM readings because the ridge and valley structure produces more scatter of light than the flat surface of FTM.

Section 4
Retroreflectivity Decay Models

This section explains the process of developing retroreflectivity decay models using regression analysis for FTM and PPM. Decay models establish a relationship between retroreflectivity and factors such as aging of markings and exposure to vehicle travel that contribute to the degradation of retroreflectivity. The types of models developed by this research and their intended purposes are listed below:

- Dry retroreflectivity decay models for FTM and PPM. These models will be used to determine service lives, retroreflectivity degradation rates, and retroreflectivity of new markings.
- Wet retroreflectivity decay models for FTM and PPM. These models will be used to determine wet retroreflectivity of new markings, wet retroreflectivity degradation rates, and wet retroreflectivity of a marking when its dry retroreflectivity reaches minimum threshold value.

4.1 Approach

The first task was to formulate databases for developing retroreflectivity decay models. Previous studies adopted two contrasting approaches to this task:

- Method One: Retroreflectivity data gathered from different survey locations for a similar type of marking (e.g., PPM) were pooled to formulate a single database. Thereafter, a decay model was developed to represent the average degradation of retroreflectivity of that marking. Bowman et al. (2001) and Lee et al. (1999) adopted this approach for their studies.
- Method Two: Establish retroreflectivity decay models and estimate the service lives for each test site separately. Then the average service life of these sites is quoted as the service life of the particular type of marking (e.g., PPM). This approach was adopted by the FHWA study (2000).

The following paragraphs describe the advantages and disadvantages of these two approaches and identify the situations where one method is preferred over the other. Thereafter, an appropriate method is chosen for developing decay models with the UTCA data.

4.1.1 Method One

The main advantage of Method One is that it gives more data to develop a single model. Such a database often contains data to represent retroreflectivity decay of markings over a larger span of life than a database pertaining to a single marking. For example, the UTCA study collected retroreflectivity data at each test site three times over a period of twelve months. These markings were installed at different points of time. When data from markings that were installed at different times are aggregated, the resulting database represents a broader range of time period than from a single marking. An underlying assumption of this approach is that the availability of data for a broad age period of markings results in a better decay curve. This approach assumes that a single decay model adequately represents the retroreflectivity variation of markings (e.g., PPM) that are installed according to one specification in a geographic region where the climatic conditions are similar. The models developed by pooled data from different entities (i.e., test sites) are called aggregate models. Such a model predicts average retroreflectivity decay of a pavement marking (e.g., PPM).

4.1.2 Method Two

This method is suitable when sufficient numbers of retroreflectivity readings are collected at individual test sites so that the retroreflectivity variation of each marking during its entire life span is well represented. The retroreflectivity decay of each test site is represented by a separate model. However, if the interest of the researcher is to predict service life of a particular type of marking (e.g., PPM), then results from individual models must be averaged. If there were few data points per site or if data refers to a shorter period than the full life span of a marking, such models may not represent the true pattern of retroreflectivity decay. These site-specific decay models are called disaggregate models because each model corresponds to an independent test site.

4.1.3 The Selection

This study collected data at approximately six-month intervals over a period of one year. If these data were modeled using Method Two, a set of decay models would be generated using only three data points for each model (i.e., for each test site). Therefore, Method One was chosen for developing decay models for FTM and PPM because its data represents marking decay over a longer time period.

4.2 Description of Databases

This section explains data used to develop retroreflectivity decay models. The data were categorized into three functional groups for the decay model: dependent variable, primary independent variables, and secondary independent variables. Retroreflectivity is the dependent variable. The age of markings and the CTP were considered as primary independent variables. The other parameters such as marking width, speed limits, and roadside development were considered as secondary independent variables. The following sections discuss these three types of data in detail.

4.2.1 Dependent Variable: Retroreflectivity

As explained in Section 4.1, the databases used for developing decay models were generated by pooling data from three tests:

- March 2002 data, referred to as Test One data
- September/November 2002 data, referred to as Test Two data
- March 2003 data, referred to as Test Three data

The retroreflectivity is expected to decline with time due to the loss of glass beads, the discoloring of the marking, and wearing of the marking. Figure 4-1 gives a sample of test sites to show the variation of retroreflectivity with time. Site 263 behaved as expected: retroreflectivity declined from Test One to Test Two to Test Three. Sites 159 and 259 did not follow the expected pattern.

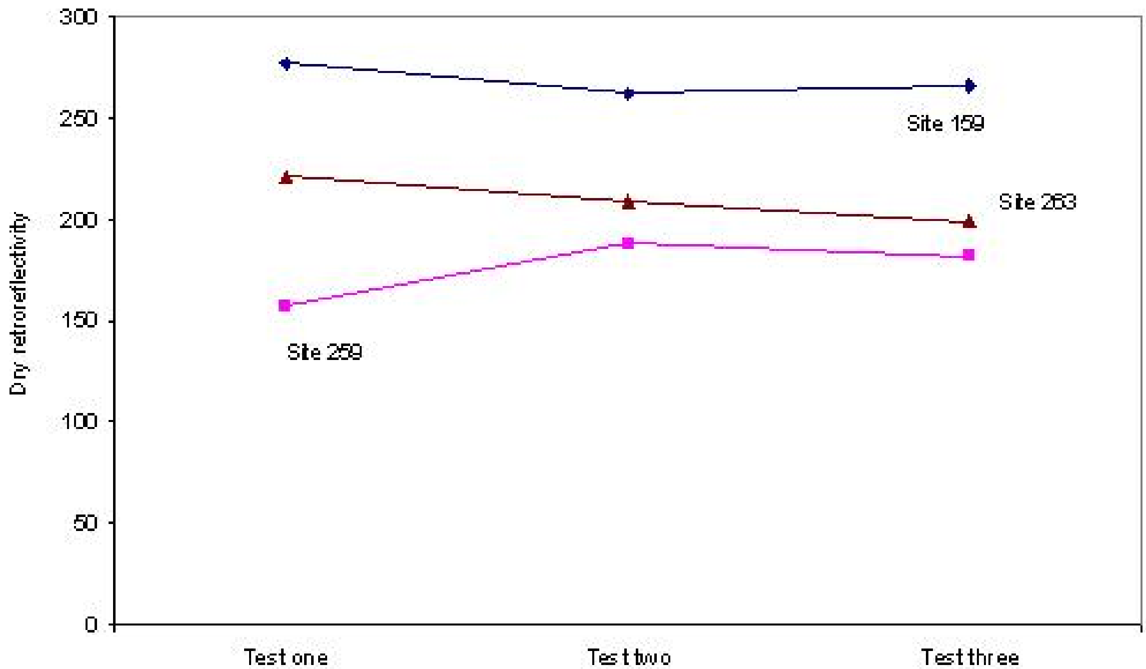


Figure 4-1. Variation of dry retroreflectivity of sample PPM test sites

Probable reasons for inconsistent variation of retroreflectivity are the application of new glass beads onto the markings between field measurements, the potential sources of variation associated with data collection as identified in the Methodology chapter, and the effect of dirt accumulation on markings and subsequent removal due to rain. A decision had to be made whether to retain the test sites that showed inconsistent variation of retroreflectivity with time or to remove them from model development. The following alternatives were considered:

- <u>Retain all data:</u> This option gives a large sample size, which is advantageous in regression analysis. However, retention of inconsistent data may skew the decay models.

- Remove inconsistent data: This option limits the database to only those sites where retroreflectivity decreased with time. The FHWA study (2000) removed all test sites that showed inconsistent variation of retroreflectivity with time. A drawback of this method is the reduction of sample size.

It is evident that both of the above-mentioned extreme solutions could potentially weaken the findings of the research. Therefore, to develop decay models with a sufficient number of observations, and at the same time to minimize the number of inconsistent observations, the following approach was adopted:

- Sites that showed an increase in retroreflectivity from Test One to Test Three were removed. It was assumed that a period of twelve months was a large enough duration for retroreflectivity to decrease purely due to traffic wear, aging, and weathering. Any increase in retroreflectivity from Test One to Test Three was attributed to sources of variations associated with data collection that were discussed in Section 3.5. Since Tests One and Three were conducted in March 2002 and March 2003, the environmental effects on test results were assumed to be similar. The sites selected based on the above criteria also included ones that showed an increase in retroreflectivity from Test One to Test Two or from Test Two to Test Three, but showed a decrease from Test One to Test Three.
- Two FTM sites identified during tests to have new glass beads were removed from the database. The reason for excluding these two sites from analysis was the unavailability of the date of refurbishment with new beads. Without a date, the CTP since the time of refurbishment to the date of survey could not be determined.

Using the criteria cited above, separate databases were generated for FTM dry retroreflectivity, FTM wet retroreflectivity, PPM dry retroreflectivity, and PPM wet retroreflectivity. In further discussions in this report, the four databases are referred to as combined databases, as they were formed by aggregating data from three tests (Tests one, two, and three). These databases were used for developing dry and wet retroreflectivity decay models for FTM and PPM.

4.2.1.1 Histograms of retroreflectivity: Histograms were used to present the distribution of retroreflectivity of combined databases. Figures A-2 to D-2 of Appendix 2 represent dry and wet retroreflectivity distributions of FTM and PPM. These histograms helped to determine the ranges of retroreflectivity values and to compare retroreflectivity of PPM and FTM.

The majority (89 percent) of FTM dry retroreflectivity values ranged between 200 and 350 $mcd/m^2/lux$. In comparison, the majority (90 percent) of PPM retroreflectivity values concentrated between 100 and 250 $mcd/m^2/lux$, showing that, in general, FTM has higher dry retroreflectivity. The wet retroreflectivity of FTM ranged between 20 and 70 $mcd/m^2/lux$, with 62 percent of the observations falling between 20 and 40 $mcd/m^2/lux$. PPM recorded wet retroreflectivity values that ranged between 30 and 130 $mcd/m^2/lux$, with 72 percent of the observations falling between 50 and 90 $mcd/m^2/lux$. These results indicate that, in general, PPM has higher wet retroreflectivity than FTM.

4.2.2 Primary Independent Variables

The next step in developing decay models was to identify the primary independent variables that were correlated with change in retroreflectivity. After reviewing previous studies, the following variables were identified as representative of retroreflectivity decay:

- Age of markings (in months)
- CTP, which represents the cumulative exposure of an edge line to vehicle travel since its installation

Since this study evaluated only edge lines, ADT was divided by number of lanes to calculate exposure of one edge marking to traffic movement. This calculation assumed ADT was equally distributed among all travel lanes. The new variable was presented as a unit-less value (e.g., 1.0 CTP means one million vehicle passages). Equation 4.1 shows the method of calculating CTP.

$$CTP \text{ per } edge\ line = \frac{ADT \times age\ of\ markings\ in\ days}{1{,}000{,}000 \times number\ of\ lanes} \text{.....................}(Equation\ 4.1)$$

The ages of markings and ADTs of test sites were obtained from ALDOT. The ADT data was for state-maintained highways for the duration of 1996-2000. This study extrapolated 1996–2000 data to estimate ADT for 2001-2003.

<u>4.2.2.1 Histograms of age and CTP:</u> Figures E-2 to F-2 of Appendix 2 present the distribution of age of the test sites that were selected for the combined databases. According to the figures, one FTM and one PPM had been in place less than six months when first tested in March 2002 (i.e., Test one). Those two were the newest markings tested by this study. At the time of Test Three (i.e., March 2003), there were four FTM and three PPM that aged between 42 and 47 months. Therefore, the maximum marking age tested in this study was 47 months.

According to Figures G-2 and H-2 of Appendix 2, the majority of FTM (80 percent) and PPM (76 percent) had been exposed to CTP less than 3.0. Two PPM test sites (six observations) had been exposed to over 7.0 CTP, whereas there were no such high traffic sites in the sample of FTM sites tested.

<u>4.2.2.2 Selecting between CTP and age variables:</u> Since the CTP variable was derived from marking age and ADT (see Equation 4.1), both CTP and marking age variables cannot be used in the same model because they are correlated. To select which of the two should be used as the primary variable for decay models, age and CTP were plotted separately against dry retroreflectivity (see Figures A-3 to D-3 of Appendix 3). Linear and non-linear regression models were fitted to those data to identify the best form of relationship between retroreflectivity and age or CTP. The general forms of the fitted models are shown below.

Linear model:

$$retroreflectivity = a + bX \text{ ....} (Equation\ 4.2)$$

Where "*X*" is CTP or age of markings, and "a" and "b" are coefficients.

Exponential model:

$$retroreflectivity = a \times \exp(bX) \text{...} (Equation\ 4.3)$$

Logarithmic model:

$$retroreflectivity = a + b \times \ln(X) \text{..} (Equation\ 4.4)$$

Power model:

$$retroreflectivity = aX^{b} \text{...} (Equation\ 4.5)$$

The coefficient of determination (R^2) of the fitted models was used as the primary way to identify the best form. According to the R^2 values, CTP had a better correlation with retroreflectivity than marking age, so CTP was chosen as the primary independent variable.

<u>4.2.2.3 Testing of age and ADT per lane as primary variables</u>: A major drawback of the age variable is that it does not show the effect of ADT on the deterioration of marking retroreflectivity. Therefore, the possibility of using both age and ADT per travel lane together as the primary variables was tested. Equation 4.6 shows the form of this model. The intention was to quantify the individual effects of the age variable and the ADT variable on the degradation of retroreflectivity. However, this model was not statistically significant at $p = 0.05$, and it was discarded. (p is the Pearson's p-value, which is a measure of the contribution of the variable to the regression equation at the chosen significance level.)

$$retroreflectivity = a + b \times (ADT\ per\ lane) + c \times (Age) \text{.................................} (Equation\ 4.6)$$

4.2.3 Secondary Independent Variables

As mentioned in the Methodology section, test sites can be categorized by road type, speed limit, width of markings, geographic locations, roadside development, etc. The possible effects of these secondary variables on retroreflectivity were investigated. First, decay models were developed using primary independent variables. Then secondary independent variables were added to the already established models and tested for statistical significance. The secondary variables were entered into models as dummy variables. For example, a new variable was defined to represent test sites that were located in rural areas. This new variable identified a test site located in a rural area by assigning it a value of "1," and assigned a "0" to an urban location. If a secondary independent variable was significant at $p = 0.05$, such variable was retained in the decay model.

4.3 Development of Retroreflectivity Decay Models

Models were calibrated to predict decay of dry and wet retroreflectivity as a function of CTP for FTM and PPM. The sequential steps involved in developing decay models are listed below:

- Microsoft® Excel was used to generate scatter plots between dry (or wet) retroreflectivity and CTP.
- Then, first order linear, power, logarithmic, and exponential models were fitted to those scatter plots.
- The R^2 and the trend of the fitted models were used to identify two of the best forms of models for further testing. Emphasis was given to models that resulted in a good fit for retroreflectivity data close to minimum replacement threshold values. The reason for selecting such models is that the main purpose of this study is to determine the stage at which retroreflectivity fell below the minimum threshold retroreflectivity values.
- Thereafter, Minitab® software was used to further analyze the selected models. At this phase of analysis, secondary variables were added to determine if they significantly explained the degradation of retroreflectivity.
- Descriptive statistics such as ANOVA, F-statistic, t-significance, and diagnostic graphs such as normal probability plot of residuals were used for analyzing selected models.
- Finally, the best model(s) was selected for service life estimations.

The possibility of developing decay models by stratifying dry retroreflectivity data by ADT was investigated. Figures I-2 and J-2 of Appendix 2 show the distribution of the estimated ADT of test sites for 2002. Separate models were developed by forming two groups: one group contained test sites that were located on low volume roads (i.e., less than 5,000) and the other contained high volume roads (i.e., more than 5,000). This attempt did not yield statistically significant models at $p = 0.05$, and the idea of developing stratified models for different ADT classes was abandoned.

4.3.1 Dry Retroreflectivity Decay Models for FTM

This analysis used a total of thirty-six observations from twelve FTM test sites that showed a decrease in dry retroreflectivity from Test One to Test Three. Figure B-3 in Appendix 3 shows the relationship between dry retroreflectivity of FTM and CTP. This figure shows linear, exponential, logarithmic, and power models fitted to the data. The R^2 of fitted models are given in Table 4-1.

Table 4-1. Fitted models for FTM dry retroreflectivity vs. CTP

Coefficient of determination (R^2)			
Linear	**Exponential**	**Logarithmic**	**Power**
0.66	0.67	0.49	0.43

The regression equations and R^2 were used to identify the models that best fit the data. According to R^2 values, exponential and linear models gave the best fit for the combined database. In addition, these two models provided a better fit for low retroreflectivity values observed in field testing (see Figure B-3 of Appendix 3). Linear and exponential models were further analyzed using the regression option of the Minitab® software. The secondary variables were tested, but none of these variables proved to be statistically significant. The results of the regression analysis are given in Tables A-4 and B-4 of Appendix 4, and an abstract is presented Table 4-2.

Table 4-2. Selected decay models for FTM dry retroreflectivity

Model type	Coefficient and (p significance)			R^2	F-statistic
	Constant	CTP	Exp (CTP)		
Linear	310 (0.00)	-31.1 (0.00)		0.66	66.6
Exponential	329 (0.00)		-0.16 (0.00)	0.67	68.3

The following observations were made regarding the two models:

- The constant and the independent variable (i.e., CTP) are statistically significant at p = 0.01.
- The constant has a positive sign, and the variable CTP has a negative sign.
- The negative sign of the independent variable indicates dry retroreflectivity decreases with increase in CTP.

The normal probability plots of residuals of linear and exponential models shown in Tables A-4 and B-4 of Appendix 4 indicate that the residuals are normally distributed. This is confirmed by the Anderson-Darling test statistic, which is greater than 0.05. If this value is greater than 0.05, then the hypothesis that distribution of residuals is normal is accepted. There is one influential data points in each model, and both of these observations refer to March 2003 data from test location 651. An influential data point is one that has a significant effect in shaping the model of fit.

Overall, there was no statistically significant difference between linear and exponential models, and both the exponential and linear models were deemed acceptable for service life estimation of FTM. Thus, in future calculations, both models were run, and the average of the two predicted values was used. The main reason for selecting both models was the relative lack of field data near the potential minimum threshold values of 100 and 150 mcd/m^2/lux. Figure A-5 in Appendix 5 shows observed dry retroreflectivity values of FTM and the average of predicted values from linear and exponential models.

4.3.2 Dry Retroreflectivity Decay Models for PPM

A total of forty-two observations from fourteen PPM test sites that showed a decrease in dry retroreflectivity from Test One to Test Three were selected for analysis. The approach was similar to that used for developing decay models for dry FTM. Figure D-3 in Appendix 3 shows a scatter plot representing the relationship between dry retroreflectivity of PPM and CTP.

It appears that two test sites (six observations) that had accumulated more than 7.5 CTP had a high influence on the fitted models. These two sites were located on multi-lane roads with ADT greater than 20,000. Due to the significant influence of these two test sites, the fitted models appear to overestimate the values corresponding to observed field data that are near the potential minimum threshold values of 100 mcd/m^2/lux. Therefore, these models may overestimate the service life of PPM.

To evaluate the influence of those six observations on the decay model, another database was generated by excluding those six observations. Figure E-3 in Appendix 3 shows the variation of dry retroreflectivity of selected sites with CTP. Thereafter, a detailed regression analysis was performed for linear and logarithmic models for relationships shown in Figures D-3 and E-3 of Appendix 3. When comparing two databases, exponential and power models were not considered, as these two models closely resemble linear and logarithmic models respectively (see Figures D-3 and E-3 of Appendix 3). The results of regression analyses for selected models are given in Tables C-4 to F-4 of Appendix 4. The following observations were made when the two sets of models were compared:

- The R^2 value increased in both models when the two high ADT sites were excluded.
- The residual errors significantly decreased when the two high ADT sites were excluded.
- The numbers of observations with large standardized residuals decreased when the two high ADT sites were excluded.

The logarithmic model, which provides the best fit for both data sets, significantly overestimates the low retroreflectivity values. Therefore, the logarithmic model is not an appropriate choice to determine the service life of PPM, despite its higher R^2 values. Since the residual errors showed a significant reduction when results from two high ADT site were discarded, the scope of analysis of PPM data was limited to sites with ADT less than 20,000. Because these two high ADT sites were eliminated from decay models, the service life estimates for PPM are valid for markings installed on roads with ADT less than 20,000. Figures I-2 and J-2 in Appendix 2 show ADTs for the roads tested, and all but two exhibit ADT below 20,000, indicating that most ALDOT roads are covered in the analysis.

Figure E-3 in Appendix 3 indicates that linear and exponential models give the best estimate for low retroreflectivity values. As a result, linear and exponential models were selected over logarithmic and power models for service life estimation, despite their slightly lower R^2 values. The regression results of linear and exponential models are given in Tables E-4 and G-4 of Appendix 4, and a summary of regression analysis is presented in Table 4-3.

Table 4-3. Selected decay models for PPM dry retroreflectivity

Model type	Coefficient and (p significance)			R^2	F-statistic
	Constant	CTP	Exp (CTP)		
Linear	239 (0.00)	-28.9 (0.00)		0.53	38.0
Exponential	244 (0.00)		-0.16 (0.00)	0.55	41.1

There is one influential data point in each model, and both influential data points were from the March 2003 test data from location 653. It was noted that both FTM and PPM test sites that recorded influential observations were located on highways maintained by the Division 6 office of ALDOT. There is no significant difference between linear and exponential models in terms of statistical indicators. As a result, both models were selected for service life estimation. The characteristics of these models are similar to those of dry FTM decay models. Figure B-5 in Appendix 5 shows observed dry retroreflectivity values of PPM and average of predicted values from linear and exponential models.

4.3.3 Wet Retroreflectivity Decay Models for FTM

A total of twenty-one observations from seven FTM test sites that showed a decrease in wet retroreflectivity from Test one to Test three were used for developing decay models. Figure F-3 in Appendix 3 shows the scatter plot of wet retroreflectivity of FTM vs. CTP. According to this figure, wet retroreflectivity did not significantly decrease with increase in CTP. As can be seen from Table 4-4, there was no statistically significant relationship between wet retroreflectivity and CTP. Since none of these models represented a statistically significant relationship between retroreflectivity at p = 0.05, no decay model was established for wet retroreflectivity of FTM.

Table 4-4. Fitted models for FTM wet retroreflectivity vs. CTP

Coefficient of determination (R^2)			
Linear	**Exponential**	**Logarithmic**	**Power**
0.01	0.02	0.00	0.00

4.3.4 Wet Retroreflectivity Decay Models for PPM

There were thirty-three observations from eleven PPM test sites that showed a decrease in wet retroreflectivity from Test One to Test Three. Figure G-3 in Appendix 3 shows the relationship between wet retroreflectivity of PPM and CTP. One test site (three observations) that recorded over 40,000 ADT and more than 7.5 CTP exhibited a contrasting wet retroreflectivity decay pattern from the rest of the sites. The field data from this site had caused the models to deviate from low wet retroreflectivity values. To evaluate the effect of those three observations, regression models were calibrated by discarding those three observations. The fitted models for the new database are given in Figure H-3 in Appendix 3. Similar to dry PPM analysis, linear and logarithmic models were selected to compare the two databases. The results of regression analyses for selected models are given from Tables H-4 to K-4 of Appendix 4. If the models were not statistically significant at p = 0.05, normal probability plots were not generated. The following observations were made when the two sets of models were compared:

- The R^2 values of all models increased when data from the high ADT site were discarded.
- The residual errors decreased when data from the high ADT site were discarded.
- The linear model was statistically insignificant at p = 0.05 when data from the high ADT site were included in the analysis. When data from the high ADT site were removed from the analysis, the model became statistically significant at p = 0.05.

- The Anderson-Darling test indicated residuals of the two logarithmic models were non-normal. Therefore, logarithmic form was not considered for representing retroreflectivity decay of wet PPM.

Based on the above observations, data from the high ADT site were discarded from decay model development for wet FTM. The scope of analysis of wet PPM retroreflectivity decay was limited to roads with ADT less than 20,000. Based on Figure H-3 of Appendix 3, linear and exponential models were selected to predict the retroreflectivity decay of wet PPM. The regression analyses of those two models are given in Tables J-4 and L-4 of Appendix 4, and a summary of regression output is presented in Table 4-5. Since residual analysis did not indicate any significant differences between linear and exponential models, both models were chosen to represent the decay of wet retroreflectivity of PPM. Figure C-5 in Appendix 5 shows observed wet retroreflectivity values of PPM and the average of predicted values from linear and exponential models.

Table 4-5. Selected decay models for PPM wet retroreflectivity

Model type	Coefficient and (p significance)			R^2	F-statistic
	Constant	CTP	Exp (CTP)		
Linear	88 (0.00)	-7.5 (0.00)		0.40	18.6
Exponential	88 (0.00)		-0.11 (0.00)	0.42	20.6

As evident from the R^2 values in Tables 4-4 and 4-5, there was a better correlation between wet PPM data and CTP than between wet FTM data and CTP. Unlike FTM, PPM appears to adequately drain water from the markings in 35 seconds, thereby exposing glass beads to the laser scanner. Therefore, the wet retroreflectivity of PPM has a better correlation with the state of marking (represented by CTP) than FTM.

4.4 Discussion

This section discusses the estimation of retroreflectivity of new markings and the determination of the rate of decay of retroreflectivity of PPM and FTM using decay models.

4.4.1 Dry Retroreflectivity of New Markings

Theoretically, retroreflectivity of a new marking is the value of the dependent variable (i.e., retroreflectivity) when the value of CTP equals zero. Therefore, the value of the constant of the decay models is equal to the retroreflectivity value of a new marking. Table 4-6 gives dry retroreflectivity of new FTM and PPM and 95% confidence intervals of these estimations. The range given in Table 4-6 refers to the values predicted by the linear and exponential models for new markings, and the next column gives the average of those two values. The confidence interval accounts for the uncertainties in the estimation of a retroreflectivity value for a new marking. For example, it can be stated with 95% confidence that retroreflectivity of a new FTM is between 292 and 361 mcd/m^2/lux for the sites tested in this research. According to Table 4-6, the average dry retroreflectivity of a new PPM is around 75 percent of a new FTM.

Table 4-6. Estimated retroreflectivity of new FTM and PPM

Marking	Retroreflectivity (mcd/m^2/lux)		Confidence intervals	
	Range	Average	Lower 95%	Upper 95%
FTM	310-329	320	292	361
PPM	239-244	242	220	270

4.4.2 Wet Retroreflectivity of New Markings

The average wet retroreflectivity of new PPM is around 88 mcd/m^2/lux (see Table 4-5). Even though a decay model for wet retroreflectivity of FTM could not be established, it is evident from Figure F-3 of Appendix 3 that the wet retroreflectivity of new FTM is significantly less than 88 mcd/m^2/lux. In Figure F-3, none of the wet retroreflectivity values for FTM are even as high as 70 mcd/m^2/lux.

4.4.3 Comparison of Decay Rates of Dry Retroreflectivity of FTM and PPM

The rate of decay of dry retroreflectivity is represented by the coefficient of CTP. When FTM is considered, the linear model predicts an approximate retroreflectivity decrease of 31 mcd/m^2/lux per CTP (in millions). The corresponding decrease in PPM is 29 mcd/m^2/lux. According to exponential models, the rate of decrease of retroreflectivity decreases with increase in CTP. Tables 4-2 and 4-3 show that exponential models for FTM and PPM have equal coefficients of CTP (-0.16), so the decrease of retroreflectivity as a percentage of initial value is identical. For example, when FTM or PPM is exposed to the first 1.0 CTP, its retroreflectivity reduces by 15 percent. After approximately 4.0 CTP, the remaining retroreflectivity is 50 percent of its initial value.

Figure 4-2 shows dry retroreflectivity of FTM and dry and wet retroreflectivity of PPM, calculated as the average of linear and exponential decay models. In general, the gradients of dry retroreflectivity decay curves of FTM and PPM are similar.

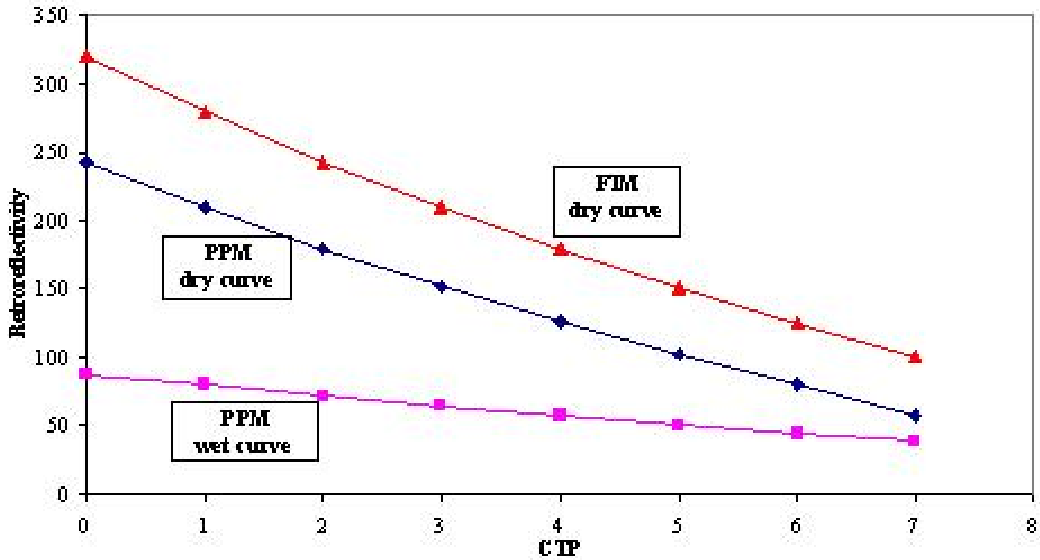


Figure 4-2. Variation of dry and wet retroreflectivity vs. CTP

4.4.4 Comparison of Decay Rates of Dry and Wet Retroreflectivity of PPM

Dry and wet retroreflectivity decay rates of PPM were compared using Figure 4-2. The wet retroreflectivity decay of FTM was not plotted since a statistically significant model could not be established. Figure 4-2 indicates that dry retroreflectivity of PPM decays at a faster rate than wet retroreflectivity. For example, when a new marking has accumulated 6.0 CTP, its wet retroreflectivity has decreased by 50 percent (i.e., from 88 to 44 mcd/m^2/lux) whereas dry retroreflectivity has decreased by 67 percent (i.e., from 242 to 80 mcd/m^2/lux).

Section 5
Service Life Estimation

This section presents service life estimations of FTM and PPM based on the dry retroreflectivity decay models. The service life of a pavement marking is the time or the number of traffic passages required for its retroreflectivity to decrease from its initial value to a minimum threshold value. Though presently there are no MUTCD specified minimum threshold values for replacement of a marking, the potential values suggested in an FHWA report were used as the bases for this analysis (FHWA 2000). These values were presented in Table 2-1 and are reproduced as Table 5-1. However, there have been other threshold retroreflectivity values suggested by previous studies (Migletz, *et al*. 1999 and Loetterle, *et al* 1999). These values ranged significantly, with the most common value being 100 mcd/m^2/lux (Bowman, *et al*. 2001).

Table 5-1. Threshold retroreflectivity values suggested by FHWA to define end of pavement marking service life (FHWA 2000)

Material	**Roadway type/speed classification**		
	Non-freeway ≤ 40 mph	**Non-freeway ≥ 45 mph**	**Freeway ≥ 55 mph**
White	85	100	150
White with lighting or RRPM	30	35	70
Yellow	55	65	100
Yellow with lighting or RRPM	30	35	70

RRPM – Raised retroreflective pavement markers
Retroreflectivity is in mcd/m^2/lux.

Table 5-1 defines threshold retroreflectivity based on speed limits. This table suggests using a threshold value for white edge lines of 85 mcd/m^2/lux when the speed limit is less than 40 mph, 100 mcd/m^2/lux when the speed limit is 45 mph, and 150 mcd/m^2/lux when the speed limit is 55 mph or greater. This thesis research did not develop decay models by segregating test data into speed classes. Therefore, this chapter will not estimate service lives for markings based on speed limits. The author selected potential threshold retroreflectivity values of 100 and 150 mcd/m^2/lux to determine the service lives of FTM and PPM. The threshold value of 85 mcd/m^2/lux was not used because few ALDOT roads have speed limits less than 40 mph.

5.1 Service Life in CTP

The selected retroreflectivity decay models for FTM and PPM reported in Section four are repeated below. These models were used to determine the CTP when pavement marking retroreflectivity reduced to potential threshold vales of 100 and 150 mcd/m^2/lux.

FTM Decay Models

$$(dry\ retroreflectivity)_{FTM} = 310 - 31.1 \times CTP \text{..............................} (Equation\ 5.1)$$

$$(dry\ retroreflectivity)_{FTM} = 329 \times \exp(-0.16 \times CTP) \text{....................} (Equation\ 5.2)$$

PPM Decay Models

$$(dry\ retroreflectivity)_{PPM} = 239 - 28.9 \times CTP \text{...............................} (Equation\ 5.3)$$

$$(dry\ retroreflectivity)_{PPM} = 244 \times \exp(-0.16 \times CTP) \text{......................} (Equation\ 5.4)$$

The service life of a marking (denoted as CTP_{SL}) was estimated using linear and exponential models separately. Then the average of those two values was selected as the service life of the marking. In addition, the 95% confidence interval of the estimate (i.e., average service life) was used to indicate the possible variation of service lives of markings that are installed on different ADT roads and in different geographic locations. The following equations show how the average service life is estimated from linear and exponential models.

$$(CTP_{SL})_{Linear} = \frac{(dry\ retroreflectivity)_{initial} - (dry\ retroreflectivity)_{threshold}}{(coefficient)_{CTP}} \text{.....} (Equation\ 5.5)$$

$$(CTP_{SL})_{Exponential} = \frac{\ln\left(\dfrac{(dry\ retroreflectivity)_{threshold}}{(dry\ retroreflectivity)_{initial}}\right)}{(coffficient)_{CTP}} \text{....................................} (Equation\ 5.6)$$

$$(CTP_{SL})_{Average} = \frac{(CTP_{SL})_{Linear} + (CTP_{SL})_{Exponential}}{2} \text{...} (Equation\ 5.7)$$

Table 5-2 gives the estimated service lives of FTM and PPM in terms of CTP. The results given in Table 5-2 lead to the following conclusions:

- FTM, which has a higher initial retroreflectivity, also has a longer service life than PPM.
- The difference between the service lives of FTM and PPM is constant irrespective of the threshold retroreflectivity value, which means both FTM and PPM lose retroreflectivity at the same rate.
- The 95% confidence interval is relatively large. Two possible reasons for a large confidence interval are the small sample size and/or a significant standard deviation of the average service lives of markings that belong to the same type (e.g., FTM).

Table 5-2. Estimated service lives in terms of CTP

Type of marking	Average service life in CTP (millions)			
	Threshold = 100 mcd/m^2/lux		Threshold = 150 mcd/m^2/lux	
	Average	95% confidence interval	Average	95% confidence interval
FTM	7.1	4.9-10.7	5.0	3.4-7.7
PPM	5.2	3.1-9.0	3.1	1.8-5.6

5.2 Expansion of Results

Service life is easier to interpret when it is expressed in terms of marking age than in terms of CTP. Equations 5.1 to 5.4 were used to predict the variation of dry retroreflectivity with time on roads with per lane ADT of 2,500, 5,000, 7,500, and 10,000. Tables A-6 and B-6 of Appendix 6 give these predictions, and Figures A-6 and B-6 of Appendix 6 present a graphical view of those retroreflectivity estimations. Figures A-6 and B-6 show that markings installed on high ADT roads lose retroreflectivity faster than those on low volume roads.

Table 5-3 gives the estimated ages of FTM and PPM when their dry retroreflectivity fell below 100 and 150 mcd/m^2/lux for selected ADT values. The values given in Table 5-3 were estimated from the results presented in Table 5-2. Table 5-3 does not present exact values of service life estimations that resulted in more than 60 months. This research did not test markings that were more than four years old. Therefore, extrapolation of results beyond twelve months of the actual age of markings that were tested was thought to be inappropriate. In addition, it was suspected that there is an increasing contribution of environmental factors to marking deterioration in addition to the traffic effect. Since environmental effects are not incorporated in the decay models, any service life predictions over 60 months are listed as 60+ in Table 5-3.

Table 5-3. Estimated service lives in terms of age of markings

ADT per lane	Average service life in months							
	Threshold = 100 mcd/m^2/lux				Threshold = 150 mcd/m^2/lux			
	FTM		PPM		FTM		PPM	
	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.
2,500	60+	60+	60+	41-60+	60+	45-60+	42	24-60+
5,000	46	33-60+	34	21-60	34	23-51	20	12-37
7,500	31	22-48	23	14-40	22	15-34	14	8-25
10,000	23	16-36	17	10-30	17	11-26	10	6-19

Avg. = average; C.I. = confidence interval.

When interpreting the results given in Table 5-3, the following factors need to be considered:

- The retroreflectivity decay models were calibrated using data from test sites on roads where the ADTs were less than 20,000 vehicles. As a result, the predicted service lives are appropriate for such roads.
- The age of markings tested by this study ranged from 5 to 47 months.

The main observations from Table 5-3 are listed below:

- On low volume roads (i.e., per lane ADT of 2,500 and less), irrespective of the threshold retroreflectivity value, the average service life of FTM is more than 60 months. The PPM on such roads has an average service life of 42 months when a threshold value of 150 mcd/m^2/lux is used, and it increases to more than 60 months when threshold value is reduced to 100 mcd/m^2/lux.
- On two-lane roads of 20,000 ADT and less (i.e., per lane ADT of 10,000 and less), the average service lives of FTM and PPM are less than 24 months.
- Since most of the markings tested were on roads that had experienced traffic volumes of 10,000 ADT and less (see Figures I-2 and J-2 of Appendix 2), the estimations given in the first two rows of Table 5-3 (i.e., ADT per lane =2,500 and 5,000) may be viewed as typical service lives of FTM and PPM that were tested by this study.
- According to the above argument, if markings were to be replaced when the retroreflectivity fell below 100 mcd/m^2/lux, FTM on roads of per lane ADT of 5,000 and less lasts from 46 to 60+ months, and PPM lasts from 34 to 60+ months. Similarly if a replacement threshold value of 150 mcd/m^2/lux is selected, FTM lasts from 34 to 60+ months, and PPM lasts from 20 to 42 months.
- The results given in Table 5-3 indicate FTM to have 6 months of more useful life than PPM on similar ADT roads. This conclusion is based on dry retroreflectivity values.

5.3 Wet Retroreflectivity of PPM at the End of Service Life

The estimated service life of PPM in CTP (see Table 5-2) was used to determine the wet retroreflectivity of PPM when the dry retroreflectivity fell below minimum threshold values of 100 and 150 mcd/m^2/lux. These wet retroreflectivity values are given in Table 5-4.

Table 5-4. Wet retroreflectivity of PPM at minimum threshold dry values

Threshold dry retroreflectivity 100 mcd/m^2/lux		Threshold dry retroreflectivity 150 mcd/m^2/lux	
Average	95% confidence interval	Average	95% confidence interval
50	21-77	64	44-86

Table 5-4 shows that the wet retroreflectivity of PPM is 0.50 and 0.43 times the threshold dry values of 100 and 150 mcd/m^2/lux. This difference in percentage is due to the different degradation rates of dry and wet retroreflectivity of PPM. Similar values for FTM were not estimated, because a statistically valid wet retroreflectivity decay curve could not be established.

5.4 Comparison with the FHWA Study Results (FHWA 2000)

The service life estimations for FTM and PPM by the FHWA study are given in Table 2-2 and are reproduced below as Table 5-5. A direct comparison of the results of the FHWA study with the results of this project is difficult due to the following reasons:

- The research project did not estimate the service lives of markings based on speed limits.
- The FHWA study used method two described in the Decay Model section to calibrate models, whereas this research project used method one.
- The FHWA presented average service lives of markings that were located in different states. Some of these sites were located in areas where markings deteriorated rapidly due to road snow removal activities.

Table 5-5. Estimated service life for FTM and PPM edge lines based on dry retroreflectivity for sites without roadway lighting or RRPM by FHWA (2000)

Roadway type	Material	Number of pavement markings in tests series	Service life in:		
			CTP (million vehicles)	Elapsed months	
			Average	Average	Range
Freeway ≥ 55 mph	FTM	14	7.5	22.6	7.4-49.7
	PPM	7	6.5	18.4	4.7-35.6
Non-freeway ≤ 40 mph	FTM	N/A	N/A	N/A	N/A
	PPM	1	25.1	55.7	-
Non-freeway ≥ 45 mph	FTM	5	6.0	36.6	26.5-49.1
	PPM	6	3.7	24.9	23.8-26.2

RRPM – Raised retroreflective pavement markers

Both studies indicated FTM has a longer service life than PPM. However, these markings may have been installed by different contractors using specifications of different highway agencies. A notable difference between the results of the FHWA study and this research is that the FHWA results indicated both FTM and PPM installed on freeways (speed limit ≥ 55mph) have a higher service life in terms of CTP than the markings on non-freeways (speed limit ≥ 45 mph). At first glance, this seems counterintuitive, as a higher threshold retroreflectivity was used to determine the service lives of markings installed on freeways (150 mcd/m^2/lux) than on non-freeways (100 mcd/m^2/lux).

A possible explanation is that freeway and non-freeway markings tested for the FHWA study were located in different states. For example, the FTM freeway test sites were located in Colorado, Louisiana, Oklahoma, and Utah, whereas the FTM non-freeway sites were located in Kansas, Missouri, and New Hampshire. Previous studies indicated geographic and climatic conditions affect the service life of markings (FHWA 2000 and Bowman, *et al*. 2001). Another possibility is that the ADT of tested non-freeways was less than the ADT of freeways. As a result, the markings on non-freeways lasted a longer time despite the fact that their service lives are lesser in terms of CTP. This claim is reinforced by Table 5-5, which indicates a longer service life of markings on non-freeways (FTM=36.6 months, PPM=24.9 months) than on freeways (FTM=22.6 months, PPM=18.4 months).

Section 6
Dry and Wet Retroreflectivity Correlation Analysis

This section describes the development of a correlation between dry and wet retroreflectivity that predicts wet retroreflectivity when dry retroreflectivity is known. A correlation model gives an approximate method for estimating wet retroreflectivity without having to measure it. This model is easy to use as it is devoid of parameters such as age of marking and ADT of the road. A correlation model can also be used to predict the wet retroreflectivity of a marking that corresponds to its minimum threshold dry retroreflectivity value. Therefore, a correlation model can help highway agencies make more rational judgments about replacing a marking by taking into consideration wet-night retroreflectivity as well as dry retroreflectivity.

6.1 Development of Correlation Models

The correlation models were developed using all dry and wet retroreflectivity data that were collected during three field tests. The reason for not discarding any inconsistent data, as was done when developing decay models, is that correlation models do not have any time sensitive variables (e.g., CTP). When dry retroreflectivity increased at a test location from Test One to Test Two or Test Three, almost invariably, wet retroreflectivity also increased. Therefore, retaining such data does not affect correlation models.

Similar to the approach adopted for developing retroreflectivity decay models, the first step of the correlation analysis was to generate scatter plots between wet and dry retroreflectivity. A total of forty-eight dry and wet retroreflectivity observations from sixteen FTM test sites and sixty-three such observations from twenty-one PPM test sites were used for correlation analysis. Figures A-7 and B-7 of Appendix 7 show the relationships between dry and wet retroreflectivity of FTM and PPM.

In addition to developing a single correlation model by considering all data for one type of marking (e.g., FTM), the possibility of developing separate models by stratifying retroreflectivity data was tested in several ways:

- <u>Grouping dry and wet retroreflectivity data into separate categories by the values of dry retroreflectivity.</u> Different threshold values were considered for categorization. For example, in one attempt, data was divided into three groups: the first group contained dry and wet retroreflectivity data in which dry retroreflectivity was less than 200 mcd/m^2/lux, the second group corresponded to dry values between 200 and 300 mcd/m^2/lux, and the last group was made of dry and wet data where dry retroreflectivity exceeded 300 mcd/m^2/lux. However, this approach did not show any significant variation between the correlations of dry and wet retroreflectivity of different categories.

- <u>Grouping dry and wet retroreflectivity data by ADT of test roads.</u> The purpose of this categorization was to examine if traffic volume affected dry and wet retroreflectivity correlation. But, there were no significant differences between the retroreflectivity correlations for different ADT strata.

Therefore, no sub-division of data was made for developing correlation models. The fitted correlation models using all FTM and PPM data are given in Figures A-7 and B-7 of Appendix 7. Since there are no significant statistical differences between linear and non-linear models, the linear model was selected. The main advantage of the linear model is its ease of use; one of the objectives of the correlation analysis was to develop an easy-to-use model. Tables A-7 and B-7 of Appendix 7 provide results of the analysis of linear models, which include estimates of standard errors and confidence limits of constants and independent variables. Table 6-1 provides a summary of the selected correlation models for FTM and PPM.

Table 6-1. Selected linear correlation models for FTM and PPM

Marking	Parameter	Coefficient and (p significance)	Confidence limits		R^2
			Lower 95%	Upper 95%	
FTM	Constant	7 (0.45)	-11	25	0.20
	Dry retroreflectivity	0.12 (0.00)	0.05	0.19	
PPM	Constant	12 (0.23)	-7	30	0.40
	Dry retroreflectivity	0.32 (0.00)	0.22	0.42	

According to the R^2 value, PPM had a better correlation between dry and wet retroreflectivity than FTM. The constant terms of both models were statistically insignificant at $p = 0.05$, and the independent variable was statistically significant at $p = 0.01$. These two correlation models were used to predict the following:

- Wet retroreflectivity of new FTM and PPM
- Wet retroreflectivity of FTM and PPM at potential threshold dry retroreflectivity values

6.2 Prediction of Wet Retroreflectivity of New FTM and PPM

Table 6-2 gives the estimated wet retroreflectivity values of new markings and their 95% confidence intervals. The wet retroreflectivity of new FTM is about 14 percent of its corresponding dry retroreflectivity. In comparison, wet retroreflectivity of new PPM is about 37 percent of its dry retroreflectivity. Large 95% confidence intervals of wet retroreflectivity values for FTM and PPM indicate that there is a significant variation of the predicted wet retroreflectivity of new markings. According to Table 6-2, the average wet retroreflectivity of new FTM is approximately 50 percent of the average wet retroreflectivity of new PPM. This result indicates that new PPM gives better wet-night visibility to drivers than new FTM.

Table 6-2. Wet retroreflectivity of new markings

Marking	Average dry retroreflectivity	Average wet retroreflectivity	Confidence limits of wet retroreflectivity	
			Lower 95%	Upper 95%
FTM	320	45	5	86
PPM	242	89	46	132

6.3 Prediction of Wet Retroreflectivity at Threshold Dry Values

Table 6-3 gives estimated wet retroreflectivity of markings when the dry retroreflectivity is equal to potential threshold values of 100 and 150 mcd/m^2/lux. The estimated wet retroreflectivity of FTM is 19 percent of its threshold dry retroreflectivity of 100 mcd/m^2/lux. In comparison, the estimated wet retroreflectivity of PPM is about 44 percent of its threshold dry retroreflectivity of 100 mcd/m^2/lux. A comparison of values in Tables 6-2 and 6-3 indicates that the average wet retroreflectivity of PPM at the end of its life is as high as the wet retroreflectivity of new FTM at the beginning of its life. However, currently there are no accepted minimum wet retroreflectivity requirements for pavement markings. Therefore, the service lives of FTM and PPM could not be determined in terms of wet retroreflectivity. It would be instructive to evaluate the adequacy of wet retroreflectivity values of FTM and PPM at the two minimum threshold dry retroreflectivity values using the opinions of human subjects.

Table 6-3. Wet retroreflectivity at threshold dry values

Marking	Threshold dry retroreflectivity 100 mcd/m^2/lux		Threshold dry retroreflectivity 150 mcd/m^2/lux	
	Average	95% confidence interval	Average	95% confidence interval
FTM	19	0-44	25	0-54
PPM	44	15-72	64	26-93

6.4 Comparison of Wet Decay and Correlation Models of PPM

Wet retroreflectivity of PPM was predicted by two models: the correlation model and the decay model. The wet retroreflectivity values predicted by those two models for new markings and for threshold dry values are given in Table 6-4. Both models give almost identical predictions for wet retroreflectivity of PPM. Since the predictions are similar for new markings and old markings, both models appear to be consistent with each other. This analysis may be considered as an indirect validation of the two models.

Table 6-4. Comparison of two wet retroreflectivity models for PPM

Estimate	Decay model		Correlation model	
	Average	95% confidence interval	Average	95% confidence interval
Retroreflectivity of new marking	88	77-100	89	46-132
Threshold 100 mcd/m^2/lux	50	21-77	44	15-72
Threshold 150 mcd/m^2/lux	64	44-86	64	26-93

Section 7
Crash Data Analysis

This portion of the study involves an analysis of crash data at sites with FTM and PPM markings. If one type of marking exhibits a significantly lower crash rate than the other, that fact could significantly impact which of the two is preferred for use in ALDOT-controlled roads.

Until early 1999, almost all ALDOT highways had FTM. Since that time, many rehabilitation projects used FTM, and many others used PPM. ALDOT provided the research team a list of projects from early 1999 to early 2001 that involved laying new markings. The Critical Analysis Reporting Environment (CARE) database provided detailed crash information for calendar years 1996-2002 (University of Alabama 2003). Thus, at least three years of crash data was available before each new marking was laid, and at least two years of crash data was available after each new marking was laid. Two analyses were performed using the crash data:

- One analysis compared crashes at the sites before new marking was laid with crashes at the same sites after new marking was laid. If one type of marking had a greater reduction in crash rate than the other marking type, then that result would be significant.
- A second analysis compared "before" crashes at sites with FTM to "before" crashes at sites with PPM and also compared "after" crashes at sites with FTM to "after" crashes at sites with PPM. If the relative rates of crashes changed from "before" to "after," that finding also would be significant.

7.1 Methodology

ALDOT provided location data, average daily traffic (ADT), and marking material data for 217 sites that had been provided with new markings between early 1999 and early 2001. The UTCA study team excluded all sites shorter than one mile because it felt crash data could be incomplete for sections shorter than that length. That exercise left 103 sections for analysis: 55 PPM sites and 48 FTM sites. The 55 PPM sites represented 378 centerline miles of road with ADTs ranging from 1,345 vpd to 77,256 vpd. The 48 FTM sites represented 357 centerline miles of road with ADTs ranging from 880 vpd to 74,182 vpd. In all, approximately 6,000 crashes were evaluated.

Each of the two major analyses contained 19 sub-analyses, one sub-analysis for each of the following categories of crashes:

- All crashes
- Night crashes

- Wet pavement crashes
- Wet/night crashes
- Rural crashes
- Urban crashes
- Two-lane road crashes
- Multi-lane road crashes
- Wet/night/rural crashes
- Wet/night/urban crashes
- Wet/night/2-lane crashes
- Wet/night/multi-lane crashes
- Wet/night/rural/2-lane crashes
- Wet/night/urban/2-lane crashes
- Off-road crashes
- Vehicle left road crashes
- Rainy day crashes
- Wet/night/off road crashes
- Wet/night/vehicle left road crashes

Other types of crashes could have been considered. For example, crashes could have been broken further into fatal, injury, and property-damage-only crashes. However, considering the limited number of sites available for analysis, the research team concluded that the most useful sub-analyses were represented in the 19 listed. Another further analysis that would have been useful to differentiate between such factors as roads with shoulders and roads without shoulders, or between roads with rumble strips and those without rumble strips. However, the number of road sections was insufficient to differentiate between additional factors that might have affected crash rates.

As previously related, the sites varied considerably with respect to the traffic volume, site length, and number of years of "before" and "after" data. To diminish the effect of these factors, at each study site the number of crashes to be used in the analyses was normalized with respect to ADT, length, and number of years of available crash data. The value thus obtained was multiplied by 10^8 to result in easily-recognizable values. The following formula was used to obtain two crash values for each site for each sub-analysis: one for "before" the application of new markings and one for "after" the application of new markings.

$$Crash\,Value = \frac{(Crashes)*(10^8)}{(Length\,of\;\;site)*(ADT)*(Number\;of\;\;years)*(365)} \qquad \text{(Equation 7.1)}$$

The units of crash value in equation 7.1 are crashes per year per 100 million vehicle-miles. Researchers calculated separate ADT for each site for its "before" and "after" conditions by averaging the ADT values during the number of years in that condition.

7.2 First Analysis

The first statistical crash data analysis compared crash values at the sites before new markings were laid with crash values at the same sites after new marking was laid. A one-tailed student "t" test was employed to check for a statistically significant reduction in the average crash value of the "after" data compared to the "before" data. Each of the 19 sub-analyses contained a different number of test sites that sustained crashes fitting that category. In each of the sub-analyses performed, the average of the crash values of all pertinent sites was used for the comparison.

Table 7-1 shows the results of the first test. The results of two "t" tests are shown in each row in the table: Table 7-1a for FTM and Table 7-1b for PPM. The following list highlights the parameters of greatest interest in Table 7-1.

- Table 7-1a compares crash values of sites that had previously used FTM and replaced it with new FTM during an overlay procedure.
- Table 7-1b compares crash values of sites that had previously used FTM but switched to PPM during an overlay procedure.
- The 19 sub-analyses are listed in the column labeled "Condition".
- The "Number of Sites" columns show the number of sites that sustained crashes fitting the analysis. It is generally agreed that 30 or more sites are required for full confidence in the results of the "t" test.
- "% change" compares the crash value "before" with the crash value "after." A positive value indicates that crash rates increased from "before" to "after." A negative value indicates that crash rates decreased from "before" to "after."
- The "α" column indicates the statistical confidence in the result of the "t" test. A low value (say 0.10) translates to a 90% confidence that crashes decreased from "before" to "after." A high value (say 0.90) translates to a 90% confidence that crashes increased from "before" to "after." A value of 0.50 indicates that there was essentially no change in the crash rate.

A review of results of several major sub-analyses in Tables 7-1a and 7-1b reveals that, in general, PPM provided no greater decrease in crash rate from "before" to "after" than FTM did, and in some instances FTM appeared to provide a more significant decrease:

- For "All" crashes, PPM provided a 0% decrease in crash rates, and this lack of change is supported by an α of 0.48. FTM provided a 6% decrease in crash rates, and the α value of 0.23 indicates a 77% confidence that the decrease is statistically significant.
- For "Wet & Night crashes," PPM provided a 19% decrease, while FTM provided a 20% decrease.
- For "Wet, Night, Rural" crashes, PPM exhibited a 23% increase, while FTM provided a 32% decrease.
- For "Wet, Night, Off Road" crashes, a type of crash thought by the researchers to be particularly affected by edge lines, PPM provided a 21% decrease, while FTM provided a 26% decrease.

Other rows in Tables 7-1a and 7-1b exhibit interesting differences in “% change.” The following observations are noteworthy:

- For “Multi-Lanes” crashes, PPM exhibited a 9% increase in crash rates, while FTM exhibited a 37% increase in crash rates. However, neither PPM nor FTM had enough sites (17 and 15, respectively) for statistical confidence in the results.
- For “Wet, Night & 2-Lanes” and “Wet, Night, Rural & 2-Lanes” crashes, PPM exhibited a 20-30% increase in crashes, while FTM exhibited a 30-40% decrease in crashes. There were 27 or more FTM and PPM sites for each of those two categories. Note that this did not meet the requirement for a minimum of 30 sites per category, but there was a greater decrease in crash rates of FTM sites.

Table 7-1a. ‘Before’ vs. ‘After’ comparison of FTM crash data

Condition	Number of sites	Average crashes (per year)		Crash Value (crashes/yr/100 million veh-mile)				
		Bef	After	Bef	After	% change	t stat	α
All	48	1,559	1,654	115.6	108.8	-6%	0.752	0.23
Night	45	411	439	37.0	33.3	-10%	0.886	0.19
Wet	44	408	506	31.9	28.6	-10%	0.555	0.29
Wet & Night	36	113	150	12.4	9.9	-20%	0.870	0.20
Rural	44	547	536	104.2	98.0	-6%	0.553	0.29
Urban	3	870	957	185.7	194.5	+5%	-1.728	0.89
Two-Lanes	32	417	386	129.9	114.4	-12%	1.282	0.10
Multi-Lanes	15	890	991	43.6	59.8	+37%	-1.482	0.92
Wet, Night & Rural	33	44	36	12.3	8.4	-32%	1.321	0.10
Wet, Night & Urban	3	61	103	9.8	18.0	+84%	-1.812	0.89
Wet, Night & 2-Lanes	27	31	26	12.7	8.6	-32%	1.195	0.12
Wet, Night & Multi-lanes	9	66	103	6.8	9.5	+40%	-0.909	0.81
Wet, Night, Rural & 2-Lanes	27	30	23	12.5	7.5	-40%	1.510	0.07
Wet, Night, Urban & 2-Lanes	3	6	8	0.5	2.0	+300%	-0.922	0.77
Off Road	44	309	366	42.5	49.3	+16%	-1.009	0.84
Vehicle Left Road	22	19	24	5.3	4.0	-25%	0.397	0.35
Raining	43	298	380	22.7	23.7	+4%	-0.181	0.57
Wet, Night, Off road	31	43	61	9.2	6.8	-26%	0.797	0.22
Wet, Night, Veh. Left road	8	2	4	1.0	0.4	-60%	0.934	0.19

Table 7-1b. 'Before' vs. 'After' comparison of PPM crash data

Condition	Number of sites	Average crashes (per year)		Crash Value (crashes/yr/100 million veh-mile)				
		Bef	After	Bef	After	% change	t stat	α
All	55	2,927	2,902	357.9	356.4	0%	0.054	0.48
Night	50	695	685	89.6	82.1	-8%	0.574	0.28
Wet	50	648	647	79.9	78.2	-2%	0.190	0.43
Wet & Night	46	168	155	23.4	19.0	-19%	0.804	0.21
Rural	43	965	879	84.6	78.5	-7%	1.019	0.16
Urban	10	1,764	1,814	1,488.9	1,542.1	+4%	-0.343	0.63
Two-Lanes	35	364	364	78.3	76.7	-2%	0.256	0.40
Multi-Lanes	17	1,984	2,067	719.0	781.9	+9%	-0.778	0.78
Wet, Night & Rural	36	56	58	6.2	7.6	+23%	-0.974	0.83
Wet, Night & Urban	10	102	86	83.3	58.7	-30%	0.962	0.18
Wet, Night & 2-Lanes	28	25	26	6.3	7.9	+25%	-1.002	0.84
Wet, Night & Multi-lanes	16	112	109	42.7	33.7	-21%	0.750	0.23
Wet, Night, Rural & 2-Lanes	26	19	20	5.9	7.6	+29%	-1.000	0.84
Wet, Night, Urban & 2-Lanes	2	3	3	6.6	6.0	-9%	1.200	0.22
Off Road	49	363	404	37.7	42.0	+11%	-1.318	0.91
Vehicle Left Road	32	28	37	3.3	6.8	+106%	-3.480	1.00
Raining	48	497	519	62.4	63.7	+2%	-0.165	0.57
Wet, Night, Off road	34	45	40	6.6	5.2	-21%	1.044	0.15
Wet, Night, Veh. Left road	10	3	1	0.5	1.8	+260%	-1.147	0.86

7.3 Second Analysis

A possible drawback of the first analyses is that it compared crashes that occurred on worn road surfaces and worn out markings with crashes that occurred on the same sites after they were re-paved and given new markings. To investigate whether that factor significantly affected the outcome of results given in Table 7-1, the second analysis was performed. The second analysis included two sub-analyses:

- Table 7-2a compares crashes that occurred on sites with worn FTM, before they were eventually replaced with new PPM, with crashes that occurred on sites with worn FTM, before they were eventually replaced with new FTM (i.e., the Before vs. Before analyses), and

- Table 7-2b compares crashes that occurred on sites with new PPM, which previously had worn FTM, with crashes that occurred on sites with new FTM, which previously had worn FTM (the After vs. After analyses).

As in the first analyses, 19 sub-analyses were performed for the two sub-analyses, and the results are shown in Table 7-2.

The "% difference" column of Table 7-2a compares crash values between the "Before" condition of PPM and the "Before" condition of FTM. The "% difference" column of Table 7-2b compares crash values between the "After" condition of PPM and the "After" condition of FTM. If the After vs. After analysis contains a lower value than the Before vs. Before analysis, that result indicates that FTM produced a lower rate of crashes than the PPM. The following sample results indicate that After vs. After values were similar to or lower than Before vs. Before values, reinforcing the results found in the first analysis:

- For "All" crashes, FTM sites exhibited a 68% less crash value than PPM sites before the pavements were overlaid and new markings were installed. After the installation of new markings, FTM sites exhibited a similar (69%) "% difference" compared to the newly laid PPM sites. Alpha statistics of 0.07 and 0.08 indicate that FTM sites continually exhibited a statistically lower crash rate than PPM sites even after the introduction of new markings. Moreover, a comparison of before and after crash values of FTM and PPM sites indicate that the crash values virtually remained unchanged from "Before" condition to "After" condition.
- Other major sub-analyses such as "Night," "Wet", "Wet & Night," and "Rural" showed a similar trend to "All" category.
- "Wet, Night, rural" and "Wet, Night, Off Road" showed significant decreases in "% difference," +98% vs. +11% and +39% vs. + 31%, respectively.

7.4 Summary

Overall, crash analyses did not indicate that PPM produces lower crash rates than FTM. For example, comparisons of all crashes, night crashes, and wet crashes indicate that FTM and PPM produce similar crash rates or show that FTM produces somewhat lower crash rates. For crash types thought to be particularly affected by edge marking type (such as wet night, off road crashes or wet, night, rural crashes) the crash results were similar. There were also a considerable number of crash types for which insufficient numbers of sites were available to produce statistically significant findings.

Table 7-2a. 'Before' vs. 'Before' comparison of crash data

Condition	Number of sites		Average crash values		% difference	Statistical comparison	
	PPM	FTM	PPM	FTM			
			Before	Before		t stat	α
All	55	48	357.9	115.6	-68%	1.47	0.07
Night	50	45	89.6	37.0	-59%	1.32	0.09
Wet	50	44	79.9	31.9	-60%	1.31	0.10
Wet & Night	46	36	23.4	12.4	-47%	0.97	0.17
Rural	43	44	84.6	104.2	+23%	-1.18	0.88
Urban	10	3	1488.9	185.7	-88%	1.57	0.06
Two-Lanes	35	32	78.3	129.9	+66%	-2.75	1.00
Multi-Lanes	17	15	719.0	43.6	-94%	1.66	0.05
Wet, Night & Rural	36	33	6.2	12.3	+98%	-1.99	0.98
Wet, Night & Urban	10	3	83.3	9.8	-88%	1.56	0.06
Wet, Night & 2Lanes	28	27	6.3	12.7	+102%	-1.85	0.97
Wet, Night & Multi-lanes	16	9	42.7	6.8	-84%	1.55	0.06
Wet, Night, Rural & 2-Lanes	26	27	5.9	12.5	+112%	-1.88	0.97
Wet, Night, Urban & 2-Lanes	2	3	6.6	0.5	-92%	3.85	0.00
Off Road	49	44	37.7	42.5	+13%	-0.46	0.68
Vehicle Left Road	32	22	3.3	5.3	+61%	-0.71	0.76
Raining	48	43	62.4	22.7	-64%	1.39	0.08
Wet, Night, Off Road	34	31	6.6	9.2	+39%	-0.77	0.78
Wet, Night, Veh. Left road	10	8	0.5	1.0	+100%	-1.03	0.85

Table 7-2b. 'After' vs. 'After' comparison of crash data

Condition	Number of sites		Average crash values		% difference	Statistical comparison	
	PPM	FTM	PPM	FTM			
			After	After		t stat	α
All	55	48	356.4	108.8	-69%	1.39	0.08
Night	50	45	82.1	33.3	-59%	1.45	0.07
Wet	50	44	78.2	28.6	-63%	1.40	0.08
Wet & Night	46	36	19.0	9.9	-48%	1.27	0.10
Rural	43	44	78.5	98.0	+25%	-1.17	0.88
Urban	10	3	1542.1	194.5	-87%	1.48	0.07
Two-Lanes	35	32	76.7	114.4	+49%	-1.83	0.97
Multi-Lanes	17	15	781.9	59.8	-92%	1.54	0.06
Wet, Night & Rural	36	33	7.6	8.4	+11%	-0.40	0.16
Wet, Night & Urban	10	3	58.7	18.0	-69%	1.39	0.08
Wet, Night & 2Lanes	28	27	7.9	8.6	+9%	-0.29	0.62
Wet, Night & Multi-lanes	16	9	33.7	9.5	-72%	1.47	0.07
Wet, Night, Rural & 2-Lanes	26	27	7.6	7.5	-1%	0.04	0.48
Wet, Night, Urban & 2-Lanes	2	3	6.0	2.0	-67%	2.52	0.01
Off Road	49	44	42.0	49.3	+17%	-0.59	0.72
Vehicle Left Road	32	22	6.8	4.0	-41%	1.43	0.00
Raining	48	43	63.7	23.7	-63%	1.37	0.08
Wet, Night, Off Road	34	31	5.2	6.8	+31%	-0.99	0.84
Wet, Night, Veh. Left road	10	8	1.8	0.4	-78%	1.37	0.08

Section 8
Life Cycle Cost Analysis

This section presents a life cycle cost analysis (LCCA) economic evaluation of FTM and PPM as they are used by ALDOT. LCCA determines the total cost of constructing, owning, and operating a facility (in this instance, pavement markings) over a period of time. The purpose of LCCA is to determine which of the two markings is more cost effective (i.e., less expensive).

8.1 Input Data

A list of the main input data for LCCA follows:

- Installation costs
- Maintenance/refurbishment costs
- Performance period of markings
- Study period (life cycle)

ALDOT provided typical maintenance costs and service lives of FTM and PPM. The service lives from ALDOT generally corresponded to service lives of FTM and PPM determined in Chapter 5. The study team obtained average installation costs of FTM and PPM from ALDOT's web site (ALDOT 2002) that provides contract letting information.

The study period was set at eight years, the life of a typical asphalt overlay. At the beginning of a cycle, new markings are placed on a new overlay and maintained as needed. When the overlay is eventually covered by a succeeding overlay and its new markings, the life cycle is completed. The data utilized for LCCA calculations are presented below.

8.1.1 Installation Costs

Table 8-1 presents average costs incurred by ALDOT for installing one mile of FTM and PPM edge lines in 2002. The table indicates that installing PPM is roughly 3.5 times more expensive than installing FTM. Another observation is that installation costs decreased somewhat when project length increased.

Table 8-1. Installation costs of FTM and PPM edge lines (ALDOT 2002)

Type	Length of project	Sample size	Average cost per mile ($)	St. deviation of cost ($)	Grand average ($)	Grand St. deviation ($)
FTM	< 3 mi	2	1,390.00	160.00	1,245.00	155.00
	> 3 mi	17	1,230.00	150.00		
PPM	< 3 mi	6	4,450.00	465.00	4,130.00	325.00
	> 3 mi	25	4,055.00	240.00		

8.1.2 Maintenance/Refurbishment Costs

Two divisional offices of ALDOT (Divisions 3 and 6) provided typical costs per mile to maintain edge markings, which includes applying a layer of paint on the existing thermoplastic markings and adding glass beads. The maintenance costs given in Table 8-2 include labor, equipment, paint, and beads. PPM has been used for such a short time that no maintenance costs have been generated for it, so the values in Table 8-2 were also used for PPM during LCCA calculations.

Table 8-2. Maintenance costs of FTM and PPM edge lines

ALDOT division	Service life (years)	Cost of maintenance ($ per edge line per mile)
Division 3	5	134.00
Division 6	2	114.00

Table 8-2 also indicates that Divisions 3 and 6 re-paint markings every two to five years. Researchers used those values as the service life of edge markings during LCCA calculations.

8.2 LCCA Methodology and Results

The researchers performed two LCCAs using Probabilistic LCCA 1.0 software, which was developed by the FHWA. The first scenario included first maintenance after five years; the second scenario involved maintenance performed every two years. The LCCA model and associated terminologies are presented below.

$$PV = A_0 + \sum A_t \times \left(\frac{1}{(1+i)^t} \right) \text{..} (\mathit{Equation}\ 8.1)$$

Where:

- Present value (PV) is the time equivalent value of past, present or future cash flows as of the beginning of the base year (i.e., 2002) (Fuller, *et al*. 1996).
- Discount rate (i) is an interest rate that reflects the time value of money. A discount rate of 4%, which is a typical value used in LCCA, was used in this analysis.
- Time (t) is the time period(s) at which future costs (maintenance costs) are incurred (e.g., at 2-year intervals).
- Initial cost (A_0) is the installation cost (see Table 8-1).
- A_t is the maintenance costs incurred at time t (see Table 8-2).

The expenditure stream diagrams for the two scenarios are given in Figures 8-1 and 8-2. A summary of results is given in Table 8-4, which indicates that the life cycle cost of FTM is clearly lower than that of PPM for both analyses, with PVs of $1,355 for FTM and $4,240 for PPM in the five-year maintenance scenario.

The LCCAs performed for this project only considered initial costs and maintenance costs. The researchers had planned to investigate offsetting some of the higher PPM costs by including a benefit to PPM for costs saved from any reduction in crashes PPM might bring. However, Chapter 7, Crash Data Analysis, indicates that PPM has not reduced crashes on Alabama highways, so crash reduction savings were not included in the analyses.

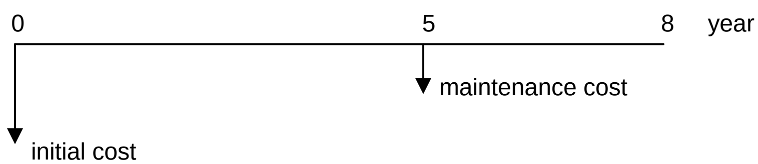


Figure 8-1. Cash flow stream with maintenance after 5 years

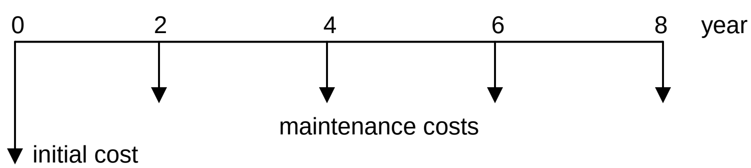


Figure 8-2. Cash flow stream with maintenance every 2 years

Table 8-3. Results of LCCA for FTM and PPM (8-year life cycle)

Scenario	Present Value (PV) $	
	FTM	PPM
Maintenance after 5 years	1,355.00	4,240.00
Maintenance after 2 years	1,538.00	4,423.00

Section 9
A Potential Alternative – Rumble Stripes

Rumble stripes are a potential alternative to PPM for providing edge stripes of high retroreflectivity. Rumble stripes consist of a rumble strip that intrudes several inches into the travel lane with an edge stripe laid on the portion of the rumble strip that is in the travel lane. The rumble strip gives the driver immediate warning of straying from the travel lane, while the stripe is designed to provide higher retroreflectivity than flat stripes because water draining from the pavement is expected to leave the markings on the ridges exposed.

The research team investigated rumble stripes in two ways. They investigated rumble stripes in Mississippi and tested the wet retroreflectivity of two short test sections in Alabama.

9.1 Mississippi Rumble Stripes

The Mississippi Department of Transportation (MDOT) constructed 50 miles of rumble stripe on I-59 near Hattiesburg in January 2002. The rumble strip cost $1,290 per mile, and the associated 6-inch wide thermoplastic cost $1,500 per mile. The total cost of $2,790 per mile is considerably less than the approximately $7,000 per mile the MDOT pays for PPM.

In November 2002, MDOT tested four, one-mile long sections of the rumble stripes on I-59 with a mobile retroreflectometer and water truck, in a method similar to the test devised in this project. Two, one-mile long sections of rumble stripe constructed with paint were tested for retroreflectivity. They averaged 123 mcd/m^2/lux dry and 58 mcd/m^2/lux wet. The two, one-mile sections of rumble stripe constructed with thermoplastic showed 169 mcd/m^2/lux dry and 61 mcd/m^2/lux wet.

MDOT also placed rumble stripes on SR 589 in June 2002 (see Figure 9-1). That road is 26-feet wide with no shoulder. The rumble strip cost $837 per mile, and the associated thermoplastic cost $1,563 per mile. MDOT tested eight, one-mile sections of rumble stripe on SR 589 in November 2002. The average wet retroreflectivity was 61 mcd/m^2/lux, and the average dry retroreflectivity was 340 mcd/m^2/lux.

The wet values of roughly 60 mcd/m^2/lux for the rumble stripes in Mississippi fall between the retroreflectivity values found in the ALDOT tests for new markings of roughly 45 mcd/m^2/lux for wet FTM and 89 mcd/m^2/lux for wet PPM. Thus, MDOT's experience indicates rumble stripes may offer higher wet retroreflectivity values than FTM, although their values may be below PPM.

MDOT mentioned two aspects of its work with rumble stripes:

- It is monitoring the rumble stripes to see if they wear out sooner than standard markings.
- It placed thermoplastic in the rumble stripes 50 mils thick to avoid ponding in the rumble strip. Normally, it would place thermoplastic 60 mils thick.

Figure 9-1. Rumble stripe on SR 589 in Mississippi

9.2 ALDOT Rumble Stripes

The researchers tested two short sections of rumble stripe in Alabama during the March 2003 test session. The sections are between mileposts 4 and 5 of the westbound lanes of US 78 near the Alabama/Mississippi border. The section of rumble stripe constructed with paint was only about 0.076 miles long, and the section of rumble stripe constructed with thermoplastic was only about 0.095 miles long.

The paint rumble stripe had the following retroreflectivity readings: dry 254 mcd/m^2/lux and wet 93 mcd/m^2/lux. The flat thermoplastic rumble stripe had the following readings: dry 306 mcd/m^2/lux and wet 41 mcd/m^2/lux. Thus, the painted rumble stripe exhibited wet retroreflectivity higher than standard flat thermoplastic and as good as PPM. The flat thermoplastic rumble stripe performed no better than standard flat thermoplastic in wet conditions. The results of the tests on the rumble stripe with paint indicate that rumble stripes may be able to provide wet retroreflectivity values near those of PPM.

There was a question concerning whether or not the painted rumble stripe had drop-on beads that were “large beads” versus “standard-sized beads”. ALDOT Division personnel were contacted with that question but could not provide the answer.

Section 10
Conclusions and Recommendations

This report presented an evaluation of FTM and PPM white edge lines used on ALDOT maintained highways. The primary objectives of this evaluation were to compare service lives, life-cycle costs, crash rates, and wet-night retroreflectivity of the two marking types. These comparisons can help ALDOT evaluate the overall usefulness and applicability of the two marking types. The study found that economics and crash data do not justify widespread use of PPM in preference to FTM.

There were several other study objectives:

- Obtain photo or video documentation of PPM sites.
- Evaluate ALDOT's test sections of 'rumble stripes' to help determine if rumble stripes provide effective wet retroreflectivity.
- Establish a correlation between wet and dry FTM markings and between wet and dry PPM markings.

10.1 Conclusions

The main conclusions of this study follow:

- It is feasible to test pavement markings at large-scale using a mobile retroreflectometer under wet pavement conditions simulated with the aid of a water truck. Such a test can be performed while the test vehicles travel at normal highway speeds with minimal interruption to regular traffic and without a survey crew physically present on the road to measure the markings. Production rates are controlled by the necessity to refill the 1,000-gallon water truck every four to five miles of testing.
- The service lives of FTM and PPM were estimated from the dry retroreflectivity decay curves provided in Chapter 5. Those curves indicated that the average dry retroreflectivity of new FTM and PPM tested by this study were 320 and 242 mcd/m^2/lux, respectively. In addition, both FTM and PPM were found to lose dry retroreflectivity at similar rates with respect to CTP. As a result, under similar ADT levels, FTM consistently provides a higher dry retroreflectivity than PPM of the same age. The decay models were developed using data from highways with 20,000 or less ADT. Therefore, the service life estimations are appropriate for highways with 20,000 or less ADT. Table 10-1 reproduces the estimated service lives of FTM and PPM. According to Table 10-1, if a threshold value of 150 mcd/m^2/lux is used, the average service life of FTM ranged from 17 to 60+ months, whereas the average service life of PPM ranged from 10 to 42 months. When a threshold value of 100 mcd/m^2/lux is used, the average service life of FTM ranged from 23 to 60+ months, whereas the average

service life of PPM ranged from 17 to 60+ months. In general, the average service life of FTM is 6 months or more longer than PPM.

Table 10-1. Estimated service lives in terms of age of markings

ADT per lane	Average service life in months							
	Threshold = 100 mcd/m^2/lux				Threshold = 150 mcd/m^2/lux			
	FTM		PPM		FTM		PPM	
	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.
2,500	60+	60+	60+	41-60+	60+	45-60+	42	24-60+
5,000	46	33-60+	34	21-60	34	23-51	20	12-37
7,500	31	22-48	23	14-40	22	15-34	14	8-25
10,000	23	16-36	17	10-30	17	11-26	10	6-19

Avg. = average; C.I. = confidence interval.

The estimated service lives that exceeded 60 months are given as 60+.

- The estimated average wet retroreflectivity of new FTM is around 45 mcd/m^2/lux, and the estimated average wet retroreflectivity of new PPM is around 89 mcd/m^2/lux. As seen from Table 10-2, the average wet retroreflectivity of PPM at the end of its service life is as high as the average wet retroreflectivity of FTM at the beginning of its life. Therefore, PPM provides higher retroreflectivity than FTM for nighttime wet pavement. However, currently there are no accepted minimum wet retroreflectivity requirements for pavement markings. Therefore, the estimated wet retroreflectivity values of FTM and PPM could not be translated to service lives of the markings.

Table 10-2. Wet retroreflectivity at threshold dry values

Marking	Threshold dry retroreflectivity 100 mcd/m^2/lux		Threshold dry retroreflectivity 150 mcd/m^2/lux	
	Average	95% confidence interval	Average	95% confidence interval
FTM	19	0-44	25	0-54
PPM	44	15-72	64	26-93

- The CARE computer program was used to compare and contrast crash rates of 103 test sections around the state to determine if PPM markings reduced crash rates more than the use of FTM markings. 55 sites used PPM, and 48 sites used FTM. The 55 PPM sites represented 378 centerline miles of road with ADTs ranging from 1,345 vpd to 77,256 vpd. The 48 FTM sites represented 357 centerline miles of road with ADTs ranging from 880 vpd to 74,182 vpd. In all, approximately 6,000 crashes were evaluated. The statistical analysis compared the crash rates of 19 types of crashes at those sites. In general, FTM crash rates were similar to or lower than PPM crash rates. No statistically-supportable evidence was found to conclude that PPM provided lower crash rates than FTM.

- Life cycle cost analyses were performed using construction costs and maintenance costs supplied by ALDOT, along with service life data from both ALDOT and this study. The results showed that for a five-year marking service life and an eight year life cycle, the cost per mile of marking was $1,355 for FTM and $4,240 for PPM.
- Two short test sections of relatively new paint and thermoplastic edge rumble stripes on the westbound lanes of US 78 (Corridor X) near milepost 5 were tested wet and dry as part of the March 2003 field tests. The paint rumble stripe had the following retroreflectivity readings: Dry 254 and Wet 93. The flat thermoplastic rumble stripe had the following readings: Dry 306 and Wet 41. Thus, the painted rumble stripe exhibited wet retroreflectivity higher than standard flat thermoplastic and as good as PPM. The flat thermoplastic rumble stripe performed no better than standard flat thermoplastic in wet conditions. The researchers also reviewed data of similar tests performed by the Mississippi DOT. Those tests indicate that rumble stripes may offer higher retroreflectivity values than FTM, although their values may be lower than PPM.
- ALDOT and UTCA personnel obtained video of wet sections of PPM and FTM shot at night by the Mississippi DOT. In general, the video indicated that PPM had higher brightness than FTM under wet/night conditions. That video is in the possession of the Bureau of Materials and Tests at ALDOT.
- Chapter 6 presents comparisons of wet and dry retroreflectivity values for the two marking types. The dry retroreflectivity values of FTM and PPM are significantly higher than their wet retroreflectivity values. On average, wet retroreflectivity of FTM is about 14 to 19 percent of its dry retroreflectivity. Similarly, wet retroreflectivity of PPM is about 37 to 44 percent of its dry retroreflectivity.

10.2 Recommendations

The following recommendations stem from the observations made during field tests and from the results of data analyses:

- This study estimated edge marking service life for roads of ADT $\leq$ 20,000. It may be helpful to estimate the service lives of markings installed on higher volume roads by taking retroreflectivity readings using mobile or hand-held retroreflectometers.
- ALDOT has recently installed more rumble stripe test sections. Testing these sites will help determine if rumble stripes provide wet retroreflectivity similar to PPM.
- It may be desirable to develop national guidelines for the minimum acceptable wet retroreflectivity for drivers. These guidelines may be established by correlating retroreflectivity measurements with human subject evaluations of pavement marking visibility. The establishment of such guidelines for wet retroreflectivity would enable highway agencies to consider both dry and wet retroreflectivity requirements when replacing pavement markings.

- In a limited comparison performed for this study, there were differences between the wet retroreflectivity readings using the UTCA test method and the test method outlined in ASTM E 2177. These differences did not affect the conclusions stated in the first paragraph of Section 10 that "economics and crash data do not justify widespread use of PPM in preference to FTM" because wet retroreflectivity results were not part of those evaluations. However, a more complete test series comparing the two test methods is advisable to determine if the UTCA method produces results comparable to the ASTM method.

References

Alabama Department of Transportation. 2000. *Alabama Standard Specifications, Special Provision No. 3200(3)*. Montgomery: Alabama Department of Transportation.

Alabama Department of Transportation Bid Tabulation. 2002. Internet. Available from http://www.dot.state.al.us/bureau/Office_Engineer/ BID_Tabs/bidtabs.htm; accessed 12 March 2003.

American Association of State Highway and Transportation Officials, National Transportation Product Evaluation Program. 1997. *Summary of Results of 1996 Field and Laboratory Evaluations of Pavement Marking Materials, Volume 1- Field Evaluations.* Washington, D.C.: American Association of State Highway and Transportation Officials.

American Society for Testing and Materials. 1998. *Annual Book of ASTM Standards, Vol. 04.03.* West Conshohocken: American Society for Testing and Materials.

American Society for Testing and Materials. 2002. *Annual Book of ASTM Standards, Vol. 06.01.* West Conshohocken: American Society for Testing and Materials.

Bowman, L. and N. Abboud. 2001. *Estimating the Effectiveness of Pavement Marking Based on Crash History.* Auburn: Auburn University. Report No. IR-01-02.

Civil Engineering Research Foundation, Highway Innovative Technology Evaluation Center. 2001. *Summary of Evaluation Findings for 30-Meter Hand-held and Mobile Pavement Marking Retroreflectometers*. Washington, D.C.: Civil Engineering Research Foundation.

Federal Highway Administration, Office of Safety Research and Development. 2000. *Evaluation of All Weather Pavement Markings.* Virginia: Federal Highway Administration.

Fuller, S. K. and S.R. Peterson. 1996. *NIST Handbook 135: Life Cycle Costing Manual for the Federal Energy Management Program*. Washington D.C.: U.S. Government Printing Office.

Highway Innovative Technology Evaluation Center (HITEC). 2000. *Evaluation Findings of the Laserlux Mobile Pavement Marking Retroreflectometer*. Washington, D.C. CERF Report # 40466.

Iowa State University, Center for Transportation Research and Education. 2001. *Durable, Cost-Effective Pavement Markings Phase 1: Synthesis of Current Research*. Ames: Iowa State University.

Lee, J., T. Maleck, and W. Taylor, "Pavement Marking Material Evaluation Study in Michigan," *ITE Journal* 69, no. 7 (1999): 44-51.

Loetterle, F., R. Beck, and J. Carlson. 1999. Public Perception of Pavement Marking Brightness. *Proceedings of the seventy-eighth annual meeting held in Washington, D.C., USA, January 10-14, 1999* by the Transportation Research Board. USA: Transportation Research Board.

Migletz, J., J. Graham, K. Baur, and D. Harwood, "Field Surveys of Pavement Marking Retroreflectivity," *Transportation Research Record 1657* (1999) : 71-78.

Rennilson, J. 1987. *Measuring Retroreflectivity of Pavement Markings.* Las Mesa: Advanced Retro Technology. Contract No. DTRS-57-86-C.

Schertz, G. *Status of Retroreflectivity Standards*. 2002. Internet. Available from http://safety.fhwa.dot.gov/fourthlevel/retrstat42202.htm; accessed 05 April 2003.

Schnell, T. and Y. Lee. 2003. *Wet Weather Visibility of Pavement Markings*. Internet. Available from http://www.ccad.uiowa.edu/~opl/wetweather.html; accessed April 7 2003.

University of Alabama. 2003. Critical Analysis Reporting Environment (CARE). Available from http://care.cs.ua.edu; accessed 15 May 2003.

U.S. Department of Transportation, Federal Highway Administration. 1998. *Manual on Uniform Traffic Control Devices for Streets and Highways, Part III- Markings.* Washington, D.C.: U.S. Department of Transportation.

Zwahlen, H. and T. Schnell. 2000. Minimum In-Service Retroreflectivity of Pavement Markings. *Proceedings of the seventy-ninth annual meeting held in Washington, D.C., USA, January 9-13, 2000* by the Transportation Research Board. USA: Transportation Research Board.

Abbreviations

ADT	Average daily traffic
ALDOT	Alabama Department of Transportation
ASTM	American Society for Testing and Materials
CARVE	Computer-Aided Roadmarking Visibility Evaluator
CTP	Cumulative traffic passages
CTP_{SL}	Cumulative traffic passages at the end of service life
FHWA	Federal Highway Administration
FTM	Flat thermoplastic markings
HITEC	Highway Innovative Technology Evaluation Center
ITE	Institute of Transportation Engineers
MUTCD	Manual on Uniform Traffic Control Devices
PPM	Profiled pavement markings
RRPM	Raised retroreflective pavement markers
UTCA	University Transportation Center for Alabama

Appendix 1
Retroreflectivity Data

Table A-1. LTL 2000 wet retroreflectivity data

Distance from the beginning milepost (feet)	FTM test site (mcd/m²/lux)	PPM test site (mcd/m²/lux)
0	10	99
200	12	90
400	9	91
600	12	84
800	8	79
1,000	10	95
1,200	11	86
1,400	14	64
1,600	13	74
1,800	21	76
2,000	13	
2,200	15	
2,400	11	
2,600	14	

Table B-1. Laserlux wet retroreflectivity data

Distance from the beginning milepost (feet)	FTM test site ($mcd/m^2/lux$)	PPM test site ($mcd/m^2/lux$)
100	23	78
200	23	102
300	23	85
400	21	72
500	22	70
600	18	70
700	19	69
800	22	72
900	21	74
1,000	23	74
1,100	22	63
1,200	26	57
1,300	22	54
1,400	25	58
1,500	23	59
1,600	20	60
1,700	22	70
1,800	21	67
1,900	16	63
2,000	19	63
2,100	18	66
2,200	18	65
2,300	15	64
2,400	20	75
2,500	24	84
2,600	20	89

Table C-1. T-Test for wet retroreflectivity data from FTM test site

Device	Procedure	Sample	Mean	Standard deviation	SE mean
LTL 2000	ASTM	14	12.36	3.20	0.86
Laserlux	UTCA	26	21.00	2.64	0.52

Difference = mean LTL 2000- mean Laserlux

Estimate for difference: -8.64

95% CI for difference: (-10.72, -6.57)

T-Test of difference = 0 (vs. not =): T-Value = -8.64 P-Value = 0.000

Table D-1. T-Test for wet retroreflectivity data from PPM test site

Device	Procedure	Sample	Mean	Standard deviation	SE mean
LTL 2000	ASTM	10	83.8	10.7	3.4
Laserlux	UTCA	18	69.7	11.4	2.7

Difference = mean LTL - mean Laserlux

Estimate for difference: 14.13

95% CI for difference: (5.12, 23.15)

T-Test of difference = 0 (vs. not =): T-Value = 3.28 P-Value = 0.004

Table E-1. Retroreflectivity data for FTM test sites

Site ID	Average retroreflectivity (mcd/m²/lux)					
	Test one		Test two		Test three	
	Dry test	Wet test	Dry test	Wet test	Dry test	Wet test
107	57	16				
108	301	36	325	44	274	54
203	241	48	222	34	202	48
204	258	62	261	44	235	39
205	125	48				
206	258	29	205	38	234	56
207	205	19	224	38	235	41
209	217	17	303	34	298	27
210	353	100	280	59	268	40
211	261	48	272	42	253	44
213	191	20	189	22	204	28
306	290	22	259	26	221	26
307	241	31	230	27	191	25
308	289	33	291	20	246	23
402	345	50	317	28	300	32
413	249	37	275	34	220	29
420	318	51	306	42	251	36
602	42	14				
651	136	24	102	20	94	34

Note: Second and third tests were not performed at sites 107, 205, and 602.

Table F-1. Retroreflectivity data for PPM test sites

Site ID	Average retroreflectivity ($mcd/m^2/lux$)					
	Test one		Test two		Test three	
	Dry test	Wet test	Dry test	Wet test	Dry test	Wet test
153	137	53	133	59	142	58
159	277	91	262	83	266	89
214	176	54	178	69	167	62
252	181	74	157	85	177	89
253	155	50	160	49	162	49
258	186	45	194	60	198	62
259	157	65	188	99	182	88
260	190	64	213	70	179	50
261	148	25	160	40	160	39
262	172	72	181	88	200	102
263	221	106	209	99	199	85
361	215	78	226	76	196	72
364	163	69	178	60	165	56
365	268	115	223	91	147	75
422	182	93	185	95	176	83
603	173	69	152	60	149	63
604	245	78	209	78	210	83
652	151	72	157	76	140	64
653	115	52	108	38	111	48
657	179	59	178	70	177	62
763	182	76	177	61	181	66

Appendix 2
Distribution of Retroreflectivity, Age, CTP, and ADT of Test Sites

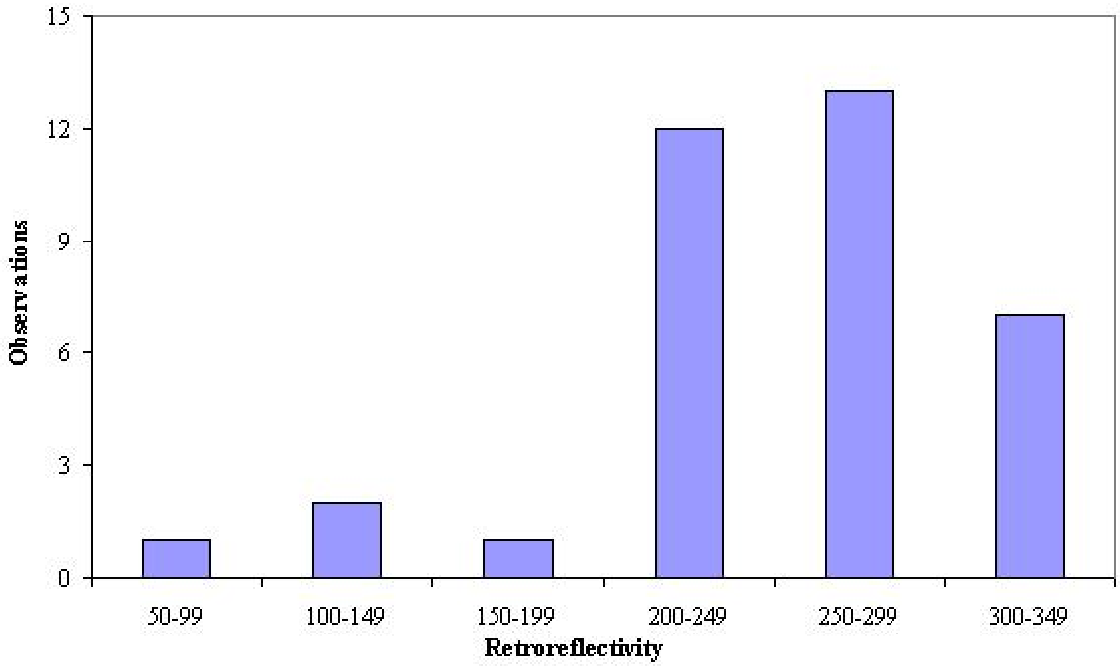


Figure A-2. Distribution of dry retroreflectivity of FTM test sites

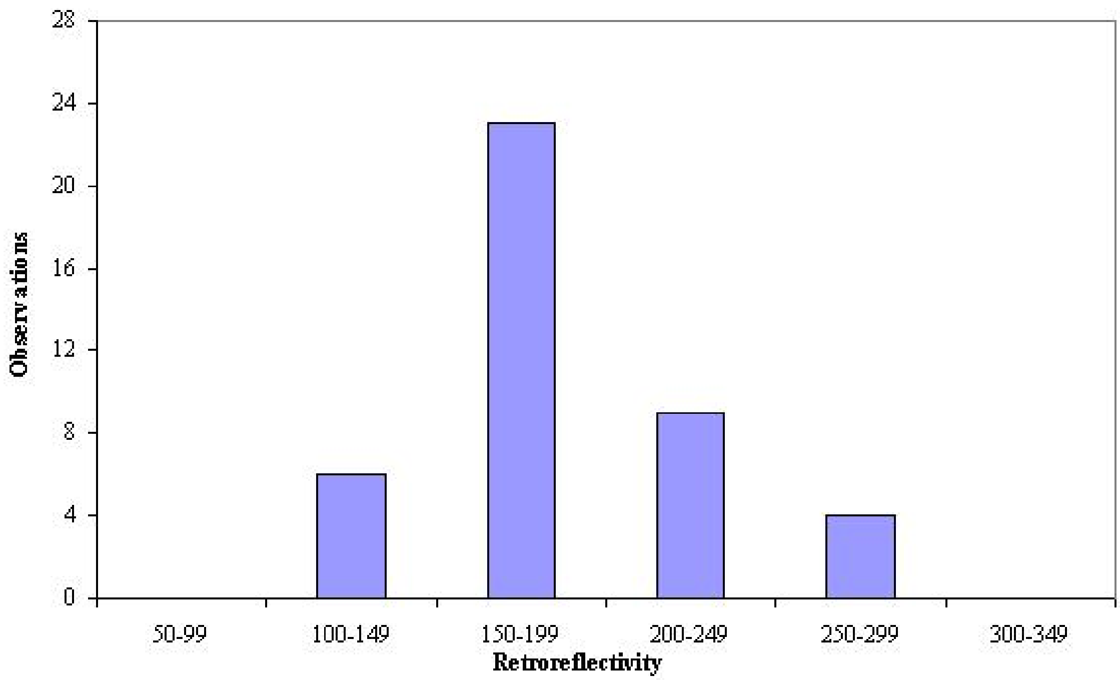


Figure B-2. Distribution of dry retroreflectivity of PPM test sites

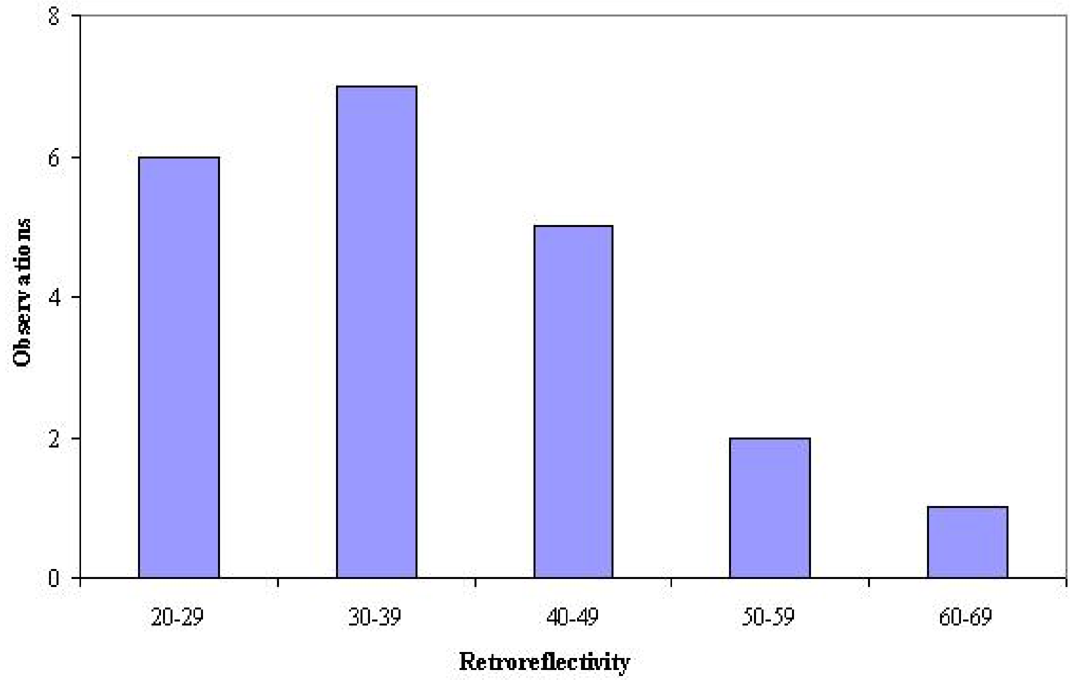


Figure C-2. Distribution of wet retroreflectivity of FTM test sites

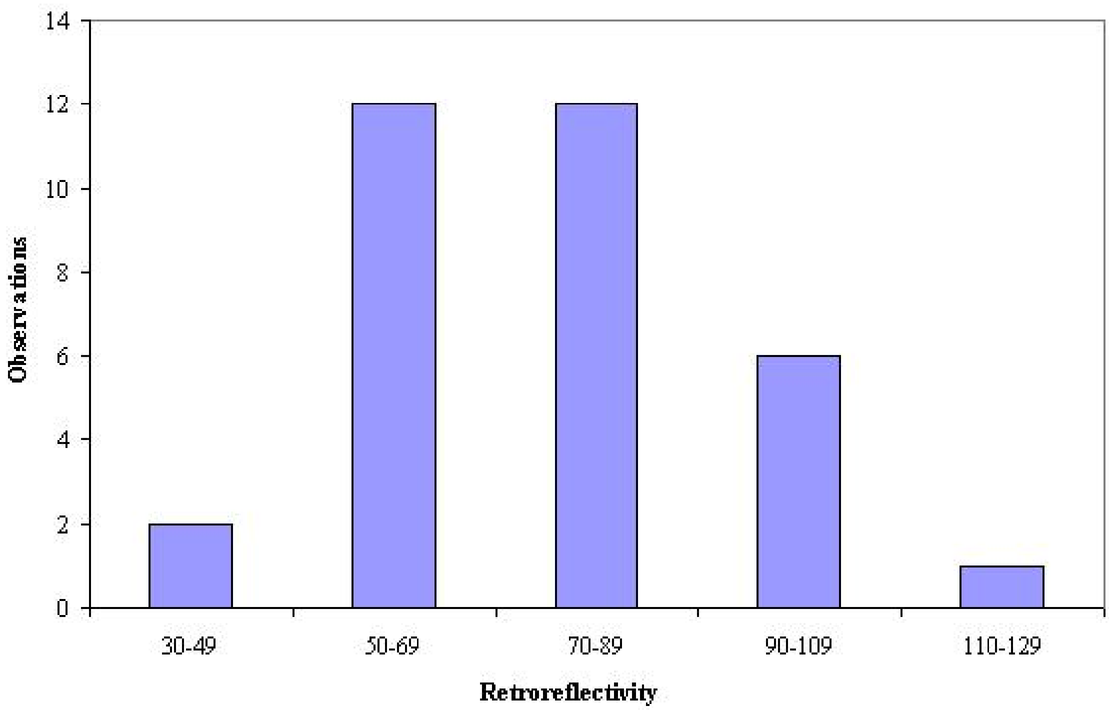


Figure D-2. Distribution of wet retroreflectivity of PPM test sites

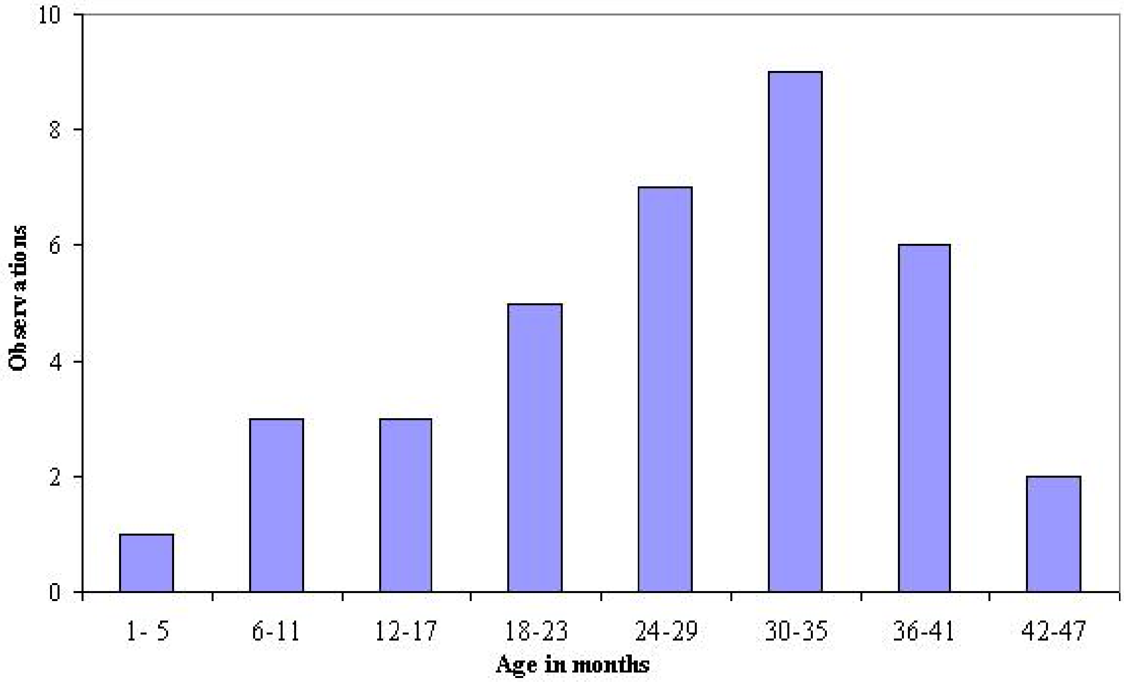


Figure E-2. Distribution of age of FTM test sites

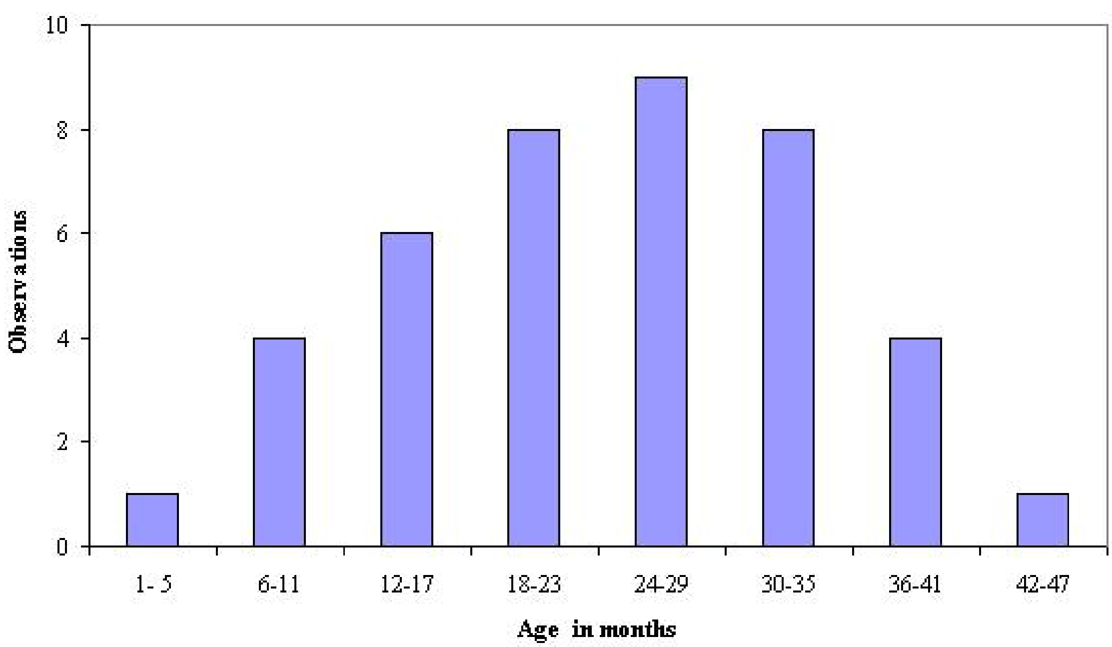


Figure F-2. Distribution of age of PPM test sites

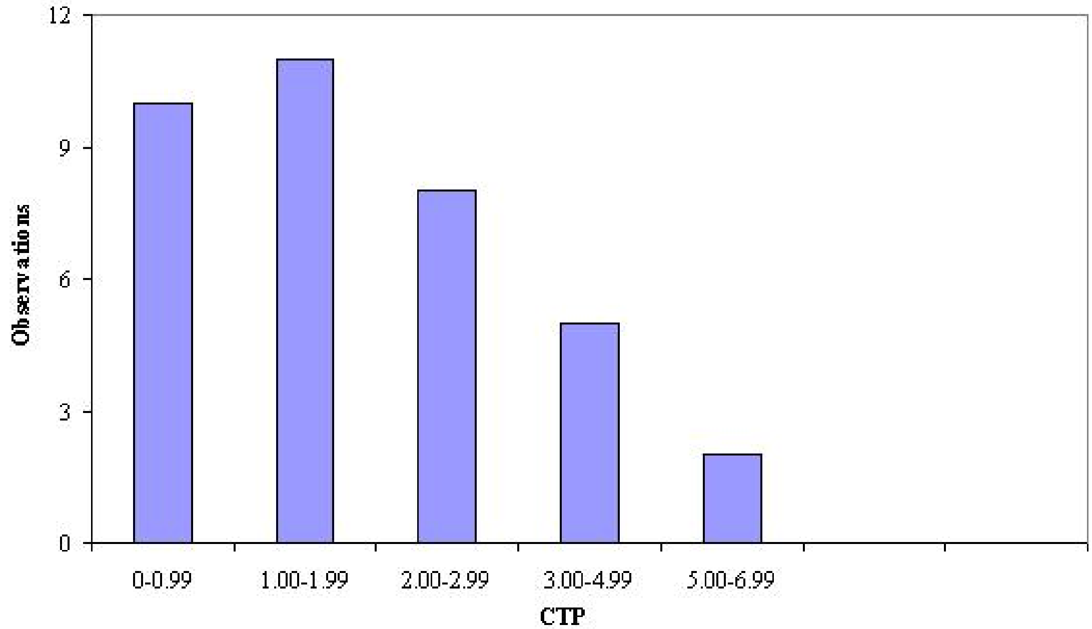


Figure G-2. Distribution of CTP of FTM test sites

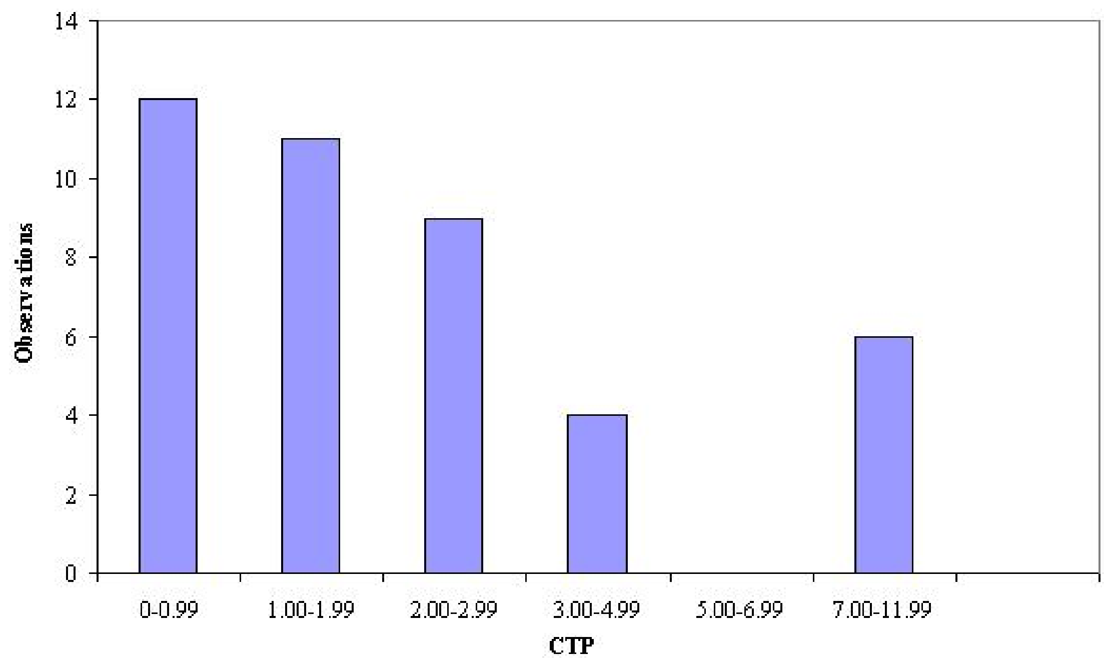


Figure H-2. Distribution of CTP of PPM test sites

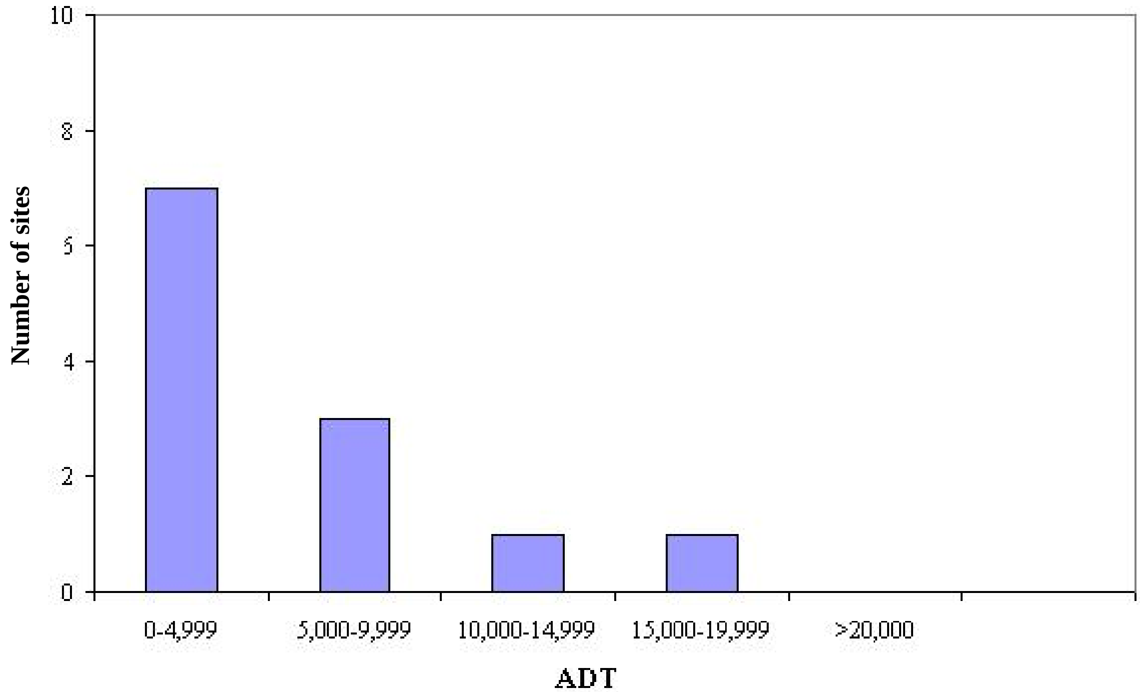


Figure I-2. Distribution of ADT of FTM test sites

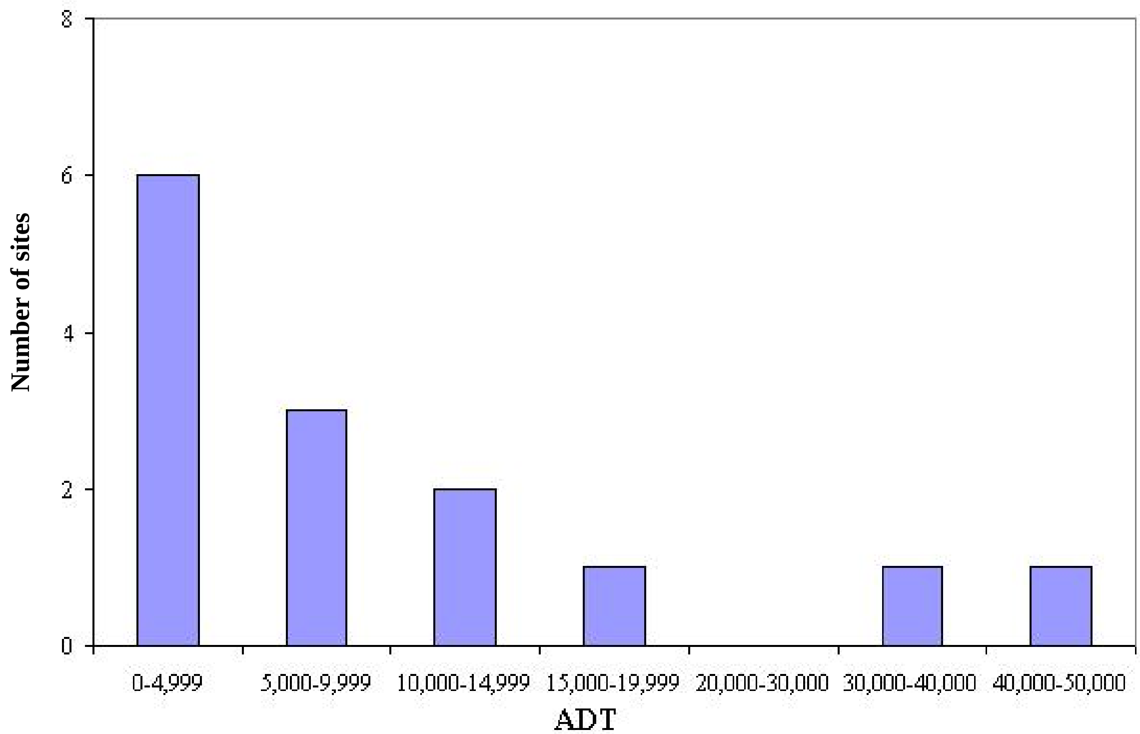


Figure J-2. Distribution of ADT of PPM test sites

Appendix 3
Scatter Plots

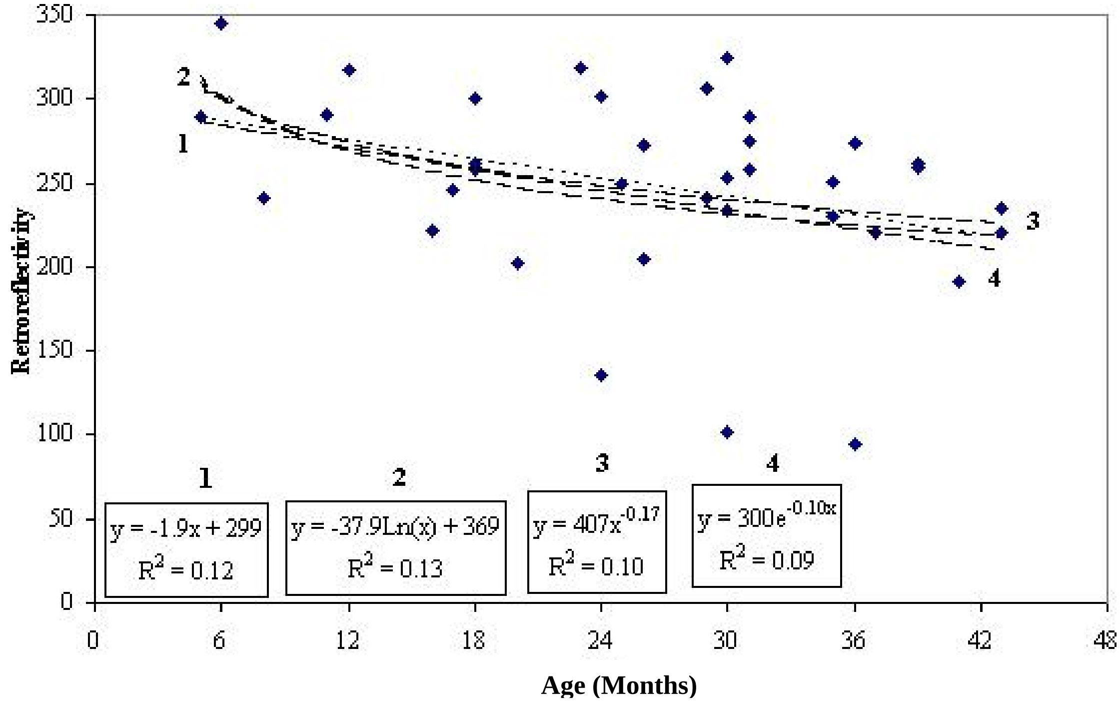


Figure A-3. Dry retroreflectivity vs. age of FTM test sites

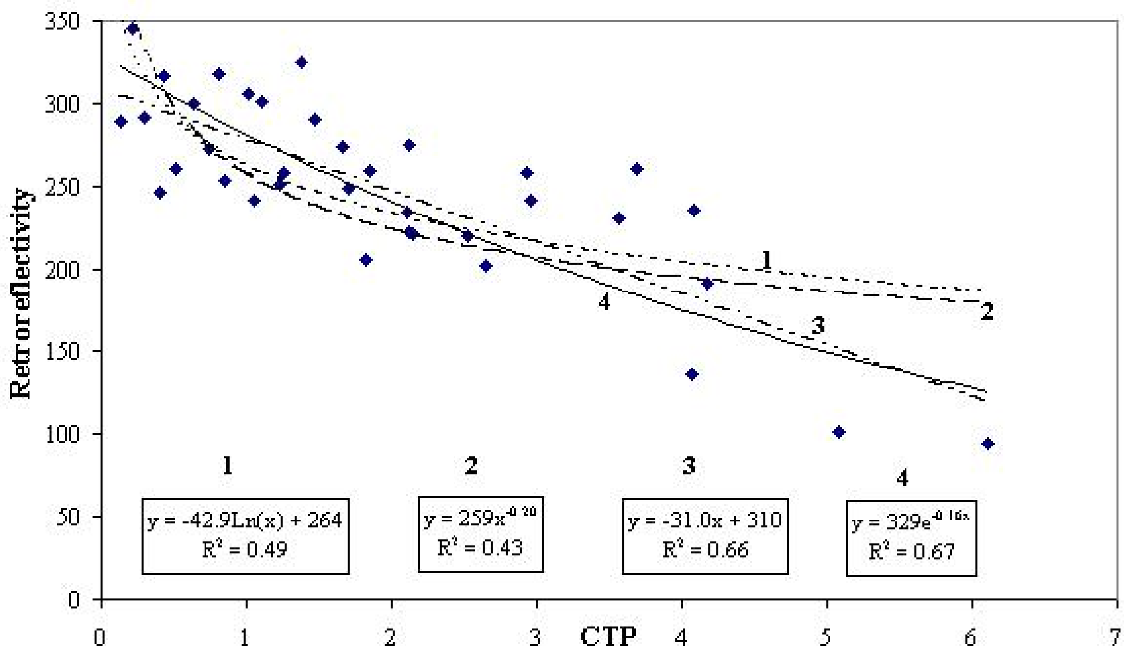


Figure B-3. Dry retroreflectivity vs. CTP of FTM test sites

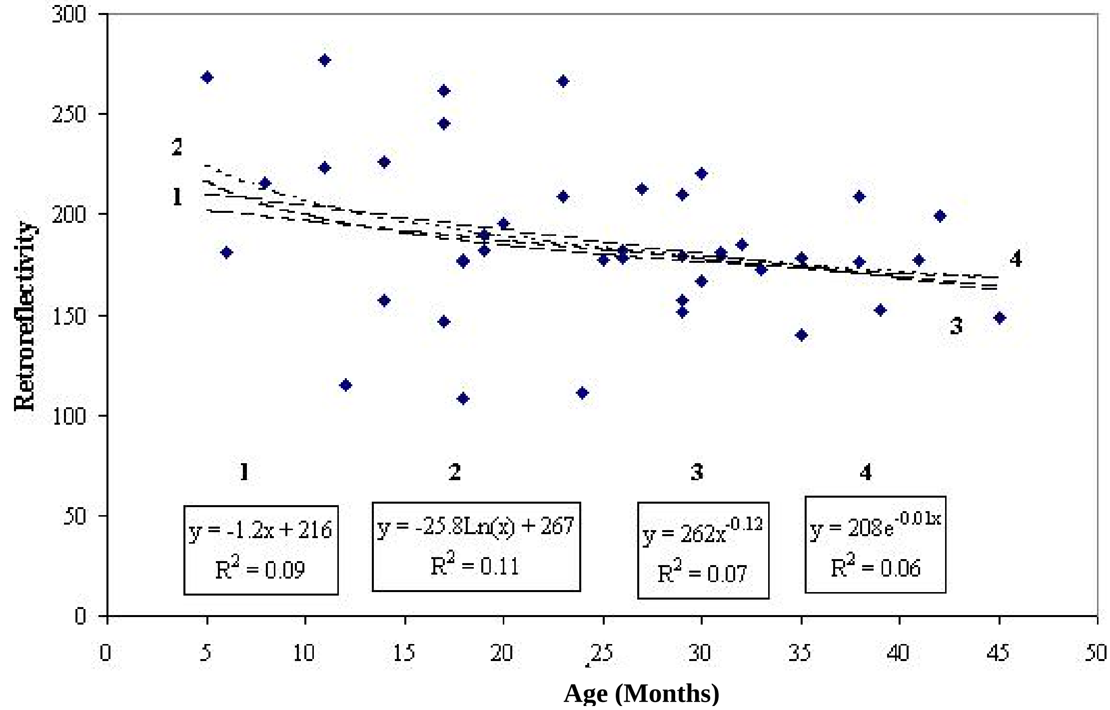


Figure C-3. Dry retroreflectivity vs. age of PPM test sites

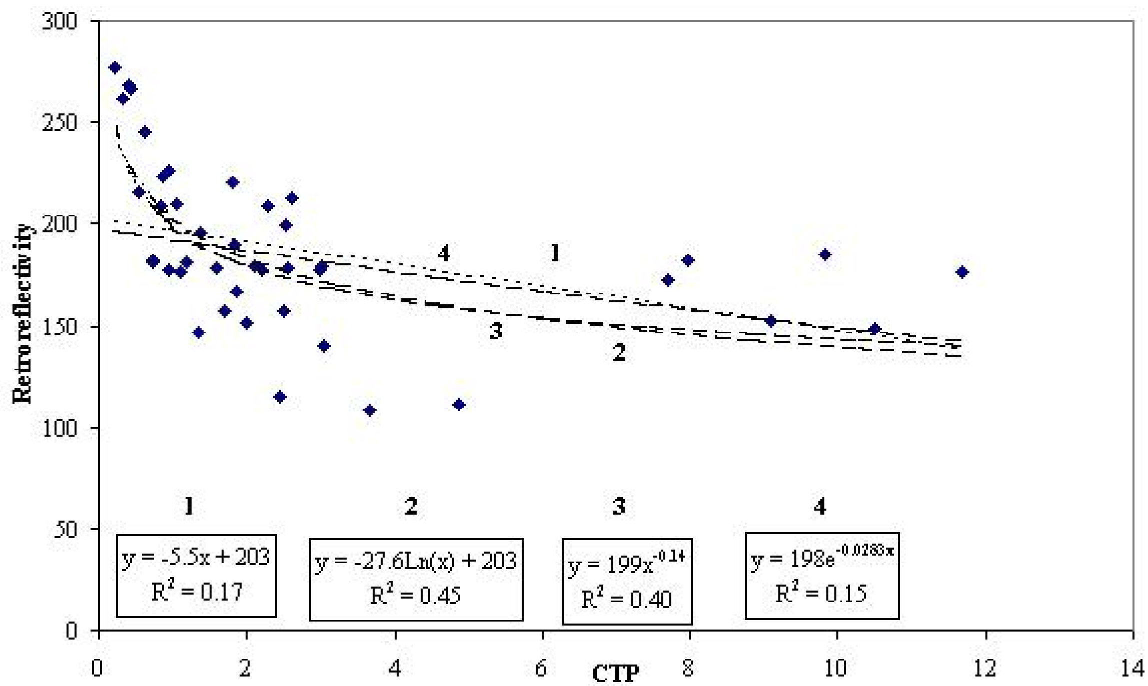


Figure D-3. Dry retroreflectivity vs. CTP of PPM test sites

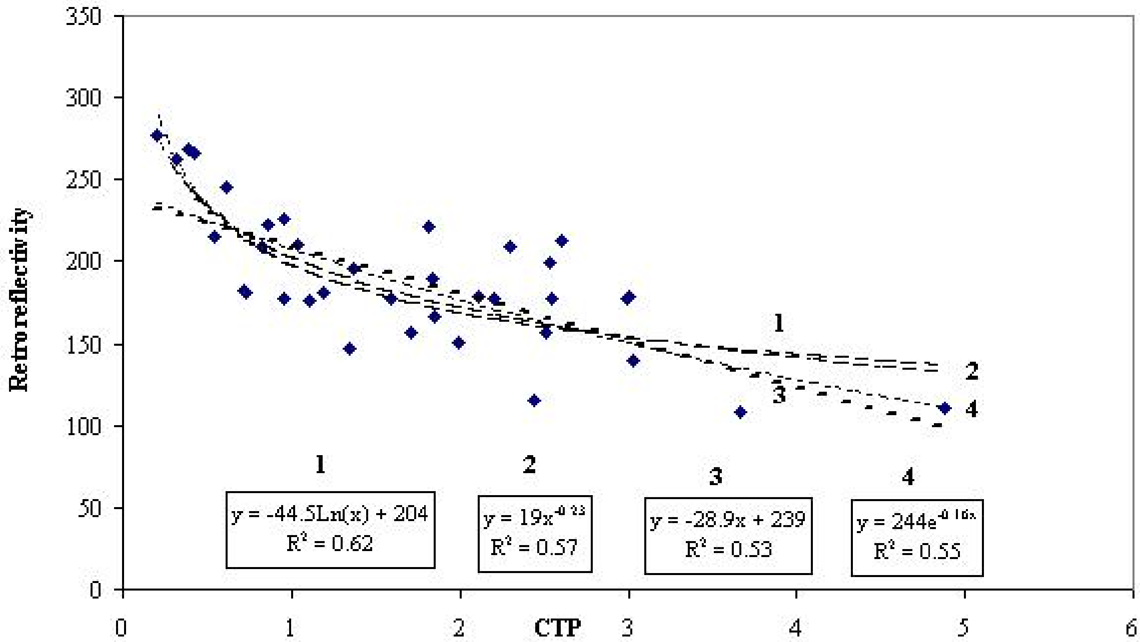


Figure E-3. Dry retroreflectivity vs. CTP of PPM test sites with ADT <20,000

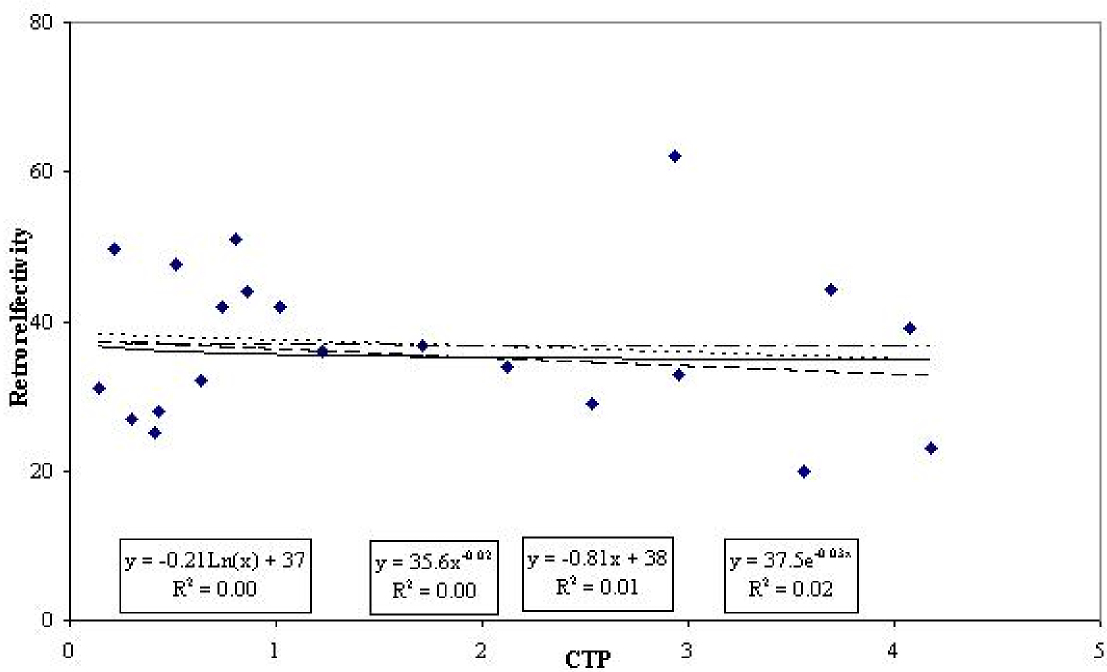


Figure F-3. Wet retroreflectivity vs. CTP of FTM test sites

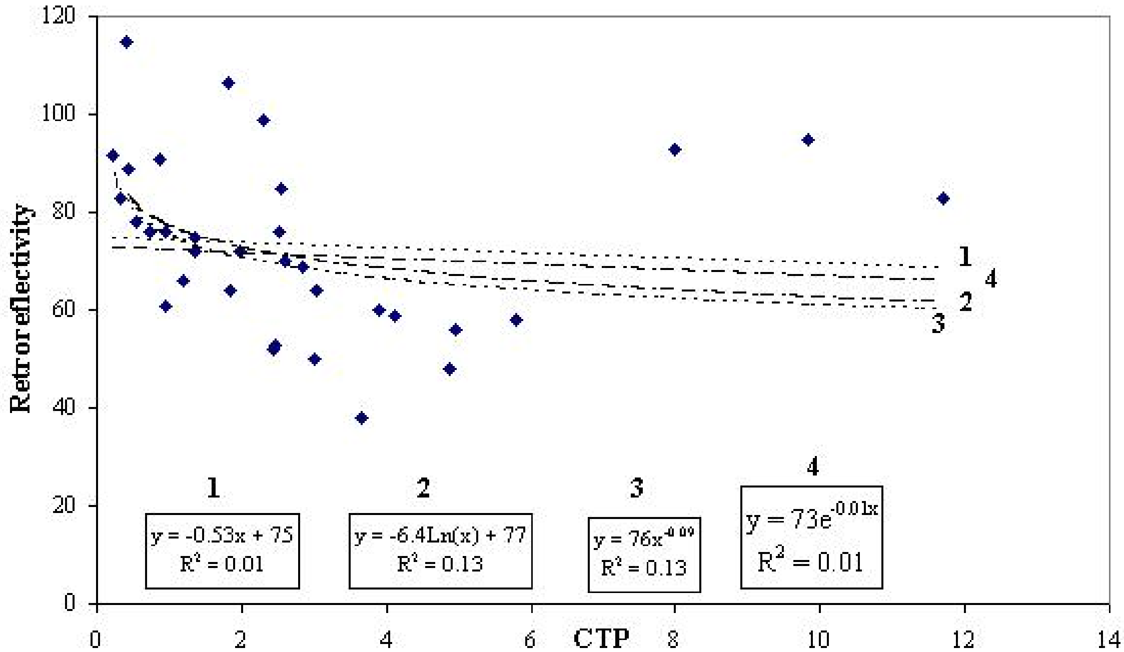


Figure G-3. Wet retroreflectivity vs. CTP of PPM test sites

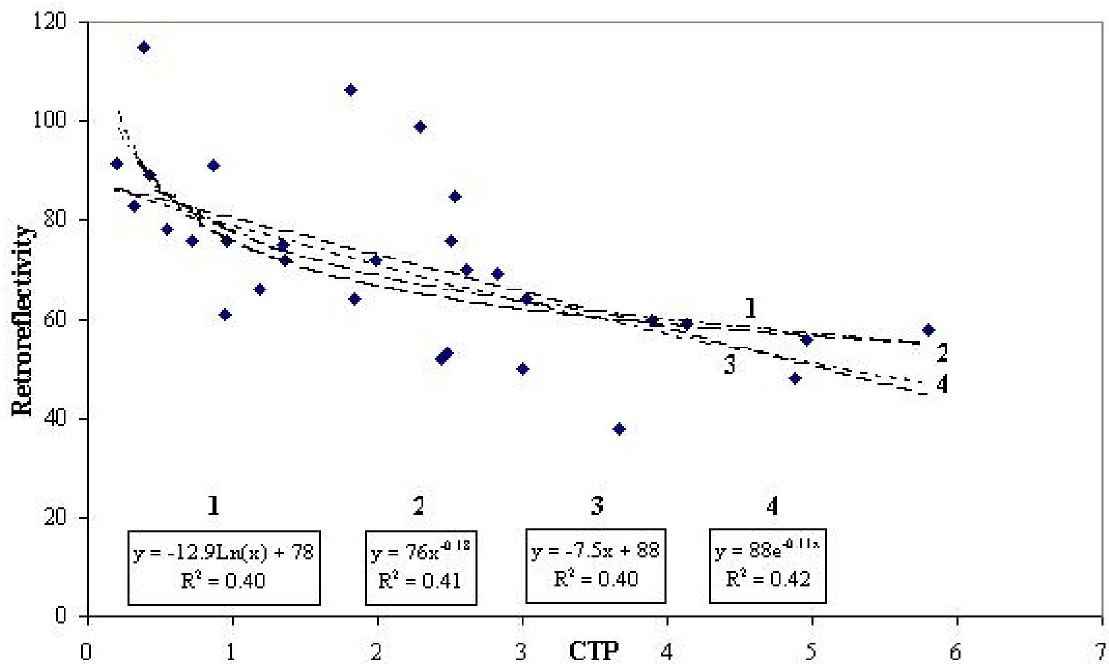


Figure H-3. Wet retroreflectivity vs. CTP of PPM test sites with ADT <20,000

Appendix 4
Regression Analyses of Retroreflectivity Decay Models

Table A-4. Linear decay model for dry retroreflectivity of FTM

The regression equation is dry = 310 - 31.1 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	310.4	9.31	291.5	329.3	33.39	0.00
CTP	-31.1	3.81	-38.8	-23.3	-8.16	0.00

S = 33.00   R-Sq = 66.2%   R-Sq(adj) = 65.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	72538	72538	66.62	0.00
Residual Error	34	37021	1089		
Total	35	109559			

Unusual Observations

Obs	CTP	dry	Fit	SE Fit	Residual	St Residual
15	3.69	261.00	195.71	8.56	65.29	2.05R
36	6.11	94.00	120.62	16.69	-26.62	-0.94 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

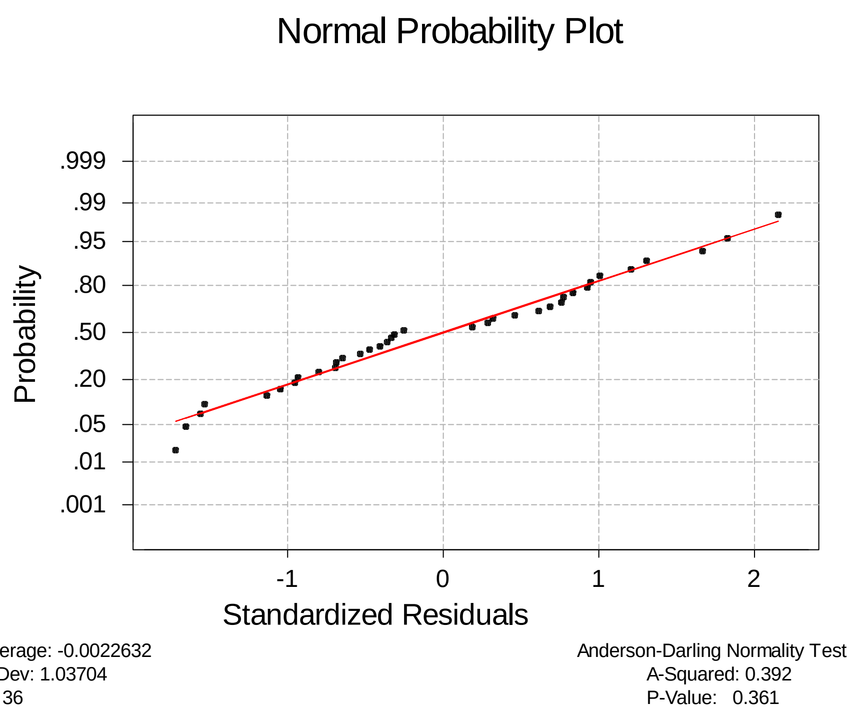


Table B-4. Exponential decay model for dry retroreflectivity of FTM

The regression equation is ln_dry = 5.80 - 0.16 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	5.8	0.046	5.70	5.89	124.4	0.00
CTP	-0.16	0.019	-0.20	-0.12	-8.27	0.00

S = 0.1654   R-Sq = 66.8%   R-Sq(adj) = 65.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.8696	1.8696	68.37	0.00
Residual Error	34	0.9297	0.0273		
Total	35	2.7992			

Unusual Observations

Obs	CTP	ln_dry	Fit	SE Fit	Residual	St Residual
15	3.69	5.5645	5.2138	0.0429	0.3507	2.20R
24	5.08	4.6250	4.9955	0.0654	-0.3705	-2.44R
36	6.11	4.5433	4.8326	0.0836	-0.2893	-2.03RX

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

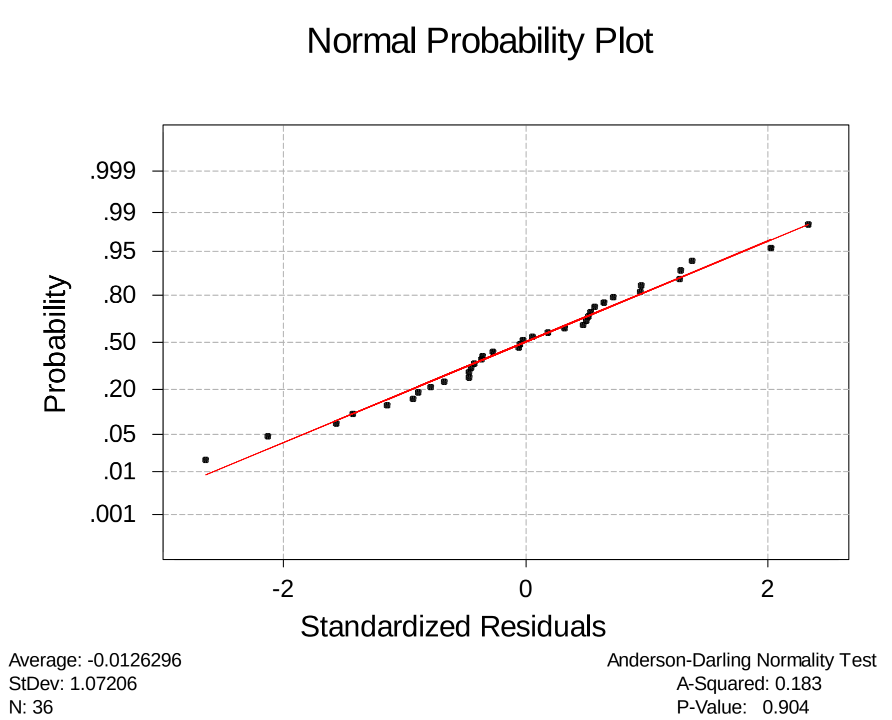


Table C-4. Linear decay model for dry retroreflectivity of PPM (Including test sites with ADT>20,000)

The regression equation is dry = 203 - 5.49 CTP

Predictor	Coef	SE Coef	T	P
Constant	202.6	7.890	25.68	0.00
CTP	-5.49	1.944	-2.82	0.01

S = 36.92   R-Sq = 16.6%   R-Sq(adj) = 14.5%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	10862	10862	7.97	0.01
Residual Error	40	54520	1363		
Total	41	65382			

Unusual Observations

Obs	CTP	dry	Fit	SE Fit	Residual	St Residual
1	0.2	277.00	201.53	7.62	75.47	2.09R
10	2.4	115.00	189.25	5.74	-74.25	-2.04R
22	3.7	108.00	182.55	5.93	-74.55	-2.05R
39	9.8	185.00	148.78	14.77	36.22	1.07 X
41	11.7	176.00	138.52	18.17	37.48	1.17 X
42	10.5	149.00	145.01	16.01	3.99	0.12 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

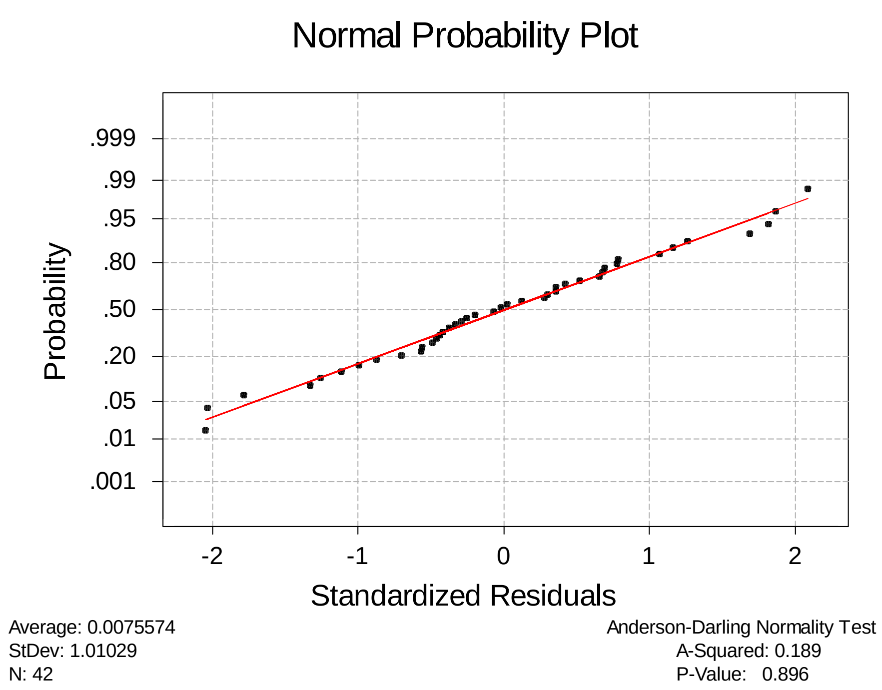


Table D-4. Logarithmic decay model for dry retroreflectivity of PPM (Including test sites with ADT>20,000)

The regression equation is dry = 203 - 27.6 ln_CTP

Predictor	Coef	SE Coef	T	P
Constant	203.2	5.39	37.68	0.00
ln_CTP	-27.6	4.81	-5.74	0.00

S = 29.93 R-Sq = 45.2% R-Sq(adj) = 43.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	29545	29545	32.98	0.00
Residual Error	40	35837	896		
Total	41	65382			

Unusual Observations

Obs	ln_CTP	dry	Fit	SE Fit	Residual	St Residual
1	-1.59	277.00	247.22	11.42	29.78	1.08 X
10	0.89	115.00	178.57	4.86	-63.57	-2.15R
22	1.30	108.00	167.37	5.77	-59.37	-2.02R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

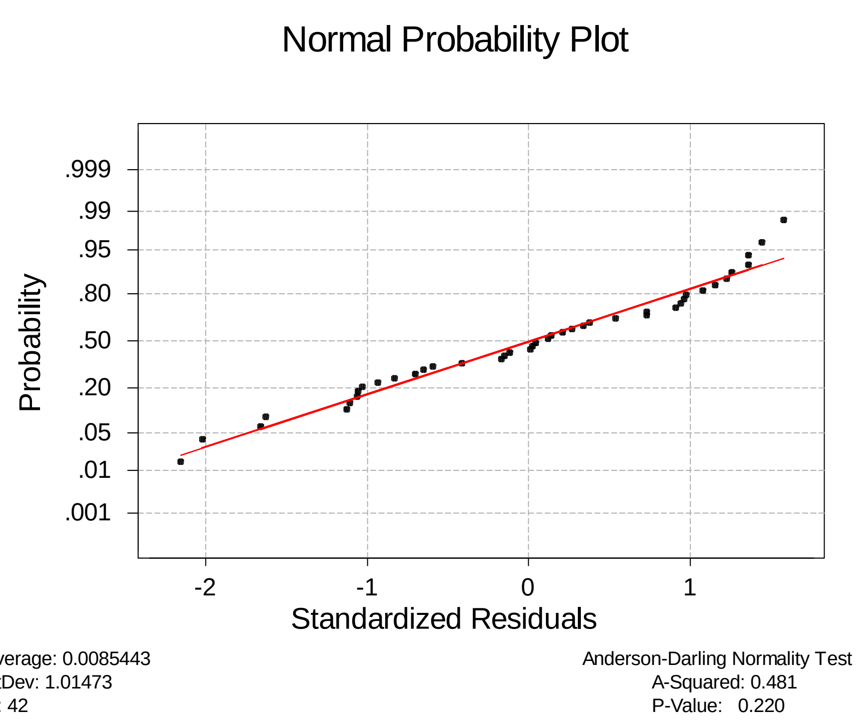


Table E-4. Linear decay model for dry retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is dry = 239 - 28.9 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	239.2	9.34	220.2	258.3	25.61	0.00
CTP	-28.9	4.68	-38.4	-19.4	-6.16	0.00

S = 29.35 R-Sq = 52.8% R-Sq(adj) = 51.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	32710	32710	37.97	0.00
Residual Error	34	29291	862		
Total	35	62002			

Unusual Observations

Obs	CTP	dry	Fit	SE Fit	Residual	St Residual
34	4.88	111.00	98.35	15.69	12.65	0.51 X

X denotes an observation whose X value gives it large influence.

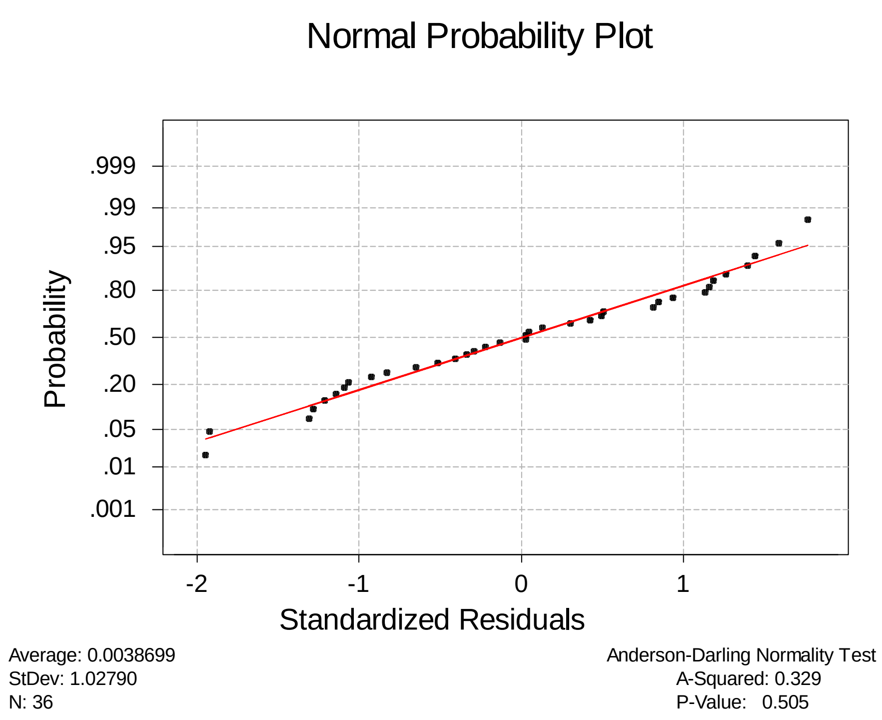


Table F-4. Logarithmic decay model for dry retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is dry = 204 - 44.5 ln_CTP

Predictor	Coef	SE Coef	T	P
Constant	203.6	4.75	42.79	0.00
ln_CTP	-44.5	5.99	-7.41	0.00

S = 26.40 R-Sq = 61.8% R-Sq(adj) = 60.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	38310	38310	54.98	0.00
Residual Error	34	23691	697		
Total	35	62002			

Unusual Observations

Obs	ln_CTP	dry	Fit	SE Fit	Residual	St Residual
1	-1.59	277.00	274.47	12.19	2.53	0.11 X
16	0.96	213.00	161.01	5.90	51.99	2.02R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

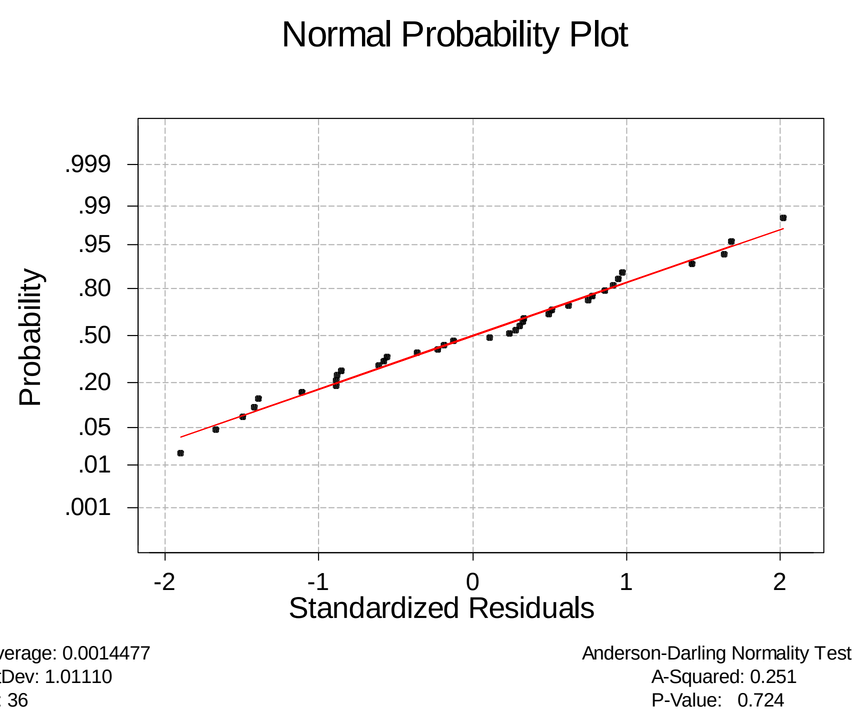


Table G-4. Exponential decay model for dry retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is ln_dry = 5.50 - 0.16 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	5.45	0.050	5.40	5.60	109.62	0.00
CTP	-0.16	0.025	-0.21	-0.11	-6.41	0.00

S = 0.1575   R-Sq = 54.7%   R-Sq(adj) = 53.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.0198	1.0198	41.08	0.00
Residual Error	34	0.8439	0.0248		
Total	35	1.8637			

Unusual Observations

Obs	CTP	ln_dry	Fit	SE Fit	Residual	St Residual
10	2.44	4.744	5.1035	0.0322	-0.3585	-2.32R
34	4.88	4.709	4.7103	0.0842	-0.0007	-0.01 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

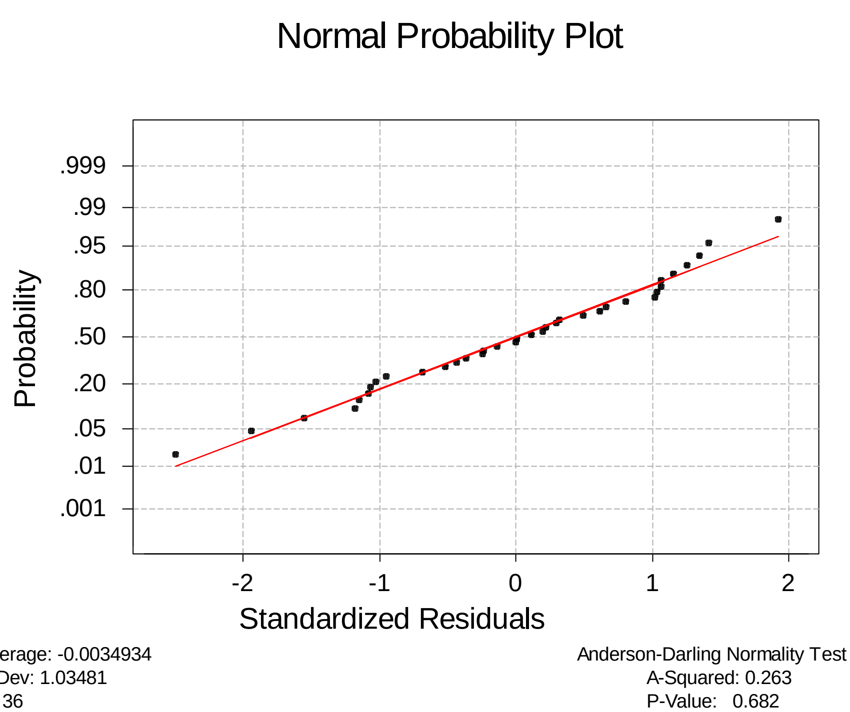


Table H-4. Linear decay model for wet retroreflectivity of PPM (Including test sites with ADT>20,000)

The regression equation is wet = 74.9 - 0.52 CTP

Predictor	Coef	SE Coef	T	P
Constant	74.90	4.66	16.07	0.00
CTP	-0.52	1.19	-0.44	0.66

S = 18.08 R-Sq = 0.6% R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	62.9	62.9	0.19	0.66
Residual Error	31	10129.1	326.7		
Total	32	10192.1			

Unusual Observations

Obs	CTP	wet	Fit	SE Fit	Residual	St Resid
6	0.4	115.00	74.73	4.33	40.27	2.29R
32	9.8	95.00	69.81	8.82	25.19	1.60 X
33	11.7	83.00	68.83	10.93	14.17	0.98 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

Table I-4. Logarithmic decay model for wet retroreflectivity of PPM (Including test sites with ADT>20,000)

The regression equation is wet = 77.6 - 6.40 ln_CTP

Predictor	Coef	SE Coef	T	P
Constant	77.59	3.55	21.83	0.00
ln_CTP	-6.40	3.04	-2.11	0.04

S = 16.96   R-Sq = 12.5%   R-Sq(adj) = 9.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1276.7	1276.7	4.44	0.04
Residual Error	31	8915.4	287.6		
Total	32	10192.1			

Unusual Observations

Obs	ln_CTP	wet	Fit	SE Fit	Residual	St Residual
1	-1.59	91.00	87.79	7.43	3.21	0.21 X
32	2.28	95.00	62.97	5.77	32.03	2.01R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

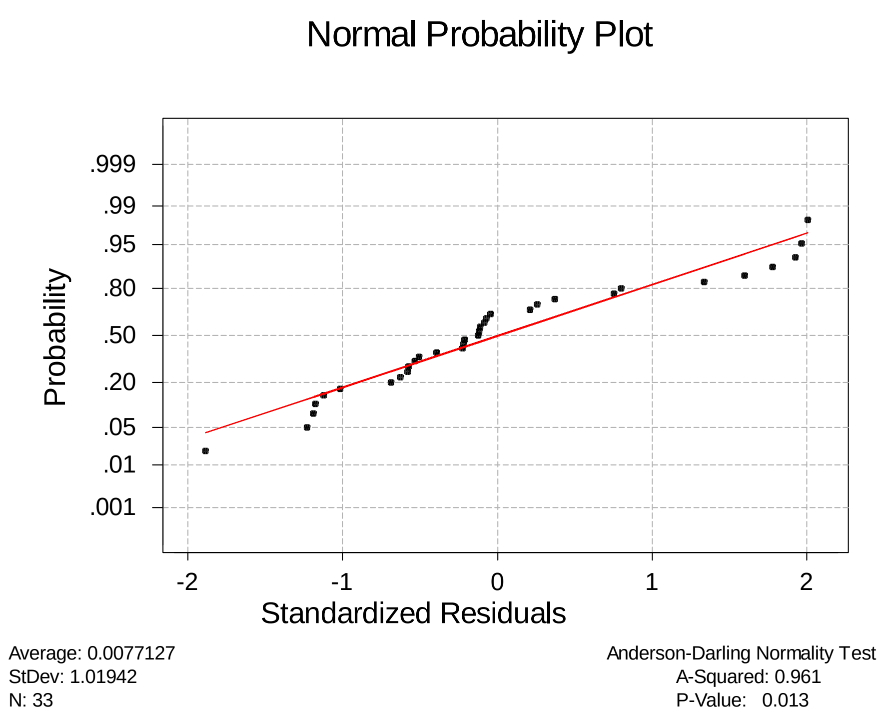


Table J-4. Linear decay model for wet retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is wet = 88.2 - 7.48 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	88.19	4.60	78.8	97.7	19.19	0.00
CTP	-7.49	1.74	-11.1	-3.9	-4.31	0.00

S = 14.02 R-Sq = 39.9% R-Sq(adj) = 37.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3659.0	3659.0	18.60	0.00
Residual Error	28	5506.9	196.7		
Total	29	9165.9			

Unusual Observations

Obs	CTP	wet	Fit	SE Fit	Residual	St Residual
3	1.81	106.00	74.63	2.65	31.37	2.28R
6	0.39	115.00	85.25	4.05	29.75	2.22R
12	2.30	99.00	71.01	2.57	27.99	2.03R
30	5.80	58.00	44.79	6.75	13.21	1.08 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

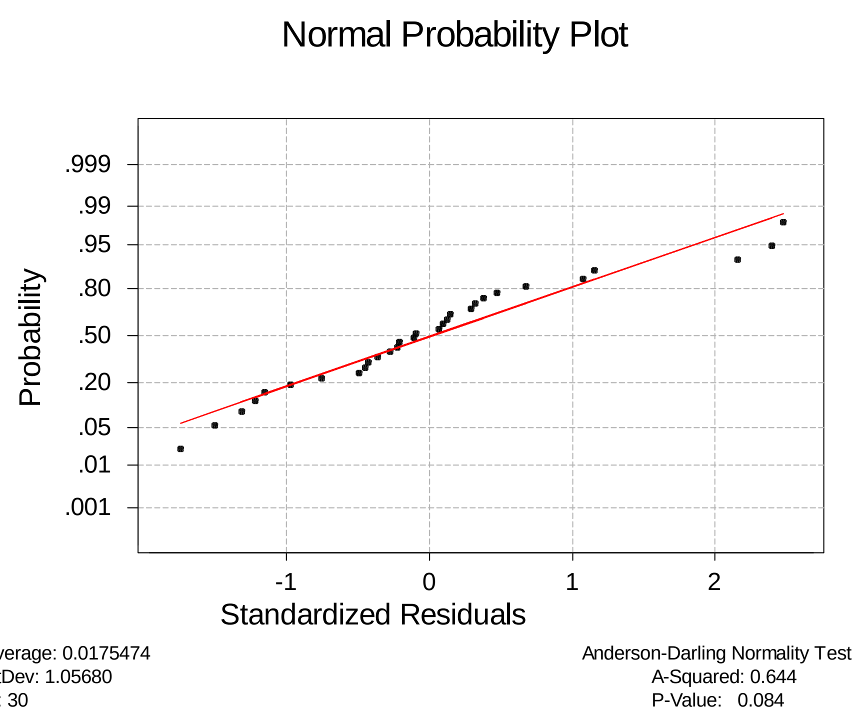


Table K-4. Logarithmic decay model for wet retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is wet = 78.0 - 12.9 ln_CTP

Predictor	Coef	SE Coef	T	P
Constant	78.02	2.929	26.63	0.00
ln_CTP	-12.86	2.951	-4.36	0.00

S = 13.96 R-Sq = 40.4% R-Sq(adj) = 38.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3706.2	3706.2	19.01	0.00
Residual Error	28	5459.7	195.0		
Total	29	9165.9			

Unusual Observations

Obs	ln_CTP	wet	Fit	SE Fit	Residual	St Residual
1	-1.59	91.00	98.52	6.65	-7.52	-0.61 X
3	0.59	106.00	70.38	2.57	35.62	2.60R
12	0.83	99.00	67.33	2.74	31.67	2.31R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.

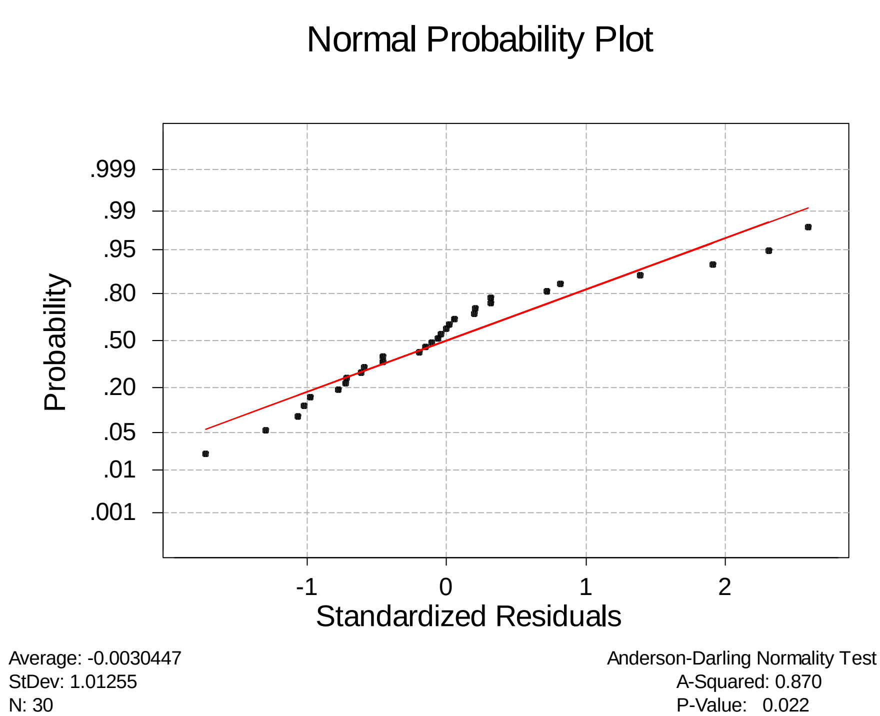


Table L-4. Exponential decay model for wet retroreflectivity of PPM (Excluding test sites with ADT>20,000)

The regression equation is ln_wet = 4.48 - 0.11 CTP

Predictor	Coef	SE Coef	Lower95%	Upper95%	T	P
Constant	4.48	0.063	4.35	4.61	70.76	0.00
CTP	-0.11	0.024	-0.16	-0.06	-4.54	0.00

S = 0.1933   R-Sq = 42.4%   R-Sq(adj) = 40.3%

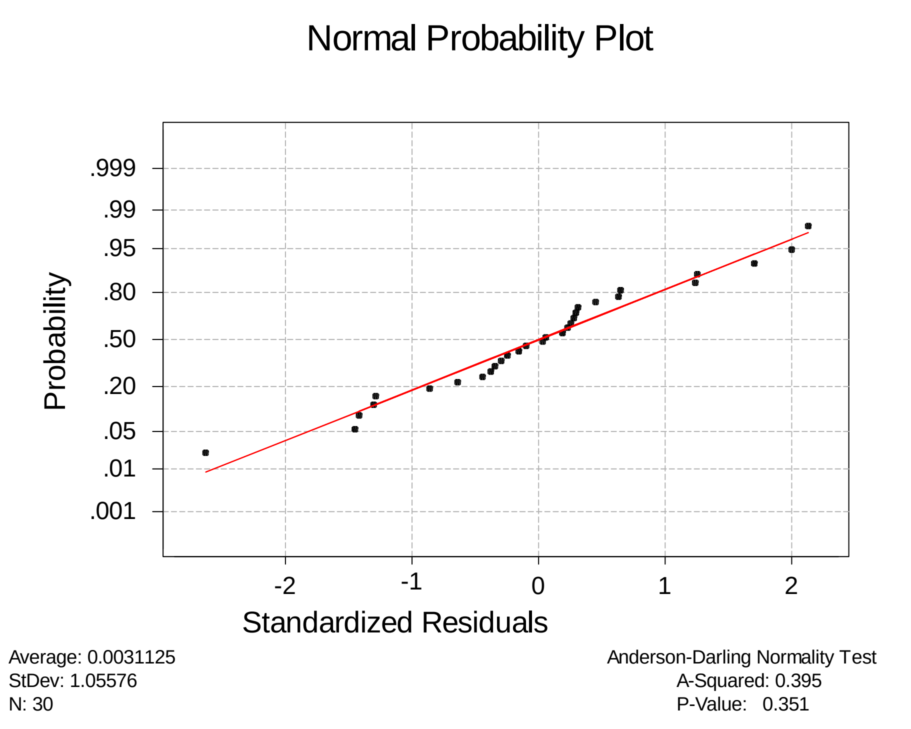
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.769	0.769	20.58	0.00
Residual Error	28	1.046	0.037		
Total	29	1.815			

Unusual Observations

Obs	CTP	ln_wet	Fit	SE Fit	Residual	St Residual
3	1.81	4.667	4.285	0.0365	0.3815	2.01R
17	3.66	3.637	4.084	0.0497	-0.4470	-2.39R
30	5.80	4.060	3.852	0.0931	0.2076	1.23 X

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence.



Appendix 5
Comparison of Observed and Predicted Retroreflectivity Values

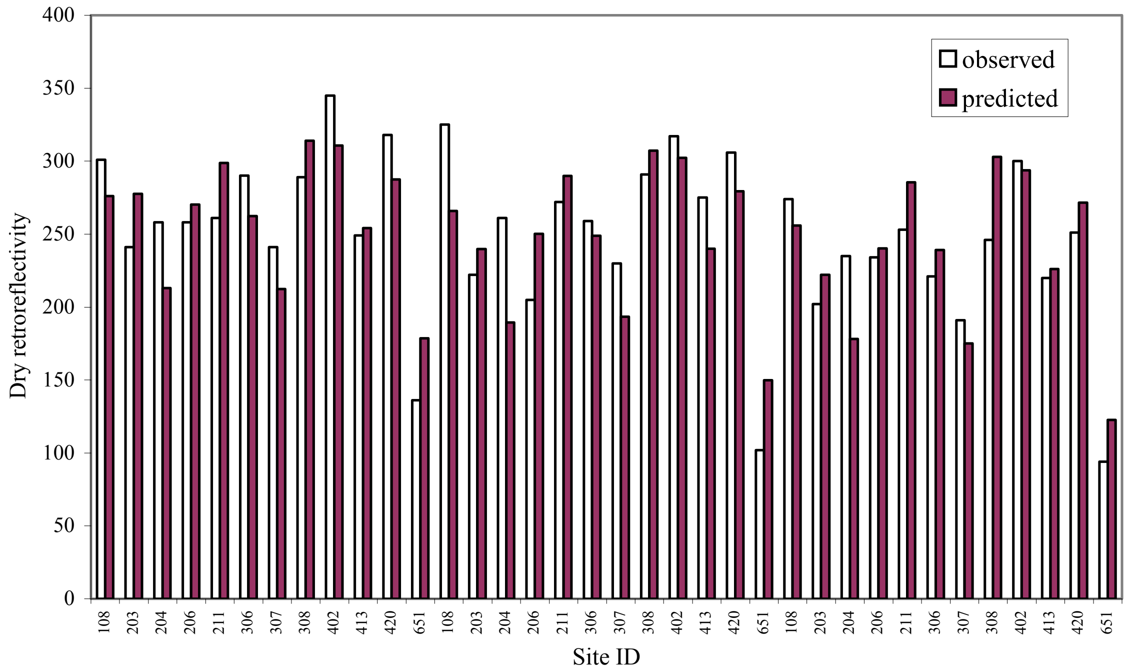


Figure A-5. Dry retroreflectivity values for FTM

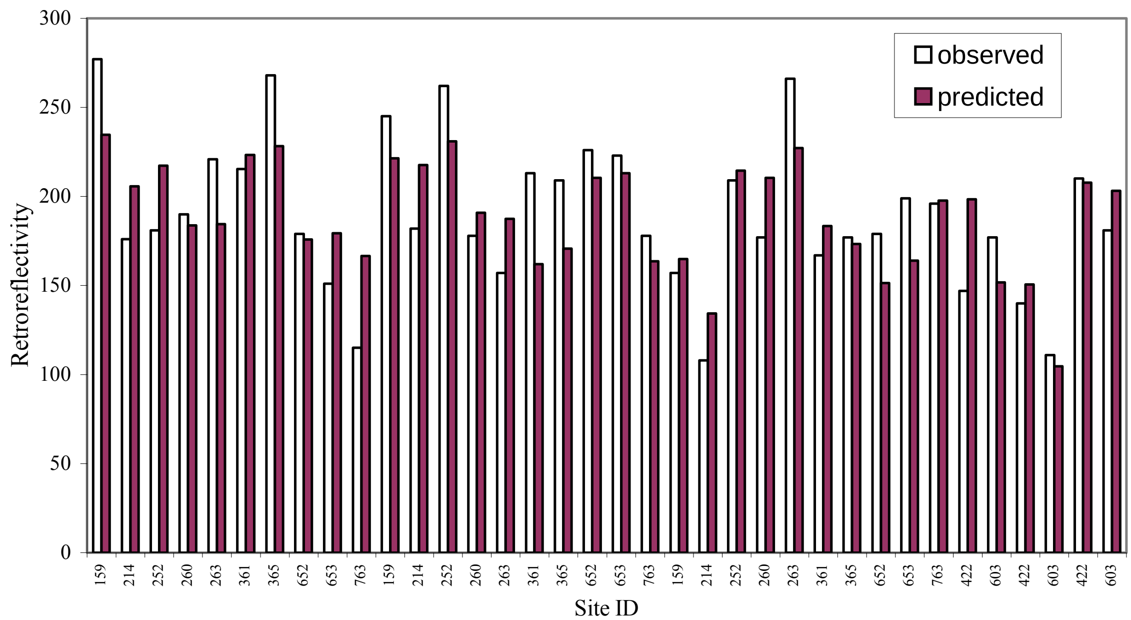


Figure B-5. Dry retroreflectivity values for PPM

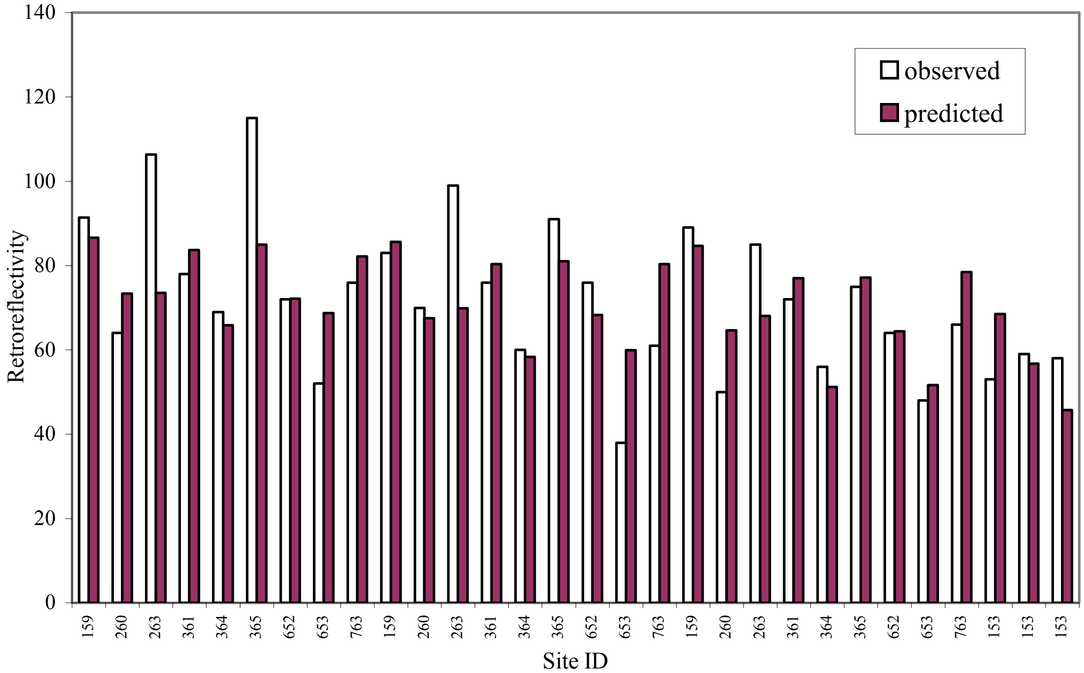


Figure C-5. Wet retroreflectivity values for PPM

Appendix 6
Prediction of Retroreflectivity Values from Decay Models

Table A-6. Prediction of dry retroreflectivity values for FTM

ADT/Lane	Age of a marking	CTP/Lane	Retroreflectivity		Average retroreflectivity
			Linear model	Exponential model	
2,500	0	0.000	310	329	320
2,500	6	0.450	296	306	301
2,500	12	0.900	282	285	283
2,500	18	1.350	268	265	267
2,500	24	1.800	254	247	250
2,500	30	2.250	240	230	235
2,500	36	2.700	226	214	220
2,500	42	3.150	212	199	205
2,500	48	3.600	198	185	191
2,500	54	4.050	184	172	178
2,500	60	4.500	170	160	165
5,000	0	0.000	310	329	320
5,000	6	0.900	282	285	283
5,000	12	1.800	254	247	250
5,000	18	2.700	226	214	220
5,000	24	3.600	198	185	191
5,000	30	4.500	170	160	165
5,000	36	5.400	142	139	140
5,000	42	6.300	114	120	117
5,000	48	7.200	86	104	95
7,500	0	0.000	310	329	320
7,500	6	1.350	268	265	267
7,500	12	2.700	226	214	220
7,500	18	4.050	184	172	178
7,500	24	5.400	142	139	140
7,500	30	6.750	100	112	106
7,500	36	8.100	58	90	74
10,000	0	0.000	310	329	320
10,000	6	1.800	254	247	250
10,000	12	3.600	198	185	191
10,000	18	5.400	142	139	140
10,000	24	7.200	86	104	95

Note: Age of a marking is in months. Retroreflectivity is in mcd/m2/lux.

Table B-6. Prediction of dry retroreflectivity values for PPM

ADT/Lane	Age of a marking	CTP/Lane	Retroreflectivity		Average retroreflectivity
			Linear model	Exponential model	
2,500	0	0.000	239	244	242
2,500	6	0.450	226	227	227
2,500	12	0.900	213	211	212
2,500	18	1.350	200	197	198
2,500	24	1.800	187	183	185
2,500	30	2.250	174	170	172
2,500	36	2.700	161	158	160
2,500	42	3.150	148	147	148
2,500	48	3.600	135	137	136
2,500	54	4.050	122	128	125
2,500	60	4.500	109	119	114
5,000	0	0.000	239	244	242
5,000	6	0.900	213	211	212
5,000	12	1.800	187	183	185
5,000	18	2.700	161	158	160
5,000	24	3.600	135	137	136
5,000	30	4.500	109	119	114
5,000	36	5.400	83	103	93
7,500	0	0.000	239	244	242
7,500	6	1.350	200	197	198
7,500	12	2.700	161	158	160
7,500	18	4.050	122	128	125
7,500	24	5.400	83	103	93
10,000	0	0.000	239	244	242
10,000	6	1.800	187	183	185
10,000	12	3.600	135	137	136
10,000	18	5.400	83	103	93

Note: Age of a marking is in months. Retroreflectivity is in mcd/m^2/lux.

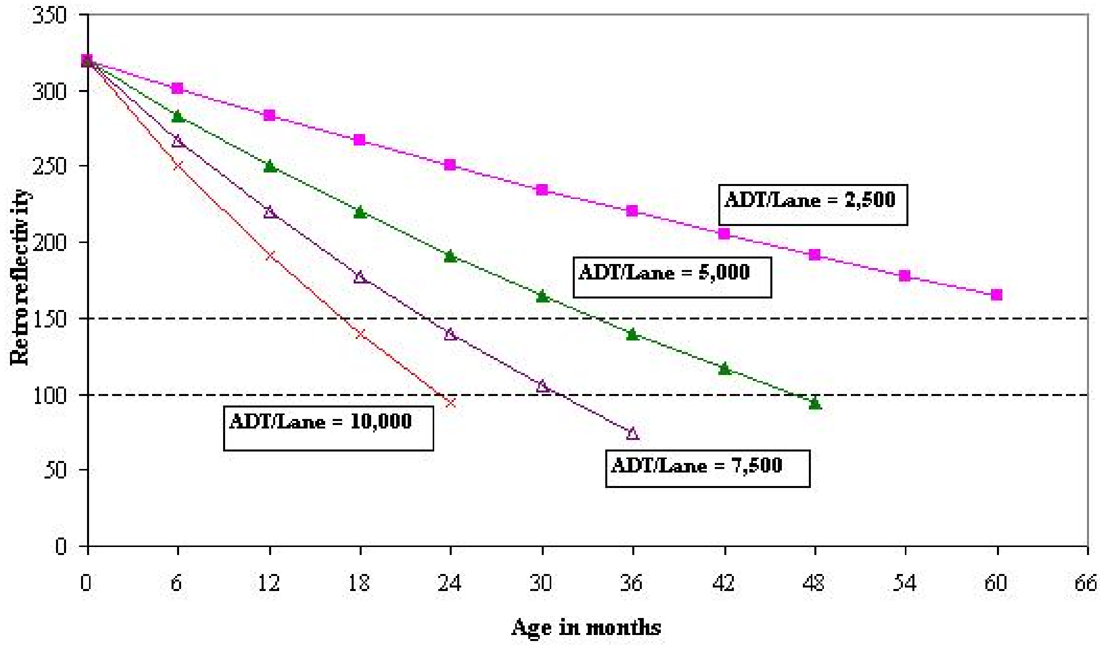


Figure A-6. Variation of dry retroreflectivity of FTM with time

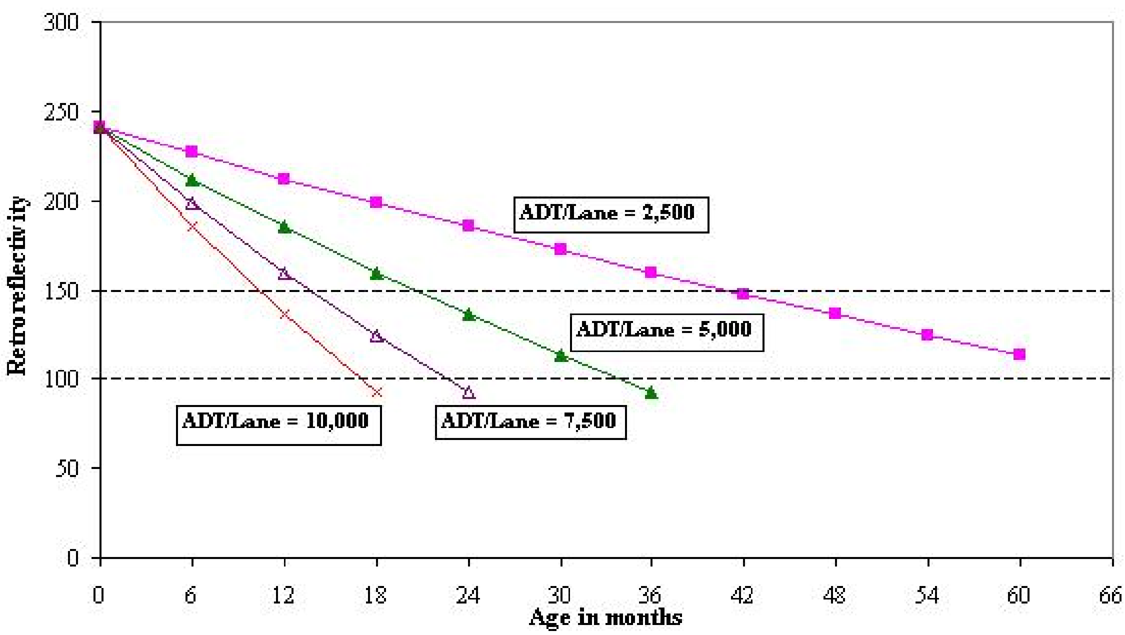


Figure B-6. Variation of dry retroreflectivity of PPM with time

Appendix 7
Correlation Between Dry and Wet Retroreflectivity

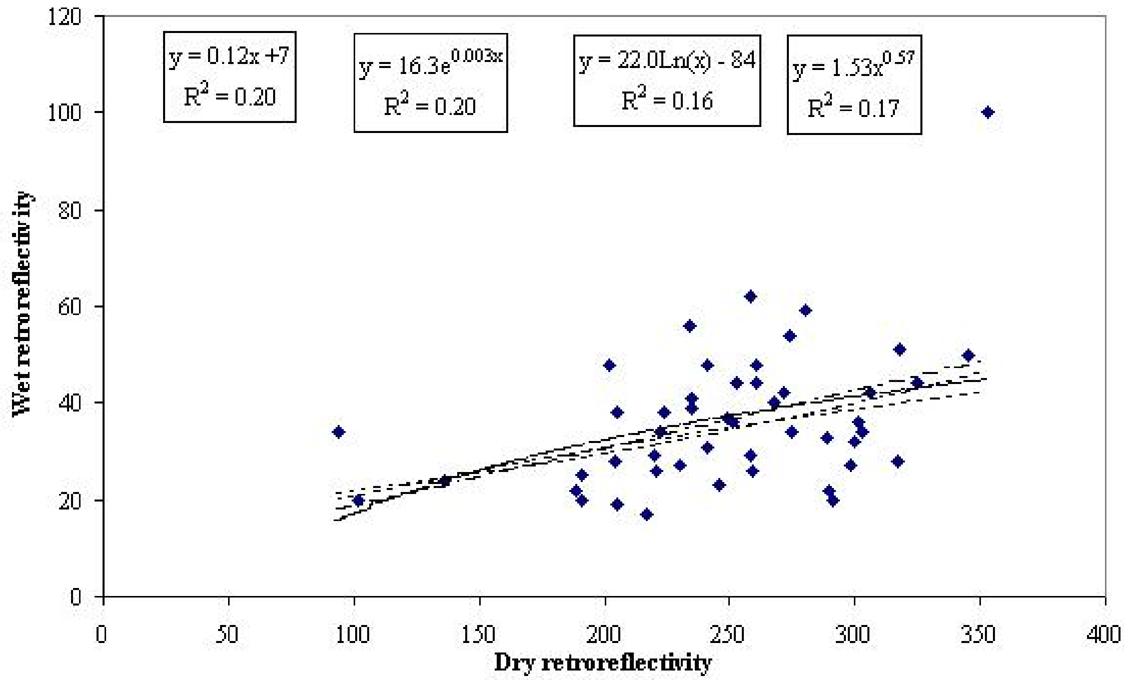


Figure A-7. Correlation between dry and wet retroreflectivity of FTM

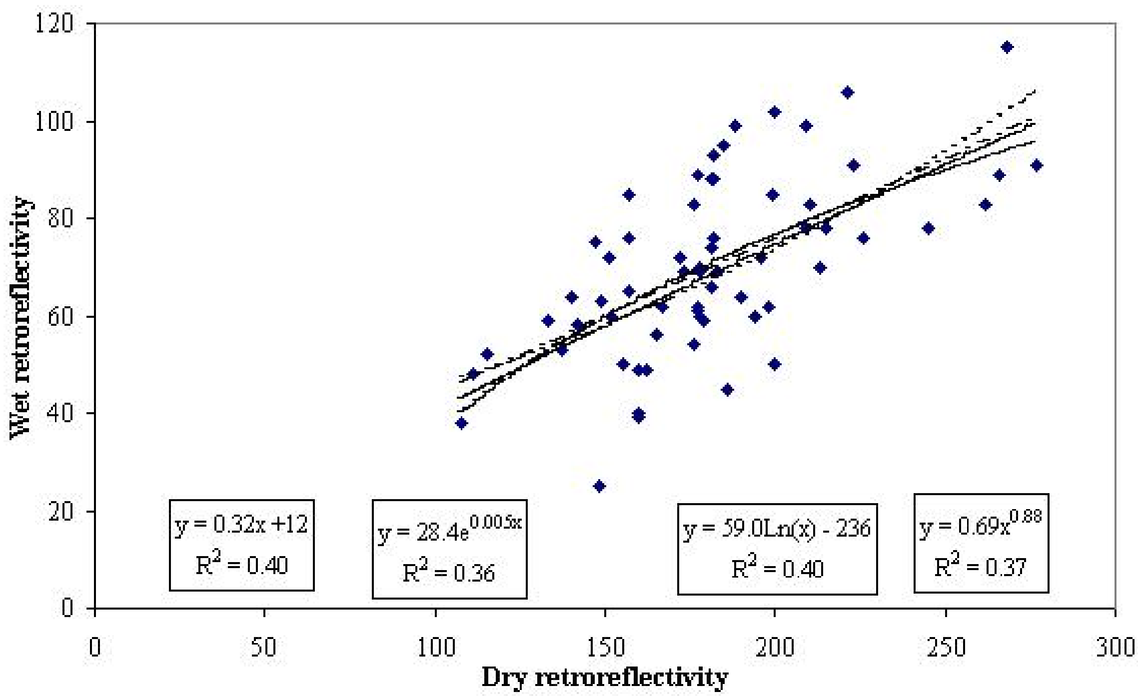


Figure B-7. Correlation between dry and wet retroreflectivity of PPM

Table A-7. Regression analysis of dry and wet retroreflectivity of FTM

The regression equation is wet retroreflectivity = 7 + 0.12* dry retroreflectivity

Regression Statistics	
Multiple R	0.45
R Square	0.20
Adjusted R Square	0.18
Standard Error	13.25
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1998.8	1998.8	11.4	0.00
Residual	46	8077.5	175.6		
Total	47	10076.3			

	Coefficients	*SE*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	6.94	9.02	0.77	0.45	-11.22	25.10
Dry retro	0.12	0.04	3.37	0.00	0.05	0.19

Table B-7. Regression analysis of dry and wet retroreflectivity of PPM

The regression equation is wet retroreflectivity = 12 – 0.32* dry retroreflectivity

Regression Statistics	
Multiple R	0.63
R Square	0.40
Adjusted R Square	0.39
Standard Error	14.30
Observations	63

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	8156.4	8156.4	39.9	0.0
Residual	61	12476.6	204.5		
Total	62	20633.0			

	Coefficients	*SE*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	11.52	9.44	1.22	0.23	-7.36	30.39
Dry retro	0.32	0.05	6.31	0.00	0.22	0.42