Evaluation of Rumble Stripe Markings

By

Dr. Jay K. Lindly and Ms. Ayse Narci
Department of Civil, Environmental and Construction 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

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This study evaluated flat thermoplastic edge markings (FTM) and Rumble Stripes (also called edgeline rumble strips) installed on highways maintained by the Alabama Department of Transportation. The primary objectives of this evaluation were to compare service life, life-cycle costs, and wet-night visibility (measured by wet retroreflectivity) of the two edge marking types. Nighttime dry and wet retroreflectivity of sixteen one-mile segments of FTM and five, two-mile segments of Rumble Stripe were measured using a mobile retroreflectometer. The limited number of segments of Rumble Stripe represented all Rumble Stripe available at the time of testing.

The average dry retroreflectivity of new FTM and new Rumble Stripe tested by this study were 320 and 236 mcd/m^2/lux, respectively. However, the Rumble Stripe was found to lose dry retroreflectivity at a lower rate with respect to cumulative traffic passes. As a result, under similar ADT levels, Rumble Stripe is estimated to provide a higher dry retroreflectivity – and thus a longer service life – than FTM.

The average wet retroreflectivity of Rumble Stripe at the beginning of its service life was found to be higher than the average wet retroreflectivity of FTM at the beginning of its life. However, a decay model for wet retroreflectivity of FTM could not be established, so the decay rate of the two types of edge lines could not be compared. 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 $2,424 for Rumble Stripe. A literature review found that other research had revealed a high benefit: cost ratio for placing Rumble Stripes due to its crash reduction abilities.

Principally due to the longer service life and potential crash reduction effects, the researchers recommend that ALDOT consider implementing rumble stripes where shoulders are constructed, reconstructed, or overlaid, and where bicyclist issues, maintenance issues, and FHWA technical requirements can be met.</td></tr>
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Executive Summary

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For these reasons, the researchers recommend that ALDOT consider implementing rumble stripes where shoulders are constructed, reconstructed, or overlaid, and where bicyclist issues, maintenance issues, and FHWA technical requirements can be met.

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 marking (FTM) edgelines and edgeline rumble stripes (also called modified edge stripes.) FTM is the edge striping method used on most ALDOT roadways. Rumble stripes have been used on an experimental basis in a limited number of sites.

The primary objectives of this evaluation were to compare service life, life-cycle costs, dry retroreflectivity, and wet-night 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.

This report is a follow-up to an earlier UTCA report which compared and contrasted FTM with another type of longitudinal edge marking. The testing and analysis methods reported in this Rumble Stripe report correspond to those in the earlier report so that different edge stripe materials will have been compared in the same way. Data for FTM that is used in this report was taken from the earlier report. Data for rumble stripes was generated specifically for this report.

1.1 Problem Statement

In recent years, state departments of transportation have been investigating using centerline rumble stripes (not covered in this report) and edgeline rumble stripes to enhance traveler safety on roadways. To help decide whether edgline rumble stripes may be appropriate for Alabama highways, ALDOT contracted with UTCA to compare FTM and rumble stripes in three ways:

- Longevity, as measured by service life
- Benefits to drivers under wet-night conditions, as measured by wet retroreflectivity
- 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 centerline miles of state-maintained highways in Alabama. The experience gained from tests reported in this report will help ALDOT to prepare a plan and to be ready for impending MUTCD requirements.

1.2 Scope of Study

The standard flat thermoplastic edge line marking and the rumble stripe as currently used by ALDOT are shown in Figure 1-1. Details of the two markings are found in ALDOT Special Drawing No. SBS-428-A, 07/30/99 and Special Drawing No. SBS-428-B, 04/15/03, respectively. Note that the rumble stripe includes a milled rumble strip and an edge stripe that are inside the normal edge of pavement. In both cases, the pavement milled strips are 7-inch by 16-inch rectangles 12-inches on center and cut 0.5-inch minimum to 0.625-inch maximum depth. In both cases, AASHTO M247, Type I intermix beads at 30% by volume were used, as well as approximately 132 pounds/mile of single drop Type I beads. In both cases, standard edge line width is six inches and edge line depth is 60 mils.

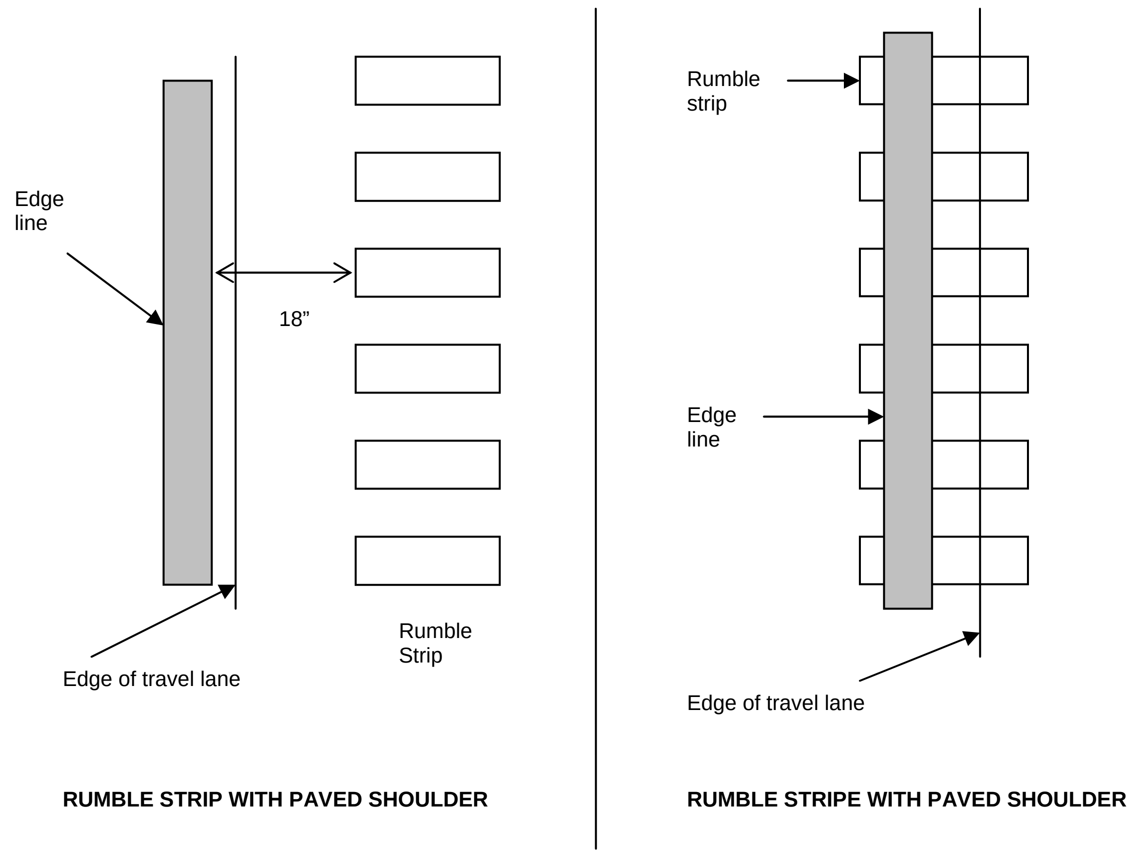

Figure 1-1. Typical Rumble Strip and Rumble Stripe in Alabama in 2003

The results of this study are based on dry and wet-night retroreflectivity testing of 12, one-mile-long FTM pavement sections and five, two-mile-long rumble stripe sections. There were actually 16 FTM pavement sections tested, but data for four of the sections was eliminated, as described later in the report. The five rumble stripe sections represent the only ALDOT rumble stripe sections available during the study period. Table 1-1 lists the test sections.

Table 1-1. Sites tested in the report

Site ID	County	Lowest state route number	Marker type	Test direction	Milepost description
108	Cullman	SR 91	FTM	NB	16-17
203	Franklin	SR 13 (US 43)	FTM	SB	297-296
204	Marion	SR 13 (US 43)	FTM	NB	275-276
206	Colbert	SR 20 (US 72 alt)	FTM	WB	40-39
211	Winston	SR 74 (US 278)	FTM	WB	28-27
306	St. Clair	SR 144	FTM	EB	2-3
307	St. Clair	SR 23	FTM	SB	3-2
308	Blount	SR 53	FTM	NB	259-260
402	Clay	SR 9	FTM	NB	173-174
413	Talladega	SR 275	FTM	NB	2-3
420	Talladega	SR 77	FTM	NB	52-53
651	Elmore	SR 14	FTM	EB	175-176
1	Marengo	SR 8 (US 80)	Rumble stripe	Both	38-40
2	Barbour	SR 30	Rumble stripe	Both	17-19
3	Calhoun	SR 4 (US 78)	Rumble stripe	Both	158.5 – 159.4
4	Morgan	SR 53 (US 231)	Rumble stripe	Both	301 – 302.7
5	Mobile	SR 13 (US 43)	Rumble stripe	Both	27-29

1.3 Organization of Report

This report consists of seven 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 rumble stripes and FTM. Service life estimation for rumble stripes and FTM is given in Section Five. Life cycle cost analysis is presented in Section Six. Section Seven 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. Because most of the existing pavement marking evaluation methodologies and retroreflectivity measurement devices were developed within the last ten years, the literature review focused on studies carried out during that period. The main sources of literature were state DOT reports, FHWA publications, NCHRP reports, 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 phenomenon of retroreflection by glass beads and constituent materials of a typical pavement marking.

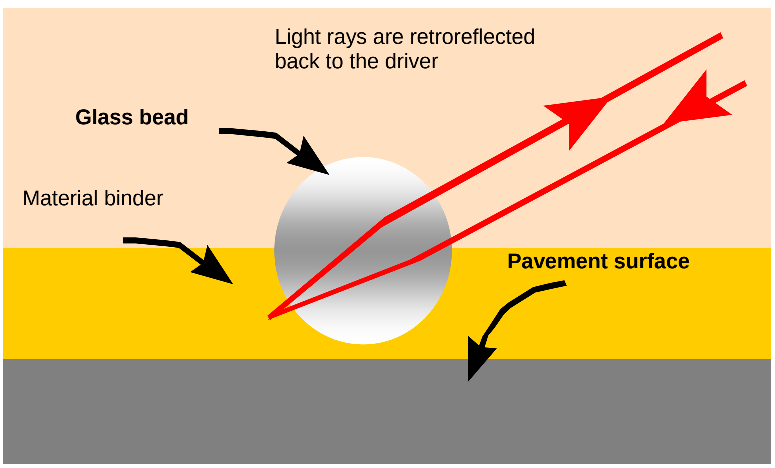

Figure 2-1. Retroreflection from glass beads (Schertz 2002)

According to FHWA (2000), thermoplastic markings are 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); ALDOT (2006) requires new FTM to be 90 mils thick on lane striping and 60 mils thick on edge striping.

2.2 Department of Transportation Appropriations Act 1993

Section 406(a) of the 1993 Department of Transportation Appropriations Act requires the MUTCD (FHWA 2003) 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 for markings. 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.

2.4 ASTM Standards

The wet/night retroreflectivity tests performed for this research are based on modifications to ASTM test procedures developed by UTCA. 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)

Because 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 some water to drain, yet markings are still in a wet condition.

ASTM E 2176 was not used for the testing in this project, nor was it used in the previous UTCA work. Continuous wetting of one to two miles of pavement in 17 locations around the state was impractical for the projects.

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. For the previous UTCA study on which the current study is based, none of the retroreflectometers could be used to measure retroreflectivity during rainfall. Since that study, hand-held retroreflectometers have been developed that can measure under conditions of continuous wetting as described in ASTM E 2176.

2.6 Rumble Strip Studies

Rumble strips have been used around the US since the early 1990s to help prevent "drift off" the road crashes, where tired or inattentive drivers leave the traveled way before they become aware of the departure. In general, the first applications of rumble strips were on freeways and other major highways, where wide shoulders provided enough space to place them. Rumble strips can be raised, formed, or milled, with milled providing the greatest amount of wheel vibration to alert the driver of a potential roadway departure. The Federal Highway Administration (FHWA) rumble strip website lists several states that report reductions in freeway run-off-road crashes of 15% - 80% where rumble strips were placed (FHWA 2005).

Rumble strips do have potential drawbacks. Bicycling may be made more difficult; in northern states, applying sand and salt in winter may be more difficult, and those materials may build up in the strips. A worry has also existed that rumble strips may "pull" a vehicle into an erratic maneuver. An FHWA Technical Bulletin provides guidance for specifying and placing rumble strips to avoid many of these difficulties (FHWA 2001).

2.7 Rumble Stripe Studies

Alabama and other states have been placing part of the rumble strip inside the traveled lane and covering that part with the white edge stripe, forming a rumble stripe. This action provides an even earlier warning than a rumble strip that the driver is about to leave the pavement. Many run-off-road crashes occur at night in wet weather, and the vertical edges of the rumble stripe are said to hold the edge line out of the rain water, giving it higher retroreflectivity in those wet-night conditions. Testing and quantifying this claim is one of the objectives of this research project.

2.7.1 TTI Study by Miles

Texas Transportation Institute (TTI) has performed two recent studies concerning rumble stripes (Miles et al. 2005) (Carlson et al. 2005). The Miles study instrumented a highway in Texas with video and pneumatic road tubes which could measure the number and distance of encroachments of vehicles onto the shoulder. The highway was observed for approximately two weeks before a rumble stripe was applied and approximately two weeks after it was applied. Roughly 6,000 encroachments onto the shoulder were observed. One helpful finding was that the edge stripe did not produce any erratic maneuvers. Another result was that for the kind of "drift off" shoulder encroachments of special concern, there was a statistically-significant reduction of 40%-45% for "all vehicles".

The Miles study also produced a benefit: cost study for rumble stripes. Based on a 20% run-off-road crash reduction and a cost of $0.25 per lineal foot for rumble strips (the stripe would be present in any case), TTI found a benefit: cost ratio ranging from 2 to 221 for applying rumble stripes. The range of values occurs because TTI calculated benefit:

cost for a variety of average daily traffic (ADT) and shoulder width situations. The result of this benefit: cost study reinforces the findings of an earlier FHWA study which reported a strong benefit for applying rumble strips (FHWA 1999)

2.7.2 TTI Study by Carlson

The TTI report by Carlson (2005) presents the results of the first year of a two-year study of wet-weather pavement markings. Much of the study centered around test subjects driving through a 1600-foot long rain tunnel with headlights on and recording when they could first see strips of marking. Subjects repeated the test during low, medium, and high "rainfall" events. Several test results of interest to ALDOT were observed:

- Large beads provide higher retroreflectivity and recover their retroreflectivity more quickly after rain events.
- A limited study indicated that six-inch-wide lines could be detected at a greater distance than four-inch-wide lines.
- Compared to FTM, rumble stripes had roughly the same detection distance during low rainfall, but for medium and high rainfall, rumble stripes could be seen at a significantly greater distance.

The report gives "preliminary recommendations" of interest to ALDOT:

- Concerning the use of smaller versus larger beads, "In their thermoplastic specification, TxDOT should begin to phase out Type II beads for mixed beads including high refractive index big beads. Alternatively, a switch to Type III beads would also be beneficial in terms of added wet-night visibility."
- "Where possible, TxDOT should be using rumble striping…. With the findings of this research, it is now clear that the touted enhanced wet-night visibility claims are indeed achievable."

2.8 NCHRP 2006 Study

The National Cooperative Highway Research Program (NCHRP) released *Pavement Marking Materials and Markers: Real-World Relationship between Retroreflectivity and Safety over Time* as Web-Only Document 92 (NCHRP 2006). The study focused on non-intersection, non-daylight crashes in California during 1992-1994 and 1997-2002 and related them to the retroreflectivity of the longitudinal paving markings on the road at the time of the crashes. Over 118,000 crashes were used in the study, which covered over 5,000 miles of state maintained freeways and highways in California. The study did not measure the retroreflectivities of the markings at the time of the crash; it modeled them based on National Transportation Product Evaluation Program (NTPEP) data. A variety of marking types were present on the roads that were studied, so the study does not comment on the safety of FTM vs. rumble stripes; instead, it focuses on the retroreflectivity of whatever marking material was present at the time of the crash.

A main finding of the study is that the amount of retroreflectivity is not important to driver safety as long as the marking is present and visible to drivers. "In summary, this study found that there is no safety benefit of higher retroreflectivity for longitudinal markings on non-intersection locations during non-daylight conditions for roads that are maintained at the level implemented in California's state highways. California's level of maintenance appears to be frequent with pavement markings being installed on higher volume highways up to three times a year with waterborne paint, or every two years with thermoplastic markings. The findings of this research study allow agencies to recognize that resources to increase the retroreflectivity of longitudinal markings, beyond normal maintenance activities, will not be cost-effective and that those resources could instead be allocated towards other safety measures."

Why doesn't "brightness" of the lines seem to be a factor in the number of crashes? The NCHRP report says "The increase in sight detection distance due to higher retroreflectivity of pavement markings and markers may cause drivers to maintain higher speeds, thereby increasing the possibility of a crash under certain geometric conditions. In other words, driver adaptation to road conditions may be minimizing any improvement in safety due to greater sight detection distances from retroreflectivity markings and markers."

The study authors hypothesize that California's rather strong pavement marking management system creates a situation where there are relatively few roads with markings below a minimum threshold value for safety. If that hypothesis is correct, the study appears to show that brightness of markings is not as important to safety as maintaining them above "minimum" values.

Section 3
Methodology

This section explains the steps involved in planning and conducting data collection. It describes selection of test sites, equipment used, dry and wet retroreflectivity tests, and observations made during tests. The procedures for the 2004-2006 series of tests on Rumble Stripes is the same as the procedures for the test series on FTM conducted from 2001-2003.

3.1 Site Selection

In Alabama, there have been five highway test sites where Rumble Stripe markings were placed since 2003. Three of these sites were tested in 2004, and all sites were tested both in 2005 and 2006. ALDOT provided route number, beginning and ending mileposts, date of completion of projects, and unit costs for installing markings for each site. Some of this data is summarized in Table 3-1.

Table 3-1. Summary of Rumble Stripe project database

ALDOT Division	County	Site #	Route #	Dates of stripe completion	Project numbers	Mile post
8	Marengo	100	US80	06/11/04	NHF-0008(507)	38-40
7	Barbour	200	SR30	12/30/03	MG-0030(500)	17-19
4	Calhoun	300	US78	08/25/04	99-304-082-004-401 99-304-082-004-402	158.5-159.4
1	Morgan	400	US231	10/13/04	ST-052-053-001	301-302.8
9	Mobile	500	US43	02/17/05	NHF-0013(515)	27-29

Data from the five Rumble Stripe sites will be compared against data for twelve Flat Thermoplastic Markings (FTM) test sites shown in Table 1-1 of this report. Striping of the FTM sites was completed from 1999 to 2001 and tested from 2001 to 2003.

For the FTM sites, test section length was set at one mile, and only one direction (e.g., north-bound or south-bound) was tested at each site. This method was possible because the large number of sites provided a large amount of data. For the five Rumble Stripe sites, longer test sections (up to two miles in length) were selected. In addition, provisions were made to test the edge line in both directions of travel so that a larger amount of data could be collected at each of the five sites. The locations of the FTM and Rumble Stripe test sites are shown in Figure 3-1.

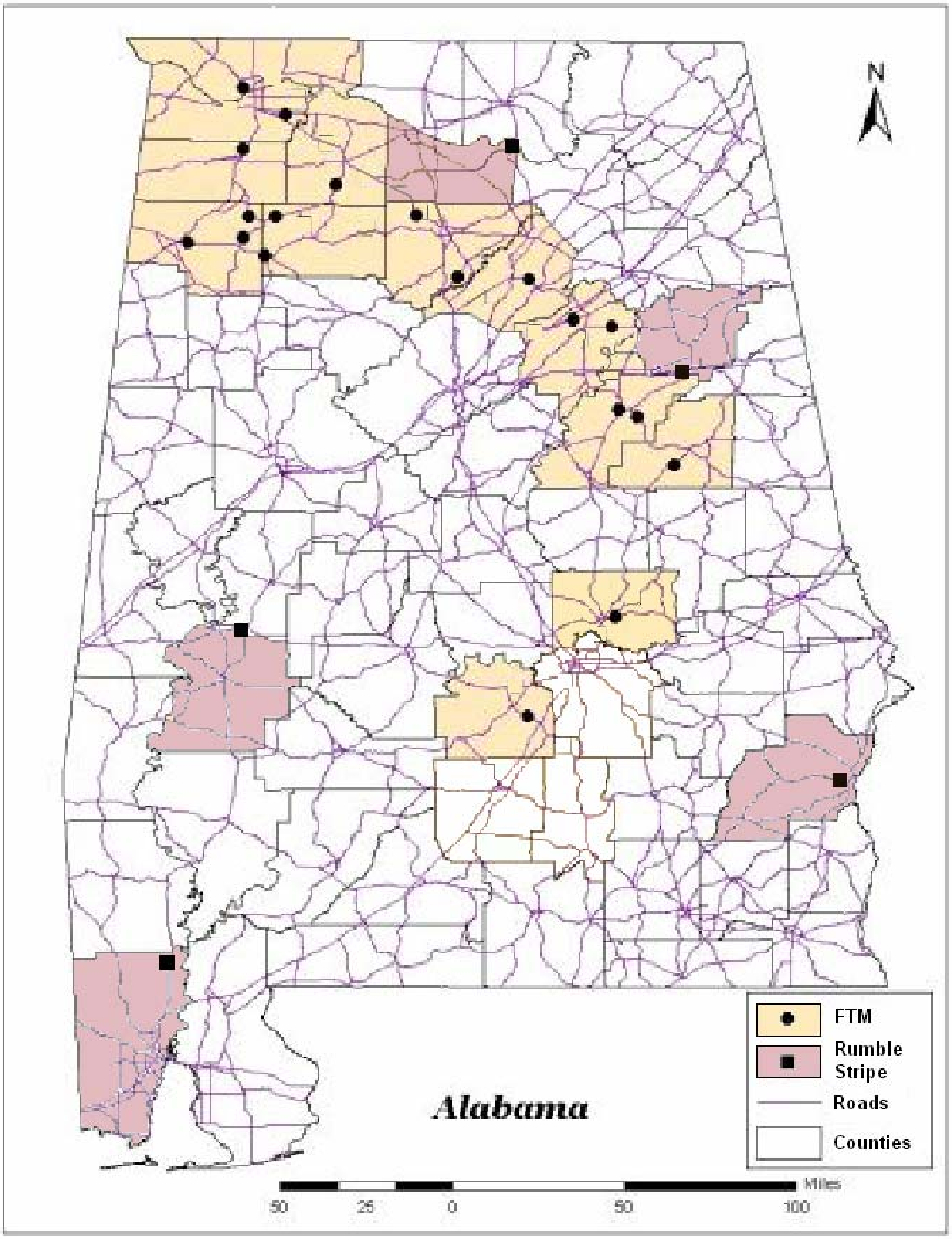

Figure 3-1. Pavement marking test sites

3.2 Pre-Survey Site Inspection

The five Rumble Stripe sites were inspected two weeks before the first retroreflectivity test. This survey was used to gather additional information on test sites such as number of lanes, roadside development (i.e., rural or urban), and speed limit. The surveys also allowed the team to select the best section within the site for retroreflectivity testing. Table 3-2 presents a summary of selected information from field inspections.

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

County	Number of lanes	Type of development	Speed limit (mph)	Shoulder	Stripe materials
Marengo	4	Rural	65	Paved	Standard thermoplastic w/bead
Barbour	2	Rural	55	Paved	Thin film spray applied thermoplastic material w/bead
Calhoun	4	Urban	45	75% are unpaved	Standard thermoplastic w/bead
Morgan	4	Rural	65	Paved & unpaved	Standard thermoplastic w/bead
Mobile	4	Urban	65	Paved	Standard thermoplastic w/bead

According to Table 3-2, the majority of test sites were located in four-lane rural roads. During the field inspections, photos of test sites and markings were taken. Typical FTM and Rumble Stripe are shown in Figures 3-2 and 3-3, respectively.

Figure 3-2. Flat thermoplastic marking

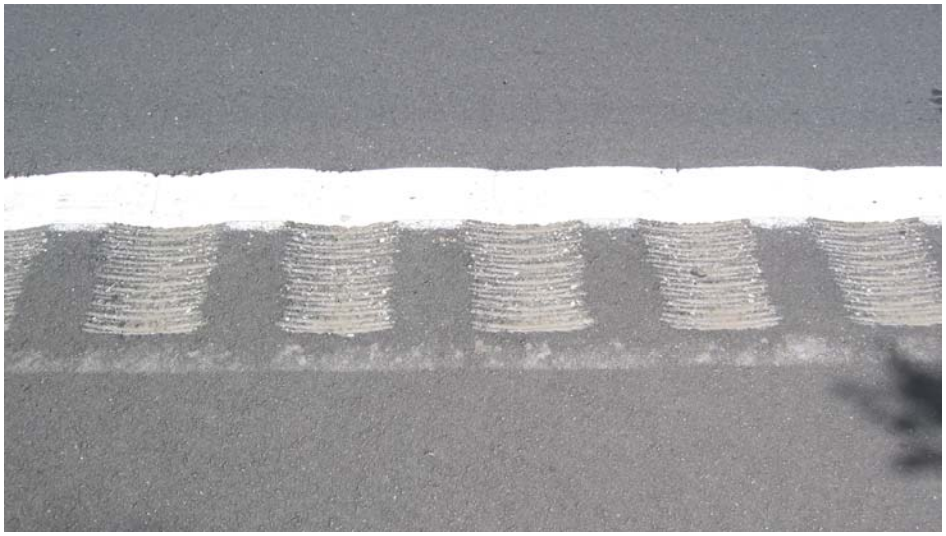

Figure 3-3. Rumble Stripe marking

3.3 Resources for Surveys

The dry retroreflectivity tests were performed without any traffic control. Therefore, the only vehicle needed for dry tests was the test 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 test van and water truck. A typical wet test train consisting of water truck, mobile retroreflectometer van (see Section 3.3.1 for more information on the Laserux van), 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 a 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.

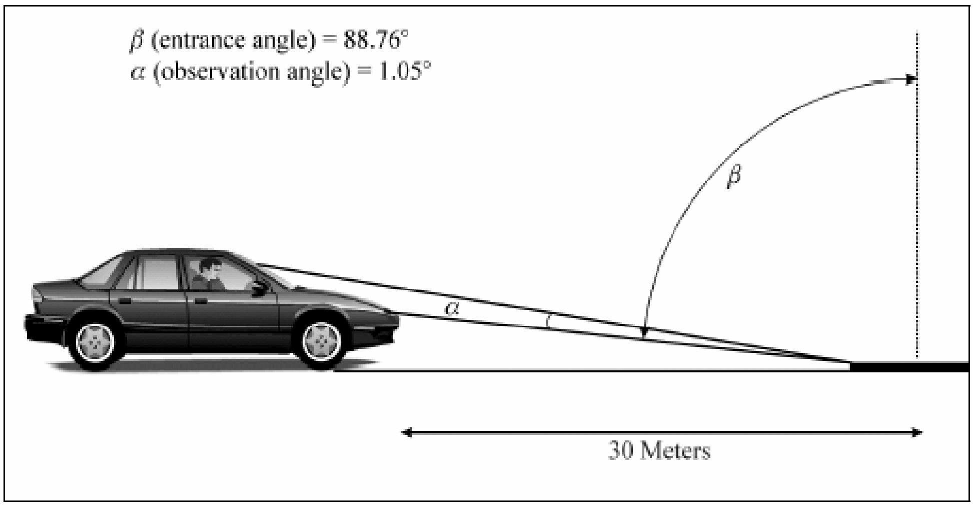

Figure 3-5. Illustration of 30-meter (98-feet) geometry [10]

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 used effectively to measure a one-mile or two-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

When possible, test sites were selected such that they began and ended at a milepost. First, a site was tested dry in both directions, then tested again in both direction 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 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 850, 700, and 500 gallons. The time taken to fill a 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 16 gallons, or about 0.3 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. Additionally, the discharge volumes for the Rumble Stripe tests were very similar to discharge volumes reported for the FTM tests in 2003.

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
850	5	4.1	121
700	5	4.4	117
500	5	4.9	105

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.

3.5 Notes on Three Surveys

Each of the Rumble Stripe locations was tested three times over a period of eighteen months from 2004 to 2006. (Sites 400 and 500 were not completed before the first test, so they were only tested twice.) The mean dry and wet retroreflectivity values measured at Rumble Stripe sites during the field tests are given in Table 3-5. The FTM data to which the Rumble Stripe data will be compared is given in Table 3-6.

Table 3-5. Retroreflectivity data for Rumble Stripe test sites

Site ID	County	Route number	Average retroreflectivity ($mcd/m^2/lux$)					
			Test one		Test two		Test three	
			Dry test	Wet test	Dry test	Wet test	Dry test	Wet test
100	Marengo	US80	212.5	53	208.5	54	133.5	32.5
200	Barbour	SR30	177	48.5	159.5	45.5	161	23
300	Calhoun	US78	240.5	47.5	186	46	147.5	24
400	Morgan	US231			280.5	57	246	24
500	Mobile	US43			247.5	68.5	260	27.5

3.5.1 Test One

Three sites were tested from October 18, 2004 to October 22, 2004. A total of six retroreflectivity values were recorded because separate tests were conducted in each direction of each test site.

3.5.2 *Test Two*

Five sites were tested on May 9, 2005 and May 10, 2005, which was seven months after the first tests. A total of ten retroreflectivity values were recorded for the 2005 test series.

3.5.3 *Test Three*

Test series three was conducted from May 15, 2006 to May 18, 2006. Ten values were obtained from these five test sites. At the completion of three rounds of testing, twenty six total retroreflectivity values for Rumble Stripe sites had been obtained.

Table 3-6. Retroreflectivity data for FTM 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
108	301	36	325	44	274	54
203	241	48	222	34	202	48
204	258	62	261	44	235	39
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
651	136	24	102	20	94	34

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 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. However, test personnel worked to ensure consistent spacing between the water truck and test van.
- 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 toward the pavement markings.

Section 4
Retroreflectivity Decay Models

This section explains the process of developing retroreflectivity decay models using regression analysis for FTM and Rumble Stripe. 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:

- <u>Dry retroreflectivity decay models for Rumble Stripe and FTM</u>. These models will be used to determine service lives, retroreflectivity degradation rates, and retroreflectivity of new markings.
- <u>Wet retroreflectivity decay models for Rumble Stripe and FTM</u>. 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:

- <u>Method One:</u> Retroreflectivity data gathered from different survey locations for a similar type of marking (e.g., Rumble Stripe) 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.
- <u>Method Two:</u> 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. 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 provides 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 three times over a period of eighteen months. These markings were installed at different points in time. When data from markings that were installed at different times are aggregated, the resulting database represents a broader time period than data 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., Rumble Stripe) 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., Rumble Stripe).

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., Rumble Stripe), 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 Rumble Stripe data three times over a period of eighteen months. 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 Rumble Stripe and FTM 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 two functional groups for the decay model: dependent variable and primary independent variables. Retroreflectivity is the dependent variable. Marking age and the cumulative traffic passages (CTP) were the primary independent variables.

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:

- October 2004 data, referred to as Test One data
- May 2005 data, referred to as Test Two data
- May 2006 data, referred to as Test Three data

The retroreflectivity of an indvidual stripe 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 the change in retroreflectivity with time of the Rumble Stripe test sites. Morgan, Calhoun and Marengo sites behaved as expected: retroreflectivity declined from Test One to Test Two to Test Three. Mobile and Barbour sites did not follow the expected pattern.

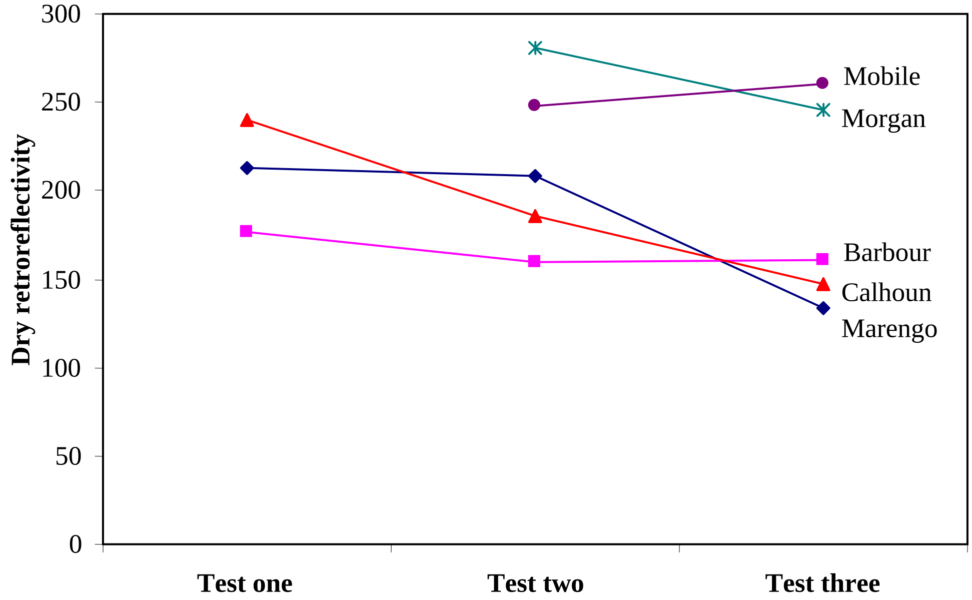

Figure 4-1. Variation of dry retroreflectivity of Rumble Stripe test sites

Possible 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:

- Retain all data: This option gives a larger 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) and the previous UTCA study (2003) 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 solutions could potentially weaken the findings of the research. However, due to the limited number of test sites, the decision was made to retain all data. If the Mobile and Barbour test sites were eliminated, only three test sites could be analyzed.

Using the criteria cited above, separate databases were generated for Rumble Stripe dry retroreflectivity and Rumble stripe wet retroreflectivity. FTM dry retroreflectivity and FTM wet retroreflectivity databases had been constituted in tests from 2001-2003. 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. These databases were used for developing dry and wet retroreflectivity decay models for Rumble Stripe and FTM.

4.2.2 Independent Variables

The next step in developing decay models was to identify the 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 2000-2005. This study extrapolated 2000–2005 data to estimate ADT for 2006.

The research team compared the ages of the FTM and Rumble Stripe edge lines at the three times the two type of stripes were tested. Rumble Stripe sites were tested in the range of 2 to 29 months. FTM sites were tested in the range of 5 to 42 months. The Rumble Stripe sites are newer simply because no significant amount of Rumble Stripe was laid in Alabama before 2003. The lack of Rumble Stripe data in 30-50 month range means that conclusions reached from the Rumble Stripe data (such as predicted age at Retroreflectivity of 100 mcd/m^2/lux) may be less supportable than conclusions reached from the FTM data.

The team also examined CTP data. For FTM, CTP at test time ranged from 0.14 to 6.11. For Rumble Stripe CTP at test time ranged from 0.49 to 6.53, showing a range similar to that of FTM.

<u>4.2.2.1 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-1 to D-1 of Appendix 1). 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 method to identify the best form. Table 4-1 shows the variation of coefficients of determination (R^2) for both CTP and marking age in months. In previous UTCA work that described FTM, the R^2 value was higher for CTP than it was for marking age, so CTP was selected as the primary independent variable. For Rumble Stripe retroreflectivity values, marking age showed better correlation with dry retroreflectivity than CTP, while CTP showed better correlation with wet retroreflectivity than marking age. Therefore, to make both comparisons using the same independent variable, CTP was chosen as the primary independent variable for both Rumble Stripe decay models. The R^2 value is high enough to say there is a good correlation between CTP and dry retroreflectivity of Rumble Stripe.

Table 4-1. Fitted models for Rumble Stripe dry and wet retroreflectivities vs. CTP and age

	Coefficient of determination (R^2) for dry rumble stripe		Coefficient of determination (R^2) for wet rumble stripe	
	CTP	Age in months	CTP	Age in months
Linear	0.24	0.36	0.73	0.71
Exponential	0.26	0.39	0.77	0.72
Logarithmic	0.23	0.31	0.67	0.59
Power	0.26	0.34	0.66	0.58

<u>4.2.2.2 Testing of Age and ADT per Lane as Independent 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 with a multiple regression model. 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.)

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

4.3 Development of Retroreflectivity Decay Models

Models were calibrated to predict decay of dry and wet retroreflectivity as a function of CTP for Rumble Stripe to compare to the models that had been developed in 2003 for FTM. The sequential steps involved in developing the 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 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 a main purpose of this study is to determine the stage at which retroreflectivity falls below the minimum threshold retroreflectivity values.
- Minitab® software was used to further analyze the selected models. Descriptive statistics such as ANOVA, F-statistic, t-significance, and normality test of residuals were used for analyzing selected models.
- Finally, an appropriate model was selected for service life estimations.

The researchers did not develop separate decay models based on stratifying dry retroreflectivity data by ADT. That investigation was performed in 2003 and did not yield statistically significant models.

4.3.1 Dry Retroreflectivity Decay Models for FTM

Earlier work analyzed 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 4-2 shows the relationship between dry retroreflectivity of FTM and CTP. This figure shows linear, exponential, logarithmic, and power models fitted to the data.

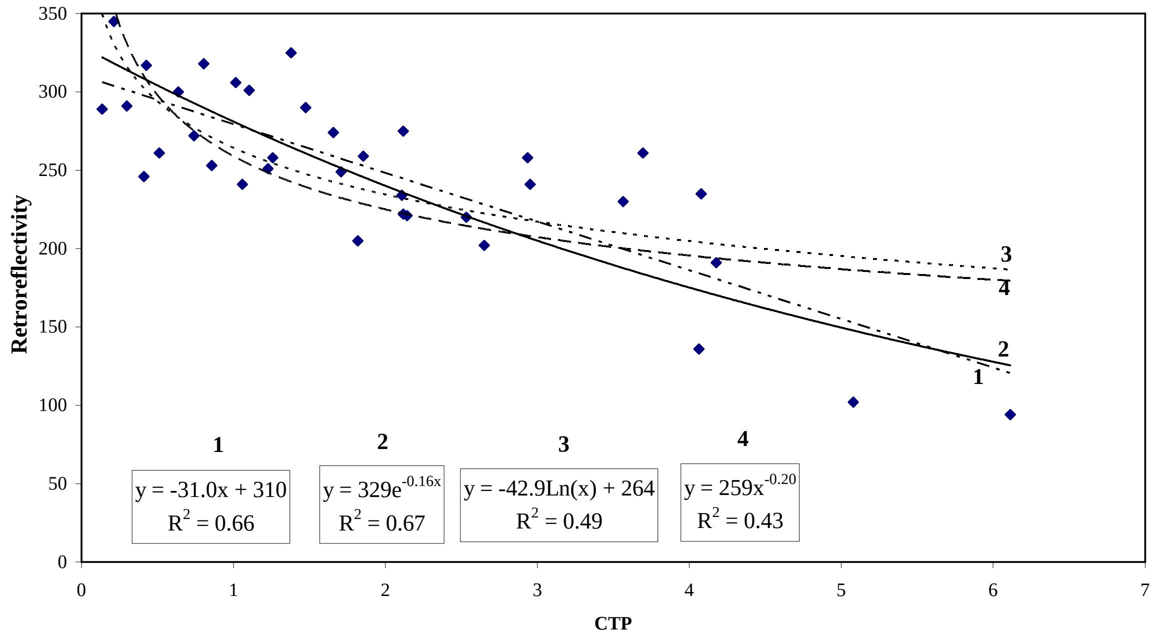

Figure 4-2. Dry retroreflectivity vs. CTP of FTM test sites

The R^2 of the fitted models are given in Table 4-2.

Table 4-2. 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 4-2). Linear and exponential models were further analyzed using the regression option of the Microsoft® Excel. Secondary variables such as speed limit and geographic location were tested, but none of these variables proved to be statistically significant. The results of the regression analysis are given in Tables A-2 and B-2 of Appendix 2, and an abstract is presented in Table 4-3.

Table 4-3. 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 result of normality test of residuals of linear and exponential models shown in Tables A-2 and B-2 of Appendix 2 indicate that the residuals are normally distributed. This is confirmed by the Anderson-Darling test statistic. The p-value for the Anderson Darling test for Normality is greater than 0.05. The null hypothesis of a normality test is that there is no significant departure from normality. When the p-value is more than 0.05, it fails to reject the null hypothesis of Normality; thus, the hypothesis that the distribution of residuals is normal is accepted and also the mean of the residuals is zero. There is one influential data point 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 $mcd/m^2/lux$.

4.3.2 Dry Retroreflectivity Decay Models for Rumble Stripe

Five different Rumble Stripe test sites were tested during three test periods for a total of thirteen occasions. At each site, retroreflectivity values were taken in two directions. Thus, 26 different observations were available. However, at each site, the observations from the two directions were very similar, and the research team elected to use the mean value at each site for a total of 13 observations. All thirteen observations from five Rumble Stripe test sites were used in this analysis, using the same methodology used for developing decay models for dry FTM. Figure 4-3 shows a scatter plot representing the relationship between dry retroreflectivity of Rumble Stripe 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 4-4. The R^2 values are significantly lower than the R^2 values for FTM in Table 4-2. This difference is apparent in the greater scatter in Figure 4-3 compared to the scatter in FTM data in Figure 4-2. However, the value of R^2 of Rumble Stripe decay model is adequate to accept correlation between CTP and dry retroreflectivity and then to predict service life.

Table 4-4. Fitted models for Rumble Stripe dry retroreflectivity vs. CTP

Coefficient of determination (R^2)			
Linear	**Exponential**	**Logarithmic**	**Power**
0.24	**0.26**	**0.23**	**0.26**

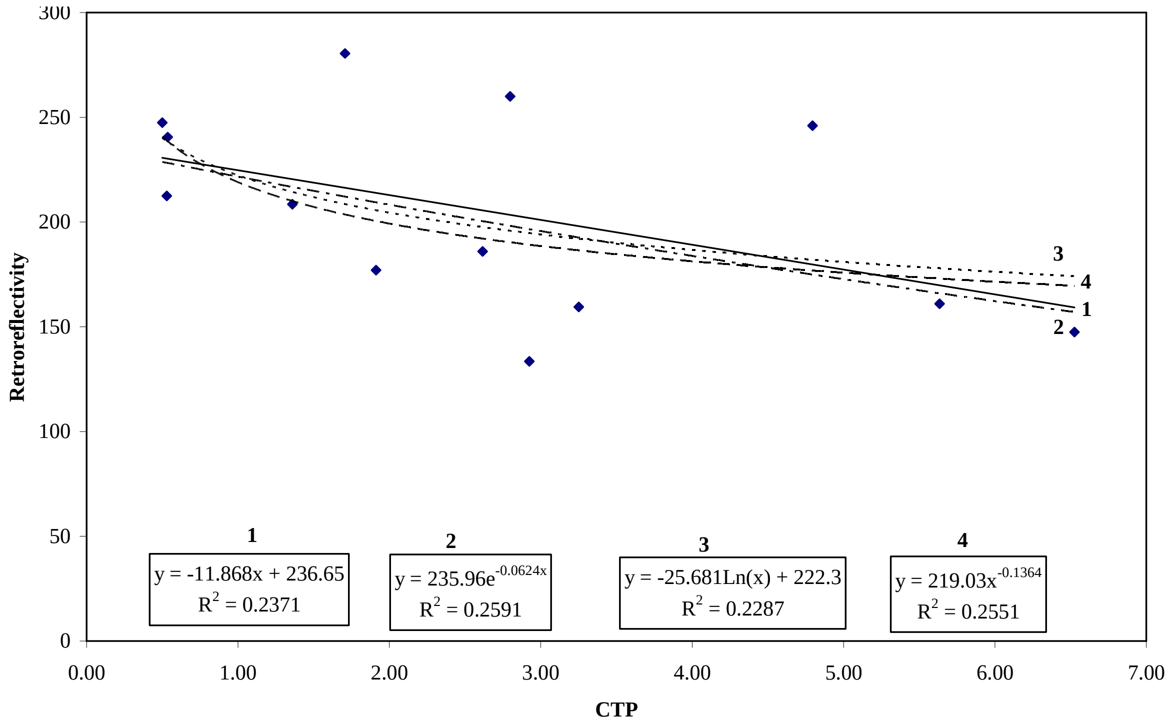

Figure 4-3. Dry retroreflectivity vs. CTP of Rumble Stripe test sites

According to Table 4-4, exponential and power models gave the best fit for the combined database. In addition, Figure 4-3 indicates that exponential and linear models gave a better estimate than the power model for low and high retroreflectivity values observed in field testing. As a result, the exponential model was selected for service life estimation and analyzed using the regression option of the Minitab® software. The results of the regression analysis are given in Tables C-2 and D-2 of Appendix 2, and an abstract is presented in Table 4-5.

Table 4-5. Selected decay model for Rumble Stripe dry retroreflectivity

Model Type	**Coefficient and (p significance)**		**R^2**	**F-Statistic**
	Constant	**Exp (CTP)**		
Exponential	236 (0.00)	-0.062 (0.00)	0.26	4

For future calculations, the exponential model was run, and predicted values were used to estimate service life depending on the potential minimum threshold values of 100 and 150 mcd/m^2/lux.

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 4-4 shows the scatter plot of wet retroreflectivity of FTM vs. CTP.

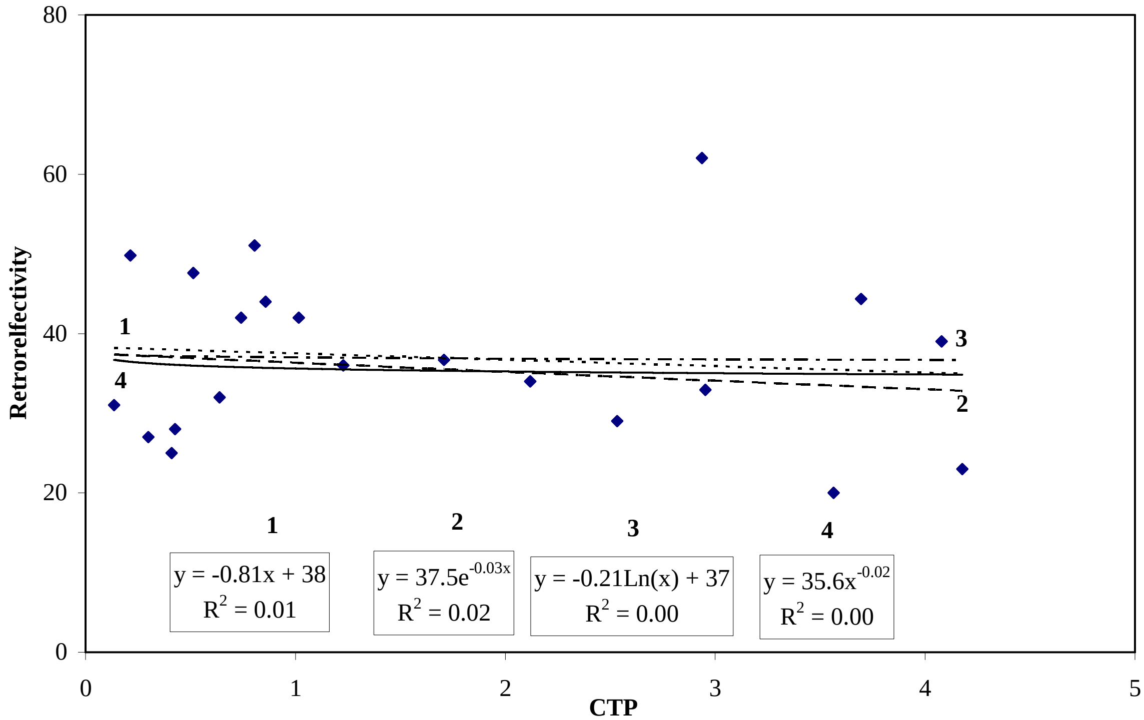

Figure 4-4. Wet retroreflectivity vs. CTP of FTM test sites

According to Figure 4-4, wet retroreflectivity did not significantly decrease with increase in CTP. As Table 4-6 shows, 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 4-6. 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 Rumble Stripe

There were thirteen observations from five Rumble Stripe test sites during three test periods, and all of the sites showed a decrease in wet retroreflectivity from Test One to Test Three. Figure 4-5 shows the variation of wet retroreflectivity with time.

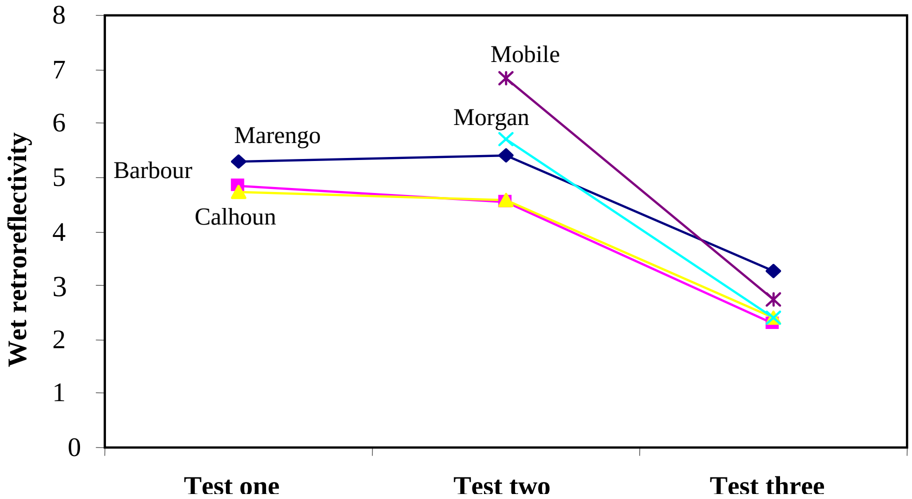

Figure 4-5. Variation of wet retroreflectivity of Rumble Stripe test sites

Figure 4-6 shows the relationship between wet retroreflectivity of Rumble Stripe and CTP. This figure shows linear, exponential, logarithmic, and power models fitted to the data.

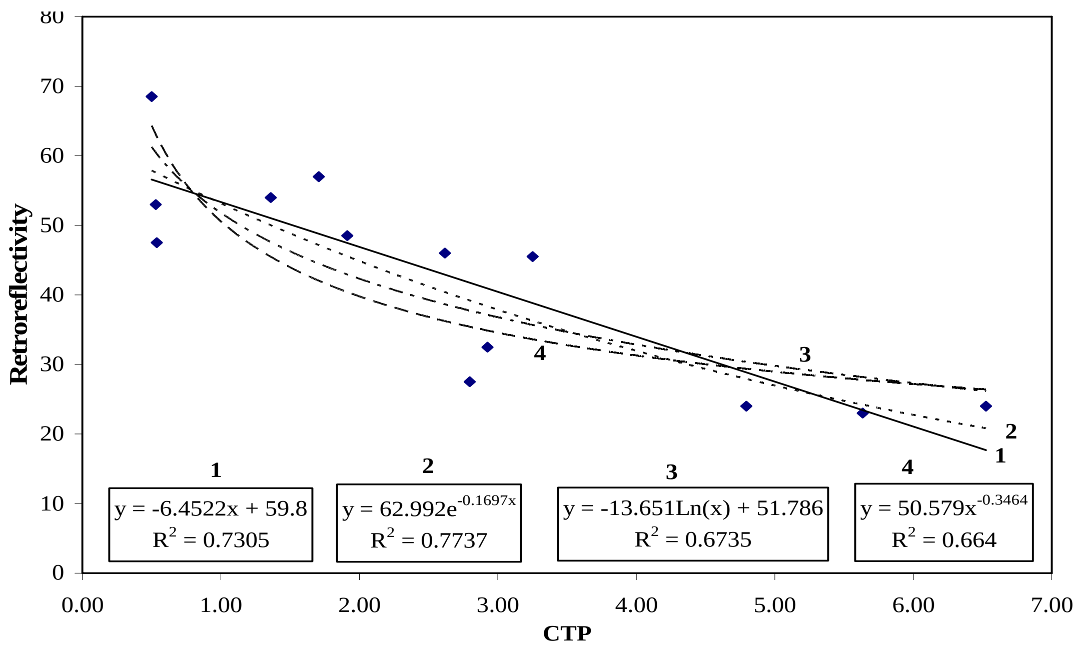

Figure 4-6. Wet retroreflectivity vs. CTP of Rumble Stripe test sites

According to the R^2 values given in Table 4-7, the exponential model gave the best fit for the combined database. Based on Figure 4-6, the exponential model was selected to predict the retroreflectivity decay of wet Rumble Stripe.

Table 4-7. Fitted models for Rumble Stripe wet retroreflectivity vs. CTP

Coefficient of determination (R^2)			
Linear	Exponential	Logarithmic	Power
0.73	0.77	0.67	0.66

The exponential model was analyzed using the regression option of the Minitab® software, and a summary of the regression output is presented in Table 4-8.

Table 4-8. Selected decay models for Rumble Stripe wet retroreflectivity

Model Type	Coefficient and (p significance)		R^2	F-Statistic
	Constant	Exp (CTP)		
Exponential	63 (0.00)	-0.17 (0.00)	0.77	37.6

As evident from the R^2 values in Tables 4-6 and 4-7, there was a better correlation between wet rumble stripe data and CTP than between wet FTM data and CTP. Therefore, the wet retroreflectivity of Rumble Stripe 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 Rumble Stripe 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 model is equal to the retroreflectivity value of a new marking. Table 4-9 gives dry retroreflectivity of new FTM and Rumble Stripe and 95% confidence intervals of these estimations. 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 Rumble Stripe is between 188 and 297 mcd/m^2/lux for the sites tested in this research. According to Table 4-9, the average dry retroreflectivity of a new Rumble Stripe is around 74 percent of a new FTM.

Table 4-9. Estimated retroreflectivity of new Rumble Stripe and FTM

Marking		Average retroreflectivity (mcd/m^2/lux)	Confidence intervals	
			Lower 95%	Upper 95%
DRY	FTM	320	292	361
	Rumble stripe	236	188	297
WET	Rumble stripe	63	52	77

4.4.2 Wet Retroreflectivity of New Markings

The average wet retroreflectivity of new Rumble Stripe is around 63 mcd/m^2/lux (see Table 4-8). Even though a decay model for wet retroreflectivity of FTM could not be established, the wet retroreflectivity of new FTM is less than 63 mcd/m^2/lux. The highest wet retroreflectivity value for FTM at any of the test sites was 62 mcd/m^2/lux.

4.4.3 Comparison of Decay Rates

The decay rates of the edge marking types are represented in Figure 4-7, which shows that the decay rate for dry FTM is more rapid than that for dry Rumble Stripe. For example, when FTM or Rumble Stripe is exposed to the first 1.0 CTP, FTM retroreflectivity reduces by 15 percent and Rumble Stripe retroreflectivity reduces by six percent. After approximately 4.0 CTP for FTM and 11.0 CTP for Rumble Stripe, the remaining retroreflectivity is 50 percent of its initial value. The less rapid decay of Rumble Stripe may occur because the sound and vibration of the rumble strip causes drivers to keep off the Rumble Stripe marking materials.

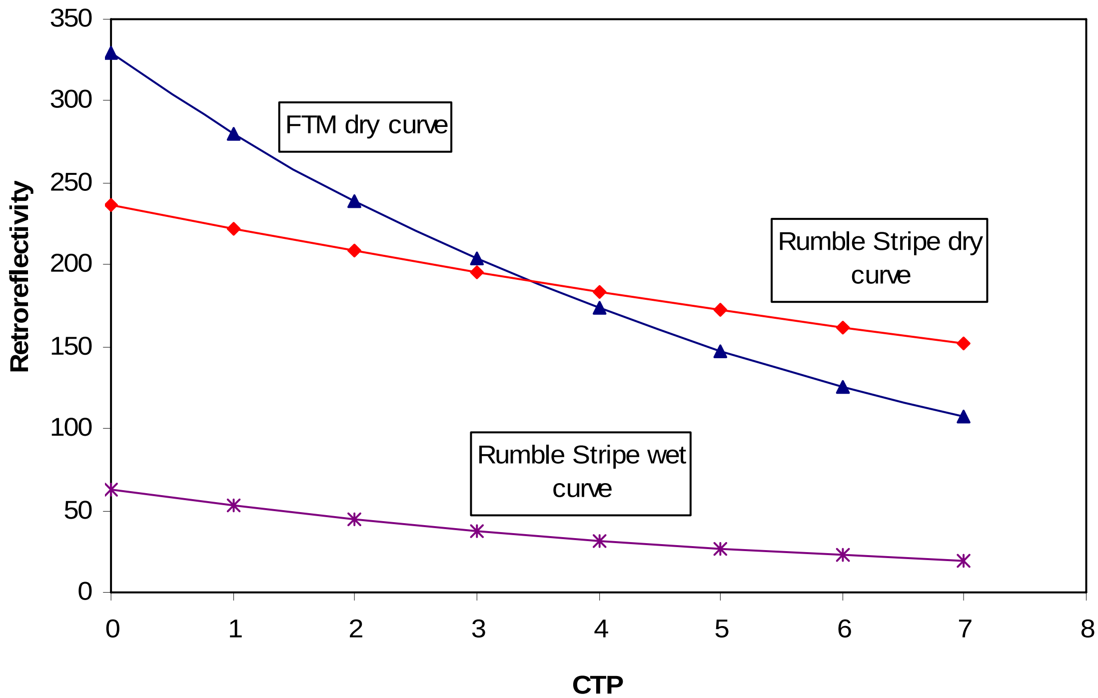

Figure 4-7. Variation of dry and wet retroreflectivity vs. CTP

4.5 Alternative Analyses

The researchers performed two alternative analyses to determine if small alterations in the analysis approach would make significant changes in the results.

4.5.1 Barbour Test Site

The Rumble Stripe test section in Barbour County was constructed with a thinner layer of thermoplastic than the other four test sections, and the researchers were concerned that including the data might influence the results. Accordingly, they performed regression analysis with only four sites, and the results are shown in Figure 4-8. The figure shows that deleting the Barbour County site would make very little difference in the regression analysis outcome.

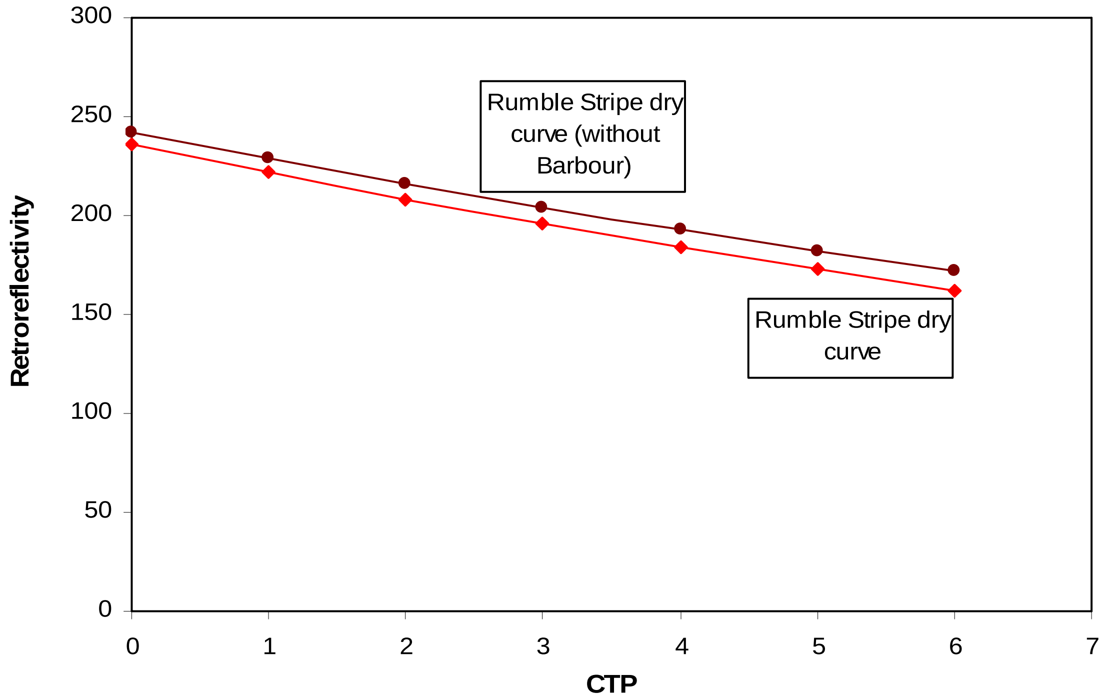

Figure 4-8. Comparison of decay rates with Barbour and without Barbour

4.5.2 Alternative Decay Curve Analysis for Rumble Stripe

In the base analysis, researchers averaged the retroreflectivity values from both travel directions to arrive at one value for each of the five Rumble Stripe sites. To determine whether the results would have been different if the values from the two directions were analyzed separately, researchers ran the regression analysis a second time using separate values for the two directions of travel. Thus, the alternative analysis used twenty-six dry and wet retroreflectivity data points from the five sites instead of thirteen. Figure 4-9 and Table 4-10 show the results of the alternative analysis compared to the base analysis. Figure 4-9 shows the plot of four regression curves, but the curves for the two analyses are so similar that there appears to be only two curves. Table 4-10 shows the R^2 values for the analyses, again showing little difference. As a result, the researchers observed that the decay rates are very similar for the two analyses.

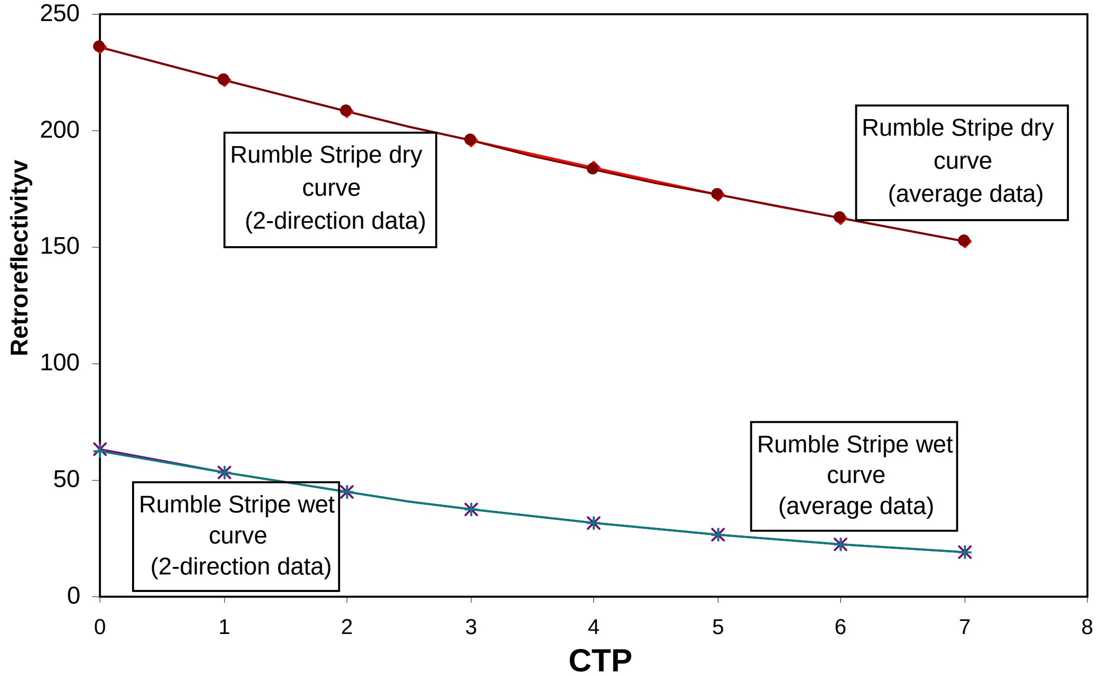

Figure 4-9. Variation of dry and wet retroreflectivity of two analysis methods vs. CTP

Table 4-10. Fitted models for 2-direction data of Rumble Stripe dry and wet retroreflectivity vs. CTP

	Coefficient of determination (R^2)			
	2-direction data		**Averaged data**	
	Dry	**Wet**	**Dry**	**Wet**
Linear	0.23	0.70	0.24	0.73
Exponential	0.25	0.76	0.26	0.77
Logarithmic	0.22	0.65	0.23	0.67
Power	0.25	0.65	0.26	0.66

Section 5
Service Life Estimation

This section presents service life estimations of Rumble Stripe based on its 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), 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, and it 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 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 authors selected potential threshold retroreflectivity values of 100 and 150 mcd/m^2/lux to determine the service life of Rumble Stripe. 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 Rumble Stripe reported in Section Four and for FTM reported in previous research are repeated below. These models were used to determine the CTP when pavement marking retroreflectivities are expected to reduce to potential threshold values of 100 and 150 mcd/m^2/lux.

FTM Decay Models

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

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

Rumble Stripe Decay Model

$$(dry\ retroreflectivity)_{rumble} = 236 \times \exp(-0.06 \times CTP) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(Equation\ 5.3)$$

For FTM, 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 (for FTM only). The service life of Rumble Stripe marking was estimated using the exponential model, and Figure 5.1 shows the 95% confidence interval bands, which were obtained using regression technique.

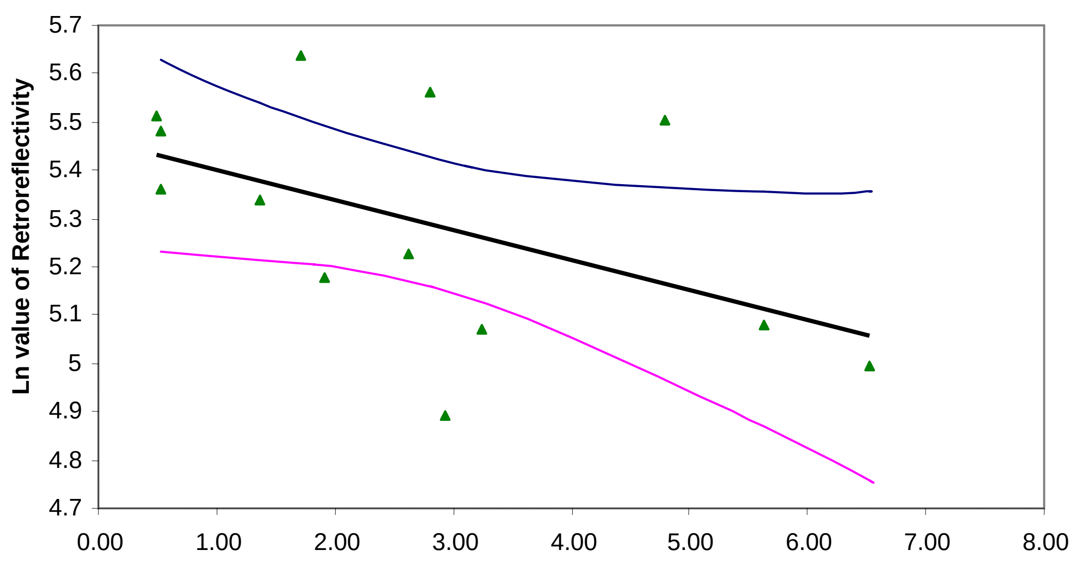

Figure 5-1. 95% confidence bands of exponential Rumble Stripe model

In addition, the 95% confidence interval of the estimated 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 for FTM is estimated from linear and exponential models.

$$(CTP_{SL})_{Linear} = \frac{(dry\ retroreflectivity)_{initial} - (dry\ retroreflectivity)_{threshold}}{(coefficient)_{CTP}} .....(Equation\ 5.4)$$

$$(CTP_{SL})_{Exponential} = \frac{\ln\left(\frac{(dry\ retroreflectivity)_{threshold}}{(dry\ retroreflectivity)_{initial}}\right)}{(coffficient)_{CTP}} ....(Equation\ 5.5)$$

$$(CTP_{SL})_{Average} = \frac{(CTP_{SL})_{Linear} + (CTP_{SL})_{Exponential}}{2} ....(Equation\ 5.6)$$

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

- FTM has a higher initial retroreflectivity (Table 4-7; 329 mcd/m²/lux for FTM and 236 mcd/m²/lux for Rumble Stripe), but Rumble Stripe has the longer service life.
- Rumble stripe has a lower decay rate than FTM.
- The 95% confidence intervals are relatively large. Two possible reasons for large confidence intervals are 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/m²/lux		**Threshold = 150 mcd/m²/lux**	
	Average	95% confidence interval	Average	95% confidence interval
FTM	7.1	4.9-10.7	5.0	3.4-7.7
Rumble stripe	13.8	9.5-20.3	7.3	4.1-12.1

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 5.3 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-3 and B-3 of Appendix 3 give these predictions, and Figures A-3 and B-3 of Appendix 3 present a graphical view of those retroreflectivity estimations.

Table 5-3 gives the estimated ages of FTM and Rumble Stripe when their dry retroreflectivity will fall 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 for two reasons. First, this research did not test markings that were more than four years old. Second, 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 =100mcd/m²/lux				Threshold =150mcd/m²/lux			
	FTM		Rumble Stripe		FTM		Rumble Stripe	
	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.
2,500	60+	60+	60+	60+	60+	45-60	60+	55-60+
5,000	46	33-60	60+	60+	34	23-51	48	27-60+
7,500	31	22-48	60	42-60+	22	15-34	32	18-54
10,000	23	16-36	45	32-60+	17	11-26	24	14-40

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 approximately 20,000 vehicles. As a result, the predicted service lives are appropriate for roads with ADTs in this range.
- The age of markings tested by this study ranged from 2 to 29 months for Rumble Stripe and from 5 to 43 months for FTM. The ages of Rumble Stripe test sites are lower because experimental Rumble Stripes were first placed in December 2003.

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 Rumble Stripe and FTM is more than 60 months.
- 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 Rumble Stripe and FTM are 45 months or less.
- Since most of the markings tested were on roads that had experienced traffic volumes per lane of 5,000 ADT and less, 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 Rumble Stripe and FTM that were tested by this study.
- According to the argument in the previous bullet, if markings were to be replaced when the retroreflectivity fell below 100 mcd/m^2/lux, Rumble Stripe on roads of per lane ADT of 5,000 and less lasts 60+ months, and FTM lasts from 46 to 60+ months. Similarly if a replacement threshold value of 150 mcd/m^2/lux is selected, Rumble Stripe lasts from 48 to 60+ months, and FTM lasts from 34 to 60+ months.
- The results given in Table 5-3 generally indicate Rumble Stripe to have a longer useful life than FTM on similar ADT roads. This conclusion is based on dry retroreflectivity values.

5.3 Wet Retroreflectivity of Rumble Stripe at the End of Service Life

The estimated service life of Rumble Stripe in terms of CTP (see Table 5-2) was used to determine the wet retroreflectivity of Rumble Stripe 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. Estimated wet retroreflectivity of Rumble Stripe at minimum threshold dry values

Threshold dry retroreflectvity 100 mcd/m²/lux			Threshold dry retroreflectivity 150 mcd/m²/lux	
	Average	95% confidence interval	Average	95% confidence interval
Rumble Stripe	6.1	2-12.6	18.3	8.1-31.4

Table 5-4 shows that wet retroreflectivity of Rumble Stripe is 6% and 12% 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 Rumble Stripe. Similar values for FTM were not estimated, because a statistically valid wet retroreflectivity decay curve could not be established.

Section 6
Life Cycle Cost Analysis

This section presents a life cycle cost analysis (LCCA) economic evaluation of FTM and Rumble Stripe 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).

6.1 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. Those values were used for both FTM and Rumble Stripe in the LCCA because no historical data is available for Rumble Stripe. The study team obtained average installation costs of FTM and Rumble Stripe from ALDOT's Office Engineer Bureau.

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.

6.1.1 Installation Costs

Table 6-1 presents average costs incurred by ALDOT for installing one mile of FTM and Rumble Stripe edge lines in 2004. The table indicates that installing Rumble Stripe (the strip plus the marking) is roughly 1.7-1.9 times more expensive than installing FTM. Another observation is that FTM installation costs decreased somewhat when project length increased.

Table 6-1. Installation costs of FTM and Rumble Stripe edge lines (ALDOT 2004)

Type	Length of project	Sample size	Average cost per mile ($)	Grand Average ($)
FTM	<3 mi > 3 mi	2 17	1,390.00 1,230.00	1,245.00
Rumble Stripe	1-2 mi	5	2,314.00	2,314.00

6.1.2 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 6-2 include labor, equipment, paint, and beads. Rumble Stripe has been used for such a short time that no maintenance costs have been generated for it, so the values in Table 6-2 were also used for Rumble Stripe during LCCA calculations.

Table 6-2. Maintenance costs of FTM and Rumble Stripe 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 6-2 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.

6.2 LCCA Methodology and Results

The researchers performed two LCCAs using standard techniques. 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.

$$PV = A_0 + \sum A_t \times \left(\frac{1}{(1+i)^t} \right) \qquad (Equation\ 6.1)$$

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., 2004) (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 6-1).
- A_t is the maintenance costs incurred at time t (see Table 6-2).

The expenditure stream diagrams for the two scenarios are given in Figures 6-1 and 6-2. A summary of results is given in Table 6-3, which indicates that the life cycle cost of FTM is clearly lower than that of Rumble Stripe, with PVs of $1,355 for FTM and $2,424 for Rumble Stripe in the five-year maintenance scenario.

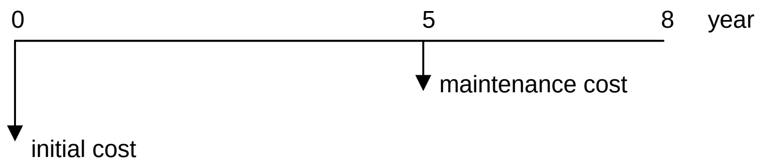

Figure 6-1. Cash flow stream with maintenance after 5 years

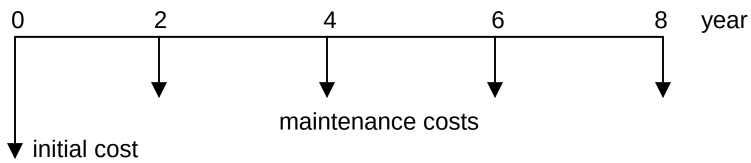

Figure 6-2. Cash flow stream with maintenance every 2 years

Table 6-3. Results of LCCA for Rumble Stripe and FTM (8-year life cycle)

Scenario	Present Value	
	FTM	Rumble Stripe
Maintenance after 5 years	1,355.00	2,424.00
Maintenance after 2 years	1,538.00	2,607.00

Section 7
Conclusions and Recommendations

This report presented an evaluation of FTM edge lines and Rumble Stripes used on ALDOT maintained highways. The primary objectives of this evaluation were to compare service lives, life-cycle costs, 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.

7.1 Conclusions

The main conclusions of this study follow:

- The service lives of FTM and Rumble Stripe were estimated from the dry retroreflectivity decay curves provided in Chapter 5. Those curves indicated that the average dry retroreflectivity of new FTM and Rumble Stripe tested by this study were 320 and 236 mcd/m^2/lux, respectively. However, Rumble Stripe appears to lose dry retroreflectivity at a lower rate with respect to CTP and is projected to have a longer service life than FTM. 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 7-1 reproduces the estimated service lives of Rumble Stripe and FTM. According to Table 7-1, 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 Rumble Stripe ranged from 23 to 60+ 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 Rumble Stripe ranged from 45 to 60+ months. In general, the average service life of Rumble Stripe is expected to be significantly longer than FTM. Note, however, that because the oldest experimental Rumble stripe site was only 29 months old during testing, these values represent extrapolations beyond Rumble Stripe ages tested.

Table 7-1. Estimated service lives in terms of age of markings

ADT per lane	Average Service Life in months							
	Threshold =100mcd/m²/lux				Threshold =150mcd/m²/lux			
	FTM		Rumble Stripe		FTM		Rumble Stripe	
	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.
2,500	60+	60+	60+	60+	60+	45-60	60+	55-60+
5,000	46	33-60	60+	60+	34	23-51	48	27-60+
7,500	31	22-48	60	42-60+	22	15-34	32	18-54
10,000	23	16-36	45	32-60+	17	11-26	24	14-40

C.I. = confidence interval.

- The estimated average wet retroreflectivity of new Rumble Stripe is approximately 63 mcd/m^2/lux. Even though a decay model for wet retroreflectivity of FTM could not be established, it is evident from Figure 4-4 that the wet retroreflectivity of new FTM is probably less than 63 mcd/m^2/lux. Again, because a decay model for FTM could not be established, the decay rates of FTM and Rumble Stripe could not be compared. However, because there are no accepted minimum wet retroreflectivity requirements for pavement markings, even if decay rates were available, estimated wet retroreflectivity values could not be translated into service lives of the markings.
- Life cycle cost analyses were performed using construction costs, maintenance costs, and service life data supplied by ALDOT. 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 $2,424 for Rumble Stripe (which includes a rumble strip and a stripe).
- Research from TTI indicates that larger beads provide higher retroreflectivity and recover their retroreflectivity more quickly after rain events. This finding indicates that ALDOT's current research into double drop beads edge lines (including larger beads) in ALDOT Project No. 930-653 will provide useful information.
- The work described in this research report is confined to edgeline rumble stripes. Centerline rumble stripes were not examined.

7.2 Recommendation

The following recommendation stems from the observations made during the literature search, field tests, and data analyses.

The dry retroreflectivity results of this report estimate that Rumble Stripe will have a longer service life than FTM. This longer life may stem in part from the sound and vibration caused by the strips causing drivers to steer away from the lines, thereby reducing the amount of contact tires have with the stripes. Federal research and research performed for TxDOT by TTI indicate that implementing rumble strips provides a benefit: cost ratio well over one. For these reasons, the researchers recommend that ALDOT consider implementing edgeline rumble stripes where shoulders are constructed, reconstructed, or overlaid, and where bicyclist issues, maintenance issues, and FHWA technical requirements can be met.

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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
RRPM	Raised retroreflective pavement markers
UTCA	University Transportation Center for Alabama

Appendix 1
Scatter Plots

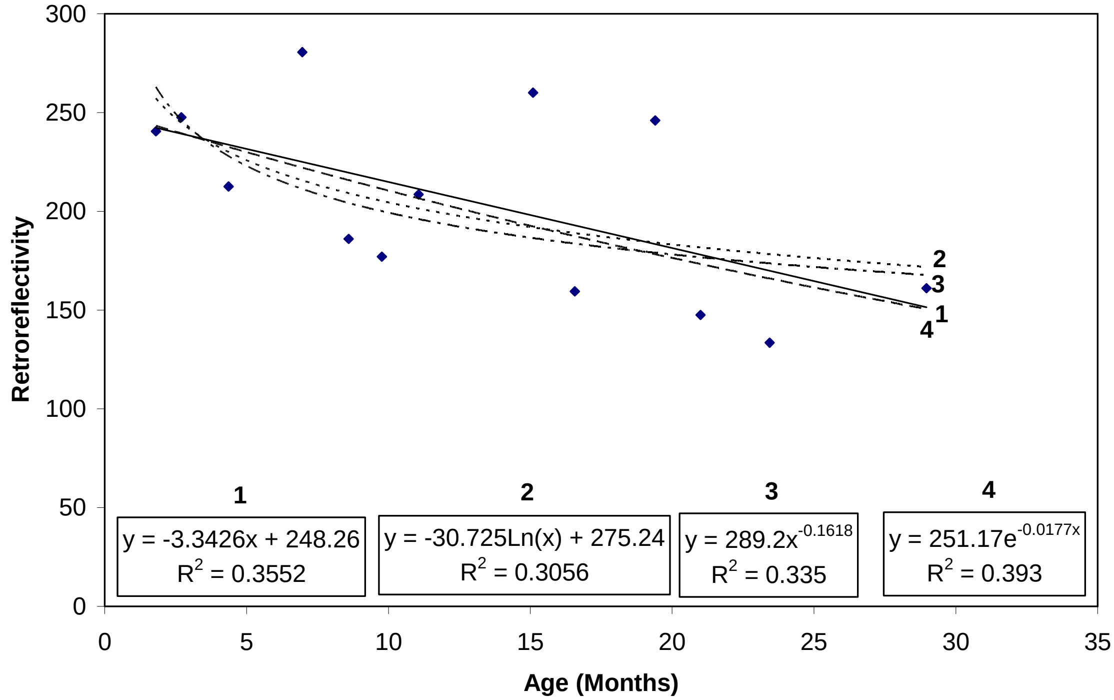

Figure A-1. Dry retroreflectivity vs. age of Rumble Stripe test sites

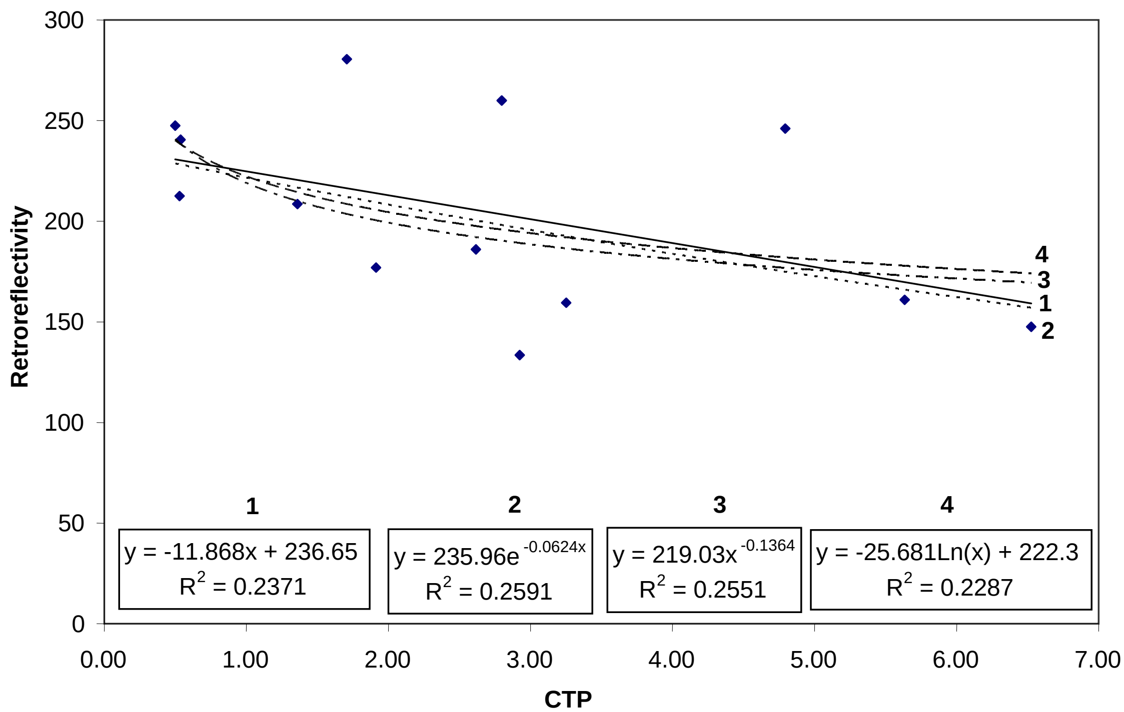

Figure B-1. Dry retroreflectivity vs. CTP of Rumble Stripe test sites

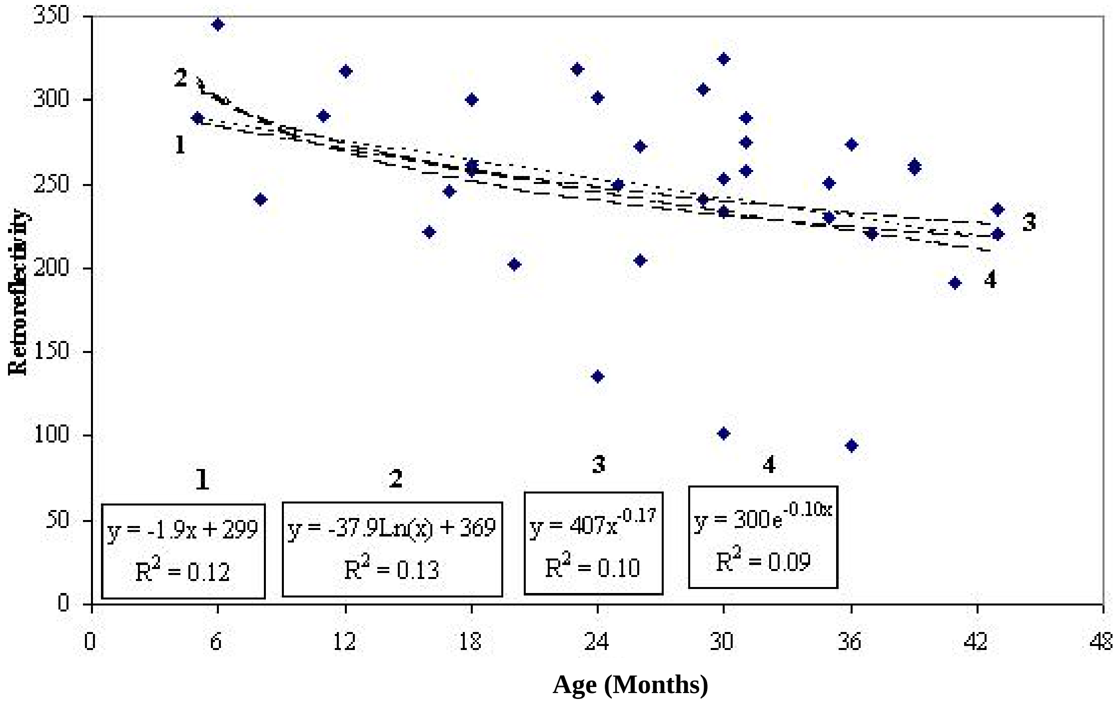

Figure C-1. Dry retroreflectivity vs. age of FTM test sites

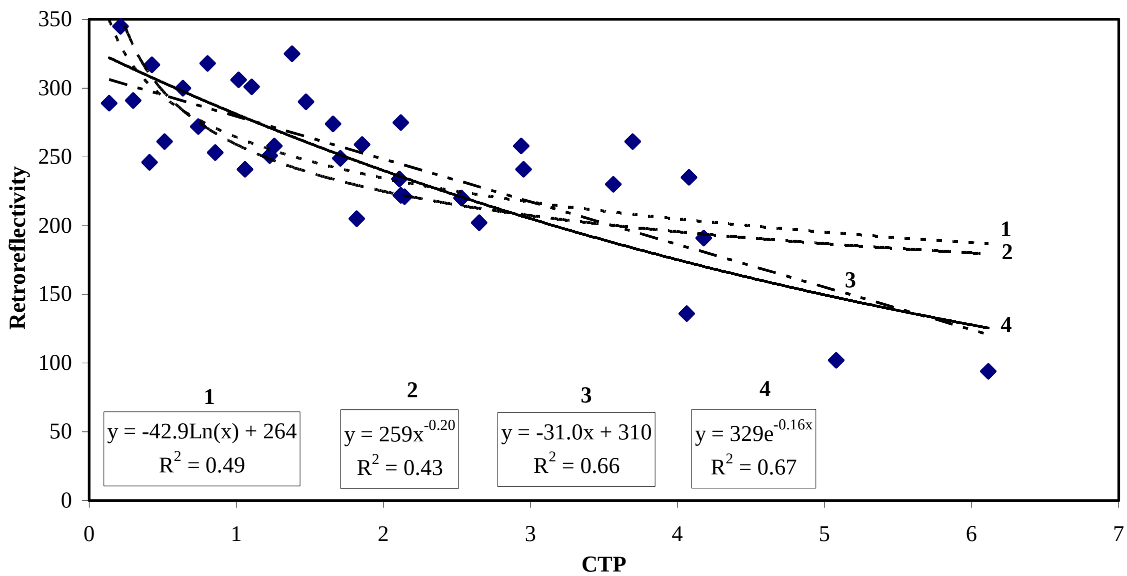

Figure D-1. Dry retroreflectivity vs. CTP of FTM test sites

Appendix 2
Regression Analyses of Retroreflectivity Decay Models

Table A-2. Linear decay model for dry retroreflectivity of FTM

The regression equation is dry = 310 - 31.1 CTP

Regression Statistics	
Multiple R	0.81
R Square	0.66
Adjusted R Square	0.65
Standard Error	33.00
Observations	36.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	72537.51	72537.51	66.62	0.00	
Residual	34.00	37021.24	1088.86			
Total	35.00	109558.75				
	Coefficients	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	310.44	9.30	33.39	0.00	291.54	329.33
CTP	-31.06	3.80	-8.16	0.00	-38.79	-23.32

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.392	0.361	-0.00226	1.037

Table B-2. Exponential decay model for dry retroreflectivity of FTM

The regression equation is ln_dry = 5.80 - 0.16 CTP

Regression Statistics	
Multiple R	0.82
R Square	0.67
Adjusted R Square	0.66
Standard Error	0.17
Observations	36.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	1.87	1.87	68.37	0.00	
Residual	34.00	0.93	0.03			
Total	35.00	2.80				
	Coefficients	*Srd Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	5.80	0.05	124.41	0.00	5.70	5.89
CTP	-0.16	0.02	-8.27	0.00	-0.20	-0.12

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.183	0.904	-0.0126	1.072

Table C-2. Linear decay model for dry retroreflectivity of Rumble Stripe

The regression equation is dry = 236.7 - 11.9 CTP

Regression Statistics	
Multiple R	0.49
R Square	0.24
Adjusted R Square	0.17
Standard Error	43.36
Observations	13.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	6427.86	6427.86	3.42	0.09	
Residual	11.00	20681.22	1880.11			
Total	12.00	27109.08				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	236.65	21.09	11.22	0.00	190.23	283.07
X Variable 1	-11.87	6.42	-1.85	0.09	-26.00	2.26

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.477	0.196	0.021	1.082

Table D-2. Exponential decay model for dry retroreflectivity of Rumble Stripe

The regression equation is ln_dry = 5.46 - 0.06 CTP

Regression Statistics	
Multiple R	0.51
R Square	0.26
Adjusted R Square	0.19
Standard Error	0.21
Observations	13.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	0.18	0.18	3.85	0.08	
Residual	11.00	0.51	0.05			
Total	12.00	0.69				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	5.46	0.10	52.28	0.00	5.23	5.69
X Variable 1	-0.06	0.03	-1.96	0.08	-0.13	0.01

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.406	0.299	0.00836	1.102

Table E-2. Linear decay model for wet retroreflectivity of Rumble Stripe

The regression equation is dry = 59.80 – 6.45 CTP

Regression Statistics	
Multiple R	0.85
R Square	0.73
Adjusted R Square	0.71
Standard Error	7.98
Observations	13.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	1899.83	1899.83	29.82	0.00	
Residual	11.00	700.75	63.70			
Total	12.00	2600.58				
	Coefficients	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	59.80	3.88	15.40	0.00	51.26	68.34
CTP	-6.45	1.18	-5.46	0.00	-9.05	-3.85

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.148	0.951	0.00186	1.103

Table F-2. Exponential decay model for wet retroreflectivity of Rumble Stripe

The regression equation is ln_dry = 4.14 - 0.17 CTP

Regression Statistics	
Multiple R	0.88
R Square	0.77
Adjusted R Square	0.75
Standard Error	0.19
Observations	13.00

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1.00	1.31	1.31	37.61	0.00	
Residual	11.00	0.38	0.03			
Total	12.00	1.70				
	Coefficients	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	4.14	0.09	45.57	0.00	3.94	4.34
CTP	-0.17	0.03	-6.13	0.00	-0.23	-0.11

TEST FOR NORMALITY

Test Statistics	*Value*	*p-value*	*Mean*	*St. Deviation*
Anderson-Darling	0.391	0.327	-0.0179	1.092

Appendix 3
Prediction of Retroreflectivity Values from Decay Models

Table A-3. 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-3. Prediction of dry retroreflectivity values for Rumble Stripe

ADT/Lane	Age of a marking	CTP/Lane	Retroreflectivity (Exponential model)
2,500	0	0.000	236
2,500	6	0.450	230
2,500	12	0.900	223
2,500	18	1.350	217
2,500	24	1.800	211
2,500	30	2.250	205
2,500	36	2.700	199
2,500	42	3.150	194
2,500	48	3.600	188
2,500	54	4.050	183
2,500	60	4.500	178
5,000	0	0.000	236
5,000	6	0.900	223
5,000	12	1.800	211
5,000	18	2.700	199
5,000	24	3.600	188
5,000	30	4.500	178
5,000	36	5.400	168
5,000	42	6.300	159
5,000	48	7.200	150
5,000	54	8.100	142
5,000	60	9.000	134
7,500	0	0.000	236
7,500	6	1.350	217
7,500	12	2.700	199
7,500	18	4.050	183
7,500	24	5.400	168
7,500	30	6.750	154
7,500	36	8.100	142
7,500	42	9.450	130
7,500	48	10.800	119
7,500	54	12.150	110
7,500	60	13.500	101
10,000	0	0.000	236
10,000	6	1.800	211
10,000	12	3.600	188
10,000	18	5.400	168
10,000	24	7.200	150
10,000	30	9.000	134
10,000	36	10.800	119
10,000	42	12.600	107
10,000	48	14.400	95

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

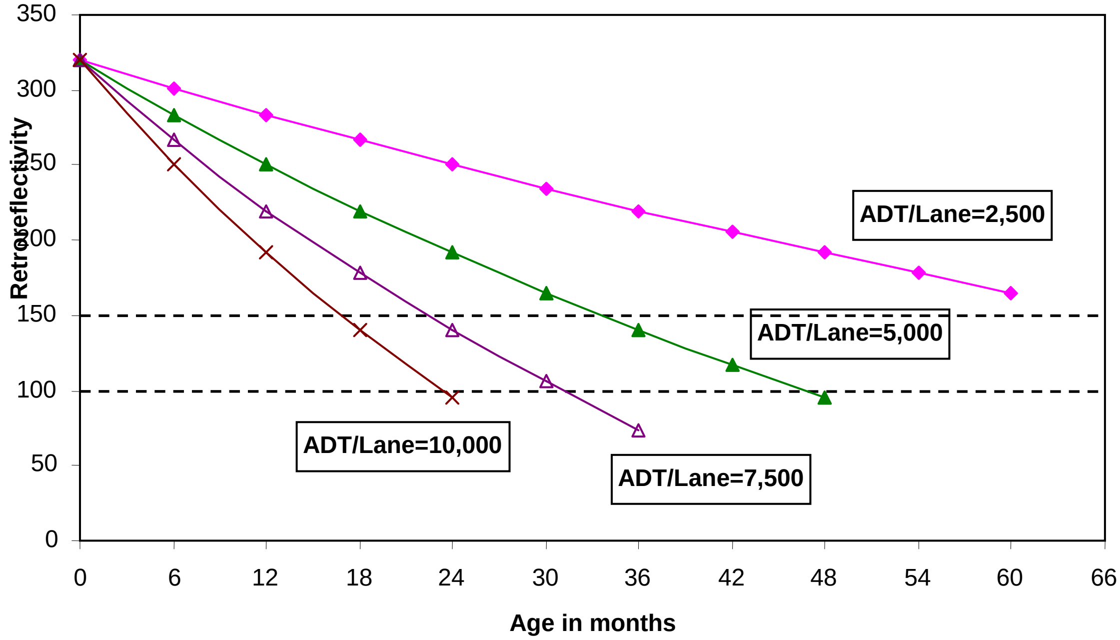

Figure A-3. Variation of dry retroreflectivity of FTM with time

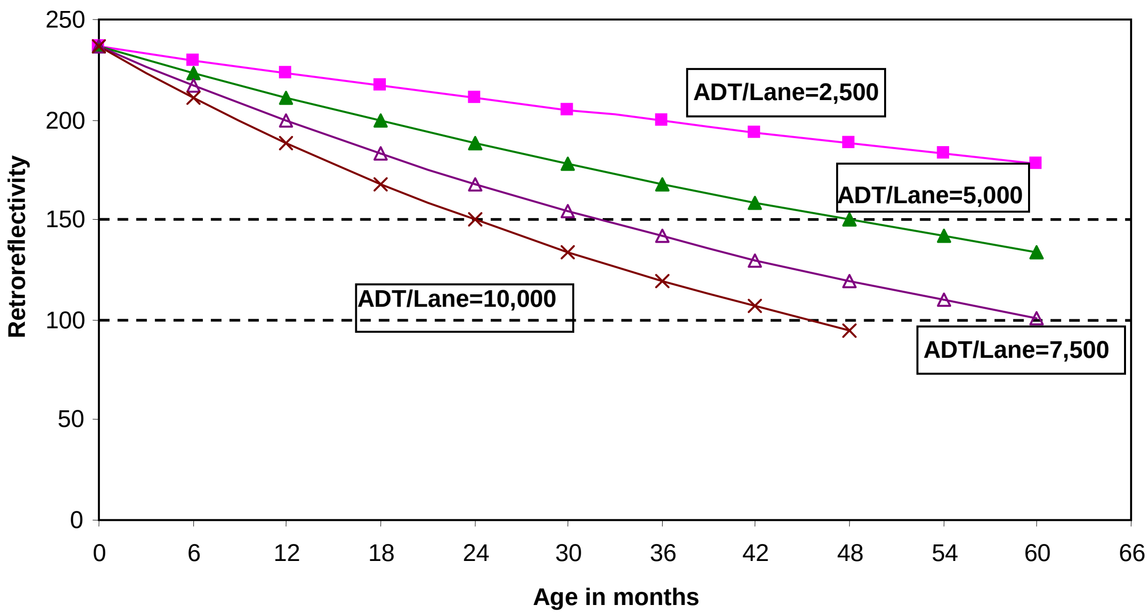

Figure B-3. Variation of dry retroreflectivity of Rumble Stripe with time