Evaluation of Double Drop Beads Pavement Edge Lines

By

Dr. Jay K. Lindly (Principal Investigator) and Ms. Ayse Narci
Department of Civil, Construction, and Environmental Engineering
The University of Alabama
Tuscaloosa, Alabama

Prepared by

UTCA

University Transportation Center for Alabama
The University of Alabama, The University of Alabama at Birmingham,
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UTCA Report Number 05409
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16. Abstract

This report presents an evaluation of Double Drop Bead (DDB) edge lines used on ALDOT-maintained highways. It compares DDB to three other pavement marking types in terms of service lives, life-cycle costs, and both dry-night retroreflectivity and wet-night retroreflectivity. The other three marking types are standard flat thermoplastic marking (FTM), Rumble Stripes, and profiled pavement marking (PPM).

Wet and dry retroreflectivity for the four pavement marking types was field-measured for marking ages ranging from a few months to approximately four years. The project estimated the average dry retroreflectivity of DDB to be significantly higher than the other marking types for the entire four-year test term, followed in order by Rumble Stripe, FTM, and PPM. In terms of wet retroreflectivity, DDB was again highest, followed by PPM and Rumble Stripe. A valid decay rate for wet FTM could not be established.

An estimate of the longevity of the markings generally indicates that DDB has the longest useful life on similar ADT roads, followed by Rumble Stripe, FTM, and PPM materials. The life-cycle cost analysis showed that over an eight-year life cycle, the cost per mile of marking was lowest for FTM, followed in order by DDB, Rumble Stripe, and PPM.

The Double Drop Beads edge marking exhibits the highest dry retroreflectivity of the four markings throughout the range of marking ages tested and for limited future projections. It provides this increased retroreflectivity for a relatively small increase in cost per mile. For those reasons, the report recommends that ALDOT should strongly consider making DDB edge markings its standard edge marking. However, because ALDOT has so far tested only one type of DDB marking, it should also work to optimize such characteristics as bead sizes, proportions of high refractive index beads, etc. before establishing a standard.

17. Key Words Pavement markings, profiled markings, pavement edge lines, rumble stripe, edge line rumble strip, thermoplastic markings, retroreflectivity	**18. Distribution Statement**

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Table of Contents

List of Tables

Number Page

List of Figures

Executive Summary

This report presents an evaluation of Double Drop Bead (DDB) edge lines used on ALDOT-maintained highways. It then compares DDB to three other ALDOT pavement marking types in terms of service lives, life-cycle costs, and both dry-night retroreflectivity and wet-night retroreflectivity. The other three marking types are standard flat thermoplastic marking (FTM), Rumble Stripes, and profiled pavement marking (PPM).

In the future, it appears that FHWA will implement minimum retroreflectivity values for centerline and edge lines measured in the dry condition. The comparisons made in this report can help ALDOT determine how the different marking types can meet the projected standard in a safe and cost-effective manner.

Wet and dry retroreflectivity for the four pavement marking types were field measured for marking ages ranging from a few months to approximately four years. The brightest markings in the dry condition in descending order are estimated to be DDB, Rumble Stripe, FTM, and PPM. The brightest markings in the wet condition in descending order are estimated to be DDB, PPM, and Rumble Stripe. The rankings were developed using data from highways with 20,000 or less ADT. Therefore, the results in this report are appropriate for highways with 20,000 or less ADT.

An estimate of the longevity of the markings generally indicates that DDB has the longest useful life on similar ADT roads, followed by Rumble Stripe, FTM, and PPM materials. This conclusion is based on dry retroreflectivity values, which FHWA will probably use in its future regulations.

The research team performed life-cycle cost analyses on the four markings. The materials ranked in the following ascending order of cost per mile: FTM, DDB, Rumble Stripe, and PPM.

Based on those analyses, ALDOT should strongly consider making DDB edge markings its standard. However, ALDOT has only tested DDB edge lines of one bead size combination, one thickness, etc. Thus, before it establishes a DDB standard, it should optimize characteristics such as bead sizes and proportions of high refractive index beads before establishing a standard.

1.0 Introduction

This study was conducted by The University Transportation Center for Alabama (UTCA) to evaluate double drop bead (DDB) edge line markings as they are used by the Alabama Department of Transportation (ALDOT). This type of material is relatively new to ALDOT, and the study is being performed to compare the characteristics of DDB markings to the characteristics of three other edge line markings used by ALDOT: standard flat thermoplastic marking (FTM), edge line Rumble Stripes (also called modified edge stripes), and profiled pavement markings (PPM). FTM, edge line Rumble Stripes, and PPM have been previously tested by UTCA.

The primary objective of this project was to evaluate service life, life-cycle costs, dry retroreflectivity, and wet-night retroreflectivity of DDB markings. The results for DDB will then be compared and contrasted to the results for the other three edge line markings. 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 *University Transportation Center for Alabama (UTCA) Report Number 01465 - Evaluation of Profiled Pavement Markings* (Lindly and Wijesundera, 2003), which compared and contrasted FTM and profiled pavement markings and to *University Transportation Center for Alabama (UTCA) Report Number 04405 - Evaluation of Rumble Stripe Markings* (Lindly and Narci, 2006), which compared and contrasted FTM and Rumble Stripes. The testing and analysis methods used for this study correspond to those in *Report 01465* and *Report 04405* so that different edge stripe materials will have been compared in the same way. Data for FTM and PPM that is used in this report was taken from *Report 01465*. Data for Rumble Stripes that is used in this report was taken from *Report 04405*. Data for DDB edge lines was generated specifically for this report.

Problem Statement

In recent years, state departments of transportation have been investigating using increased weight of beads per foot as well as larger beads to enhance traveler safety on roadways. To help decide whether DDB stripes may be appropriate for Alabama highways, ALDOT contracted UTCA to compare DDB edge lines, PPM, 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, 2003). As a result, ALDOT wants to develop an appropriate plan to monitor 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.

Scope of Study

Generally, on ALDOT roadways, six-inch wide edge lines are laid down near the edge of the traveled way and are composed of thermoplastic and glass beads. Table 1-1 presents several characteristics of the different edge line types studied in this report. All stripes are placed six-inches wide and contain a similar type and percent volume of intermix beads. However, DDB edge lines are thicker than the standard line and contain a much higher amount of drop beads. Fifty percent of the drop beads are also larger than the drop beads in the standard markings, both in amount and size (AASHTO M247, Type 4 beads are larger than Type I beads). Note: the DDB sites tested for this report exhibited the characteristics shown in the table; however, ALDOT may alter those specifications as they gain experience with this type of edge line.

Table 1-1. Characteristics of Edge Stripe Types in Alabama

Stripe Type	Intermix Beads		Drop Beads			
	Bead Size	% by Volume	Bead Size	# Beads per Mile	Stripe Width	Stripe Thickness
Standard FTM	Type 1	30%	Type 1	132	6”	0.06”
Rumble Stripe	Type 1	30%	Type 1	132	6”	0.06”
DDB	Type 1	30%	50% 1 50% 4	530 total	6”	0.09”
PPM	Type 1	35%	40% 1 60% 1*	150 225	6”	0.14” at highest point of profile

* Type 1 Modified as per ALDOT “Standard Specification”, 2002, Section 856.05(a)

Edge Line Appearance

In the field, standard FTM markings and DDB markings have similar appearances. Figure 1-1 shows an example of an FTM marking. However, PPM and Rumble Stripes have a different appearance, with a typical Rumble Stripe shown in Figure 1-2 and a typical PPM shown in Figure 1-3. The Rumble Stripe consists of seven-inch by 16-inch milled strips 12-inches on center with the thermoplastic edge line incorporated into the inside portion of the milled strips. The “ridged” or “profiled” appearance of the PPM is imparted by a wheel that is rolled over the hot thermoplastic immediately after it has been applied.

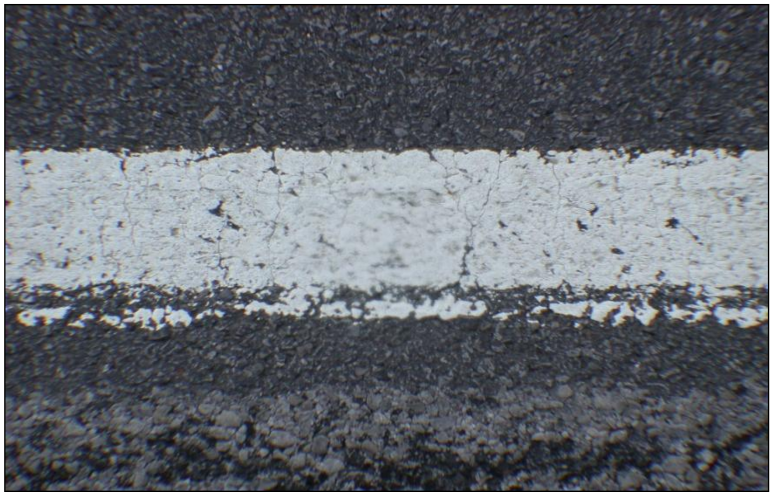

Figure 1-1. Flat thermoplastic marking.

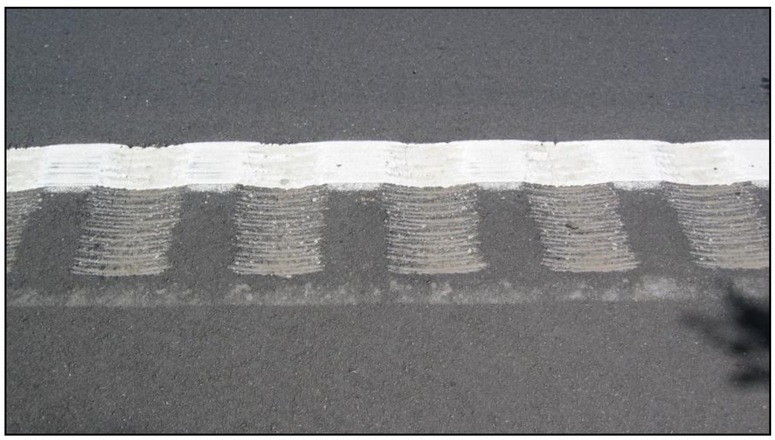

Figure 1-2. Rumble stripe pavement marking.

Figure 1-3. Profiled pavement marking.

Locations Tested

The results of this study are based on dry and wet-night retroreflectivity testing of the eight, typically one-mile-long DDB test sites shown in Table 1-2. Those sections represent the ALDOT DDB sections available during the study period.

Table 1-2. Sites Tested in the Report

Site ID	County	Lowest State Route Number	Marker type	Test Direction	Milepost Description
1	Pickens	SR 32	Double Drop Beads	Both	0.0-1.0
2	Greene	SR 14	Double Drop Beads	Both	44.0-45.0
3	Baldwin	US 31	Double Drop Beads	Both	23.0-24.0
4	Mobile	SR 163	Double Drop Beads	Both	1.0-1.75
5	Randolph	SR 22	Double Drop Beads	Both	154.0-155.0
6	Marshall	SR 69	Double Drop Beads	Both	266.4-267.3
7	Mobile	US 43	Double Drop Beads	Both	16.0-17.0
8	Cullman	SR 91	Double Drop Beads	Both	8.0-9.0

Organization of Report

This report consists of seven sections. Section 1 gives an introduction to the study and defines the scope of this study. Section 2 presents the review of relevant literature, and Section 3 explains the test methodology. Section 4 describes development of dry and wet retroreflectivity decay curves for DDB edge lines and compares them to decay curves obtained previously for the other three edge types. Service life estimation for DDB test sites is computed in Section 5 and compared to the other three edge types. Life-cycle cost analysis for the four edge line types is presented in Section 6. Section 7 summarizes conclusions and recommendations of this study.

2.0 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 15 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.

Thermoplastic Pavement Markings

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

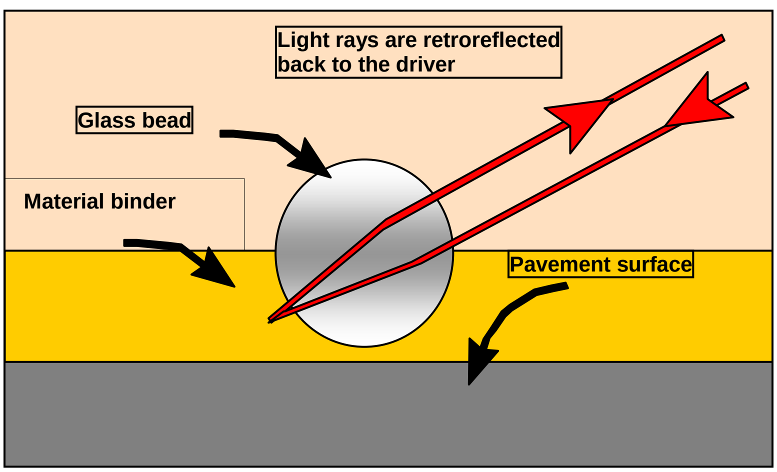

Figure 2-1. Retroreflection from glass beads (Schertz, 2002).

According to FHWA (2000), 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 four inches and six 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, while ALDOT (2008) requires FTM to be 100 mils thick regardless of lane or edge stripe type.

1993 Department of Transportation Appropriations Act

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 has twice evaluated the potential threshold retroreflectivity values (FHWA, 2000 and Turner-Fairbank, 2007). Once these studies are fully processed and any further required research is accomplished, FHWA may require states to replace a pavement marking once its retroreflectivity falls below the minimum value.

FHWA and Turner-Fairbank Studies

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. The top line of values in Table 2-1 represents the edge lines in question during this study.

Table 2-1. Threshold Dry Retroreflectivity Values Suggested by FHWA to Define End of Pavement Marking Service Life (FHWA, 2000)

Material	Roadway Type/Speed Classification		
	Non-freeway ≤ 40 mph	Non-freeway ≥ 45 mph	Freeway ≥ 55 mph
White	85	100	150
White with lighting or RRPM	30	35	70
Yellow	55	65	100
Yellow with lighting or RRPM	30	35	70

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

The Turner-Fairbank study updated the CARVE results by using a new computer program named TARVIP, written at the University of Iowa (Turner-Fairbank, 2007). TARVIP extends CARVE by allowing "changes in roadway marking materials, headlamps, or types of roadway surfaces." The results are updated recommended minimum levels for retroreflectivity for both yellow and white lines as shown in Table 2-2. Note that the required minimum RL values have decreased from Table 2-1 to Table 2-2. For example, for white edge lines without raised retroreflective pavement markers (RRPMs), the highest value in Table 2-1 is150 mcd/m^2/lux, while the corresponding value in Table 2-2 is 90 mcd/m^2/lux.

In this case, "recommended minimum" means that markings should be replaced or scheduled for replacement before they fall below the levels in the Table 2-2. Additionally, the Turner-Fairbank report points out that the minimum requirements should not be applied to each individual point along the roadway but should be applied to sections of the roadway.

Table 2-2. Recommended Minimum R_L Values in mcd/m^2/lux (Turner-Fairbank, 2007)

Roadway Marking Configurations	Without RPPMs			With RRPMs
	≤50 mi/h	55-65 mi/h	≥70 mi/h	
Fully marked roadways (with center line, lane lines, and/or edge line, as needed)*	40	60	90	40
Roadways with center lines only	90	250	575	50

* Applies to both yellow and white pavement markings.

The Turner-Fairbank report indicates that further research will be required before all variables in the predictions for minimum R_L can be accounted for. For example, the researchers note that their research was limited to "the investigation of dry, dark, rural, straight roads and longitudinal pavement markings." No field research supported the effort. Among other areas for further research, the report lists the following items:

- Effects of varying preview time (time during which lines are in sight to allow the driver to navigate)
- Effects of snow, rain, etc.
- Effects of different material types (TARVIP only studied white alkyd paint with beads.)
- Effects of different types of headlamps
- Effects of glare from oncoming vehicles
- Effects of varying line width
- Effects of the interaction between lines and RRPMs

ASTM Standards

The wet/night retroreflectivity tests performed for this research are based on modifications to ASTM test procedures developed in UTCA (Lindly and Wijesundera, 2003). The American Society for Testing and Materials (ASTM) outlines two methods for testing wet 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)

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 two to five 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 two previous rounds of UTCA testing (Lindly and Wijesundera, 2003 and Lindly and Narci, 2006). Continuous wetting of one to two miles of pavement in several locations around the state was impractical for the projects.

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, 2000). This report stated that the Laserlux device (a mobile retroreflectometer) had a precision of 15%. 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 to115 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 two UTCA studies (Lindly and Wijesundera, 2003 and Lindly and Narci, 2006) 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.

Bead Studies

Alabama and other states have been investigating increasing the size of reflectorized glass beads used in edge lines. Each of the three studies described below has found that increasing the size of beads increases retroreflectivity.

TTI Study "First Year Report"

The Texas Transportation Institute (TTI) report by Carlson, et al. (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.
- 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 smaller Type II beads and larger Type III 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."

TTI Study "Final Report"

The TTI "Final Report" report (Carlson, et al. 2007) concludes the study described in Section 2. It expands TTI's initial effort studying wet-night pavement marking products and adds a benefit-cost analysis of several different pavement marking systems.

The additional work confirmed some aspects of *First Year Report* and added some new findings:

- Confirmed benefit of larger Type III beads compared to Type II beads
- Indicated that the results of a study to determine how varying pavement widths (four inches compared to six inches) affect R_L were inconclusive.
- Indicated that "a rumble stripe will enhance the wet-night visibility of a typical flatline pavement marking system used in Texas (thermoplastic with Type II beads). However, under wet conditions, a flatline with big beads (Type III beads) will perform better than a rumble stripe with Type II beads."

- Produced a table of costs per year of service for a variety of marking products. In the table, the following service lives were used:
    - Paint: One year
    - Flat thermoplastic: Three years
    - Inverted (profiled) thermoplastic: Four years
    - Rumble Stripe with thermoplastic: Three years. The report indicated that the value for this material could probably be higher.
    - RRPMs: Three years
- In the table of costs, RRPMs cost per mile was approximately 11%-13% of the cost of flat thermoplastic marking.
- Indicated that most pavement markings have wet-night detection distances of 140 to 200 feet. RRPMs have the highest wet-night detection distance at over 550 feet.
- Concluded that for Texas roads "Overall, currently the most cost-effective system for Texas is spray-applied thermoplastic with supplemental RRPMs, although special situations may necessitate alternative treatments (e.g., PCC pavements and very high ADT roadways)."

VTRC Study

The Virginia Transportation Research Council completed a study in 2007 that asked 53 drivers to evaluate the visibility of four different pavement marking materials in a closed test course at night simulating rain conditions of 0.8 inches/hour:

- Standard latex paint with standard glass beads
- Standard latex paint with large glass beads
- Profiled thermoplastic
- Wet reflective tape (3M 750)

The study resulted in several findings:

- "Standard VDOT paint with standard size beads do not perform as well as other products. Large beads perform better than standard beads and perform equally with profiled thermoplastic products. Tape material designed specifically for wet-night conditions performed superiorly to all of the products" (VTRC, 2007).
- "VDOT's Traffic Engineering Division should adopt an initial minimum retroreflectivity in wet conditions of 200 mcd/m^2/lx, measured in accordance with ASTM Standard 2176 for continuous wetting of pavement markings" (VTRC, 2007).

The VTRC-recommended minimum retroreflectivity value of 200 mcd/m^2/lx under wet conditions is far more stringent than the FHWA preliminary recommendations shown in Tables 2-1 and 2-2. In fact, for the materials that VTRC tested, only the expensive tape material was able to meet the recommendation, and the report suggests that higher performing materials such as RRPMs may be required to meet the standard in a cost-effective manner.

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 individual pavement marking types; 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.

3.0 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 2006-2008 series of tests on DDB edge lines is the same as the procedures for the test series on FTM PPM conducted from 2001-2003 and on Rumble Stripes conducted from 2004-2006.

Site Selection

UTCA personnel worked with ALDOT to identify any double drop bead projects which had been completed by the time the first round of field testing began May 15, 2006. Six sites (Site #1 - #6) were identified and tested in that year. Two more sites were identified before the second round of field testing began a year later (Site #7 and Site #8). Thus, a total of eight sites were tested, although two of the sites yielded retroreflectivity data for two years rather than the three years desired. Table 3-1 summarizes important data for the test sites.

Table 3-1. Summary of Double Drop Bead Project Database

County	Site #	Route #	Dates of Stripe Completion	Project Numbers	Mile Post	Number of Lanes
Pickens	1	SR 32	8/4/2005	ST-054-032-001	0.0-1.0	2
Greene	2	SR 14	6/17/2005	ST-032-014-001	44.0-45.0	2
Baldwin	3	US 31	2/10/2005	ST-002-003-003	23.0-24.0	2
Mobile	4	SR 163	11/9/2004	ST-049-163-001	1.0-1.75	3
Randolph	5	SR 22	5/11/2005	ST-056-022-003	154.0-155.0	2
Marshall	6	SR 69	4/25/2004	99-301-484-069-402	266.4-267.3	3
Mobile	7	US 43	3/2/2006	MGF-0013(520)	16.0-17.0	4
Cullman	8	SR 91	7/31/2005	ST-022-091-002	8.0-9.0	2

Data from the eight DDB sites will be compared against data for 16 FTM test sites and 21 PPM test sites described in *University Transportation Center for Alabama (UTCA) Report Number 01465 – Evaluation of Profiled Pavement Markings* (Lindly and Wijesundera, 2003). Striping of those sites was completed from 1999 to 2001, and they were tested from 2001 to 2003. Additionally, data from the eight DDB sites will be compared against data for five Rumble Stripe test sites described in *University Transportation Center for Alabama 9UTCA) Report Number 04405 – Evaluation of Rumble Stripe Markings* (Lindly and Narci, 2006). Striping of those five sites was completed from 2003 to 2005, and they were tested from 2004 to 2006.

For the FTM and PPM 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 DDB sites were only one mile long, but they were also tested in both travel directions so that as much data as possible could be collected. The locations of the DDB test sites are shown in Figure 3-1.

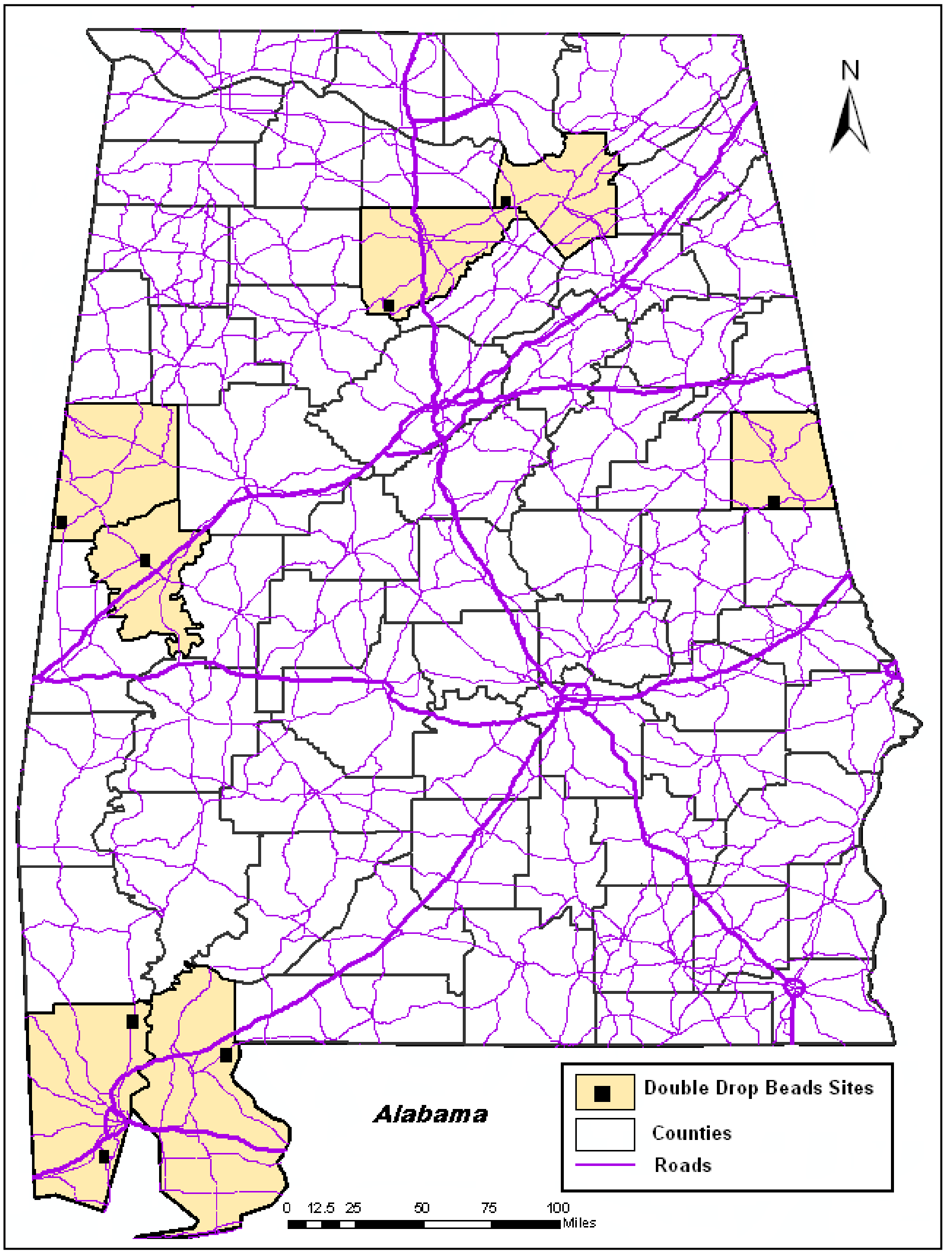

Figure 3-1. DDB pavement marking test sites.

Pre-Survey Site Inspection

The first six DDB sites were inspected two weeks before the first retroreflectivity test. This trip 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 results were useful during testing because they identified such items as places for the test equipment to start and stop safely.

Resources for Surveys

The dry retroreflectivity tests were performed without any traffic control. Therefore, the only vehicle needed for dry tests was the Laserlux van. However, for wet tests, a thousand-gallon water truck was used to wet the markings, and an attenuator truck was used to provide protection for the Laserlux van and water truck. A typical wet test train consisting of water truck, mobile retroreflectometer, and attenuator truck is shown in Figure 3-2.

Figure 3-2. Wet test train of water truck, Laserlux, and attenuator truck.

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 3-3 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.

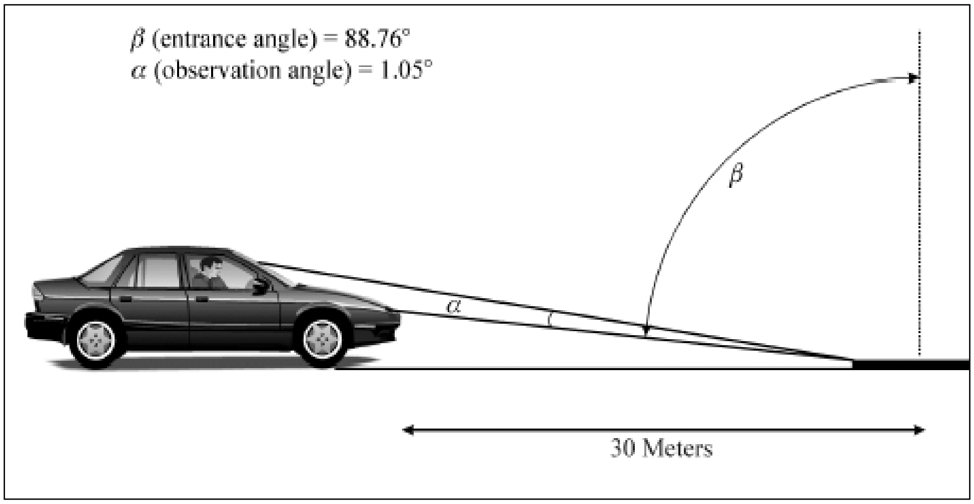

Figure 3-3. Illustration of 30-meter (98-feet) geometry.

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 3-2 (HITEC, 2001).

Table 3-2. 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

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.

Retroreflectivity Tests

When possible, test sites were selected such that they began and ended at a milepost. First, a test location was tested dry in both directions, then tested again in both directions 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 53 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.

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.

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, 2001). A wet test run on a one-mile site required around seven minutes after the Laserlux van returned from performing the dry test.

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 five-gallon bucket was measured using a stopwatch. Table 3-3 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 3-3, 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 DBB tests were very similar to discharge volumes reported for the FTM, PPM, and Rumble Stripe tests performed previously.

Table 3-3. 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

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.

Notes on Three Surveys

Each of the DDB locations was tested three times over a period of 24 months from 2006 to 2008. (Sites 7 and 8 were not identified before the first test, so they were only tested twice. Site 5 was not tested during Test Three because the Laserlux vehicle was involved in a property-damage-only crash at that site.) The mean dry and wet retroreflectivity values measured at DDB sites during the field tests are given in Table 3-4.

Table 3-4. Retroreflectivity Data for Double Drop Bead Test Sites

Site ID	County	Route Number	Average Retroreflectivity (mcd/m²/lux)					
			Test One		Test Two		Test Three	
			Dry Test	Wet Test	Dry Test	Wet Test	Dry Test	Wet Test
1-E	Pickens	SR 32	561	139	542	191	347	150
1-W	Pickens	SR 33	669	109	627	222	526	156
2-E	Greene	SR 14	488	73	493	110	382	109
2-W	Greene	SR 15	423	40	438	96	373	98
3-N	Baldwin	US 31	587	97	497	155	379	85
3-S	Baldwin	US 32	604	109	441	109	299	68
4-E	Mobile	SR 163	409	81	379	80	316	71
4-W	Mobile	SR 164	448	45	387	119	254	49
5-E	Randolph	SR 22	683	136	531	114		
5-W	Randolph	SR 23	629	74	475	97		
6-N	Marshall	SR 69	259	39	262	42	267	32
6-S	Marshall	SR 70	277	47	250	41	244	35
7-N	Mobile	US 43			422	117	407	86
7-S	Mobile	US 44			347	79	295	60
8-N	Cullman	SR 91			338	74	324	62
8-S	Cullman	SR 91			335	79	329	65

Test One

Six sites were tested from May 15, 2006 to May 19, 2006. A total of 24 retroreflectivity values were recorded because separate wet and dry tests were conducted in each direction at each test site.

Test Two

Eight sites were tested on May 21, 2005 and May 23, 2007, almost exactly one year after the first tests. A total of 32 retroreflectivity values were recorded for the 2007 test series.

Test Three

Test series three was conducted from May 19, 2008 to May 21, 2008. Twenty-eight values were obtained from seven test sites. (One site was not tested due to the Laserlux crash.) At the completion of three rounds of testing, 84 total retroreflectivity values for DDB sites had been obtained.

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%. Therefore, retroreflectivity values obtained at a test site can vary by 15% 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.

4.0 Retroreflectivity Decay Models

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

- Dry retroreflectivity decay models for DDB: These models will be used to determine service lives, retroreflectivity degradation rates, and retroreflectivity of new markings.
- Wet retroreflectivity decay models for DDB: 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.

Approach

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

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

Method One

The main advantage of Method One is that it gives more data to develop a single model. Such a database often contains data to represent retroreflectivity decay of markings over a larger span of life than a database pertaining to a single marking. For example, the UTCA study collected

DDB retroreflectivity data three times over a period of 24 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 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., DDB) 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., DDB).

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., DDB), 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.

The Selection

This study collected DDB data three times over a period of 24 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 at five of the test sites and using only two data points for the other three test sites. Therefore, Method One was chosen for developing decay models for DDB because its data represents marking decay over a longer time period.

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.

Dependent Variable: Retroreflectivity

As explained earlier in Section 4, the databases used for developing decay models were generated by pooling data from three tests:

- May 2006 data, referred to as Test One data

- May 2007 data, referred to as Test Two data
- May 2008 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 dry retroreflectivity with time of the DDB test sites. Retroreflectivity of all test sites declined from Test One to Test Three when the average of the two directions of travel was used as the value for the site. Thus, data from all eight test sections could be used in later analyses. However, in analyses of the previous three types of markings, data from a small number of sites was not used in the analyses because their dry values increased from Test One to Test Three (Lindly and Wijesundera, 2003 and Lindly and Narci, 2006).

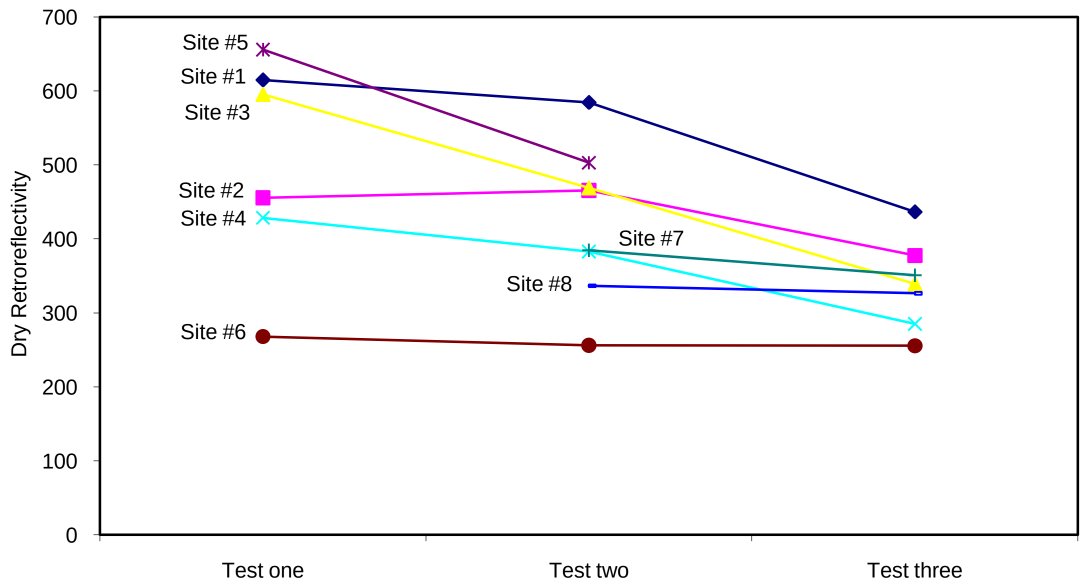

Figure 4-1. Variation of dry retroreflectivity of Double Drop Bead test sites.

Using the criteria cited above, separate databases were generated for DDB dry retroreflectivity and DDB wet retroreflectivity. In further discussions in this report, the two databases are referred to as combined databases, as they were formed by aggregating data from three test periods. These databases were used for developing dry and wet retroreflectivity decay models for DDB edge lines.

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)

- Cumulative traffic passages (CTP), which represents the cumulative exposure of an edge line to vehicle travel since its installation

Because 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. ALDOT provided ADT data for 2000-2007, and the project team extrapolated 2008 ADT data from that base data.

The research team examined the ages of the DDB edge lines at the three times the eight sites were tested. The age of the lines at testing ranged from nine months to 49 months. By comparison, the FTM sites that the DDB sites will be compared to were tested in the range of five to 42 months. Thus, comparisons of retroreflectivities for the different edge line types can be made on a common basis.

The team also examined CTP data. For DDB, the CTP at test time ranged from 0.19 to 10.56. By comparison, CTP at test time for FTM ranged from 0.14 to 6.11, and CTP at test time for Rumble Stripe ranged from 0.49 to 6.53. Again, the data for DBB can be appropriately compared to that of the other edge line types.

Selecting between CTP and Age Variables Because 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 B-1 through B-4 of Appendix B.) 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:

$$retroreflectivity = a + bX \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Equation\,4.2)$$

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

Exponential model:

$$retroreflectivity = a \times \exp(bX) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Equation\,4.3)$$

Logarithmic model:

$$retroreflectivity = a + b \times \ln(X) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Equation\,4.4)$$

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. For wet DDB, the R^2 for CTP is significantly higher than the R^2 for marking age, while R^2 values for CTP and marking age are much more similar for dry DDB.

In the previous UTCA studies of PPM, FTM, and Rumble Stripes, CTP was chosen as the primary independent variable (Lindly and Wijesundera, 2003 and Lindly and Narci, 2006). That fact, combined with the R^2 values shown in Table 4-1, led to the decision to use CTP as the independent variable for both DDB decay models.

Table 4-1. Fitted Models for DDB Dry and Wet Retroreflectivities vs. CTP and Age

	Coefficient of Determination (R^2) for Dry DDB		Coefficient of Determination (R^2) for Wet DDB	
	CTP	Age in Months	CTP	Age in Months
Linear	0.50	0.53	0.35	0.10
Exponential	0.55	0.54	0.44	0.16
Logarithmic	0.44	0.53	0.34	0.06
Power	0.44	0.52	0.34	0.16

Development of Retroreflectivity Decay Models

Models were calibrated to predict decay of dry and wet retroreflectivity as a function of CTP for DDB so that they could be compared to the models that had been developed in 2003 for FTM and PPM and in 2006 for Rumble Stripes. The sequential steps involved in developing the decay models are listed below:

1. Microsoft® Excel was used to generate scatter plots between dry (or wet) retroreflectivity and CTP.
2. Then, first order linear, power, logarithmic, and exponential models were fitted to those scatter plots.
3. 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.
4. Thereafter, 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.
5. 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 *University Transportation Center for Alabama (UTCA) Report Number 01465* (Lindly and Wijesundera, 2003) and did not yield statistically significant models.

Dry Retroreflectivity Decay Models for DDB

Eight different DDB test sites were tested during three test periods for a total of 21 occasions. At each site, dry retroreflectivity values were taken in two directions. Thus, 42 different dry 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 21 observations. All 21 observations from eight DDB test sites were used in this analysis, using the same methodology used for developing decay models for dry FTM, dry PPM, and dry Rumble Stripes in previous studies. Figure 4-2 shows a scatter plot representing the relationship between dry retroreflectivity of DDB edge lines and CTP. This figure shows linear, exponential, logarithmic, and power models fitted to the data.

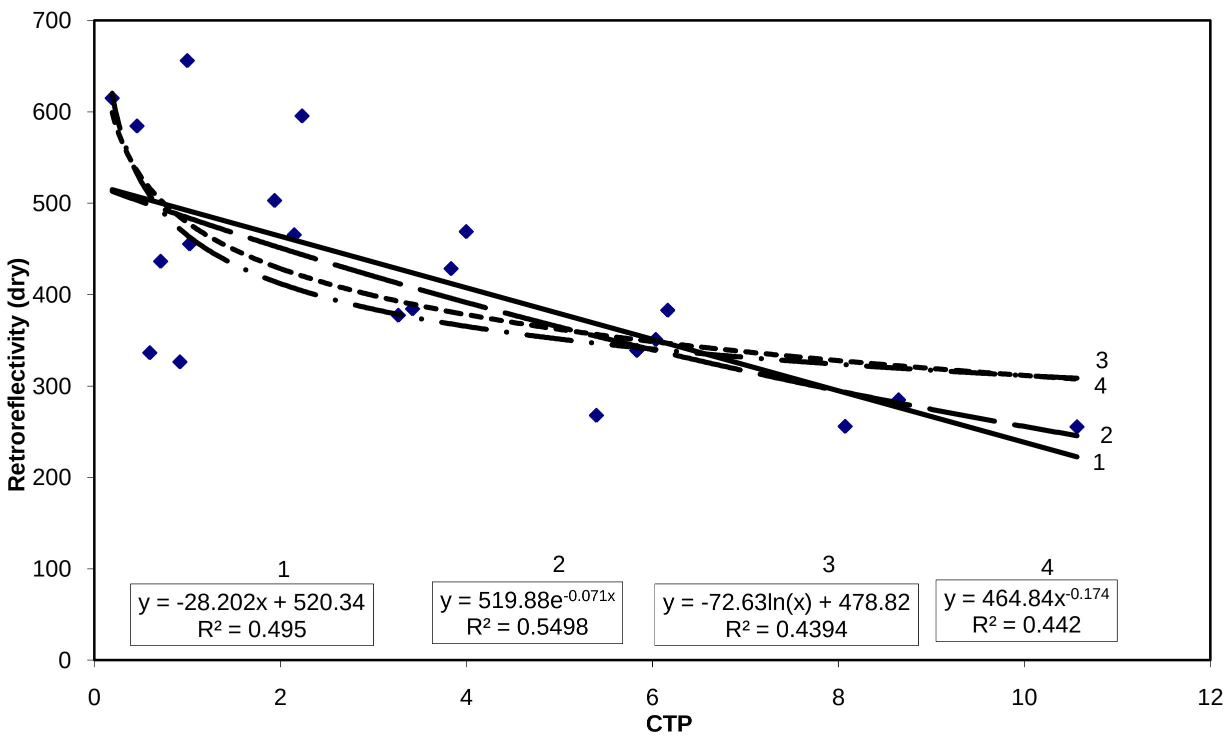

Figure 4-2. Dry retroreflectivity vs. CTP of DDB test sites.

The R^2 values of the fitted models are given in Table 4-2. The R^2 values are not high, but they are adequate to accept correlation between CTP and dry retroreflectivity and then to predict service life.

Table 4-2. Fitted Models for DDB Dry Retroreflectivity vs. CTP

Coefficient of Determination (R^2)			
Linear	**Exponential**	**Logarithmic**	**Power**
0.50	0.55	0.44	0.44

According to Table 4-2, exponential and linear models gave the best fit for the combined database. In addition, Figure 4-2 indicates that those two models gave a better estimate than the power and logarithmic models for low and high retroreflectivity values observed in field testing. Another consideration was that the exponential model had been chosen in the recent research performed on Rumble Stripes. Considering all those factors, 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 Table C-1 of Appendix C, and an abstract is presented in Table 4-3.

Table 4-3. Selected Decay Model for DDB Dry Retroreflectivity

Model Type	Coefficient and (p significance)		R^2	F-Statistic
	Constant	**Exp (CTP)**		
Exponential	520 0.00	-0.071 0.00	0.55	23

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 90 and 60 mcd/m^2/lux.

Wet Retroreflectivity Decay Models for Double Drop Beads

There were 21 observations from eight DDB test sites during three test periods, and six of the eight sites showed a decrease in wet retroreflectivity from Test One to Test Three. Two of the sites (Site #1 in Pickens County and Site #2 in Greene County) exhibit a situation where the retroreflectivity values do not decline between the first and third test periods, as would be expected given the normal deterioration of edge lines. As explained earlier in Section 4, in some of the previous studies, data from those two sites would not be used in the analyses. For PPM and FTM, retroreflectivity at several sites did not decline over time, and data from some sites was not used (Lindly and Wijesundera, 2003). However, after the questionable PPM and FTM sites were removed, there still remained 21 PPM sites and 16 FTM sites for use in the analyses.

When a similar situation occurred in the Rumble Stripe analysis, two out of five sites were considered questionable. In that case, data from all five sites was used in the analyses because the researchers did not want to disqualify 40% of their data and work with only three sites worth of data. The DDB sites present a situation similar to the Rumble Stripe situation, and the researchers elected to use data from all eight sites.

Figure 4-3 shows the relationship between wet retroreflectivity of DDB edge lines and CTP. This figure shows linear, exponential, logarithmic, and power models fitted to the data.

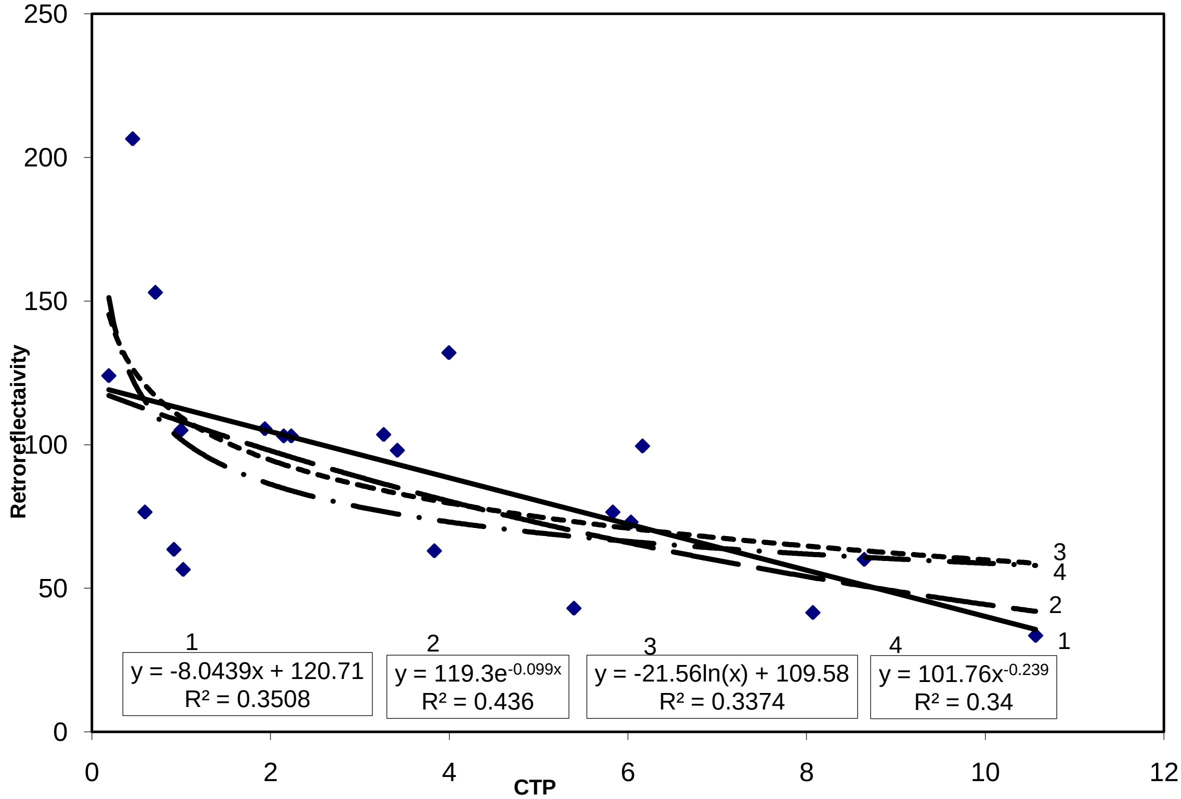

Figure 4-3. Wet retroreflectivity vs. CTP of DDB test sites.

According to the R^2 values given in Table 4-4, the exponential model gave the best fit for the combined database. Based on Table 4-4 and the fact that the exponential model conforms well to the lower R_L values in Figure 4-3, the exponential model was selected to predict the retroreflectivity decay of wet DDB.

Table 4-4. Fitted Models for DDB Wet Retroreflectivity vs. CTP

Coefficient of Determination (R^2)			
Linear	**Exponential**	**Logarithmic**	**Power**
0.35	0.44	0.34	0.34

The exponential model was analyzed using the regression option of the Minitab® software (See Table C-2 of Appendix C.), and a summary of the regression output is presented in Table 4-5.

Table 4-5. Selected Decay Model for DDB Wet Retroreflectivity

Model Type	Coefficient and (p significance)		R^2	F-Statistic
	Constant	Exp (CTP)		
Exponential	119 0.00	-0.099 0.00	0.44	15

For future calculations, the exponential model was run for wet DDB edge line data.

Discussion

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

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 4-6 gives dry retroreflectivity of new DDB edge lines and 95% confidence intervals of these estimations. The table also shows values for Rumble Stripes calculated in the 2006 UTCA report as a comparison point. 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 dry DDB edge line is between 450 and 601 mcd/m^2/lux for the sites tested in this research. According to Table 4-6, the average dry retroreflectivity of a new DDB edge line is more than double that of a new, dry Rumble Stripe.

Table 4-6. Estimated Retroreflectivity of New, Dry DDB Edge Lines

Marking		Average retroreflectivity (mcd/m²/lux)	Confidence intervals	
			Lower 95%	Upper 95%
DRY	Rumble stripe	236	188	297
DRY	Double Drop Beads	520	450	601
WET	Rumble stripe	63	52	77
WET	Double Drop Beads	119	93	154

Wet Retroreflectivity of New Markings

The average wet retroreflectivity of new DDB edge line is approximately 119 mcd/m^2/lux. (See Table 4-6.) That value compares favorably to the average wet retroreflectivity of a new Rumble Stripe, which was estimated at 63 mcd/m^2/lux.

Comparison of Decay Rates

The decay rates of the four edge marking types investigated by UTCA since 2002 are represented in Figure 4-4. There are seven curves in the figure, and it may be best to think of the data by dividing it into two parts: the four dry retroreflectivity curves and the three wet retroreflectivity curves. (The researchers were unable to construct a reliable curve for wet FTM; however, wet FTM values were lower than the values for any of the other three edge line types tested.)

For the dry curves, the DDB edge line clearly demonstrates the highest retroreflectivity values over the range of CTP. In descending order of retroreflectivity, other edge lines tested were Rumble Stripe, FTM, and PPM. FTM does exceed Rumble Stripe early in its life, but the slower decay rate of Rumble Stripe indicates that it will maintain high retroreflectivity longer than FTM. The slower decay rate of Rumble Stripe may occur because the sound and vibration of the rumble strip causes drivers to keep off the Rumble Stripe marking materials.

The three wet curves are the three lowest curves in Figure 4-4. Again, DDB exhibits the highest retroreflectivity over the range of CTP, followed by PPM and Rumble Stripe. The decay rates of the three curves appear relatively parallel.

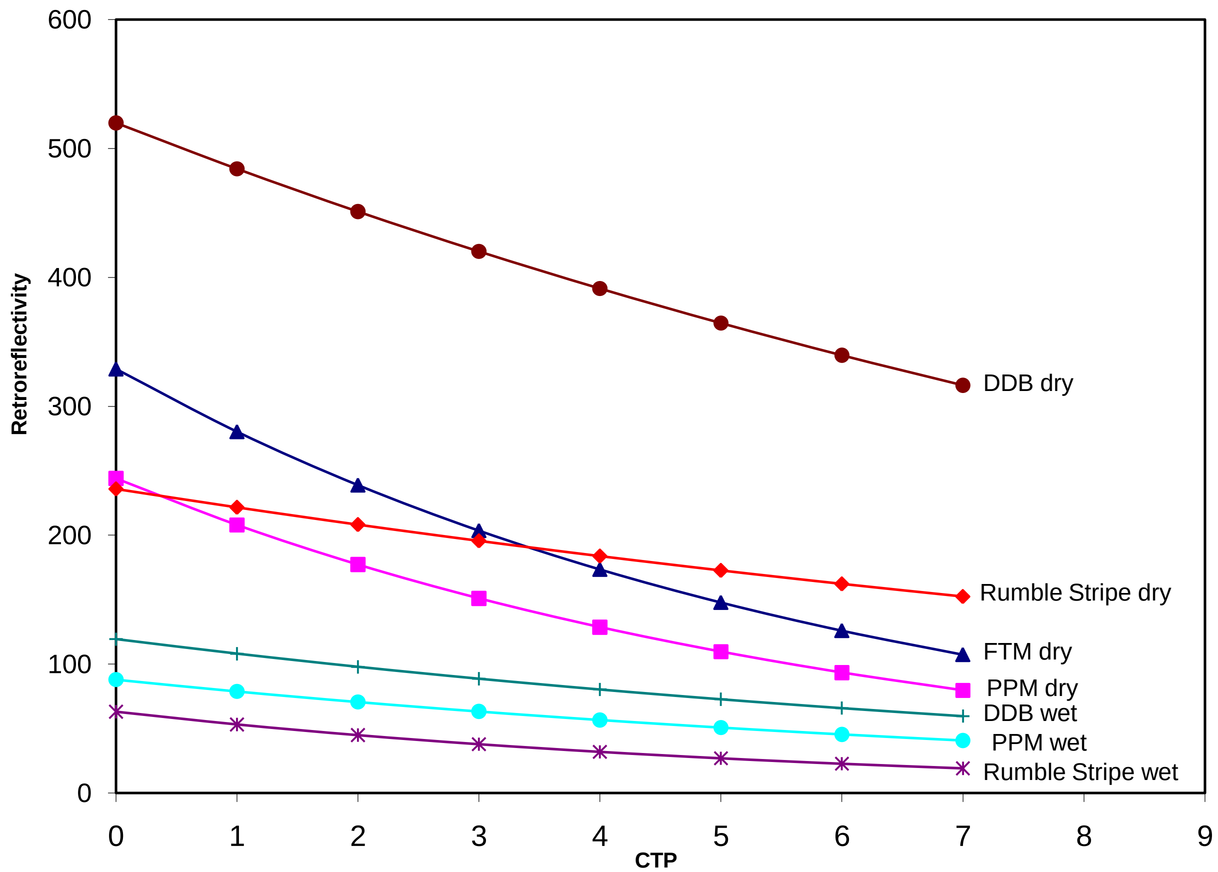

Figure 4-4. Variation of dry and wet retroreflectivity vs. CTP.

Alternative Analysis

The researchers performed an alternative analysis to determine whether choosing not to delete data the Pickens and Green County sites would make significant changes in the wet DDB results. Figure 4.5 shows the results of that analysis. At low levels of CTP, the curve for the data that was used in the original analysis (the "whole data") shows higher R_L values than the curve that would have been used if data from two sites had been eliminated. However, the curves converge as CTP increases. Thus, in Figure 4-4, the DDB wet curve would still have shown higher values than the other two wet curves, and this would be particularly true at the high levels of CTP that are of most concern in this study.

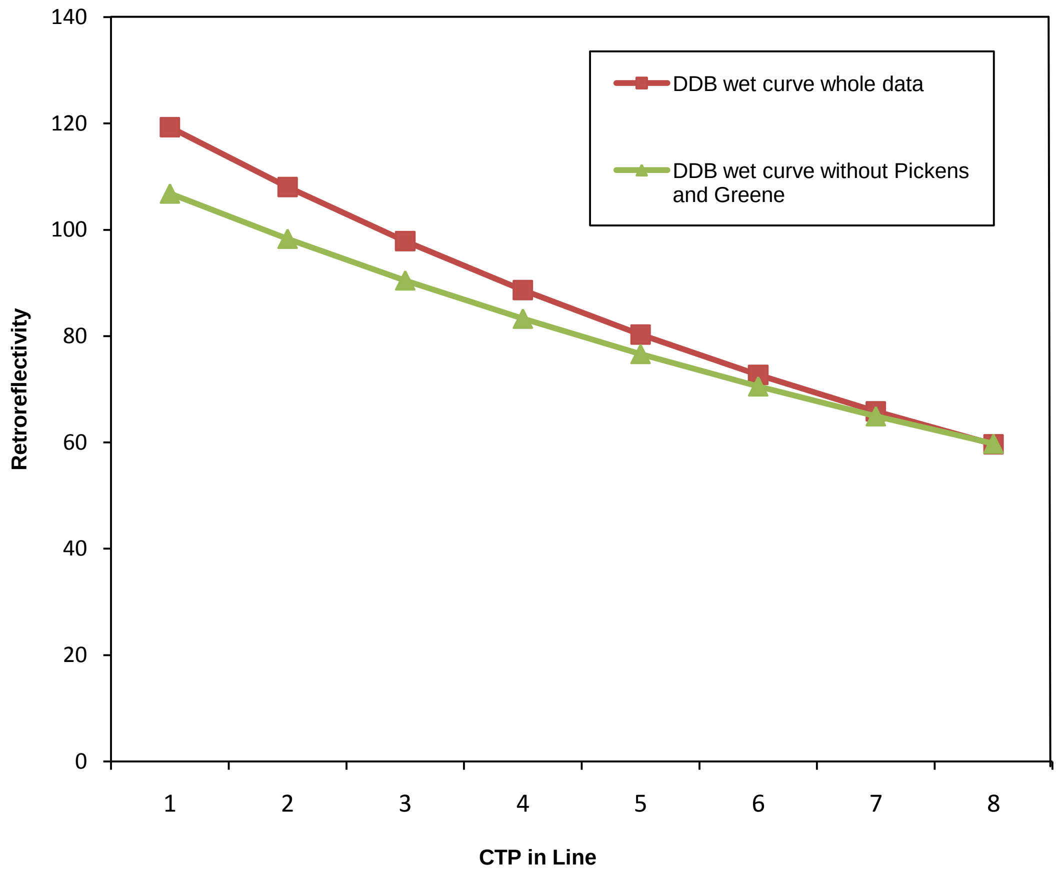

Figure 4-5. Comparison of wet decay rates with and without Pickens and Greene.

5.0 Service Life Estimation

This section presents service life estimations of DDB edge lines based on 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 (Turner-Fairbank, 2007). These values were presented in Table 2-2 and are reproduced as Table 5-1. However, there have been other threshold retroreflectivity values suggested by previous studies (Migletz, et al. 1999, Loetterle, et al. 1999, and FHWA, 2000). These values ranged significantly, with the most common value being 100 mcd/m^2/lux (Bowman and Abboud, 2001).

Table 5-1. Recommended Minimum R_L Values in mcd/m^2/lux (Turner-Fairbank, 2007)

Roadway Marking Configurations	Without RPPMs			With RRPMs
	≤50 mi/h	55-65 mi/h	≥70 mi/h	
Fully marked roadways (with center line, lane lines, and/or edge line, as needed)*	40	60	90	40
Roadways with center lines only	90	250	575	50

* Applies to both yellow and white pavement markings.

Table 5-1 defines threshold retroreflectivity based on speed limits. This table suggests using a threshold value for dry white edge lines of 40 mcd/m^2/lux when the speed limit is less than or equal to 50 mph, 60 mcd/m^2/lux when the speed limit is 55-65 mph, and 90 mcd/m^2/lux when the speed limit is 70 mph or greater. This UTCA/ALDOT research did not develop decay models by segregating test data into speed classes. Therefore, this section will not estimate service lives for markings based on speed limits. The authors selected potential threshold retroreflectivity values of 60 and 90 mcd/m^2/lux to determine the service life of DDB edge lines. The threshold value of 40 mcd/m^2/lux was not used because few ALDOT roads have speed limits less than 50 mph.

Service Life in CTP

The selected retroreflectivity decay model for dry DDB edge lines reported in Section 4 is repeated below. In this section, the model will be used to determine the CTP when pavement marking retroreflectivities are expected to fall to potential threshold values of 60 and 90 mcd/m^2/lux. The process used for these predictions is the same model that was used in the previous two studies (Lindly and Wijesundera, 2003 and Lindly and Narci, 2006) to calculate threshold values for FTM, PPM, and Rumble Stripes. Later in this section, the DDB values will be compared and contrasted to values for FTM, PPM, and Rumble Stripes.

Dry DDB Edge Line Decay Model

$(Dry\ retroreflectivity)_{DDB} = 520 \times \exp(-0.071x\ CTP)$*………………..(Equation 5.1)*

The service life of DDB marking was estimated using Equation 5.1, and Figure 5.1 shows the 95% confidence interval bands, which were obtained using a regression technique.

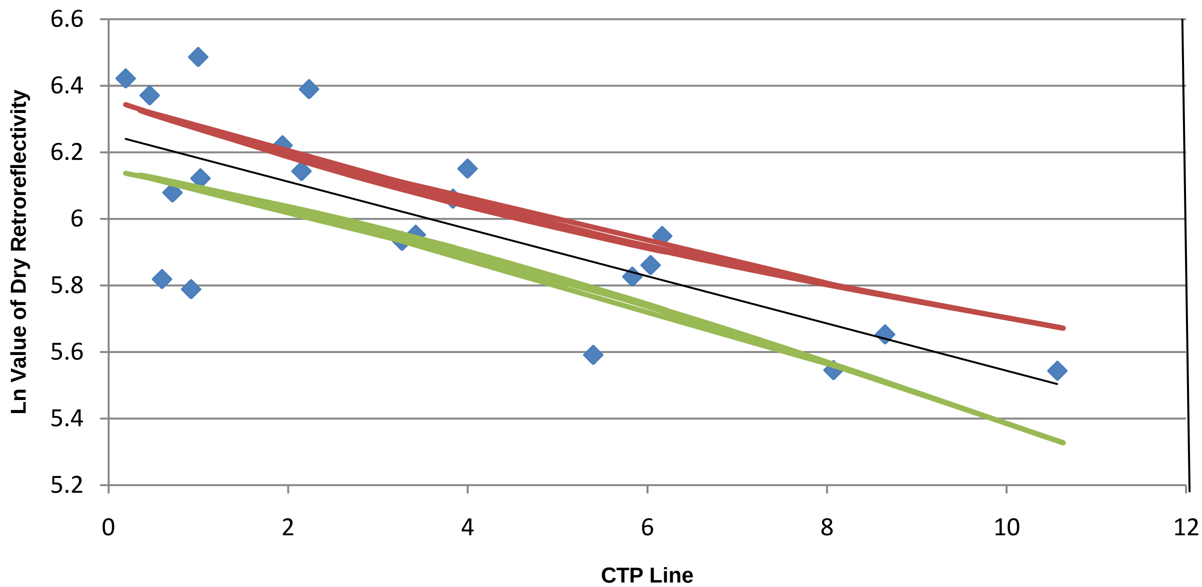

Figure 5-1. Ninety-five percent confidence bands of exponential dry DDB model.

In addition, the 95% confidence interval of the estimated service life was used to indicate the possible variation of service lives of DDB markings that are installed on different ADT roads and in different geographic locations. The following equations show how the average service life for DDB is estimated from the exponential model.

$$(CTP_{SL})_{Exponential} = \frac{\ln\left(\frac{(dry\ retroreflectivity)_{threshold}}{(dry\ retroreflectivity)_{initial}}\right)}{(coffficient)_{CTP}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(Equation\ 5.2)$$

Table 5-2 gives the estimated service lives of the four marking types UTCA has studied for ALDOT in terms of CTP. The results given in Table 5-2 lead to the following conclusions:

- DDB has double the initial retroreflectivity of its nearest competitor (Table 4-6) 520 mcd/m²/lux for DDB and 236 mcd/m²/lux for Rumble Stripe) and a significantly longer estimated service life than any of the other products studied.

- 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., DDB).

Table 5-2. Estimated Service Lives in Terms of CTP for Dry Tests

Type of Marking	Average Service Life in CTP (millions)			
	Threshold=60 mcd/m²/lux		Threshold=90 mcd/m²/lux	
	Average	95% Confidence Interval	Average	95% Confidence Interval
FTM	10.6	6.0-15.0	8.1	5.2-11.6
PPM	8.8	4.2-13.7	6.2	3.4-10.0
Rumble	21.9	16.3-30.6	15.5	10.9-22.4
Double Drop Beads	30.4	27.6-33.7	24.7	22.2-27.5

Expansion of Results

Service life is easier to interpret when it is expressed in terms of marking age than in terms of CTP. Equation 5.1 was used to predict the variation of dry DDB retroreflectivity with time on roads with per lane ADT of 2,500, 5,000, 7,500, and 10,000. Table D-1 of Appendix D gives these predictions, and Figure D-1 of Appendix D presents a graphical view of those retroreflectivity estimations. (Similar calculations were made for the other three pavement marking materials previously tested by UTCA for ALDOT. Note: these calculations were updated in 2009, because when the UTCA 2003 and UTCA 2006 reports were written, FHWA used higher minimum threshold values.)

Table 5-3 gives the estimated ages of the four pavement marking materials when their dry retroreflectivity will fall below 60 and 90 mcd/m^2/lux for selected ADT values. The values given in Table 5-3 were estimated from the results presented in Table 5-2. Table 5-3 does not present exact values of service life estimations that resulted in more than 60 months. This research did not test markings that were more than four years old. In addition, it was suspected that there is an increasing contribution of environmental factors to marking deterioration in addition to the traffic effect. Because 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 =60 mcd/m²/lux								Threshold =90 mcd/m²/lux							
	FTM		PPM		Rumble Stripe		DDB		FTM		PPM		Rumble Stripe		DDB	
	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.
2,500	60+	60+	60+	56-60+	60+	60+	60+	60+	60+	60+	60+	45-60+	60+	60+	60+	60+
5,000	60+	40-60+	59	28-60+	60+	60+	60+	60+	54	35-60+	41	23-60+	60+	60+	60+	60+
7,500	47	27-60+	39	19-60+	60+	60+	60+	60+	36	23-52	28	15-44	60+	48-60+	60+	60+
10,000	35	20-50	29	14-46	60+	54-60+	60+	60+	27	17-39	21	11-33	52	36-60+	60+	60+

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 such roads.
- The age of markings tested by this study ranged from two to 29 months for Rumble Stripe, from five to 43 months for FTM (with PPM having similar marking ages), and from nine months to 49 months for DDB . 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 all four materials tested 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), only DDB has estimated average service life of 60+ months for both thresholds.
- Because most of the markings tested for the four pavement materials 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. In those rows, both Rumble Stripe and DDB had estimated service lives of 60+ months for both the 60 and 90 mcd/m^2/lux thresholds. Neither FTM nor PPM could meet the 90 mcd/m^2/lux threshold for 60+ months.
- The results given in Table 5-3 generally indicate DDB to have the longest useful life on similar ADT roads, followed by Rumble Stripe, FTM, and PPM materials. This conclusion is based on dry retroreflectivity values.

Wet Retroreflectivity of Rumble Stripe at the End of Service Life

The wet DDB edge line decay model that was calculated in Section 4 and is repeated below.

$$(wet\ retroreflectivity)_{DDB} = 119.3 \times \exp(-0.099 \times CTP) \ldots\ldots\ldots\ \ldots\ldots\ldots\ \ldots(Equation\ 5.3)$$

The values for estimated service life of DDB edge lines in terms of CTP (See Table 5-2.) were substituted into Equation 5.3 to determine the estimated wet retroreflectivity of DDB when the dry retroreflectivity fell below minimum threshold values of 60 and 90 mcd/m^2/lux. These wet retroreflectivity values are given in Table 5-4, along with values for other pavement marking materials that had been tested in previous research projects.

Table 5-4. Estimated wet Retroreflectivity at Minimum Threshold Dry Values

Type of Marking	Threshold = 60 mcd/m²/lux		Threshold = 90 mcd/m²/lux	
	Average	95% Confidence Interval	Average	95% Confidence Interval
PPM	21.5	9.8-44.9	32.6	17.8-51.1
Rumble Stripe	1.5	0.4-4.0	4.5	1.4-9.9
Double Drop Beads	5.9	4.3-7.8	10.4	7.9-13.3

Table 5-4 contains values for only three of the four materials tested because a valid decay model could not be obtained for FTM in the earlier research projects. Table 5-4 shows that the estimated wet retroreflectivity of PPM is still roughly 1/3 of its dry retroreflectivity when the PPM line decays to minimum threshold values. Neither DDB nor Rumble Stripe retain as much of their wet retroreflectivity when their dry readings reach 60 or 90 mcd/m^2/lux. This difference is explained by the different rates of dry and wet degradation that each of the materials displays.

At first, such a finding may appear to favor PPM. (Its wet readings are still relatively bright when its dry readings decay to minimum threshold levels.) However, a review of Table 5-3 indicates that PPM will reach dry minimum threshold levels after three or four years of service and must be replaced. After three or four years, both the dry and wet readings for DDB will still remain high compared to PPM (as shown by the relative positions of the retroreflectivity curves near the right edge of Figure 4-4). In a similar analysis, after three or four years of service life, Rumble Stripe dry retroreflectivity will exceed that of PPM, but its wet retroreflectivity would be estimated to be lower than PPM.

6.0 Life-cycle Cost Analysis

This section presents a life-cycle cost analysis (LCCA) economic evaluation of DDB edge lines 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. Later in this section, the LCCA results for DBB will be compared to the three other pavement marking types that UTCA has studied for ALDOT. The purpose of LCCA is to determine which of the four marking types is more cost effective (i.e., less expensive).

Input Data

A list of the main input data for LCCA follows:

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

ALDOT provided typical maintenance costs and service lives of FTM. Those values were used for all four marking types in the LCCA because little historical data is available for the other three marking types. The study team obtained average installation costs of the four marking types 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.

Installation Costs

Table 6-1 presents average costs per mile incurred by ALDOT for installing one mile of the four pavement marking materials 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. Installing DDB is roughly 1.5 times as expensive, and installing PPM is roughly 3.3 times as expensive. Another observation is that FTM installation costs decreased somewhat when project length increased. Because there is less experience installing Rumble Stripe and DDB, the cost per mile of installing these materials may decrease if their use becomes more widespread or if they are used in longer sections of Alabama's roadways.

Table 6-1. Installation Costs of Edge Line Marking Materials

Type	Length of Project	Sample Size	Average Cost per mile ($)	Grand Average ($)
FTM	<3 mi	2	1,390.00	1,245.00
	> 3 mi	17	1,230.00	
Rumble Stripe	0-2 mi	5	2,314.00	2,314.00
DDB	0-1 mi	6	1,943.13	1,943.13
PPM	<3 mi	6	4,450.00	4,131.45
	> 3 mi	25	4,055.00	

Maintenance Costs

Two divisional offices of ALDOT (Divisions 3 and 6) provided typical costs per mile to maintain FTM 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. Again, little information is available for maintenance costs of the other three materials, so the values in Table 6-2 were also used for them during LCCA calculations.

Table 6-2. Maintenance Costs of FTM 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.

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 and Peterson, 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 two-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 lowest, followed by DDB, Rumble Stripe, and PPM.

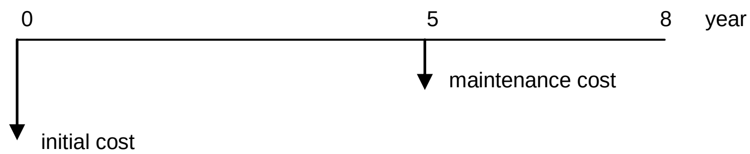

Figure 6-1. Cash flow stream with maintenance after five years.

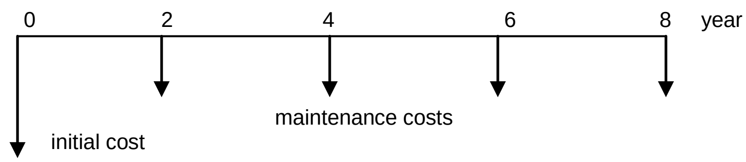

Figure 6-2. Cash flow stream with maintenance every two years.

Table 6-3. Results of LCCA for Four Pavement Marking Materials (Eight-Year Life Cycle)

	Present Value			
Scenario	**FTM**	**Rumble Stripe**	**PPM**	**DDB**
Maintenance after Five Years	1,355.00	2,424.00	4,241.59	2,053.27
Maintenance every Two Years	1,538.00	2,607.00	4,464.65	2,236.07

7.0 Conclusions and Recommendations

This report presented an evaluation of Double Drop Bead (DDB) edge lines used on ALDOT-maintained highways. It then compared DDB to three other ALDOT pavement marking types in terms of service lives, life-cycle costs, and both dry-night retroreflectivity and wet-night retroreflectivity. The other three marking types are standard flat thermoplastic marking (FTM), Rumble Stripes, and profiled pavement marking (PPM).

In the future, it appears that FHWA will implement minimum retroreflectivity values for centerline and edge lines measured in the dry condition. The comparisons made in this report can help ALDOT determine how the different marking types can meet the projected standard in a safe and cost-effective manner.

Conclusions

The main conclusions of this study follow:

- Wet and dry retroreflectivity for the four pavement marking types was field measured for marking ages ranging from a few months to approximately four years. (Rumble Stripes were an exception: the oldest Rumble Stripe tested was only 30 months old.) The retroreflectivity data was used to estimate decay rates of the four edge marking types, which are shown in Figure 7-1. In that figure, CTP represents the cumulative traffic passes experienced by the markings (a measure of the amount of traffic the markings have experienced). The figure estimates the average dry retroreflectivity of new materials as follows:
    - DDB: 520 mcd/m^2/lux
    - FTM: 320 mcd/m^2/lux
    - PPM: 242 mcd/m^2/lux
    - Rumble Stripe: 236 mcd/m^2/lux
- The retroreflectivities of the four markings decay at different rates, as shown on Figure 7-1. At roughly the three to four year marking age (the right side of Figure 7-1), the brightest markings in the <u>dry</u> condition in descending order are estimated to be DDB, Rumble Stripe, FTM, and PPM. The decay models were developed using data from highways with 20,000 or less ADT. Therefore, the results in this report are appropriate for highways with 20,000 or less ADT.
- As shown at the right side of Figure 7-1, at roughly the three to four year marking age, the brightest markings in the <u>wet</u> condition in descending order are estimated to be DDB, PPM, and Rumble Stripe. Wet FTM is not present in the figure because the researchers

could not construct a valid wet decay model for that material; however, its field data indicated that its wet retroreflectivity would be the lowest of the four materials tested.

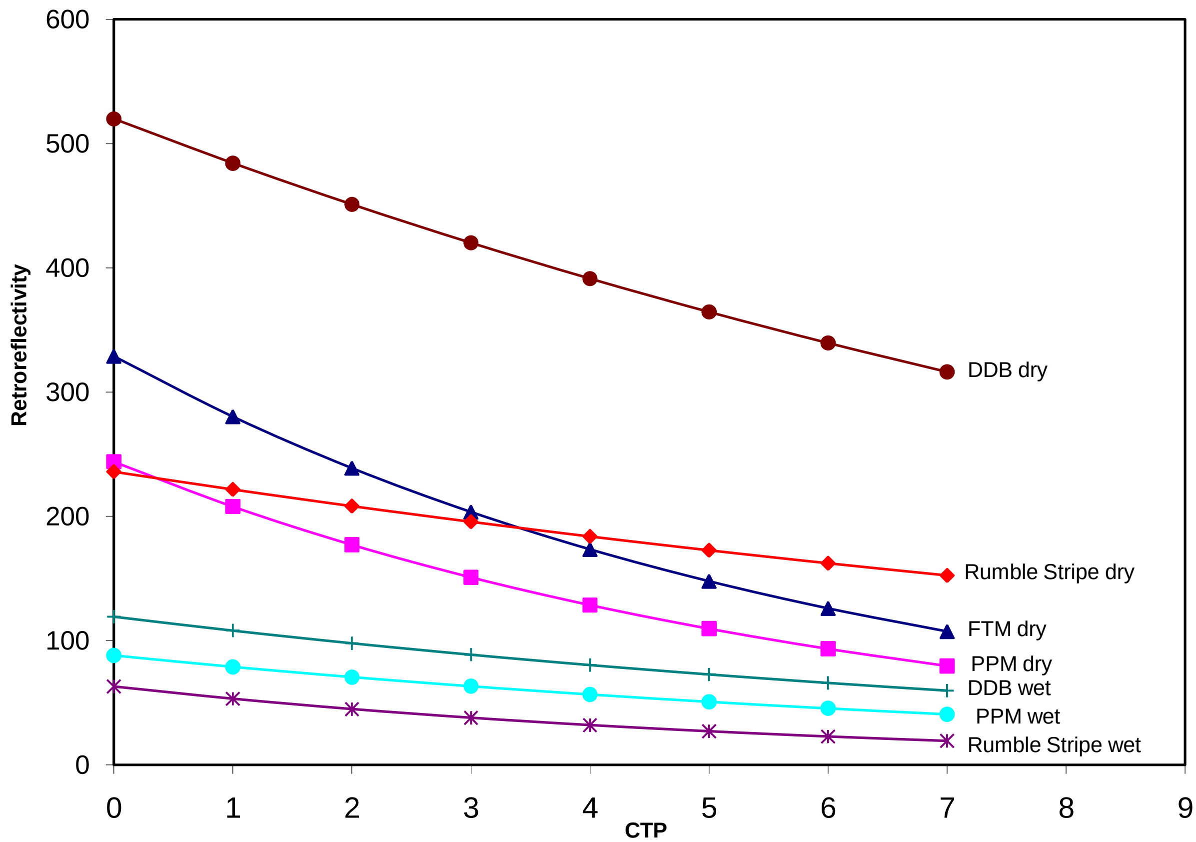

Figure 7-1. Variation of dry and wet retroreflectivity vs. CTP.

- The FHWA has not yet set minimum threshold values for dry retroreflectivity (the point at which the line must be maintained or replaced). However, their most recent estimates of those threshold values are 60 mcd/m^2/lux for 55-65 mph roads and 90 mcd/m^2/lux for roads at or above 70 mph. The researchers took the data from Figure 7-1 and converted it into estimates of pavement marking life at the two thresholds, as shown in Table 7-1.
  - 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 all four materials tested is estimated to be more than 60 months. The researchers did not extrapolate beyond 60 months because environmental factors may exert larger effects on retroreflectivity beyond that point.
  - On two-lane roads of 20,000 ADT and less (i.e., per lane ADT of 10,000 and less), only DDB has an estimated average service life of 60+ months for both thresholds.
  - The results given in Table 7-1 generally indicate DDB to have the longest useful life on similar ADT roads, followed by Rumble Stripe, FTM, and PPM materials. This conclusion is based on dry retroreflectivity values.

Table 7-1. Estimated Service Lives in Terms of Age of Markings

ADT per lane	Average Service Life in Months															
	Threshold =60 mcd/m²/lux								Threshold =90 mcd/m²/lux							
	FTM		PPM		Rumble Stripe		DDB		FTM		PPM		Rumble Stripe		DDB	
	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.	Avg.	95% C.I.
2,500	60+	60+	60+	56-60+	60+	60+	60+	60+	60+	60+	60+	45-60+	60+	60+	60+	60+
5,000	60+	40-60+	59	28-60+	60+	60+	60+	60+	54	35-60+	41	23-60+	60+	60+	60+	60+
7,500	47	27-60+	39	19-60+	60+	60+	60+	60+	36	23-52	28	15-44	60+	48-60+	60+	60+
10,000	35	20-50	29	14-46	60+	54-60+	60+	60+	27	17-39	21	11-33	52	36-60+	60+	60+

C.I. = confidence interval.

- The research team performed life-cycle cost analyses using construction costs, maintenance costs, and service life data supplied by ALDOT. The life-cycle cost estimates are shown in Table 7-2 for the four materials. Two scenarios are shown, each with a life cycle of eight years. In the first scenario, maintenance is performed on the markings only one time – after five years. In the second scenario, maintenance on the markings is performed every two years. Both scenarios show the life-cycle costs of the markings in the same ascending order: FTM, DDB, Rumble Stripe, and PPM.

Table 7-2. Results of LCCA for Four Pavement Marking Materials (Eight-Year Life Cycle)

Scenario	Present Value			
	FTM	Rumble Stripe	PPM	DDB
Maintenance after Five Years	$1,355	$2,424	$4,242	$2,053
Maintenance every Two Years	$1,538	$2,607	$4,465	$2,236

Recommendation

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

Federal standards for minimum threshold retroreflectivity will probably be based on dry pavement markings. The Double Drop Beads edge marking exhibits the highest dry retroreflectivity of the four markings throughout the range of marking ages tested and for limited future projections. It provides this increased retroreflectivity for a relatively small increase in cost/mile. For those reasons, ALDOT should strongly consider making DDB edge markings its standard. However, ALDOT has only tested DDB edge lines of one bead size combination, one thickness, etc. (See Table 7-3, which reproduces Table 1-1.) For those reasons, ALDOT should also investigate the following situations when specifying double drop beads:

- Optimizing intermix bead sizes and proportions
- Optimizing intermix bead volume percentage
- Optimizing drop bead sizes and proportions

- Optimizing drop bead rate (pounds per mile)
- Optimizing the amount of high refractive index beads in both intermix beads and drop beads

Table 7-3. Characteristics of Edge Stripe Types in Alabama

Stripe Type	Intermix Beads		Drop Beads			
	Bead Size	% by Volume	Bead Size	# Beads per Mile	Stripe Width	Stripe Thickness
Standard FTM	Type 1	30%	Type 1	132	6"	0.06"
Rumble Stripe	Type 1	30%	Type 1	132	6"	0.06"
DDB	Type 1	30%	50% 1 50% 4	530 total	6"	0.09"
PPM	Type 1	35%	40% 1 60% 1*	150 225	6"	0.14"at highest point of profile

* Type 1 Modified as per ALDOT "Standard Specification", 2002, Section 856.05(a)

This recommendation does not reflect negatively on Rumble Stripes. The rumble strip portion of Rumble Stripes provides an additional safety aspect which can continue to be valuable.

This recommendation also does not reflect negatively on RRPMs. As noted in the Review of Literature, TxDOT has found that RRPMs have detection distances that are two-to-three times higher than most other pavement markings, and they can be added to a thermoplastic edge line for roughly an additional 11-13% cost.

8.0 References

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Appendix A: 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
DDB	Double Drop Bead
FHWA	Federal Highway Administration
FTM	Flat thermoplastic markings
HITEC	Highway Innovative Technology Evaluation Center
ITE	Institute of Transportation Engineers
MUTCD	Manual on Uniform Traffic Control Devices
PPM	Profiled pavement markings
RRPM	Raised retroreflective pavement markers
UTCA	University Transportation Center for Alabama

Appendix B: Scatter Plots

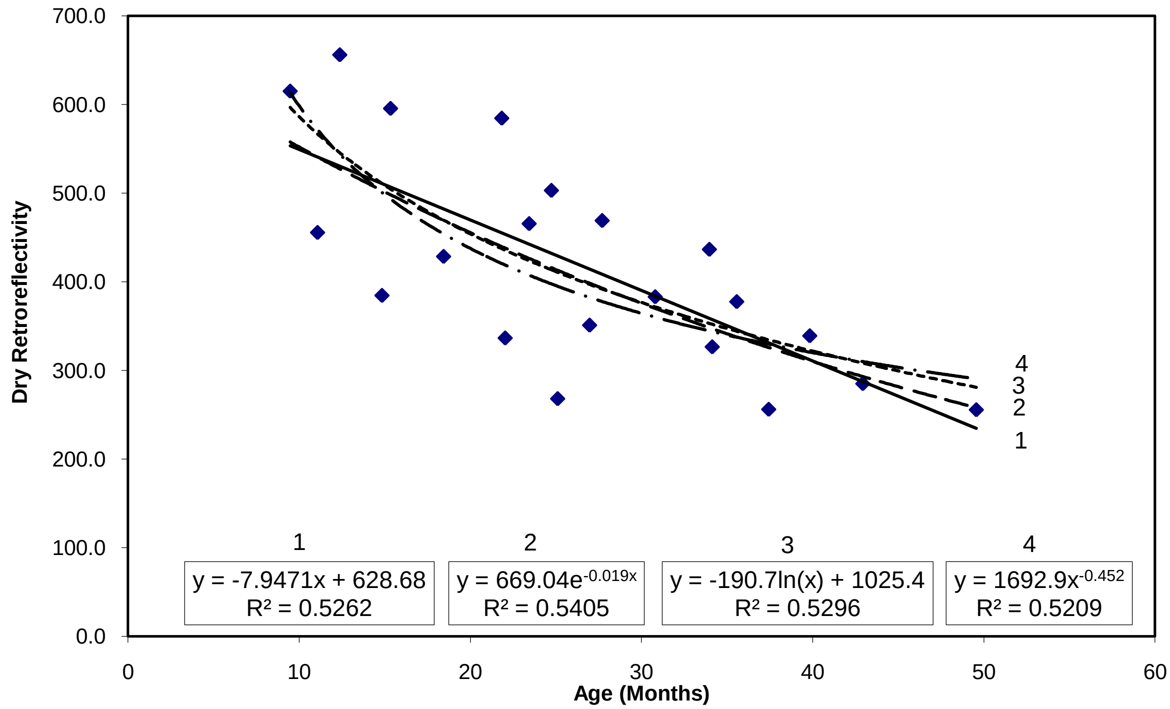

Figure B-1. Dry retroreflectivity vs. age of Double Drop Beads test sites.

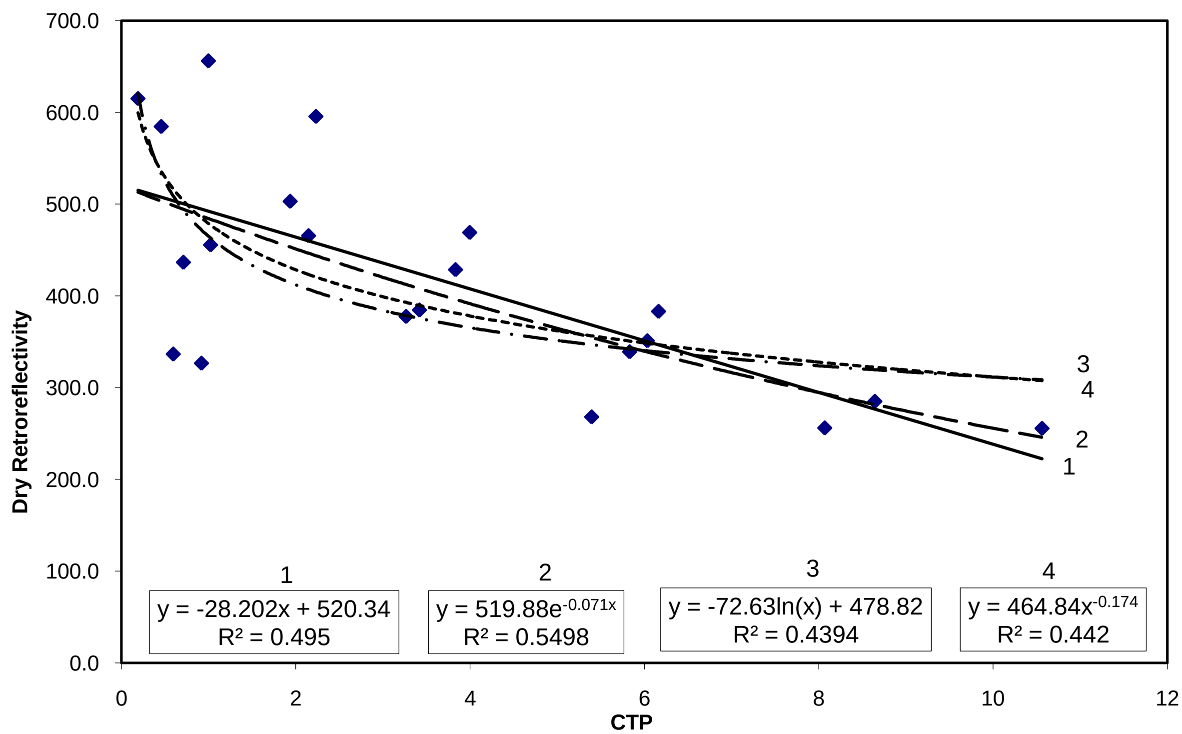

Figure B-2. Dry retroreflectivity vs. CTP of Double Drop Beads test sites.

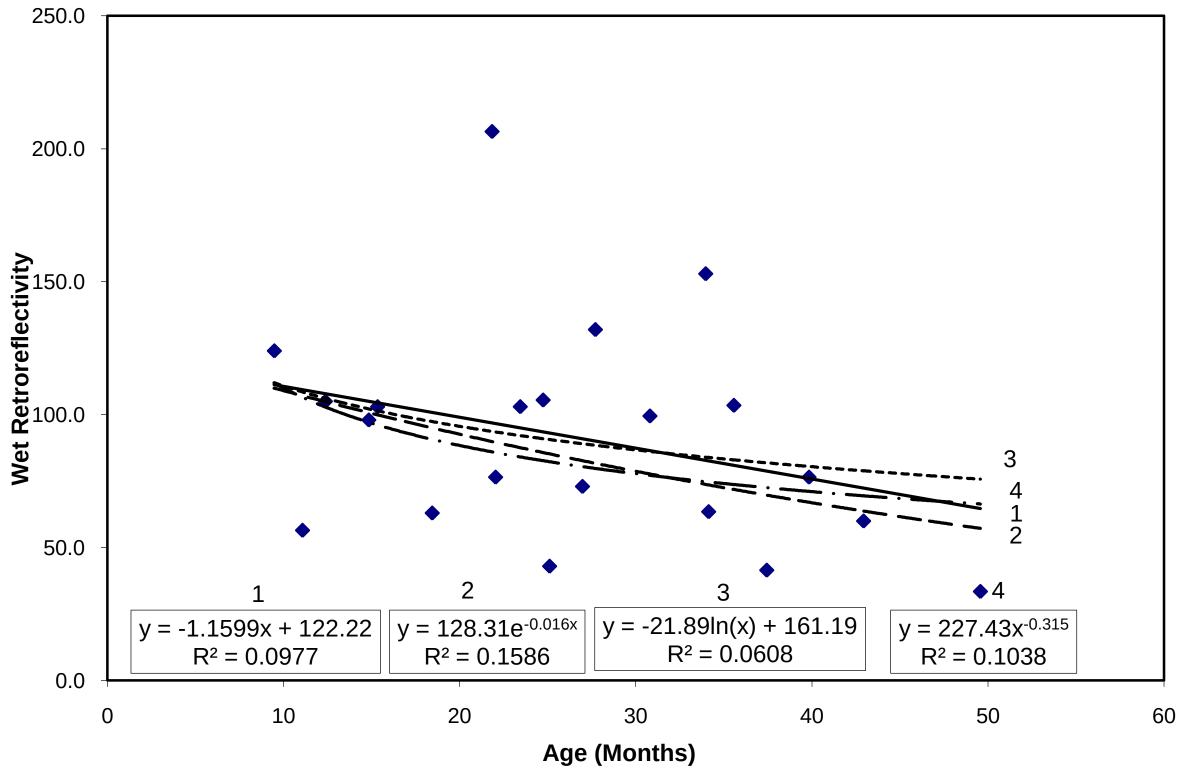

Figure B-3. Wet retroreflectivity vs. age of Double Drop Beads test sites.

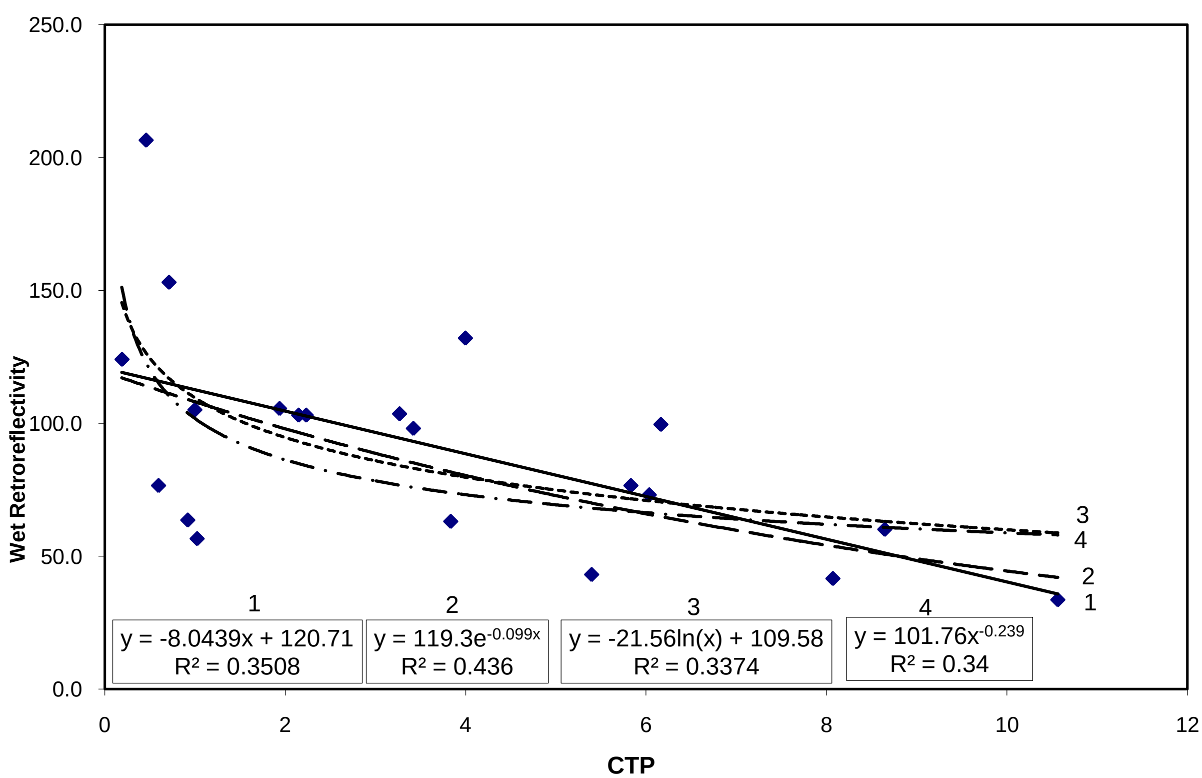

Figure B-4. Wet retroreflectivity vs. CTP of Double Drop Beads test sites.

Appendix C: Regression Analyses of Retroreflectivity Decay Models

Table C-1. Exponential Decay Model for Dry Retroreflectivity of Double Drop Beads

The regression equation is (ln dry) = 6.25 - 0.071 CTP

Regression Statistics	
Multiple R	0.74
R Square	0.55
Adjusted R Square	0.53
Standard Error	0.20
Observations	21.00

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.91	0.91	23.20	0.00
Residual	19	0.75	0.04		
Total	20	1.66			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	6.25	0.07	90.76	0.00	6.11	6.40
X Variable 1	-0.07	0.01	-4.82	0.00	-0.10	-0.04

TEST FOR NORMALITY				
Test Statistics	*Value*	*p-value*	*Mean*	*Standard Deviation*
Anderson-Darling	0.347	0.446	-0.001	1.019

Table C-2. Exponential Decay Model for Wet Retroreflectivity of Double Drop Beads

The regression equation is (ln wet) = 4.78 - 0.099 CTP

Regression Statistics	
Multiple R	0.66
R Square	0.44
Adjusted R Square	0.41
Standard Error	0.35
Observations	21

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.77	1.77	14.69	0.00
Residual	19	2.29	0.12		
Total	20	4.06			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	4.78	0.12	39.63	0.00	4.53	5.03
X Variable 1	-0.10	0.03	-3.83	0.00	-0.15	-0.04

TEST FOR NORMALITY				
Test Statistics	*Value*	*p-value*	*Mean*	*Standard Deviation*
Anderson-Darling	0.439	0.265	-0.006	1.023

Appendix D: Prediction of Retroreflectivity Values from Decay Models

Table D-1. Prediction of Dry Retroreflectivity Values for Double Drop Beads

ADT/Lane	Age of a Marking	CTP/Lane	Retroreflectivity (Exponential model)	ADT/Lane	Age of a Marking	CTP/Lane	Retroreflectivity (Exponential model)
2,500	0	0	520	7,500	0	0	520
2,500	6	0.45	504	7,500	6	1.35	472
2,500	12	0.9	488	7,500	12	2.7	429
2,500	18	1.35	472	7,500	18	4.05	390
2,500	24	1.8	458	7,500	24	5.4	354
2,500	30	2.25	443	7,500	30	6.75	322
2,500	36	2.7	429	7,500	36	8.1	293
2,500	42	3.15	416	7,500	42	9.45	266
2,500	48	3.6	403	7,500	48	10.8	241
2,500	54	4.05	390	7,500	54	12.15	219
2,500	60	4.5	378	7,500	60	13.5	199
5,000	0	0	520	10,000	0	0	520
5,000	6	0.9	488	10,000	6	1.8	458
5,000	12	1.8	458	10,000	12	3.6	403
5,000	18	2.7	429	10,000	18	5.4	354
5,000	24	3.6	403	10,000	24	7.2	312
5,000	30	4.5	378	10,000	30	9	274
5,000	36	5.4	354	10,000	36	10.8	241
5,000	42	6.3	332	10,000	42	12.6	213
5,000	48	7.2	312	10,000	48	14.4	187
5,000	54	8.1	293	10,000	54	16.2	165
5,000	60	9	274	10,000	60	18	145

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

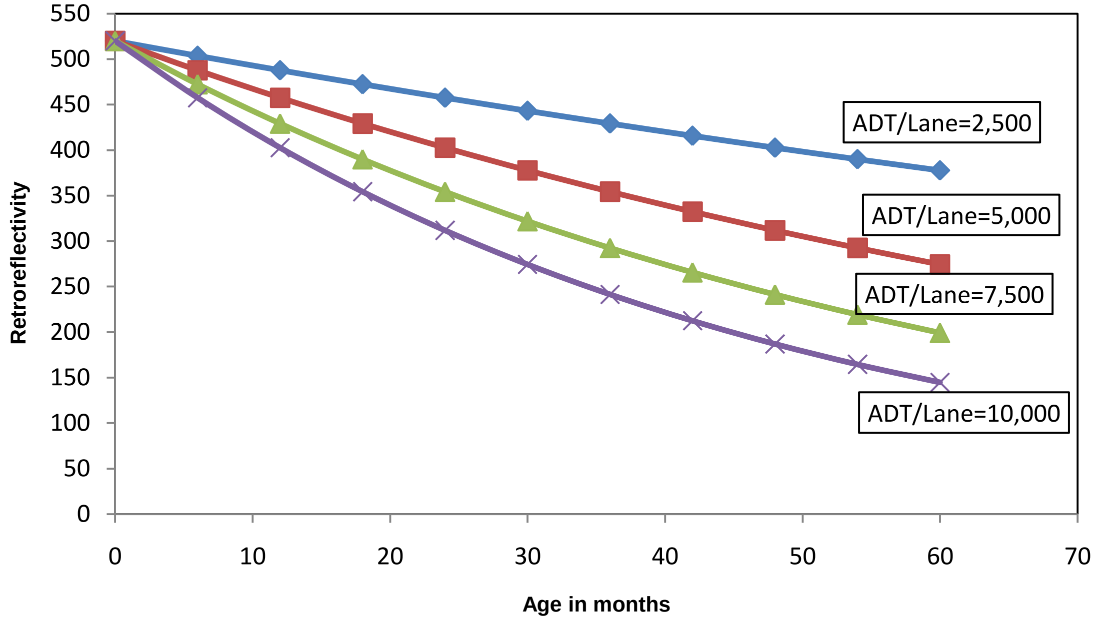

Figure D-1. Variation of dry retroreflectivity of Double Drop Beads with time.