REPORT CDOT-2021-04

MAY 2021

Striping Materials Performance Curves – Life Cycle Analysis

APPLIED RESEARCH & INNOVATION BRANCH

Ivan A. Cornejo

COLORADO Department of Transportation

Technical Report Documentation Page

1. Report No. CDOT-2021-04	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Striping Materials Performance Curves – Life Cycle Analysis		5. Report Date May 2021 6. Performing Organization Code
7. Author(s) Ivan A. Cornejo		8. Performing Organization Report No.
9. Performing Organization Name and Address Colorado School of Mines		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 317-01 (PO 471001110)
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 2829 W. Howard Pl. Denver CO, 80204		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration
KC Matthews, CDOT Traffic & Safety (Retired)
Esayas Butta, CDOT Traffic & Safety
Shane Chevalier, CDOT Traffic & Safety
Charles Meyer, CDOT Traffic & Safety
Thomas Dinardo, CDOT Traffic & Safety

16. Abstract

In this report, region-specific Retro-reflectivity Performance Curves are presented and discussed as a function of pavement marking materials, AADT, terrain, surface type, line color, line type, road bound direction, and road name. In addition, laboratory aging, and abrasion test results are presented and discussed. In addition to this written report, five separate dynamic graphical tool were submitted; one for each of the Colorado regions. A clear and concise description of these tools are discussed and a few examples are given and interpreted. The intention of these dynamic tools is that the road managers will continue adding data, and making corrections to the database presented. Another objective of this report, is to allow the users at CDOT to better determine appropriate times to restripe roads, increase cost efficiency, and overall road safety attributed to road striping practices in Colorado.

17. Keywords CDOT, Colorado, Striping Materials, Performance Curves.	18. Distribution Statement This document is available on CDOT's website https://www.codot.gov/programs/research		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Striping Materials Performance Curves - Life Cycle Analysis

Final Report

Type: Combination of SP&R and HSIP

Start: 06/21/2017 - End: 12/31/2020

Principal Investigator(s):

Ivan Cornejo, PhD, Colorado School of Mines

Study Manager:

David Reeves, CDOT Applied Research & Innovation Branch

Study Panel Members:

KC Matthews, CDOT Traffic & Safety (Retired)

Esayas Butta, CDOT Traffic & Safety

Shane Chevalier, CDOT Traffic & Safety

Charles Meyer, CDOT Traffic & Safety (Retired)

Thomas Dinardo, CDOT Traffic & Safety

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EXECUTIVE SUMMARY

The majority of pavement marking materials available on the market have been tested by CDOT, and several are currently in-use throughout the State of Colorado. This study found that not only geographical location, but other attributes such as; line type, terrain, and even annual average daily traffic (AADT), offered different life-cycle performance. This research project implemented a scientific approach to evaluate different striping materials in various locations throughout the State of Colorado.

The purpose of the study was to produce Striping Materials Performance Curves for all the five CDOT Regions to help traffic engineers select the best available pavement marking material for a particular Region. In addition to this report, five Decision Support Systems (DSS) were created, one for each region, and delivered to CDOT in additional files.

This field study was conducted over a three year period, measuring 27,288 miles on 66 roads, and 120 sections. In addition, laboratory tests were performed to understand aging, abrasion resistance on epoxy as a function of time and ultraviolet radiation.

For future investigation on this topic, the author of this research proposes the following changes in the retroreflection measurements as a tool to calculate aging and durability of striping materials:

1. Careful selection of the roads and sections to be surveyed. Paying closer attention to the statistical significance of the miles to be tested.
2. Maintain a more robust database with the date of the striping material installation, type of line, material used, and type of terrain. In addition, if a section is partially striped, this change must be noted on the database.
3. The retroreflection system must provide a certificate of control, and calibration tests conducted before each measurement.
4. Variability on the field data is expected, but if significant variability is present in the data gathered (more than 100mCd or 15% of the average), an indication of the potential cause must be indicated.

As a next step, the author of this report proposes to hold focused meetings ranging between four to eight hours per region, to discuss those sections where the performance curve obtained

showed anomalies and/or inconsistences. The value of this exercise will enrich the database provided by this research, and the database that historically has been maintained by CDOT. Thus making DSS files more comprehensive and robust for each region. This proposal will greatly improve the decision making process on striping materials for the State of Colorado.

INTRODUCTION

Automotive transportation is a major aspect of modern day life, and as such, the safety of those who travel in this manner is critical in preventing unnecessary harm or loss of human life. The primary elements used to caution drivers of various changes or conditions on roadways are signs adjacent or above a roadway, which provide a visual sign of road conditions and hazards. Also, road striping materials, which in some cases can act similarly to signs, but are more often used to create organization on roadways through the means of lines of different varieties. The primary focus of this investigation is on striping materials, particularly in the context of the pavement materials in which they are applied to.

Pavement striping is one of the most useful and reliable passive traffic control devices used in use on America's highways. Travel lanes provide drivers incredibly valuable guidance especially during inclement weather, and poor visibility conditions. Considering the varied geography of Colorado, pavement marking materials, are subject to extreme fluctuations in weather conditions, intense ultra-violet radiation, wild fluctuations in temperature, a variety of harsh roadway maintenance materials including magnesium chloride or other salts, sand, and gravel, as well as the punishing wear exerted by tires and snow plows.

Pavement marking materials currently available to the Colorado Department of Transportation (CDOT) include thermoplastics, profiled thermoplastics, heated-in-place thermoplastics, water-based paints, preformed tapes, thermosets such as polyuria, modified urethane, methyl methacrylate (MMA), epoxy, and modified epoxy.

Many of these materials have been tested by CDOT, and several are currently in-use throughout the state; as expected. Depending on location, some materials inherently offer better life-cycle cost performance than others. Considering the varied environment, and weather conditions across CDOT's five regions, the harshness of snow removal materials and operations, and the wide variety of pavement marking materials available; this research project proposed a scientific approach to evaluate different striping materials in various locations under different climatic conditions.

In this report, region-specific Retro-reflectivity Performance Curves will be presented and discussed as a function of pavement marking materials, AADT, terrain, surface type, line color, line type, road bound direction, and road name. In addition, laboratory aging, and abrasion test results will be presented. In addition to this written report, five separate dynamic graphical tool will be submitted; one for each of the Colorado regions. A clear and concise description of these tools will be discussed and a few examples will be given and interpreted. The intention of these dynamic tools is that the road managers will continue adding data, and making corrections to the database presented. Another objective of this report, is to allow the users at CDOT to better determine appropriate times to restripe roads, increase cost efficiency, and overall road safety attributed to road striping practices in Colorado.

EXPERIMENTAL APPROACH AND DATA ANALYSIS

Field Data

Accurate and safe data collection is critical to overall project success. The project approach included gathering field reflectivity information using mobile retroreflectometers (see Figure 1.) for all CDOT Engineering Regions in the state (Figure 2.) The mobile retroreflectometer units (MRU) used in this research were subcontracted from Beck Enterprises of Woodbury, LLC meeting all the minimum specification noted in the project's Scope of Work and following CDOT safety standards, and regulations during all field work activities. The MRUs used in this investigation are compliant with ASTM E1710 (ASTM, E1710, 2018) where this test method covers measurement of the retroreflective properties of horizontal pavement marking materials containing retroreflecting beads, such as traffic stripes and surface symbols, using a portable retroreflectometer that can be placed on the road delineation to measure the retroreflection at a prescribed geometry. Gathering data with mobile retroreflectometry units is accurate and inherently safer than using other data collection methods. Mobile units gathered data in July and October of 2017, January, April, August, and October of 2018, June/July of 2019, and June/July of 2020. The overall project covered during the three-year period 120 sections of test material in 66 different road, totaling 27,288 line miles of existing striping.

Data was taken every 4 feet or less, and then rolled up into 1/10th mile or 528 feet intervals. Measurements were taken on mainline through lanes only excluding ramps, turn lanes, climbing lanes, and auxiliary lanes. Measurements were taken on all edge, center, and lane line pavement markings. Based on these criteria and using shapefile information of the routes provided by CDOT, we have estimated a total of 3,411-line miles measured per measurement during this project (see Table A.)

Figure 1. Mobile retroreflectometer system.

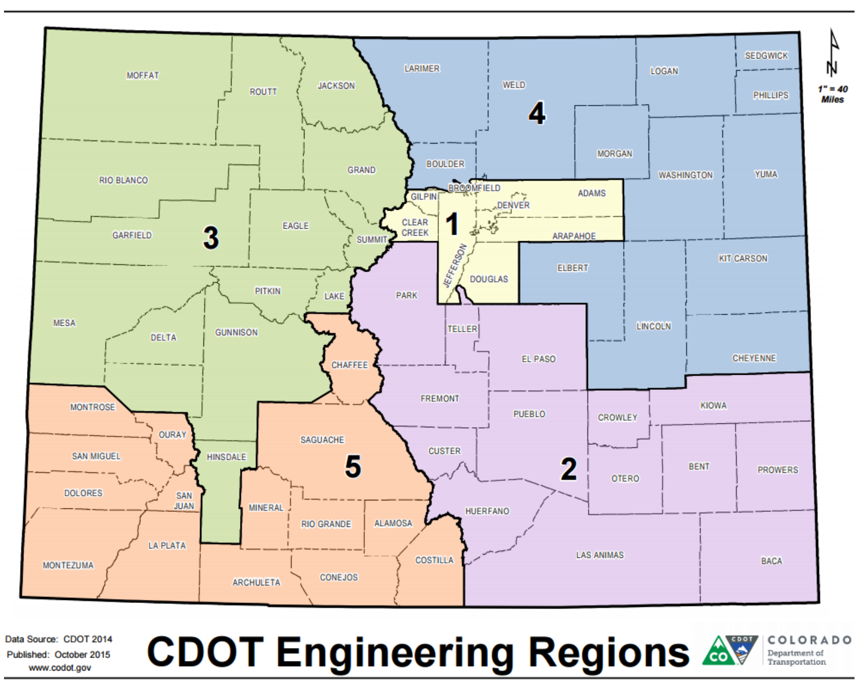

Figure 2. Map of the engineering regions in Colorado.

Table A. Summary of the total number of line miles, roads, and sections measured.

Region	Miles	Roads	Sections
1	13,313	23	55
2	7,083	12	18
3	1,589	12	17
4	3,028	13	16
5	2,275	6	14
TOTAL	**27,288**	**66**	**120**

In general, for highway striping operations, there are a variety of lines that can be seen in Figure 3. From left to right, according to the perspective of the driver proceeding down a road in the intended direction, the first line is either referred to as a center line (CL) or left edge line (LEL), depending on whether the road is a two-way or one-way road, respectively. These lines are either a continuous double line with a yellow pigmentation for CL, or a continuous single line with also a yellow pigmentation for LEL. These lines represent the edge of the permitted driving area.

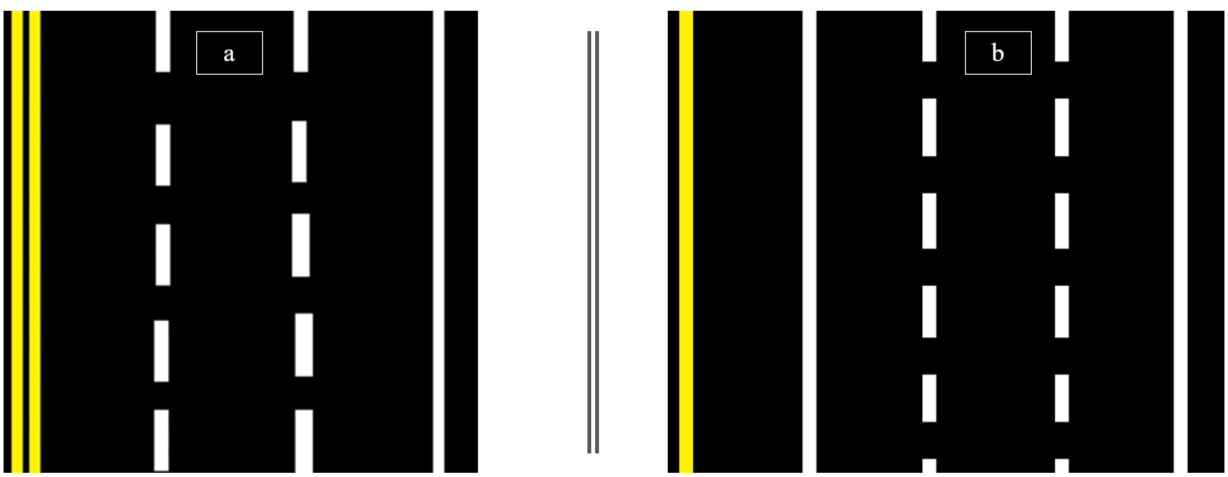

Figure 3 A display of different types of road lines. From left to right, the lines displayed are: (a) a centerline, two lane lines, and a right edge line, and (b) a left edge line, an HOV line, two lane lines, and a right edge line.

To the right of the CL or the LEL can be a range of zero to four lane lines (LL) (from the roads observed in this investigation). These lines are dashed lines with a white pigmentation, and are used to delineate different paths that a vehicle may take while travelling in a determined direction. This helps avoid vehicle collision and to increase physical space optimization for vehicles in high traffic conditions. On the far right hand side of the road is a line referred to as a right edge line (REL). This is a continuous single line with a white pigmentation. This line, like the LEL, is used to delineate drivable and non-drivable areas.

A final type of line is used in unique circumstances, and is known as a high occupancy vehicle (HOV) line. These lines are continuous lines with a white pigmentation, typically one line to the right of the LEL or CL. These lines are used to denote HOV lanes in which vehicles are legally required to have at least two occupants.

Laboratory Data

In addition to the experimentation conducted in the field, laboratory tests were also conducted on samples prepared in the laboratory. Several circular slabs of 10 cm in diameter were cut from a concrete pavement sample provided by CDOT. The slabs were then painted with a white polyacrylate striping material provided from CDOT, allowed to fully cure at room temperature, and lab ambient conditions for several days before durability versus color tests. Furthermore, durability versus wear resistance tests were performed.

Durability versus color was done following ASTM G154 (ASTM, G154, 2016). The samples were aged up to 300 hours in a QUV – Accelerated Weathering Tester. Color data was taken every 100 hours of aging utilizing a color spectrophotometer to gather L, a, and b color space values (Figure 4.) Durability versus wear resistance test was performed following ASTM C501-84 (ASTM, C501 - 84, 2009). The aged slabs were subjected to 1000 wear cycles using a ceramic tile abraser (see Figure 5). The wear index number (I_w) was then calculated by :

$$I_{w=} {}^{88}/_{(Wa-Wf)}$$

Where, w_a is the original weight of the specimen plus holder and w_f is the final weight of the specimen and holder.

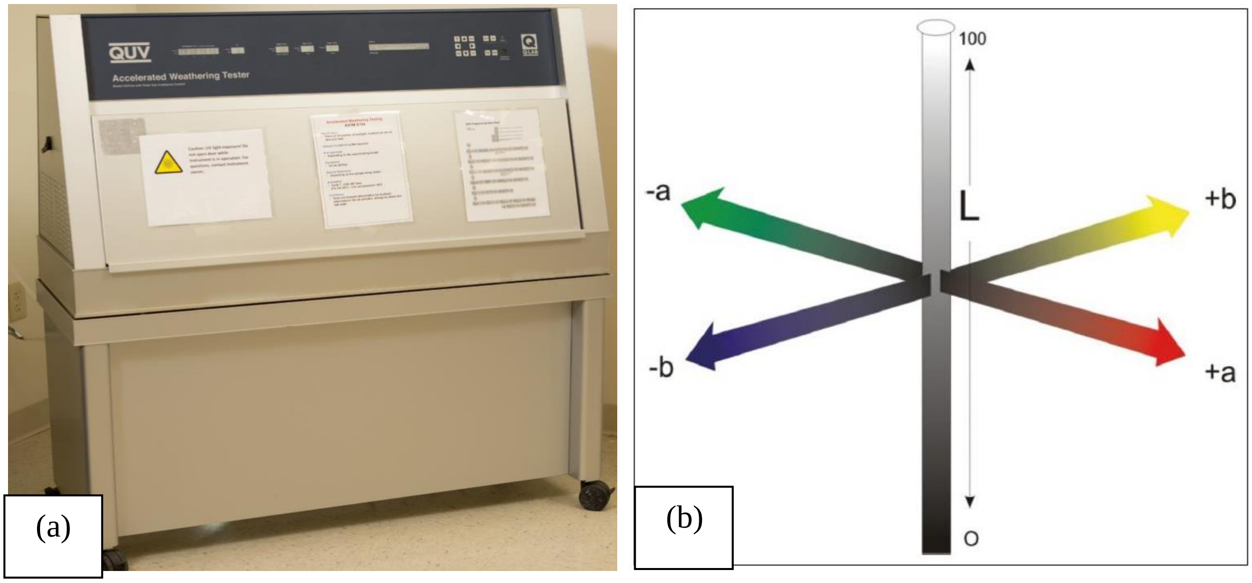

Figure 4. (a) Accelerated Weathering Tester QUV system used for aging lab samples, and (b) color space diagram L, a, and b.

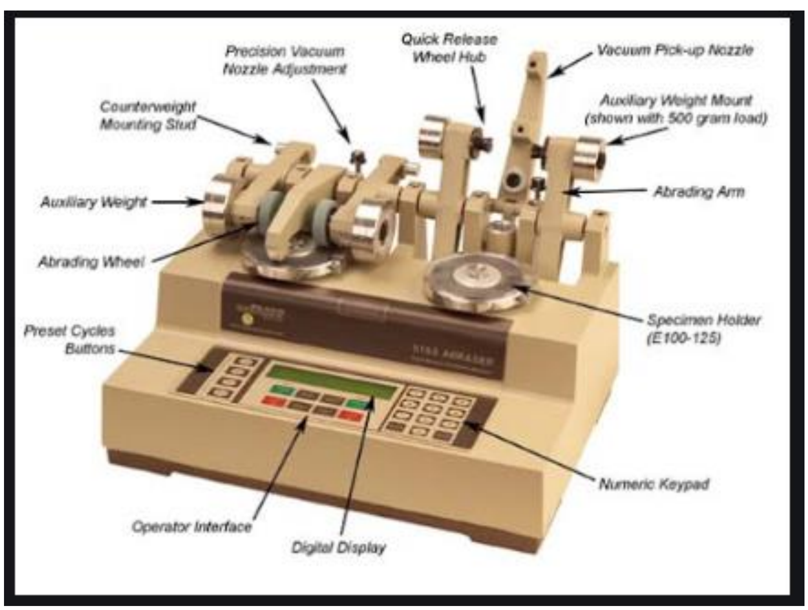

Figure 5. Rotary abraser used to wear the acrylic stripe on a concrete slab - Model Taber 5135.

Raw Data, Database, and Data Analysis

With the main purpose of processing more than 30,000 of miles with retroreflectivity data through an interactive, accessible and easy to understand/use tool, a Decision Support System (DSS) was created in excel for each region. Thus, the data collected in the field together with the strip date information received from CDOT, the DSS is capable to transform retroreflectivity data into knowledge.

A typical report from the retroreflectivity data collected by Beck Enterprises is shown in Figure 6 for Colorado route 070A, section 252-255 in Region 1, for a left edge line (LEL) measured in the eastbound direction. Each datasheet is then summarized in the report and thus, one data point for future analysis is created. This single data point is then stored in the DSS file created by this research for further analysis. This process continued until the entire DSS file was populated. The DSS files created, one per each region, contain four sections: (1) a database with both the measured raw data, and the additional historical information provided by CDOT, (2) a dynamic graphical analysis tool designed to visualize and inspect the data mile point by mile point as a function of measuring time, (3) a second dynamic graphical analysis tool that has the function or purpose of "stitching" all the data together as a function of installation date, thus capable to provide a life-time cycle curve for the specific section or sections being evaluated, and (4) a general tab designed to give the user general statistical information.

Section 1 of the DSS file (called **Database**) includes the following information, measured route and section name, start and end mile points, surface, terrain and material's type, as well as annual average daily traffic (AADT), direction of measurement, line type, retroreflectivity average values, measurement date and age. Age is a calculated value (in months) from the difference between striping date (provided by CDOT) and the retroreflectivivity measurement date. Figure 7 shows how the raw data, received from those entities previously mentioned, is distributed and stored in the Database Section of the DSS.

CO 070A - 252-255 EB 252-255 LEL 18		2072KC4LC1.7L0.csv			
Client	Colorado School	057gpaVO			
State	CO	OoyN1Z49			
District	1				
County					
Project Number					
Highway	070A - 252-255				
Control Section					
Direction	EB				
Start Mile Point	252				
End Mile Point	255				
Line Type	LEL				
Material	DURABLES				
Installation Date	Invalid date	AADT: High	Event #	Event Type	# of Occ.
Surface	Bituminous Rural	Terrain: Mountainous	-----------	------------------------------------	--------------
Start GPS Coordinates	39.70404000N	105.3269000W	1	NO LINER	0
End GPS Coordinates	39.70649500N	105.2775333W	2	CONST ZONE	0
Date	#####		3	THRU A TOWN	0
Start Time			4	MAT CHANGE	0
Stop Time			5	CRACK SEAL	0
White Calib_Factor	1		6	INT SEC/CHG	0
Yellow Calib_Factor	1		7	TURN LANE	0
Operator ID	SETH		8	BRIDGE33	0
Hardware ID	115		9	LINE DAMAGE	0
Software Version	7.3.12.0		10	DIRT ON LINE	0

Retroreflectivity: Average	360	Percent of Intervals < 300	9.68%	Station Interval	0.1
Retroreflectivity: Standard Deviatio	47	300 <= Percent of Intervals < 350	38.71%	Lower Validation Threshold	100
Valid Interval Percentage	99.17%	350 <= Percent of Intervals <= 449	48.39%	Upper Validation Threshold	100
Average Left Stripe Width (in)	NA	449 < Percent of Intervals <= 499	3.23%	Rejection Threshold	1400
Average Right Stripe Width (in)	NA	499 < Percent of Intervals <= 699	0.00%	Sample Size	400
Contrast Ratio	NA	699 < Percent of Intervals	0.00%		

Chain	Ave	Valid	Inv	Dval	LAve	RAve	Ctr/Rati	RdAve	Event Code	Stdev	GPSLat	GPSLon	Hinv	Temp	Line Sub	Treatme	Surface Type
252	338	213	3	0	0	0	-1	31	YTS10V	51	39.70404000N	105.3269000W	0	25	3	Rumble	Concrete
252.1	335	215	0	0	0	0	-1	18	YTS10V	42	39.70492000N	105.3255000W	0	25	3	Rumble	Concrete
252.2	348	211	1	0	0	0	-1	14	YTS10V	37	39.70584500N	105.3241333W	0	25	3	Rumble	Concrete
252.3	381	192	0	0	0	0	-1	17	YTS10V	36	39.70679833N	105.3226500W	0	25	3	Rumble	Concrete
252.4	398	213	0	0	0	0	-1	17	YTS10V	76	39.70775667N	105.3212667W	0	25	3	Rumble	Concrete
252.5	411	183	0	0	0	0	-1	13	YTS10V	46	39.70871833N	105.3199333W	0	25	3	Rumble	Concrete
252.6	355	207	0	0	0	0	-1	18	YTS10V	67	39.70982500N	105.3184833W	0	25	3	Rumble	Concrete
252.7	417	209	0	0	0	0	-1	13	YTS10V	65	39.71083500N	105.3172500W	0	25	3	Rumble	Concrete
252.8	431	188	6	0	0	0	-1	13	YTS10V	68	39.71198167N	105.3160833W	0	25	3	Rumble	Concrete
252.9	367	201	0	0	0	0	-1	19	YTS10V	79	39.71299667N	105.3146333W	0	25	3	Rumble	Concrete
253	324	218	0	0	0	0	-1	16	YTS10V	34	39.71389833N	105.3133500W	0	25	3	Rumble	Concrete
253.1	288	210	0	0	0	0	-1	17	YTS10V	34	39.71418167N	105.3115167W	0	25	3	Rumble	Concrete
253.2	304	209	0	0	0	0	-1	20	YTS10V	45	39.71398333N	105.3095167W	0	25	3	Rumble	Concrete
253.3	319	209	0	0	0	0	-1	23	YTS10V	40	39.71353500N	105.3078333W	0	25	3	Rumble	Concrete
253.4	322	200	0	1	343	153	-1	16	YTS10V	27	39.71308167N	105.3060500W	0	25	3	Rumble	Concrete
253.5	285	200	1	0	0	0	-1	12	YTS10V	32	39.71256833N	105.3042333W	0	25	3	Rumble	Concrete
253.6	334	194	0	1	350	126	-1	22	YTS10V	42	39.71210500N	105.3024500W	0	25	3	Rumble	Concrete
253.7	319	188	0	1	312	322	-1	14	YTS10V	31	39.71168833N	105.3008167W	0	25	3	Rumble	Concrete
253.8	339	186	0	0	0	0	-1	14	YTS10V	30	39.71117333N	105.2990500W	0	25	3	Rumble	Concrete
253.9	335	201	0	0	0	0	-1	24	YTS10V	48	39.71073000N	105.2972167W	0	25	3	Rumble	Concrete
254	301	196	0	0	0	0	-1	23	YTS10V	31	39.71032500N	105.2953333W	0	25	3	Rumble	Concrete
254.1	287	185	14	0	0	0	-1	19	YTS10V	78	39.70982333N	105.2935667W	0	25	3	Rumble	Concrete
254.2	439	213	0	0	0	0	-1	17	YTS10V	26	39.70951667N	105.2918167W	0	25	3	Rumble	Concrete
254.3	368	185	0	3	378	342	-1	20	YTS10V	46	39.70924667N	105.2899667W	0	25	3	Rumble	Concrete
254.4	409	186	0	0	0	0	-1	21	YTS10V	42	39.70911500N	105.2880833W	0	25	3	Rumble	Concrete
254.5	405	182	0	0	0	0	-1	23	YTS10V	35	39.70905167N	105.2862000W	0	25	3	Rumble	Concrete
254.6	418	165	0	0	0	0	-1	20	YTS10V	36	39.70888667N	105.2842500W	0	25	3	Rumble	Concrete
254.7	353	158	26	0	0	0	-1	11	YTS10V	95	39.70854833N	105.2825167W	0	25	3	Rumble	Concrete
254.8	425	180	0	0	0	0	-1	19	YTS10V	48	39.70779667N	105.2808667W	0	25	3	Rumble	Concrete
254.9	456	175	0	1	472	410	-1	21	YTS10V	51	39.70721000N	105.2791500W	0	25	3	Rumble	Concrete
255	400	192	0	0	0	0	-1	22	YTS10V	49	39.70649500N	105.2775333W	0	25	3	Rumble	Concrete

Figure 6. Retroreflectivity data for route 070A, section 252-255, LEL line measured in July 2nd, 2020.

Road	Section	Helper	Line Colo	Striped Dat	Specific ma	Route	Start M	End Mi	ABS	Distric	Surface Typ	Material Type	Terrain	AADT	Directio	Line Typ	Value	Measurment	Measuring Mon	Measuring Yea	Age (Month
024A	220-225	220-225 EB LL	WHITE	8/1/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	LL	236	8/2/2018	Aug	2018	1
024A	220-225	220-225 WB RE	WHITE	8/1/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	334	8/2/2017	Aug	2017	1
024A	220-225	220-225 WB RE	WHITE	8/1/2018	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	228	8/2/2018	Aug	2018	1
024A	220-225	220-225 EB RE	WHITE	8/1/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	282	8/2/2017	Aug	2017	1
024A	220-225	220-225 EB RE	WHITE	8/1/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	170	8/2/2018	Aug	2018	1
024A	220-225	220-225 WB CL	YELLOW	8/1/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	190	8/2/2017	Aug	2017	1
024A	220-225	220-225 WB CL	YELLOW	8/1/2018	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	122	8/2/2018	Aug	2018	1
024A	220-225	220-225 EB CL	YELLOW	8/1/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	181	8/2/2017	Aug	2017	1
024A	220-225	220-225 EB CL	YELLOW	8/1/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	115	8/2/2018	Aug	2018	1
024A	220-225	220-225 EB LL	WHITE	8/2/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	LL	269	10/2/2017	Oct	2017	3
024A	220-225	220-225 EB LL	WHITE	8/2/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	LL	212	10/2/2018	Oct	2018	3
024A	220-225	220-225 WB RE	WHITE	8/2/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	418	10/2/2017	Oct	2017	3
024A	220-225	220-225 WB RE	WHITE	8/2/2018	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	245	10/2/2018	Oct	2018	3
024A	220-225	220-225 EB RE	WHITE	8/2/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	308	10/2/2017	Oct	2017	3
024A	220-225	220-225 EB RE	WHITE	8/2/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	173	10/2/2018	Oct	2018	3
024A	220-225	220-225 WB CL	YELLOW	8/2/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	253	10/2/2017	Oct	2017	3
024A	220-225	220-225 WB CL	YELLOW	8/2/2018	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	94	10/2/2018	Oct	2018	3
024A	220-225	220-225 EB CL	YELLOW	8/2/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	276	10/2/2017	Oct	2017	3
024A	220-225	220-225 EB CL	YELLOW	8/2/2018	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	80	10/2/2018	Oct	2018	3
024A	220-225	220-225 WB RE	WHITE	8/4/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	91	1/2/2018	Jan	2018	5
024A	220-225	220-225 EB RE	WHITE	8/4/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	98	1/2/2018	Jan	2018	5
024A	220-225	220-225 WB CL	YELLOW	8/4/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	65	1/2/2018	Jan	2018	5
024A	220-225	220-225 EB CL	YELLOW	8/4/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	61	1/2/2018	Jan	2018	5
024A	220-225	220-225 WB RE	WHITE	8/4/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	REL	121	4/2/2018	Apr	2018	8
024A	220-225	220-225 EB RE	WHITE	8/4/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	99	4/2/2018	Apr	2018	8
024A	220-225	220-225 WB CL	YELLOW	8/4/2017	PAINT	024A - 220-225	225	220	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	72	4/2/2018	Apr	2018	8
024A	220-225	220-225 EB CL	YELLOW	8/4/2017	PAINT	024A - 220-225	220	225	5	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	82	4/2/2018	Apr	2018	8
024A	220-225	220-225 EB CL	YELLOW	8/5/2018	PAINT	024A - 220-225	219.9	225	5.1	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	CL	65	6/2/2019	Jun	2019	10
024A	220-225	220-225 WB CL	YELLOW	8/5/2018	PAINT	024A - 220-225	225	219.9	5.1	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	WB	CL	66	6/2/2019	Jun	2019	10
024A	220-225	220-225 EB LL	WHITE	8/5/2018	PAINT	024A - 220-225	219.9	225	5.1	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	LL	103	6/2/2019	Jun	2019	10
024A	220-225	220-225 EB RE	WHITE	8/5/2018	PAINT	024A - 220-225	219.9	225	5.1	5	BITUMINOUS	PAINT	MOUNTAINOUS	LOW	EB	REL	138	6/2/2019	Jun	2019	10

Figure 7. Data distribution in the DSS file, section 1: database.

All eight measurements – over 30K of miles data – were exhaustively mined for errors for the five different regions. These include, but not limited to, materials type definitions, materials install date, age information, missing data (both age and retroreflectivity), etc. However, the data complemented by CDOT (not measured by this research) might still have errors and therefore, as seen in the Results and Discussion section of this report, the calculated age of a giving strip materials may be inaccurate.

Section 2 of the DSS file (dynamic graphical analysis tool, called **Time Chart**) was designed to see, and inspect visually the retroreflectivity data mile point by mile point. With this tool, the user can use a series of hierarchical filters to select the data to inspect by AADT → Surface → Material → Terrain → Line Color → Direction → Line Type → Road Name. In addition, the specific measuring year(s), and measuring month(s) can also be selected in the analysis if desire. Figure 8 shows how the data looks in this section for Region 5. These data was filtered the following manner: low AADT, Bituminous surface, mountainous terrain, and white line color. The tool section also indicates the region number, the total number of miles satisfying the selection criteria, the total number of roads satisfying the filtered criteria, and the total number of sections.

Section 3 of the DSS or Age Chart is also a dynamical graphical analysis tool that "stich" together all the data as a function of age, with a given set of filter conditions, to determine the performance life curve for such conditions of the strip material. Figure 9 shows the life cycle curve for the same filtering conditions used in Figure 8. Three curves are plotted together, the maximum retroreflectivity measurement in red (maximum dispersion of all the data), the minimum retroreflectivity data in blue (minimum dispersion), and the average value in grey. In this curve, the user will see the retroreflectivity measured as a function of time (in months).

The last Tab in this DSS file, is a simple general filter pivot table to get general information of the region. For example, Figure 10 shows relevant statistics achieved by this research for Region 5, such as total miles measured, number of roads and sections surveyed, distribution of materials, etc.

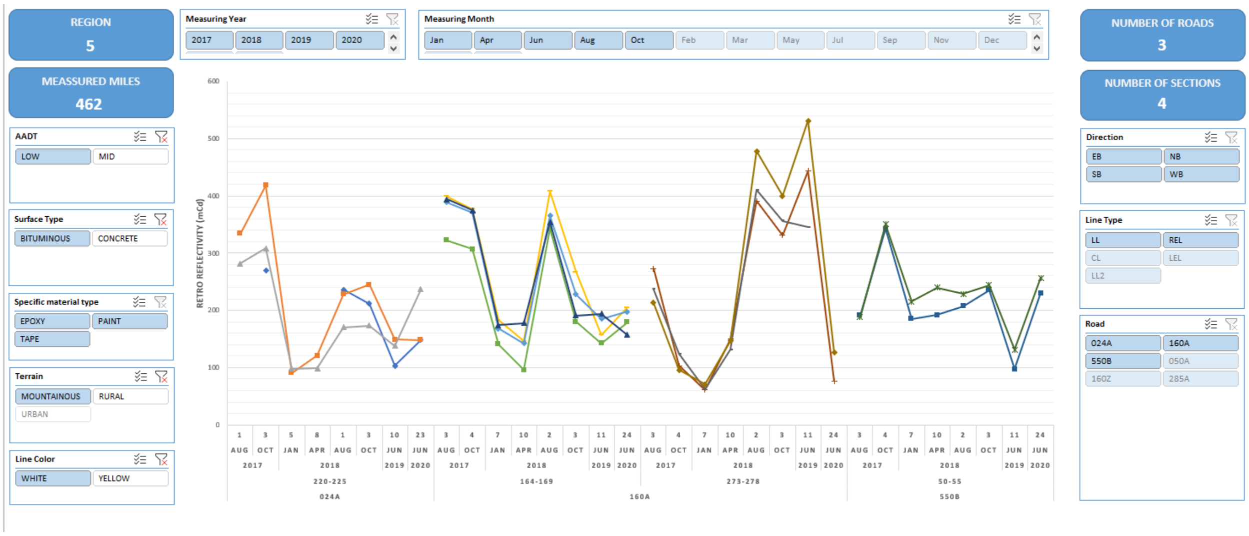

Figure 8. Section 2 of the DSS file for Region 5 showing four sections and three roads satisfying the AADT, Surface, Terrain, and Line color criteria used (filtered). The vertical axis shows the retroreflectivity measured and in the horizontal axis the age (top row), date of measurement (middle row), section and road name (two bottoms rows) are shown.

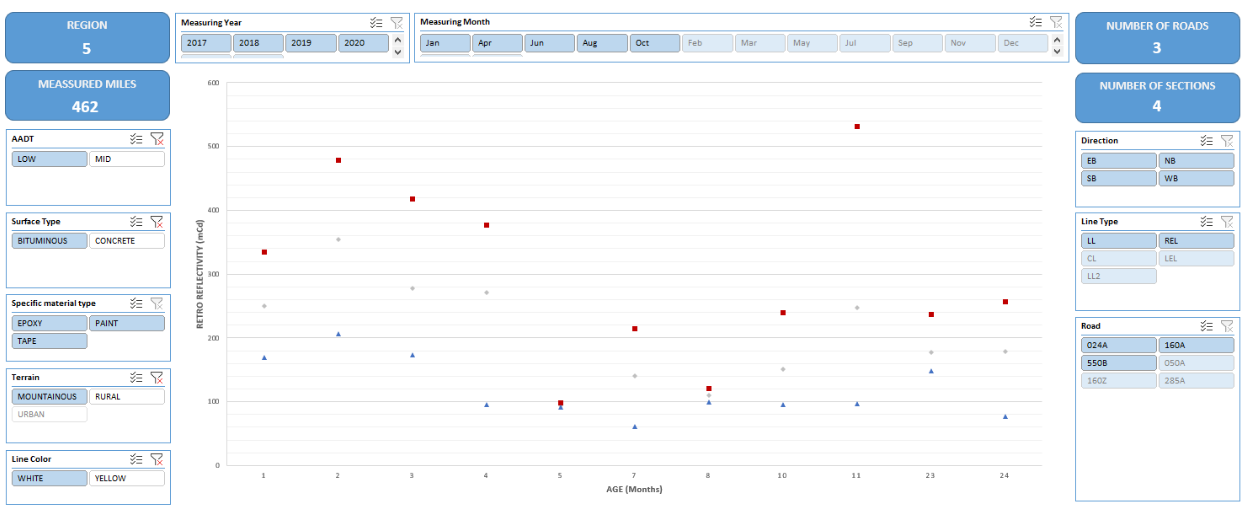

Figure 9. Life cycle curve (age) for the same conditions used in Figure 8.

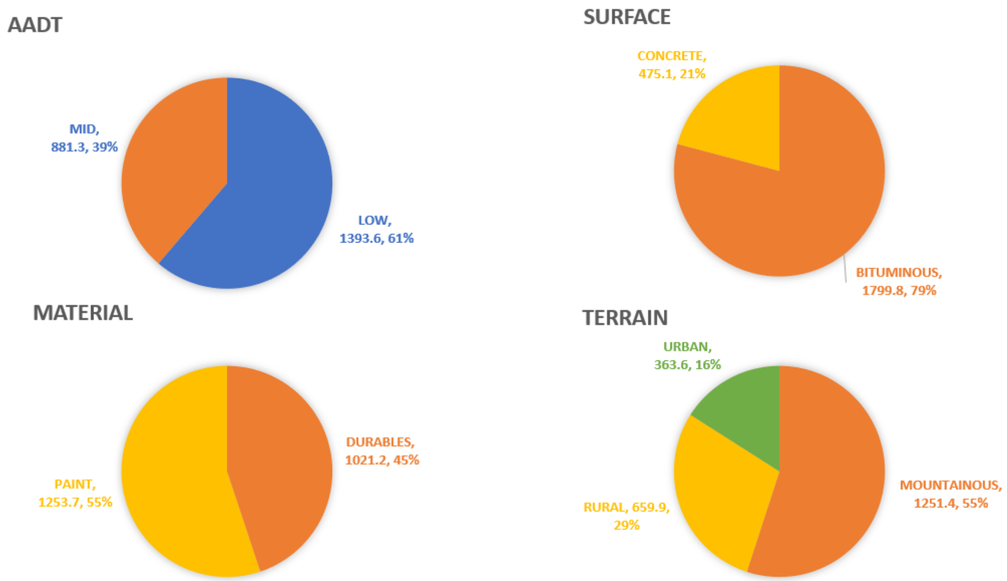

Figure 10. General statistic information for Region five for a total of 2275 miles, in six roads with 14 sections.

RESULTS AND DISCUSSION

Laboratory Results

As mentioned in the experimental approach and data analysis section; physical testing of unaged and accelerated aged samples were performed to understand degradation behavior of durables-based striping materials. UV durability versus color results are tabulated in Table B, as it can be seen, yellowing (+b component) of the samples materials started to increase rapidly in samples exposed to UV radiation for as little as 100 hours. Other parameters, such as visible light reflection (Rvis) remained almost unaffected during the time frame of the measurement. It is well known that there is no perfect correlation between QUV and real life durability, however, a good rule of thumb is that for each hour of QUV exposure is equivalent to one day real exposure.

Table B. Durability versus color and visible light reflection.

Sample ID	UV Exposure (hrs)	L*	a*	b*	Rvis
EP01	0h	93.14	-1.84	1.47	83.29
EP02	0h	94.19	-1.87	1.28	85.71
EP03	0h	94.81	-1.86	1.2	87.17
EP04	0h	94.96	-1.76	1.41	87.51
EP06	0h	93.14	-1.84	1.47	83.29
EP07	0h	93.51	-1,86	1.2	84,13
EP08	0h	94.61	-2.07	1.67	86.69
EP05	0h	93.87	-1.95	1.56	84.97
EP11	0h	93.58	-1.92	1.29	94.3
EP13	0h	94.13	-1.82	1.1	85.57
EP09	0h	94.64	-2.16	1.94	86.8
EP10	0h	94.25	-2.07	1.59	85.86
EP12	0h	91.69	-1.84	1.33	80.02
Average Value		**93.89**	**-1.92**	**1.42**	**85.93**
EP06	100h	91.98	-1.53	5.08	80.65
EP07	100h	93.14	-1.64	3.54	83.28
EP08	100h	94.41	-1.92	3.5	86.24
Average Value		**93.18**	**-1.70**	**4.04**	**83.39**
EP05	200h	92.36	-1.62	6.42	81.51
EP11	200h	91.27	-1.69	5.35	79.07
EP13	200h	92.27	-1.35	6.46	81.66
Average Value		**91.97**	**-1.55**	**6.08**	**80.75**
EP09	300h	93.72	-1.3	7	85.01
EP10	300h	94.15	-1.79	4.83	85.85
EP12	300h	93.01	-1.38	6.68	83.35
Average Value		**93.63**	**-1.49**	**6.17**	**84.74**

In Table C, the QUV durability is presented as a function of wear index after 1000 cycles of abrasion for the same samples presented in Table B. From the data, the reader can observe that a fast wear abrasion start to occur after samples have being exposed to UV radiation for more than 200 hours. This is a very aggressive laboratory test, and could explain why we observed different life-cycle curves in different lines with the same age in the field.

Table C. QUV durability exposure versus wear resistance.

Sample ID	UV Exposure (hrs)	Wear Index (1000 cycles)
EP01	0h	126
EP02	0h	184
EP03	0h	180
EP04	0h	203
Average Value		**173**
EP06	100h	200
EP07	100h	175
EP08	100h	194
Average Value		**190**
EP05	200h	629
EP11	200h	710
EP13	200h	561
Average Value		**633**
EP09	300h	898
EP10	300h	765
EP12	300h	571
Average Value		**745**

Field Results

During these three years of data collection, a total of 27,288 miles were surveyed in 66 roads and in 120 different road sections. The number of miles, roads and road sections surveyed were selected by CDOT's managers, as well as, the frequency and number of measurements per year. In addition, the relative ratio of road features, such as material type ratios (ex. Durables/ paints, etc.), were also selected by CDOT managers.

In this section, some correlation between strip age and retroreflectivity will be presented and discussed. In addition, general and specific observations, and anomalies will be mentioned and discussed as appropriate.

Region 1.

In Region 1, 13,313 miles were surveyed in about 23 roads and 55 sections. The roads attributes such as AADT, Surface, Materials and Terrain type surveyed for this region is presented in Figure 11. In this Region, the relative percentages of roads with MID/HIGH and HIGH/VERY HIGH AADT as well PAINT as a material type are too small to make statistical significant conclusion. Therefore, these sections will be omitted in this discussion.

Figure 11. Road feature surveyed in Region 1 for AADT, Surface Type, Material Type and Terrain. In each inserted figure, the callout indicates feature, total mileage, and percentage.

If we use the DSS file created for this region and we select the following conditions in the "age Chart" section 3 of this DSS file: AADT → SURFACE → MATERIAL → TERRAIN → COLOR = High → Bituminous → Epoxy → Urban → White; the following performance curve is found for all the roads, and sections meeting the above conditions (see Figure 12). In this curve the retroreflectivity goes from 350 mCd at 4 monthsof age to a minimum retroreflectivity of 125 mCd at month 26. From month 26 to 41 the retroreflectivity data remains mainly constant if the data for month 37 is neglected. The jump of the reflection data from 150 to 350 in months 41 to 45 suggest that the striping data reported to this research is not accurate.

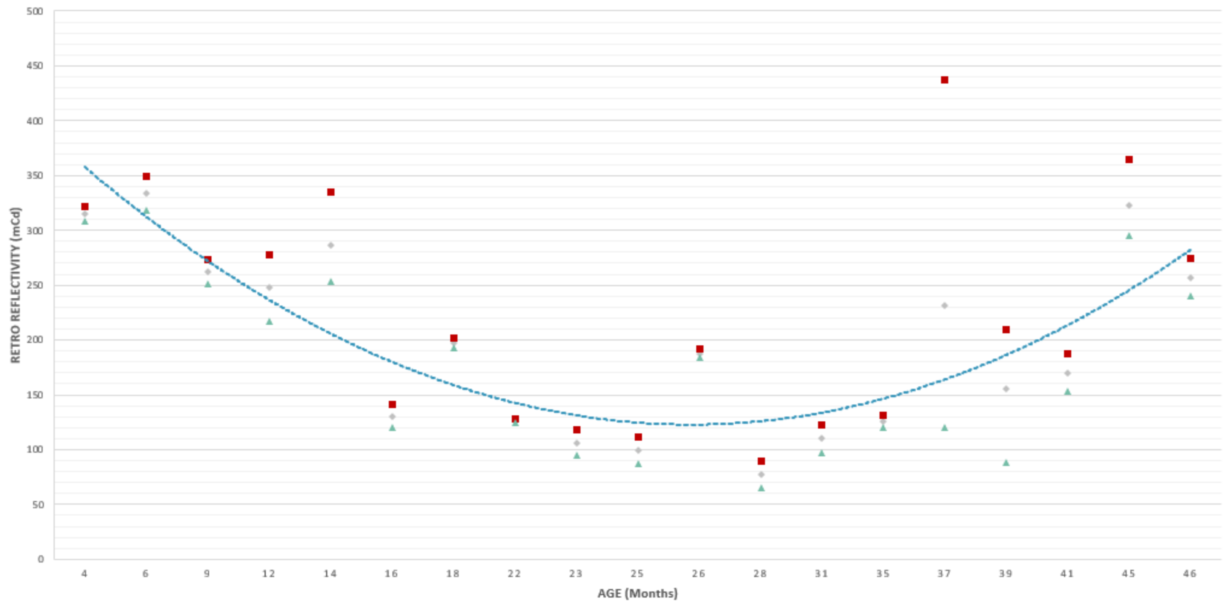

Figure 12. Performance curve for Region 1 when the following criteria is selected; High → Bituminous → Epoxy → Urban → White. This selection creates a performance curve for line type REL in Roads 006G, 070A, 270A, and 470A.

If we further inspect the age chart in Figure 12, and narrow the selection down to road level, we can see the following: (a) Road 006G decay in retroreflectivity occurs at about month 16 and the curve remains practically unchanged to month 39 (see Figure 13), (b) the curve formed for road 470A has not enough information (enough data) to conclude anything, and therefore it should be removed from the analysis (see Figure 14), (c) Road 270A shown in Figure 15, shows an inverted curve suggesting that the age data provided is not accurate, and (d) road 070A performance curve is depicted in Figure 16, where a minimum occur around month 29 and if last data at week 45 is neglected, it appears that the performance curve remains constant. This suggest that month age (45 months) is not correct. If we look at the same sets of conditions used in Figure 16 but this time using the DSS section 2 or Time Chart, we can see that the age reported for June of 2019 cannot be 45 months but should be 0 or 1 month old (Figure 17.)

Because the data collected for Region 1 is about 99% Durable Materials, we just need to change the criteria used before from Epoxy to Tape. Figure 18 shows the performance curve obtained for this selection: HIGH → BITUMINOUS → TAPE → URBAN → WHITE, four roads with five sections fulfill the filter used. The graph shows a minimum at 28 months and then an almost constant retroreflectivity to month 46.

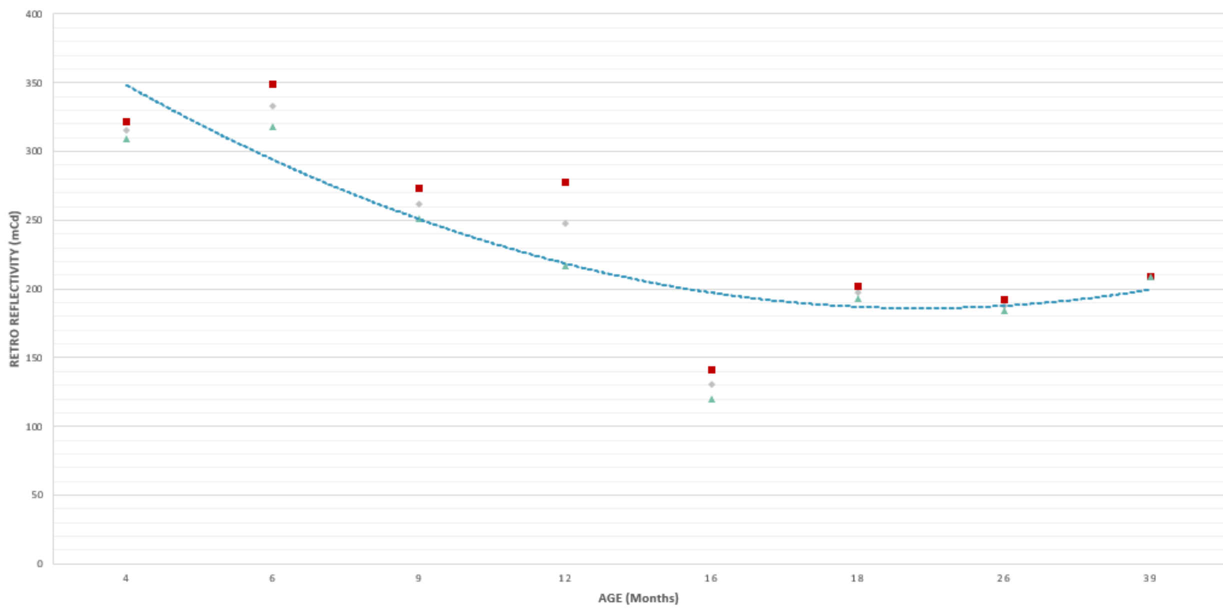

Figure 13. Performance curve for road 006G when the following criteria is selected; High → Bituminous → Epoxy → Urban → White.

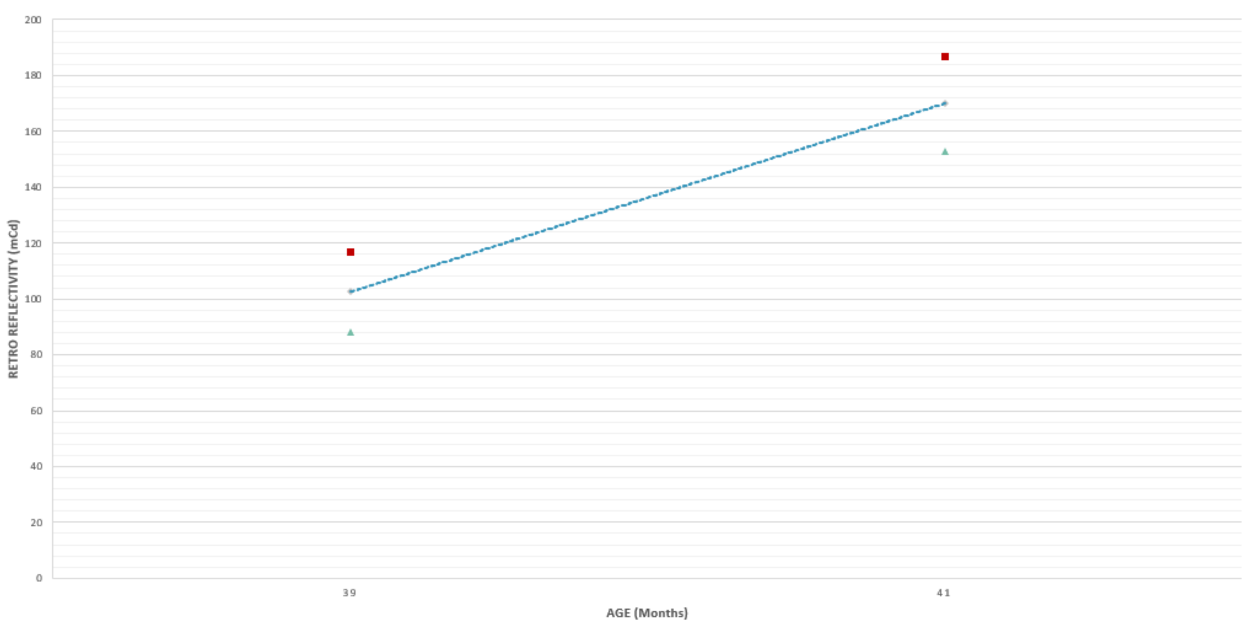

Figure 14. Performance curve for road 470A when the following criteria is selected; High → Bituminous → Epoxy → Urban → White.

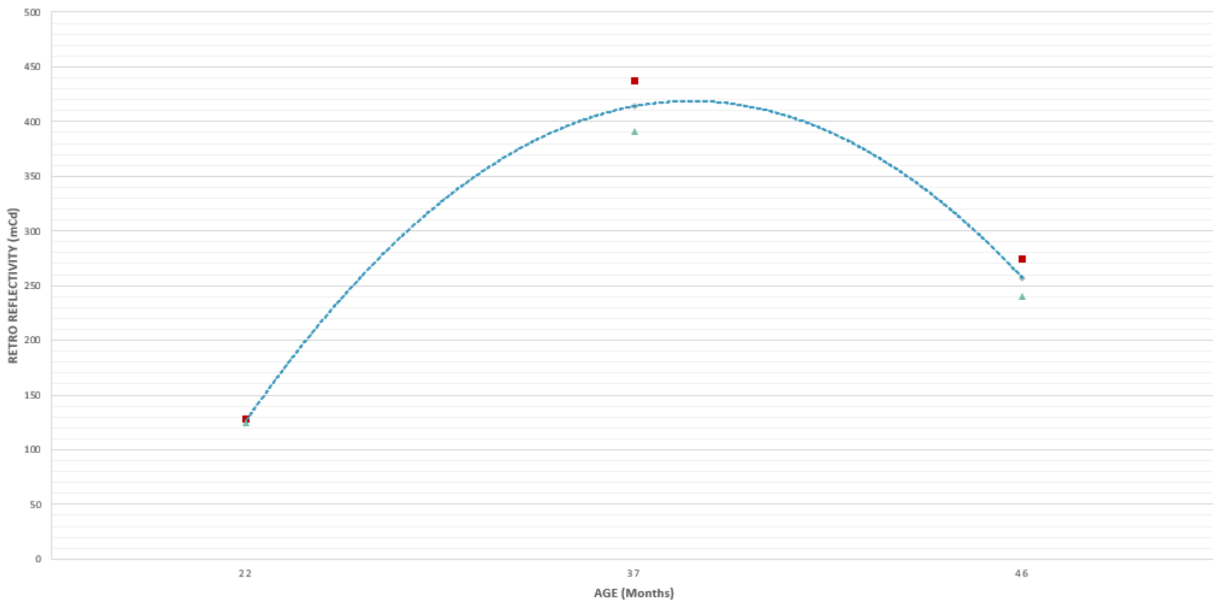

Figure 15. Performance curve for road 270A when the following criteria is selected; High → Bituminous → Epoxy → Urban → White.

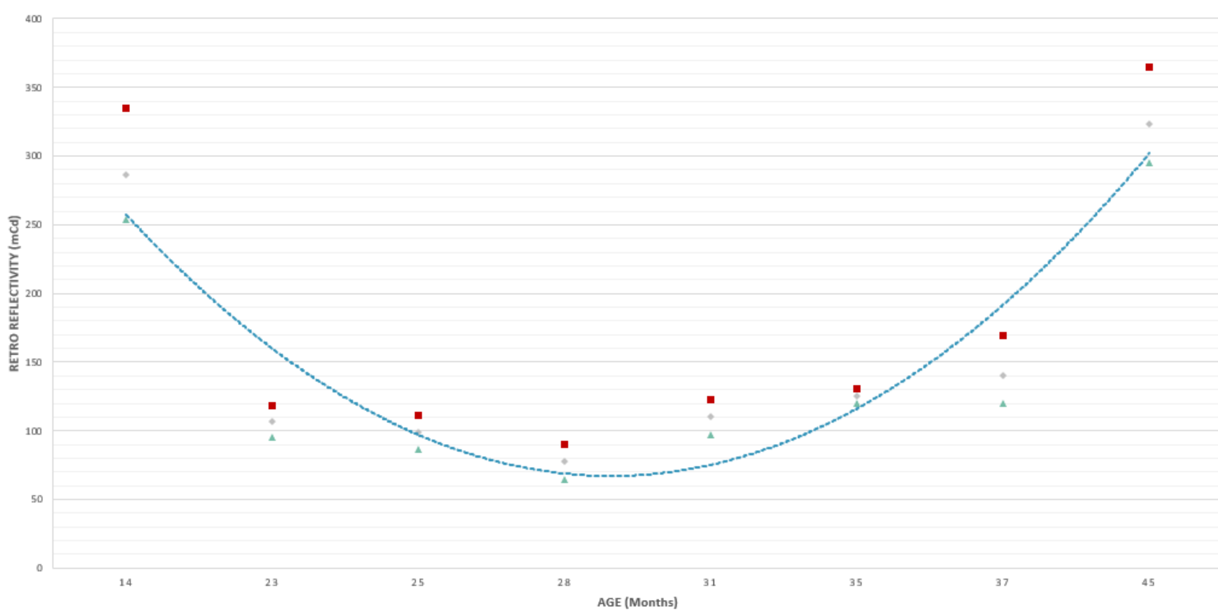

Figure 16. Performance curve for road 070A when the following criteria is selected; High → Bituminous → Epoxy → Urban → White

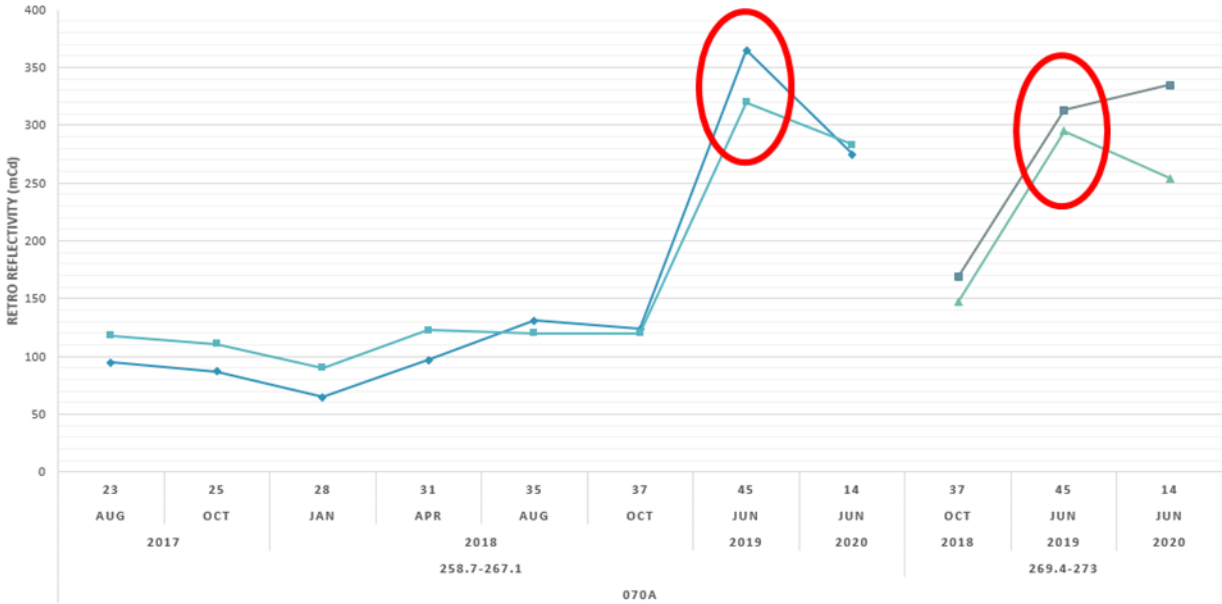

Figure 17 Time chart for road 070A indicates that the age data reported for June of 2019 (circled) is not correct.

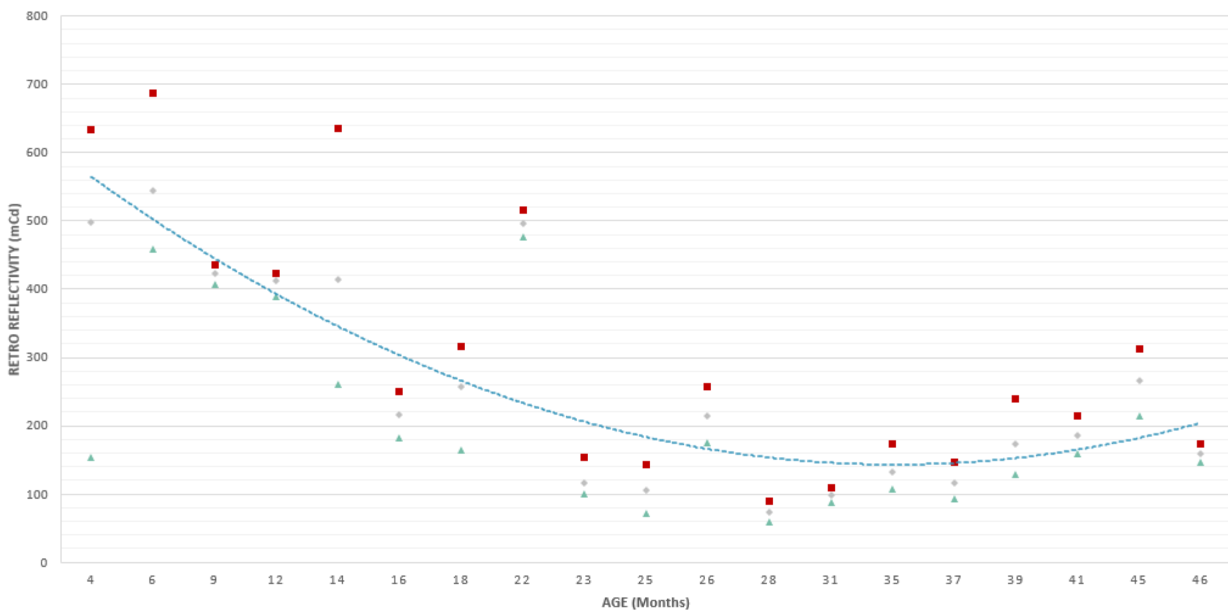

Figure 18. Performance curve obtained when the selection HIGH → BITUMINOUS → TAPE → URBAN → WHITE is applied to Region 1.

Region 2

In Region 2, a total of 7,083 miles were measured. These miles were distributed among 12 roads and 18 road sections. The road attributes, as well as, their distribution in the data collected are presented in Figure 19 below. In this Region only 4% of the data collected was in concrete surfaces and all (100%) material types surveyed were on DURABLE materials.

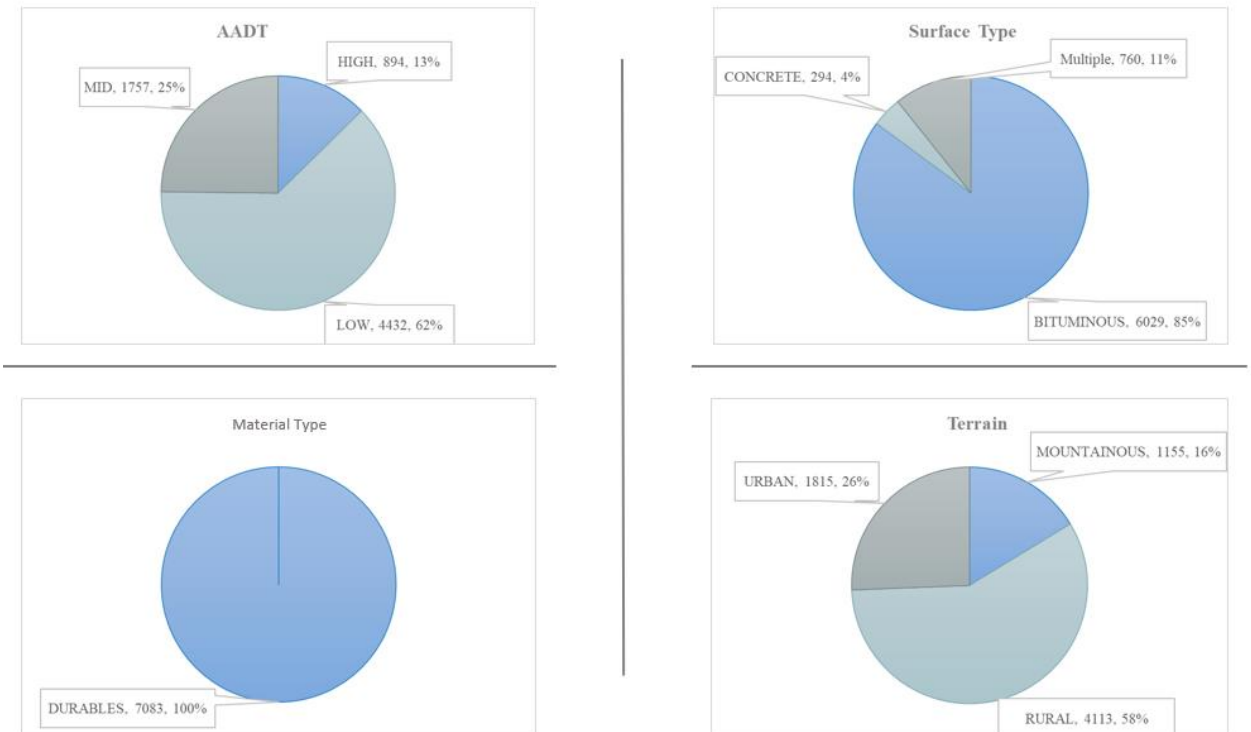

Figure 19. Road feature surveyed in Region 1 for AADT, Surface Type, Material Type and Terrain. In each inserted figure, the callout indicates feature, total mileage, and percentage.

Figure 20 shows the performance curve obtained for HIGH AADT → CONCRETE → DURABLES (both Epoxy and Tape are included) → URBAN → WHITE selections. In the Figure, it can be seen that the retroreflectivity drops abruptly after only six month of age, then remained relatively constant at 250mCd until month 20, and then further decreased below 200mCd at month 33. If we further filter the data to only epoxy, the same behavior noted in Figure 20 is observed, however, the data is less dispersed than the data showed in Figure 20. This drop could be attributed to weather conditions at the time of the measurement, but that information was not recorded (see Figure 21). If indeed the data at month 6 was affected by weather conditions, and is removed from the analysis, then a much smoother performance curve would have been observed until month 19th, as indicated by the red arrow in Figure 21. The dispersability of the data in Figure 20, is attributed that the filter condition used (HIGH AADT → CONCRETE → DURABLES → URBAN → WHITE, generated a performance curve for four types of lines, named LL, LL2, LL3 and REL, and these lines will wear differently. Figure 22 shows the behavior of LL, LL2, and LL3 of this road 025A, section 146.1-149.3.

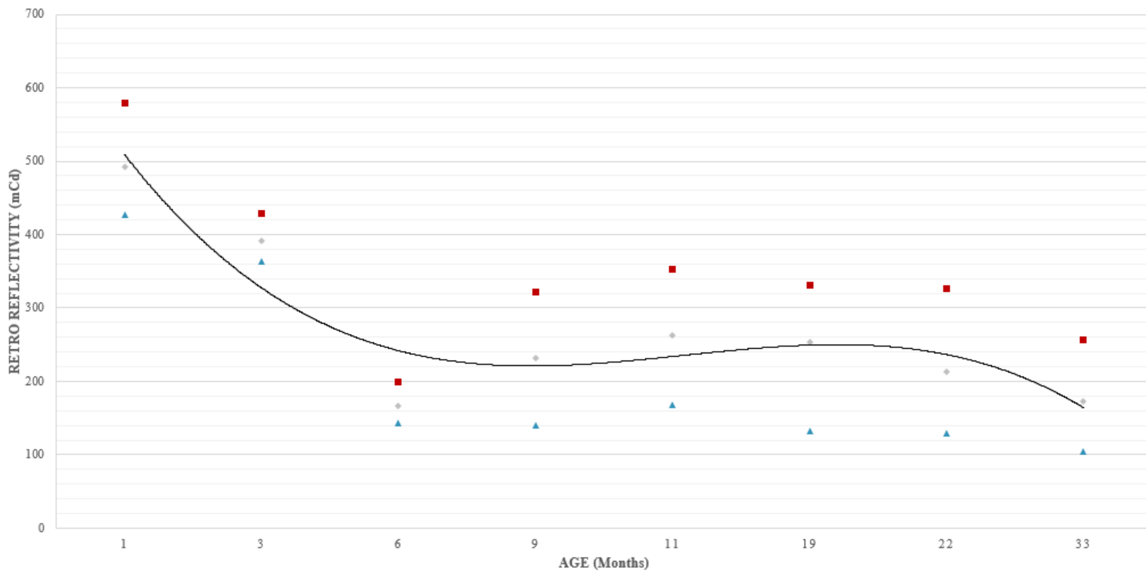

Figure 20. Performance curve obtained when the selection HIGH → CONCRETE → DURABLE (BOTH Tape and Epoxy) → URBAN → WHITE is applied to Region 2.

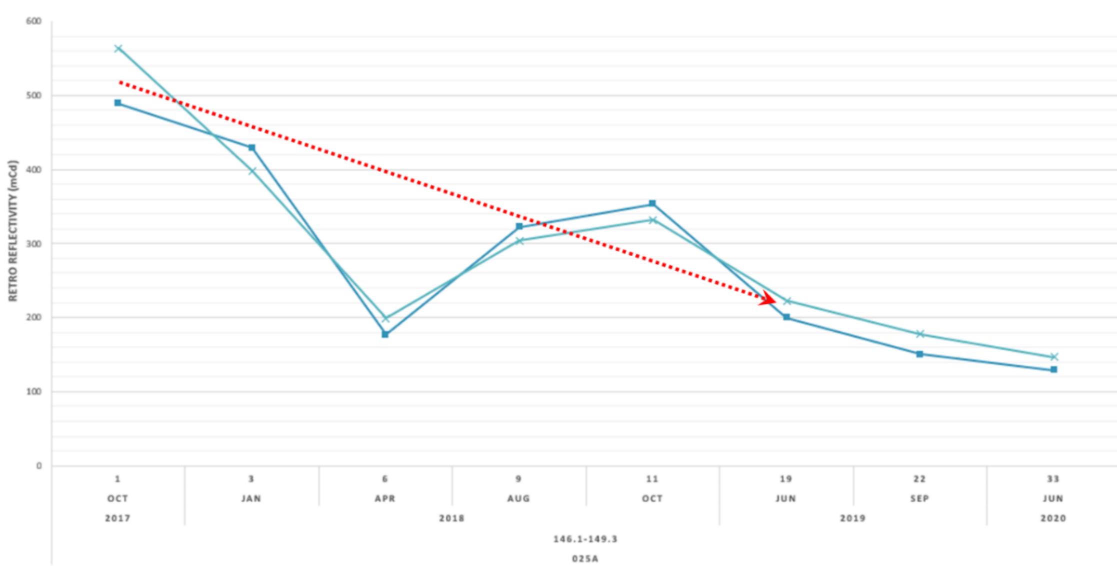

Figure 21. Performance curve obtained when the selection HIGH → CONCRETE → EPOXY → URBAN → WHITE is applied to Region 2.

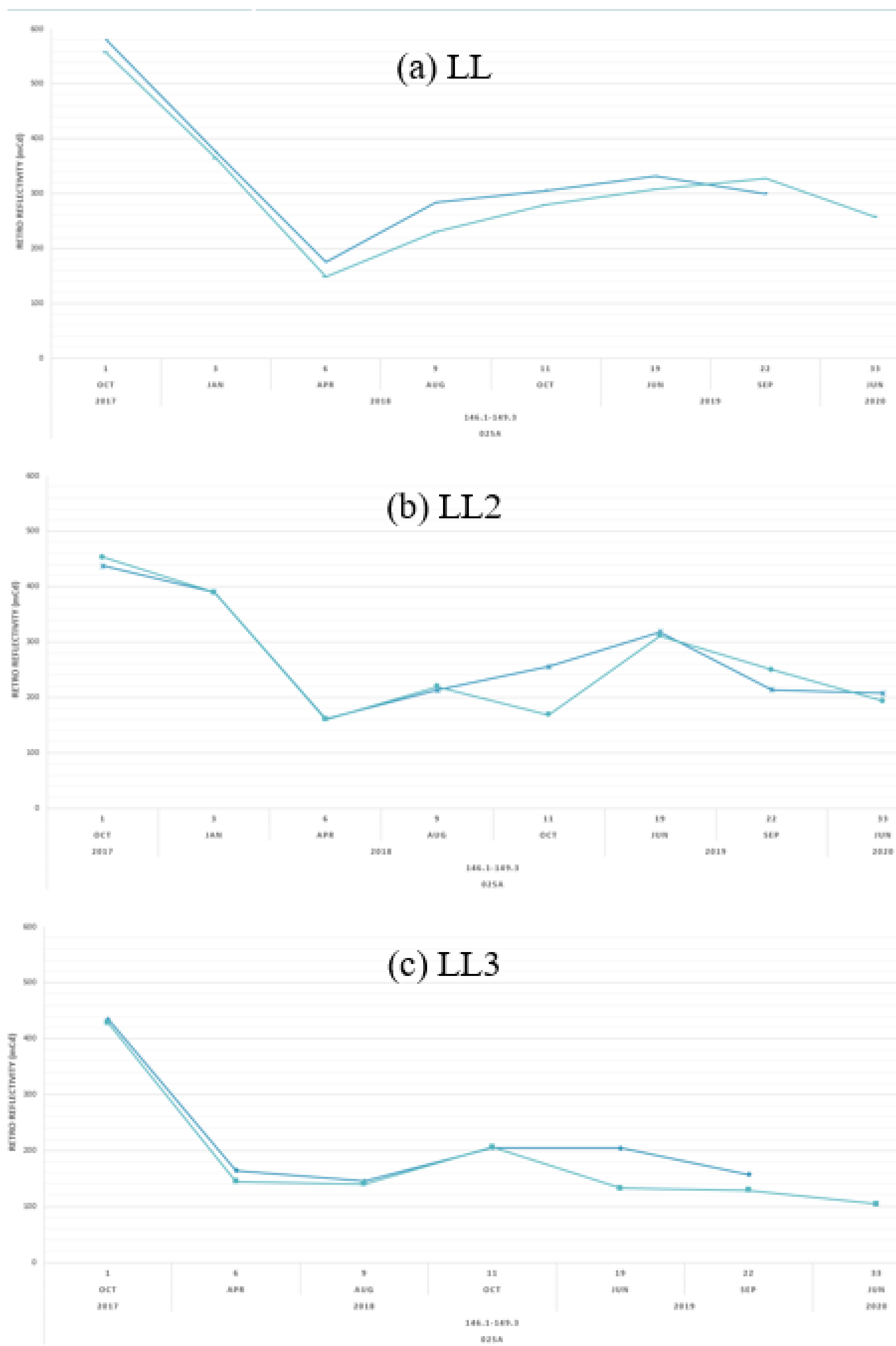

Figure 22. Lines (a) LL, (b) LL2, and (c) LL3 of road 025A showing the different wear effect in retroreflectivity.

Region 3.

A total of 1589 miles were surveyed in 12 roads and 17 sections. The characteristics of the roads surveyed are shown in Figure 23. In this region, only 1% of the roads surveyed are concrete, and the results obtained on concrete surfaces might not be statistically significant.

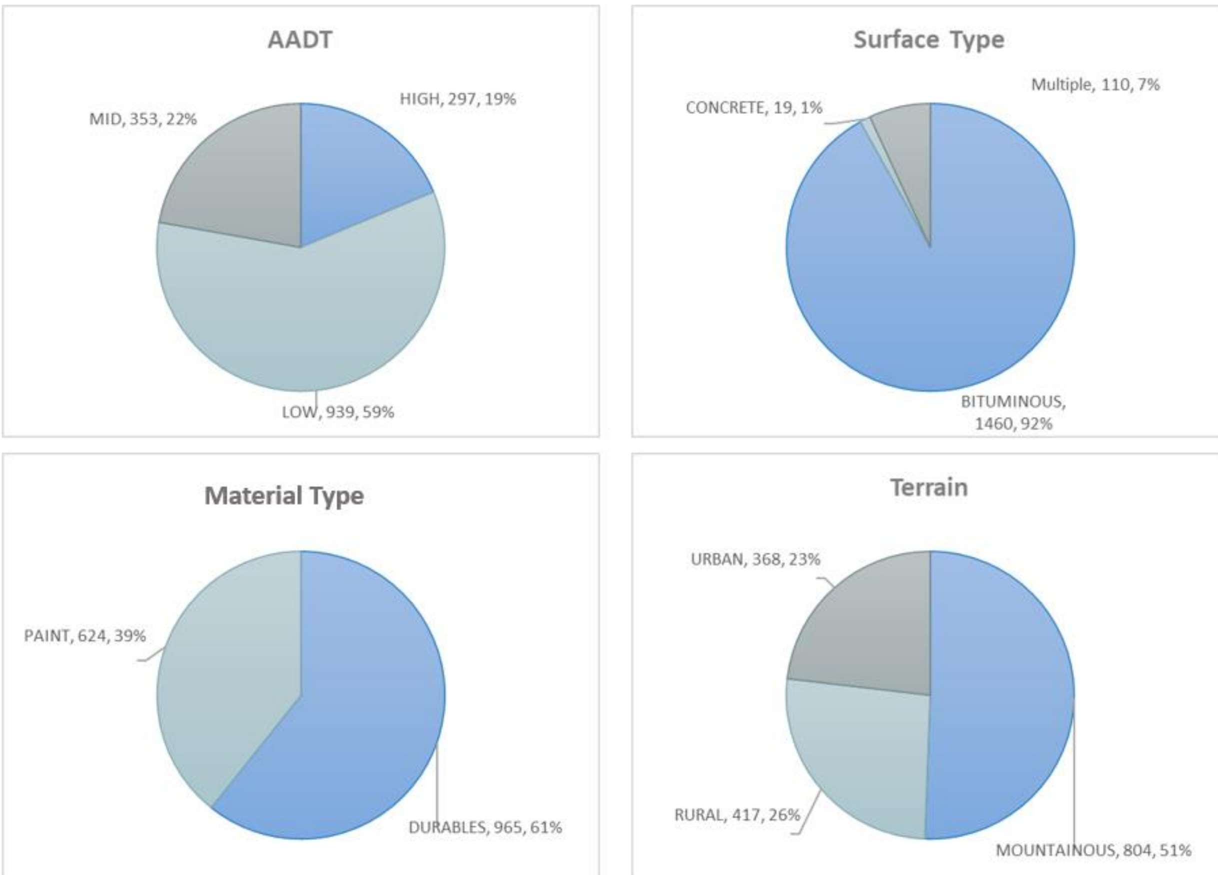

Figure 23. Road features surveyed in Region 3 for AADT, Surface Type, Material Type and Terrain. In each inserted figure, the callout indicates feature, total mileage measured, and relative percentage.

Figure 24 shows the performance curve found in Region 3 when the following selection criteria is chosen: LOW → BITUMINOUS → PAINT → RURAL → WHITE. The performance curve shows a faster decay in retroreflection from 400 mCd to 200mCd in the 14 first months, and then a practically constant average reflection of 200mCd to month 27. The performance curve generated is for 2 roads (050A and 125A) for two types of lines, LL and REL. Figure 25 shows the performance curve for line (a) LL and (b) REL for the same set of conditions used before.

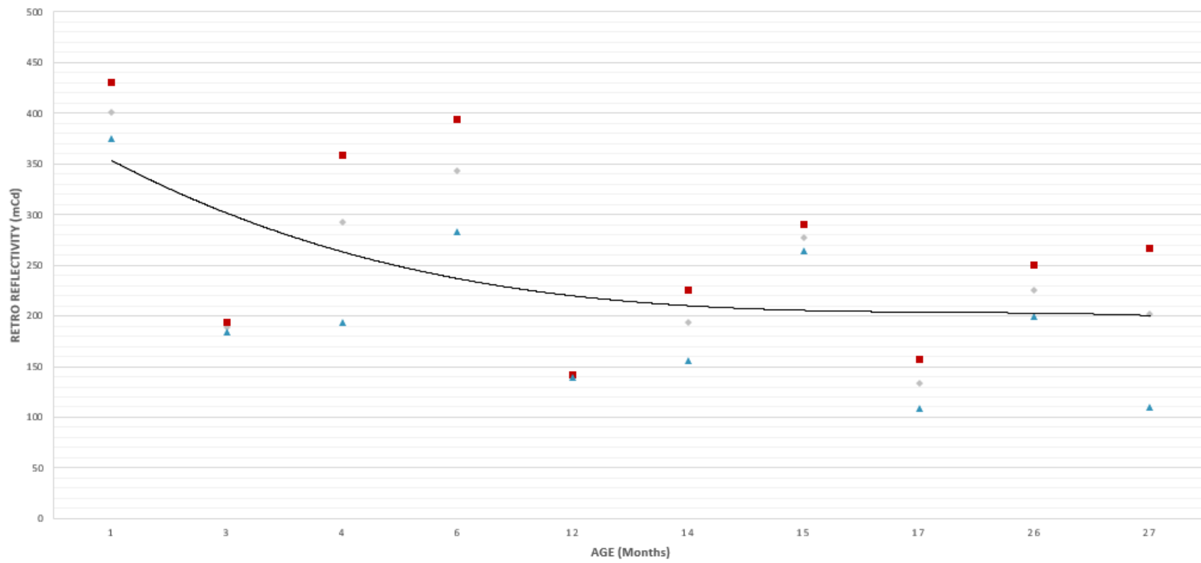

Figure 24. Performance curve obtained in Region 3 when the following selection is used: : LOW → BITUMINOUS → PAINT → RURAL → WHITE

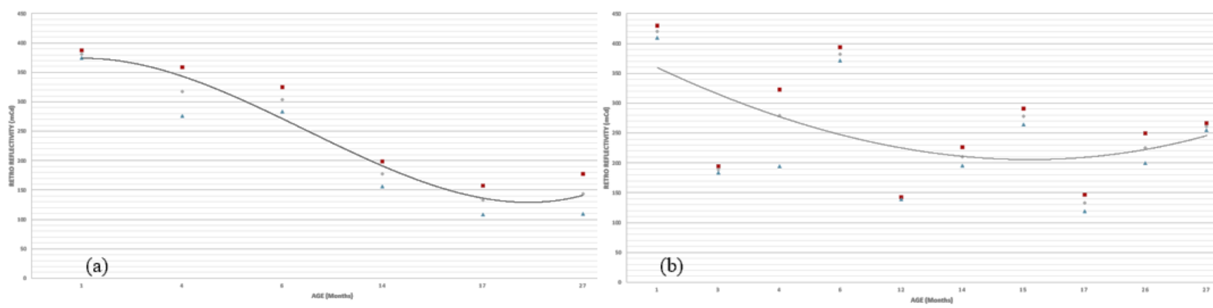

Figure 25. Performance curve obtained in Region 3 when the following selection is used: : LOW → BITUMINOUS → PAINT → RURAL → WHIT. (a) is the curve obtained for LL lines and (b) for REL.

Region 4.

In Region 4, 3028 miles were surveyed on 13 roads, and 16 sections. Figure 26 shows the distribution of these miles in terms of AADT, Surface Type, Materials Type, and Terrain. Figure 27 shows the performance curve obtained when the following criteria is selected: High AADT → Multiple → Durables (Both epoxy and Tape) → RURAL → WHITE. The graph in Figure 27 suggests a decay trend of the retroreflectivity data but the dispersion is too large to assume that this is correct. Further refinement of the data from DURABLES to EPOXY (Figure 28) and from DURABLES to TAPES (Figure 29), clearly shows that these two DURABLE Materials aged in a very different manner in this region.

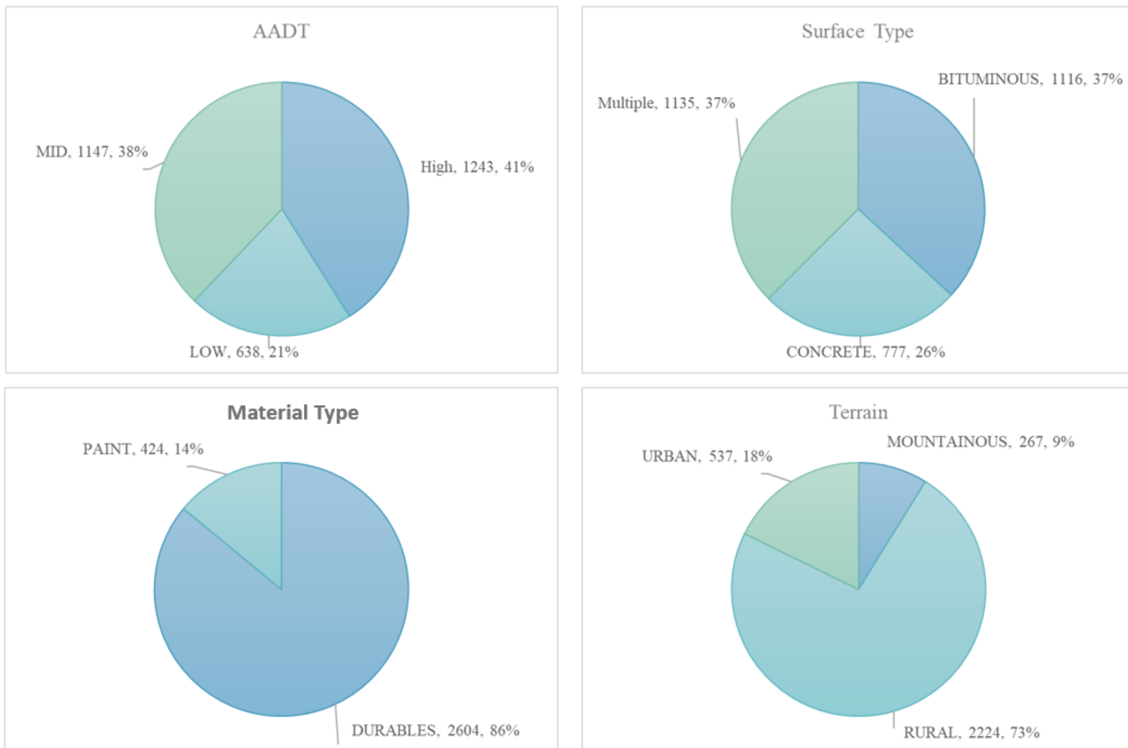

Figure 26. Road features surveyed in Region 4 for AADT, Surface Type, Material Type and Terrain.

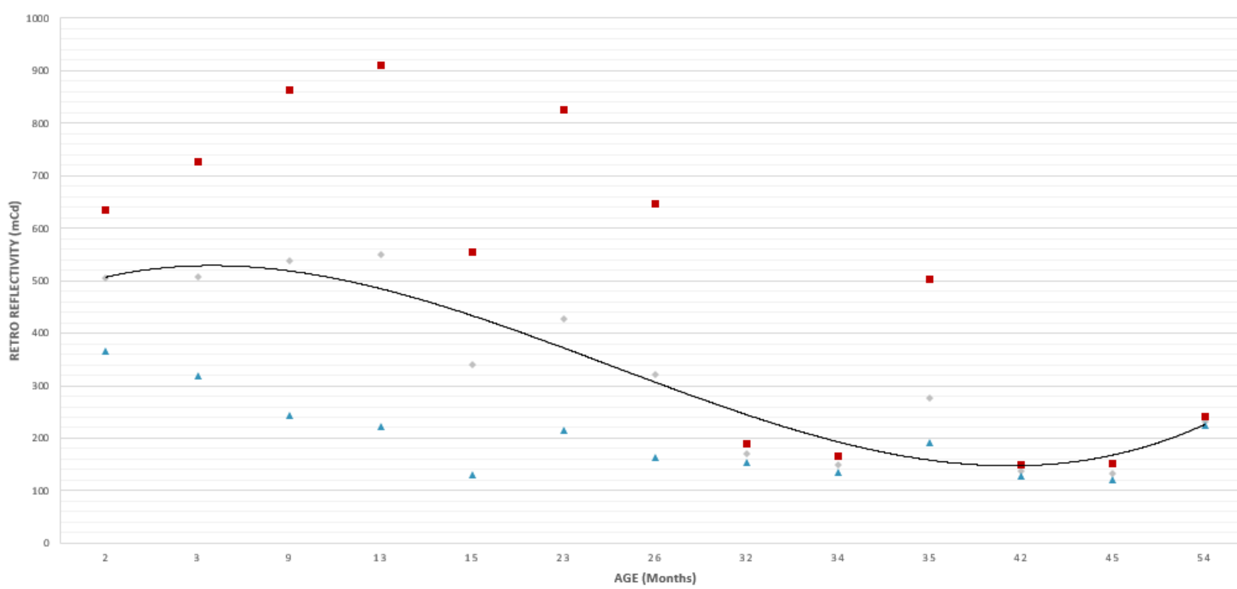

Figure 27. Performance curve obtained in Region 4 when the following selection criteria is used: : HIGH → MULTIPLE → DURABLES → RURAL → WHITE.

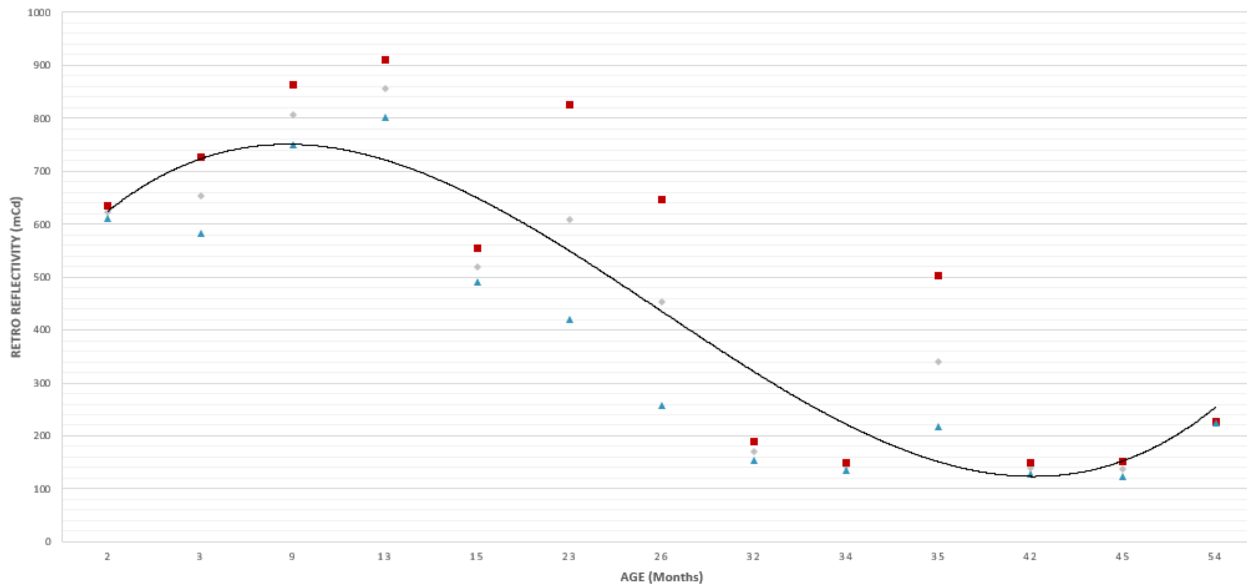

Figure 28.Further refinement of the selection criteria used in Figure 27, this time Durable is changed for TAPE.

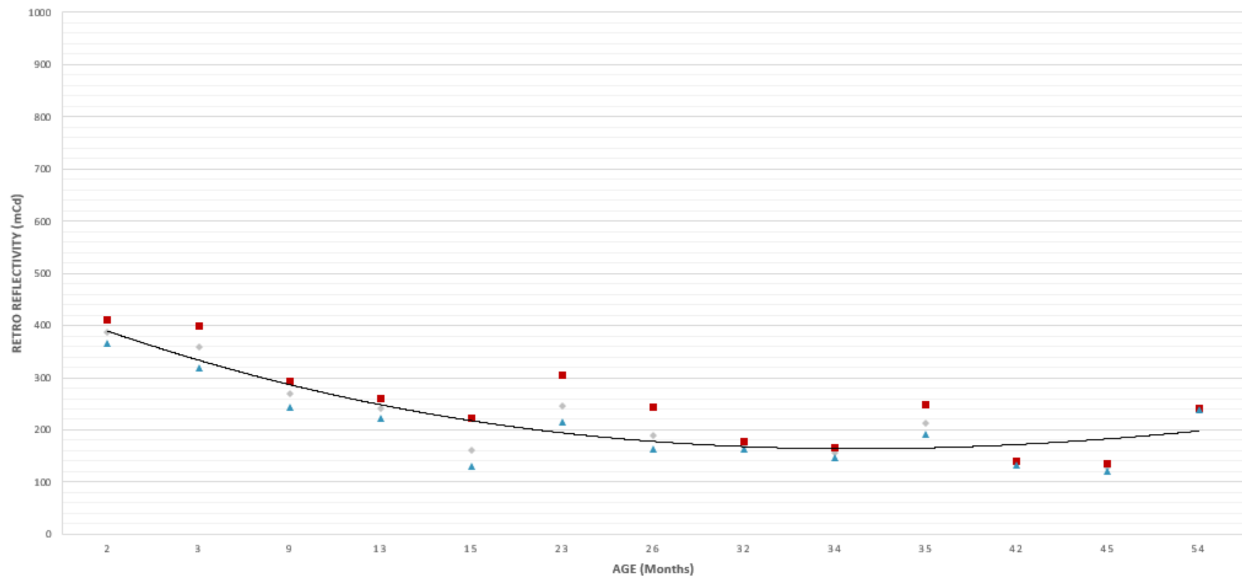

Figure 29. Further refinement of data selection shown in Figure 27, this time Durable was replaced by EPOXY.

Region 5

In this region, a total of 2,275 miles were measured on 6 roads, and 14 sections. Figure 30 shows the distribution of characteristics in this region.

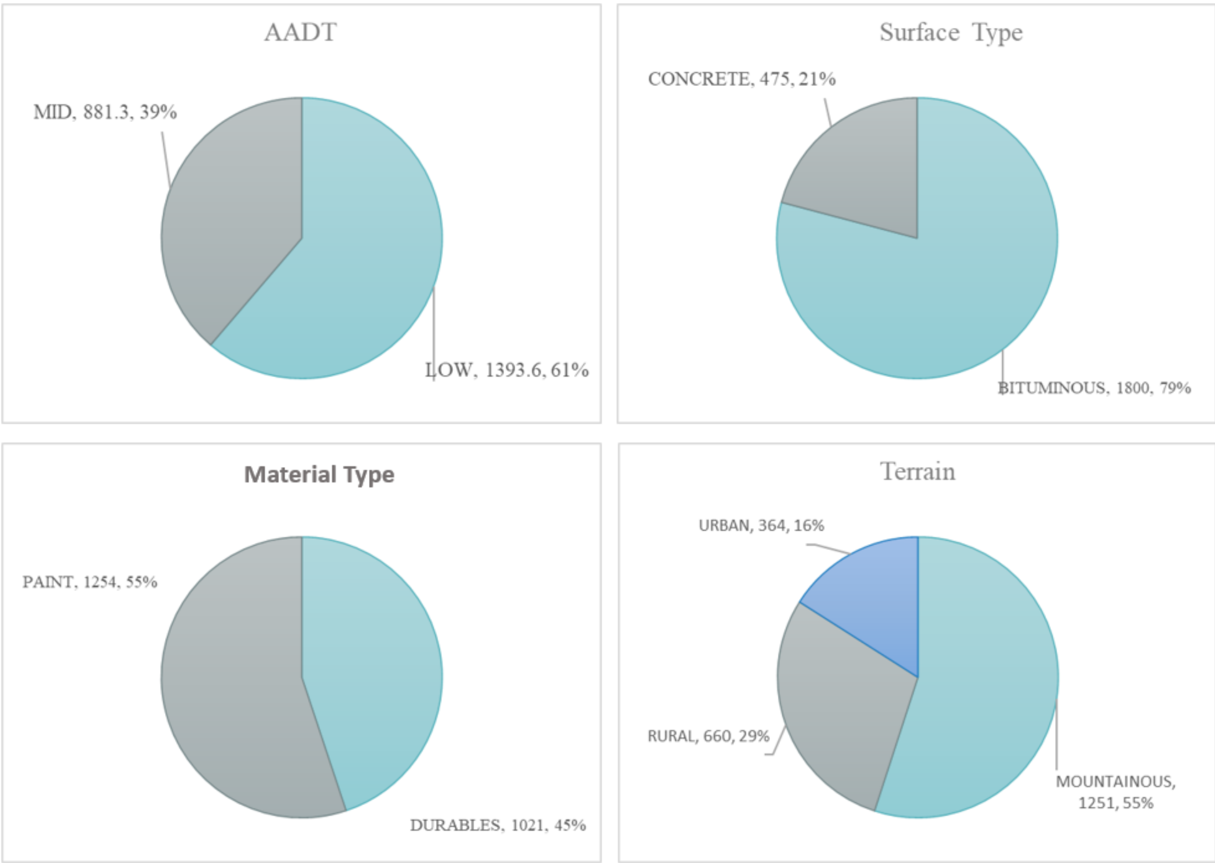

Figure 30. Road features surveyed in Region 5 for AADT, Surface Type, Material Type and Terrain.

Figure 31 shows the performance curve obtained when the following selection criteria was utilized: LOW, Bituminous, Durables (both Epoxy and Tape), Mountainous, White. This figure shows more than 200mCd dispersion for the first data set at two and three months of age. If the data is further refined for EPOXY (Figure 31) and TAPE (Figure 32), the reader will see that most of the dispersibility of the data occurred in the lines striped by EPOXY.

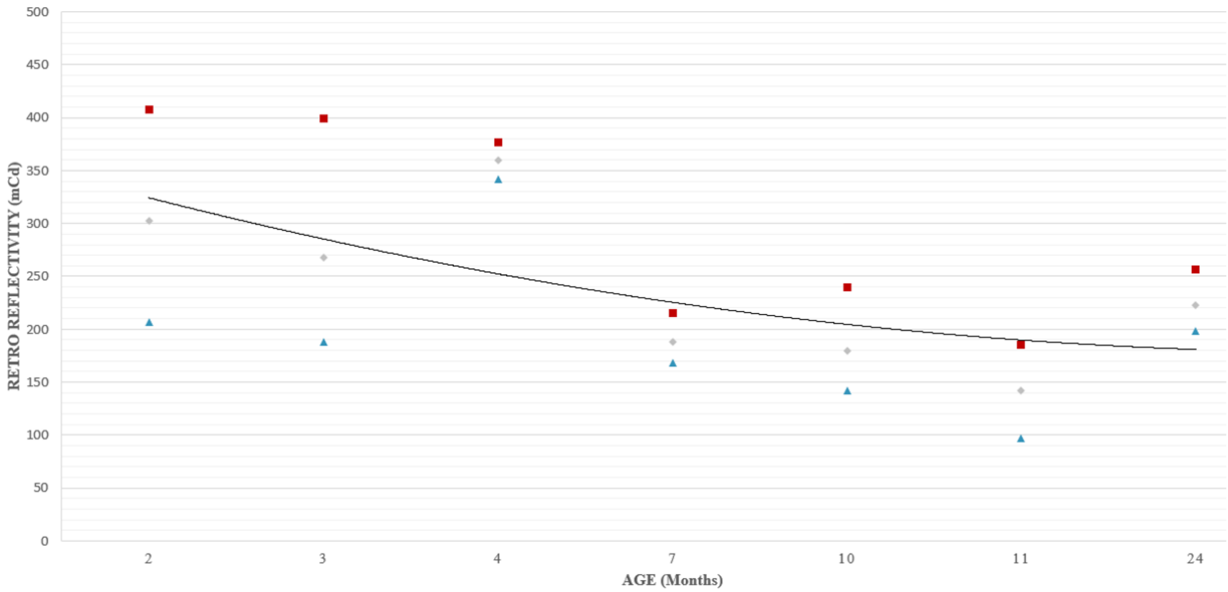

Figure 31. Performance curve obtained in Region 5 when the following criteria was used: LOW, Bituminous, Durables (both Epoxy and Tape), Mountainous, and White

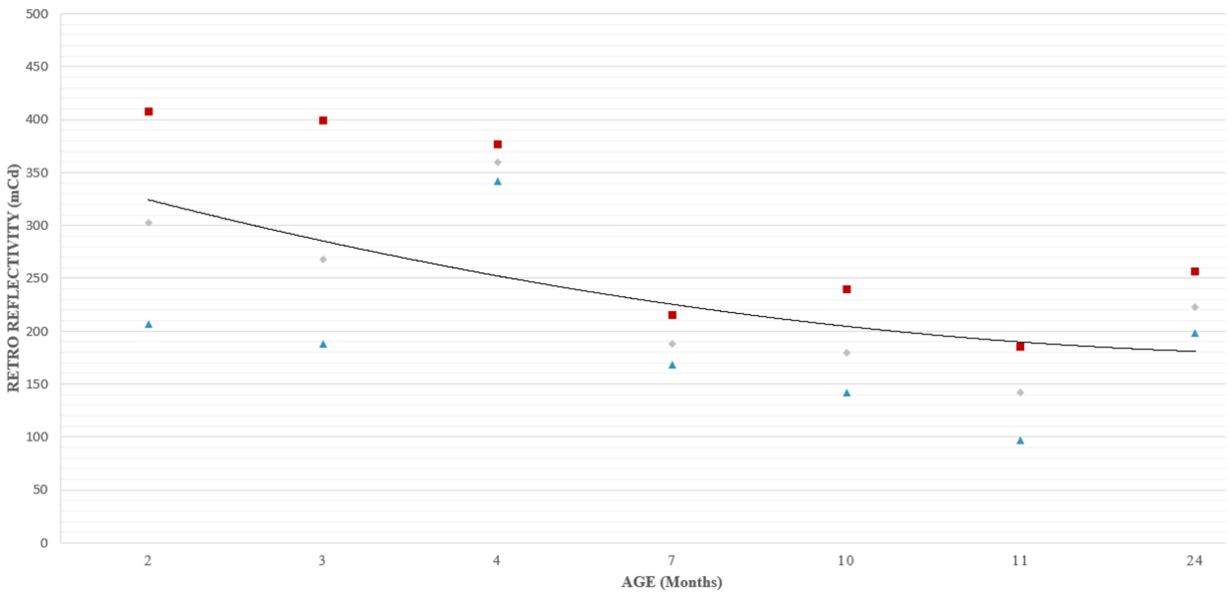

Figure 32. Performance curve obtained in Region 5 when the following criteria was used: LOW, Bituminous Epoxy, Mountainous, and White.

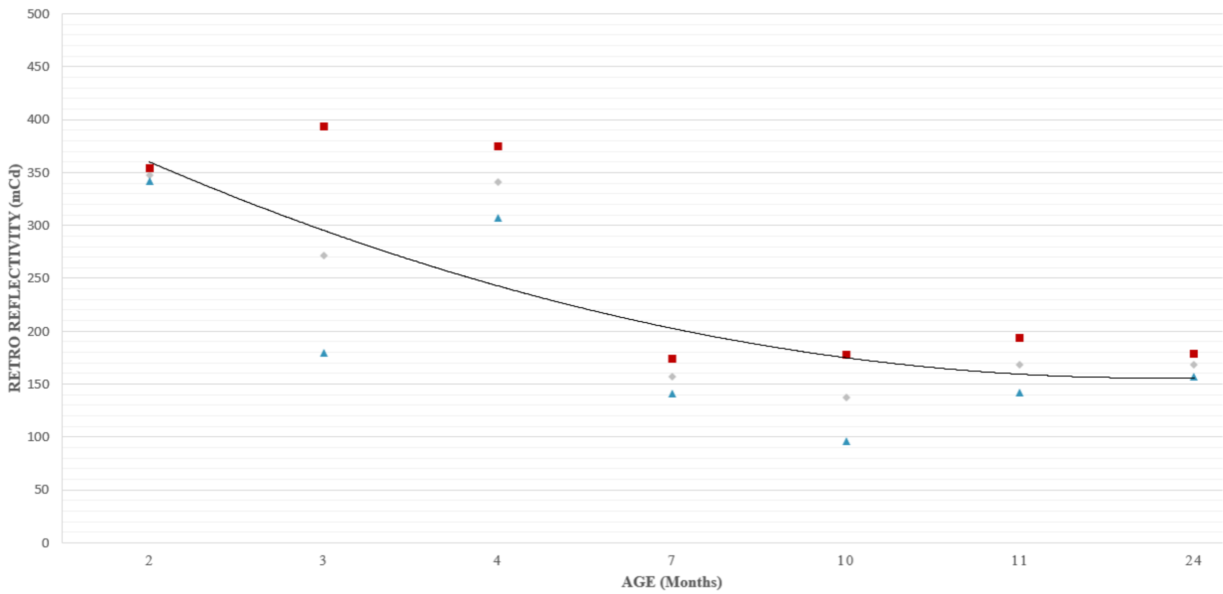

Figure 33. Performance curve obtained in Region 5 when the following criteria was used: LOW, Bituminous, Tape, Mountainous, and White.

SUMMARY

This field study was conducted over a three year period, measuring 27,288 miles on 66 roads, and 120 sections in the State of Colorado. In addition, laboratory tests were performed to further understand aging, abrasion resistance of epoxy materials as a function of time, and ultraviolet radiation.

Five DSS files were created and submitted to CDOT as the final products of this research.

Performance curves can be obtained, but careful analysis, and interpretations must be done before general conclusions can be reached. The data obtained by retroreflection shows in some instances too much dispersion, and this potential issue must be investigated further with the contractor.

Comparison of the retroreflectivity data and the striped date provided by CDOT is sometimes not accurate, and it is the recommendation of the authors of this research that further and focalized data mining sessions with the respective CDOT regional managers and this author be accomplished. Thus making the DSS files more comprehensive and robust for each region.

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ASTM. (2018). E1710. *Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer*. USA: ASTM International.