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COMPARISON OF WET REFLECTIVE ELEMENTS WITH TAPE – A PAVEMENT MARKING STUDY BASED ON FIELD MEASUREMENTS

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16. Abstract

This field-based evaluation summarizes the performance, in terms of retroreflectivity, of a number of treatments for pavement markings applied to continuous yellow and white edge lines, as well as broken white lane lines. Measurements were taken using mobile and semi-mobile setups for dry conditions and wet conditions, respectively, along a test deck installed by UDOT on I-215 during August of 2017. Wet conditions included readings from a dry state, transitioning through a continuous wetting phase until saturation, and reaching a steady state after wet recovery. Datasets were collected by a third-party contractor, using equipment and following procedures according to the applicable ASTM standards. A total of four datasets were evaluated, starting with measurements soon after installation, and ending with a dataset collected after 802 days of service. Treatments installed in the test deck included an all-weather tape (3M 380 AW tape), treatments with proprietary elements in paint and epoxy (3M elements Series 50), and Utah blends also in paint and epoxy. The retroreflectivity of the all-weather treatment indicated superior performance and durability both in dry and wet conditions, and across all line types, as expected. After 460 days in service, all treatments remained well above 100 mcd/m2 in dry conditions, but the wet recovery retroreflectivity values were at or below that threshold, except the all-weather treatment. Additional results from a dataset collected at a different location on UT-167 are also included in this report. Recommendations for future research include expansion of data collection to additional sites with varied geometries and traffic demands, as well as economic analyses including materials, installation costs, traffic demands, and potential safety benefits based on local crash data and research related to crash modification factors associated to retroreflectivity levels. These recommendations are conducive to establishing an objective decision-making support system to optimize pavement marking investment plans.

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LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
AW	All-weather, as the manufacturer labeled the treatment
CL	Center line
FHWA	Federal Highway Administration
LEL	Left edge line
LL	Lane line
MUTCD	Manual on Uniform Traffic Control Devices
REL	Right edge line
SNPA	Supplemental Notice of Proposed Amendment
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

This field-based evaluation summarizes the performance, in terms of retroreflectivity, of a number of treatments for pavement markings applied to continuous yellow and white edge lines, as well as broken white lane lines. Measurements were taken using mobile and semi-mobile setups for dry conditions and wet conditions, respectively, along a test deck installed by UDOT on I-215 during August of 2017. Wet conditions included readings from a dry state, transitioning through a continuous wetting phase until saturation, and reaching a steady state after wet recovery. Datasets were collected by a third-party contractor, using equipment and following procedures according to the applicable ASTM standards.

Multiple datasets were collected along the test deck, not only spanning the longitudinal extension of individual sections, but also covering changes in performance over time. A total of four datasets were included in this effort, starting with measurements soon after installation, and ending with a dataset collected after 802 days of service.

Treatments installed in the test deck included an all-weather tape (3M 380 AW tape), treatments with proprietary elements in paint and epoxy (3M elements Series 50), and Utah blends also in paint and epoxy.

The retroreflectivity of the all-weather treatment indicated superior performance and durability both in dry and wet conditions, and across all line types, as expected. After 460 days in service, all treatments remained well above 100 mcd/m^2 in dry conditions, but the wet recovery retroreflectivity values were at or below that threshold, except the all-weather treatment.

This report contains graphical representations of the results for each section and each dataset, and both dry and wet conditions.

Results from an additional dataset collected at a different location on UT-167, also known as Trapper's Loop, are also included in this report. At this location, in addition to center yellow lines using the 3M Elements Series 50, the white edge and broken lane lines used a high-performance 3M 380 IES tape. Dry and wet retroreflectivity values were also obtained at the Trapper's Loop location.

Overall, the datasets collected as part of this study provide valuable information on the performance of different pavement marking treatments at different points in time on freeway conditions. It is noted that the datasets collected showed consistent results across sections, and indicated repeatability and accuracy levels that allowed side-by-side comparisons between all sections in the test deck.

Materials and installation costs were not available for this study, but they constitute an important element recommended to complement future field-based evaluations. Economic analysis based on treatment costs, performance, and durability indicators, is expected to lead to direct guidelines to make decisions on treatment selections by considering long-term cost benefit of multiple alternatives. Economic analysis should also take traffic demand levels into consideration, as well as possible effects on safety and safety-related costs based on local crash data and research related to crash modification factors associated with retroreflectivity levels.

Lastly, data collection and analysis at additional sites with varied cross sections and traffic demands is also recommended. A larger number of sites will contribute to further validation of the results in this evaluation, and will also provide additional data points to model the effects of geometry and traffic on the performance and longevity of pavement marking treatments. Such models, in combination with economic analyses from future evaluations, can provide the basis for an objective decision-making support system to optimize pavement marking investment plans.

1.0 INTRODUCTION

Pavement marking visibility in wet conditions is a known problem for motorists. The problem is intensified at night when water film on the pavement surface reflects light in random directions rather than back to the driver. Winter maintenance practices often limit the thickness of pavement markings or devices above the road surface, and this may create difficulties for drivers, and particularly for older drivers, to see pavement markings under wet-night road conditions.

In 2011, UDOT installed a test deck using 3M Elements and two other wet reflective bead products in grooved waterborne paint on Bangerter Highway. After an initial inspection during rainy conditions, 3M Elements appeared to provide greater retroreflectivity than the other two treatments, but a consistent comparison was not performed due to changes in the longitudinal profile along the test section. A new test deck installed in August 2017 included different 3M Elements recessed at the manufacturer's recommended depth, each along a 1-mile stretch on I-215 in both EB and WB directions between mile markers 7 and 10. This location has a flatter profile than the test deck installed in 2011, providing a more consistent run-off across all product applications and allowing for side-by-side comparisons.

The new test deck includes road sections with the following marking treatments:

1) 3M 380 AW tape,

2) 3M Elements Series 50 / Utah blend in paint,

3) 3M Elements Series 50 / Utah blend in epoxy,

4) Utah blend in epoxy (Poli-carb Mark-55.9), and

5) Utah blend in paint.

A diagram that more clearly depicts the test deck configuration is shown in the next section in Figure 1.

According to the manufacturer, the performance of the 3M 380 AW tape is expected to provide superior retroreflectivity in wet conditions compared to the Series 50 elements in paint and epoxy, while providing adequate performance in dry conditions. It is noted that the Series 50 elements' target is a balanced all-weather performance with about 50% wet 2.4 refractive index beads and 50% dry 1.9 refractive index beads. In comparison, the 3M Series 70 and 90 are formulated with about 80% wet 2.4 refractive index beads and 20% dry 1.9 refractive index beads.

The coefficient of retroreflected luminance for the three 3M treatments in the test deck, per product specification at the time of product installation, is shown in Table 1. It is noted that differences in expected performance for each product between dry and wet conditions is smallest for the 3M AW tape, indicating reduced perceived differences in drivers' perceptions between the two conditions.

Table 1. Manufacturer Specifications of 3M Products in Test Deck

Coefficient of Retroreflected Luminance [mcd/m2/lux]	White		Yellow	
	Dry (ASTM E1710)	Wet (ASTM E2832-12)	Dry (ASTM E1710)	Wet (ASTM E2832-12)
3M AW tape	500	250	300	200
Series 50 in paint	700	200	525	150
Series 50 in epoxy	750	175	550	125

* Product sheets indicate that values for the AW tape are minimum initials whereas for the Series 50 they are average initials

Even though manufacturer specifications indicate superiority of some products in dry or wet conditions, actual field implementations with grooved recessed surfaces may result in significantly different performance.

Currently, there are no federally required minimum levels of retroreflectivity for pavement markings, but a notice of proposed amendment pending FHWA rulemaking is intended to provide such guidelines in future editions of the MUTCD [1]. A number of requirements for retroreflectivity are included in the referenced document, with minimum retroreflectivity levels based on roadway type (e.g., two-lane roads with center line markings only, and all other roads) and their speed limit (e.g., ≤ 30 mph, 35-50 mph, ≥ 55 mph).

Specifically, the 2016 Supplemental Notice of Proposed Amendment (SNPA) includes an article to be part of the standard for longitudinal markings of roadways with statutory or posted speed limits of 35 mph or greater, calling for a method designed to maintain retroreflectivity at or above 50 mcd/m^2/lx. In addition, the SNPA goes on to adhere to more restrictive levels of retroreflectivity, raising the minimum maintained levels to 100 mcd/m^2/lx for roadways with statutory or posted speed limits of 70 mph or greater.

In anticipation of FHWA rulemaking leading to incorporation of minimum retroreflectivity levels into the MUTCD, and considering the safety implications of reduced retroreflectivity due to in-service wear and also under wet conditions, this project aims at providing comparisons between pavement marking treatments based on field measurements along the I-215 test deck installed in 2017.

1.1 Objectives

The test deck on I-215 is expected to provide objective comparisons between pavement marking (i.e., striping) products, with the overall goal of identifying differences in performance both in dry and wet conditions.

Retroreflectivity is widely considered as a key performance indicator of pavement marking and is the primary quantitative performance measure in this study.

To achieve this goal, the following objectives were proposed as part of this project:

1. Compare the dry and wet retroreflectivity of the pavement striping products on the I-215 test deck over at least 3 years using readings from a mobile retroreflectometer.

2. Evaluate the slow cure and modified epoxies as binders relative to retroreflectivity (durability) and color comparison to each other.

An initial objective of the project included the collection and analysis of video images, but the use of video was limited as a qualitative part of this effort. The data collection contractor holds video recordings obtained during the execution of this project, and these are available to UDOT upon request.

1.2 Report Outline

The remainder of this report is organized in the following sections:

- I-215 Test Deck Description
- Field Data Collection
- Data Analysis
- Conclusions and Recommendations

2.0 I-215 TEST DECK DESCRIPTION

As mentioned in the introduction, the I-215 test deck was completed in August 2017. It comprises three miles of roadway on I-215 between mileposts 7 and 10, where each treatment was installed along a one-mile stretch so that three treatments were installed per direction, for a total of six sections. It is noted that all mainline line sections were treated with the corresponding product, and product/section transitions were located at physical mileposts.

According to UDOT engineers, this stretch of road has a relatively flat profile so that all treatments can be expected to have similar run-off, deeming appropriate a direct comparison between them. In addition, pavement was grooved to 140 millimeters before all treatments were applied, so that plowing operations had a reduced impact on their durability.

The six sections were selected to include different combinations of binding materials, reflective elements, and a tape-based application. One of the treatments was repeated, resulting in five unique treatments along the six sections. The repeated treatment provides a measure of repeatability and consistency, indicating potential installation or measuring issues during the field data collection.

The five unique treatments were listed in the introduction, and their actual spatial location along the test deck is shown in a diagram provided by UDOT, and shown below in Figure 1.

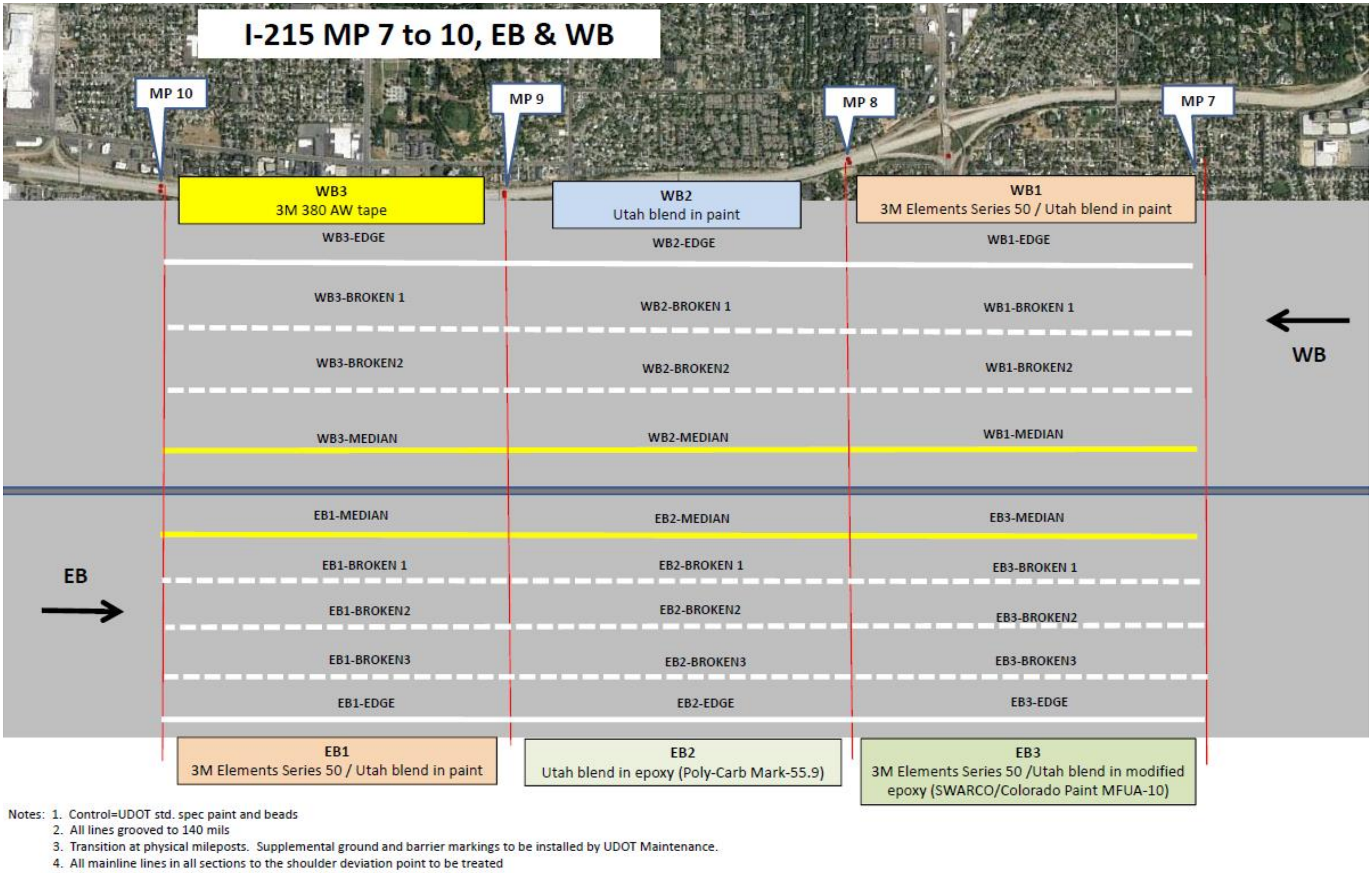


Figure 1. Test Deck Diagram

3.0 FIELD DATA COLLECTION

3.1 Methodology

To assess the performance of the pavement marking treatments it was necessary to collect retroreflectivity measurements in dry and wet conditions, not only including multiple measurements along the physical extension of the test sections, but also at different points in time. Time degradation of a treatment's performance is an essential metric to determine expected costs and to perform life-cycle cost-benefit analysis for decision making.

The field data collection was completed by Beck Enterprises, a third-party contractor with capabilities in taking retroreflectivity readings in dry and wet conditions, using mobile and semi-mobile setups. Services from Beck Enterprises were executed through a contract with UDOT, with input on the scope of work and data collection specifications from the University of Utah.

Standard collection of retroreflectivity measurements are dictated by ASTM International, specifically through the following documents:

- ASTM E1710 – 11: Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer [2].
- ASTM E2177 – 11: Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (RL) of Pavement Markings in a Standard Condition of Wetness [3].
- ASTM E2832 – 12: Standard Test Method for Measuring the Coefficient of Retroreflected Luminance of Pavement Markings in a Standard Condition of Continuous Wetting [4].
- ASTM D7585/D7585M − 10 (Reapproved 2015): Standard Practice for Evaluating Retroreflective Pavement Markings Using Portable Hand-Operated Instruments [5].

In addition, it is noted that pavement marking retroreflectivity measurements using either hand-held or mobile instruments are made in the field under dry conditions, but wet recovery and wet continuous conditions can also be measured using such devices [6].

In general, field measurements are collected following a setup that is intended to replicate the light reflected and received by a driver at a viewing distance of 30 meters, a headlight mounting height of 0.65 meters directly over the stripe, and a height of 1.2 meters over the stripe. Such a setup is often referred to as 30-meter geometry, and can be also specified by an entrance angle of 88.76 degrees and an observation angle of 1.05 degrees, as written in the proposed text for MUTCD. A schematic representation of the 30-meter geometry, taken directly from ASTM E2177-11 is shown in Figure 2.

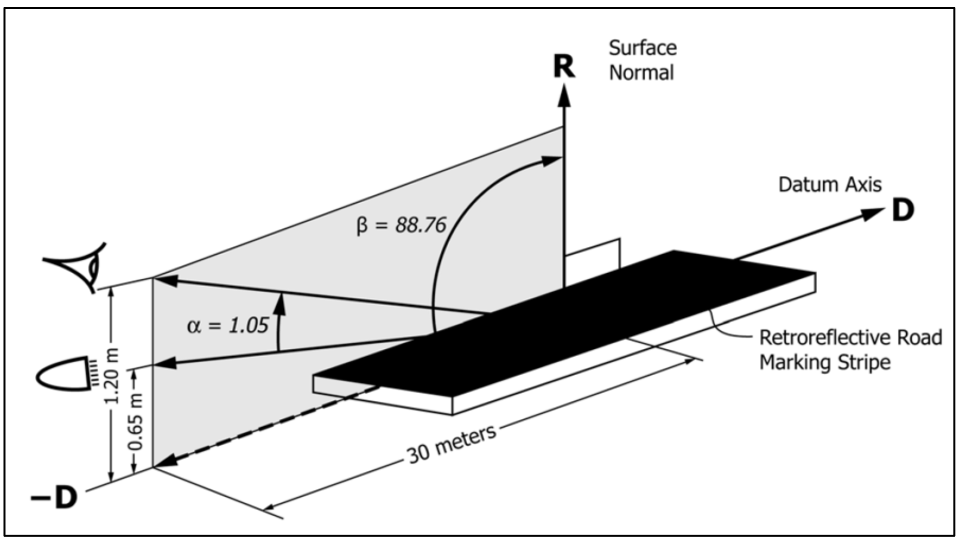


Figure 2. Schematic Representation of 30-m Geometry (adapted from ASTM E2177-11)

Initial estimations of the number of observations from each 1-mile section required for adequate analysis were made based on the Standard Evaluation Protocol defined in Section 6.3 of ASTM D7585/D7585M, as follows:

- Measurements should be taken at regular intervals throughout the evaluation section. For continuous edge lines, one measure should be taken every 20 ft, for a total of 20 measurements per section. For lane lines, two measurements should be taken on each skip line for a total of 20 measurements per section, assuming a 10-ft line followed by a 30-ft gap.

- The average of the 20 measurements will be used to determine the retroreflectivity of the marking within the section, and all sections with the same treatment will also be averaged to obtain a grand average. The standard deviation and coefficient of variation will be taken into account to determine the variability of the measurements.

When dealing with field measurements, it is important to highlight a note in ASTM D7585/D7585M referring to the actual locations within sections being subject to observations: "When measuring existing or in-service pavement markings, *care should be taken so that representative sections of pavement markings are measured*. There are particular conditions where excessive pavement marking wear can be associated with a specific cause such as vehicle tracking along horizontal curves, access points to gravel pits, and high weave areas. Pavement markings can also collect dirt, grime, and debris." (italics added).

It is noted that standard practices for field measurements of retroreflectivity of pavement marking are currently defined only for portable hand-operated instruments, leaving practices for field measurements using mobile instruments outside of the standard. However, the sampling rates of mobile measuring devices, such as the one used by Beck Enterprises for dry measurements, typically exceed minimum requirements to ensure adequate statistical analyses.

3.2 Data Collection Setup

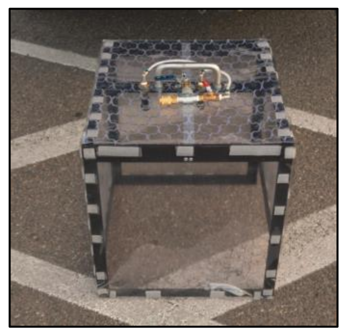
A combination of mobile and semi-mobile setups was used to collect dry and wet retroreflectivity measurements, respectively.

The mobile setup is comprised of a mobile retroreflectometer mounted on the side of an SUV, laser optics boxes, and onboard hardware and software acquisition systems provided by Beck Enterprises. The system is assembled to provide an equivalent 30-meter geometry and the reflectometers comply with ASTM E 1710-95, per information on Beck Enterprise's website. Using this setup, data is collected at a high rate and while the SUV travels at freeway speeds, minimizing impacts to live traffic and without the need of temporary traffic control crews.

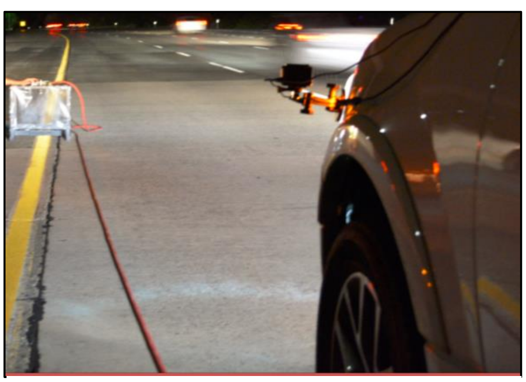
The semi-mobile setup used for the collection of wet retroreflectivity also used the mobile data collection system mounted in the SUV and described above, in addition to a system to simulate precipitation at the measurement point. The rate of precipitation is calibrated by Beck Enterprises to meet the standard 2 in/hr as established in ASTM E2832, and representing the upper limit of what is meteorologically classified as heavy rainfall. Measurements of wet performance are taken at separate time intervals, starting after the material is saturated (i.e., after about 30 seconds of continuous wetting), and then every 5-10 seconds as the water output is shut off and the material enters a "recovering" process until the measured retroreflectivity values reach a steady condition. This semi-mobile setup requires live traffic control measures in the form of a moving lane closure to allow the data collection crew to perform the wet measurements. In this study, the traffic control was arranged by UDOT.

Images of the data acquisition system used by Beck Enterprises at the test deck are shown in Figure 3 for illustration purposes.

(a) SUV with side-mounted retroreflectometer



(b) Portable Continuous Wetting Device



(c) Forward-facing view of wetting device from SUV

(d) Equipment in place and ready to take wet measurements

Figure 3. Data Collection Equipment and Setup

3.3 Data Collection Over Time

A total of three datasets at different points in time were collected as part of the project, but an initial set collected soon after the installation of the test deck was also provided by Beck Enterprises and included in the results and analysis. Therefore, a total of four points in time were represented in the data, covering a period of 802 days, or about 2.2 years after installation, as described below:

- Dataset 1: Collected in August 2017, 19 days after installation
- Dataset 2: Collected in July 2018, 351 days after installation
- Dataset 3: Collected in November 2018, 460 days after installation
- Dataset 4: Collected in October 2019, 802 days after installation

The datasets are also depicted over time in Figure 4.

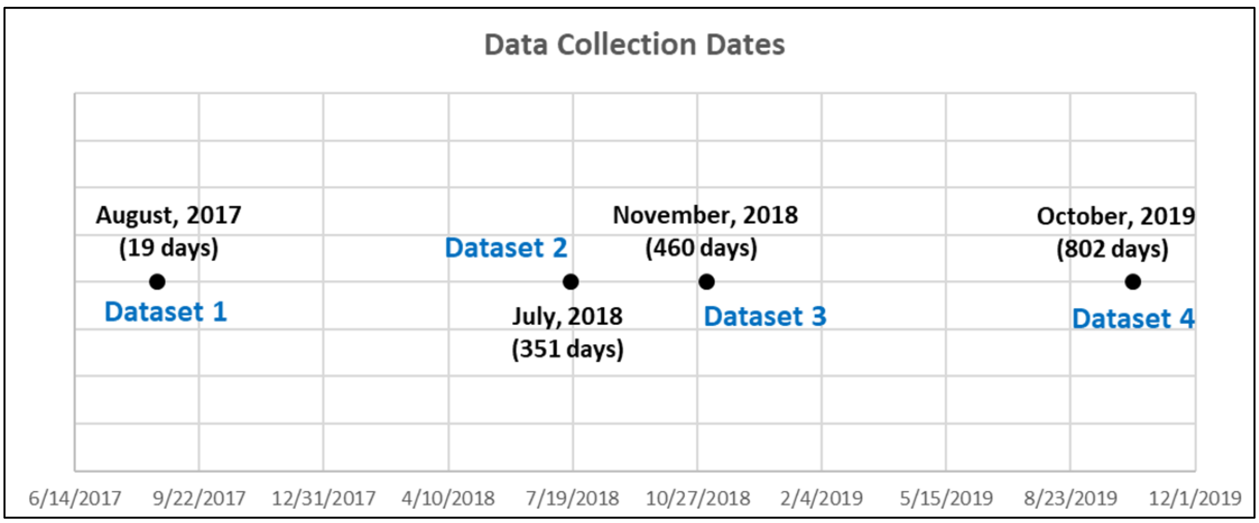


Figure 4. Datasets Collected Over Time

4.0 DATA ANALYSIS

As described above, a total of four datasets from the test deck were available in this study and covered a period of 802 days between installation and the last data collection date. This section presents the results of those four datasets, organized by pavement condition (i.e., dry or wet), and by pavement marking line, including: 1) Continuous left yellow edge line, 2) continuous right white edge line, and 3) broken white lane lines. It is noted that all treatments had at least three sets of measurements from the first three data collection dates, except for the 3M AW tape, which had data collected at the fourth date (i.e., after 802 days). This was the case since the other treatments had been refreshed by maintenance crews prior to the last round of data.

Data was received at the University of Utah in the form of csv files by the third-party contractor, Beck Enterprises, and also through their web data portal at https://data.beckenterprises.co/. The University of Utah provided updates and in-person presentations to the Technical Advisory Committee on the data collection and results after each of the datasets was obtained. This section includes the data presented in those meetings and additional updates based on new analysis. It is noted that the data used to create the figures in this section is further detailed in the Appendix of this report.

4.1 Retroreflectivity in Dry Conditions

Collection of dry retroreflectivity was completed using the SUV-mounted mobile setup, allowing for data collection to be performed at freeway speeds. This also indicates that the rate of data collection was managed by the data collection system directly instead of being dictated by selected points along the treatment segments.

The original datasets contained summary statistics for retroreflectivity values every 0.1 miles including average, standard deviation, and number of valid points, among others. It is noted that over 150 valid points were registered for typical 0.1-mile segments with a continuous line, and about 50 points were typical for measurements along broken white lane lines.

Results are summarized in graphical form, where the test sections are depicted in the same order and orientation as shown in the test deck diagram in Figure 1. For example, the upper left corner refers to the section with 3M AW tape and the lower right corner refers to the 3M Elements Series 50 with the Utah blend in modified epoxy.

4.1.1 Left Yellow Edge Line

Figure 5 shows a summary of the average readings every 0.1 miles for the six test sections and for each of the four datasets (where available) along the left yellow edge line. Note that a bold dashed line has been added as a reference to all sections indicating the average retroreflectivity of the AW tape. Detailed data used to create Figure 5 can be found in Appendix A.1.

In general, it is noted that measurements along each section maintain relative consistence at different numbers of in-service days (between datasets), with retroreflectivity values displaying similar trends for points collected at a given date (within datasets). Also, it is noticed that the initial measurements from August 2017 had the largest variations, particularly for the two sections with the 3M Elements Series 50 and the Utah blend in paint.

The highest initial retroreflectivity values were observed for the 3M Elements Series 50. The sections with the Utah blend in paint had an average of 708 mcd/m^2 on the eastbound, and 868 mcd/m^2 on the westbound, followed by the 3M Elements Series 50 with the Utah blend in modified epoxy, with an average of 512 mcd/m^2.

However, by the second set of readings after 351 days from the installation date, retroreflectivity values from all treatments fell below those obtained from the 3M AW tape. The 3M AW tape averaged 431 mcd/m^2 in the second dataset, compared to averages of 257 mcd/m^2 and 322 mcd/m^2 for the 3M Elements Series 50 sections with the Utah blend in paint, and to 341 mcd/m^2 for the 3M Elements Series 50 with the Utah blend in modified epoxy.

By the third reading, i.e., 460 days after installation, the retroreflectivity of the 3M AW tape remained at similar levels (average of 386 mcd/m^2), while all other treatments had averages lower than 250 mcd/m^2. It is noted that even though all treatments except the 3M AW tape experienced reductions in retroreflectivity to values lower than 250 mcd/m^2, all sections remained at levels above minimum recommended values according to the draft text proposed for the MUTCD.

Lastly, it is also important to point out that the degradation of performance in terms of retroreflectivity was significant at the 460-day reading, except for the 3M AW tape, where the changes over time did not show significant differences compared to the initial reading after installation.

A more detailed representation of the change in average retroreflectivity for the yellow edge line over time is shown in Figure 6 (see Appendix A.5. for the figure data). Recall that all sections contain results from the first three datasets, except for the 3M AW tape which includes a fourth point from measurements at the 802-day mark after installation.

4.1.2 Right White Edge Line

Similar representations to those shown for the left yellow edge line were also created for the right white edge line. Figures 7 and 8 present this data, where average values along the sections every 0.1 miles and the change in retroreflectivity over time are shown, respectively. (See detailed data used to create these figures in Appendix A.2. and A.6.)

Overall, the data for the white edge line indicates consistent readings along the test sections for all treatments. However, there are significant trend differences compared to some of those highlighted for the yellow edge line.

First, the white edge line in the section with the 3M AW tape had the highest retroreflectivity averages from all datasets, but it also showed degradation in the performance over time unlike the constant values observed for the yellow edge line. Nonetheless, the retroreflectivity of the 3M AW tape after 802 days (an average of 485 mcd/m^2) was significantly higher than those observed for the other treatments at the previous reading (after 460 days).

Second, for all sections the degradation over time occurred at a higher rate along the white lines, so even when some of the initial retroreflectivity values were higher, the overall residual performance was not necessarily higher than for the yellow edge line after 460 days.

Even so, the retroreflectivity for all segments remained at average values in the range of 150 to 250 mcd/m^2, still well within their serviceable life.

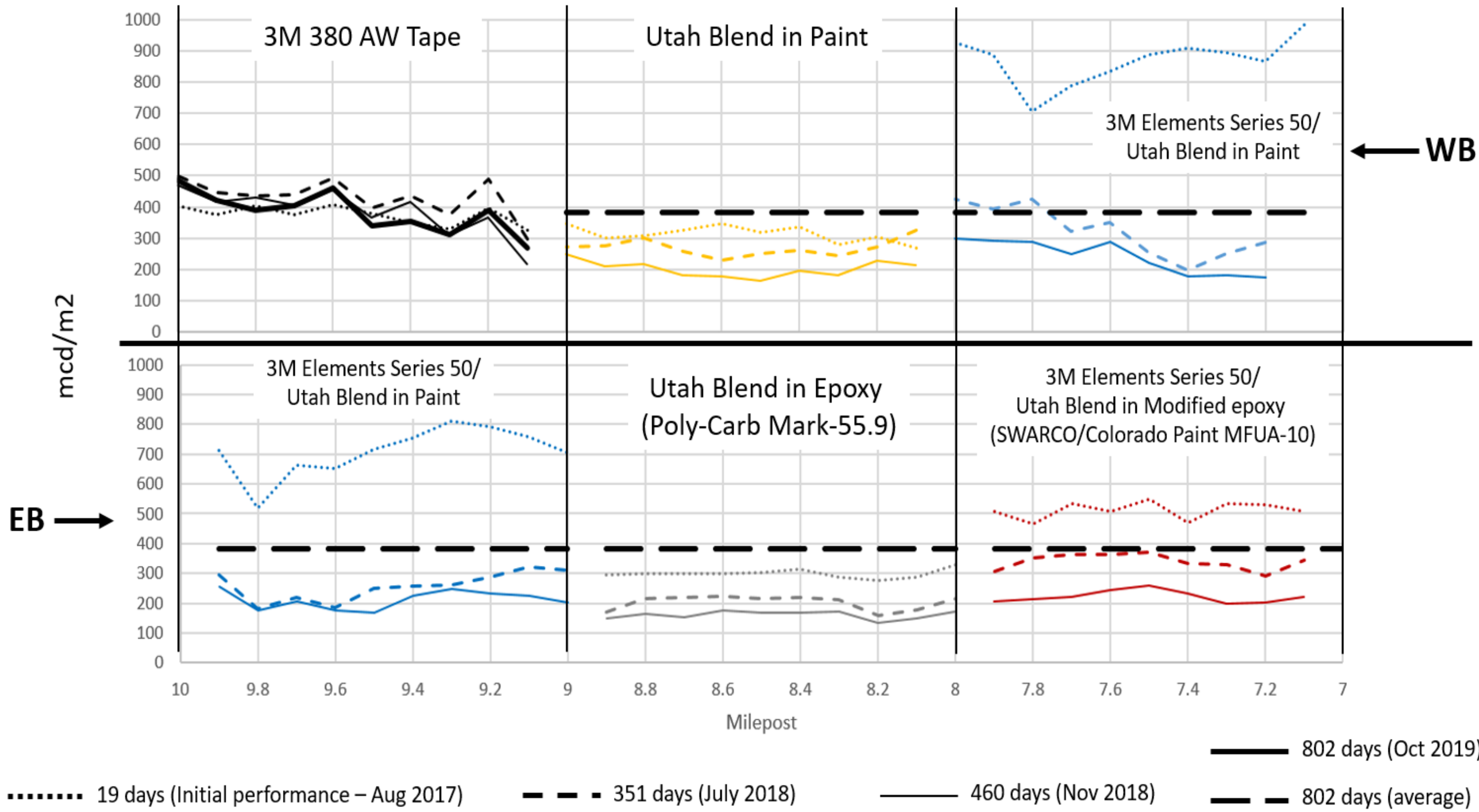


Figure 5. Summary of Retroreflectivity for the Left Yellow Edge Line – Along Section

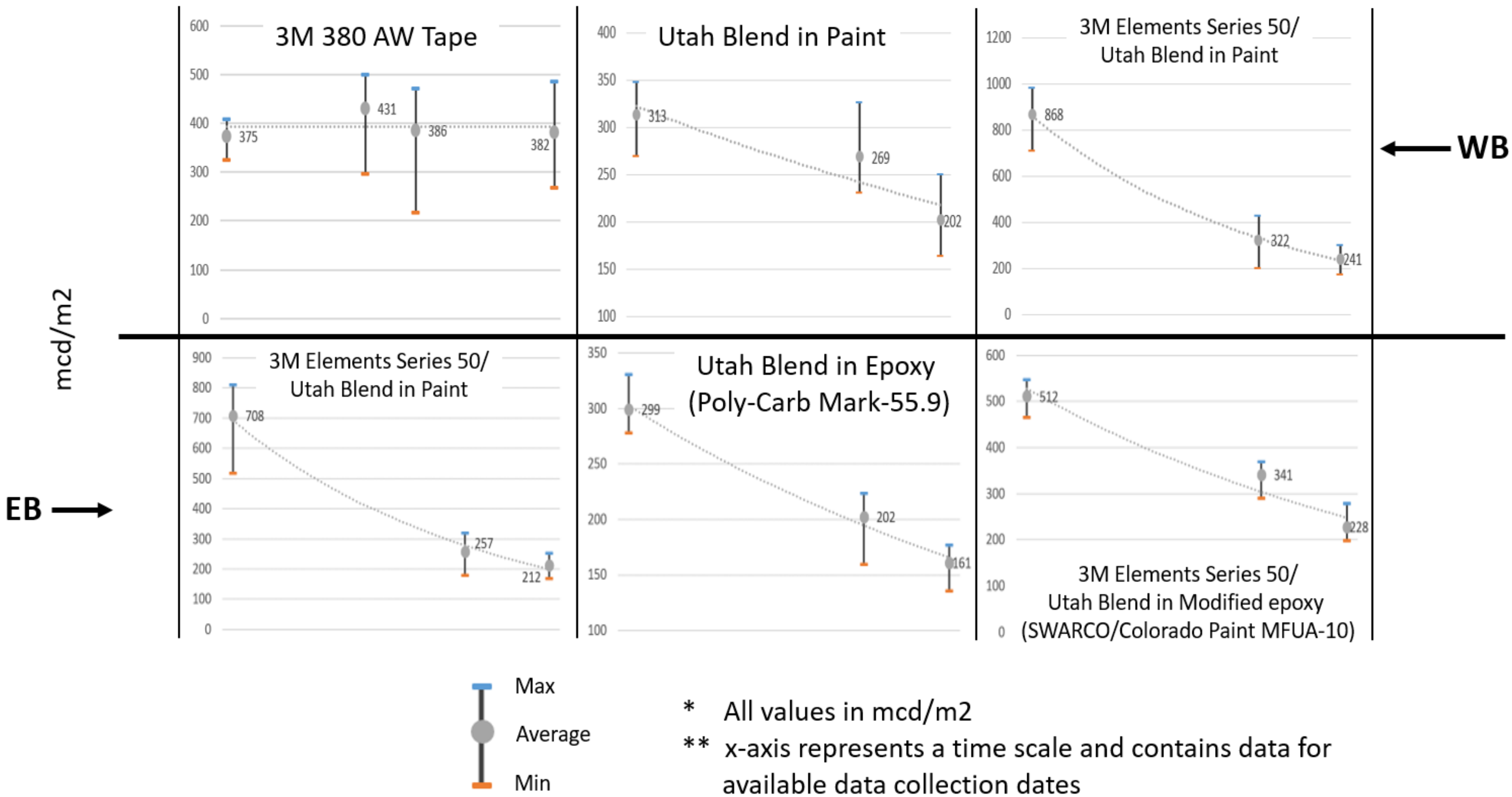


Figure 6. Summary of Retroreflectivity for the Left Yellow Edge Line – Averages Over Time

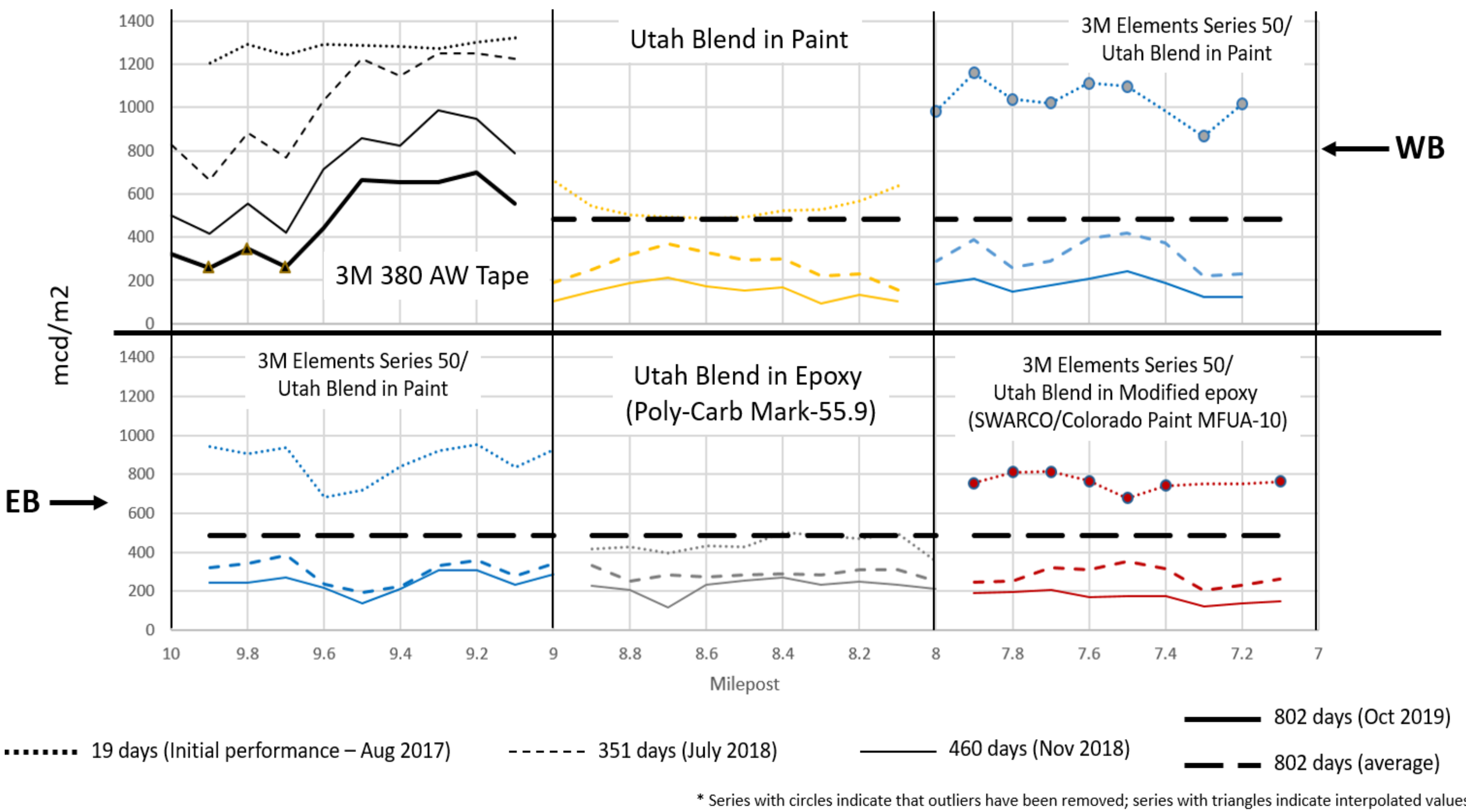


Figure 7. Summary of Retroreflectivity for the Right White Edge Line – Along Section

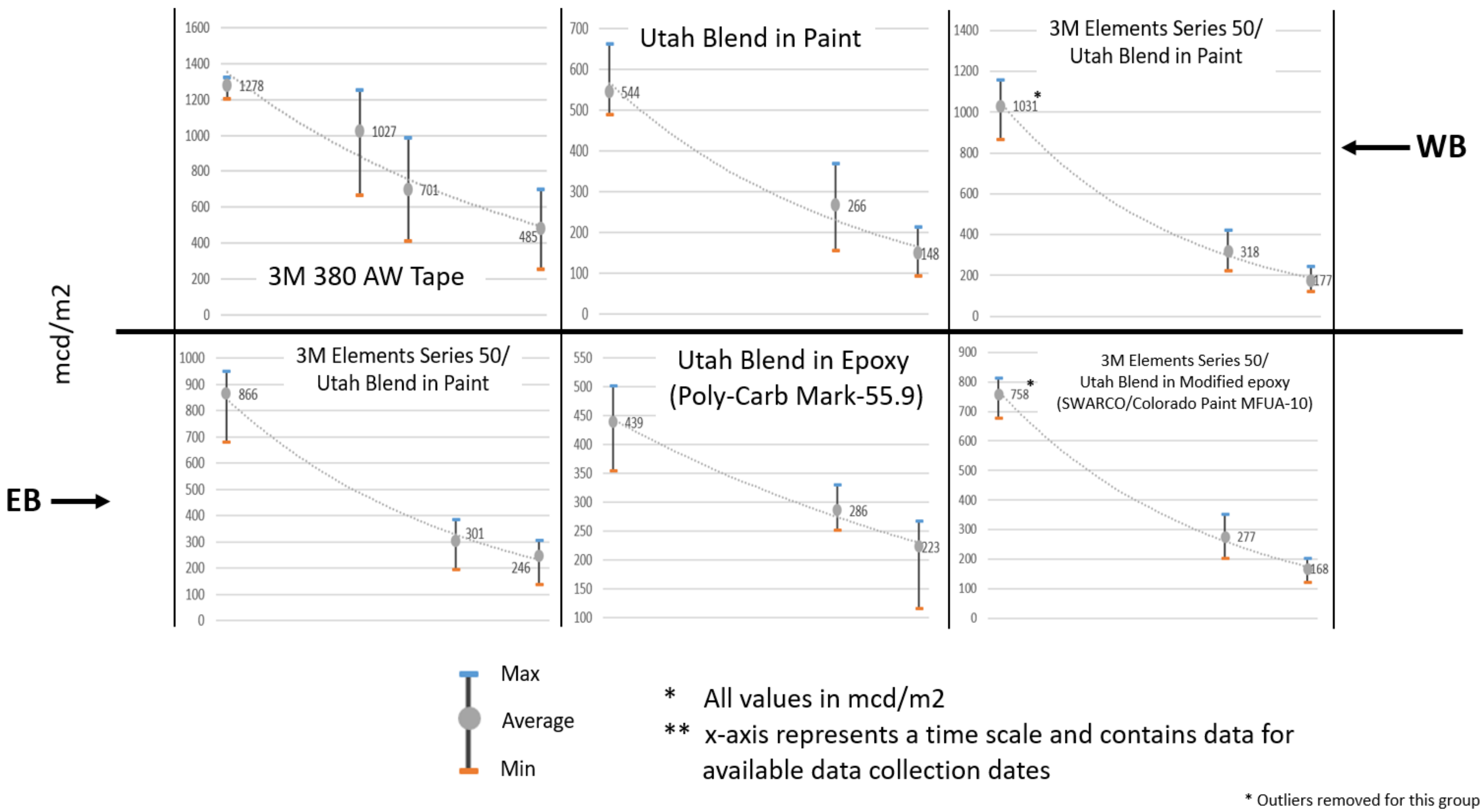


Figure 8. Summary of Retroreflectivity for the Right White Edge Line – Averages Over Time

4.1.3 Broken White Lane Lines

Data was also analyzed for the two sets of broken white lane lines along the test deck: 1) line 1, between the left lane and the center lane, and 2) line 2, between the center lane and the right lane. The results are summarized in Figures 9 through 12, using the same format described above for the continuous yellow and white lines (see Appendix A.3., A.4., A.7., and A.8., respectively, for the detailed data used to create the figures).

Results provide consistent trends, with reductions in the retroreflectivity over time, as expected for all treatments based on the results from the white edge line, including the 3M AW tape. Moreover, the actual performance of the broken lane lines is also comparable in magnitude to the performance of the continuous white line.

Trends are also consistent across lines, with the performance of the broken lane line 1 remaining at a higher level compared to the broken lane line 2. This is also within expectations, given that on average lower traffic is expected along broken lane line 1 (closer to the median), producing a lower rate of wear. This was observed across all treatments.

4.1.4 Overall Comparisons Dry Retroreflectivity

An overall comparison of the retroreflectivity from all treatments for the two continuous lines and the two broken lane lines is shown in Figures 13 and 14. These figures provide a different perspective by combining the plots in previous figures into one single chart, so that the relative magnitude of the retroreflectivity values can be appreciated.

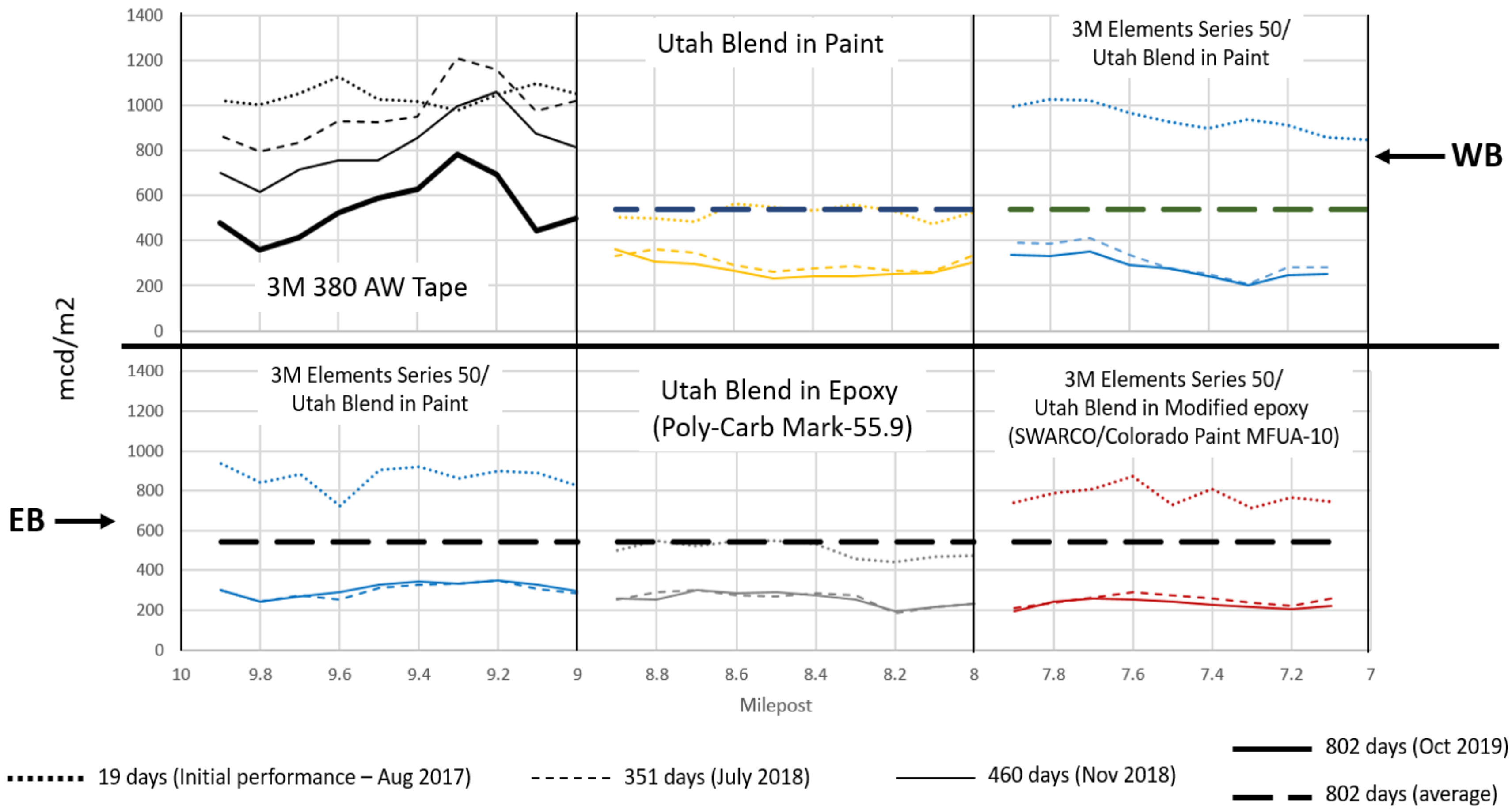


Figure 9. Summary of Retroreflectivity for Broken White Lane Line 1– Along Section

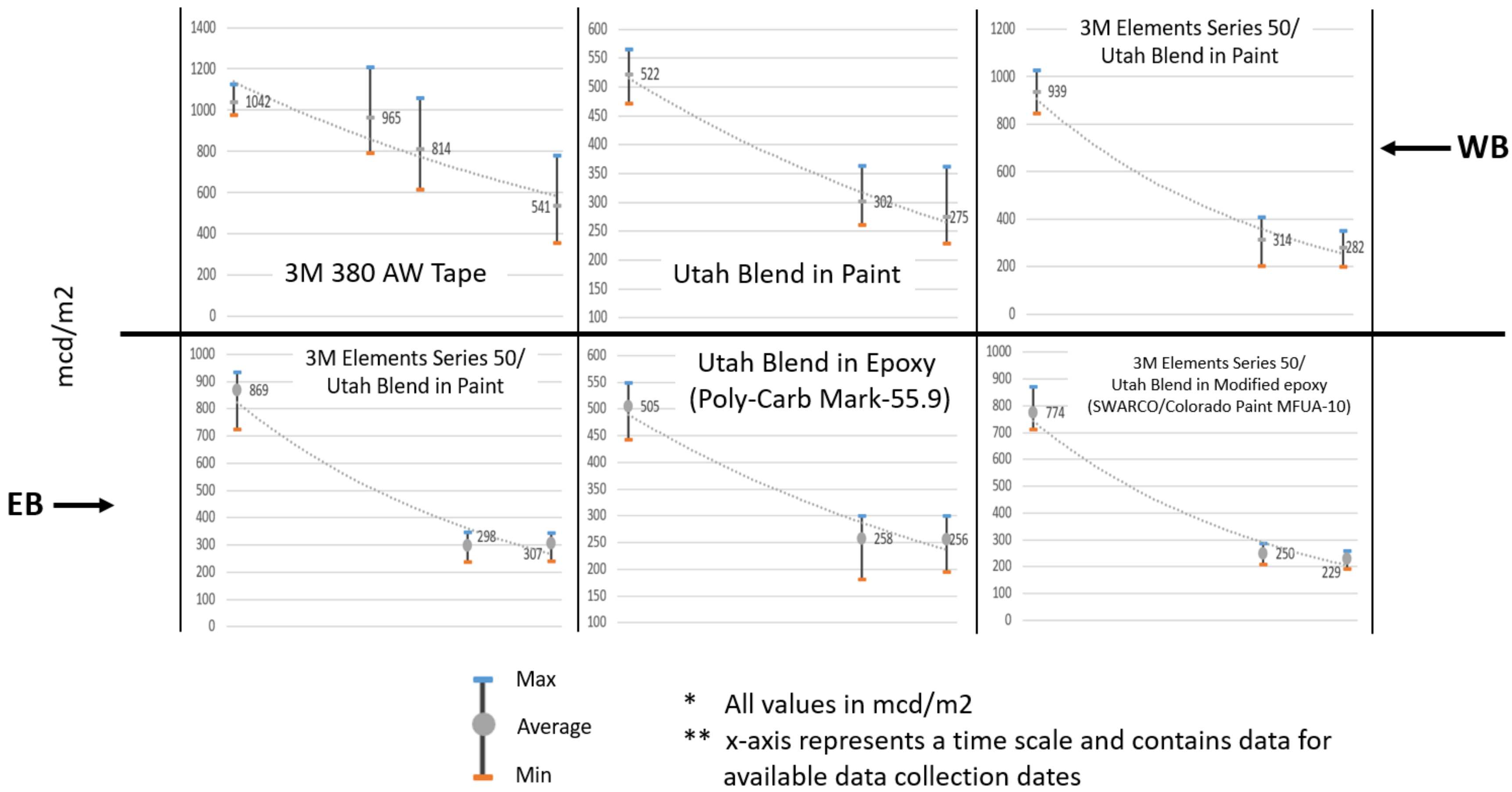


Figure 10. Summary of Retroreflectivity for the Broken White Lane Line 1 – Changes Over Time

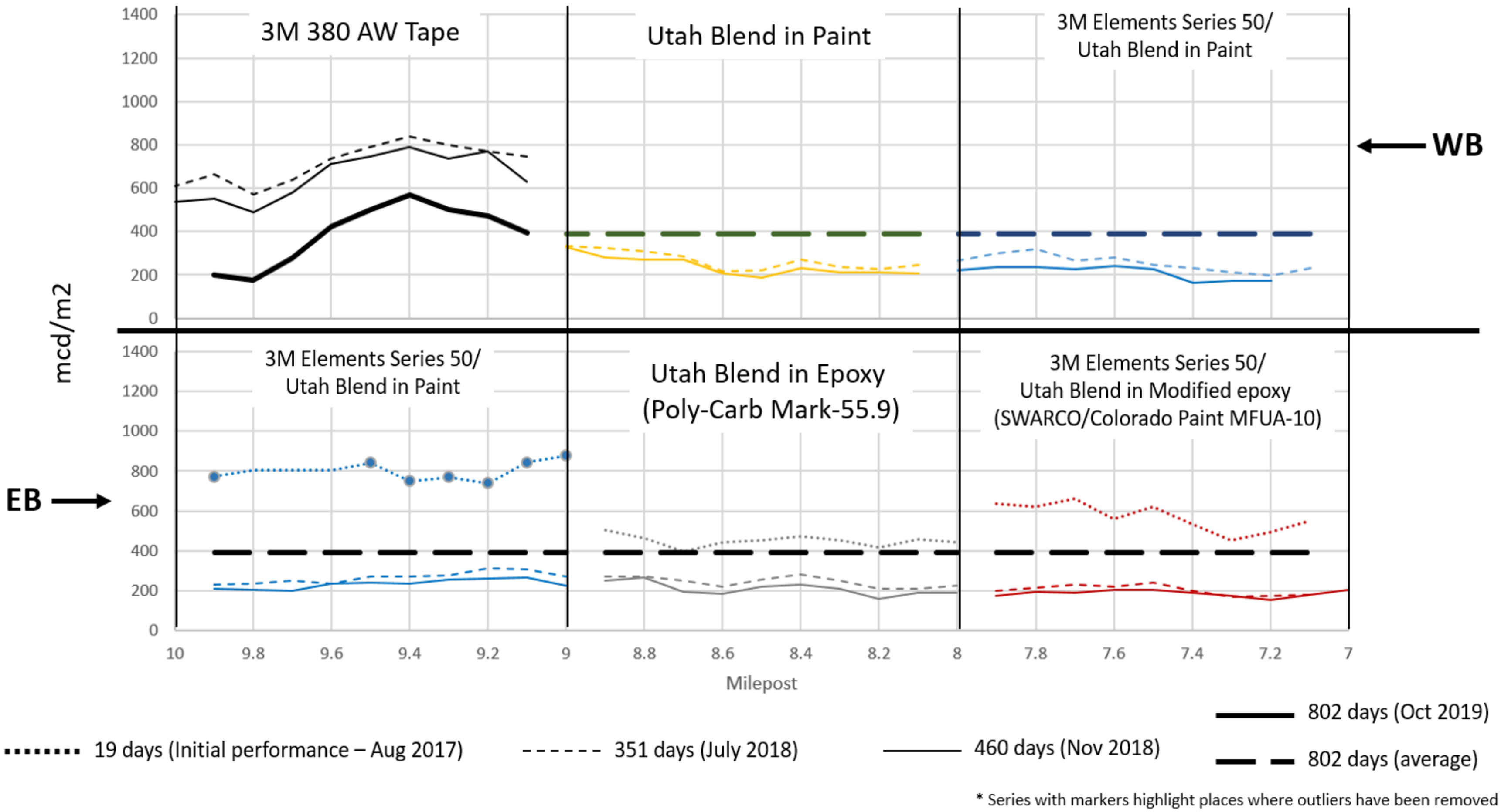


Figure 11. Summary of Retroreflectivity for Broken White Lane Line 2 – Along Section

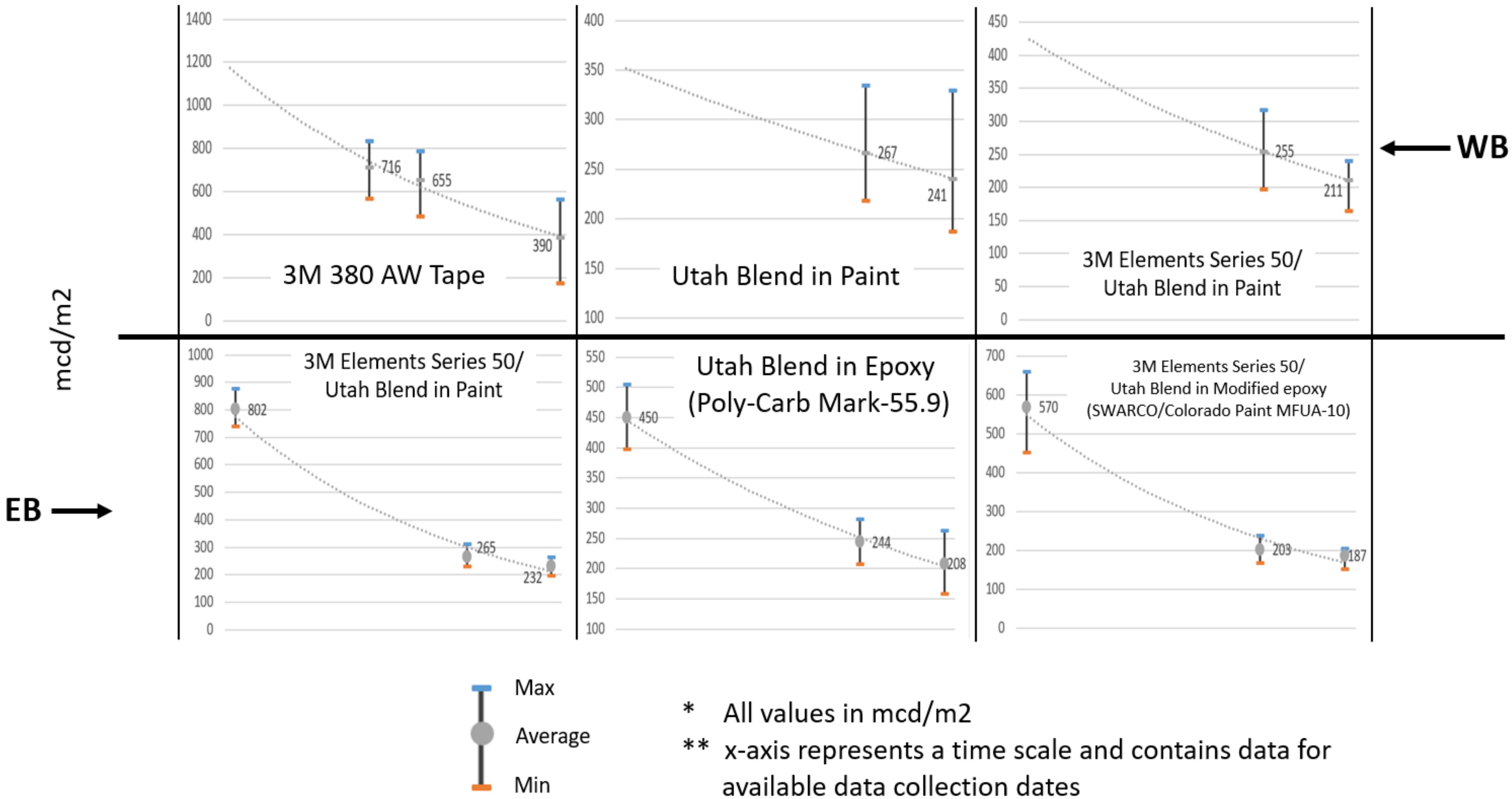
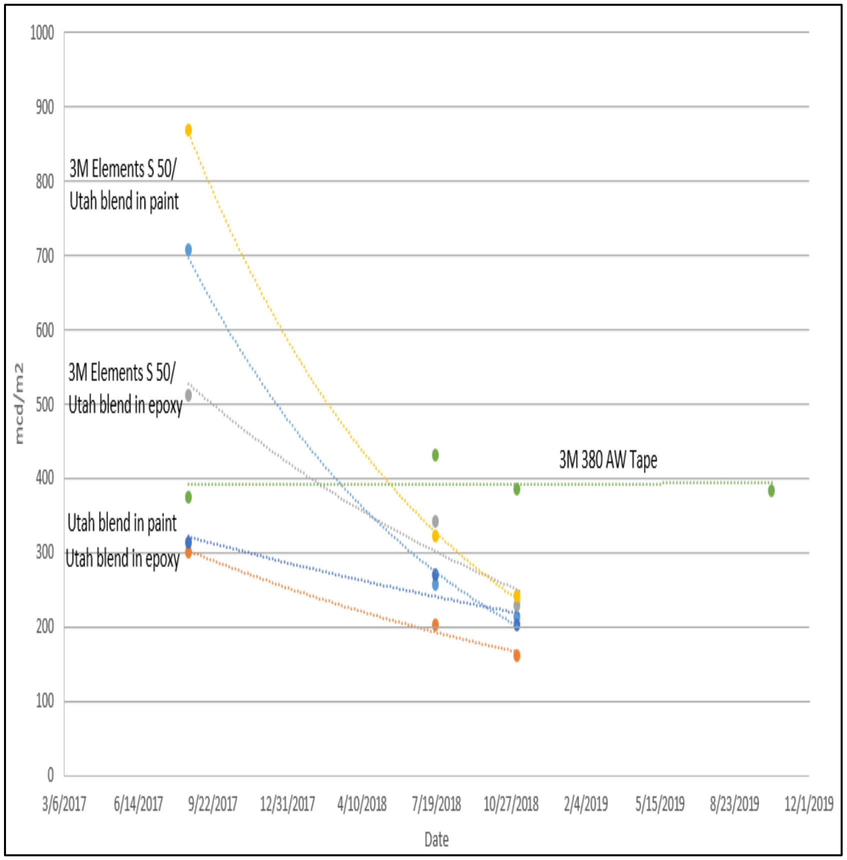
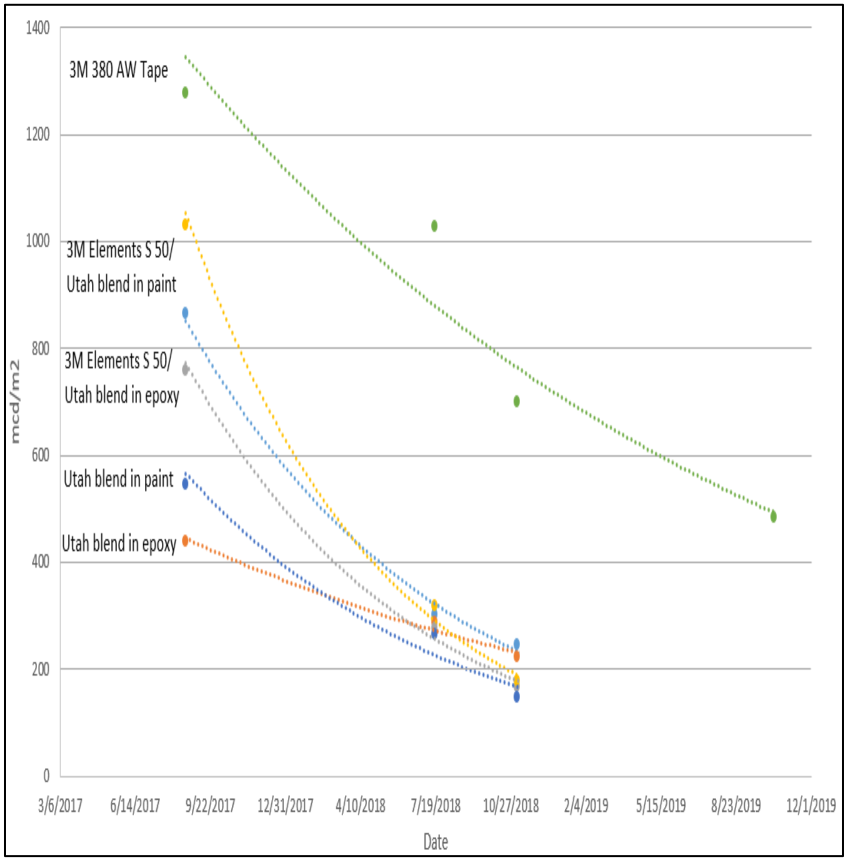


Figure 12. Summary of Retroreflectivity for the Broken White Lane Line 2 – Changes Over Time

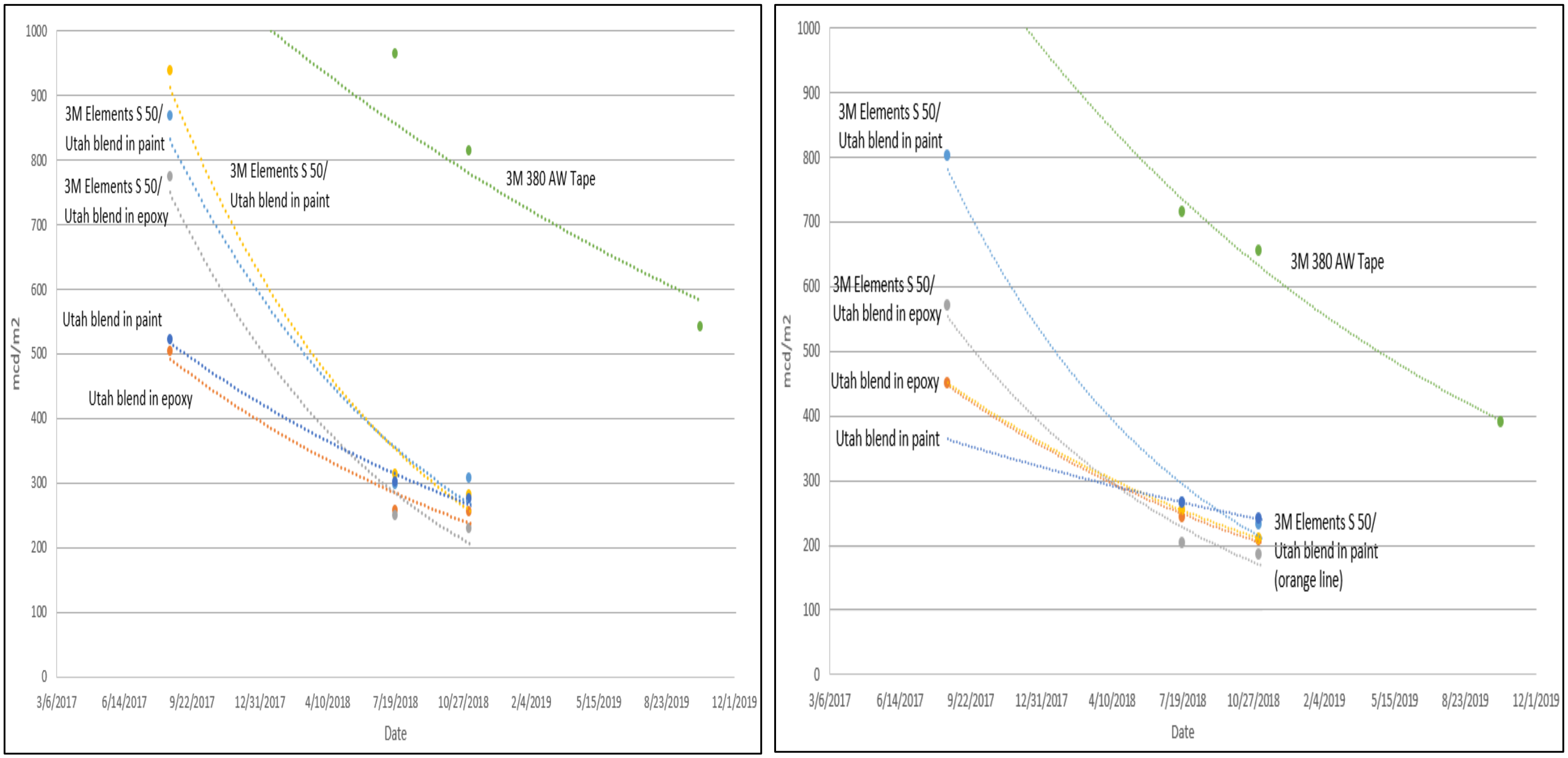


(a) Comparison of continuous yellow lines



(b) Comparison of continuous white lines

Figure 13. Comparison of Average Retroreflectivity of Continuous Lines Over Time



(a) Comparison of broken lane line 1

(b) Comparison of broken lane line 2

Figure 14. Comparison of Average Retroreflectivity of Broken Lane Lines Over Time

4.2 Retroreflectivity in Wet Conditions

As described above, field measurements for the wet retroreflectivity were collected using a semi-mobile setup that included a portable device for continuous wetting of the roadway surface. Once a measuring area is selected and the equipment is in place, the process to collect retroreflectivity readings included three main stages:

- Initial dry conditions (first 10 seconds)
- Continuous wetting (after the first 10 seconds through 40 seconds)
- Wet recovery (after the first 40 seconds, and until a steady state – through 90 seconds)

So, the process to measure the wet performance has at least three defined areas of interest, where the retroreflectivity is measured before, during, and after simulated heavy rainfall.

Datasets from the wet conditions were obtained on the same dates as the dry datasets, but were not available for the initial measurements (19 days after installation). It is also noted that the last dataset only included measurements from the 3M AW tape, since new pavement marking had been reapplied by maintenance crews over the other test treatments by that time.

4.2.1 Left Yellow Edge Line

The results from the three sets of wet data collected for the left yellow edge lines are provided in graphical form in Figure 15 through 17 (see Appendix A.9., A.10., and A.11. for the data used to create the figures). As expected, the ranges of retroreflectivity values for the 3M AW tape were significantly higher than for other treatments, and by the last reading (802 days after installation) remained well within serviceable ranges, with steady-state wet recovery values of over 200 mcd/m^2.

Other treatments had significant reductions in their retroreflectivity in wet conditions, with values dropping from the 200-300 mcd/m^2 range in the initial dry condition for the two 3M Elements Series 50 treatments, to lower than 100 mcd/m^2 in the recovery stage, to a slightly higher steady wet state of about 100 mcd/m^2. Similarly, the two remaining treatments without the 3M elements showed significant reduction in the retroreflectivity during the wet continuous phase to levels closer to 50 mcd/m^2, and with a smaller magnitude in recovery as it reached steady states that held values well under 100 mcd/m^2.

In terms of performance degradation over time, the first and second datasets were only 109 days apart, and thus the observed change in wet performance was of lower magnitude, particularly for treatments with the 3M elements and the Utah blends. The 3M AW tape remained at satisfactory levels 802 days after installation, with a decrease in wet performance between July 2018 (318 mcd/m^2) and November 2018 on average (234 mcd/m^2), but a different progression with practically no further reduction through October 2019 (225 mcd/m^2 on average). A summary of the results for the 3M AW tape from the three datasets is provided in Figure 18.

4.2.2 Right White Edge Line

Using a similar format, the results for the wet data collected along the right white edge lines are shown in Figures 19 through 22, including a summary of the performance of the 3M AW tape over time (see Appendix A.12., A.13., and A.14. for the data used to create the figures).

Overall, the range of retroreflectivity values of the 3M AW tape were significantly higher than for other treatments, and remained between 150 to 250 mcd/m^2 in the wet recovery period after reaching steady state as of the last dataset collected (802 days after installation). Readings from the second dataset, collected in November 2018 showed higher-than-expected increases in the retroreflectivity during the recovery period. These values are the result of averages from three separate measurements, all of which were consistent with this increase (515, 516, and 627 mcd/m^2), and serve as a reminder that spot measurements provide valuable indications of expected performance, but need to be confirmed by repeated instances in space and time. A more appropriate trend over time could be traced when observing all data collected as part of the three datasets from July 2018, through October 2019, as shown in Figure 22.

All other treatments including the 3M elements and the Utah blends in paint and epoxy had steady-state recovery retroreflectivity values between 80 and 120 mcd/m^2 in the first dataset of July 2018, and between 40 and 80 mcd/m^2 in the second dataset, indicating a continued reduction in performance over time, in this case over a time span of 109 days after the first year of installation.

4.2.3 Broken White Lane Lines

Wet field measurements were also collected for the broken white lane lines dividing the three lanes on the test deck. Materials and installation of the broken lane lines are identical to the continuous white edge line and are expected to result in similar retroreflectivity values, with potential variations stemming out of heightened wear as they are subject to traffic on the two lanes they divide. Summaries of the performance of the broken white lane lines are provided in Figure 23 through 25 (see Appendix A.15. through A.17. for the data used to create the figures).

The first dataset from July 2018 (Figure 23) shows ranges of retroreflectivity that closely resemble the data collected on the same date for the continuous white edge line, with the performance of the 3M AW tape at significantly higher levels compared to the other treatments. In this first dataset, the 3M Elements Series 50 and the Utah blend in paint had final wet steady-state values around 100 mcd/m^2, and values close to 50 mcd/m^2 for the Utah blend in epoxy.

The second dataset (Figure 24) reflects a similar trend for the 3M Elements series 50 and the Utah blends, with retroreflectivity values lowering further to the 50 to 75 mcd/m^2 range at the steady state of the recovery stage, whereas the reductions on performance for the 3M AW tape were less substantial and the retroreflectivity measures sustained levels over 250 mcd/m^2. It is important to note that the results observed for the continuous white edge lane with the 3M AW tape in the November 2018 dataset (Figure 20), showed an increase in the recovery stage that surpassed ranges from July 2018, but a more appropriate reference point is perhaps provided in Figure 24 by the recovery trajectory for the broken lane line.

The third dataset focused on the 3M AW tape section alone, as mentioned for the previous lines. Results in Figure 25 indicate a further decrease in the retroreflectivity compared to the continuous white edge line, with average recovery values in the 100 to 200 mcd/m^2 range for the left broken line (L1 - lower traffic) and in the 50 to 150 mcd/m^2 range for the right broken line (L2 – higher traffic). This indicates that the broken lines are still within serviceable retroreflectivity ranges (~100 mcd/m^2) in wet conditions and during the recovery state.

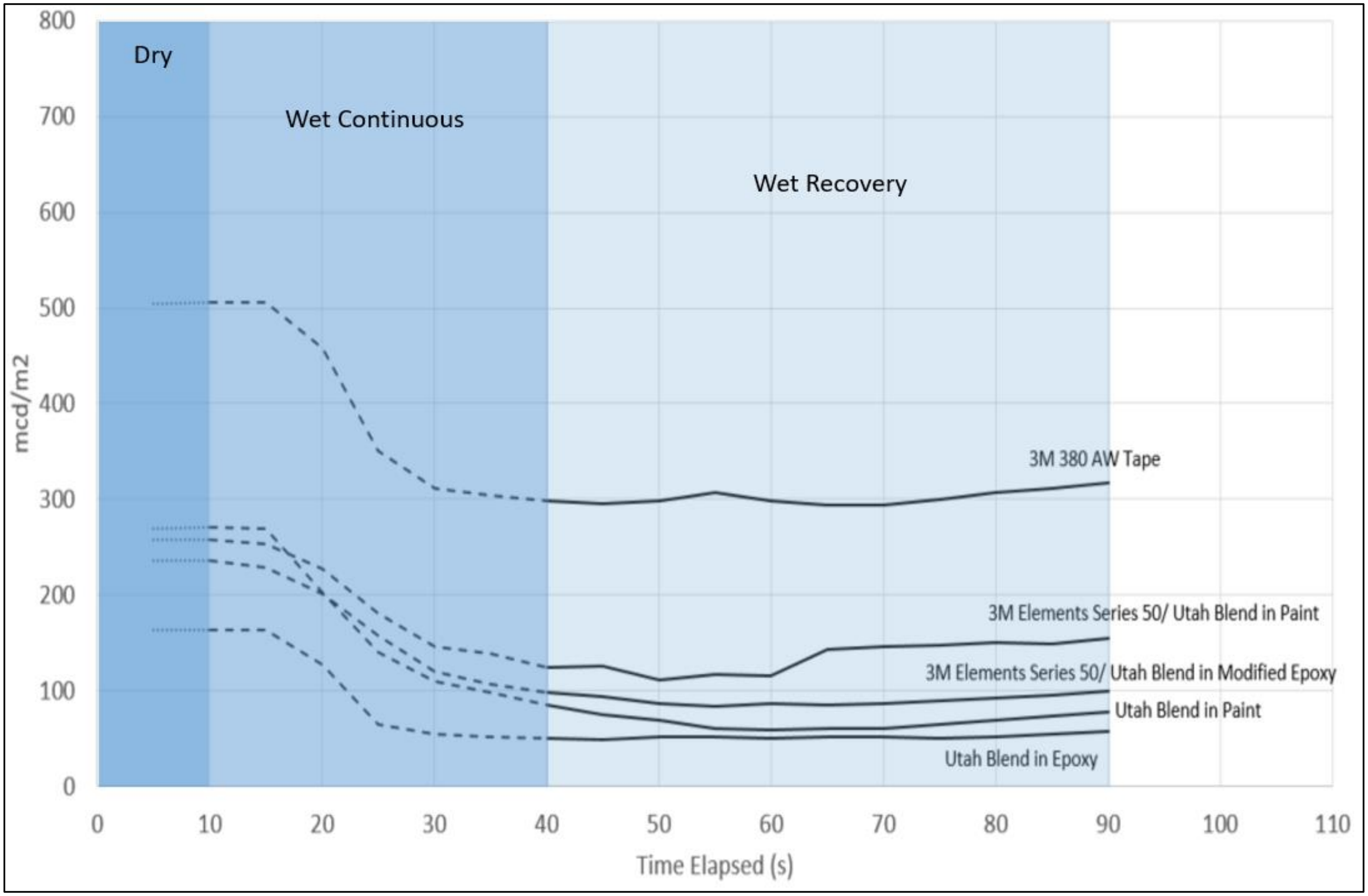


Figure 15. Average Wet Retroreflectivity for the Left Yellow Edge Line – from July 2018 (351 Days After Installation)

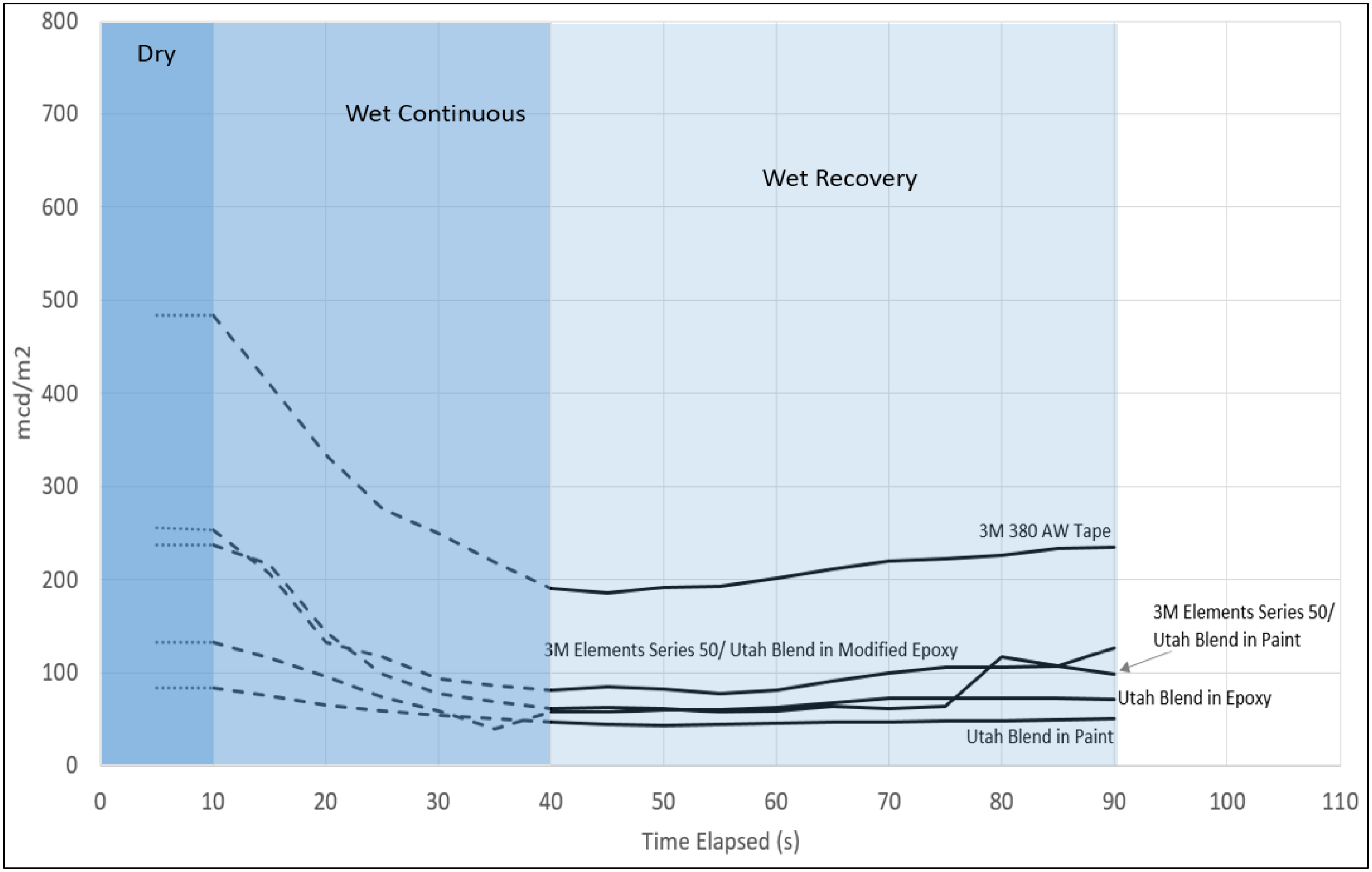


Figure 16. Average Wet Retroreflectivity for the Left Yellow Edge Line – from November 2018 (460 Days After Installation)

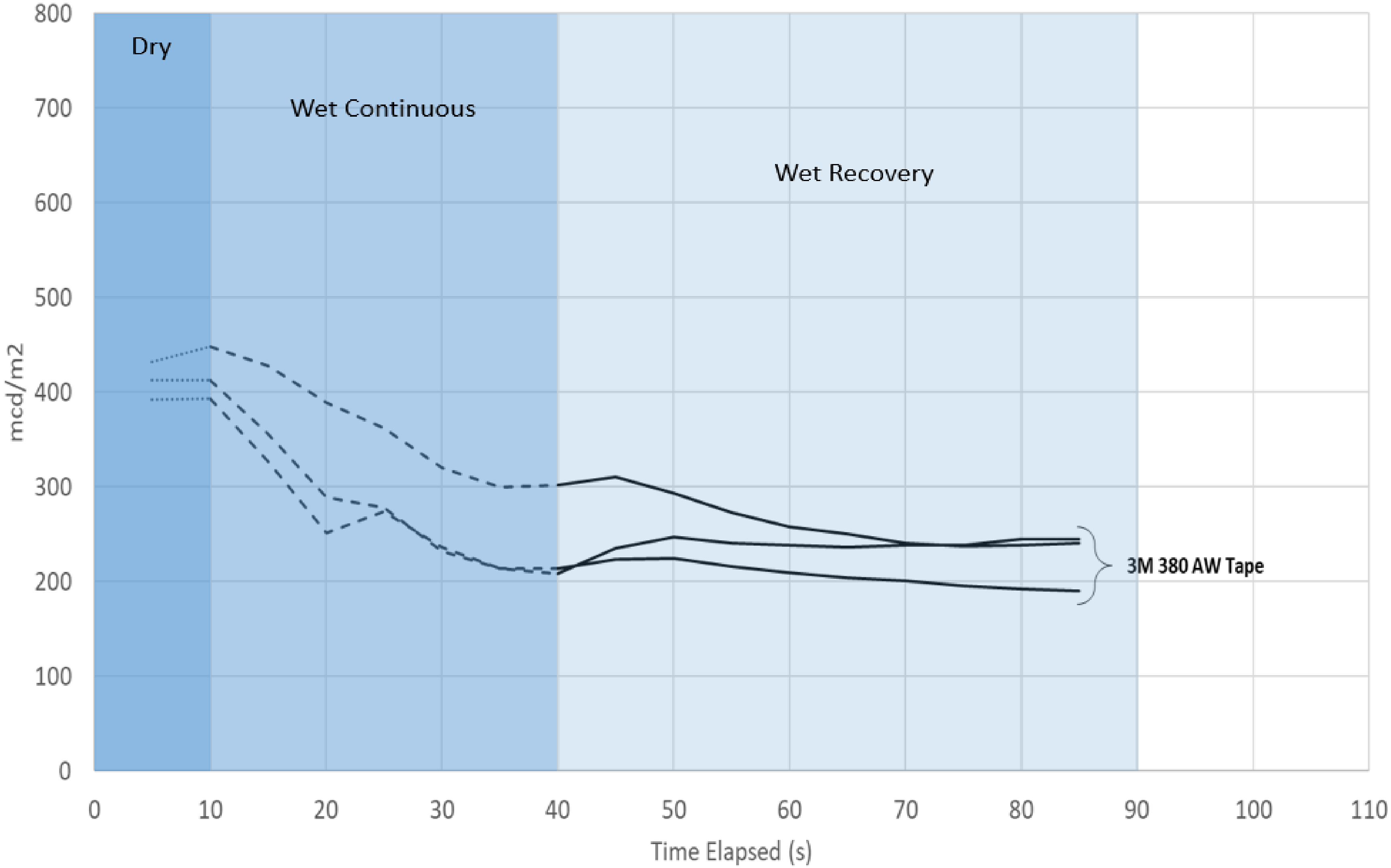


Figure 17. Average Wet Retroreflectivity for the Left Yellow Edge Line – from October 2019 (802 Days After Installation)

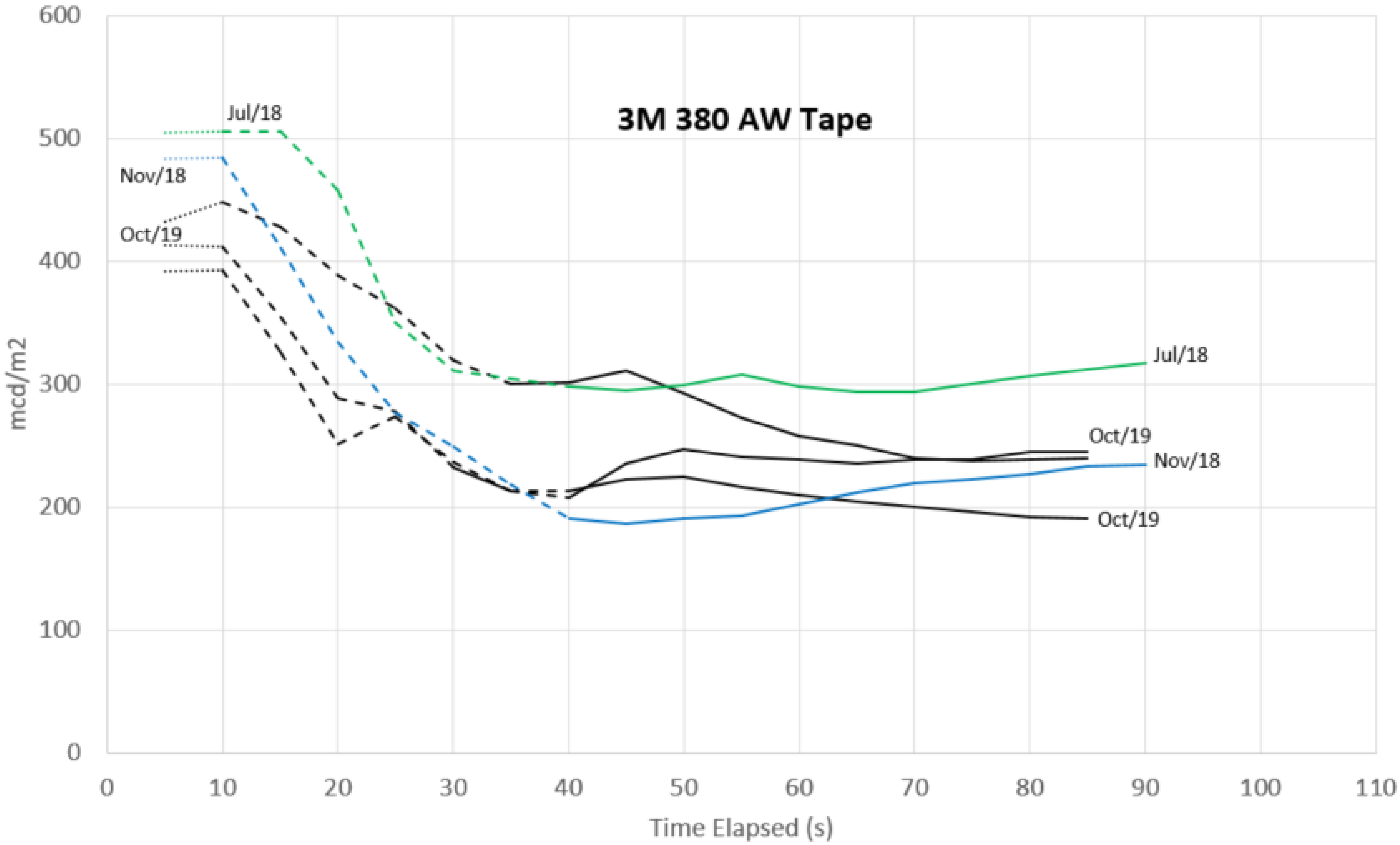


Figure 18. Average Wet Retroreflectivity for the Left Yellow Edge Line Over Time – 3M AW Tape Only

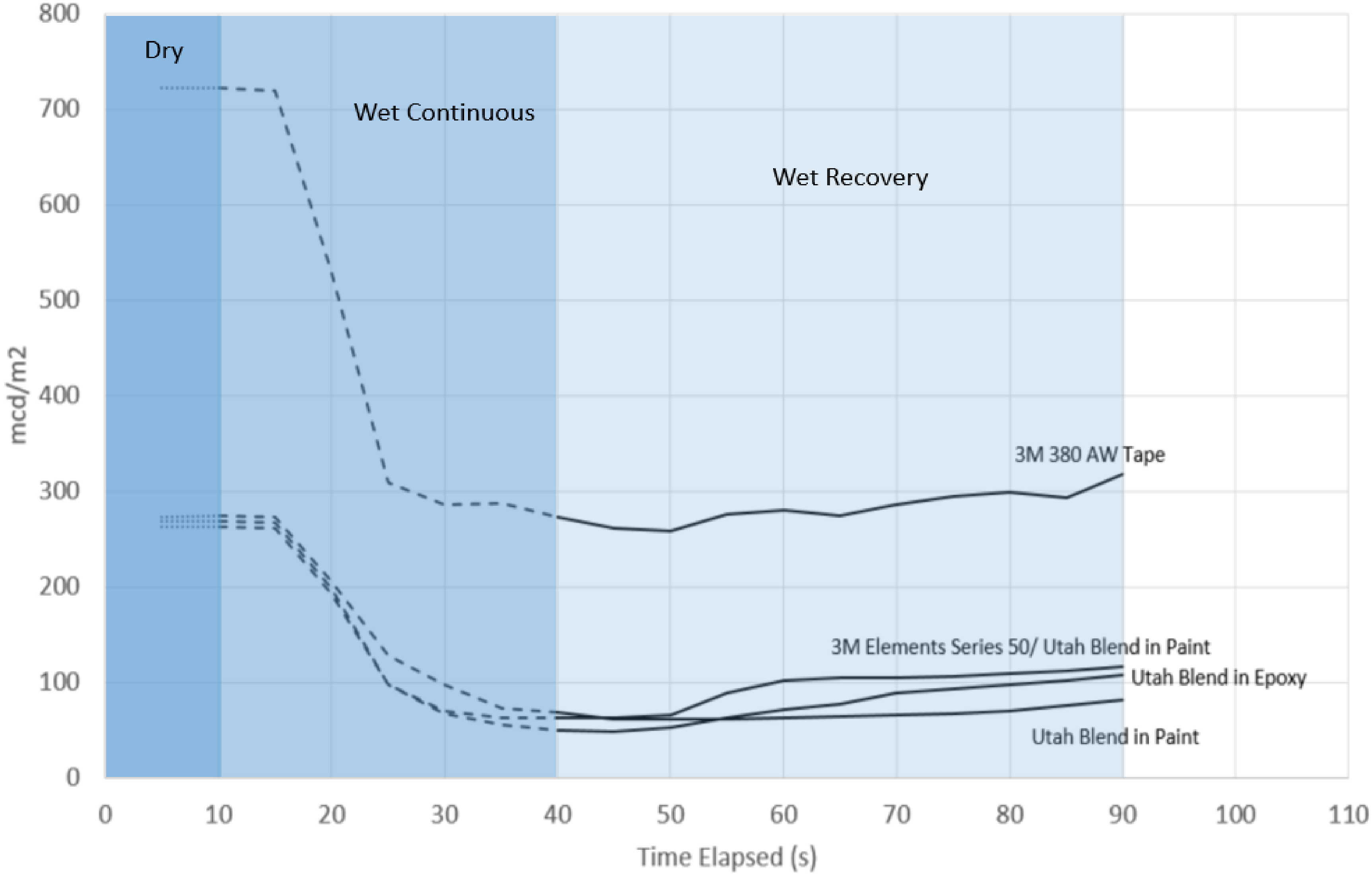


Figure 19. Average Wet Retroreflectivity for the Right White Edge Line – from July 2018 (351 Days After Installation)

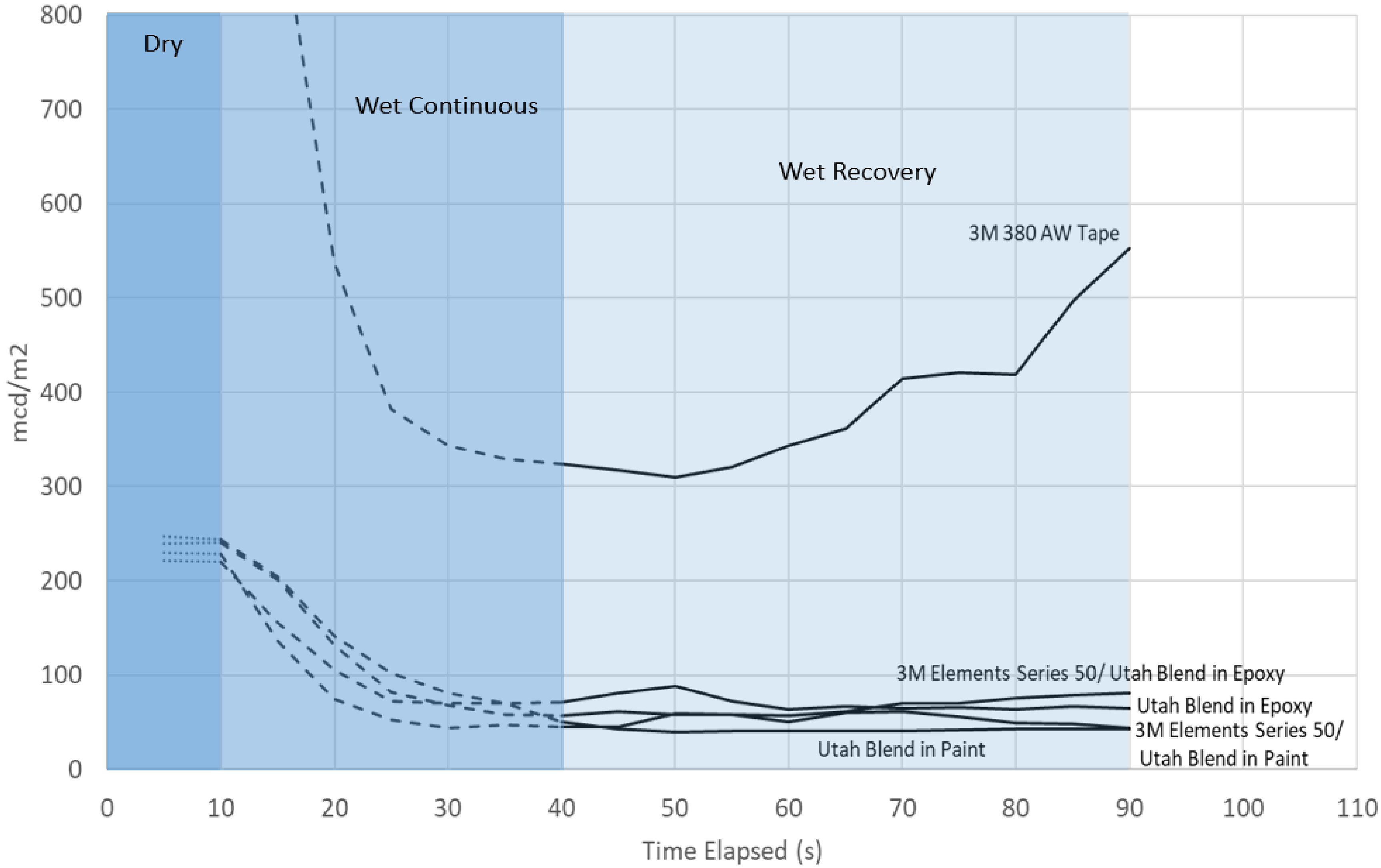


Figure 20. Average Wet Retroreflectivity for the Right White Edge Line – from November 2018 (460 Days After Installation)

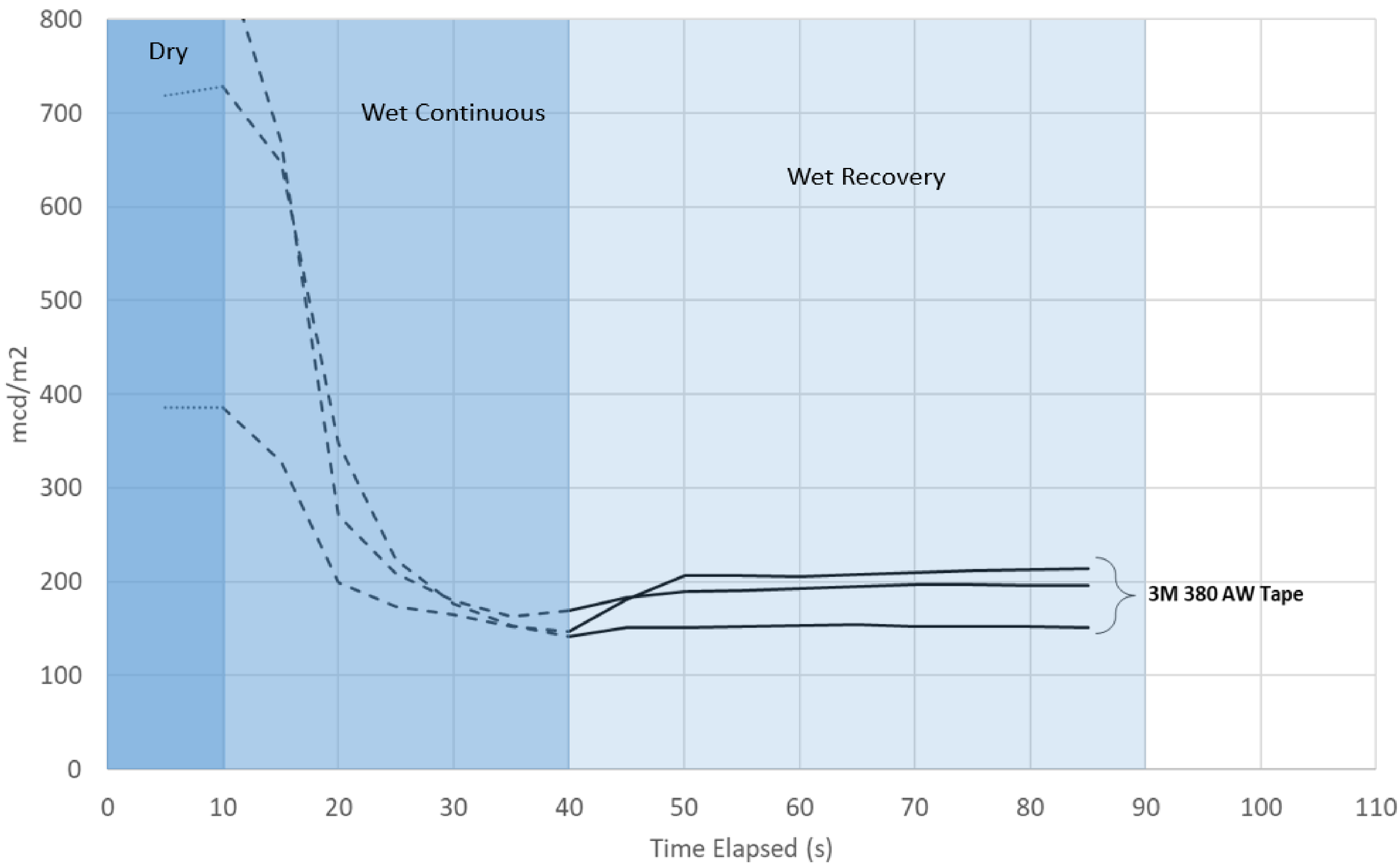


Figure 21. Average Wet Retroreflectivity for the Right White Edge Line – from October 2019 (802 Days After Installation)

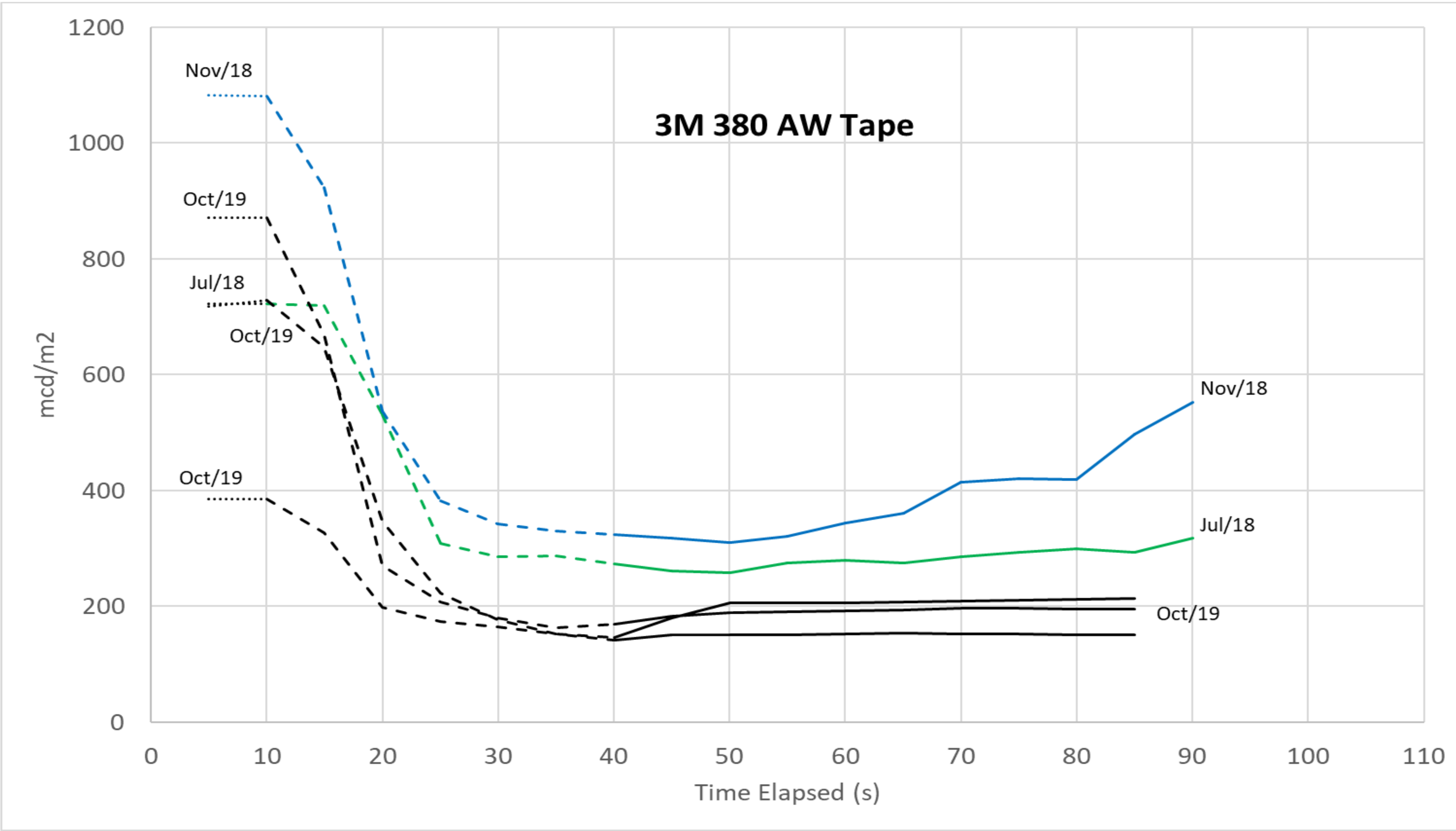


Figure 22. Average Wet Retroreflectivity for the Right White Edge Line Over Time – 3M AW Tape Only

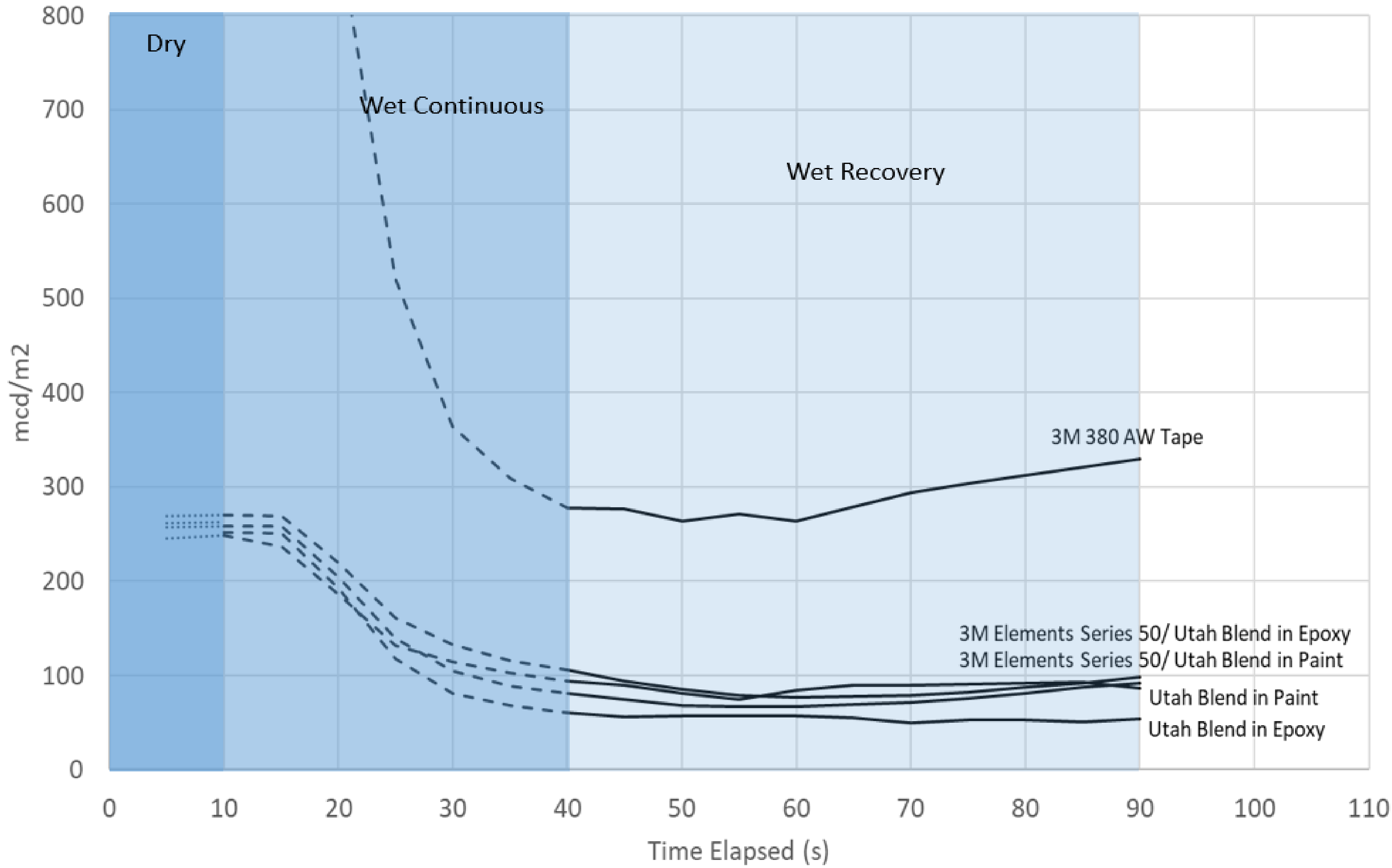


Figure 23. Average Wet Retroreflectivity for the Broken Lane Lines – from July 2018 (351 Days After Installation)

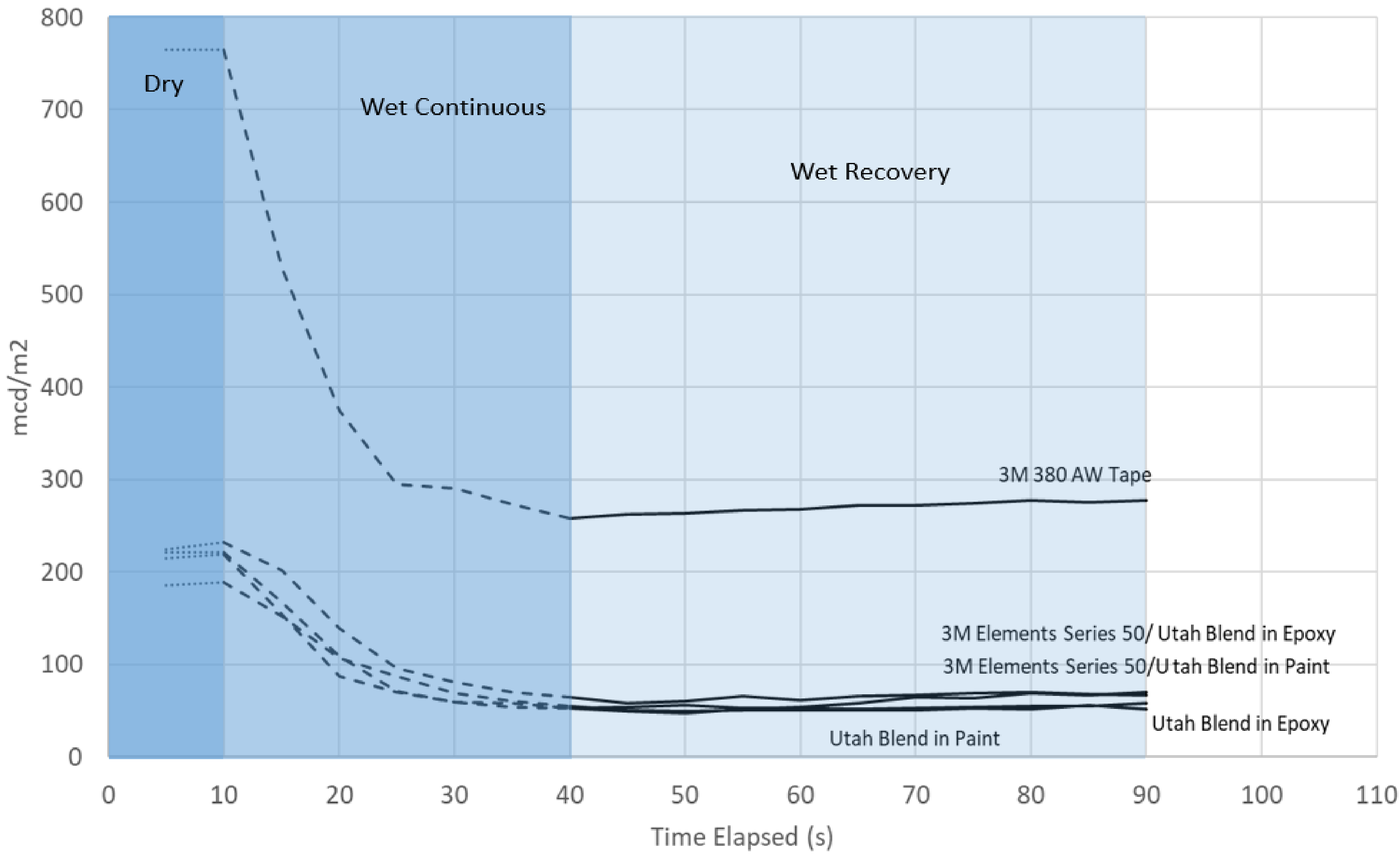


Figure 24. Average Wet Retroreflectivity for the Broken Lane Lines – from November 2018 (460 Days After Installation)

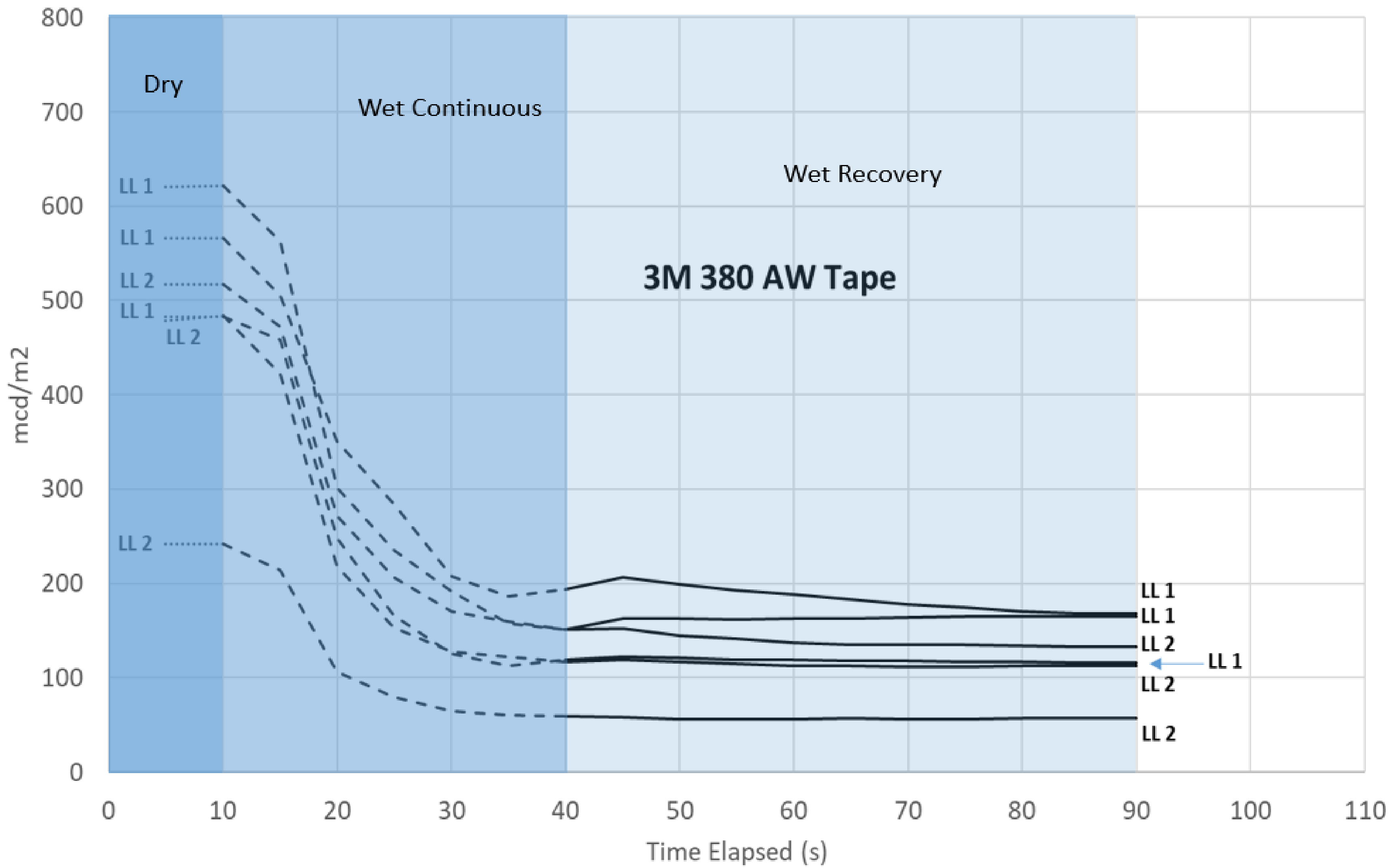


Figure 25. Average Wet Retroreflectivity for the Broken Lane Lines – from October 2019 (802 Days After Installation)

4.3 Additional Location Outside of the Test Deck (Utah-167 Trapper's Loop)

In addition to measurements conducted along the test deck, UDOT expressed interest in collecting data at a location that had been recently marked with 3M Stamark High Performance 380 IES Tape on the right white edge line and the broken white lane lines, and with 3M Series 50 with ceramic beads on the center line. The installation of the treatment date was estimated to be October 2018, and the measurements were taken in October 2019, so they are indicative of performance 12 months after installation.

The subject sections are located on Utah Highway 167, also known as Trapper's loop. This is a scenic highway that connects Huntsville Town with I-84, and it also serves traffic to major ski resort areas. Data was collected between mileposts 4.6 and 9.1, where the roadway cross section changes to provide climbing and passing lanes as shown in Figure 26.

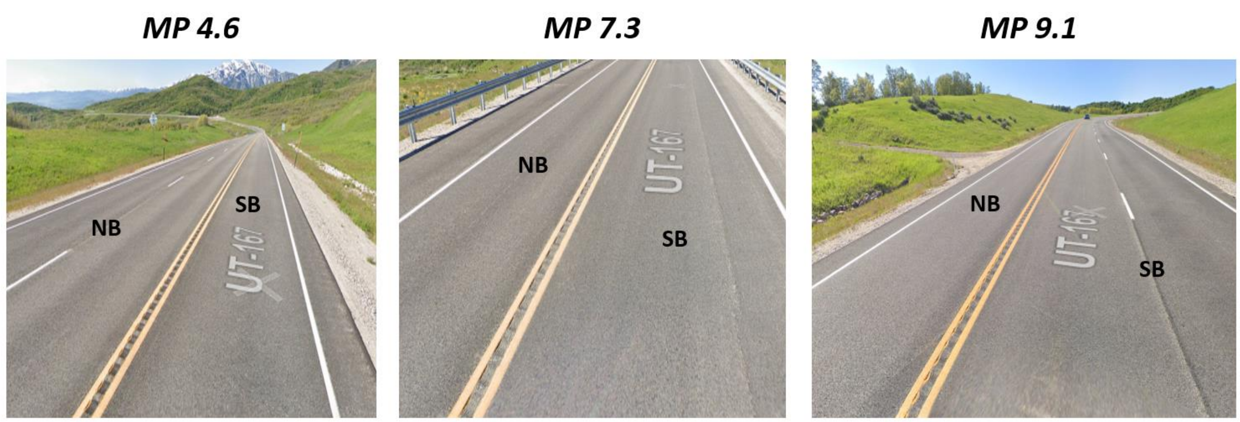


Figure 26. Data Collection Sections Along Utah 167 (Trapper's Loop)

Data collection followed the same protocols described for the test deck, where dry retroreflectivity was obtained from a mobile setup, and wet measurements were obtained from a semi-mobile setup.

Figure 27 shows the dry retroreflectivity between mile posts 4.6 and 9.1. Note that the broken lane line (LL) is not present during the transition around mile post 7.3, where the cross section only has two lanes. The ranges of retroreflectivity values for the 3M 380 IES tape for the right white edge lines were comparable in the two directions of traffic and generally in the order of over 600 mcd/m^2, whereas the broken white lane lines showed a lower range and were significantly different from each other. On the south end of the section (south of mile post 7), retroreflectivity values were higher and in the order of 600 mcd/m^2, but on the southbound they were on average close to 400 mcd/m^2 and less consistent throughout the section. Nonetheless, the residual retroreflectivity for both directions is well above recommended minimum values. (See Appendix A.18, A.19., and A.20. for the data used to create Figure 27).

Measurements along the center line (3M Series 50) showed retroreflectivity values that consistently fluctuated around 200 mcd/m^2 when measured in both directions of traffic. This is an interesting case that provides a confident perspective on the repeatability and accuracy of the data collected, given that the two continuous double yellow lines should have similar wear and show comparable performance, as the data in fact indicated. Also, it is pointed out that in comparison to measurements of the left yellow edge line from the test deck, values obtained from UT-167 showed lower ranges, which could be attributed to increased wear over time, again in part due to the roadway cross section. However, without initial readings at installation, this assumption could not be verified.

Figure 28 through 30 present a summary of the performance in wet conditions for the three sections at mile posts 4.6, 7.3, and 9.1, respectively. The broken white lane line (LL in the figures) at both three-lane sections showed the highest retroreflectivity at steady-state wet recovery condition, and in both sections with values above 300 mcd/m^2. Also, it is worth noting that the broken white lane line (3M 380 IES tape) showed a more prominent recovery immediately after the wet continuous phase, but these sections also had significant slope that could affect run-off compared to flatter profiles. (See Appendix A.21., A.22., and A.23. for the data used to create the figures.)

Performance of the continuous right white edge line (3M 380 IES tape) in the recovery stage was flat for the three northbound sections and for two of the southbound sections, only showing some increase in retroreflectivity to reach steady state at mile post 9.1. The range of values at wet recovery steady state was consistently between 150 to 200 mcd/m^2, except on the southbound section at mile post 9.1 where the steady-state values were well above 200 mcd/m^2.

Lastly, the yellow center line (3M series 50) also showed consistency, with the lowest range of values along the middle section at milepost 7.3, where the most wear is expected given the two lanes of traffic. On this section, values for the steady state recovery were in the order of 100 mcd/m^2 from initial dry levels of around 200 mcd/m^2. However, in the two remaining sections where the roadway consists of three lanes, the performance in wet recovery steady state was in the order of 120 to 220 mcd/m^2, from initial values that were higher than those for the center section.

Overall, even though the roadway sections evaluated on UT-167 were on rolling terrain, results were also consistent with expectations within and between lines and treatments. Retroreflectivity levels in dry conditions remain at satisfactory levels and they also maintain at least a minimum of 100 mcd/m^2 for wet recovery conditions at the time of data collection, providing an indication of their in-service performance after 12 months of operation.

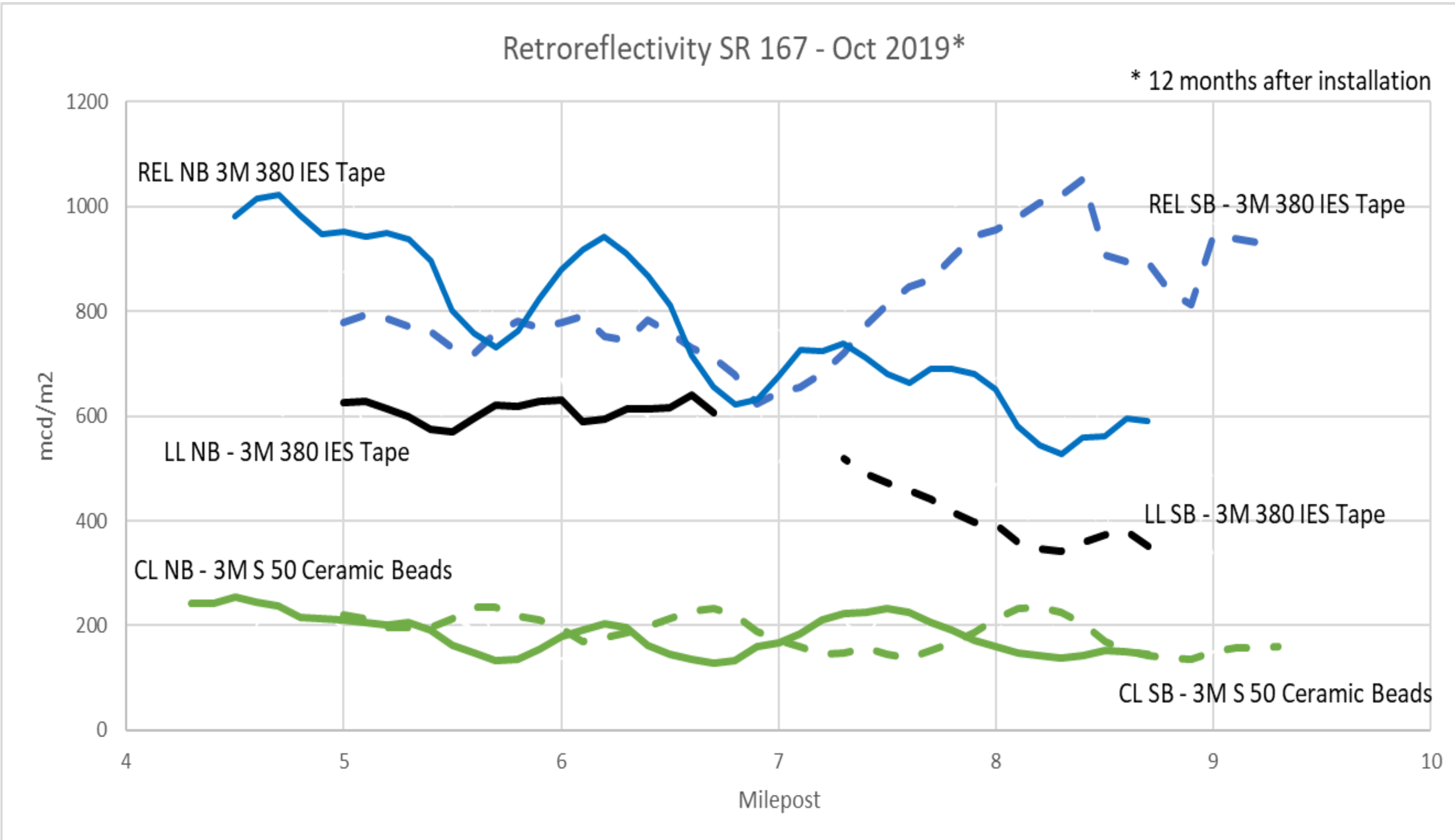


Figure 27. Moving Average (5-point) of Dry Retroreflectivity on UT-167 – from October 2019 (12 Months After Installation)

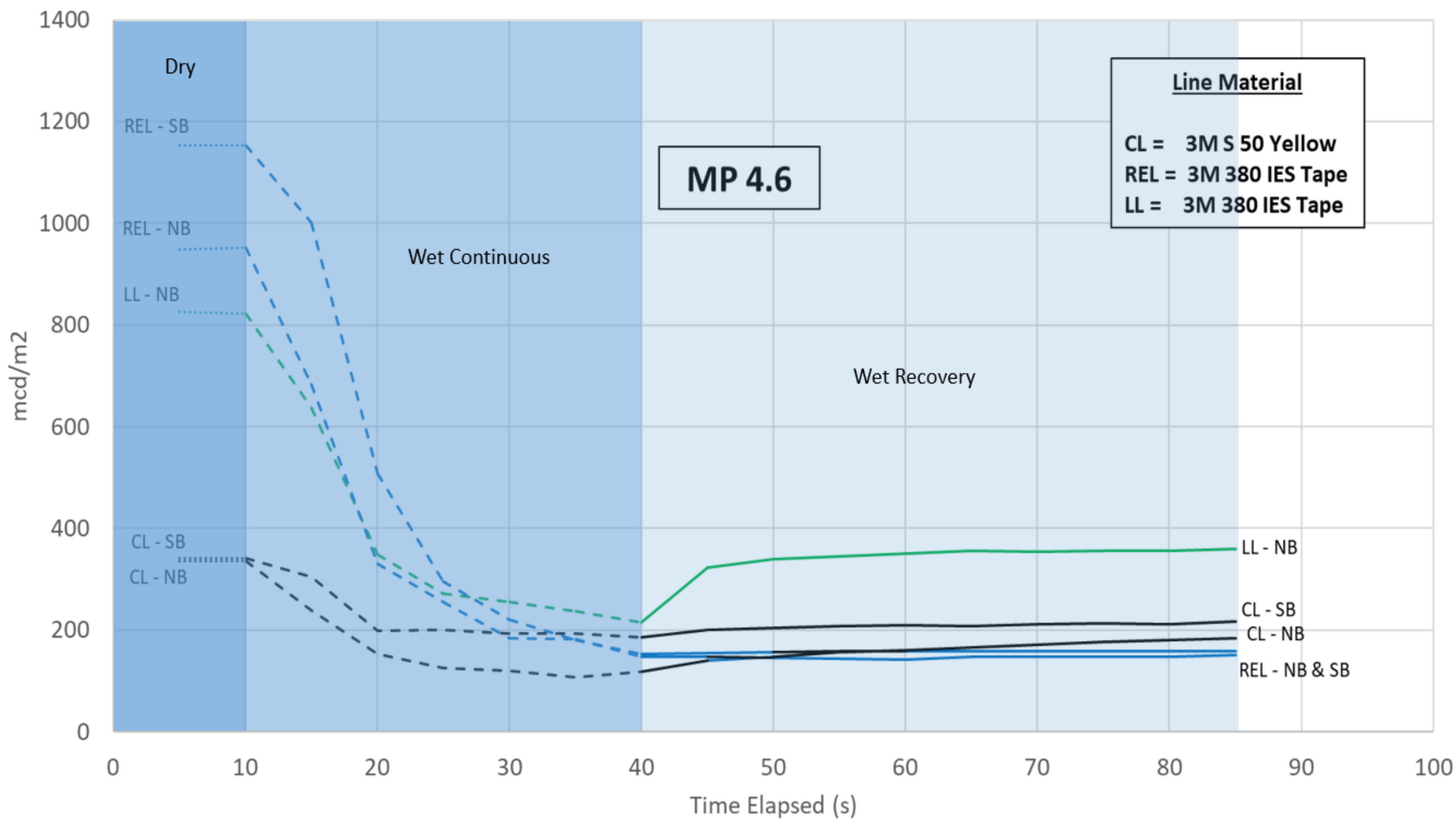


Figure 28. Average Wet Retroreflectivity on UT-167 at Mile Post 4.6 – from October 2019 (12 Months After Installation)

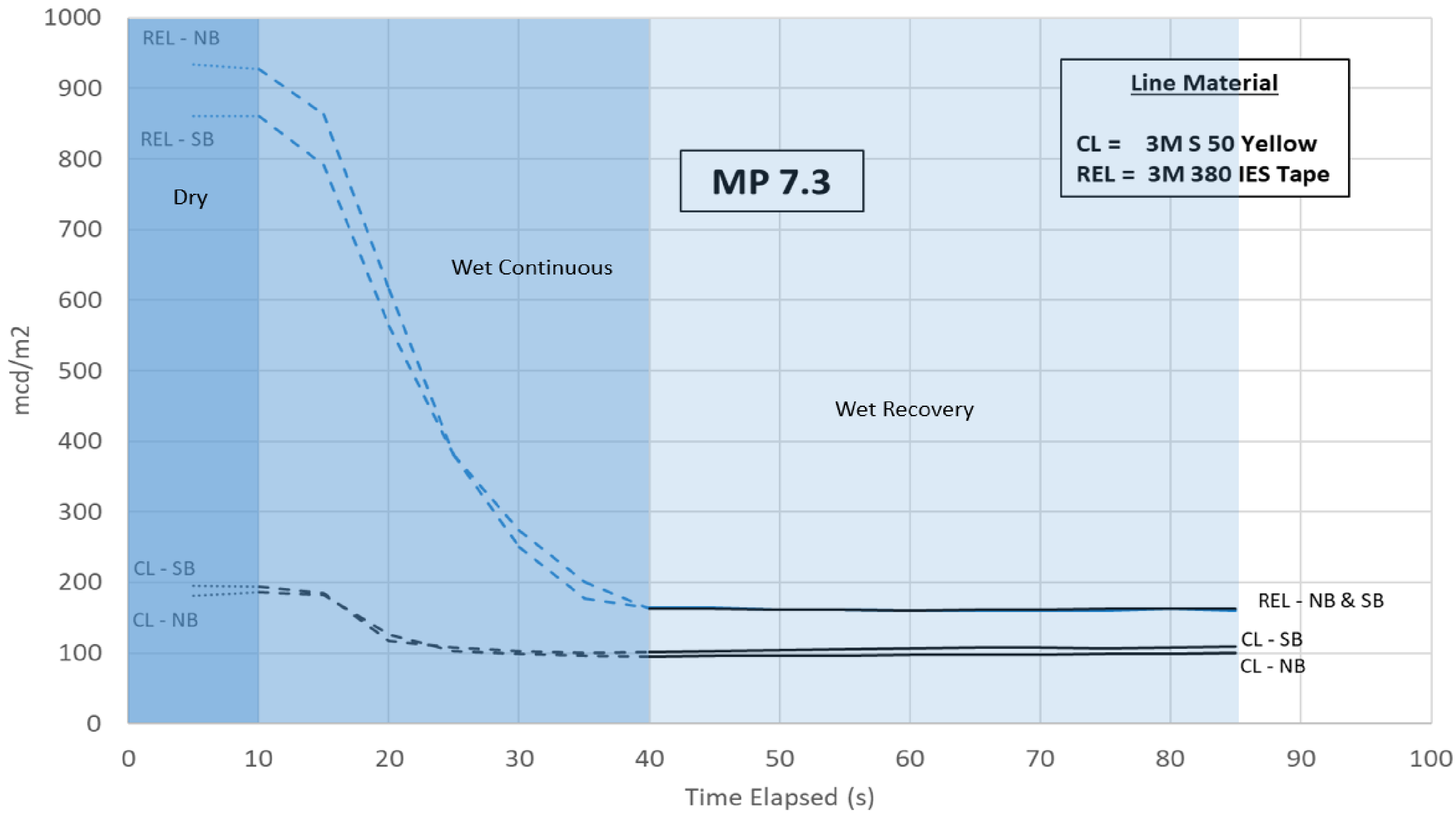


Figure 29. Average Wet Retroreflectivity on UT-167 at Mile Post 7.3 – from October 2019 (12 Months After Installation)

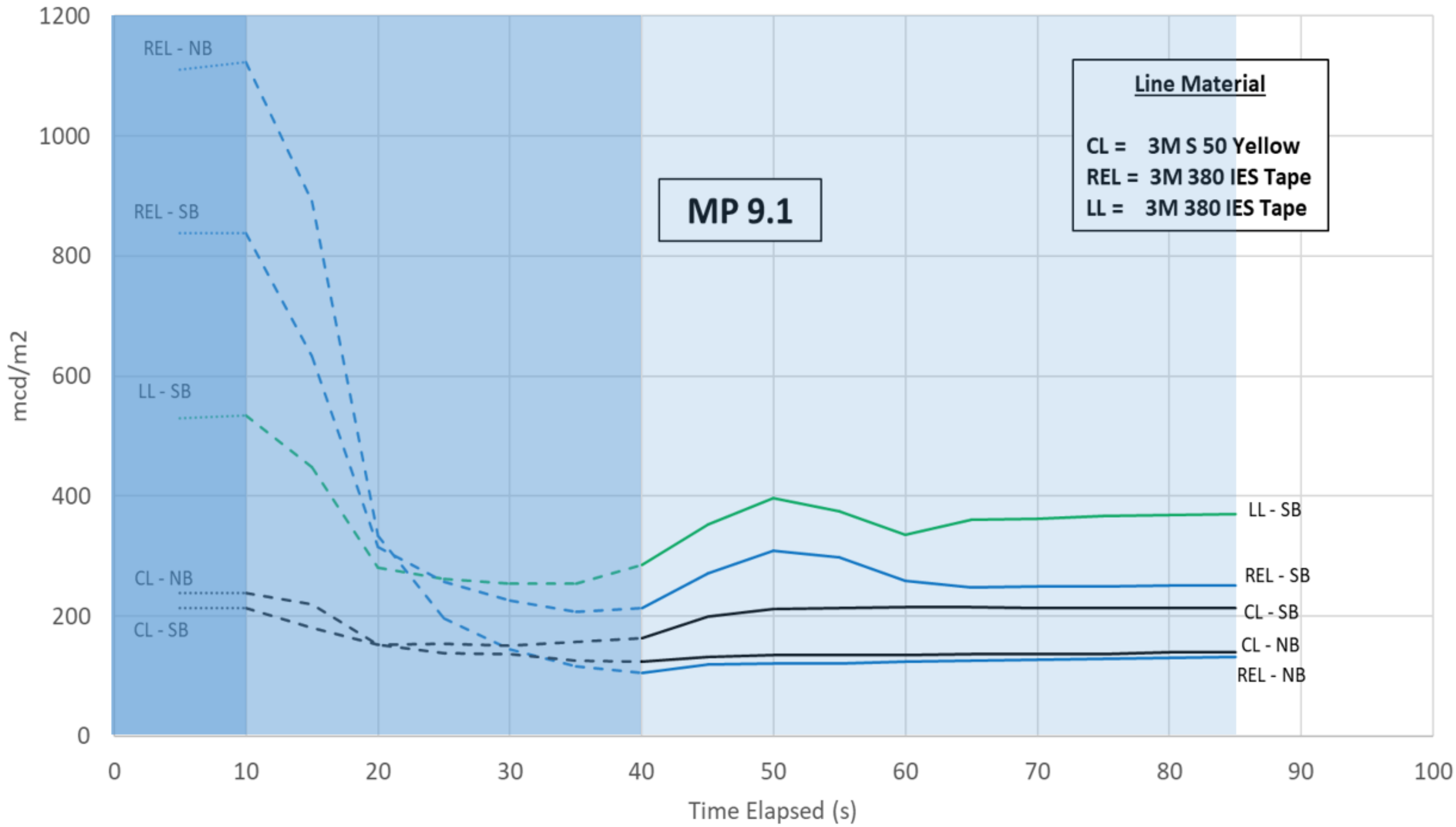


Figure 30. Average Wet Retroreflectivity on UT-167 at Mile Post 9.1 – from October 2019 (12 Months After Installation)

5.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

This field-based evaluation compares the retroreflectivity of a number of treatments for pavement markings applied to continuous yellow and white edge lines, as well as broken white lane lines. Measurements were taken along a test deck installed by UDOT in August 2017 on a section of I-215 with an even profile.

Results from an additional dataset collected at a different location on UT-167, also known as Trapper's Loop, are also included in this report. At this location, in addition to center yellow lines using the 3M Elements Series 50, the white edge and broken lane lines used a high-performance 3M 380 IES tape. Dry and wet retroreflectivity values were also obtained at the Trapper's Loop location.

Overall, the datasets collected as part of this study provide valuable information on the retroreflectivity of different pavement marking treatments at different points in time in freeway conditions. It is noted that the test deck installation and the datasets collected provided consistent results across sections, and indicated repeatability and accuracy levels that allowed side-by-side comparisons between all sections.

The retroreflectivity of the all-weather treatment (3M AW tape) indicated superior performance and durability both in dry and wet conditions, and across all line types, as expected. After 460 days in service, all treatments remained well above 100 mcd/m^2 in dry conditions, but the wet recovery retroreflectivity values were at or below that threshold, except the all-weather treatment. The 3M AW tape remained at satisfactory levels 802 days after installation (above 150 mcd/m^2) even in wet conditions for the continuous lanes, but lower ranges were observed for the right broken lane line, where increased wear was expected due to traffic in the center and right-most lanes.

Materials and installation costs were not available for this study, but they constitute an important element recommended to complement future field-based evaluations. Economic analysis based on treatment costs, performance, and durability indicators, is expected to lead to direct guidelines to make decisions on treatment selections by considering the long-term cost benefit of multiple alternatives. Economic analysis should also take traffic demand levels into consideration, as well as possible effects on safety and safety-related costs based on local crash data and research related to crash modification factors associated with retroreflectivity levels.

Continued data collection at the test deck for the section with the all-weather tape is also recommended to further document the performance of the treatment at and beyond the 3-year in-service mark. This extended evaluation period is well within the expected life of the material, and thus it would be important to better understand its long-term capabilities within a regional context.

Lastly, data collection and analysis at additional sites with varied cross sections and traffic demands is also recommended. A larger number of sites will contribute to further validation of the results in this evaluation, and also provide additional data points to model the effects of geometry and traffic on the performance and longevity of pavement marking treatments. Such models, in combination with economic analyses from future evaluations, can provide the basis for an objective decision-making support system to optimize pavement marking investment plans.

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[2]. ASTM E1710 – 11: Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer.

[3]. ASTM E2177 – 11: Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (RL) of Pavement Markings in a Standard Condition of Wetness.

[4]. ASTM E2832 – 12: Standard Test Method for Measuring the Coefficient of Retroreflected Luminance of Pavement Markings in a Standard Condition of Continuous Wetting.

[5]. ASTM D7585/D7585M − 10 (Reapproved 2015): Standard Practice for Evaluating Retroreflective Pavement Markings Using Portable Hand-Operated Instruments.

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APPENDICES

A.1. Retroreflectivity Data for the Left Yellow Edge Line – Along Section

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	9.9	713	297	254	
	9.8	518	181	176	
	9.7	663	221	208	
	9.6	650	184	176	
	9.5	715	251	170	
	9.4	753	256	226	
	9.3	812	263	249	
	9.2	790	287	233	
	9.1	759	320	225	
	9	704	310	201	
Utah Blend in Epoxy	8.9	295	169	149	
	8.8	298	214	164	
	8.7	299	218	152	
	8.6	299	224	177	
	8.5	303	214	169	
	8.4	313	218	170	
	8.3	289	212	172	
	8.2	278	160	136	
	8.1	287	177	149	
	8	331	217	172	
3M Elements Series 50 - Utah Blend in Modified Epoxy	7.9	509	305	208	
	7.8	466	353	214	
	7.7	534	363	222	
	7.6	509	364	245	
	7.5	548	370	260	
	7.4	469	332	233	
	7.3	533	328	199	
	7.2	532	291	203	
	7.1	506	343	221	
	7		364	279	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	7.1	982			
	7.2	867	285	173	
	7.3	894	251	183	
	7.4	908	198	178	
	7.5	887	254	219	
	7.6	835	349	287	
	7.7	788	322	249	
	7.8	707	425	289	
	7.9	888	393	290	
	8	926	424	299	
Utah Blend in Paint	8.1	269	326	214	
	8.2	305	271	227	
	8.3	280	243	181	
	8.4	335	260	194	
	8.5	318	250	164	
	8.6	346	230	178	
	8.7	325	258	181	
	8.8	306	301	218	
	8.9	300	277	211	
	9	348	272	250	
3M 380 AW Tape	9.1	326	296	217	269
	9.2	396	489	368	389
	9.3	330	376	311	313
	9.4	352	434	415	355
	9.5	380	397	366	341
	9.6	408	493	456	460
	9.7	374	440	404	402
	9.8	404	436	432	388
	9.9	376	445	417	421
	10	403	500	471	486

A.2. Retroreflectivity Data for the Right White Edge Line – Along Section

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	9.9	944	318	246	
	9.8	903	344	246	
	9.7	939	384	270	
	9.6	680	236	217	
	9.5	718	193	139	
	9.4	842	227	213	
	9.3	922	332	306	
	9.2	951	358	306	
	9.1	833	276	235	
	9	927	342	284	
Utah Blend in Epoxy	8.9	415	330	228	
	8.8	424	251	204	
	8.7	393	284	116	
	8.6	430	270	232	
	8.5	424	282	256	
	8.4	501	289	268	
	8.3	483	283	231	
	8.2	469	309	250	
	8.1	496	312	232	
	8	354	254	212	
3M Elements Series 50 - Utah Blend in Modified Epoxy	7.9	754	248	193	
	7.8	809	251	194	
	7.7	812	323	204	
	7.6	766	308	168	
	7.5	677	352	176	
	7.4	740	317	173	
	7.3	751.5	203	122	
	7.2	751.5	232	136	
	7.1	763	260	146	
	7				

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	7.1				
	7.2	1015	229	123	
	7.3	867	222	123	
	7.4	982.5	374	187	
	7.5	1098	420	242	
	7.6	1112	393	205	
	7.7	1021	290	176	
	7.8	1037	261	149	
	7.9	1159	388	206	
	8	984	288	183	
Utah Blend in Paint	8.1	639	155	102	
	8.2	569	231	135	
	8.3	529	222	94	
	8.4	523	299	169	
	8.5	494	295	154	
	8.6	489	328	175	
	8.7	495	369	212	
	8.8	503	319	187	
	8.9	541	249	147	
	9	662	188	104	
3M 380 AW Tape	9.1	1324	1227	786	554
	9.2	1301	1252	946	697
	9.3	1271	1251	989	653
	9.4	1284	1147	823	654
	9.5	1288	1224	857	665
	9.6	1292	1031	714	443
	9.7	1244	767	420	260.6
	9.8	1293	882	556	345.0
	9.9	1204	665	415	257.5
	10		826	499	322

A.3. Retroreflectivity Data for the Broken White Lane Line 1 – Along Section

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	9.9	935	302	301	
	9.8	843	240	241	
	9.7	882	273	268	
	9.6	726	251	291	
	9.5	906	310	329	
	9.4	918	329	343	
	9.3	860	333	332	
	9.2	901	347	346	
	9.1	890	304	326	
	9	826	287	295	
Utah Blend in Epoxy	8.9	500	252	258	
	8.8	550	291	254	
	8.7	524	300	300	
	8.6	550	276	287	
	8.5	549	268	291	
	8.4	534	283	274	
	8.3	457	275	255	
	8.2	443	182	195	
	8.1	467	218	216	
	8	473	233	234	
3M Elements Series 50 - Utah Blend in Modified Epoxy	7.9	738	210	193	
	7.8	786	238	241	
	7.7	809	262	260	
	7.6	872	289	255	
	7.5	729	273	240	
	7.4	807	257	227	
	7.3	714	238	215	
	7.2	768	222	205	
	7.1	743	258	221	
	7				

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	7.1	848			
	7.2	859	282	251	
	7.3	914	282	248	
	7.4	936	206	201	
	7.5	898	251	241	
	7.6	926	276	279	
	7.7	968	339	292	
	7.8	1024	411	354	
	7.9	1027	389	333	
	8	993	392	338	
Utah Blend in Paint	8.1	522	333	301	
	8.2	472	262	258	
	8.3	535	269	250	
	8.4	557	286	244	
	8.5	535	276	241	
	8.6	551	263	230	
	8.7	565	291	265	
	8.8	482	345	295	
	8.9	499	364	307	
	9	506	330	363	
3M 380 AW Tape	9.1	1051	1021	817	500
	9.2	1094	973	874	442
	9.3	1048	1160	1061	693
	9.4	977	1208	995	781
	9.5	1018	948	853	626
	9.6	1028	923	755	589
	9.7	1128	929	755	526
	9.8	1050	833	713	413
	9.9	1004	793	618	359
	10	1023	863	702	481

A.4. Retroreflectivity Data for the Broken White Lane Line 2 – Along Section

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2			
		Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	9.9	772	232	209	
	9.8	806.5	234	205	
	9.7	806.5	248	199	
	9.6	806.5	235	235	
	9.5	841	271	238	
	9.4	751	270	233	
	9.3	771	275	254	
	9.2	741	314	261	
	9.1	844	304	265	
	9	877	270	224	
Utah Blend in Epoxy	8.9	505	271	249	
	8.8	460	272	264	
	8.7	398	248	193	
	8.6	444	218	185	
	8.5	454	255	220	
	8.4	473	282	229	
	8.3	451	251	209	
	8.2	417	208	159	
	8.1	455	211	189	
	8	440	224	187	
3M Elements Series 50 - Utah Blend in Modified Epoxy	7.9	636	199	174	
	7.8	621	215	194	
	7.7	661	228	187	
	7.6	558	220	204	
	7.5	620	239	206	
	7.4	535	200	191	
	7.3	453	169	174	
	7.2	495	172	153	
	7.1	548	181	179	
	7			203	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2			
		Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	7.1		231		
	7.2		198	173	
	7.3		213	173	
	7.4		230	165	
	7.5		247	227	
	7.6		280	240	
	7.7		265	229	
	7.8		317	236	
	7.9		299	236	
	8		266	220	
Utah Blend in Paint	8.1		244	205	
	8.2		225	211	
	8.3		235	214	
	8.4		269	230	
	8.5		221	188	
	8.6		219	209	
	8.7		286	268	
	8.8		308	271	
	8.9		324	281	
	9		335	330	
3M 380 AW Tape	9.1		745	630	394
	9.2		773	771	470
	9.3		800	738	501
	9.4		837	790	567
	9.5		788	748	499
	9.6		739	711	423
	9.7		639	581	277
	9.8		570	487	178
	9.9		662	554	199
	10		610	536	

A.5. Retroreflectivity Data for the Left Yellow Edge Line – Changes Over Time

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	812	320	254	
	Minimum	518	181	170	
	Average	707.7	257	211.8	
Utah Blend in Epoxy	Maximum	331	224	177	
	Minimum	278	160	136	
	Average	299.2	202.3	161	
3M Elements Series 50 - Utah Blend in Modified Epoxy	Maximum	548	370	279	
	Minimum	466	291	199	
	Average	511.8	341.3	228.4	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	982	425	299	
	Minimum	707	198	173	
	Average	868.2	322.3	240.8	
Utah Blend in Paint	Maximum	348	326	250	
	Minimum	269	230	164	
	Average	313.2	268.8	201.8	
3M 380 AW Tape	Maximum	408	500	471	486
	Minimum	326	296	217	269
	Average	374.9	430.6	385.7	382.4

A.6. Retroreflectivity Data for the Right White Edge Line – Changes Over Time

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	951	384	306	
	Minimum	680	193	139	
	Average	865.9	301	246.2	
Utah Blend in Epoxy	Maximum	501	330	268	
	Minimum	354	251	116	
	Average	438.9	286.4	222.9	
3M Elements Series 50 - Utah Blend in Modified Epoxy	Maximum	812	352	204	
	Minimum	677	203	122	
	Average	758.2	277.1	168	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	1159	420	242	
	Minimum	867	222	123	
	Average	1030.6	318.3	177.1	
Utah Blend in Paint	Maximum	662	369	212	
	Minimum	489	155	94	
	Average	544.4	265.5	147.9	
3M 380 AW Tape	Maximum	1324	1252	989	697
	Minimum	1204	665	415	257.5
	Average	1277.9	1027.2	700.5	485.1

A.7. Retroreflectivity Data for the Broken White Lane Line 1– Changes Over Time

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	935	347	346	
	Minimum	726	240	241	
	Average	868.7	297.6	307.2	
Utah Blend in Epoxy	Maximum	550	300	300	
	Minimum	443	182	195	
	Average	504.7	257.8	256.4	
3M Elements Series 50 - Utah Blend in Modified Epoxy	Maximum	872	289	260	
	Minimum	714	210	193	
	Average	774.0	249.7	228.6	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	1027	411	354	
	Minimum	848	206	201	
	Average	939.3	314.2	281.9	
Utah Blend in Paint	Maximum	565	364	363	
	Minimum	472	262	230	
	Average	522.4	301.9	275.4	
3M 380 AW Tape	Maximum	1128	1208	1061	781
	Minimum	977	793	618	359.0
	Average	1042.1	965.1	814.3	541.0

A.8. Retroreflectivity Data for the Broken White Lane Line 1– Changes Over Time

Marking Treatment (Eastbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum	877	314	265	
	Minimum	741	232	199	
	Average	801.65	265.3	232.3	
Utah Blend in Epoxy	Maximum	505	282	264	
	Minimum	398	208	159	
	Average	449.7	244	208.4	
3M Elements Series 50 - Utah Blend in Modified Epoxy	Maximum	661	239	206	
	Minimum	453	169	153	
	Average	569.7	202.6	186.5	

Marking Treatment (Westbound Lanes)	Mile Marker	Retroreflectivity mcd/m2 Date of Data Collection			
		8/20/2017	7/18/2018	11/4/2018	10/12/2019
3M Elements Series 50 - Utah Blend in Paint	Maximum		317	240	
	Minimum		198	165	
	Average		254.6	211.0	
Utah Blend in Paint	Maximum		335	330	
	Minimum		219	188	
	Average		266.6	240.7	
3M 380 AW Tape	Maximum		837	790	567
	Minimum		570	487	178.0
	Average		716.3	654.6	389.8

A.9. Wet Retroreflectivity Data for the Left Yellow Edge Line – from July 2018

3M Elements Series 50 - Utah Blend in Paint

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	257.4		
10	257.2	257.2	
15		253.2	
20		227.4	
25		181	
30		145.6	
35		138.4	
40		123.6	123.6
45			126
50			111.6
55			117.6
60			115
65			142.4
70			146.4
75			147.4
80			150.6
85			149.2
90			154.2

Utah Blend in Epoxy

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	163.3		
10	163.7	163.7	
15		163.0	
20		127.7	
25		64.3	
30		54.3	
35		52.0	
40		50.3	50.3
45			49.3
50			51.7
55			51.3
60			50.7
65			52.0
70			51.0
75			50.0
80			51.0
85			54.0
90			56.7

3M Elements Series 50 - Utah Blend in Mod. Epoxy

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	235.6		
10	236.4	236.4	
15		229.0	
20		201.0	
25		157.6	
30		120.0	
35		106.4	
40		98.6	98.6
45			93.2
50			86.6
55			83.2
60			86.2
65			85.4
70			86.6
75			89.2
80			92.2
85			95.0
90			99.8

Utah Blend in Paint

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	270.0		
10	271.3	271.3	
15		270.0	
20		203.0	
25		139.7	
30		110.0	
35		98.3	
40		84.7	84.7
45			74.7
50			68.7
55			60.7
60			59.3
65			60.7
70			60.3
75			64.7
80			69.3
85			73.3
90			78.0

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	504.7		
10	505.3	505.3	
15		505.7	
20		458.0	
25		350.3	
30		311.3	
35		304.0	
40		297.7	297.7
45			295.0
50			298.7
55			307.3
60			298.0
65			293.7
70			294.0
75			300.0
80			306.3
85			312.0
90			317.7

A.10. Wet Retroreflectivity Data for the Left Yellow Edge Line – from November 2018

3M Elements Series 50 - Utah Blend in Paint

Utah Blend in Epoxy

3M Elements Series 50 - Utah Blend in Mod. Epoxy

Utah Blend in Paint

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.11. Wet Retroreflectivity Data for the Left Yellow Edge Line – from October 2019

3M 380 AW Tape – Sample 1 | 3M 380 AW Tape – Sample 2 | 3M 380 AW Tape – Sample 3

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	412.0		
10	442.3	442.3	
15		426.0	
20		288.3	
25		268.0	
30		230.0	
35		200.0	
40		203.0	203.0
45			220.3
50			294.0
55			240.3
60			208.3
65			200.3
70			200.0
75			198.3
80			198.0
85			190.0
90			

A.12. Wet Retroreflectivity Data for the Right White Edge Line – from July 2018

3M Elements Series 50 - Utah Blend in Paint

Utah Blend in Epoxy

3M Elements Series 50 - Utah Blend in Mod. Epoxy

ecovery

Utah Blend in Paint

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.13. Wet Retroreflectivity Data for the Right White Edge Line – from November 2018

3M Elements Series 50 - Utah Blend in Paint

Utah Blend in Epoxy

3M Elements Series 50 - Utah Blend in Mod. Epoxy

Utah Blend in Paint

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.14. Wet Retroreflectivity Data for the Right White Edge Line – from October 2019

3M 380 AW Tape – Sample 1

3M 380 AW Tape – Sample 2

3M 380 AW Tape – Sample 3

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			

A.15. Wet Retroreflectivity Data for the Broken Lane Lines – from July 2018

3M Elements Series 50 - Utah Blend in Paint

Utah Blend in Epoxy

3M Elements Series 50 - Utah Blend in Mod. Epoxy

Utah Blend in Paint

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.16. Wet Retroreflectivity Data for the Broken Lane Lines – from November 2018

3M Elements Series 50 - Utah Blend in Paint

Utah Blend in Epoxy

3M Elements Series 50 - Utah Blend in Mod. Epoxy

Utah Blend in Paint

3M 380 AW Tape

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.17. Wet Retroreflectivity Data for the Broken Lane Lines – from October 2019

3M 380 AW Tape – Lane Line 1 Sample 1

3M 380 AW Tape – Lane Line 1 Sample 2

3M 380 AW Tape – Lane Line 1 Sample 3

3M 380 AW Tape – Lane Line 2 Sample 1

3M 380 AW Tape – Lane Line 2 Sample 2

3M 380 AW Tape – Lane Line 2 Sample 3

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			[illegible]

A.18. Retroreflectivity Data on UT-167 – Center Lines (CL) – from October 2019

Marking Treatment: 3M Series 50 in Microcrystalline Ceramic Beads

Northbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
4.6	202
4.7	246
4.8	245
4.9	219
5	195
5.1	164
5.2	160
5.3	239
5.4	217
5.5	280
5.6	280
5.7	159
5.8	155
5.9	184
6	194
6.1	151
6.2	199
6.3	199
6.4	245
6.5	268
6.6	231
6.7	215
6.8	144
6.9	89
7	175
7.1	171
7.2	145
7.3	156
7.4	135
7.5	123
7.6	133
7.7	215
7.8	230
7.9	236
8	248
8.1	233
8.2	233
8.3	177
8.4	128
8.5	82
8.6	145
8.7	184
8.8	155
8.9	114
9	149
9.1	182
9.2	190
9.3	165

Southbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
9.1	111
9	138
8.9	189
8.8	159
8.7	126
8.6	143
8.5	146
8.4	146
8.3	124
8.2	152
8.1	173
8	205
7.9	207
7.8	221
7.7	223
7.6	271
7.5	236
7.4	179
7.3	207
7.2	156
7.1	147
7	143
6.9	141
6.8	76
6.7	131
6.6	182
6.5	196
6.4	223
6.3	246
6.2	173
6.1	122
6	137
5.9	95
5.8	147
5.7	160
5.6	198
5.5	206
5.4	247
5.3	219
5.2	138
5.1	216
5	236
4.9	259
4.8	229
4.7	244
4.6	258
4.5	277
4.4	204
4.3	226

A.19. Retroreflectivity Data on UT-167 – Right Edge Line (REL) – from October 2019

Marking Treatment: 3M 380 IES Tape

Northbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
4.6	731
4.7	782
4.8	741
4.9	763
5	876
5.1	802
5.2	742
5.3	676
5.4	707
5.5	728
5.6	752
5.7	930
5.8	791
5.9	648
6	775
6.1	815
6.2	736
6.3	750
6.4	838
6.5	651
6.6	669
6.7	639
6.8	594
6.9	559
7	765
7.1	718
7.2	775
7.3	783
7.4	823
7.5	965
7.6	892
7.7	837
7.8	999
7.9	1023
8	1033
8.1	1002
8.2	976
8.3	1077
8.4	1176
8.5	305
8.6	945
8.7	954
8.8	802
8.9	1051
9	967
9.1	920
9.2	920

Southbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
9.1	572
9	484
8.9	535
8.8	769
8.7	587
8.6	601
8.5	316
8.4	525
8.3	609
8.2	673
8.1	775
8	671
7.9	672
7.8	662
7.7	669
7.6	637
7.5	758
7.4	833
7.3	799
7.2	589
7.1	648
7	508
6.9	616
6.8	743
6.7	765
6.6	956
6.5	971
6.4	898
6.3	963
6.2	920
6.1	843
6	776
5.9	619
5.8	650
5.7	765
5.6	974
5.5	1004
5.4	1082
5.3	859
5.2	830
5.1	941
5	1047
4.9	1059
4.8	1040
4.7	1027
4.6	897
4.5	883

A.20. Retroreflectivity Data on UT-167 – Broken Lane Lines (LL) – from October 2019

Marking Treatment: 3M 380 IES Tape

Northbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
4.6	565
4.7	598
4.8	616
4.9	669
5	680
5.1	578
5.2	524
5.3	544
5.4	544
5.5	662
5.6	707
5.7	652
5.8	525
5.9	599
6	671
6.1	500
6.2	674
6.3	628
6.4	598
6.5	676
6.6	630
6.7	501
6.8	-
6.9	-
7	-
7.1	-
7.2	-
7.3	-
7.4	-
7.5	-
7.6	-
7.7	-
7.8	-
7.9	-
8	-
8.1	-
8.2	-
8.3	-
8.4	-
8.5	-
8.6	-
8.7	-
8.8	-
8.9	-
9	-
9.1	-
9.2	-

Southbound readings

Mile Marker	Retroreflectivity mcd/m2
	Average
9.1	249
9	335
8.9	451
8.8	400
8.7	324
8.6	391
8.5	306
8.4	378
8.3	312
8.2	352
8.1	447
8	471
7.9	410
7.8	409
7.7	467
7.6	533
7.5	551
7.4	486
7.3	557
7.2	-
7.1	-
7	-
6.9	-
6.8	-
6.7	-
6.6	-
6.5	-
6.4	-
6.3	-
6.2	-
6.1	-
6	-
5.9	-
5.8	-
5.7	-
5.6	-
5.5	-
5.4	-
5.3	-
5.2	-
5.1	-
5	-
4.9	-
4.8	-
4.7	-
4.6	-
4.5	-
4.4	-

A.21. Wet Retroreflectivity Data near Mile Marker 4.6 – from October 2019

Center Line Northbound – Mile Marker 4.6

Center Line Southbound – Mile Marker 4.7

Lane Line Southbound – Mile Marker 4.6

Right Edge Line Northbound – Mile Marker 4.6

Right Edge Line Southbound – Mile Marker 4.8

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			

Line Treatments:

Center Lines: 3M Series 50 in Microcrystalline Ceramic Beads

Right Edge Lines: 3M 380 IES Tape

Lane Lines: 3M 380 IES Tape

A.22. Wet Retroreflectivity Data near Mile Marker 7.1 – from October 2019

Center Line Northbound – Mile Marker 7.3

Center Line Southbound – Mile Marker 7.1

Lane Line Southbound – N/A

Right Edge Line Northbound – Mile Marker 7.3

Right Edge Line Southbound – Mile Marker 7.1

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			

Line Treatments:

Center Lines: 3M Series 50 in Microcrystalline Ceramic Beads

Right Edge Lines: 3M 380 IES Tape

Lane Lines: 3M 380 IES Tape

A.23. Wet Retroreflectivity Data near Mile Marker 9.1 – from October 2019

Center Line Northbound – Mile Marker 9.1

Center Line Southbound – Mile Marker 9.1

Lane Line Southbound – Mile Marker 9.1

Right Edge Line Northbound – Mile Marker 9.1

Right Edge Line Southbound – Mile Marker 9.1

Seconds Elapsed	Retroreflectivity mcd/m2		
	Test Stage		
	Dry	Wet Continuous	Wet Recovery
5	[illegible]		
10	[illegible]	[illegible]	
15		[illegible]	
20		[illegible]	
25		[illegible]	
30		[illegible]	
35		[illegible]	
40		[illegible]	[illegible]
45			[illegible]
50			[illegible]
55			[illegible]
60			[illegible]
65			[illegible]
70			[illegible]
75			[illegible]
80			[illegible]
85			[illegible]
90			

Line Treatments:

Center Lines: 3M Series 50 in Microcrystalline Ceramic Beads

Right Edge Lines: 3M 380 IES Tape

Lane Lines: 3M 380 IES Tape