Deterioration Characteristics of Pavement Markings

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By
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Authorization to Submit

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Abstract

Pavement markings assist drivers in navigating rural highways especially during night time. For this study, white waterborne pavement marking retroreflectivity data was collected on two lane rural highways in Idaho and then compared to an accelerated lab test using pavement slabs. Retroreflectivity readings were taken for thirty-eight test sites with six-inch markings and thirty-eight control sites with four-inch markings. The relationship between the field data over the course of one year and the accelerated lab data was linked by comparing the number of traffic passes in the field to the number of passes from the three-wheel polisher device in the lab. To establish this relationship a pneumatic, steel, and pneumatic with scraper blade wheel conditions were run in the lab to correlate the field data and normalized ground snow loads for each traffic district in Idaho. A logarithmic relationship was determined for waterborne pavement markings in the lab and field. Finally, crash data was analyzed for both the test and control sites to examine the crash rates of the normal and wide white waterborne pavement markings. It was found that the wider pavement markings did slightly improve the safety of the rural highways in Idaho.

Keywords: Pavement Markings, Waterborne Paint, Retroreflectivity Deterioration, Three-Wheel Polisher, Snowplowing, Wide Pavement Markings, Crash Analysis

Supplementary Files:

Andy Skinner Pavement Marking Lab and Field Data.xlsx: Raw data collected for lab and field data, analysis of lab and field data.

Andy Skinner WIDE Crash Data Master Final.xlsx: Raw crash data and crash analysis.

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Dedication

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Chapter 1: Introduction

Pavement markings provide a visual guide for drivers to navigate the road and help drivers stay in their lane especially during nighttime and tough weather conditions. It is important that pavement markings are well maintained by state DOTs to ensure drivers can get to their destinations safely. The two most important qualities of pavement markings that assist drivers are the visibility and durability of the markings. The visibility relates to how bright the pavement markings are reflected back to the driver. Visibility is especially important during the night when these markings are the primary guide for drivers. Durability is percent of the marking painted that remains on the road. It is critical that pavement markings are both visible and durable. (1)

Pavement markings are classified as durable and nondurable. Durable pavement markings can contain a variety of chemical compounds such as epoxy, thermoplastics, methyl methacrylate, polyurea, polyurethane, and tape (3,4,5). While these markings will maintain their visibility and durability far longer than nondurable markings, they are more harmful to the environment. Nondurable pavement markings have a lower expected lifetime (one year) than durable markings (three or more years depending on type). The lifetime of nondurable pavement markings can vary based on traffic, weather, and other environmental conditions. Nondurable markings are composed of solvent and water-based paints that are friendly to the environment. Also, nondurable pavement markings cost significantly less than durable pavement markings.

The factors considered in choosing a pavement marking include: line type, pavement surface, traffic volume, speed, road type, snowfall, and geometry. For areas with high traffic volumes and snowfall, a durable pavement marking would be better than a nondurable one due to increased service life. It is the responsibility of the state DOT to select the most appropriate pavement marking for a road segment. Each DOT’s criteria is different regarding what kind of marking to apply based on the state’s weather conditions, traffic, and other factors. Roughly 98 percent of pavement markings in Idaho are waterborne.

Waterborne Pavement Markings

Waterborne pavement markings are nondurable and have a short-estimated service life of one year. The short service life is a result of the wearing caused by traffic, weather, and snow plowing. Waterborne pavement markings are suitable for low-volume roads and temporary marking situations. Idaho has many low-volume roads, which is why 98 percent of Idaho's roads use waterborne paints. Waterborne paints obtain their reflective property from small glass beads embedded within the paint. These glass beads are small spherical balls that sink into the paint and reflect light. The beads are commonly sprayed on top of the binder while the pavement markings are being applied. It is critical that these glass beads have the correct refractive index, diameter, roundness, and embedment in the pavement markings. Research has shown that having 60% of the bead embedded in the paint is the most efficient practice. This embedment is key for driver visibility as well as keeping the beads sealed into the paint when the wearing process occurs during the service life. The AASHTO M 247 classified five types of glass beads (I, II, III, IV, and V) with Type I being the standard and most common. (5,7,8).

Pavement Marking Performance Evaluation

There are currently no regulations in the MUTCD regarding minimum standards for retroreflectivity of pavement markings. Several studies have been sponsored by the Federal Highway Administration to establish these regulations (10,11). The current standard of practice for testing pavement markings is performed using a test deck created by the American Association of State Highway and Transportation Official's (AASHTO) National Transportation Product Evaluation Program (NTPEP). This test deck consists of applying pavement markings to a section of road horizontally and then monitoring the wearing of the markings over time by continuous traffic. The retroreflectivity readings are recorded for a period of up to three years depending on the kind of markings. (8). This process requires significant effort to stripe the pavement markings, collect the retroreflectivity readings, and then analyze the performance for up to three years. It would be much simpler to test pavement markings using an accelerated laboratory test since less manpower is required and would be less time consuming than the current practice.

There are accelerated pavement marking wear testing machines that have been proposed for research. Three examples of these machines are the Model Mobile Load Simulator, third scale (MMLS3), and the Three Wheel Polisher Device (TWPD). Originally, the TWPD was designed to evaluate skid resistance in asphalt pavements. Recently, the Illinois Department of Transportation attempted to use the TWPD to evaluate pavement markings in a research project. Preliminary results revealed that the TWPD produces gradual decay of pavement markings. The exact relationship between the TWPD and field conditions was determined. This means that the TWPD was not nearly as correlated to the field conditions as the NTPEP test deck procedure (17).

Pavement Marking Deterioration Models

Due to the complex nature of determining a pavement marking deterioration model, a variety of functions have been developed to estimate the rate at which pavement markings degrade over their lifetime. These models include: linear, exponential, natural logarithmic, quadratic, Arima, multiple series regression, and inverse polynomial with the most recent studies preferring the multiple linear regression models (5,6,7). These models included independent variables such as age, traffic volume, weather, and road geometry. The performance measures for evaluating the markings included retroreflectivity, durability, and color retention. While most research agreed that snow plowing degrades pavement markings, there was conflicting research regarding the effect of traffic. Some researchers claim that traffic has a very small impact of deterioration while others did not find AADT to be statistically significant. The objective of these models was to create pavement marking deterioration models for the study area and provide this information to state DOTs so that the markings could be replaced at the correct time.

Snowplowing is the process of removing snow and ice from roads in colder regions using a truck with a snow scraping blade mounted on the front. Snow scraping blades can either be classic, dowel-type steel with carbide inserts or serrated blades. In addition to snowplowing, anti-icing and de-icing can be applied to roads to prevent or mitigate ice. Anti-icing materials are commonly applied before the snow season to prevent ice from accumulating on road surfaces. De-icing chemicals can be applied to ice that is currently on the road to melt the ice. A study in Virginia in 1994 aimed to quantify the impact of snow removal processes including snow plowing, chemicals, and abrasives. This study concluded that snow removal resulted in 24% of pavement markings retroreflectivity loss in a single year. In addition to this study, researchers in North Carolina also attempted to quantify the effect of the snow plow itself and concluded that each pass of a snowplow reduces the retroreflectivity by 3.22 mcd⁄m2⁄lux. (12,13)

Wide Pavement Marking Safety Evaluation

Research has shown that wider, six-inch-long, pavement markings do not result in conclusive evidence regarding the impact on driving safety. Wider pavement markings have more glass beads and, intuitively, should deteriorate at a slower rate than the normal four-inch-wide pavement markings. Park et al. conducted a study regarding wider pavement marking safety on rural highways in Kansas, Michigan, and Illinois. The study concluded that wider edge pavement markings do reduce the risk of crashes. However, a different study conducted by Lum and Hughes was unable to find a link between wide pavement markings and safety. They were only able to conclude that wide pavement markings reduce lane encroachments (9,10).

Safety evaluation research for pavement markings has also commonly been analyzed at night time. Drivers are significantly more likely to crash at nighttime if their main guide to the road is not present enough on the roadway. Studies have been conflicting regarding the relationship between the quality of pavement markings and nighttime single vehicle run-off-the-road (SVROR) crashes. Road segments with higher retroreflectivity pavement markings had fewer crashes than the segments with lower retroreflectivity. In addition to reducing crashes, crash severity is also reduced. Higher quality pavement markings will lead to less severe crashes. It should be noted that it is often difficult to establish crash databases related to pavement markings since most of state DOTs do not have a category in the police form regarding an inability to see pavement markings. (14)

Chapter 2: Objectives

The objective of this research is to evaluate the field performance of pavement markings using rural road segments in Idaho and develop a field deterioration model. This model will then be compared a deterioration model developed in the lab using a TWPD. Finally, the safety of the wider pavement markings will be evaluated using a generalized linear segmented regression. The following steps were taken to complete these objectives:

- Test and control road segments were randomly selected throughout each of the six traffic districts in Idaho.
- Retroreflectivity data was collected over the course of one year to provide adequate data to create a deterioration model. A unique model was developed for each district.
- A normalized ground snow load map was generated for each district in Idaho. Idaho has unique climates in each district (some with much more snow than others) so the effect of snowfall could be easily compared.
- Asphalt slabs were prepared in the lab and painted with waterborne paint similar to how they are applied everywhere in Idaho at the Idaho Transportation Department's (ITD) District 2 office in Lewiston.
- The asphalt slabs were then tested in the lab using a TWPD under the loading conditions of pneumatic tires, steel tires, and pneumatic with scraper blade. Data for retroreflectivity, color retention, and presence were recorded for each loading condition.
- The relationship between the lab and field data measurement for retroreflectivity was investigated.
- Crash data was retrieved through WebCARS for the test and control sites. Linear regression models were then developed to compare the effects of the normal and wide pavement markings.

Chapter 3: Methodology

Field Data Collection

Thirty-eight two-lane rural highways in Idaho were randomly selected for this study. The test sites, containing 175.39 miles of white edgeline pavement markings, and the control sites, with 168 miles of regular white edgeline pavement markings, were chosen from the criteria of waterborne paint, flexible pavement, and an ADT of less than 4,000 vehicles. Generally, pavement markings in Idaho are striped between early April and late August every year. The exact timing of the pavement marking most depends on the weather conditions. Roads cannot be striped during wet and rainy conditions or at low temperatures. Three data collection trips were completed in July, November, and April in order to develop the field deterioration models for each district. Retroreflectivity measurements were taken using an MX 30 retroreflectometer as seen in Figure 3.1. Three measurements at three different areas near the mile marker were taken for a total of nine readings at each mile marker. In total, three measurements (averaged from the three readings at the same location) were recorded by hand at each mile point and then transferred to a database. These results can be seen in Appendix A.

Figure 3.1: MX 30 Retroreflectometer

Laboratory Data Collection

Asphalt slabs were prepared using a steel mold and plate compacter as seen in Figures 3.2a, b and c below. The steel mold ensured that each slab would be twenty inches wide by twenty inches long by two inches tall. The plate compactor was used to compact the asphalt into the mold. Once the slab preparation was complete, they were transported to the District 2 ITD office in Lewiston to be painted. The same truck (Figure 3.2e and f) that paints all the roads in District 2 was used on the slabs. The paint was classified on the most current Qualified Products list as color of category 707, sub category No. 14 waterborne while the striping truck was calibrated per ASTM D713-90. After the slabs were implanted into the ground (Figure 3.2d) and the striping equipment was calibrated, the truck applied the waterborne paint to the asphalt slabs moving at roughly 5 mph and a bead drop rate of 8lbs/gal (Figures 3.2e and f). The resulting paint wet mil thickness was 17 mils as it is throughout Idaho.

Figure 3.2: (a, b, c) Slab preparation, (d) Slab placement for striping, (e,f) Striping of slabs

Laboratory Testing

Once the pavement slabs were painted by ITD, they were then subjected to testing in the lab by the TWPD. The TWPD polishes in a circular pattern using three wheels of 11-inch diameter while constantly applying water as seen in Figure 3.3a. A pneumatic, steel, and pneumatic with scraper blade wheelset conditions were used in evaluating the pavement markings. The pneumatic only wheelset simulated the wearing caused by traffic in the field while the steel wheel simulated the effect of snowplowing alone. Finally, the pneumatic with scraper blade wheelset was designed as seen in Figure 3.4a and b to simulate the effect of traffic and snowplowing together. All tests were conducted at room temperature. Due to the nature of the research, it was uncertain how many cycles would be necessary to reach the end of the pavement marking service life. Data was taken every fifty cycles for the first slab and then it was determined that taking readings at regular logarithmic base 10 intervals was appropriate.

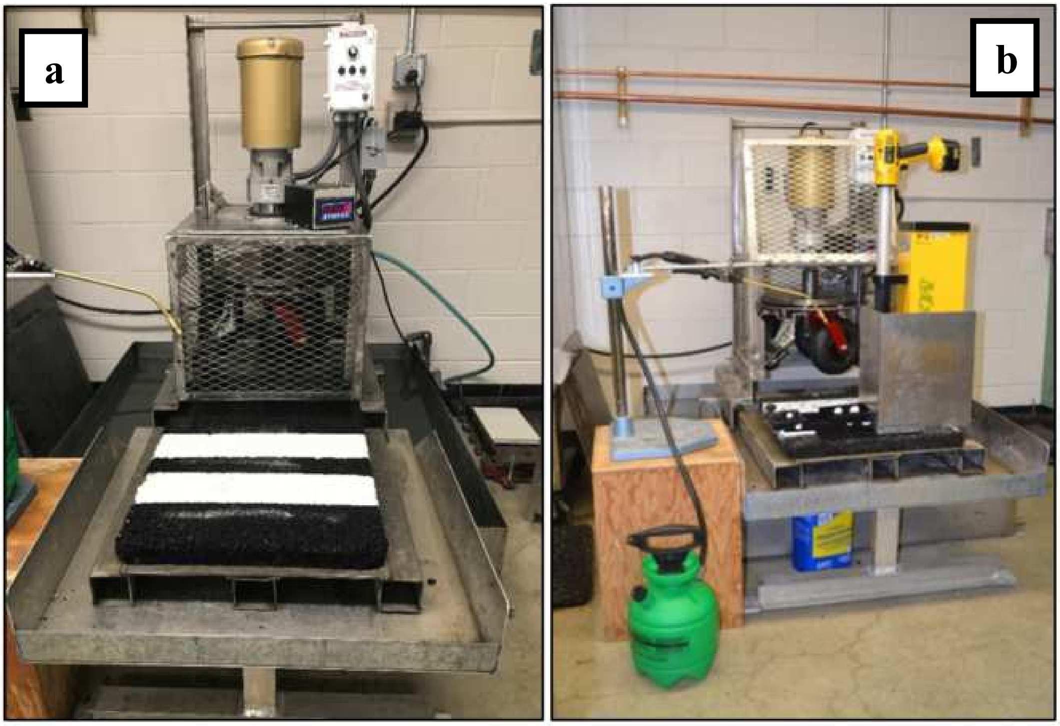


Figure 3.3: (a) TWPD, (b) Taking readings on test slab

The surface of the pavement marking affected by the wheel path was chosen for data collection. Areas not affected by the TWPD were originally studied but later used as a reference point. Since the MX 30 retroreflectometer gathered readings in an area of 4 x 3.5 inches and wheel path only affected an area of 1.57 x 3.15 inches, a permanent frame was used during all retroreflectivity readings. Before any readings were taken, this frame was calibrated to determine adjustment factors for all retroreflectivity readings. These adjustments can be seen in Appendix B.

After running the TWPD for a set number of cycles, three performance measures were recorded: retroreflectivity, color retention, and presence. Retroreflectivity was recorded using the same MX 30 retroreflectometer that was used in the field. Three readings were taken at two locations along the wheel path and then averaged. Readings were taken for the dry (R_L) (ASTM E1710-11), recovery (R_{L1}) (ASTM E-2177-11), and continuous wetting (R_{L2}) (ASTM E2176-08) conditions. Recovery readings were taken first after the TWPD had finished running. Fines were washed out of the pavement surface. Afterwards, the continuous wetting condition was taken per ASTM E2176-08 by applying a constant water spray to the slab. Then, a hair dryer was used on the study locations for ten minutes each. Once the surfaces were determined dry, the dry readings were recorded. It was found that using a hair dryer significantly reduced the time to take readings compared to the original way of simply waiting eight or more hours for the slabs to dry.

The second performance measure recorded was color retention. These measurements were taken using an NR200 high-quality portable colorimeter with an 8-millimeter diameter aperture in accordance with ASTM D-2244 (Figure 4.4c). The CIELab color space was chosen to be recorded. The color change was calculated using the Euclidean distance formulae as seen in equations 1 and 2 below.

$$\Delta E_{ab} = [\Delta L^2 + \Delta a^2 + \Delta b^2]\ \wedge^{1/2} \tag{1}$$

$$\Delta L = [\Delta L_{\text{Reference}}{}^2 - \Delta L_{\text{Sample}}{}^2]\ \wedge^{1/2} \tag{2}$$

where ΔL, Δa, and Δb represented the differences between the initial and final values of L, a, and b, respectively. Higher L values indicated that the sample was illuminating. A color tended to be redder with an increase in a (+Δa) and greener with a decrease (-Δa), while a color tended to be more yellow with an increase in b (+Δb) and bluer with a decrease (-Δb).

Finally, the presence of the pavement markings was evaluated using an image analysis technique. The high-resolution camera was mounted at a constant height in a consistent lighting environment. ASTM D6359-99 and ASTM D7585 / D7585M were used as guidance. Pictures were taken and then imported into ImageJ (15). This software was then used to estimate the percent loss of glass beads after each set cycle was run.

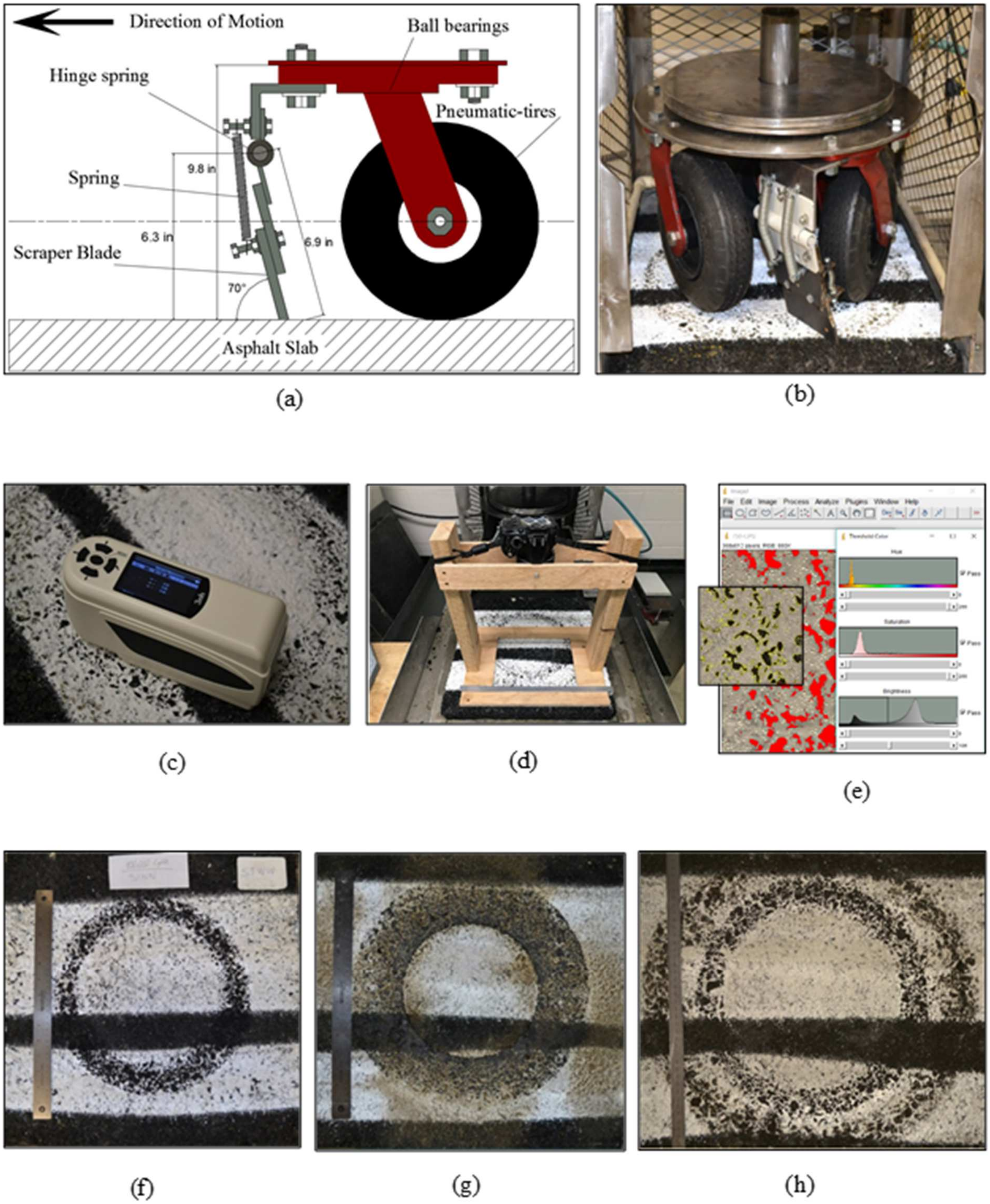


Figure 3.4: (a, b) Snowplow simulator, (c) colorimeter, (d) camera stand, (e) ImageJ software interface, and (f, g, h) polished samples of waterborne markings.

Crash Data Collection

Crash data was retrieved through WebCARS and can be seen in Appendix C. Criteria for any crash that may have had poor pavement markings as the potential cause of the crash was selected. The criteria for these crashes included: daytime and nighttime crashes, dry and wet pavement surface, asleep, drowsy, and fatigued crashes, drunk or drugged driving, careless driving crashes, lost control due to shifting load, and skidding. Icy surfaces and crashes related to animal collisions were excluded. The "Most Harmful Event" category represents the event that caused the crash in WebCARS. The targeted crashes in this data are identified as all crashes which might have a relationship to pavement markings' performance for towards the driver such as right run-off-the-road (ROR) crashes or other miscellaneous one vehicle crashes. After the removal of non-targeted crashes from WebCARS data, the remaining crashes were:

    - Bridge Rail
    - Concrete Traffic Barrier
    - Culvert
    - Delineator Post
    - Ditch
    - Embankment
    - Fence
    - Guardrail End
    - Guardrail Face
    - Immersion
    - Mailbox
    - Other Fixed Object
    - Other Non-Collision
    - Other Object Not Fixed
    - Overturn
    - Parked Car
    - Pedalcycle
    - Pedestrian

  - Traffic Sign Support
  - Tree
  - Utility Pole
  - Utility/Light Support

Chapter 4: Results

Field Deterioration Models

The retroreflectivity data gathered from the test and control sites were used to create deterioration models for each district. Figure 4.1a shows an example of the deterioration model developed from US 26 in District 5. Measurements were taken 1, 5, and 11 months after the markings had been restriped. A logarithmic model was found to have the best correlation to field conditions. Using a similar process for each of the other test sites in the district, Figure 4.1b was created for District 5. The deterioration curves for each segment in the district revealed similar deterioration rates and the dashed line was computed as the average deterioration model for the district. Following the same logic as district 5, Figure 4.1c then shows the average logarithmic decay models developed for each district in Idaho. The logarithmic decay functions for each district can be seen in Figure 4.2a.

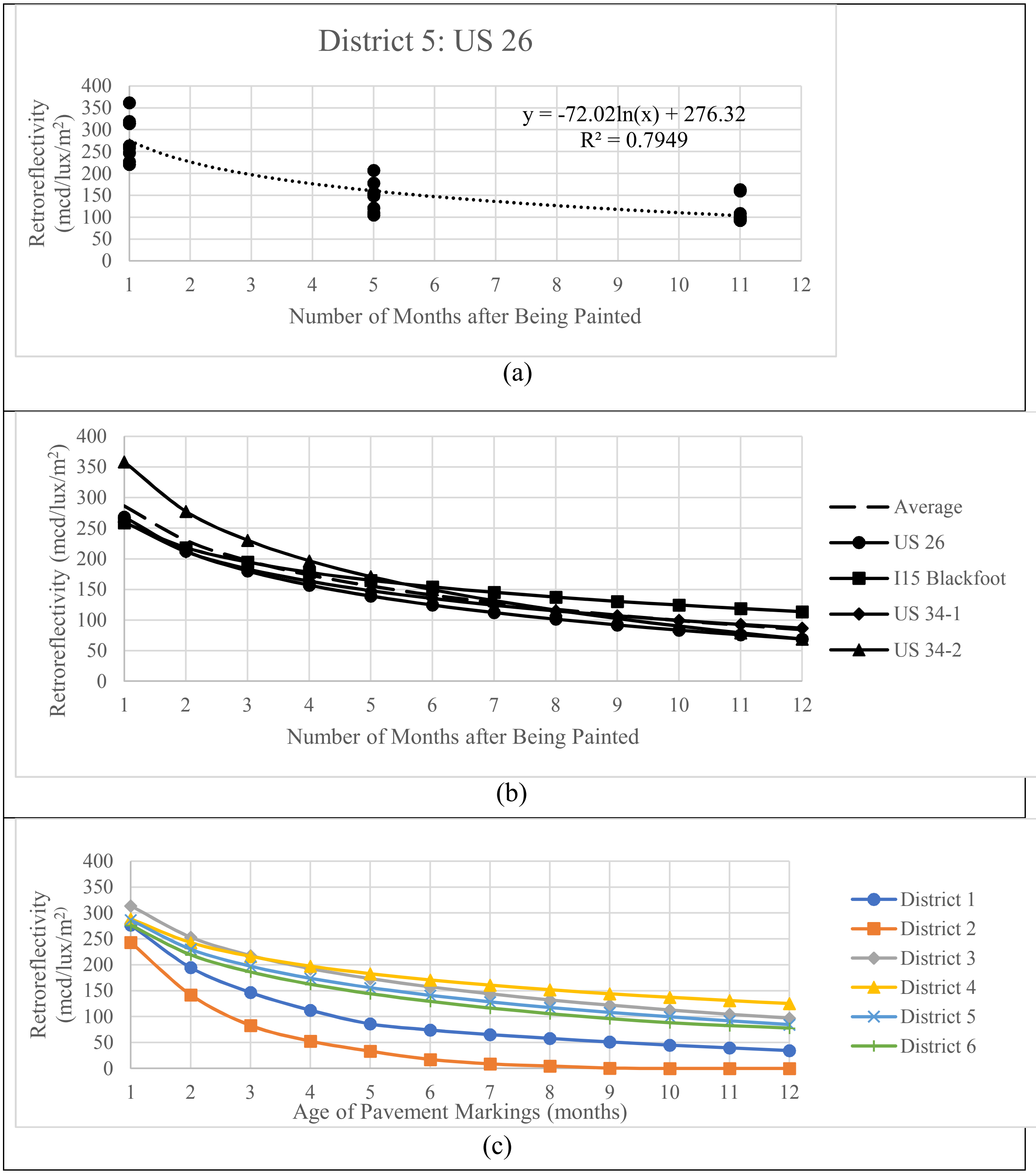
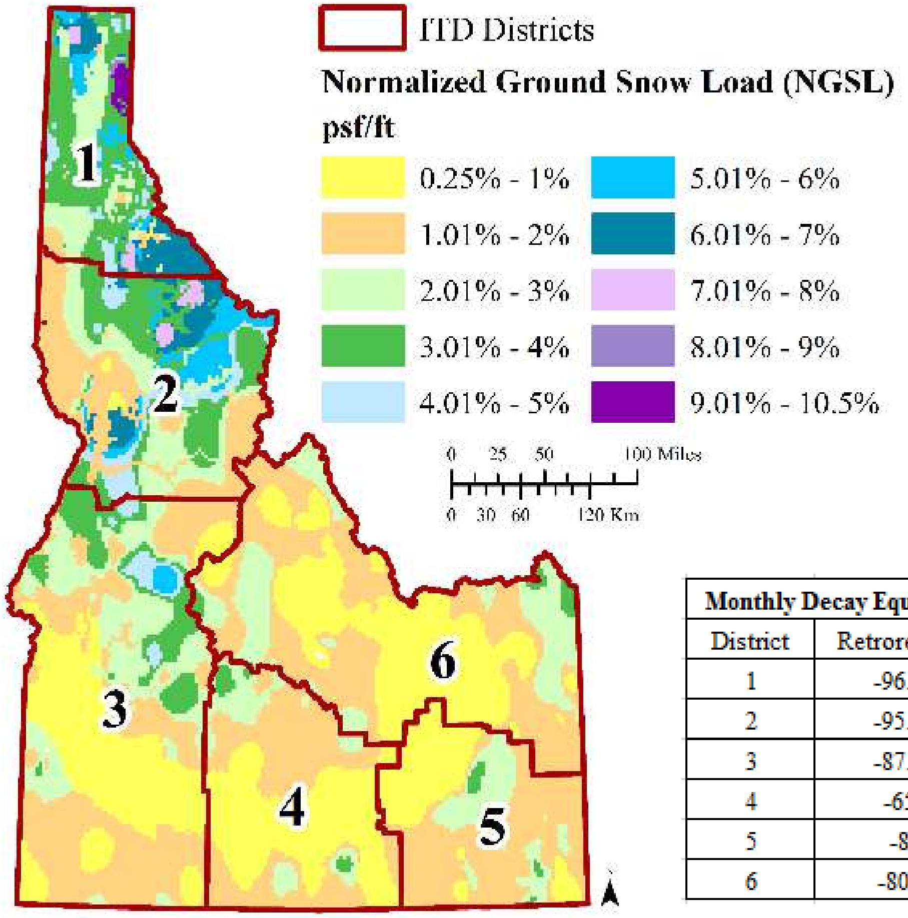


Figure 4.1: (a) An example of data collection, (b) change in retroreflectivity with time in District 5, and (c) retroreflectivity prediction per month after paint per district.

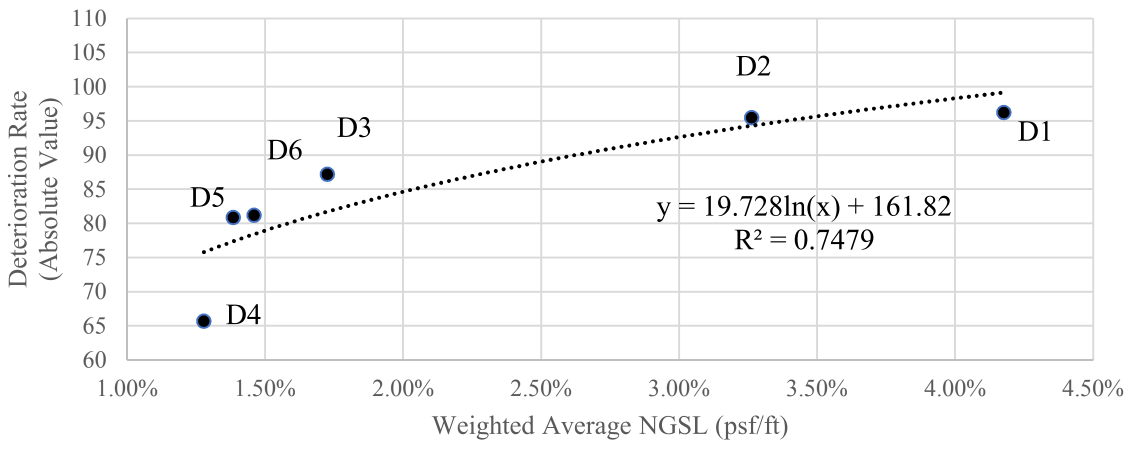
As seen in Figure 4.1c, Districts 1 and 2 contained pavement markings that deteriorated at a faster rate than the rest of the Districts. As the previous research had suggested, snowplowing may have influenced these pavement markings since they deteriorated at a higher rate than areas were fewer snowplowing events occur. To further investigate this phenomenon, Figure 6a was developed to show the normalized ground snow loads for Idaho based on the 2015 snow load map data (16). Next, Figure 4.2b displays the relationship between the deterioration rate of pavement marking retroreflectivity and the weighted average normalized ground snow load (NGSL) for all districts for Idaho. The NGSL was calculated based on the snow load at each measurement site divided by the elevation of the station in feet to normalize the data to psf/ft. Districts 1 and 2 had higher NGSLs (3.26% to 4.18% psf/ft) compared to Districts 3, 4, 5, and 6, (1.28% to 1.72% psf/ft). This relationship illustrated that a higher NGSL caused greater deterioration (loss) in retroreflectivity, which was likely attributed to the increase in winter maintenance activities (e.g., snowplowing).



Monthly Decay Equations per District

District	Retroreflectivity Equation
1	-96.25ln(x) + 258.99
2	-95.53ln(x) + 207.97
3	-87.22ln(x) + 313.67
4	-65.7ln(x) + 288.52
5	-81.2ln(x) + 286.5
6	-80.89ln(x) + 275.14

(a)



(b)

Figure 4.2: (a) NGSL for Idaho and (b) correlation between NGSLs and deterioration rate of pavement marking retroreflectivity.

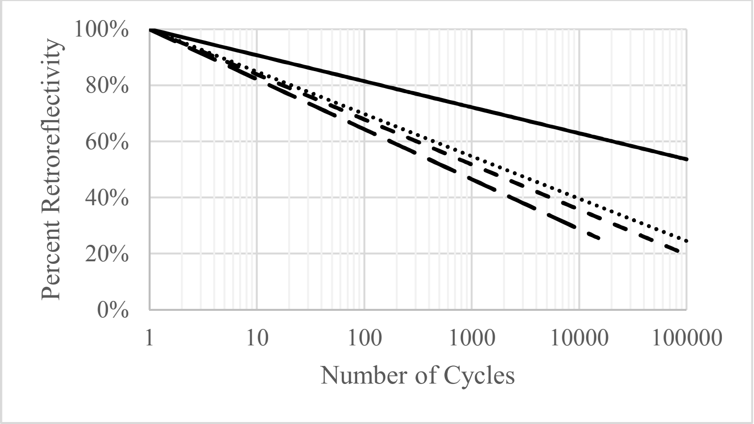
Lab Deterioration Models

Next, the lab performance measures were evaluated. Figure 4.3a shows the R_l readings for the different wheelsets versus the number of cycles. The correlation coefficient, R^2, for the pneumatic, steel, pneumatic with scraper blade, and scraper blade only were 0.90, 0.97, 0.80, and 0.99 respectively, with the section where the pneumatic and scraper blade passed over having the least deterioration. The equations shown in Figure 7a represent how the TWPD deteriorated the retroreflectivity markings at a logarithmic rate. The graphs display the deterioration based on percent retroreflectivity lost. This was done to normalize the initial retroreflectivity for each slab sample. The pneumatic wheelset deteriorated the pavement marking 75% from its initial retroreflectivity after 100,000 cycles (Figure 3f). The steel wheel test was terminated after 10,000 cycles since the surface was completely polished due to harsh changes of the asphalt texture and the surface had changed from its original state to a smooth compacted state. The pneumatic with scraper blade had the least percent retroreflectivity deterioration compared to the other wheel sets. Since the wheels caused little rutting on the pavement surface, the scraper blade was not abrading the section underneath the wheel path. For this reason, other points on the pavement surface were chosen to observe the full effect of the scraper blade.

The R_{L1} percent retroreflectivity readings versus the number of cycles under recovery conditions is shown in Figure 4.3b. The correlation coefficients, R^2, for the pneumatic, steel, pneumatic with scraper blade, and scraper blade were 0.86, 0.77, 0.75, and 0.90 respectively. These correlation coefficients were less than the dry percent readings due to the variability caused by taking readings when the pavement markings were wet. The pneumatic wheel with the scraper blade had the lowest rate of degradation while the steel wheels had the highest rate. Another observation from this data set was that the pneumatic wheels only and scraper blade only have very similar rates of degredation based on the logarithmic decay functions and could be attributed to pavement surface wetness.

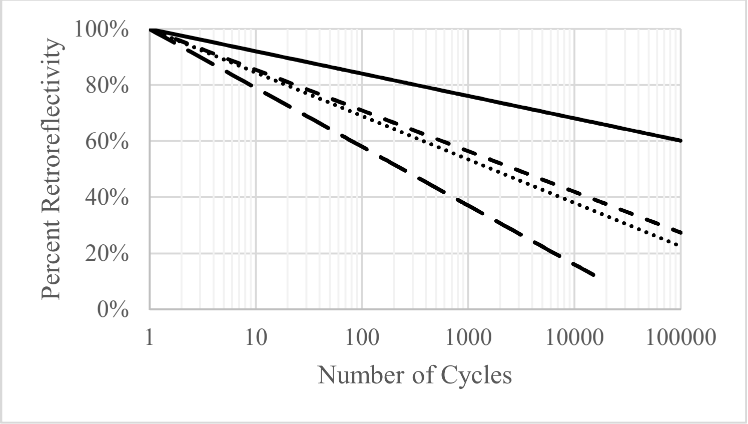
Figure 4.3c shows the R_{L2} percent retroreflectivity readings versus the number of cycles under continuous wetting conditions. The correlation coefficients for the pneumatic, steel, pneumatic with scraper blade, and scraper blade were 0.81, 0.90, 0.73, and 0.85, respectively. Based on laboratory testing observations, the voids on top of the pavement surface were filling with water and affecting the continuous wetting readings for each tested condition. The change in percent retroreflectivity in continuous wetting was relatively close for the different wearing methods. Many issues were had taking readings during the continuous wetting condition since the water would often flood the surface of the pavement markings and result in a zero value of retroreflectivity. Since the recovery and dry readings were much simpler and more reliable, it is recommended that the recovery and dry readings are primarily used in future research.

After 1000 cycles, it was observed that the scraper blade had decreased the pavement marking retroreflectivity by 0.194 mcd for the dry, 0.161 for the recovery, and 0.041 for the continuous wetting readings. If the snow plowing event deterioration of a pavement marking retroreflectivity in one pass was available, this field snow pass deterioration value could be divided by 0.194 in order to determine a relationship between the lab and field data. This number could then be multiplied by the number of snow plowing events in a year to predict how much the markings would deteriorate over the winter. It is recommended for future researchers to investigate the relationship between the scraper blade pass in the lab and the snow blade pass in the field.



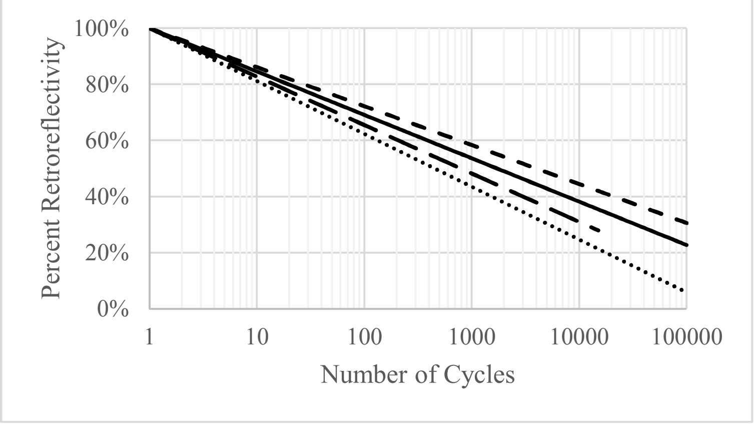
(a)

Set	Retroreflectivity Equation	R^2
P	y=-24.94ln(x) + 380.52	0.90
S	y=-22.55ln(x) + 291.52	0.97
P w SB	y=-14.87ln(x) + 369.09	0.80
SB	y=-25.00ln(x) + 330.25	0.99



(b)

Set	Retroreflectivity Equation	R^2
P	y=-16.63ln(x) + 247.18	0.86
S	y=-15.84ln(x) + 173.90	0.77
P w SB	y=-10.35ln(x) + 299.18	0.75
SB	y=-16.37ln(x) + 259.84	0.90



(c)

Set	Retroreflectivity Equation	R^2
P	y=-8.31ln(x) + 101.62	0.81
S	y=-4.10ln(x) + 54.72	0.9
P w SB	y=-11.76ln(x) + 175.15	0.73
SB	y=-9.41ln(x) + 156.1	0.85

Figure 4.3: Percent retroreflectivity deterioration due to different loadings and conditions: (a) dry RL, (b) recovery RL1, and (c) continuous wetting RL2. (Note: The tables above are based on retroreflectivity values and not on percent retroreflectivity.)

Field and Lab Deterioration Comparison

In order to relate the retroreflectivity deterioration field models to the laboratory models, Figure 4.4 was used to compare the cumulative number of traffic passes (CTP) in the field with the estimated retroreflectivity. The pneumatic, steel, pneumatic with scraper blade, and only scraper blade laboratory tests were completed to establish this relationship. A similar trend between retroreflectivity versus CTP and retroreflectivity versus number of cycles from the TWPD with pneumatic wheels was observed. Based on the average field retroreflectivity value for each district after 100,000 CTPs and the dry pneumatic (R_L) results in the laboratory after 100,000 cycles, it was determined that 1.58 cycles of the TWPD was equivalent to one CTP in the field.

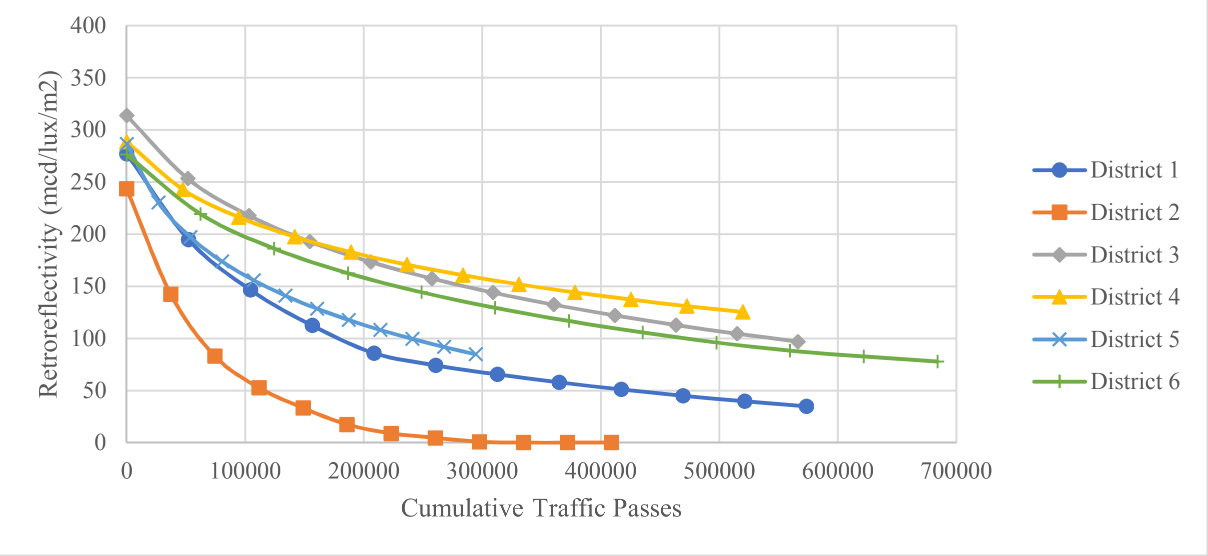
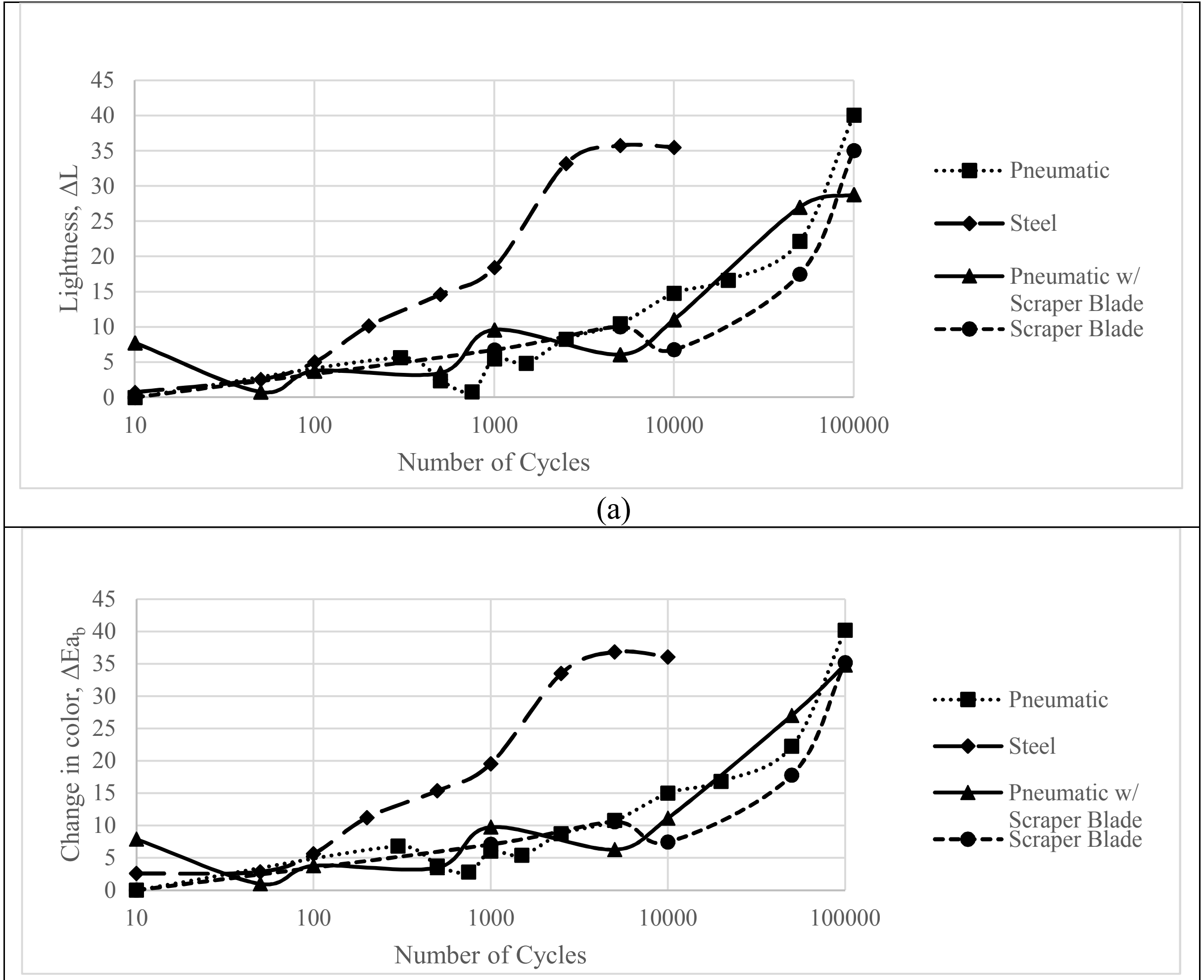


Figure 4.4: Retroreflectivity prediction per CTPs

Lab Color Results

Figures 4.5a and b show the changes in lightness (ΔL) and total color (ΔE_{ab}) of the waterborne pavement marking surfaces at different wheelsets and loading intervals for all the traffic loading types. The steel wheelset had the highest ΔL and ΔE_{ab} after loading, a likely result caused by compaction of the markings rather than a wearing effect. The ΔL and ΔE_{ab} results from the pneumatic, pneumatic with scraper blade, and scraper blade only were similar; their ΔE_{ab} ranged from 35 to 40 after applying 100,000 cycles but the steel wheelset reached this level within 10,000 cycles. In other words, the steel wheelset was more abrasive than other wheelsets and especially the scraper blade. A gradual change in ΔL and ΔE_{ab} was observed throughout the experiment. ΔL for the pneumatic, pneumatic with the scraper blade, and scraper blade followed the same trend as that of ΔE_{ab} at 10,000 to 100,000 cycles of exposure. Both ΔL and ΔE_{ab} increased for all wheelsets up to 10,000 cycles for the steel wheels and 100,000 cycles for the others, and the logarithmic scale showed a drastic increase in ΔL and ΔE_{ab} between 10,000 and 100,000 cycles of exposure.

The color of the markings darkened when the number of cycles using the pneumatic wheels increased. The main reason the markings lost lightness and changed their color to black was due to the TWPD tires simulating traffic and the appearance of the asphalt background. When the tire rotated over the pavement surface, the rubber on the outside of the tire was scraped off and onto the pavement surface. These results were consistent with other trials of the same material under the same conditions. Initial traffic loading of waterborne marking surfaces resulted in color darkening and further traffic loading caused stability in color. The running wheels essentially polished the pavement markings located on the upper peaks of asphalt texture while the lower peaks still retained marking material.



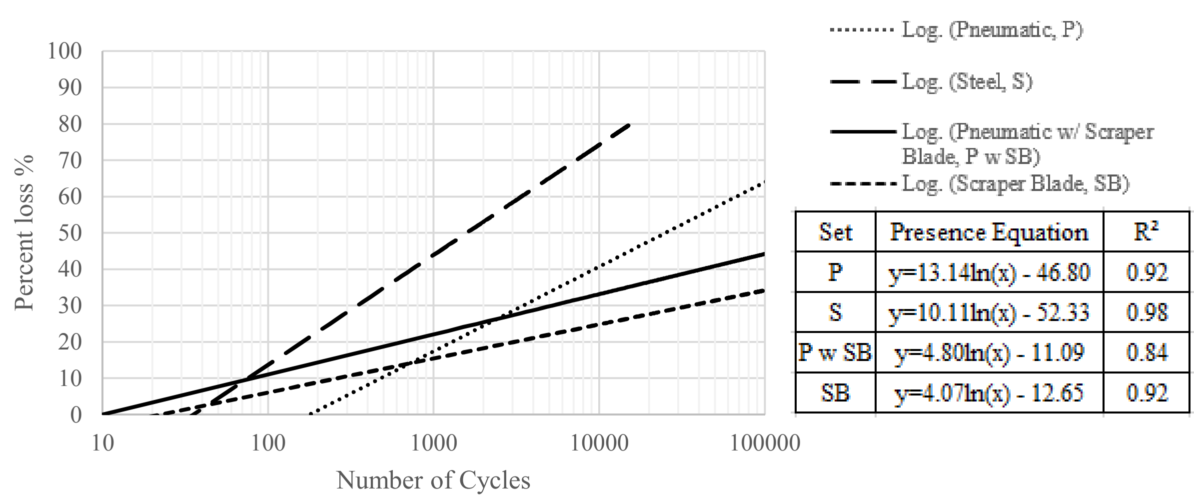
(a)

(b)

Figure 4.5: (a) Lightness, (b) color change under different operating conditions

Lab Presence Results

Finally, the presence of the study locations was evaluated. Figure 4.6 shows the results of the image analysis for percent loss versus the number of cycles. The correlation coefficients for the pneumatic, steel, pneumatic with scraper blade, and scraper blade were 0.92, 0.98, 0.84, and 0.92, respectively. The pneumatic wheelset did not experience any loss in presence until roughly two hundred cycles from the TWPD. As expected, the steel wheels caused the most rapid deterioration with a 75% loss after only 10,000 cycles. The scraper blade, on the other hand, caused the least percent loss and was attributed to the blade dragging along the surface; as the blade drug over the marking, the markings wore off quicker than any other wheelset but after completely removing all of the top markings, a small change in retroreflectivity was observed after 10,000 cycles. The rutting from the pneumatic, steel, and pneumatic with scraper blade resulted in an increase in percent loss compared to just the scraper blade.



Set	Presence Equation	R²
P	y=13.14ln(x) - 46.80	0.92
S	y=10.11ln(x) - 52.33	0.98
P w SB	y=4.80ln(x) - 11.09	0.84
SB	y=4.07ln(x) - 12.65	0.92

Figure 4.6: Presence under different operating conditions

Crash Data Results

Figures 4.7 and 4.8 show the crash rates for the test and control sites from 2010 to 2016 with 2015 excluded. These crash rates were computed by using the sum of the fatal, A, B, and C injuries for each year for the number of crashes and the traffic was computed by summing the AADT of all the segments in either the test or control sites. Data for property damage only crashes was not available for 2016 at the time of the study. The test sites had higher crash rate values than the control sites did, however, the trend for the crash rate in Figure 4.7 shows that there is a small decrease in the rate over time. The control site crash rate in Figure 4.8 is steadily trending upwards, indicating that an improvement may have occurred after the application of the wider pavement markings.

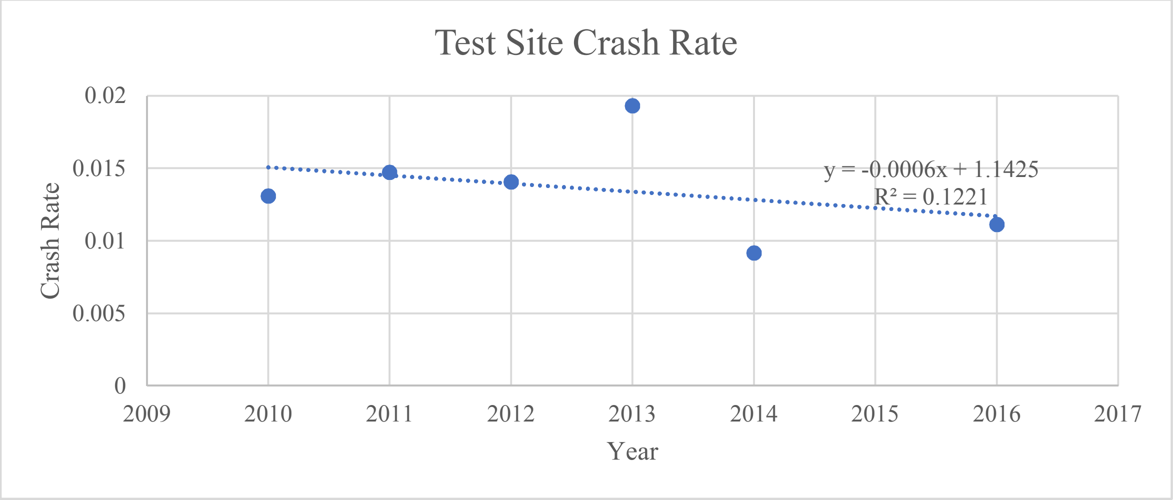


Figure 4. 7: Test site crash rate

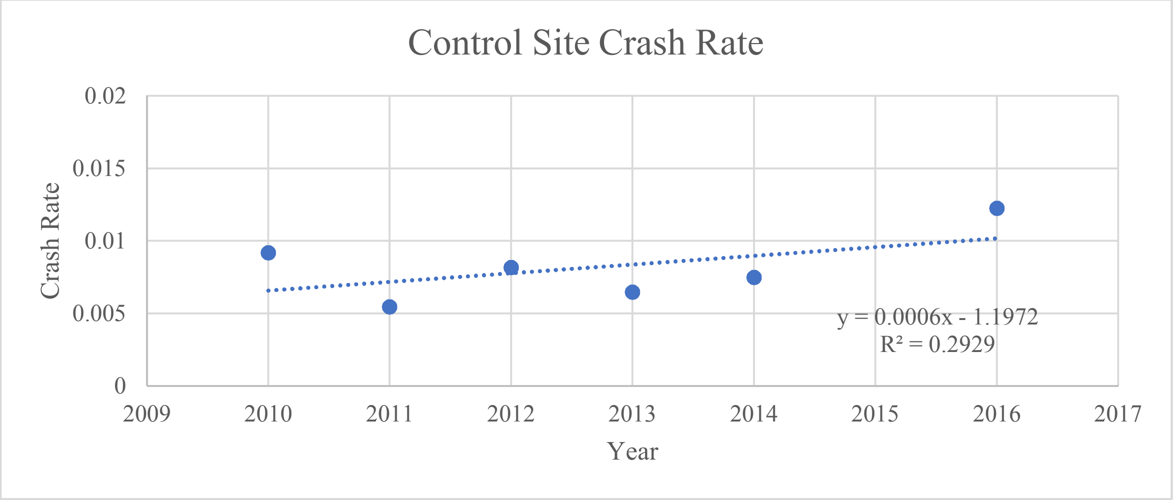


Figure 4.8: Control Site Crash Rate

Figures 4.9 and 4.10 show the frequency of crashes for both the test and control sites. Again, these are the crashes only for fatal, A, B, and C injury crashes. It can be seen from these figures that there were more crashes on the test sites than there were on the control sites. This is likely why the crash rates for the test sites are higher than that of the control sites since only the number of miles in the segment would change in the crash rate equation. However, the trends for the frequency of crashes in slightly decreasing in the test sites and slightly increasing in the control sites. This is a better indication of the fact that the wider pavement markings do influence the number of crashes on rural highways in Idaho.

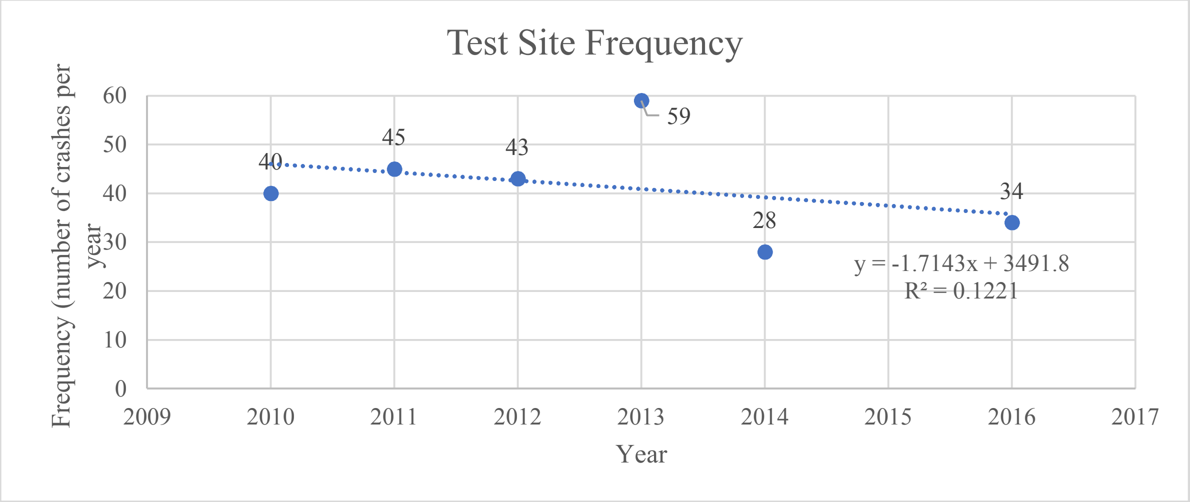


Figure 4. 9: Test Site Frequency

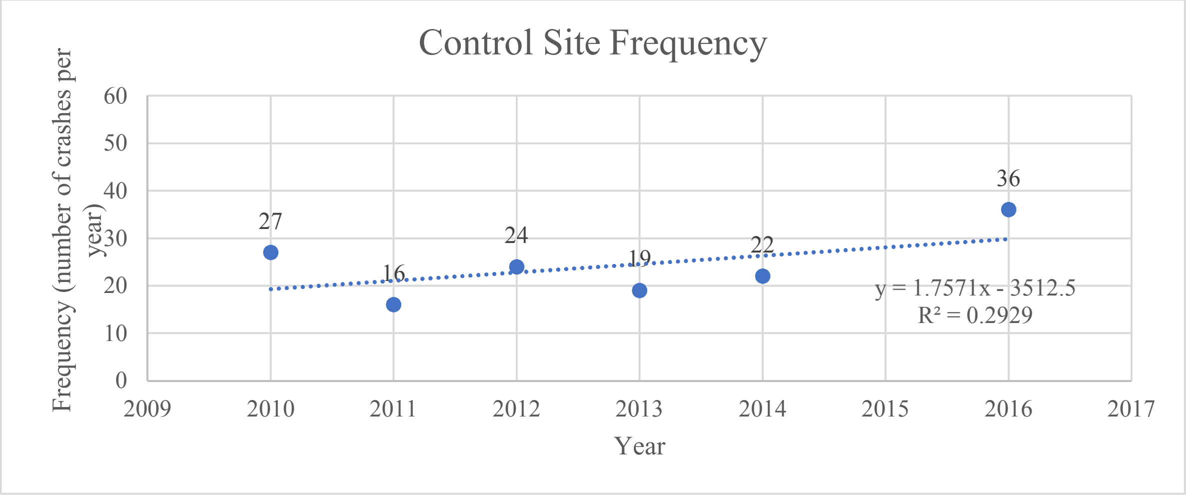


Figure 4.10: Control Site Frequency

Figure 4.11 below shows the retroreflectivity comparison for the test and control sites over time. As seen in the equations on the chart, the test sites degrade at a slope of -17.1 while the control sites degrade at a rate of -14.5. While these slopes are similar, it does not prove that the six-inch-wide pavement markings degraded at a slower rate than the four-inch-wide markings did.

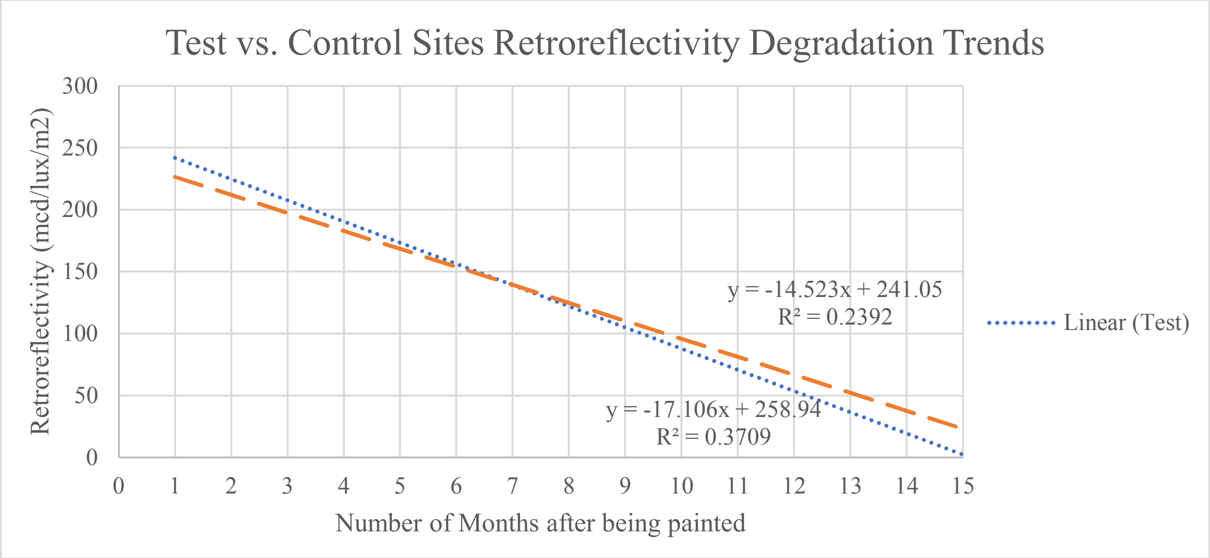


Figure 4. 11: Test vs. control sites retroreflectivity trends

Based on the results from Figures 4.7 through 4.11, it may be said the wider pavement markings do have a small effect on increasing safety for drivers. The crash rates for the before and after of the test sections slightly decreased while the rates for the control section slightly increased. A decreasing rate in the wider pavement marking section indicates that the wider markings would have increased safety. The frequency trends for the test sites showed a slight decrease while the frequency for the control sites trended somewhat upwards. This is another indicator of performance increase in wider pavement markings. The results of the retroreflectivity for the test and control sites proved no significant improvement in retroreflectivity for the wider pavement markings over time. The difference between the increase of the test sites and decrease of the control sites could quantify the amount decrease in the number of crashes. Figure 4.12 below projects this difference and shows that the wider pavement markings could have had 20 less crashes average for 2016 if the control sites had wide pavement markings based on the frequency trends alone.

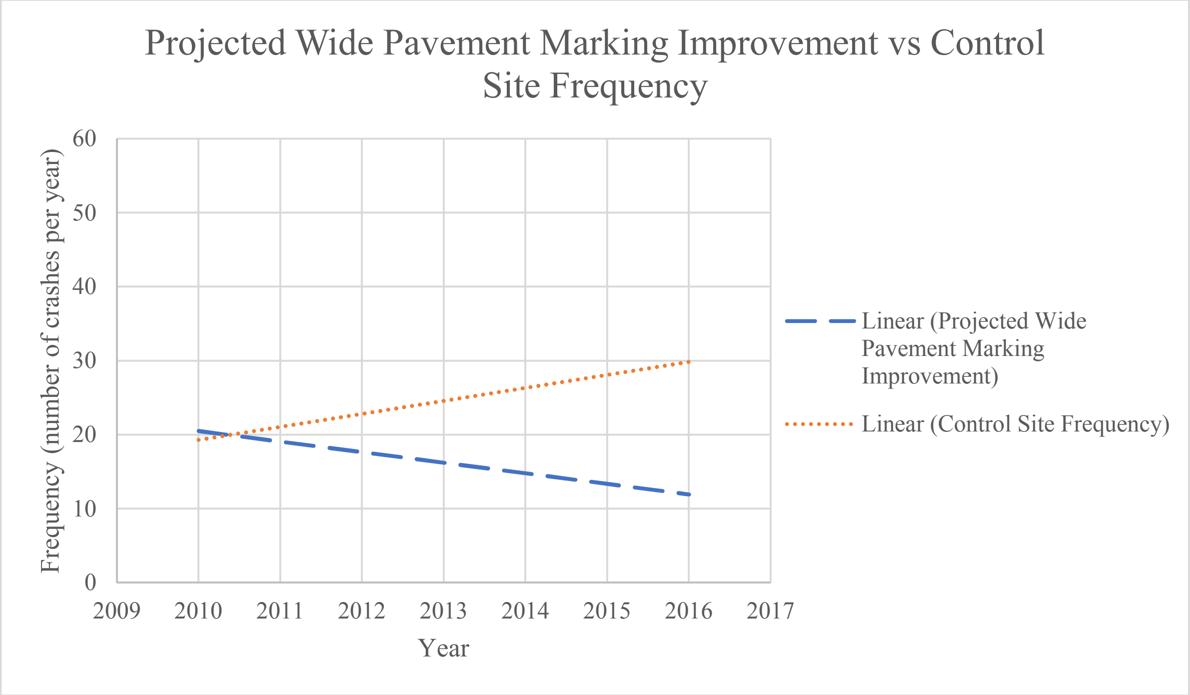


Figure 4.12: Projected wide pavement marking improvement

Chapter 5: Conclusion

Waterborne marking retroreflectivity deterioration was modeled using field and laboratory data. Field retroreflectivity data for each targeted rural road in Idaho was collected three times over the course of one year. Retroreflectivity deterioration was modeled in the laboratory using a TWPD under four loading scenarios (pneumatic, steel, pneumatic with scraper blade, and scraper blade). Color retention and percent loss due to the same loading scenarios were monitored and used to validate the results from the retroreflectivity data. Finally, crash data for the test and control sites was retrieved and analyzed to evaluate the safety impact of wide pavement markings. The following conclusions can be drawn from this data.

- The best fit curve to predict waterborne pavement markings retroreflectivity deterioration in Idaho was a logarithmic decay function.
- There was a strong relationship between the deterioration rate of pavement marking retroreflectivity and the weighted average NGSL for all districts in Idaho. The higher the NGSL, the faster deterioration (loss) in retroreflectivity. This could be attributed to the increase in winter maintenance activities (e.g. snowplowing).
- The TWPD was used successfully to replicate traffic to study the waterborne pavement marking degradation. The TWPD can be used to simulate the wearing of traffic similar to the NTPEP test deck currently used in the field to evaluate the wearing of pavement markings. However, the TWPD was much more beneficial since it was less expensive, easier to operate, and took less time to complete.
- Based on the average field retroreflectivity value for each district and the dry pneumatic (R_L) results in the laboratory, 1.58 cycles of the TWPD is equivalent to one CTP in the field.
- The recovery and continuous wetting readings were used to observe the variability in retroreflectivity readings when water was present on the surface of the pavement marking.
- A decrease in lightness (ΔL), total color change (ΔE_{ab}), and presence was directly correlated to a loss in retroreflectivity.
- Wider pavement markings did not deteriorate at a slower rate than regular pavement markings.

- Wider pavement markings could have had 20 less crashes average for 2016 if the control sites had wide pavement markings based on the frequency trends alone.
- Wider pavement markings do have a small effect on increasing safety for drivers.

Due to the success of using the TWPD for simulating traffic loading, it is recommended that future research include the effect of aging and weathering on the pavement marking materials. This could be tested using the laboratory oven and an accelerated weathering machine. Other pavement markings attributes such as color and type of marking (e.g. thermoplastic, tape, MMA) could also be tested and compared to the white waterborne samples that were used in this study. In addition, the effect of anti-icing and de-icing substances on the pavement marking materials may also be quantified through the laboratory testing. The TWPD can be equipped with an environmental chamber to simulate the performance of pavement markings in different regions. The addition of snowplow field data to relate to the scraper blade would also be beneficial to equate the number of laboratory scraper blade passes with the number of snowplow passes in the field.

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Appendix A: Field Data

See attached media.

Appendix B: Lab Data

See attached media.

Appendix C: Crash Data

See attached media.