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# Paint Pavement Marking Performance Prediction Model That Includes the Impacts of Snow Removal Operations

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**PAINT PAVEMENT MARKING PERFORMANCE PREDICTION MODEL THAT INCLUDES THE IMPACTS OF SNOW REMOVAL OPERATIONS**

THESIS

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AFIT/GEM/ENV/11-M04

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**Wright-Patterson Air Force Base, Ohio**

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PAINT PAVEMENT MARKING PERFORMANCE PREDICTION MODEL THAT INCLUDES THE IMPACTS OF SNOW REMOVAL OPERATIONS

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## Abstract

The results of this research effort were captured in two manuscripts drafted for publication in peer reviewed journals. The first manuscript validated a previously published model with an expanded data set, updated service life predictions for painted pavement markings using recently released pavement marking retroreflectivity minimums, and incorporated recent cost data to evaluate two alternative methods of compliance with new retroreflectivity minimums for two-lane roads. The second manuscript developed a new performance prediction model for paint pavement markings that includes the impact of snow removal operations and then applied the model to four real-world roadways to determine if replacement is required.

This research determined that each snow plow event degrades paint pavement markings by 3.22 mcd/m$^2$/lux which is more than one month of service life. The work also showed that with no snow fall, an Annual Average Daily Traffic (AADT) of 4,000, and an Initial $R_L$ of 220 mcd/m$^2$/lux, paint pavement markings have a service life greater than five years on roads with posted speeds less than 55 mph. Finally, the research confirmed that AADT has a small but significant impact on the degradation of painted pavement markings. The results also indicated the model developed for North Carolina might be useful in other states.

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*This work is dedicated foremost to my beloved wife and my dear son.*

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PAINT PAVEMENT MARKING PERFORMANCE PREDICTION MODEL
THAT INCLUDES THE IMPACTS OF SNOW REMOVAL OPERATIONS

## I. Introduction

The North Carolina Department of Transportation (NCDOT) currently replaces paint pavement markings on an annual basis (Sitzabee 2009). The policy is very simple and easy to understand. As a result, it is also easy to predict restriping work schedules and budget requirements. They are essentially the same from year to year. Most importantly, the policy gets the job done, ensuring that pavement markings maintain sufficient retroreflectivity for safe operation of motor vehicles throughout the year.

However, with increasing infrastructure age and new pavement marking minimum retroreflectivity standards, a more sophisticated pavement marking management system is needed. Maintenance demands for our nation's aging transportation infrastructure have increased. The American Society of Civil Engineers' 2009 Report Card for America's Infrastructure states, "One-third of America's major roads are in poor or mediocre condition and 45% of major urban highways are congested. Current spending of $70.3 billion per year for highway capital improvements is well below the estimated $186 billion needed annually to substantially improve conditions" (ASCE 2009). The increased requirements for maintenance dollars demand that asset managers optimize their budgets in order to address some of the maintenance funding shortfall. Performance prediction models are the key to optimization. Additionally, the Federal Highway Administration has published proposed minimum pavement marking retroreflectivity standards for the Manual of Uniform Traffic Control Devices (MUTCD)

(Federal Highway Administration 2010). Physical measurement of the entire pavement marking inventory is impractical. Instead, performance prediction models can estimate the system condition and facilitate compliance with the new MUTCD requirements.

Unfortunately, models for paint pavement marking degradation currently in the literature all have weaknesses that limit their utility as an asset management tool. Many models have fairly low coefficients of determination which translates to high levels of error in predicted pavement marking performance. Even models with a high $R^2$ have limitations in their statistical validity (Sitzabee et al. 2009). As a result, some asset managers may have limited confidence in the model's predictions.

None of the models for paint pavement markings include the contribution of snow removal operations on pavement marking degradation, although many authors acknowledge that winter maintenance does degrade pavement marking retroreflectivity (Dale 1988; Martin et al. 1996; Lu & Barter 1998; Lee et al. 1999; Migletz et al. 2001; Sarasua et al. 2003; Kopf 2004; Fitch & Ahearn 2007; Sitzabee et al. 2009). An accurate performance prediction model should include a known degradation factor such as snow removal.

## Background

### *Pavement Marking Materials*

Paints make up nearly 60% of the pavement-marking inventory nationwide (Migletz & Graham 2002) and NCDOT is no different (Sitzabee et al. 2009). Table 1 shows the primary pavement marking materials and their relative proportions of use. Installed paint pavement markings are the least expensive form of marking (Migletz & Graham 2002), but the sheer volume of paint used makes this asset a significant budget item. For example, pavement markings alone already cost North Carolina approximately $14.5 million a year in contractor-performed work (Sitzabee et al. 2009). The use of refined performance models to improve life-cycle management can free funds for other pressing maintenance requirements.

**Table 1. Pavement Marking Materials**

| | **Pavement Marking Material** | **Percentage of Use** |
|---|---|---|
| 1 | Waterborne Paint | **59.9** |
| 2 | Thermoplastics | 22.7 |
| 3 | Conventional solvent paint | 6.5 |
| 4 | Polyester | 3.8 |
| 5 | Epoxy | 2.7 |
| 6 | Preformed tape – flat | < 1.0 |
| 7 | Preformed tape -- profiled | < 1.0 |
| 8 | Methyl methacrylate | < 1.0 |
| 9 | Thermoplastics profiled | < 1.0 |
| 10 | Polyurea | < 1.0 |
| 11 | Cold applied plastics | < 1.0 |
| 12 | Experimental | < 1.0 |
| 13 | Green lite powder | < 1.0 |
| 14 | Polyester profiled | < 1.0 |
| 15 | Tape, removable | < 1.0 |
| 16 | HD-21 | < 1.0 |

Adapted from Migletz and Graham 2002.

### ***Retroreflectivity***

To improve visibility, pavement markings rely on retroreflectivity, which is the process where light emitted from a vehicle's headlight strikes the pavement marking and is reflected back toward the eye of the driver. Retroreflectivity is achieved through the use of glass beads embedded in pavement markings and is represented by the Coefficient of Retroreflected Luminance ($R_L$).

The American Society for Testing and Materials (ASTM) defines the Coefficient of Retroreflected Luminance as "the ratio of the luminance, *L*, of a projected surface to the normal illuminance, *E*, at the surface on a plane normal to the incident light, expressed in candelas per square meter per lux ($cd/m^2/lux$)." The organization further recommends use of millicandelas per square meter per lux as the standard unit for pavement marking retroreflectivity due to the low luminance values prevalent in pavement markings (ASTM 2005).

Non-reflectorized pavement markings, as with any other physical material, have an inherent level of natural reflectivity associated with the material's physical construction. Glass or ceramic beads mixed into the material before application, or spread upon the surface of the marking material before it has dried, provide pavement marking retroreflectivity and increase the material’s visibility at night. Figure 1 details the physics of how glass beads enhance retroreflectivity (Craig et al. 2007). A bead embedment of 60% into the marking material maximizes the bead's retroreflective properties (Rasdorf et al. 2009).

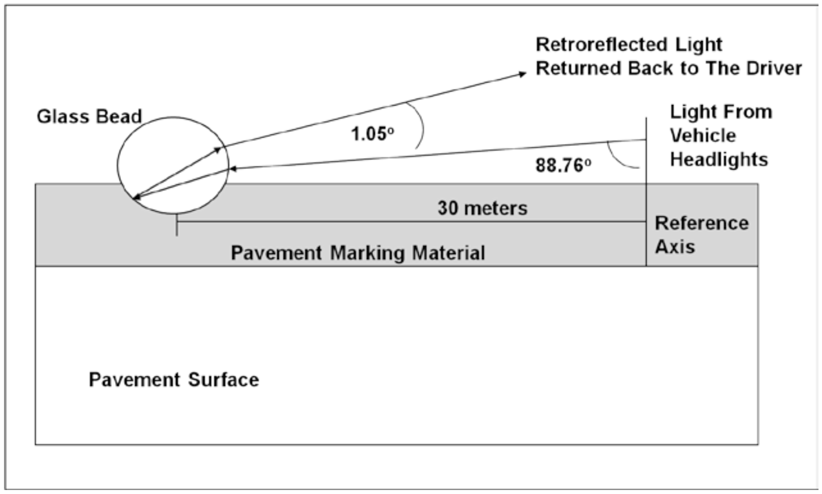


**Figure 1. Glass bead retroreflectivity physics (Rasdorf et al. 2009).**

Non-reflectorized, or presence, pavement markings were the national standard for many years. Reflectorization was first mentioned in the 1942 Manual of Uniform Traffic Control Devices (MUTCD) that described the practice of using glass beads in paint to provide retroreflectivity. The 1948 edition of the MUTCD added a small passage suggesting use of retroreflectorized pavement markings in a limited number of situations, and the 1954 revision of the 1948 MUTCD first required retroreflectorized pavement markings for rural roads intended for nighttime use. In 1961, the retroreflectivity requirement was expanded to all pavement markings intended for nighttime use (Hawkins 2000). However, from 1971 through the present day, the MUTCD language has simply read as follows: "Markings which must be visible at night shall be reflectorized unless ambient illumination assures adequate visibility. All markings on Interstate highways shall be reflectorized" (Hawkins 2000). The requirement for reflectorized pavement markings has been in place for 57 years; however, there has been no specified minimum retroreflectivity value.

Congress directed the Secretary of Transportation to establish minimum retroreflectivity standards in 1993 (United States Congress 1993). As a result, the Federal Highway Administration (FHWA) has proposed minimum retroreflectivity standards be included in the first revision of the 2009 edition of the Manual of Uniform Traffic Control (MUTCD) (Federal Highway Administration 2010). These proposed standards are shown in Table 2 and should be followed by all Departments of Transportations (DOTs) to minimize exposure to litigation and to maximize access to federal transportation funds.

**Table 2. Proposed Pavement Marking Retroreflectivity Minimums**

| | Posted Speed (mph) | | |
|---|---|---|---|
| | ≤ 30 | 35-50 | ≥ 55 |
| Two-lane roads without edge lines | n/a | 100 | 250 |
| All other roads | n/a | 50 | 100 |

Measured in mcd/$m^2$/lux; adapted from FHWA 2010.

***Snow Removal Operations and Management***

Chemical application, grit application, and snow plowing are standard snow management techniques. Salt and other chemicals, such as magnesium, are applied before snow events to prevent snow from freezing to the roadway. Pre-applied chemicals can only deal with low volume snowfall. Transportation agencies also apply sand or limestone grit to increase traction on the roadway.

If the accumulation exceeds a predefined threshold, the roads must be plowed. As one example, the city of Beavercreek, OH, does not plow unless the accumulation exceeds three inches (Brown 2009). Typical equipment used by transportation agencies to manage snow on the roadways includes a snow plow attached to the front of a dump truck and a hopper filled with sand or grit placed in the back of the truck. Sometimes a large tank with liquid brine solution or other chemical solution is used in place of the hopper.

**The Standard Test Method**

The ASTM has determined a standard method for testing the retroreflectivity of pavement markings. ASTM E1710, Standard Test Method for Measurement of Retroreflective Pavement Markings with CEN-Prescribed Geometry Using a Portable Retroreflectometer, directs the use of a 30 meter geometry which is shown in Figure 2. 30 Meter Geometry(ASTM, 2009).

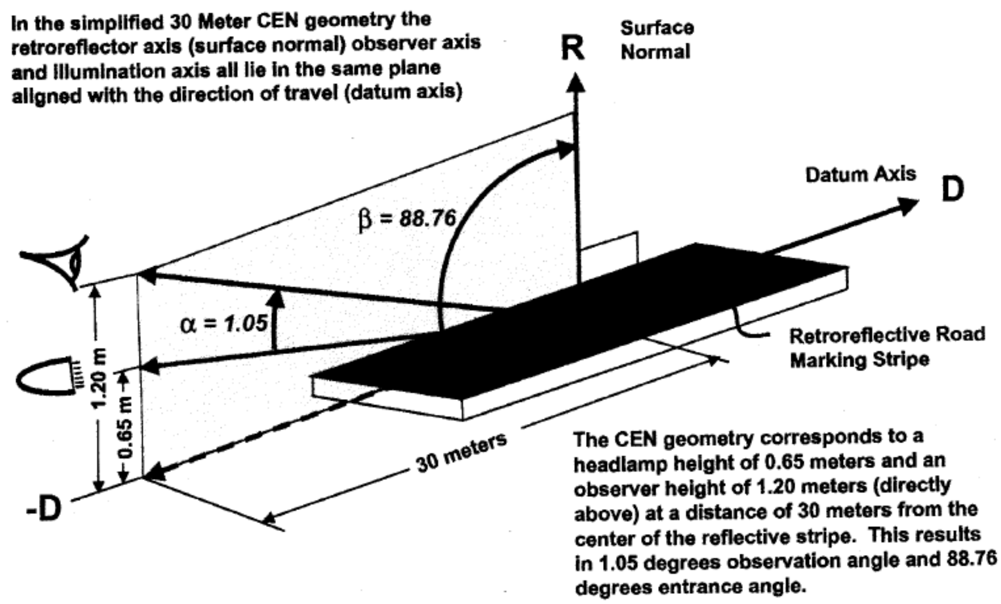


**Figure 2. 30 Meter Geometry (ASTM 2009)**

**Asset Management**

The ultimate objective of this research effort is to facilitate wiser use of maintenance funds, which are a limited resource. This process is often called Asset Management. Figure 4 shows one interpretation of the Asset Management process as presented in the US Department of Transportation's (USDOT) Asset Management Primer

(1999). Asset Management uses performance modeling, cost estimates, and public policy to evaluate alternatives and optimize maintenance programs.

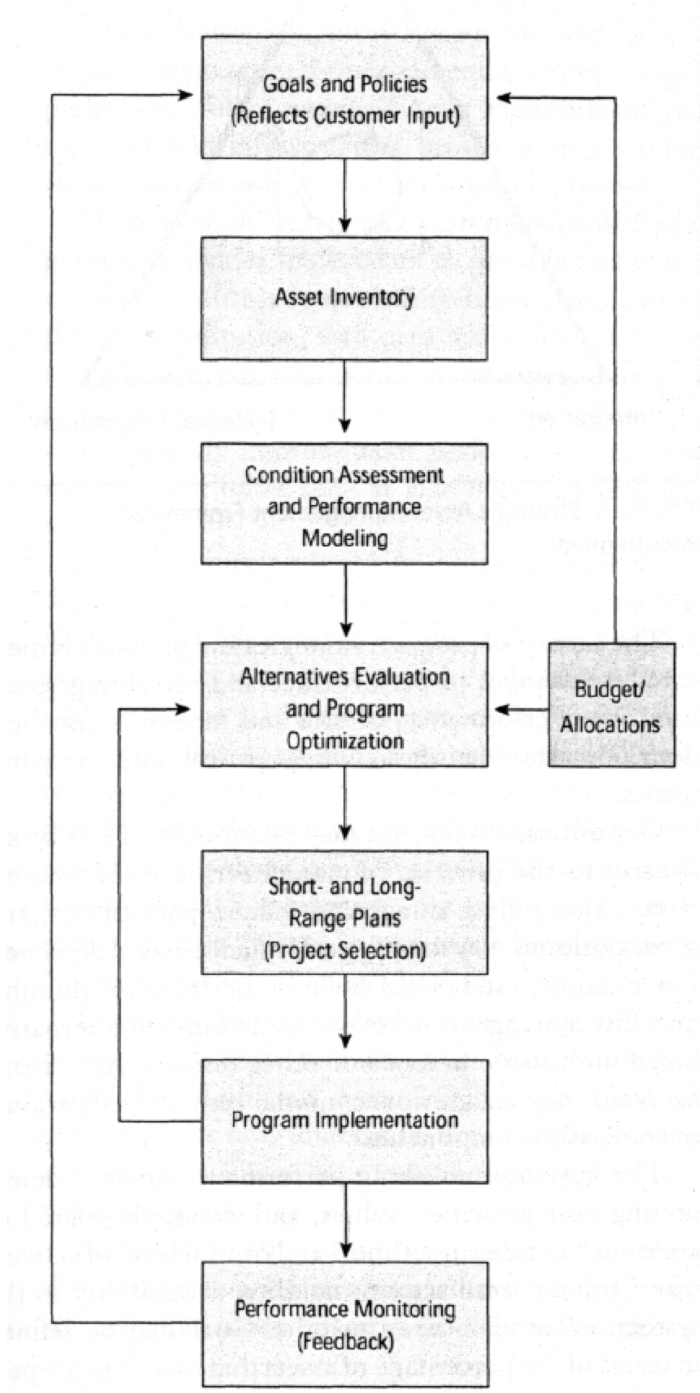


**Figure 3. The Asset Management Process (USDOT 1999)**

## Objective and Scope

The objective of this research was to quantify the impact of snow removal operations on pavement marking degradation. The specific research question was: what is the impact of snow removal operations on painted pavement markings?

Specifically this work:

- Creates a general degradation model to provide insight into the relationship snow operations have on pavement marking degradation.
- Determines rates, relationships and correlations between snow removal and other known variables that impact pavement markings.
- Provides an estimate of the deterioration rate due to snow removal operations.
- Provides an asset management implementation strategy that considers snow removal operations.

## Format of Remaining Chapters

This thesis document follows the scholarly article format. The work and results of this research effort are captured in two manuscripts drafted for publication in the Journal of Infrastructure Systems and the Journal of Transportation. Chapter Two presents the first manuscript which (1) validates a previously published model by Sitzabee et al. (2009) with an expanded data set, (2) updates service life predictions for painted pavement markings using recently released Manual of Uniform traffic Control (MUTCD) pavement marking retroreflectivity minimums, and (3) incorporates recent paint application cost data to evaluate two alternative methods of compliance with the new MUTCD retroreflectivity minimums for two-lane roads. The second manuscript is presented in Chapter 3 and develops a new performance prediction model for paint pavement markings that includes the impact of snow removal operations and then applies the model to four real-world roadways to determine if replacement is required after one year of service.

## II. The Economics of Compliance with New Pavement Marking Retroreflectivity Minimums

Dale M. Mull[1]; William E. Sitzabee, Ph.D., P.E.[2]

**Abstract**

The Federal Highway Administration has proposed to add the minimum retroreflectivity standards to the First Revision of the 2009 edition of the Manual of Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration, 2010). This paper (1) validates the previously published Sitzabee model with an expanded data set, (2) updates service life predictions for painted pavement markings using recently released Manual of Uniform Traffic Control (MUTCD) pavement marking retroreflectivity minimums, and (3) incorporates recent paint application cost data to evaluate two alternative methods of compliance with the new MUTCD retroreflectivity minimums for two-lane roads. The authors show that paint pavement markings can last as long as four years on roads with posted speeds of 30 mph or less. The authors also show that the use of centerlines and no edge lines on roads with a posted speed of less than 55 mph is the most economical method of compliance when using paint pavement markings.

**Background**

Congress directed the Secretary of Transportation to establish minimum retroreflectivity standards in 1993 (United States Congress, 1993). As a result, the

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Federal Highway Administration (FHWA) has proposed minimum retroreflectivity standards be included in the first revision of the 2009 edition of the Manual of Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration, 2010). The proposed standards presented in Table 3 show a matrix of values separated by road type and speed limit. States should maintain compliance with the MUTCD to minimize exposure to litigation and to maximize access to federal transportation funds. Transportation agencies in the United States already spend an estimated $2 billion a year on pavement marking maintenance, and compliance with this new standard will further increase that cost. The estimated increase in maintenance cost could be as much as $64 million per year (Hawkins, 2010).

**Table 3. Proposed Retroreflectivity Minimums**

| | Posted Speed (mph) | | |
|---|---|---|---|
| | ≤ 30 | 35-50 | ≥ 55 |
| Center line markings only | n/a | 100 | 250 |
| Center lines and edge lines | n/a | 50 | 100 |
| Measured at standard 30-m geometry in units of mcd/m$^2$/lux. | | | |

A quick review of Table 3 reveals that there are two acceptable alternative methods for striping two-lane roads: (1) use centerline markings only, but maintain a high retroreflectivity, or (2) use both centerlines and edgelines, but maintain a lower retroreflectivity level. The advantage of using both center and edge lines is a reduced retroreflectivity minimum, while reduced initial cost is the advantage of only marking center lines. So which alternative is the most economically beneficial? Answering questions such as this one is a fundamental goal of asset management. Asset managers use condition performance modeling, public policy, and cost data to establish performance goals and evaluate alternatives (Federal Highway Administration, 1999).

To support transportation asset managers, Sitzabee et al. (2009) presented a highly predictive degradation model for paint pavement markings. Unfortunately, the model did not pass the statistical tests for constant variance and normality due to the limited availability of data. This paper (1) validates the model with an expanded data set, (2) updates service life predictions for painted pavement markings using recently released Manual of Uniform Traffic Control (MUTCD) pavement marking retroreflectivity minimums, and (3) incorporates recent paint application cost data to evaluate two alternative methods of compliance with the new MUTCD retroreflectivity minimums for two-lane roads.

**Validation of Paint Degradation Model**

Sitzabee et al. (2009) analyzed the deterioration and performance characteristics of North Carolina thermoplastic pavement markings to produce a degradation model. They also created a model for paint pavement markings. The result was a degradation model with an adjusted coefficient of determination of 0.75, which is highly predictive. The model is:

$$R_L = 55.2 + 0.77 * R_{L,Initial} - 4.17 * t \quad (1)$$

where $R_L$ = retroreflectivity level in mcd/m$^2$/lux; $R_{L, Initial}$ = initial retroreflectivity in mcd/m$^2$/lux; and $t$ = time in months (Sitzabee et al. 2009). Unfortunately, the paint degradation model exhibited constant variance and non-normality problems due to the limited availability of data. The authors tried log, exponential, and polynomial transformations, but all were ineffective. Sitzabee et al. (2009) concluded that "further validation in future studies is desired."

The original model was developed using data collected by the North Carolina Department of Transportation (NCDOT) over a five year period. NCDOT has since provided an additional three years which was added to the original five years of data to produce a more robust data set with which to validate the model by Sitzabee et al (2009). A visual analysis of the *Q*-*Q* plot using the five year data set compared to the *Q*-*Q* plot created with the larger eight year data set revealed that the additional data reduced the constant variance problem to an acceptable level.

The null hypothesis of the Shapiro-Wilk test states that the population is normal. Any value of the test statistic below 0.05 would support rejecting the null hypothesis. The Shapiro-Wilk test for the original model resulted in a probability of 0.0414 (Sitzabee, 2009). This suggests rejection of the null hypothesis and concluding that the distribution is not normal. However, in the case of the eight year data set, the probability of $P < W$ equaled 0.2577, providing statistical evidence to keep the null hypothesis and assume that the distribution is normal. This is an important step in validating a regression model since the model relies heavily on the assumption of normality.

**Pavement Marking Service Lives**

The time and effort invested in creating a statistically sound performance model is wasted unless asset managers actually use the model to influence the decision making process. For this reason, we employed the validated model to gain valuable insights into two alternative methods of compliance with the new MUTCD pavement marking retroreflectivity minimums.

Sound asset managers must often explore economic alternatives which require the calculation of services lives for the asset of interest. We inserted the validated paint pavement marking model into a Monte Carlo simulation to determine the service lives of paint pavement markings in each of the MUTCD categories. A Monte Carlo simulation incorporates independent variable uncertainties which then translate into a probability distribution for the final output. This technique allows the decision maker to view the uncertainty in the computed answer. The magnitude and distribution of the uncertainty may change the perceived best solution.

The Sitzabee et al. (2009) model selected for this analysis was originally configured to calculate a predicted retroreflectivity value. However, when calculating service lives, the formula must be algebraically rearranged to predict time in months. The altered form of the model becomes:

$$t = (55.2 + 0.77 * R_{L,Initial} - R_{L,Minimum}) / 4.17 \quad (2)$$

where, $t$ = time in months; $R_{L,Initial}$ = initial retroreflectivity in mcd/m$^2$/lux; and $R_{L, Minimum}$ = the new retroreflectivity minimum for road type and speed limit in mcd/m$^2$/lux. Certain assumptions were made concerning each of the predictor variables. The variables and their respective assumptions are outlined below.

***Time***

Time is a continuous variable measured in months from marking installation. This is the unknown variable when calculating pavement marking performance lives.

***Observed $R_L$***

Observed $R_L$ is a continuous variable measured in mcd/m$^2$/lux. The values for the Observed $R_L$ term come straight from the minimum $R_L$ values proposed by the Federal Highway Administration shown in Table 3.

***Initial $R_L$***

Initial Retroreflectivity is a continuous variable measured in mcd/m$^2$/lux. The variable is the initial retroreflectivity value of the pavement marking, and it is measured within the first 30 days of application (Sitzabee et al. 2009). There are two ways to approach the Initial $R_L$ value for calculating service lives; asset managers can use either the contract specified minimums or empirical data of actual Initial $R_L$ values obtained across the state. We chose to use the empirical data because it was available and would result in more accurate service life estimates. An examination of North Carolina road data reveals a normal distribution with a sample mean of 227 mcd/m$^2$/lux and a standard deviation of 56 mcd/m$^2$/lux.

After defining the variables and their distributions, we then turned our attention to calculating the service lives of pavement markings under the different scenarios defined by the new MUTCD standard. For roads with posted speeds less than or equal to 30 mph, the MUTCD does not establish a minimum retroreflectivity. Therefore, the only requirement is that the marking be present on the roadway. We have observed through direct measurement that presence markings without any added beads for retroreflectivity generally have a retroreflectivity of 30 mcd/m$^2$/lux. Therefore, a retroreflectivity minimum of 30 mcd/m$^2$/lux was adopted for roads with posted speeds less than or equal to 30 mph for the purposes of determining service lives.

A Monte Carlo simulation was run for 1000 iterations. Table 4 shows the results of the service life simulation. Note that the table does not include a service life for two-lane roads with posted speeds greater than or equal to 55 mph. This is because the MUTCD minimum for the category (250 mcd/$m^2$/lux) is higher than the North Carolina contract specified minimums of 200 mcd/$m^2$/lux for yellow and 225 mcd/$m^2$/lux for white (North Carolina Department of Transportation, 2007). It is also higher than the mean actual initial retroreflectivity of 227 mcd/$m^2$/lux. Therefore, current practice results in a negative service life for two-lane roads with speeds greater than or equal to 55 mph.

**Table 4. Summary of Painted PM Service Lives (Years)**

| | Posted Speed (mph) | | |
|---|---|---|---|
| | ≤ 30 | 35-50 | ≥ 55 |
| Center line markings only (years) | 4.0 | 2.7 | 0 |
| Center line and edge lines (years) | 4.0 | 3.7 | 2.7 |

Prior to 2009, NCDOT replaced paint pavement markings annually (Sitzabee et al. 2009). The model indicated that the service lives were actually over two years, but the analysis was based on recommended minimum retroreflectivity values published in 1998 by J.D. Turner (Sitzabee et al. 2009). However, based on the minimum retroreflectivity values proposed by the MUTCD, NCDOT should replace paint markings every two, three, or four years depending on road type and speed limit. As stated by Sitzabee et al. (2009), "this has critical budget implications for pavement-marking managers."

**Economic Analysis of Alternatives**

Knowledge of an asset's service life allows asset managers to make budget predictions and informed evaluations of economic alternatives. The retroreflectivity minimums proposed by the MUTCD present two alternatives for marking two-lane roads.

The options are (1) use centerline markings only, but maintain a high retroreflectivity, or (2) use both centerlines and edgelines, but maintain a lower retroreflectivity level.

As seen in Table 4, a lower retroreflectivity minimum directly translates into a longer service life. The use of edge lines to obtain the longer service life may appear to be the best option. However, the greater initial cost of edgeline application might outweigh the benefits of a longer service life. So which option truly is the most economical? To answer that question, we used another Monte Carlo analysis to calculate the Equivalent Annual Cost (EAC) of each alternative.

The following paragraphs explain the assumptions associated with each of the independent variables.

### *Initial Cost*

For this variable, we used the average cost of four inch pavement markings over the last five years in North Carolina. The average cost was $0.13 per linear foot (NCDOT, unpublished internal report, November 2010). We also assumed one solid yellow line as the centerline for this simulation. In reality, centerline markings range from skip lines to double solid lines, but we assumed paint applied on all centerline marking combinations average to the equivalent of one solid line. Accordingly, we assumed only one linear foot of paint per linear foot of pavement is applied when using only centerlines, and that three linear feet of paint per foot of pavement is applied when edge lines are used in addition to center lines.

The unquantified cost of risking injury to highway workers during restriping efforts does exist, but it does not change the final outcome of this particular economic analysis. Since the cost is estimated as the cost per linear foot, increasing the known material, labor, and equipment costs by adding a risk of exposure cost does not change the final outcome. This omission is acceptable because the goal of this analysis is not to determine a final price, but to determine the best course of action. Once a course of action is selected, a thorough cost estimate should be calculated.

### *Marginally Acceptable Rate of Return*

We used discount rates obtained from the Federal OMB Circular No. A-94 APPENDIX C Revised December 2009 (Orszag, 2009). The circular states, "A forecast of real interest rates from which the inflation premium has been removed and based on the economic assumptions from the 2011 Budget. These real rates are to be used for discounting constant-dollar flows, as is often required in cost-effectiveness analysis." The authors used a uniform distribution between 0.009 and 0.027 to simulate the MARR in the Monte Carlo analysis.

**Table 3. Real Interest Rates on Treasury Notes and Bonds of Specified Maturities (in percent)**

| 3 Year | 5 Year | 7 Year | 10 Year | 20 Year | 30 Year |
|---|---|---|---|---|---|
| 0.9 | 1.6 | 1.9 | 2.2 | 2.7 | 2.7 |

The equivalent annual cost of pavement markings on roads with center line markings only is,

$$EAC = (1*c)(A/P,i,n) \qquad (3)$$

where *EAC* is the equivalent annual cost; *c* is the initial install cost per linear foot of marking; *i* is the marginally acceptable rate of return; and *n* is the calculated service life in years rounded down to the nearest integer. Similarly, the equivalent annual cost of pavement markings on roads with both center lines and edge lines is,

$$EAC = (3*c)(A/P,i,n) \tag{4}$$

Table 5 summarizes the results of the equivalent annual cost simulation.

**Table 5. Equivalent Annual Costs**

| | Posted Speed (mph) | | |
|---|---|---|---|
| | ≤ 30 | 35-50 | ≥ 55 |
| Center line markings only | $0.04 | $0.07 | -- |
| Center line and edge lines | $0.12 | $0.14 | $0.22 |
| Center lines only savings | $0.08 | $0.07 | -- |

The economic analysis reveals that the use of centerlines only on two-lane roads produces the lowest equivalent annual cost. The data thus supports a blanket policy of using only centerlines on all two lane roads with speeds less than 55 mph. As stated earlier, current NCDOT contract specifications allow initial retroreflectivity values that are lower than the retroreflectivity requirements for centerlines only at speeds greater than or equal to 55 mph. Therefore, edge lines must be used in this case to qualify for the less stringent retroreflectivity minimum standards.

**Conclusion**

This paper statistically validated the previously published pavement marking performance model by Sitzabee et al. (2009). With additional data from North Carolina, the model satisfies the statistical requirements of linear regression. The model is now a useful tool for the asset manager.

This paper also estimated the service lives of paint pavement markings with a Monte Carlo simulation. Under the new MUTCD minimums, paint pavement markings should be maintained on two, three, and four year cycles depending upon road type and speed limit. Abandoning the old routine of annual replacement will yield tremendous savings.

Finally, this paper evaluated the economic cost of two alternative methods of compliance with the new MUTCD standard for marking two-lane roads. It is more economical to mark two-lane roads with centerline markings only for any road with a posted speed of less than 55 mph.

The authors recommend that asset managers evaluate the increased cost of raising the contract and in-house minimum initial retroreflectivity specifications. If the costs of increasing the specifications are negligible, then it may be cost effective to paint centerlines only on two-lane roads with speeds greater than or equal to 55 mph. Additionally, asset managers could explore the option of separate contract specifications for two-lane roads with speeds greater than or equal to 55 mph.

**References**

ASTM. (2009). *Standard Test Method for Measuring the Coefficien of Retroreflected Luminance of Pavement Markings in a Standard Condition of Wetness.* West Conshohocken: American Society for Testing and Materials.

Brown, G. (2009). *2009/2010 Snow and Ice Removal Strategy.* City of Beavercreek, Superintendent of Public Service. Beavercreek: City of Beavercreek.

Carlson, P. J. (2009). Benefits of Pavement Markings: A Renewed Perspective Based on Recent and Ongoing Research. *Transportation Research Record: A Journal of the Transportation Reasearch Board , 2009* (2107), 59-68.

Craig, N., Sitzabee, W. R., & Hummer, J. E. (2007). Statistical Validation of the Effect of Lateral Line Location on Pavement Marking Retroreflectivity Degredation. *Public Works Management and Policy , 12* (2), 431-450.

Federal Highway Administration. (1999). *Asset Management Primer.* Washington, D.C.: U.S. Department of Transportation.

Federal Highway Administration. (2010). Notice of Proposed Amendments. *Federal Register* , 20935-20941.

Federal Highway Administration. (2010, April 22). *Proposed Revision 1 of the 2009 MUTCD - Maintaining Minimum Retroreflectivity of Logitudinal Pavement Markings.* Retrieved May 3, 2010, from Manual on Uniform Traffic Control Devices (MUTCD): http://mutcd.fhwa.dot.gov

Field, A. (2009). *Discovering Statistics Using SPSS* (3rd Edition ed.). Dubai: Oriental Press.

Hawkins, H. G. (2010). Answers to MUTCD Questions. Microsoft Outlook.

Hawkins, H. G. (2000). *Evolution of the U.S. Pavement Marking System.* College Station: Texas Transportation Institute.

Hawkins, H. G., Lupes, M., Schertz, G., Satterfield, C., & Carlson, P. (2010). *Revised Assessment of Economic Impacts of Implementing Minimum Levels of Pavement Marking Retroreflectivity*. Office of Safety. Washington D.C.: Federal Highway Administration.

Lee, J.-T., Maleck, T. L., & Taylor, W. C. (1999). Pavement Marking Material Evaluation Study in Michigan. *Institute of Transportation Engineers ITE Journal , 69* (7), 44.

Migletz, J., & Graham, J. (2002). *NCHRP Synthesis 306 Long-term Pavement Marking Practices.* Washington D.C.: Transportation Research Board.

North Carolina Department of Transportation. (2007). Pavement Marking Rodeo. Raleigh.

Rasdorf, W. J., Zhang, G., & Hummer, J. E. (2009). The Impact of Directionality on Paint Pavement Marking Retroreflectivity. *Public Works Managment & Policy , 13* (3), 265-277.

Sasidharan, L., Karwa, V., & Donnell, E. T. (2009). Use of Pavement Marking Degradation Models to Develop a Pavement Marking Management System. *Public Works Managment & Policy , 14* (2), 148-173.

Sitzabee, W. E., Hummer, J., & Rasdorf, W. (2009). Pavement Marking Degredation Modeling and Analysis. *Journal of Infrastructure Systems , 15* (3), 190-199.

Turner, J. D. (1998). *Pavement Marking Retroreflectivity: Research Overview and Recommendations.* Federal Highway Administration.

United States Congress. (1993). *United States Department of Transportation and Related Agency Appropriation Act.* Washington D.C.

USDOT. (1999). *Asset Management Primer.* Federal Highway Administration, Office of Asset Management. Washington D.C.: U.S. Department of Transportation.

## III. Paint Pavement Marking Performance Prediction Model

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**Abstract**

The purpose of this research effort was to develop a new performance prediction model for paint pavement markings that includes the impact of snow removal operations. The paper first develops a model based on data from North Carolina. The authors then apply the model to a small stretch of road in Ohio to explore the utility of the model in other states. Recently proposed Manual of Uniform Traffic Control Devices minimum standards for pavement marking retroreflectivity were combined with the newly developed degradation model to determine the remaining service life of four road segments due for pavement marking replacement according to standard operating procedure. This model indicated three years of service life remaining for two of the road segments indicating pavement marking replacement is unnecessary. Using the model developed in this paper, the remaining service life of a paint pavement marking can be estimated, and asset managers can avoid premature replacement of pavement markings. A key finding of this research is that each snow removal event subtracts more than one month of service life from paint pavement markings.

**CE Database Subject Headings:** Snow; Pavement markings; Pavement management; Traffic control devices; Service life; Regression models; Degradation; Management methods

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## Introduction

The North Carolina Department of Transportation (NCDOT) currently replaces paint pavement markings on an annual basis (Sitzabee 2009). The policy is very simple and easy to understand. As a result, it is also easy to predict restriping work schedules and budget requirements. They are essentially the same from year to year. Most importantly, the policy gets the job done, ensuring that pavement markings maintain sufficient retroreflectivity for safe operation of motor vehicles throughout the year.

However, with increasing infrastructure age and new pavement marking minimum retroreflectivity standards, a more sophisticated pavement marking management system is needed. Maintenance demands for our nation's aging transportation infrastructure have increased. The American Society of Civil Engineers' 2009 Report Card for America's Infrastructure states, "One-third of America’s major roads are in poor or mediocre condition and 45% of major urban highways are congested. Current spending of $70.3 billion per year for highway capital improvements is well below the estimated $186 billion needed annually to substantially improve conditions" (ASCE 2009). The increased requirements for maintenance dollars demand that asset managers optimize their budgets in order to address some of the maintenance funding shortfall. Performance prediction models are the key to optimization. Additionally, the Federal Highway Administration has published proposed minimum pavement marking retroreflectivity standards for the Manual of Uniform Traffic Control Devices (MUTCD) (Federal Highway Administration 2010). Physical measurement of the entire pavement marking inventory is impractical. Instead, performance prediction models can estimate the system condition and facilitate compliance with the new MUTCD requirements.

Unfortunately, models for paint pavement marking degradation currently in the literature all have weaknesses that limit their utility as an asset management tool. Many models have fairly low coefficients of determination ($R^2$ values) which translates to high levels of error in predicted pavement marking performance. Even models with a high $R^2$ have limitations in their statistical validity (Sitzabee et al. 2009). As a result, some asset managers may have limited confidence in the model's predictions.

None of the models for paint pavement markings include the contribution of snow removal operations on pavement marking degradation, although many authors acknowledge that winter maintenance does degrade pavement marking retroreflectivity (Dale 1988; Martin et al. 1996; Lu & Barter 1998; Lee et al. 1999; Migletz et al. 2001; Sarasua et al. 2003; Kopf 2004; Fitch & Ahearn 2007; Sitzabee et al. 2009). Therefore, the purpose of this paper is to present a valid degradation model for paint pavement markings that includes the inputs of snow removal.

## Background

### *Pavement Marking Materials*

Paints make up nearly 60% of the pavement-marking inventory nationwide (Migletz & Graham 2002) and NCDOT is no different (Sitzabee et al. 2009). Installed paint pavement markings are the least expensive form of marking (Migletz & Graham 2002), but the sheer volume of paint used makes this a significant budget item. For example, pavement markings alone already cost North Carolina approximately $14.5 million a year in contractor-performed work (Sitzabee et al. 2009). The use of refined performance models to improve life-cycle management can free funds for other pressing maintenance requirements.

***Retroreflectivity***

To improve visibility, pavement markings rely on retroreflectivity, which is the process where light emitted from a vehicle's headlight strikes the pavement marking and is reflected back toward the eye of the driver. Retroreflectivity is achieved through the use of glass beads embedded in pavement markings and is represented by the Coefficient of Retroreflected Luminance ($R_L$).

The American Society for Testing and Materials (ASTM) defines the Coefficient of Retroreflected Luminance as "the ratio of the luminance, *L*, of a projected surface to the normal illuminance, *E*, at the surface on a plane normal to the incident light, expressed in candelas per square meter per lux ($cd/m^2/lux$)." The organization further recommends use of millicandelas per square meter per lux as the standard unit for pavement marking retroreflectivity due to the low luminance values prevalent in pavement markings (ASTM 2005).

Non-reflectorized pavement markings, as with any other physical material, have an inherent level of natural reflectivity associated with the material's physical construction. Glass or ceramic beads mixed into the material before application, or spread upon the surface of the marking material before it has dried, provide pavement marking retroreflectivity and increase the material’s visibility at night.

Presence pavement markings were the national standard for many years. Reflectorization was first mentioned in the 1942 Manual of Uniform Traffic Control Devices (MUTCD) that described the practice of using glass beads in paint to provide retroreflectivity. The 1948 edition of the MUTCD added a small passage suggesting use of retroreflectorized pavement markings in a limited number of situations, and the 1954 revision of the 1948 MUTCD first required retroreflectorized pavement markings for rural roads intended for nighttime use. In 1961, the retroreflectivity requirement was expanded to all pavement markings intended for nighttime use (Hawkins 2000). However, from 1971 through the present day, the MUTCD language has simply read as follows: "Markings which must be visible at night shall be reflectorized unless ambient illumination assures adequate visibility. All markings on Interstate highways shall be reflectorized" (Hawkins 2000). The requirement for reflectorized pavement markings has been in place for 57 years; however, there has been no specified minimum retroreflectivity value.

Congress directed the Secretary of Transportation to establish minimum retroreflectivity standards in 1993 (United States Congress 1993). As a result, the Federal Highway Administration (FHWA) has proposed minimum retroreflectivity standards be included in the first revision of the 2009 edition of the Manual of Uniform Traffic Control (MUTCD) (Federal Highway Administration 2010). These proposed standards are shown in Table 6 and should be followed by all DOTs to minimize exposure to litigation and to maximize access to federal transportation funds.

**Table 6.** Proposed Pavement Marking Retroreflectivity Minimums

| | Posted Speed (mph) | | |
|---|---|---|---|
| | ≤ 30 | 35-50 | ≥ 55 |
| Two-lane roads without edge lines | n/a | 100 | 250 |
| All other roads | n/a | 50 | 100 |

Measured in mcd/m$^2$/lux; Adapted from FHWA 2010.

### *Snow Removal Operations and Management*

Chemical application, grit application, and snow plowing are standard snow management techniques. Salt and other chemicals, such as magnesium, are applied before snow events to prevent snow from freezing to the roadway.  Pre-applied chemicals can only deal with low volume snowfall.  Transportation agencies also apply sand or limestone grit to increase traction on the roadway.

If the accumulation exceeds a predefined threshold, the roads must be plowed.  As one example, the city of Beavercreek, OH, does not plow unless the accumulation exceeds three inches (Brown 2009).  Typical equipment used by transportation agencies to manage snow on the roadways includes a snow plow attached to the front of a dump truck and a hopper filled with sand or grit placed in the back of the truck.  Sometimes a large tank with liquid brine solution or other chemical solution is used in place of the hopper.

***Previous Studies***

Over the last few decades, researchers have established various models for predicting the degradation of pavement marking retroreflectivity.  Factors such as the Annual Average Daily Traffic (AADT), initial retroreflectivity, marking material, marking color, pavement material, pavement surface condition, lateral line location on the roadway, and direction of travel during application are all taken into consideration (Sitzabee et al. 2009; Rasdorf et al. 2009; Craig et al. 2007).  However, none of the models include snow removal activities.  Currently, no one has been able to quantify to what degree snow removal operations impact pavement marking performance.  Table 7 is a summary of the literature representing over 20 years of pavement marking research.

**Table 7.** Summary of Significant Paint Pavement Marking Performance Studies

| Year | Author | Key Findings |
|---|---|---|
| 1988 | Dale | Annual Snowfall affects degradation rates |
| 1996 | Martin et al. | Paint lasts longer on Portland Cement Concrete |
| 1998 | Lu & Barter | Significant retroreflectivity loss in winter: 62% white, 21% yellow |
| 1999 | Lee et al. | Snowfall highly correlated to pavement marking degradation. |
| 2001 | Migletz et al. | - 67% of models created were linear.<br>- Winter maintenance causes variations in service lives |
| 2002 | Abboud et al. | Developed logarithmic model with $R^2$ = 0.31. |
| 2003 | Sarasua et al. | Snow plowing/winter maintenance affects PMs |
| 2004 | Kopf | -Developed 13 models with high variability.<br>-Hypothesized that snow plows wear down mountain road pavement markings. |
| 2007 | Craig et al. | -Edge lines degrade slower than center/skip lines |
| 2007 | Fitch & Ahearn | -Age & winter maintenance have highest correlation to degraded performance.<br>-Recessed markings withstand winter maintenance better than surface markings. |
| 2009 | Sitzabee et al. | - Created paint model; $R^2$=0.75, but with statistical issues.<br>- Impact from snow categorically analyzed, but not significant. |

*Dale, 1988.*

As part of a larger synthesis for the Transportation Research Board, Dale tested various pavement marking materials to determine useful service lives under differing conditions. Dale considered the effects of initial retroreflectivity, annual snowfall, pavement type, and AADT on pavement marking performance. Unfortunately, annual snowfall was a categorical variable which does not yield itself to a quantitative impact coefficient. In addition, Dale does not identify a correlation between snowfall quantity and snow removal operation intensity (Dale 1988).

*Martin, Perrin, Jitprasithsiri, & Hansen, 1996.*

In a report for Utah DOT, Martin et al. studied pavement marking performance in Utah. The primary goal was to establish the most cost effective material for statewide use. Martin et al. developed models to describe the relationship between retroreflectivity, age, degradation rate, and AADT. In addition to age and AADT, the authors used pavement type and initial retroreflectivity to create the models. They discovered that paint pavement markings last 80% longer on Portland Cement Concrete than Asphalt Concrete at low AADT values. The effect of winter maintenance was not evaluated (Martin et al. 1996).

*Lu & Barter, 1998.*

Lu and Barter conducted a study of pavement marking performance in Alaska, Idaho, Oregon, and Washington. The study reviewed past reports, studies, and databases, executed a field survey that subjectively evaluated existing markings, and conducted a small field test of pavement markings in Alaska's central region. The field test revealed that painted pavement markings exhibited a significant decrease in retroreflectivity after just one winter season. White markings lost 62% of retroreflectivity, while yellow markings lost 21%. Lu and Barter attributed the sizable degradation to snow removal, sand application, and studded tires (Lu & Barter 1998).

*Lee, Maleck, & Taylor, 1999.*

Michigan State University (MSU) evaluated the performance of several pavement marking materials for the Michigan DOT. Their research goal was to show how to implement cost effective procedures for pavement marking asset management. A significant finding was the high correlation between snowfall and pavement marking degradation (Lee et al. 1999).

*Migletz, Graham & Garwood, 2001.*

Migletz et al. evaluated the visibility and durability performance of durable pavement markings for specific marking materials, colors, and types. The study did not find any one model to fit the data collected across the nation. Therefore, the report modeled each test site independently. The resulting models were 67% first order linear, 25% exponential decay, 2% second order linear, and the study could not fit models to 6% of the data. The report also attributes "weather conditions" and "winter maintenance snow removal policies" as causes for variations in pavement marking service lives between roads with identical material types (Migletz et al. 2001).

*Abboud & Bowman, 2002.*

Abboud and Bowman sought to establish a restriping scheduling method that factors in application cost, service life, and user costs related to crashes. The model they created to estimate service life was a logarithmic model.

$$R_L = -19.457 * Ln(VE) + 26.27 \tag{5}$$

where, $R_L$ = Pavement Marking Retroreflectivity in mcd/m$^2$/lux; $Ln$ = Natural Logarithm; and $VE$ = Vehicle Exposure, in thousands of vehicles.

$$VE = \frac{ADT}{Lane} * Age * 30.4 * 10^{-3} \tag{6}$$

where, age is measured in months. The $R^2$ value for the model is 0.3139. The study used 15-meter geometry to collect the data; therefore, the results are not directly comparable to the other models mentioned in this literature review. Also, because the research only included data from Alabama, the study encourages practitioners to limit application of the results to rural highways in warm climates where snow plowing is not a factor (Abboud & Bowman 2002).

*Sarasua, Clarke & Davis, 2003.*

Sarasua et al., while conducting research for the South Carolina DOT, surveyed the other 49 states in the union regarding pavement marking management practices. Thirty of the state DOTs responded. Nine of those states indicated using "snow plowing" or "winter maintenance" to influence pavement marking management decisions. Also, the states in northern regions indicated that in their opinion winter maintenance activities have a strong influence on pavement marking service life. Sarasua et al. confirmed the state's opinions with observations of sharp drops in retroreflectivity after snow removal activities, but they did not include snow removal in their models. Only Minnesota and Oregon used predictive models in their asset management program. The authors did not develop a model for paint pavement markings (Sarasua et al. 2003).

*Kopf, 2004.*

Kopf worked to develop degradation curves for roadway pavement markings for the Washington State Transportation Center. Kopf created 13 models based on pavement marking material, color, and time. The coefficients of determination for the 13 models varied from 0.03 to 0.69. The data collected exhibited significant variability casting doubt on the models produced from the data. Kopf acknowledged that "sections from the mountain passes may experience more wear if snowplows frequently travel the roadway" (Kopf 2004).

*Craig, Sitzabee, Hummer & Rasdorf, 2007.*

Craig et al. examined the effect of lateral line location on the degradation of thermoplastic pavement markings. The study concluded there is a significant difference in the degradation rates between edge lines and center lines. Center lines degrade faster than edge lines. This suggests that subsequent degradation models for other materials should include lateral line location as an independent variable (Craig et al. 2007). Snowplow activities may contribute to increased degradation of the center line pavement markings.

*Fitch & Ahearn, 2007.*

Fitch and Ahearn studied 25 newly constructed pavement projects in Vermont between 2002 and 2005 in a report for the State of Vermont. None of the pavement marking materials in this study were traditional paint. Factors included in their degradation model were age, seasonal application, and recessing. Traffic volume and regional placement were also evaluated and found to have no statistically significant effect on degradation. As expected, age and winter maintenance had the largest correlation to the degradation of retroreflectivity. Unique to this study is the experimentation with recessed pavement markings. The authors found the loss of retroreflectivity is much more pronounced on surface markings than on recessed markings. This finding appears to support the hypothesis that the abrasion of snow plows is the primary cause of retroreflectivity degradation experienced during winter maintenance (Fitch & Ahearn 2007).

*Sitzabee, Hummer & Rasdorf, 2009.*

Sitzabee et al. determined the performance characteristics of pavement markings in North Carolina. The authors developed the following degradation model for painted pavement markings:

$$R_L = 55.2 + 0.77\left(R_{L,Initial}\right) - 4.17\left(time\right) \quad (7)$$

where $R_L$ = retroreflectivity in mcd/m$^2$/lux; $R_{L,\ initial}$ = initial retroreflectivity in mcd/m$^2$/lux; and *time* = months after installation. The adjusted coefficient of determination was 0.75. The model failed the Shapiro-Wilk test for normality so the model's statistical validity is questionable. However, the model is still useful given that in the last ten years the only other model created had a coefficient of determination of 0.31. The authors examined snow plowing as a categorical variable for the model, but discovered it was not statistically significant, and recommended future research on the effects of snow plowing on pavement markings (Sitzabee 2009).

**Methodology**

This section presents the methodology used for data collection and subsequent data analysis. The North Carolina Department of Transportation (NCDOT) provided a data base of retroreflectivity data collected by an independent contractor over a seven year period on roads throughout the state. The data was originally collected for quality assurance purposes, but the robust nature of the data facilitates pavement marking research. The data set contains observations of many pavement marking materials, but only observations of paint pavement markings were used for this study.

Least-squares analysis was utilized to model the NCDOT data. The researchers developed an initial model with a randomly selected 80% of the data points and then validated the variables in the initial model using the remaining 20% of the data. Several variables were analyzed for inclusion in the model; however, only variables with a significance at $p = 0.05$ or less were accepted in the initial model. A final model was then developed from the full data set using the independent variables established by the initial model.

***Data***

The NCDOT contractor used a modified Laserlux mobile retroreflectometer (model LLR5) mounted on a Chevy Suburban to collect the data. The Laserlux uses standard 30-m geometry required by ASTM. Every tenth of a mile, the $R_L$ readings were averaged and recorded in an onboard computer. The tenth-mile readings are then averaged to obtain the $R_L$ value, measured in mcd/m$^2$/lux, for the test section of roadway. The data collected for paints included 165 segments that represent approximately 490 miles of roadway.

Before each data collection activity, the Laserlux unit was calibrated using a pavement marking test bed made up of various pavement markings whose retroreflectivity values were previously established with the LTL-2000 handheld device. The LTL-2000 calibration process satisfied ASTM standards for measurement of pavement marking retroreflectivity. Using the known test bed, the technician calibrated the Laserlux. This calibration corrected errors induced by changes in vehicle load, tire pressure, and ambient light. Once in the field, the LTL-2000 was used to verify the continued correct calibration of the Laserlux. The Laserlux was recalibrated in the field prior to each collection segment and during collection when conditions changed.

### ***Modeling the Data***

*Initial Model*

A mixed step-wise selection process using JMP® statistical software was used to develop the initial model. Pavement-marking retroreflectivity values, time, initial retroreflectivity, AADT, geographical region within North Carolina, line width, line thickness, snowplow activity, bead size, color, pavement type, and lateral line location were all considered, but only variables that reached a significance level less than $p = 0.05$ were kept in the model. The resultant initial pavement marking retroreflectivity degradation model for paint is

$$R_L = 59.9 + 0.74 * R_{L,Initial} - 2.45 * t - 3.86 * s - 0.0004 * AADT \qquad (8)$$

where, $R_L$ = retroreflectivity level in mcd/m$^2$/lux; $R_{L,\,Initial}$ = initial retroreflectivity in mcd/m$^2$/lux; $t$ = time in months; $s$ = number of snow plow events; and $AADT$ = Annual Average Daily Traffic. The coefficient of determination ($R^2$) for the model is 0.77 and the adjusted $R^2$ is 0.76.

Linear regression assumes a normal residual population and constant variance of residuals across the range of predicted values. The authors used three statistical tools to verify that the initial model satisfied the assumptions of linear regression. A plot of the residuals versus the predicted $R_L$ values tested for constant variance of the residuals. A Q-Q plot of the residuals, and the Shapiro-Wilk test verified the normality of the residual distribution. All three tests indicated the model satisfied the assumptions of linear regression.

The independent variables identified by the initial model are defined as:

1. Initial Retroreflectivity -- a continuous variable measured in mcd/m$^2$/lux. It is the initial value achieved by the paint application crew.

2. Time -- a continuous variable that is measured in months from marking installation. Time acts as a surrogate for physical processes that affect degradation, but are not significant in their own right.

3. Snow Plow Events -- a continuous variable representing the cumulative number of times the road was cleared using snow plows since the pavement marking was first applied.

4. Annual Average Daily Traffic (AADT) -- a continuous variable measured in vehicles per day for the entire roadway.

*Initial Model Validation with Hold-Back Data*

The Mean Absolute Percentage Error (MAPE) was used to measure how well the initial model predicted the observed retroreflectivity of the twenty percent hold-back data.

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \qquad (9)$$

where $A_t$ is the actual value and $F_t$ is the forecast, or predicted, value. The mean absolute percentage error of the initial model with respect to the validation data is 14% with a standard deviation of 11%.

*Final Model*

The final model was developed by recombining the 20% hold-back data with the 80% used to develop the initial model and analyzing the entire data set using the independent variables established in the initial model. The final pavement marking retroreflectivity degradation model for paint is

$$R_L = 65.5 + 0.72 * R_{L,Initial} - 2.55 * t - 3.22 * s - 0.0005 * AADT \qquad (10)$$

where, $R_L$ = retroreflectivity level in mcd/m$^2$/lux; $R_{L,Initial}$ = initial retroreflectivity in mcd/m$^2$/lux; $t$ = time in months; $s$ = number of snow plow events; and $AADT$ = Annual Average Daily Traffic. Table 8 shows the summary parameter estimates and also lists the standard error, t-ratio and probability > |t| values. The $R^2$ decreased from 0.77 in the initial model to 0.76 and the adjusted $R^2$ also decreased from 0.76 to 0.75. This is the best coefficient of determination in the literature for any paint pavement marking performance model.

**Table 8. Parameter Estimates for the Final Model**

| Estimator | Estimate | Std. Error | t Ratio | Probability>\|t\| |
|---|---|---|---|---|
| Intercept | 65.5 | 8.71 | 7.51 | <0.0001 |
| RL Initial | 0.72 | 0.03 | 20.76 | <0.0001 |
| Time | -2.55 | 0.26 | -9.82 | <0.0001 |
| Plow Events | -3.22 | 0.65 | -4.98 | <0.0001 |
| AADT | -0.0005 | 0.00 | -4.07 | <0.0001 |

A plot of the residuals versus the predicted $R_L$ values, a Q-Q plot of the residuals, and the Shapiro-Wilk test were again used to test the assumptions of linear regression. Figure 4 shows the residuals versus the predicted $R_L$ values. The desired outcome of this plot is an evenly distributed set of data points about a mean value of zero. The data points are fairly well distributed about the mean indicating constant variances among the residual values. Figure 5 shows the Q-Q plot of the residual data and clearly demonstrates a straight line pattern which visually confirms a normally distributed residual population. The Shapiro-Wilk goodness-of-fit test also confirmed the normality of the residuals. The null hypothesis states that the data are from a normal distribution. In this case, the probability that $P < W$ equals 0.5637 which is greater than the confidence level of 0.05.  Therefore, the test supports the assumption that the residuals form a normal distribution.

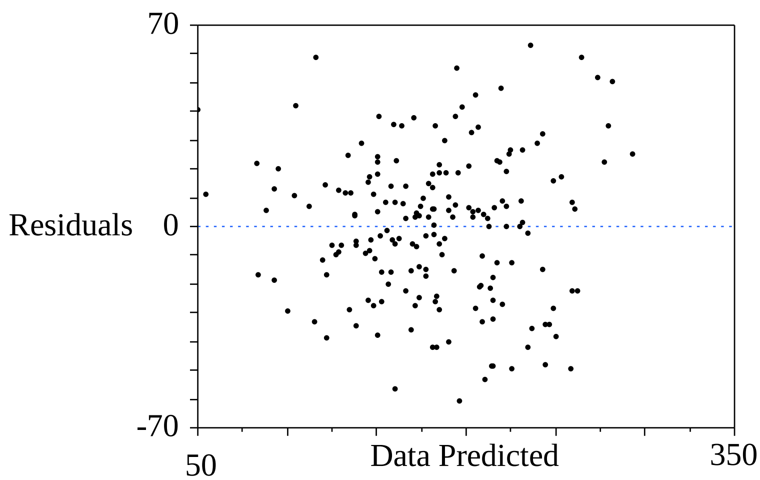


**Figure 4.  Residuals of the Final Model**

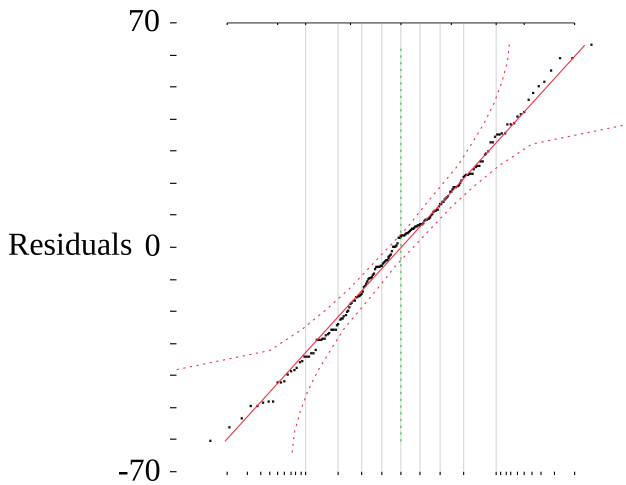


**Figure 5.  Q-Q Plot of Residuals for the Final Model**

The new model validates the assertion by Sitzabee et al. and others that *time* is a surrogate for all sorts of variables that are either immeasurable or statistically insignificant.  A graph of standardized beta values demonstrates this concept.  A standardized beta value is a measure of the predictive power of any given independent variable in a model with respect to the other independent variables in the model.  Figure 6 shows the standardized beta values for the final model. The pie chart reveals that *Initial* $R_L$ and *Time* are the two most predictive independent variables. This validates the work of Sitzabee et al. in 2009 where *Initial* $R_L$ and *Time* were the only independent variables found to be significant predictors of *Observed* $R_L$. As Figure 6 shows, most of the predictive power of the new variables in the new model comes from the predictive power previously attributed to *time* in the Sitzabee model.

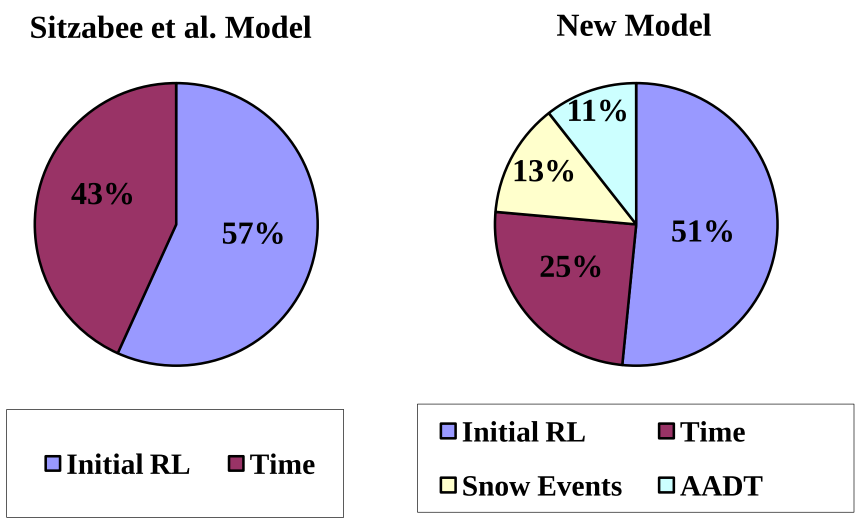


**Figure 6. Predictive Power of the Independent Variables**

***Test of the North Carolina Model in Ohio***

The final model developed from the North Carolina dataset appears to be the best model yet, but it can only be used with confidence within the state of North Carolina. A far better model would be one that could be used nationwide. To test how well the North Carolina model might predict painted pavement marking performance outside the state of North Carolina, a small study was performed in Beavercreek, Ohio.

A 1,955 foot section of Beaver Valley Road was chosen as the test deck. The pavement markings on this road had been repainted the summer prior to data collection, were less than one year old, and had never been snow plowed. This was an important consideration because fresh pavement markings ensured that the full impact of snow removal would be detectable.

The research team began collecting data on 12 December 2009 and collected data on a weekly basis as long as snow was not covering the pavement markings. Data were collected at 39 randomly selected test sites along the test deck. Both the yellow centerline and white edge line were measured at each test site. Three retroreflectivity readings were recorded at each sample location then averaged to determine the retroreflectivity levels. Observations showed little variation between the three readings. The readings for the entire test deck were collected on eight separate occasions. Salt/sand applications, brine solution applications and snow plowing frequencies were recorded for each snow event. The research team stored and transported the retroreflectometer at temperatures very near to ambient outdoor temperatures. The team also calibrated the device once upon arrival at the test deck each day data were collected, as per ASTM E1710-05. $R_{L,Initial}$ for the centerline was 155 mcd/m$^2$/lux while the $R_{L,Initial}$ for the edge line was 170 mcd/m$^2$/lux. AADT was 8,000 vehicles per day.

There are two limitations with this data collection methodology. First, ASTM 1710-05 specifies an ambient temperature of 40 degrees Fahrenheit or greater when collecting data (2005). The research team was unable to comply with this requirement as part of this experiment design because ambient temperatures between snow events were often below freezing. Data between snow events is valuable, and there was no practical way to collect it and satisfy the ASTM ambient temperature requirement.

Second, ASTM also specifies that the "surface of the marking shall be clean and dry."  The research team was unable to comply with this specification during some of the winter months.  Brine solution on the road after a snow event often kept the road wet or at least damp for weeks at a time.  This was particularly true for the edge line that was often only inches away from melting snow.  The markings were all measured as they were found in the natural environment.  The research team chose to measure the markings as viewed by the public.  This produced a more realistic understanding of the performance level of pavement markings during the snow season.  In addition, cleaning the pavement marking surface could result in an unnaturally polished surface that would negatively affect the accuracy of the data.  So an artificially cleaned surface would not necessarily be any more accurate than measuring the markings as found on the roadway.

The Mean Absolute Percentage Error (MAPE) was used to measure how well the North Carolina model predicted the $R_L$ on Beaver Valley Road.  The mean absolute percent error of the North Carolina model with respect to Beaver Valley Road is 13% with a standard deviation of 10%.  Because the error found between the initial and the final North Carolina models was a similar 14% with a standard deviation of 11%, the research seems to indicate that the North Carolina model predicts paint pavement marking performance equally well outside the state as inside.  Additional research is needed to confirm the conclusion, but the model does show promise of widespread utility.

**Practical Application (Service Life Prediction)**

One key application of the model is to predict the remaining service life of specific pavement markings in an inventory.  Three randomly selected records from the

North Carolina data set and the one record from Ohio were evaluated for demonstration purposes. The prediction model was applied to each road segment's data and the calculated remaining service life is shown in Table 9. The service life predictions extend beyond the two year range of data used to create the model, but the predictions are considered valid for making management decisions.

The three North Carolina records were chosen because in each case the marking age was approximately 12 months. The authors chose this time frame because NCDOT previously believed that paint markings had a useful service life of approximately one year (Sitzabee et al. 2009). In addition, Migletz et al. estimated the paint marking service life to be slightly less than one year in 2001. Selecting records with markings roughly one year old demonstrates the power of the performance prediction model to impact maintenance decisions and ultimately save maintenance funds. Of the four one-year-old segments selected, only one is estimated to need replacement to prevent failure within the next year. Two of the segments indicate remaining service lives of three or more years. These figures will change if the markings experience additional snow removal events, but the figures make a strong argument against immediate replacement for those two segments.

**Table 9. Predicted Service Life Remaining**

| Minimum $R_L$ ($mcd/m^2/lux$) | Initial $R_L$ ($mcd/m^2/lux$) | Marking Age (months) | Snow Plow Events | AADT | Service Life Remaining (months) | State |
|---|---|---|---|---|---|---|
| 100 | 241 | 13 | 4 | 1700 | 36 | NC |
| 100 | 252 | 10 | 5 | 100 | 41 | |
| 100 | 128 | 13 | 0 | 5000 | 8 | |
| 50 | 163 | 4 | 16 | 8,000 | 18 | OH |

**Conclusions**

Specifically for paint pavement markings, this study determined:

1. Each snow plow event degrades paint pavement markings by 3.22 mcd/$m^2$/lux which is more than one month of service life in North Carolina.

2. Under the proposed standards with no snow fall, an AADT of 4,000, and an $R_{L, Initial}$ of 220, paint pavement markings have a service life greater than five years.

3. AADT has a small but significant impact on the degradation of painted pavement markings. This is likely due to the fact that North Carolina only applies paint to roadways with an AADT of 4,000 or less as a matter of policy.

4. The lessons learned about pavement marking degradation in North Carolina appear to be useful in other regions of the United States.

We have successfully verified that snow removal operations do impact paint pavement marking performance, and we established a degradation value of 3.22 mcd/$m^2$/lux per snow plow event. This gives a statistically significant quantity to a phenomenon observed by researchers over the last 22 years. Asset managers now have an empirical tool with which to evaluate regional pavement marking alternatives, and to predict the budgetary impacts of just one unusually harsh winter. Additionally, asset managers can revise snow removal operations in light of increased knowledge regarding the negative impacts of snow removal on painted pavement markings.

The service life of painted pavement markings is another significant finding. It builds upon the work by Sitzabee et al. (2009) who suggested pavement markings have longer service lives than typically assumed by asset managers. Most transportation agencies assume a life cycle of one year or less and replace paint pavement markings annually. Asset managers could save large sums of money by abandoning the old pattern of annual replacement and using the pavement marking performance model as presented in this paper.

There have been conflicting conclusions concerning the contribution of AADT to pavement marking degradation. Sitzabee et al. (2009) was able to establish that AADT does impact thermoplastics, but they were unable to validate that AADT impacts paint pavement markings as well. With a larger data set, this research effort was able to establish that AADT does have a statistically significant impact on paint pavement marking performance.

Finally, we have shown via a small validation study that the degradation model developed in North Carolina has the potential to prove very useful to users outside of North Carolina. Additional research is required to prove this assertion for other areas of the county. However, there is nothing to prohibit individual transportation agencies from experimenting with the model to see if there is strong correlation between the model's predictions and the observed pavement marking performance in their area of responsibility. In many cases, transportation agencies would only have to collect snow plow event data to utilize the model presented in this paper. $R_{L\ Initial}$, AADT, and pavement marking age are data that most transportation agencies already maintain.

**Future Research**

It is highly recommended that researchers conduct additional studies on the validity of this model in states other than North Carolina. The local study was limited in scope. A more widespread evaluation with the assistance of multiple state transportation agencies would be appropriate.

**Acknowledgements**

Special thanks to the North Carolina Department of Transportation for providing the tremendous amount of data that became the foundational element to this effort. Thanks are also due to the personnel at the Maintenance Department for the City of Beavercreek, Ohio for extensive assistance with the local data collection effort. Both agencies provided significant resources and expertise that made this project a success.

**Disclaimer**

The views expressed in this article are those of the writers and do not reflect the official policy or position of the U.S. Air Force, Department of Defense, the U.S. Government, the Air Force Institute of Technology, NCDOT, or the City of Beavercreek, OH.

**References**

Abboud, N. and Bowman, B.L. (2002). "Cost and longevity-based scheduling of paint and thermoplastic striping." *Transportation Research Record. 1794*, Paper No. 02-2170.

American Society for Testing and Materials (ASTM). (2005). "Standard test method for measurement of retroreflective pavement marking materials with CEN-prescribed geometry using a portable retroreflectometer." *ASTM E 1710-05*, West Conshohoken, PA.

American Society of Civil Engineers(ASME). (2009). *2009 Report Card for American's Infrastructure*. ASCE. Washington, D.C..

Brown, G. (2009). *2009/2010 Snow and Ice Removal Strategy.* Unpublished Internal Memorandum, Superintendent of Public Service. Beavercreek, OH.

Craig, W. N., Sitzabee, W. E., Hummer, J. E., and Rasdorf, W. J. (2007). "Impact of line location on pavement marking retroreflectivity degradation." *Public Works Management and Policy*, 12(2), 431-450.

Dale, J.M. (1988) "Pavement Markings: Materials and Application for Extended Service Life", *NCHRP Report 138*, Transportation Research Board, National Research Council, Washington, D.C.

Federal Highway Administration. (2010). "Notice of Proposed Amendments." *Federal Register*, 75(77), 20935-20941.

Fitch, J. M., and Ahearn, W. E. (2007). "Pavement Marking Durability Statewide Final Report." Materials and Research Section, State of Vermont Agency of Transportation. Montpelier, VT.

Hawkins, H. G., (2000). "Evolution of the U.S. Pavement Marking System," *NCHRP Project 4-28 -- Feasibility Study for an All-White Pavement Marking System,* Transportation Research Board, National Research Council, Washington, D.C.

Kopf, J. (2004). "Reflectivity of pavement markings: Analysis of retroreflectivity degradation curves." Washington State Transportation Center (TRAC). Seattle, WA

Lee, J., Maleck, T. L., and Taylor, W. C. (1999). "Pavement Marking material study in Michigan." *Inst. Transp. Eng. J.I*, 69(7), 44-50.

Lu, J. J., & Barter, T. (1998). Evaluation of traffic markings in cold regions. *ASCE Journal of Transportation*, 124(1), 42-51.

Martin, P. T., Perrin, T., Jitprasithsiri, S., Hansen, B. (1996). "A Comparative Analysis of the Alternative Pavement Marking Materials for the State of Utah." Utah Department of Transportation. Salt Lake City, UT.

Migletz, J., and Graham, J. (2002). *NCHRP Synthesis 306 Long-term Pavement Marking Practices.* Transportation Research Board. Washington, D.C..

Migletz, J., Graham, J., Harwood, D. W., and Bauer, K. M. (2001). "Service life of durable pavement markings." *Transportation Research Record. 1749*, TRB, National Research Council, Washington D.C., 13-21.

Sarasua, W. A., Clarke, D. B., and Davis, W.J. (2003). "Evaluation of interstate pavement marking retroreflectivity." *Rep. Prepared for South Carolina Department of Transportation, Rep. No FHWA-SC-03-01.*

Sitzabee, W. E., Hummer, J. E., & Rasdorf, W. (2009). "Pavement Marking Degredation Modeling and Analysis." *Journal of Infrastructure Systems,* 15(3), 190-199.

United States Congress. (1993). *United States Department of Transportation and Related Agency Appropriation Act of 1993.* Washington GPO,Washington D.C.

# IV. Conclusion

The ultimate goal of this research was to improve the management of painted pavement marking assets through an increased understanding of marking life cycle performance. The goal was achieved in two parts. First, the authors validated a previously published degradation model for painted pavement markings by using a larger data set. With the basic model validated, the authors then expanded the model to include snow plow operations and Average Annual Daily Traffic.

The first journal manuscript produced four primary results. The paper:

1. Statistically validated a previously published pavement marking performance model. With additional data from North Carolina, the model passes the assumption of linear regression. The model is now a useful tool for the asset manager.

2. Estimated the service lives of paint pavement markings with a Monte Carlo simulation. Under the new MUTCD minimums, paint pavement markings should be maintained on two, three, and four year cycles depending upon road type and speed limit. Abandoning the old routine of annual replacement will yield tremendous savings.

3. Evaluated the economic cost of two alternative methods of compliance with the new MUTCD standard for marking two-lane roads. It is more economical to mark two-lane roads with centerline markings only provided the road has a posted speed of less than 55 mph.

4. Recommend that asset managers evaluate the increased cost of raising the contract and in-house minimum initial retroreflectivity specifications. If the costs of increasing the specifications are negligible, then it may be cost effective to paint centerlines only on two-lane roads with speeds greater than or equal to 55 mph. Additionally, asset managers could explore the option of separate contract specifications for two-lane roads with speeds greater than or equal to 55 mph.

The second journal manuscript also produced four significant results. Specifically, the paper:

1. Determined each snow plow event degrades paint pavement markings by 3.22 mcd/m$^2$/lux which is more than one month of service life in North Carolina.

2. Showed that with no snow fall, an AADT of 4,000, and an $R_{L,\ Initial}$ of 220, paint pavement markings have a service life greater than five years.

3. Confirmed that AADT has a small but significant impact on the degradation of painted pavement markings. This is likely due to the fact that North Carolina only applies paint to roadways with an AADT of 4,000 or less as a matter of policy.

4. Indicated the lessons learned about pavement marking degradation in North Carolina appears to be useful in other regions of the United States.

In summary, asset managers in transportation departments at all levels of government can benefit from the information presented herein. No one policy of replacement after a standard time has elapsed can optimize service life utilization. Rather, to optimize maintenance budgets, asset managers should evaluate each road segment individually utilizing the refined degradation model developed in chapter three. Such application should result in significant cost savings.

It is highly recommended that researchers conduct additional studies on the validity of this model in states other than North Carolina. The local study was limited in scope. A more widespread evaluation with the assistance of multiple state transportation agencies would be appropriate.

Researchers should also explore adaption of this model to airfield pavement markings. Not much is known quantitatively about airfield pavement marking degradation factors. The author suspects that premature replacement of airfield pavement markings may cost the military and civilian aviation industry millions of dollars each year in unnecessary runway closures.

Finally, the results presented in this thesis can reduce costs for the US Air Force. Currently, some installations replace pavement markings annually. This research has shown that annual replacement is unnecessary for roads with posted speeds up to 55 miles per hour. With most speed limits on Air Force installations well below 55 mph, Air Force pavement marking replacement expenditures need only be a small fraction of current costs.

## V. Bibliography

American Society of Civil Engineers (ASCE). (2009). *2009 Report Card for American's Infrastructure*. ASCE. Washington, D.C..

ASTM. (2009). *Standard Test Method for Measuring the Coefficien of Retroreflected Luminance of Pavement Markings in a Standard Condition of Wetness.* West Conshohocken: American Society for Testing and Materials.

Brown, G. (2009). *2009/2010 Snow and Ice Removal Strategy.* City of Beavercreek, Superintendent of Public Service. Beavercreek: City of Beavercreek.

Craig, N., Sitzabee, W. R., & Hummer, J. E. (2007). Statistical Validation of the Effect of Lateral Line Location on Pavement Marking Retroreflectivity Degredation. *Public Works Management and Policy , 12* (2), 431-450.

Dale, J.M. (1988) "Pavement Markings: Materials and Application for Extended Service Life", *NCHRP Report 138,* Transportation Research Board, National Research Council, Washington, D.C.

Federal Highway Administration. (2010). Notice of Proposed Amendments. *Federal Register* , 20935-20941.

Fitch, J. M., and Ahearn, W. E. (2007). "Pavement Marking Durability Statewide Final Report." Materials and Research Section, State of Vermont Agency of Transportation. Montpelier, VT.

Hawkins, H. G. (2000). *Evolution of the U.S. Pavement Marking System.* College Station: Texas Transportation Institute.

Kopf, J. (2004). "Reflectivity of pavement markings: Analysis of retroreflectivity degradation curves." Washington State Transportation Center (TRAC). Seattle, WA

Lee, J.-T., Maleck, T. L., & Taylor, W. C. (1999). Pavement Marking Material Evaluation Study in Michigan. *Institute of Transportation Engineers ITE Journal , 69* (7), 44.

Lu, J. J., & Barter, T. (1998). Evaluation of traffic markings in cold regions. *ASCE Journal of Transportation,* 124(1), 42-51.

Martin, P. T., Perrin, T., Jitprasithsiri, S., Hansen, B. (1996). "A Comparative Analysis of the Alternative Pavement Marking Materials for the State of Utah." Utah Department of Transportation. Salt Lake City, UT.

Migletz, J., Graham, J., Harwood, D. W., and Bauer, K. M. (2001). "Service life of durable pavement markings." *Transportation Research Record. 1749*, TRB, National Research Council, Washington D.C., 13-21.

Migletz, J., & Graham, J. (2002). *NCHRP Synthesis 306 Long-term Pavement Marking Practices.* Washington D.C.: Transportation Research Board.

Rasdorf, W. J., Hummer, J. E., Zhang, G., & Sitzabee, W. E. (2009). *Pavement Marking Performance Analysis*. Raleigh, NC: North Carolina State University.

Rasdorf, W. J., Zhang, G., & Hummer, J. E. (2009). The Impact of Directionality on Paint Pavement Marking Retroreflectivity. *Public Works Managment & Policy , 13* (3), 265-277.

Sarasua, W. A., Clarke, D. B., and Davis, W.J. (2003). "Evaluation of interstate pavement marking retroreflectivity." *Rep. Prepared for South Carolina Department of Transportation, Rep. No FHWA-SC-03-01.*

Sitzabee, W. E., Hummer, J., & Rasdorf, W. (2009). Pavement Marking Degredation Modeling and Analysis. *Journal of Infrastructure Systems , 15* (3), 190-199.

United States Congress. (1993). *United States Department of Transportation and Related Agency Appropriation Act.* Washington D.C.

USDOT. (1999). *Asset Management Primer.* Federal Highway Administration, Office of Asset Management. Washington D.C.: U.S. Department of Transportation.

NONPRINT FORM

| 1. Type of Product: | 2. Operating System/Version: | 3. New Product or Replacement: | 4. Type of File: |
|---|---|---|---|
| Scanned Documents<br>Raw Database | Microsoft Windows | New Products | Data Files |

**5. Language/Utility Program:**
Portable Digital Format (*.pdf) Adobe Reader Version 9.4.1
JMP Statistical Discovery from SAS (*.jmp) Version 8.0

| 6. # of Files/# of Products: | 7. Character Set: | 8. Disk Capacity: |
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| Two (2) Files | N/A | 552 MB |
| | 9. Compatibility: | 10. Disk Size: |
| Two (2) Products | N/A | 700 MB |

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&
"North Carolina Paint Pavement Marking Data"

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|---|---|---|
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The results of this research effort were captured in two manuscripts drafted for publication in peer reviewed journals. The first manuscript validated a previously published model with an expanded data set, updated service life predictions for painted pavement markings using recently released pavement marking retroreflectivity minimums, and incorporated recent cost data to evaluate two alternative methods of compliance with the new retroreflectivity minimums for two-lane roads. The second manuscript developed a new performance prediction model for paint pavement markings that includes the impact of snow removal operations and then applied the model to four real-world roadways to determine if replacement is required.

This research determined that each snow plow event degrades paint pavement markings by 3.22 mcd/m2/lux which is more than one month of service life. The work also showed that with no snow fall, an AADT of 4,000, and an RL, Initial of 220 mcd/m2/lux, paint pavement markings have a service life greater than five years on roads with posted speeds less than 55 mph. Finally, the research confirmed that AADT has a small but significant impact on the degradation of painted pavement markings. The results also indicated the developed for North Carolina might be useful in other states.


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