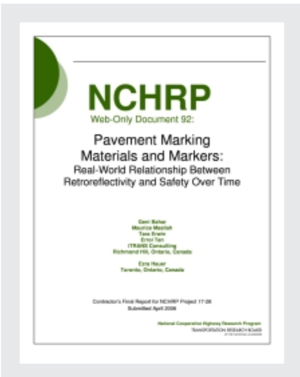

Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time

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Pavement Marking Materials and Markers:

Real-World Relationship Between Retroreflectivity and Safety Over Time

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Brief Contents

Table of Contents

List of Figures

List of Tables

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Executive Summary

Background and Objectives

Longitudinal pavement markings are found on nearly all freeways and highways in the United States, and previous research has emphasized the importance of quantifying the impact of different pavement marking material types on safety. While important, quantifying safety of pavement marking and marker of material types has remained elusive. This study takes a unique approach compared to previous research, and instead focuses upon quantifying the relationship between retroreflectivity and safety over time, independent of marking or marker material type.

Study Methodology

This study examined the safety effect of retroreflectivity of longitudinal pavement markings and markers over time on non-intersection locations during non-daylight conditions. The National Transportation Product Evaluation Program (NTPEP) is a service provided by the American Association of State Highway and Transportation Officials (AASHTO) which collects data and evaluate pavement markings and markers (among other products) using a formal and detailed work plan. For this study, NTPEP data were assembled into a database and used to derive mathematical models of retroreflectivity performance as a function of age, color, marking material type or marker type, climate region, and amount of snow removal. As a result of this modeling, a significant contribution of this study is the generation the retroreflectivity performance models as a function of various factors, which has never previously been achieved using other datasets. Those models were used to estimate the retroreflectivity of pavement markings and markers on state-maintained freeways and highways in California for 1992-1994 and 1997-2002, covering over 5,000 miles of road segments.

An innovative study approach was developed which solves for multipliers that represent the change in the expected number of crashes as a function of retroreflectivity. Safety effect multipliers were solved for yellow and white pavement markings separately and in combination, and for pavement markers for different road types and crash severity, using the retroreflectivity models and California's data of over 118,000 non-intersection, non-daylight (night, dawn, and dusk) recorded crashes.

Discussion of Results

The study has produced retroreflectivity models for epoxy, methyl methacrylate, permanent tape, solvent, thermoplastic and waterborne paint for both white and yellow pavement markings. Retroreflectivity models for markers are a function of their type (snowplowable or non-snowplowable). Both markings and markers are modeled as a function of climate region, and the amount of snow removal. Look-up tables based upon the retroreflectivity models in Appendix A may be useful to jurisdictions seeking estimates of their pavement marking and marker retroreflectivity, or for comparing the performance of new products to the average performance of a particular material type.

The analysis methodology used in this study solved for multipliers representing the safety effect for different retroreflectivity ranges (bin ranges). The analysis methodology was tested thoroughly with simulated data and it proved that it was able to correctly identify safety effects. The analysis methodology was tested again through sensitivity analysis using the California data set. *The approach used in this study was found to be reliable and straightforward to implement and is recommended for safety treatments which change over time*. The advantages of this approach were that it allowed for maximum inclusion of historical data and did not have the same sampling problems of traditional before-after studies.

In order to correctly analyze the data as a time-series, it was necessary to separate out the monthly seasonal effect from the cyclic pattern of pavement marking and marker installation. Seasonal multipliers were developed for the three road types using all state data for each one of the road types but were not divided by climate regions, thus producing an average seasonal effect. The seasonal effect multipliers showed higher crash counts in January, November, and December which provided support for the validity of the analysis methodology. For pavement markings and markers, *the safety difference between high retroreflectivity and low retroreflectivity markings during non-daylight conditions and on non-intersection locations was found to be approximately zero*, for all roads that are maintained at the level implemented by California. Our study provides a level of certainty that builds upon previous research such as Lee et al. (1), Migletz et al. (2), and Cottrell and Hanson (3) which were unable to identify any relationship between retroreflectivity and nighttime crashes.

In conclusion

What appears to be important is that markings are present and visible to drivers, but what is less important with respect to safety is whether the markings have high retroreflectivity or relatively low retroreflectivity. One hypothesis is that drivers compensate by reducing their speed under lower visibility conditions, and maintain higher speeds under higher visibility conditions. Therefore, any effect of the level of brightness of pavement markings or markers may be minimized by driver adaptation to road conditions. In other words, the best estimate of the joint effect of retroreflectivity and driver adaptation is approximately zero for non-intersection road segments during non-daylight conditions.

In summary, this study found that there is no safety benefit of higher retroreflectivity for longitudinal markings on non-intersection locations during non-daylight conditions for roads that are maintained at the level implemented in California's state highways. California's level of maintenance appears to be frequent with pavement markings being installed on higher volume highways up to three times a year with waterborne paint, or every two years with thermoplastic markings. The findings of this research study allow agencies to recognize that resources to increase the retroreflectivity of longitudinal markings, beyond normal maintenance activities, will not be cost-effective and that those resources could instead be allocated towards other safety measures.

This report recommends the following issues be considered for future research: calibration of California retroreflectivity data, study replication in other states, examining the effect of longitudinal markings and markers retroreflectivity on intersection related crashes, examining the effect of marking and marker retroreflectivity on crashes at curves, examining the benefit of pavement marking and marker management systems, retroreflectivity effects on traffic operations, and the human factors of marker and marking visibility.

1. Chapter 1 Introduction

According to the Fatality Analysis Reporting System (FARS), in 2004 there were 38,253 fatal crashes resulting in 42, 636 fatalities (4). By comparison, the attack on Pearl Harbor killed 2,403 Americans (5), while the September 11, 2001 attacks killed 2,986 people (6). Both attacks united the nation for a commitment to victory in response. While not as commanding of national attention, traffic crashes kill more people than all the fatalities from wars put together. Therefore, any safety measure which increases visibility and potentially assists drivers in staying within their lanes deserves serious consideration.

Longitudinal pavement markings and to a lesser extent pavement markers are ubiquitous on highways and freeways in the United States. Pavement markings and markers provide drivers with information about their position within their own lane, and provide previews of upcoming changes in the roadway geometry, including curves, lane drops, narrowing, and the start and end of passing zones. Visibility of pavement markings and markers are particularly important during dark or unlighted conditions. The visibility of pavement markings and markers at night is related to their retroreflectivity, defined as reflected brightness, where the reflected light source is usually automobile headlights and is expressed in units of millicandellas per meter squared per lux ($mcd/m^2/lux$). The performance of pavement markings and markers is a function of the materials used such as waterborne paint, thermoplastic, and epoxy (while markers may be designed as plowable or non-plowable), color (white or yellow), traffic volume, pavement surface type (asphalt or concrete), and climate. However the most important factor is the *age* of the pavement markings and markers since over time the materials used are worn off of the pavement.

As pavement markings are worn off and markers separated from the pavement over time, their visibility naturally degrades. This study focuses upon how non-intersection, non-daylight (night, dawn, and dusk) safety is impacted by the change in retroreflectivity of longitudinal pavement markings and markers. In order to estimate retroreflectivity, models were developed as a function of key performance variables and applied retroactively to locations of known pavement marking and maker installation dates and materials. The estimated retroreflectivity was then compared to the number of non-intersection, non-daylight crashes occurring over time on multilane freeways, multilane highways, and 2-lane highways using an innovative analysis methodology developed for this study.

The body of this report has been structured into six chapters: the findings of the review of the related pavement marking and marker literature (Chapter 2), the description of the innovative methodology developed for this study (Chapter 3), the data collection and preparation (Chapter 4), the modeling of retroreflectivity and safety analysis (Chapter 5), the discussion of the study results (Chapter 6), and the final conclusions and recommendations (Chapter 7).

2. Chapter 2 Literature Review

This literature review is the result of a review of research conducted by various state DOTs, academic institutions, private and public sector materials testing laboratories, manufacturers and suppliers of materials, and the National Transportation Product Evaluation Program (NTPEP), derived from the following sources:

- Personal and organization libraries of research team members;
- Institute of Transportation Engineers (ITE) digital library;
- TAC (Transportation Association of Canada) library catalogue;
- TRIS (U.S. National Transportation Library);
- IRRD (International Road Research Database);
- OECD Library (Organization of Economic Cooperation and Development); and
- FHWA publications.

Relevant publications were located by conducting manual and online searches. The online search was initiated with an Internet search of well-defined keywords. In total, the research team reviewed more than 200 publications. A few reports, not cited in these databases, were accessed through personal contacts. The References section lists only cited publications. The literature reviewed covered topics related to pavement markings and markers such as:

- Visibility and retroreflectivity;
- Safety;
- Human factors;
- Implementation guidelines;
- Specifications and maintenance practices; and
- Cost benefits.

Studies were critically reviewed to the extent that the information in those sources provided for a detailed assessment. In addition, some marking and marker manufacturers and installers (3M, Ennispaint, and Interstate Road Management) were also contacted to obtain recent developments and cost estimates.

The four main purposes for using road markings and symbols, as identified by Elvik and Vaa (7), are to:

1. Direct traffic by indicating the path of the traffic on a road in relation to the surroundings;

2. Control traffic, for example, by reserving certain parts of the road for certain traffic groups (e.g., public transport), and by allowing or prohibiting overtaking and lane changing;
3. Warn road users about specific or hazardous conditions related to the road alignment; and
4. Supplement and reinforce information traffic signs.

This synthesis focuses on longitudinal markings, for purpose #1 concerning directing traffic.

2.1. Pavement Marking and Marker Materials

Sixteen types of pavement marking materials and four types of pavement markers are currently being used for longitudinal pavement markings. Table 1 (8) lists the various types:

Table 1. Degree of use of pavement marking materials by type, from Migletz and Graham (8)

Types of markings	Transportation Agencies Reporting Using the Marking Material									
	Total		State		Canadian		County		City	
	(51)[a]	%[b]	(37)[a]	%[b]	(5)[a]	%[b]	(5)[a]	%[b]	(4)[a]	%[b]
Longitudinal Markings										
Waterborne paints	40	78	33	89			5	100	2	50
Thermoplastic	35	69	30	81			3	60	2	50
Preformed tape - flat	22	43	19	51			2	40	1	25
Preformed tape - profiled	21	41	20	54					1	25
Epoxy	20	39	19	51			1	20		
Conventional solvent paint	20	39	13	35	5	100	1	20	1	25
Methyl methacrylate	10	20	9	24			1	20		
Thermoplastic - profiled	9	18	9	24						
Polyester	5	10	5	14						
Polyurea	2	4	2	5						
Cold applied plastic	1	2	1	3						
Experimental	1	2	1	3						
Green lite powder	1	2	1	3						
Polyester – profiled	1	2	1	3						
Tape (removable)	1	2	1	3						
HD-21	1	2					1	20		
Pavement Markers										
Raised retroreflective	16	31	14	38					2	50
Recessed retroreflective	4	8	4	11						
Snowplowable retroreflective	16	31	14	38			2	40		
Non-retroreflective	5	10	4	11					1	25

Note:
[a] Number of transportation agencies that responded to survey
[b] Percentage of the responding agencies reporting using the marking material

In 1994, the FHWA released a memorandum describing the impact of a new Environmental Protection Agency (EPA) regulation on the use of pavement marking material. The regulation was developed to reduce Architectural and Industrial Maintenance (AIM) coating emissions by 40% by 2004. It led to the establishment of a 150 g/L (1.25 lb/gal) limit by 2000 and a 100 g/L (0.83 lb/gal) limit by 2004 on Volatile Organic Compound (VOC) content for pavement marking materials. Over the past 10 years, transportation agencies in the United States have gradually replaced conventional solvent paints with waterborne paints (that have low VOC contents) and other newer pavement marking materials.

2.1.1. Waterborne Paints

Waterborne traffic paints are the most widely used and least expensive pavement marking material available. Glass beads are either pre-mixed into the paint or dropped onto the waterborne paint while the marking is wet to provide retroreflectivity. Paints generally provide equal performance on asphalt and concrete pavements but have the shortest service life of all pavement marking materials. Waterborne paints are single-component paints that are ready for application and do not require additional ingredients (8). They are environmentally friendly, are much easier to handle than conventional solvent paints, and greatly decrease the safety hazard to workers given their low VOC content (typically less than 150 g/L or 1.25 lb/gal of VOC). This, coupled with the low cost, is the major advantage of waterborne paints (9).

Compared to other pavement marking materials, waterborne paints wear off rapidly and lose retroreflectivity quickly after being exposed to factors such as high traffic volumes and winter-maintenance activities. Although waterborne paints are still the most widely used pavement marking material, none of the 19 state agencies surveyed by Gates et al. (10) recommended them as the top-performing long-term material. Several state agencies even stated that they use waterborne paint as an interim marking material until they can apply something more durable. McGinnis (11) further added that given the short service life of waterborne paint markings, many state agencies often choose to repaint those markings on a fixed schedule instead of restriping when some objective measure such as retroreflectivity drops below a specified threshold. With the easy availability of more durable pavement marking materials on the market, Gates et al. (10) suggested that waterborne paint is not a suitable marking material for high-volume roadways despite its inexpensive application cost.

2.1.2. Conventional Solvent Paints

Conventional solvent paints are single-component paints that contain a binder resin, pigments or fillers, and solvents or additives. Similar to waterborne paints, glass beads are either pre-mixed into the paint or dropped onto the paint while the marking is still wet to provide retroreflectivity. Solvent-borne paints are normally classified according to the resin binder used in the formulation. Some common types of solvent paints include alkyd, acrylic, and chlorinated polyolefins or chlorinated rubber (9,8).

Due to the ingredients used in the formulation of these paints, they typically contain 440 g/L (3.70 lb/gal) of VOCs, far exceeding the maximum of 150 g/L (1.25 lb/gal) recommended by the EPA. Although some solvent-borne paints, such as chlorinated-rubber paints, have been shown to be very durable (9), the use of these paints have gradually diminished with the introduction of the EPA limits on VOCs.

2.1.3. Thermoplastic

Thermoplastics materials have been used in the United States since the 1950s and consist of four basic components: binder, pigment, glass beads, and filler (sand or calcium carbonate). There are two types of thermoplastics: hydrocarbon and alkyd (8). Due to its low VOC content, moderate cost and durability, it is one of the most widely used pavement marking materials. In fact, the vast majority of longitudinal pavement markings in some states, such as Texas, are thermoplastic. One of the added advantages of using thermoplastic is that the material can be re-applied over older thermoplastic markings, thereby refurbishing the older marking as well as saving on the costs of removing old pavement markings. Although thermoplastic materials usually perform very well on all types of asphalt surfaces, there have been mixed results when they have been applied on concrete pavements (10,12). Gates et al. (10) reviewed pavement marking practices in 19 states and found that even though thermoplastic was used on Portland cement concrete pavements in 37% of the states, only 16% of state DOTs considered it to be the best performing material. Some state DOTs have had great success with thermoplastic markings on concrete, while many others discontinue its use for concrete pavements. One of the disadvantages of thermoplastic is its color and appearance. Thermoplastic is grayish, making it less visible by day, and has a tendency to crack. Further, the application of thermoplastic marking materials in areas with colder climates is limited due to the poor adhesion of the material to pavement surfaces in lower temperatures. Successful thermoplastic performance on concrete is highly dependent on correct thermoplastic material formulation, proper surface cleaning, moisture removal, and priming (if necessary) before installation. In contrast to the inconsistent performance of thermoplastic markings on concrete pavements in Texas and some other states, the findings of Ahmad et al. (13) suggested that the bonding strength of thermoplastic markings to concrete pavements was independent of the surface cleaning methods used, and the bonding strengths on both asphalt and concrete pavements were the same for the most part. A review of results from NTPEP tests (10) appeared to concur with the findings of Ahmad et al. (12).

2.1.4. Tape

Several types of tapes are currently in use, including flat preformed tape and profiled preformed tape. Tapes tend to have a high initial cost and are generally used in areas that require minimal marking and need to perform under severe conditions. Glass beads that provide retroreflectivity in tapes are incorporated into material during factory manufacturing. Freshly installed tape markings typically have initial retroreflectivity values four to six times that of waterborne traffic paints. In a review of studies in several states, Andrady (9) found evidence from Kentucky and North Carolina that suggested that tapes lose their retroreflectivity rapidly and their useful life may be as little as three years. Findings by Lee et al. (1) also indicated that there was a dramatic drop in retroreflectivity over time. Given the wide variety of tape materials available commercially, it is not surprising that there is such a broad range of estimates for their useful life. However, the consensus is that if applied properly, tape will provide between 4 and 8 years of use. The successful performance on tape depends on many stringent requirements, including proper pavement and air temperature, adequate preparation of the surface (e.g., dry and free of existing markings), the use of quality adhesives (if markings are overlaid), and the need for proper curing time. Nevertheless, according to many agencies, the advantages of using preformed tape appear to outweigh the disadvantages or strict requirements. In fact, permanent preformed tape was most frequently recommended as the marking material with the best long-term performance by 19 state DOTs surveyed (10). In general, inlaid markings (where the tape is pressed into the pavement surface while it is still warm) outlast overlaid markings (where tape is adhered to the pavement surface through the use of an adhesive or installed by heat fusion) and both are snowplowable. Tapes are devoid of VOCs but when they are applied as overlaid markings, the VOC content of the adhesive primer or surface preparation adhesive must also be considered.

2.1.5. Epoxy

Similar to polyester, polyurea, and methacrylate, epoxy is a type of two-component material that is produced on site through the reaction of two separate chemical reactants. Epoxy paint has traditionally been viewed as a marking material that provides exceptional adhesion to both asphalt and concrete pavements when the pavement surface is properly cleaned before application (10). The strong bond that forms between epoxy paints and both asphalt and concrete pavement surfaces results in the material being highly durable when applied on both pavement surfaces. In addition, epoxy markings have low VOC content, but the chemicals used to produce them are classified as hazardous materials. The first component of the epoxy typically contains resin, pigment, extenders, and fillers, while the second component acts as a catalyst to accelerate setting time. Glass beads are either applied on the surface of the stripe while it is still wet or is pre-mixed into the first component. Although epoxy markings are generally considered to have moderate cost and have a service life of 2 to 4 years, a review of research efforts in Texas and California by Andrady (9) revealed that epoxy stripes have been shown to discolor with age, particularly when exposed to intense ultraviolet light. Gates et al. (10) pointed out that another usual complaint with many epoxy materials is the long drying times (sometimes more than 40 minutes) that limit the use of this material under high traffic conditions. Regardless of its shortcomings, a survey conducted by Gates et al. (10) found that more agencies used epoxy markings on concrete surfaces with high traffic volumes than any other pavement marking material, although the majority of the agencies responding to the survey selected preformed tape as the top performer on concrete.

2.1.6. Methyl Methacrylate

Methyl methacrylate is another two-component material with negligible VOC content that is produced onsite through the chemical reaction of two separate reactants. The reacting components consist of a pigmented material containing a methyl methacrylate monomer, pigments, fillers, glass beads and silica (as first component), and a liquid or powder catalyst (8). Methacrylate markings are highly durable and can be sprayed or extruded but generally require long no-track times (9). According to Gates et al. (10), methyl methacrylate is an attractive pavement marking material because it can be applied in low temperatures, is resistant to oils, anti-freeze, and other chemicals commonly found on roadways, and bonds well to both asphalt and concrete surfaces. A 2002 survey conducted by the researchers revealed that the use of methyl methacrylate pavement markings is still very limited in the United States. Of the 19 state agencies surveyed, only Oregon, Alaska and California used methyl methacrylate pavement markings. All three states rated the material very highly. In California and Alaska, methyl methacrylate pavement markings were found to outperform thermoplastic and paint markings in terms of durability, cost, visibility, and service life when applied in heavy snowfall areas. Based on the information available on this pavement marking material, Gates et al. (10) suggested that methyl methacrylate pavement markings are particularly suited to cold climates. No evidence was found to support its use in warm-weather climates, especially given the high cost of the material, the slow no-track times, and need for specialized equipment for application.

2.1.7. Polyester

Polyester marking materials are produced onsite through the mixture of two separate groups of reactants (chemicals) immediately before application. Glass beads are dropped onto the surface of the stripe while it is still wet to provide retroreflectivity. Polyester is best used on asphalt pavements and can be applied over existing markings. Although polyester markings have low VOC content, the chemicals used to produce the material are classified as hazardous materials (9).

2.1.8. Polyurea

Polyurea is a two-component material that is produced onsite through the chemical reaction of two separate components. The first component of this material consists of a mixture of resins, pigments, and fillers, while the second component is a cross linker. Glass beads are dropped onto the wet surface to provide retroreflectivity. One manufacturer uses a combination of glass beads and a layer of reflective elements (with microcrystalline, 1.9 refractive index, ceramic beads) to provide a higher level of retroreflectivity (8). Polyurea is a relatively new pavement marking material that is often marketed by manufacturers as a durable marking material that maintains good color stability when exposed to ultraviolet light, cures quickly (3 to 8 minutes at all temperatures), may be applied at low ambient pavement surface temperatures (as low as 40°F), is not affected by humidity, and works equally well on asphalt and concrete pavements. A survey conducted by Gates et al. (10) found that 18 of 19 state agencies surveyed cited little experience with the material and that there are limited data on the performance of polyurea markings. Initial findings suggest that while the material is highly durable, the durability and abrasion resistance of the ceramic elements that enhance the retroreflectivity of the material is questionable. A major disadvantage identified was the need for special equipment and high cost compared to most other marking materials.

2.2. Visibility and Retroreflectivity

The condition and effectiveness of pavement markings degrade over time due to a variety of factors, as identified by Thamizharasan et al.(14). These factors include traffic volumes, the presence of heavy vehicles, weather/climate, quality control in the application of the marking material, age, and the type of pavement surface. When installing pavement marking materials, the challenge for transportation agencies is to reconcile the different service lives and costs of the various pavement marking materials with the remaining service life of the existing pavement surface, while maintaining an acceptable level of performance for road users. Given that longitudinal pavement markings provide visual guidance to drivers, the key issue is to understand what constitutes an effective visible pavement marking.

The visibility of pavement markings at night is dependent on their retroreflectivity, which represents the portion of light from a vehicle's headlight reflected back toward the eye of the driver of that same vehicle, as discussed by Migletz et al.(15). Retroreflection means that the light is reflected back at the same angle that it is projected. If light from the headlights was to be perfectly retro-reflected, it would not reach the driver's eyes, which are above the headlights. Since retro-reflection is imperfect, some of the light reaches the driver's eyes, increasing the contrast between the delineator and the low-reflectance pavement background. The higher the percentage of light that is retro-reflected, the greater the contrast and the further away the delineator will be seen. Both the retroreflectivity value (represented by the coefficient of retroreflected luminance, R_L, the coefficient of retroreflected luminance, in millicandelas per square meter per lux (mcd/m^2/lux) and the degree of contrast between the retroreflectivity of the pavement marking and the retroreflectivity of the adjacent pavement surface are important to the visibility of a pavement marking (15). Results from a study by Loetterle et al. (16) indicated that the minimum acceptable level of retroreflectivity ranges from 80 to 120 mcd/m^2/lux.

The retroreflectivity of pavement markings is the most important factor when determining driver detection distances at night. Parker and Meja (17) compared objective measures (retroreflectivity measurements) with subjective evaluations (ratings by evaluators), and found a high correlation between retroreflectivity and visibility ratings. According to Parker and Meja (17), the relationship between the objective and subjective measures is non-linear, as shown in Figure 1. However, also in Figure 1, the range of retroreflectivity values of the markings (white edgelines (WEL), yellow centerlines (YEL), and skip lines (SPL)) tested by Parker and Meja (17) was narrow, ranging from about 100 to 300 mcd/m^2/lux, and no pavements markings which would fall under the "not acceptable" range were tested. For the subjective ratings, on a 5-point scale (5 - Very clearly visible, 4 - Visible with no difficulties, 3 - Visible with some difficulties, 2 - Visible with great difficulties, and 1 – Invisible) none of the markings received a score of less than 3. Nonetheless, this non-linear relationship between retroreflectivity and visibility ratings has also been established by Loetterle et al. (16), as shown in Figure 2 using a similar 5-point rating scale.

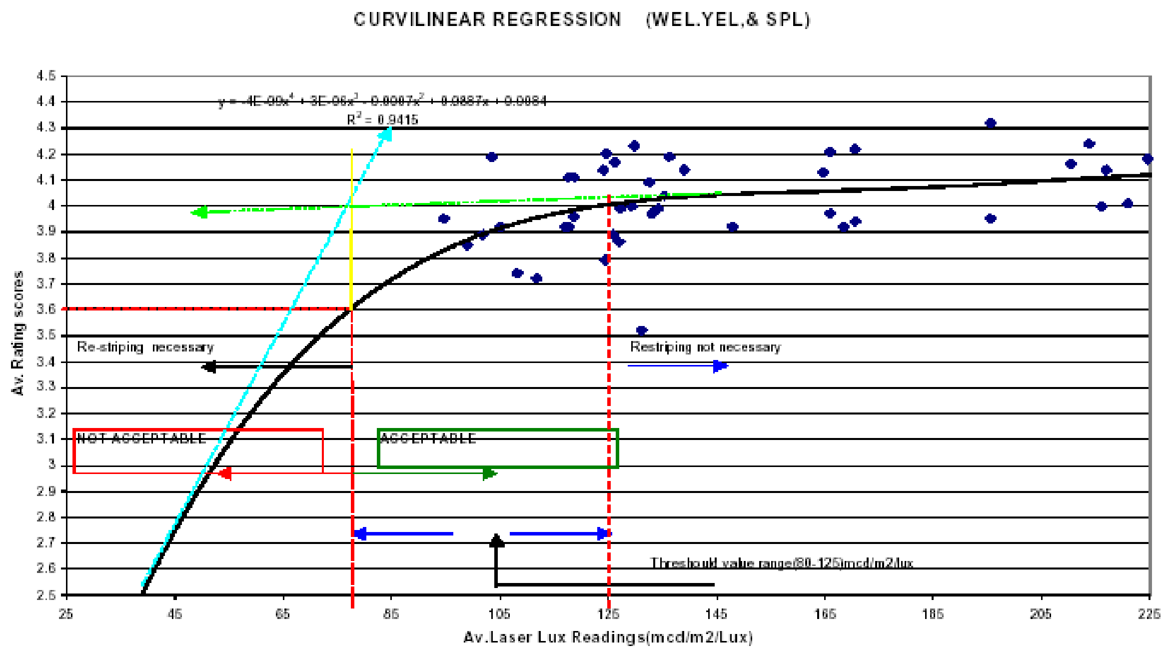


Figure 4: Curvilinear regression for both WEL, YCL AND SPL.

Figure 1. Non-linear relationship between retroreflectivity and participant ratings, from Parker and Meja (17)

Figure 2 --- Curvelinear Regression: Center Lines and Edge Lines

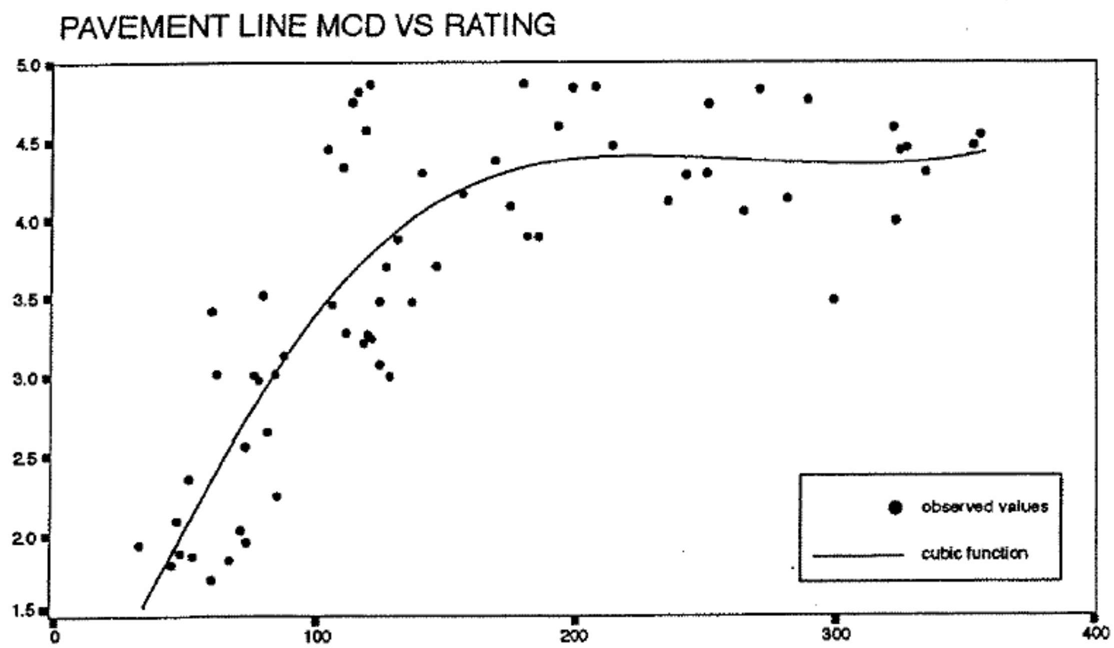


Figure 2. Non-linear relationship between retroreflectivity and participant ratings, from Loetterle, Beck and Carlson (16)

2.2.1. Contrast

The visibility of markings and markers is dependent on the physical aspects of the delineation, their placement, head-lighting, highway geometry, and driver visual capabilities. Drivers detect the presence of markers and markings by means of *contrast*: differences in brightness between the delineator and the road surface. Contrast (the difference in brightness between two objects) can be defined using Equation 1 (calculation of contrast).

Equation 1

$$C = \frac{L_T - L_B}{L_B}$$

where

C	=	Contrast ratio,
L_T	=	Target luminance (e.g., markings or markers), and
L_B	=	Background luminance (e.g., pavement surface).

The use of Equation 1 for markings and markers should result in positive values from 0 to infinity. Using Equation 1 for targets with less luminance than the background will result in values ranging from 0 to -1. During the day, the visibility of delineators depends only on the contrast between the delineator and the pavement background. At night, visibility depends on the light from headlights as well as on the retroreflectivity of the delineator and the pavement background.

Two types of contrast are of particular interest when dealing with pavement markings: color contrast and luminance contrast (8). Color contrast is the degree of difference in the color, or between the lightest and darkest, of the pavement marking and adjacent pavement surface (18). The luminance contrast is the relative difference in luminance between a pavement marking and the adjacent pavement surface both during the daytime and nighttime (15). At night, the retroreflectivity of the marking directly influences the luminance and contrast. To provide guidance to drivers during daytime, the color contrast of the pavement marking relative to the adjacent pavement surface is critical (9). During nighttime, both color and luminance contrasts are important, especially where there are no markers or roadway lighting. Pavement markings with high contrasts are considered preferable to those with lower contrasts because the high contrast ratios make it easier for a driver to distinguish the pavement marking from its background. Migletz et al. (8) found that a contrast of 2.0 or greater is required for older drivers. In a similar study conducted in Europe, a contrast of 0.6 was deemed to be sufficient to ensure that adequate visibility distances are provided to drivers under daylight conditions and for illuminated roadways (19). That study added that while retroreflectivity is a major factor to ensure visibility, the surface area of the road marking is also equally important. For example, a wider or continuous longitudinal line is considered to be more visible than dashed/skip line (19). These results may not be entirely applicable to North American conditions because European headlights have different specifications, road pavement types are different, and most European highways are illuminated.

2.2.2. Effect of the Color of Pavement Markings on Contrast and Retroreflectivity

Several previous studies have firmly established that white pavement markings generally have higher retroreflectivity values than yellow pavement markings (9,11,18). While the retroreflectivity values for white and yellow markings may be different, it has been suggested that the rate of retroreflective decay for both is equivalent (20). In addition to differences in retroreflectivity, Migletz et al. (15) also found that the luminance contrast ratios for yellow and white pavement markings are significantly different. White markings were shown to have a substantially higher luminance contrast ratio (average of 14.3) compared to yellow markings (average of 9.2), although this difference is less distinct when the markings are applied on Portland cement concrete pavements compared to asphalt pavements. The contrast ratios for yellow lines were 9.1 for asphalt pavement surfaces and 10.1 for Portland cement concrete pavement surfaces (considerably more asphalt data was collected than for concrete). The contrast ratios for white lines were 14.7 for asphalt and 12.3 for Portland cement concrete pavement surfaces. The retroreflectivity of road surfaces under dry conditions typically fell within the range of values from 5 to 30 mcd/m^2/lux. The lower end of the range is representative of asphalt road surfaces with dark stone aggregates, while the upper end of the range can usually be found for asphalt pavements with lighter stone aggregates and Portland cement concrete surfaces (19).

2.2.3. NTPEP Testing Facility Data

The National Transportation Product Evaluation Program (NTPEP) is an engineering and technical services program operated by the American Association of State Highway and Transportation Officials (AASHTO). The program pools the physical and professional resources of member states to evaluate commercially available products for use by state and local agencies. These products are typically evaluated using established AASHTO and ASTM-specified tests and when standards do not exist, the NTPEP Oversight Committee convenes and establishes evaluation protocols through AASHTO ballot. A wide variety of products are tested, including pavement marking materials, sign sheeting materials, markers and adhesives, and flexible delineators. Many state agencies use NTPEP test results to screen commercially available products for pre-qualification of materials for use in their states, while others, such as Texas, continue to conduct much of their own testing. A survey of state transportation agencies was conducted in 2001 to determine the degree of state reliance on NTPEP results and gauge their attitudes towards the NTPEP program (21). The survey revealed that while many agencies continue to conduct their own testing of products, two-thirds (67%) of the states surveyed indicated that NTPEP saves time and costs by reducing the need for state testing, while the majority (57%) intended to make greater use of NTPEP test results in the near future.

As part of the effort to evaluate pavement marking materials, NTPEP conducts two types of tests: field testing and laboratory evaluations. The laboratory evaluation consists of a number of AASHTO and ASTM tests depending on the material. The list of tests conducted for each material can be found in the project work plan for the evaluation of pavement marking materials released by NTPEP (22). The laboratory tests evaluate certain attributes and "fingerprint" the marking materials submitted for testing. This fingerprinting allows states to ensure that once a product is approved for use by an agency, no changes have been made since testing.

The locations of the field tests are shown in the screenshot in Figure 3. Field-testing procedures are conducted on test decks throughout the United States and are based on ASTM D713, "Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials." Site locations are selected in accordance with the ASTM standard that requires the site to have the following characteristics:

- Four-lane divided sections;
- Average Daily Traffic greater than 5000 vehicles/day;
- Free rolling no grades, curves or intersections;
- Good drainage; and
- Uniform wear with full exposure to the sun during daylight hours.

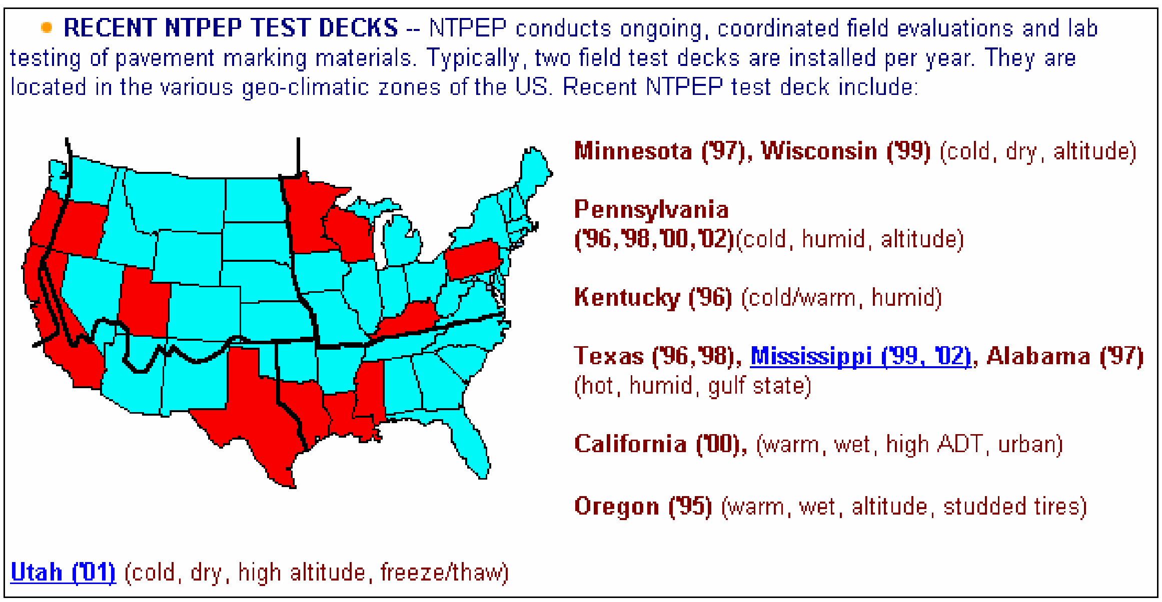


Figure 3. Screenshot from the NTPEP website (23).

For field testing, four beaded transverse lines are applied across the travel lane from the right edgeline to the lane line/skip line for each marking material being tested (as shown in Figure 4, Figure 5, and Figure 6). NTPEP collects the following information:

- Site location, including ADT, type, age, and special treatment of pavement surface material;
- Company information, including name, class of material, binder, color, primer, or other adhesives (if needed) and indication if material contains lead;

- Application information, including application equipment, equipment description, thickness, temperature of material, relative humidity, no-track time, and type and rate of application of beads;
- Retroreflectivity values;
- Durability ratings;
- Appearance; and
- Information on snowplow damage.

Figure 4. Typical set-up for field tests using test decks. (24)

Figure 5. ASTM D713 field test for pavement marking material (24)

Field performance tests are scheduled to be conducted within 7 days after the application of a marking material, and approximately every 30 days thereafter during the first year on materials such as paint that have shorter service lives. Evaluations continue for more durable products such as thermoplastics, and readings/measures are recorded approximately every 4 months until the end of the field testing (usually 2 to 3 years). During the course of the field evaluation, the appearance and/or color of the markings are determined using color measuring equipment which provides Commission Internationale de l'Eclairage (CIE) color coordinate units and luminance factor measurements (Y%). The evaluation is done on the unbeaded areas of the line to minimize the effect of the accumulation of dirt and growth of mold. In terms of retroreflectivity measurements, readings are taken with an LTL2000 retroreflectometer or other approved equal retroreflectometers in the left wheel path and the lane line/skip line area (Figure 6). The readings on the left wheel path measure the change in the retroreflectivity of pavement markings exposed to traffic wear and environmental conditions, such as lane lines, while the readings on the centerline area evaluate the retroreflective performance of pavement markings exposed to environmental conditions and minimal traffic wear. The durability of the various pavement marking materials are evaluated by assigning a rating on a scale of 1 to 10 (with a rating of 10 representing a new line) based on the percentage of marking material left on the surface. Similar to retroreflectivity readings, durability evaluations are also made in left-wheel-path and lane-line/skip-line areas.

Figure 6. Retroreflectivity measurements on the left wheel path and centerline(25)

Each pavement marking material submitted for NTPEP evaluation undergoes lab testing by state DOT Materials Labs, depending on the class of product. In recent years, NTPEP has attempted to keep the same lab facilities for testing. They are in Pennsylvania, New York, Louisiana, Minnesota, and Kansas.

Figure 7 and Figure 8 show the type of data available from NTPEP. Figure 7 shows the retroreflectivity results from four different waterborne markings tested on asphalt in Pennsylvania in 2000. Figure 8 shows four other retroreflectivity results from waterborne markings tested on concrete in Pennsylvania in 2002. The roads are closed during testing, but open to normal traffic at other times. For all pavement markings, the predominant factor that determines the degradation of retroreflectivity is the degree to which the marking is exposed to traffic wear. Given that longitudinal lines on straight roads are less exposed to the wear resulting from the impact of the tires of passing vehicles, it is expected that the degradation of retroreflectivity of these types of lines would be less significant compared with longitudinal markings on horizontal curves. However, no models exist for retroreflectivity for different road geometries. Curve markings would experience greater wear from drivers cutting corners. For markings on curves, the retroreflectivity of transverse markings, such as the NTPEP left wheel markings, may be more representative of actual road conditions. The left-wheel retroreflectivity measurements for the same four waterborne paint markings shown in Figure 8 are illustrated in Figure 9.

	Selected Products	
(brown)	PMM-146 (2000) - 2000, Pennsylvania (Asphalt) Rohm & Haas Company - DCS-2760-1	Remove
(green)	PMM-014 (2000) - 2000, Pennsylvania (Asphalt) Aexcel Corporation - 72W-A086	Remove
(blue)	PMM-062 (2000) - 2000, Pennsylvania (Asphalt) Ennis Paint, Inc. - EP415W04	Remove
(magenta)	PMM-109 (2000) - 2000, Pennsylvania (Asphalt) LaFarge Road Markings Inc. - LRMOOWB-18	Remove

Displaying **2** graphs for selected properties:

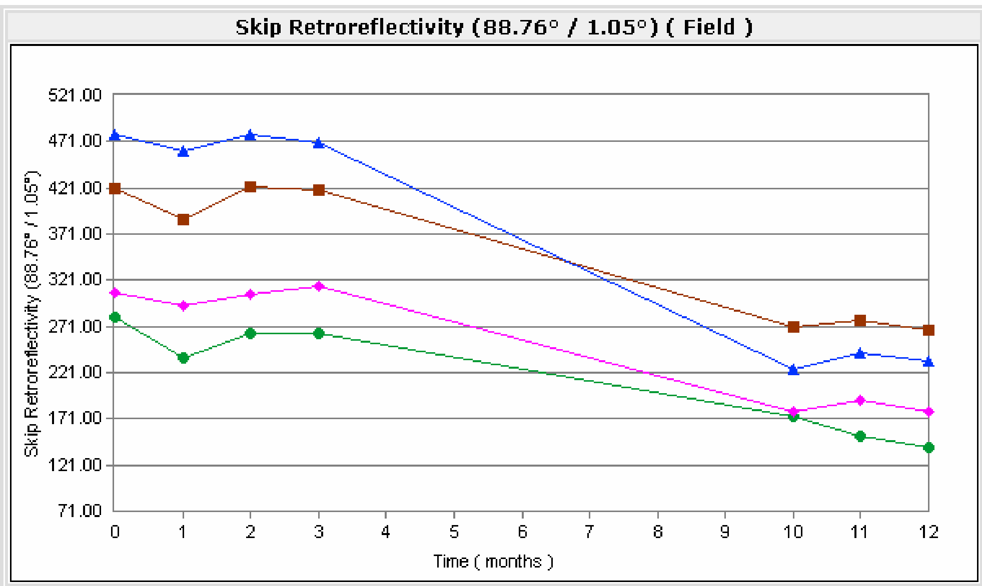


Figure 7. Four waterborne pavement markings retroreflectivity skip readings on asphalt for a 12 month period, from NTPEP (23).

Selected Products	
PMM-PA-221 (2002) - 2002, Pennsylvania (Concrete) Vogel Paint & Wax - VLX13989-01	Remove
PMM-PA-174 (2002) - 2002, Pennsylvania (Concrete) Sherwin-Williams Company - Yellow Waterborne, BP 19403	Remove
PMM-PA-104 (2002) - 2002, Pennsylvania (Concrete) Ennis Paint, Inc. - LRM2002LNT-48 Yellow LF Waterborne	Remove
PMM-PA-042 (2002) - 2002, Pennsylvania (Concrete) Ennis Paint, Inc. - 991006	Remove

Displaying **2** graphs for selected properties:

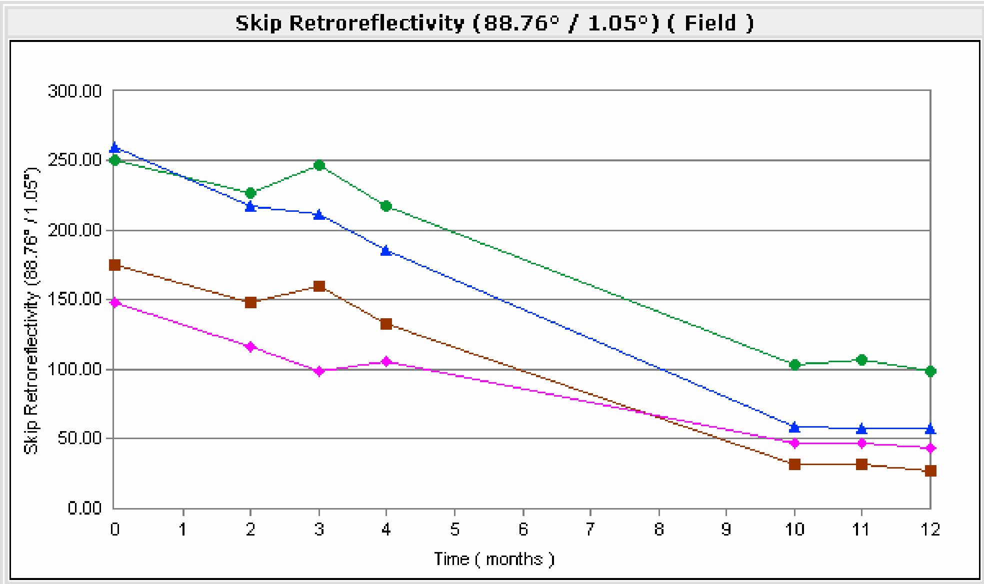


Figure 8. Four waterborne pavement markings retroreflectivity skip readings on concrete for a 12 month period from NTPEP (23).

Selected Products	
PMM-PA-221 (2002) - 2002, Pennsylvania (Concrete) Vogel Paint & Wax - VLX13989-01	Remove
PMM-PA-174 (2002) - 2002, Pennsylvania (Concrete) Sherwin-Williams Company - Yellow Waterborne, BP 19403	Remove
PMM-PA-104 (2002) - 2002, Pennsylvania (Concrete) Ennis Paint, Inc. - LRM2002LNT-48 Yellow LF Waterborne	Remove
PMM-PA-042 (2002) - 2002, Pennsylvania (Concrete) Ennis Paint, Inc. - 991006	Remove

Displaying **2** graphs for selected properties:

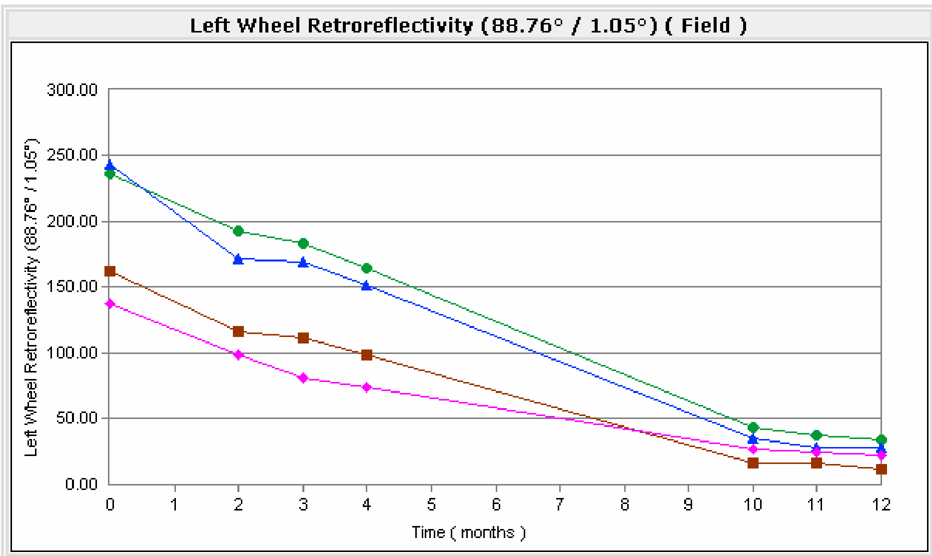


Figure 9. Left-wheel retroreflectivity pavement markings readings of the four markings in Figure 8, from NTPEP (23).

As shown in the NTPEP field tests, the retroreflectivity of markings drop over time. The factors which degrade pavement markings and markers as identified by Thamizharasan (14) include:

- Traffic volumes;
- Heavy vehicle percentages;
- Weather/climate;
- Winter maintenance activities (snowplowing, use of de-icing and anti-icing materials);
- Type of marking material;
- Quality control in applying the marking material; and
- Type of pavement surface.

The markings in Figure 8 and Figure 9, for example, drop below most minimum retroreflectivity thresholds (between 100 to 150 mcd/m^2/lux) within the first year of application.

Nearly all agencies that apply waterborne paint apply their markings on a yearly basis, although some may have 2-year cycles, and few agencies remark on a cycle of less than 1 year. Therefore, for most jurisdictions, the visibility of their waterborne paint pavement markings, the most common type of marking in use today, at night falls below what most practitioners would consider to be a minimum threshold.

2.2.4. Retroreflectivity Performance Testing

Migletz and Graham (8) surveyed a large number of agencies and found that all the agencies used some combination of objective and subjective evaluations to substantiate the retroreflectivity and performance of long-term pavement markings after they are applied.

Objective evaluations are done using retroreflectometers or colorimeters that record the value of the retroreflectivity. These values are then compared with some standard specified value to determine if the marking is acceptable. With the growing number of transportation agencies recording retroreflectivity measurements of the pavement markings in their respective jurisdictions, a multitude of companies are manufacturing retroreflectometers. Four types of retroreflectometers have been traditionally used by U.S. transportation agencies: 30-m (98.4-ft) hand-held, 30-m (98.4-ft) mobile, 15-m (49.2-ft) hand-held, and 12-m (39.4-ft) hand-held instruments (26). The 30-meter geometry is used by the European Committee on Standardization (CEN) simulates the performance of a marking that is 30 meters in front of a vehicle. ASTM has adopted that same geometry as the standard for measuring pavement marking retroreflectivity with hand-held retroreflectometers and 30-meter retroreflectometers are now the industry standard, although instruments using other geometries are still being used. There is no direct relationship between measurements made using earlier geometries (i.e., 12 m and 15 m) and the 30-meter retroreflectivity measurements, meaning that 12 and 15 meter instruments cannot be used to measure pavement marking retroreflectivity at a 30-meter geometry in a manner that complies with ASTM standard (26). Figure 10 illustrates the entrance and observation angles associated with a 30-meter geometry.

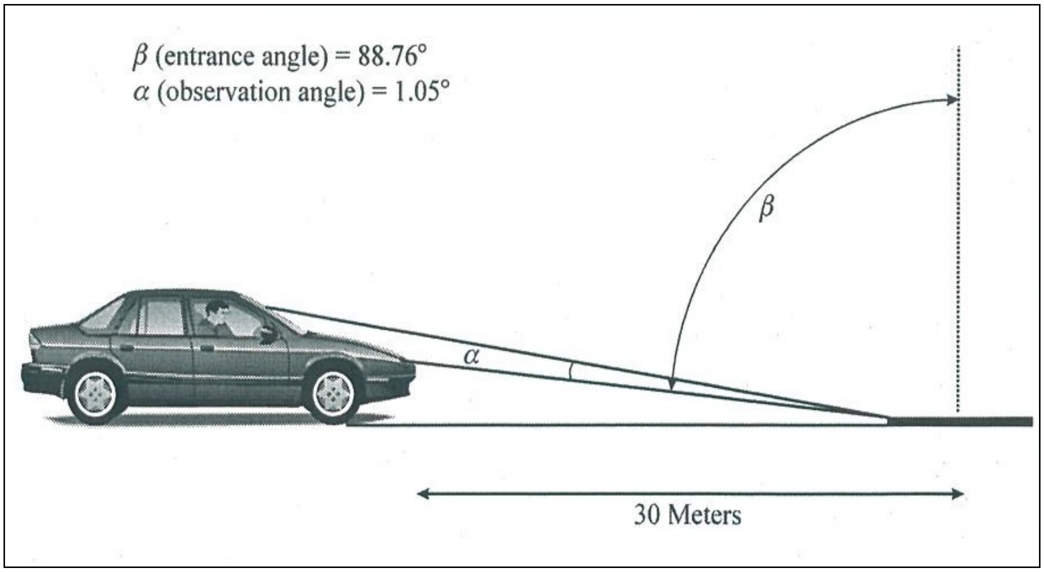


Figure 10. Entrance and observation angles for 30-meter geometry, from the Highway Innovative Technology Center (26)

Table 2 presents a summary of agencies using three objective evaluations with a retroreflectometer.

Table 2. Degree of usage of retroreflectometers, from Migletz and Graham (8)

Agency	N	Dry Performance[a]	%	Luminance Contrast Ratio[b]	%	Wet Performance[c]	%
State	37	25	68	4	11	2	5
Canadian	5	1	20	0	0	0	0
County	5	2	40	1	20	0	0
City	4	1	25	0	0	1	25
	51	29	57	5	10	3	6

Note: N = Number of transportation agencies that responded to survey

[a] Dry performance of pavement markings - measurement of pavement-marking retroreflectivity, day or night
[b] Luminance contrast ratio - relative difference in retroreflectivity between pavement-marking and the adjacent pavement surface
[c] Wet performance of pavement markings - measurement of pavement-marking retroreflectivity, day or night, during condition of rain

Retroreflectometers from different manufacturers perform differently under varying conditions, even for those that use the same geometry details on the various retroreflectometers, and comparisons on their individual performances can be found in studies by the Highway Innovative Technology Evaluation Center (HITEC) (26) and Clarke et al. (27).

Although objective evaluations are becoming more common, subjective evaluations are still widely used (8). Subjective evaluations require the inspector to examine the marking and use judgment, based on established guidelines, to assign a rating to it. A variety of subjective tests and the degree of usage for each of these tests are summarized in Table 3.

Table 3. Degree of usage of various subjective evaluations, from Migletz and Graham (8)

Agency	N	Dry Performance[a]	%	Durability[b]	%	Bead Retention[c]	%	Color Scale[d]	%	Wet Performance[e]	%	Pocket Microscope[f]	%	Color Chart[g]	%	Other	%
State	37	24	65	15	41	11	30	11	30	9	24	10	27	7	19	4	11
Canadian	5	3	60	1	20	1	20	1	20	1	20	1	20	0	0	1	20
County	5	3	60	2	40	2	40	2	40	1	20	0	0	0	0	1	20
City	4	3	75	2	50	2	50	1	25	2	50	0	0	0	0	1	25
	51	33	65	20	39	16	31	15	29	13	25	11	22	7	14	7	14

Note: N = Number of transportation agencies that responded to survey

[a] Dry performance of pavement markings - subjective evaluation made at night using vehicle headlights during dry conditions (e.g., using a scale of 1 to 10)

[b] Pavement marking durability - subjective evaluation of a material's resistance to wear and loss of adhesion to pavement surface over time (e.g., percentage of material remaining on a scale of 1 to 10)

[c] Bead retention - subjective evaluation of retroreflectivity and bead distribution during the daytime under sunny conditions (e.g., using the sunlight-shadow technique with a pass-fail rating)

[d] Color scale - subjective evaluation of marking color (e.g., using a scale of 1 to 10)

[e] Wet performance - subjective evaluation made at night using vehicle headlights during wet conditions (e.g., using a scale of 1 to 10)

[f] Pocket microscope - a microscopic evaluation of bead distribution, embedment, and damage

[g] Pavement marking color - subjective evaluation of yellow color using a yellow color tolerance chart of standard colors

2.2.5. Retroreflectivity Modeling

Three basic patterns in terms of the degradation or decay of retroreflectivity over time identified by Thamizharasan et al. (14) are shown in Figure 11. In Figure 11, “A” illustrates how the retroreflectivity for newly placed pavement markings increases initially because glass beads become exposed after some amount of wear, and then peaks before reducing over time as the pavement markings wear out. In Figure 11, “B” shows how the retroreflectivity of older pavement markings (older than 300 days) is represented by a straight line and gradually decreases over time. Thamizharasan et al. (14) found that the line depicting the rate of degradation appeared to be linear for readings larger than 50 or 60 mcd/m^2/lux, a highly relevant finding given that if a minimum retroreflectivity value of 100 mcd/m^2/lux is adopted, then a linear model to predict retroreflectivity degradation of older established markings may be sufficient. In Figure 11, “C” demonstrates how the retroreflectivity of a pavement marking can be dramatically affected by activities, such as remarking (marked improvement in retroreflectivity) and winter maintenance (sharp decrease in retroreflectivity). Studies by Filchek et al. (28), Thamizharazan et al. (14), Migletz et al (15), and Lee et al. (1) have shown that winter maintenance activities, such as snowplowing, have a pronounced adverse effect on the retroreflectivity of pavement markings. For example, Migletz et al. (15) found that the mean retroreflectivity of pavement markings was between 15% and 34% lower compared with the same pavement markers over the previous fall. Although the decrease in pavement marking retroreflectivity with the passage of a winter season was found to vary with the color of the pavement marking and marking material, the researchers could not make any definitive comparisons between the material types because the relative ages of the marking materials were not known. Lee et al. (1) even suggested that winter maintenance activities, such as snowplowing and ice control materials (e.g., de-icing materials), have a greater impact on the rate of decay of the retroreflectivity of pavement markings than traffic volume and trucks.

As a result of their findings, Thamizharasan et al. (14) developed two models to predict the retroreflectivity of pavement markings: a non-linear model to predict the number of days required as the retroreflectivity of a newly-applied pavement marking rises before dropping back to the initial value; and a linear model to predict the number of days needed for the retroreflectivity of a pavement marking to drop (after the initial rise) to a minimum specified value.

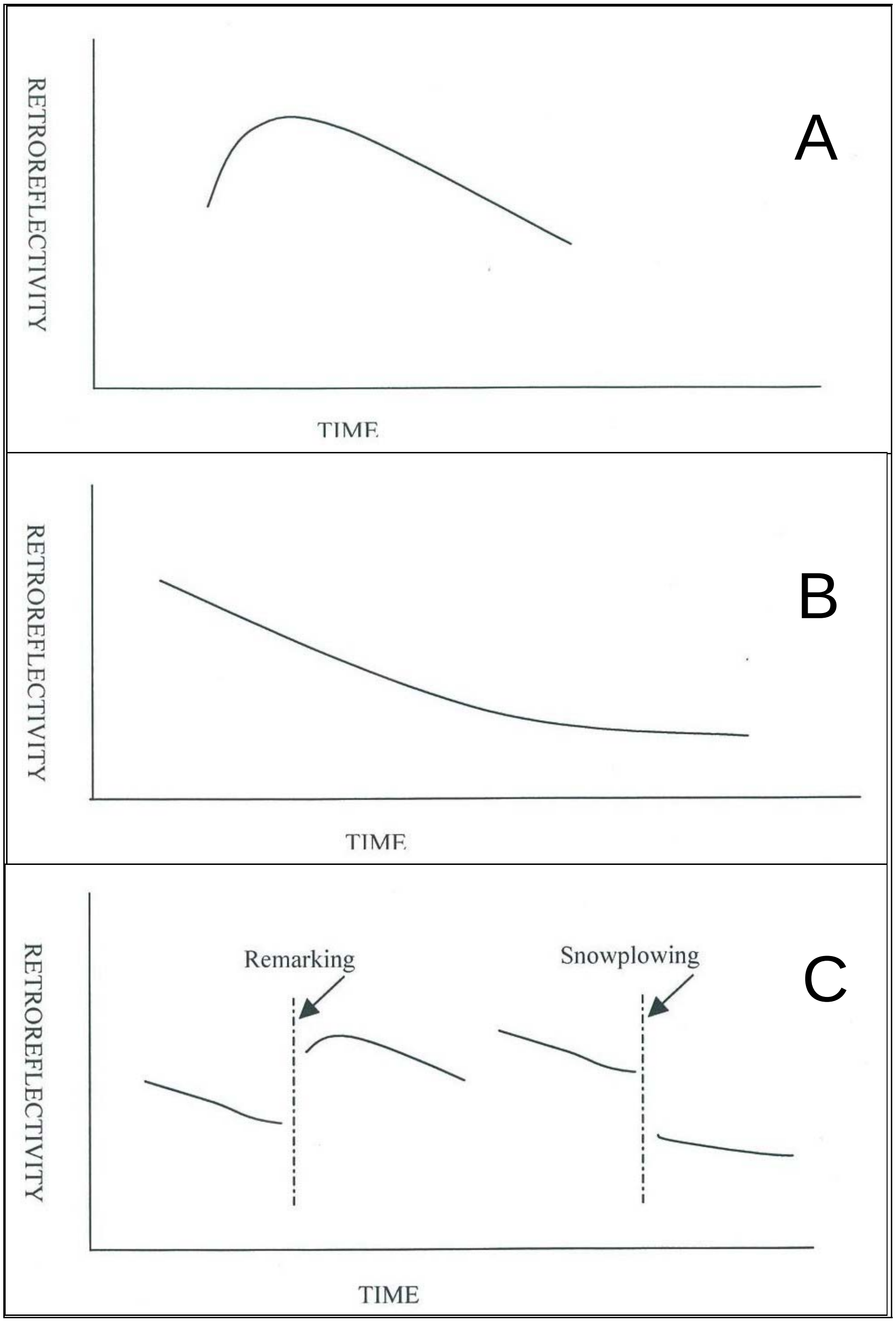


Figure 11. Retroreflectivity degradation pattern of new (A), established (B), pavement markings, and degradation due to snowplowing (C), from Thamizharasan et al. (14)

2.2.6. Retroreflectivity Performance Requirements

Visibility is often measured in terms of the detection of a target at a distance. For example, in the case of retroreflective centerlines and edgelines on a two-lane rural road with shoulders, the preview distance at which the curve is visible under nighttime conditions would be a measure of the curve's visibility. In 1992, Congress legislated the 1993 Transportation Appropriations Act, which said, "The Secretary of Transportation shall revise the Manual of Uniform Traffic Control Devices to include - (a) a standard for a minimum level of retroreflectivity that must be maintained for pavement markings and signs, which shall apply to all roads open to public travel" (29). FHWA has been conducting research on visibility needs for drivers for some time. The underlying assumptions of specifying minimum retroreflectivity standards are two-fold:

1. Increased retroreflectivity equals increased visibility for drivers under nighttime conditions; and
2. Increased visibility equals increased safety for road users.

The first assumption is usually tested under controlled conditions in a simulator or in the field. Such controlled experiments conclude that with an increase in the amount of light reaching the driver's eyes, the visibility of those lighted features are visible at greater distances. The second assumption is much more difficult to prove because at first glance, the statement seems intuitively obvious given the inverse statement, "If I can't see then I can't be safe." If not seeing is unsafe, then seeing must be safe. But seeing what? Visibility under controlled conditions is measured in terms of a detection distance. However, the complexity involving a driving task cannot be boiled down to a single number given as a distance measurement. In other words, defining visibility simply as a detection distance misrepresents drivers' visibility requirements. Driving is a self-paced task that involves drivers adapting to what and how far they see. The adaptation may take the form of externally visible behavior (such as speed choice) or behavior that is not easily observable (e.g., arousal, alertness, fatigue, and drowsiness). There is no general theory that allows predicting whether the adaptation induced by some change (e.g., more visible edgelines) will reduce crash frequency or severity, or have the contrary effect. The assertion "more visibility leads to fewer crashes" may not necessarily be valid. Thus, what is required to answer the question is empirical support showing that an improvement in the index is causally associated with fewer or less severe crashes.

The literature review conducted by Abboud and Bowman (30) finds that an accepted minimum value of retroreflectivity is generally in the range of 100±30 mcd/m^2/lx. Abboud and

Bowman's research shows a retroreflectivity threshold value in the range of 140-156 mcd/m^2/lx based upon maintaining a crash rate below the overall average.

In an attempt to structure the information deficiencies that can contribute to a crash, Taylor et al. (31) included the following driver information requirements, for curve navigation:

- Advance warning of curve;
- Location of beginning of curve;
- Direction of curve;
- Degree of curvature;
- Location of apex; and
- Lateral position limits.

The relationship between increasing detection distance, or visibility as discussed above, and speed is not well understood. One study by Zwahlen and Schnell (32) found that drivers do not decrease their driving speed as a function of reduced pavement marking visibility. Thus it may be that higher visibility conditions may cause drivers to drive at higher speeds, which may in turn increase the frequency and severity of crashes as they go too fast for conditions. Increasing retroreflectivity, thereby increasing detection distances, may not necessarily increase safety. The relationship between driver detection distances and driver behavior needs to be better understood to make definite conclusions about the effect of increased retroreflectivity requirements.

As an example of higher retroreflectivity that leads to longer detection distances, work by Zwahlen and Schnell (33) concluded that the combination of both edgelines and centerlines provides detection distances that are on average about twice as long as the detection distances than can be achieved with a centerline alone. In two controlled field experiments, Zwahlen and Schnell applied "medium" retroreflective (yellow R_L= 347 mcd/m^2/lx, white R_L= 425 mcd/m^2/lx) and "high" retroreflective (yellow R_L= 483 mcd/m^2/l, white R_L= 515 mcd/m^2/lx) on a closed airport test site. Participants were asked to report on the detection distance to the end of the applied markings. The Zwahlen and Schnell (33) research consisted of higher retroreflective materials than can be found typically on highways. Given the range of retroreflectivity tested (347 to 515 mcd/m^2/lx), it is not clear if the findings of Zwahlen and Schnell would also apply to lower retroreflective values (i.e., less than 350 mcd/m^2/lx).

A series of studies on markings and markers as measured by detection distances were conducted by Molino et al. (34,35,36). The addition of pavement markers to pavement markings increases the retroreflectivity of the road delineation. In theory, the same level of retroreflectivity can be maintained by allowing the markings to fade if markers are installed. The first Molino et al. (34) experiment consisted of a simulator study designed to address the question “How much can the retroreflectivity of roadway pavement markings be reduced if retroreflective raised pavement markers of a certain retroreflectivity are installed on the road?” Molino et al. discuss the concept of a *trading ratio*, which refers to trading off the retroreflectivity of markings and instead installing markers. In the simulator experiment shown in Table 4, curve recognition distance was used to determine the trading ratio of markers to marking condition. The driving simulator task consisted of straight-line driving only without motion with speakers for the engine and roadway noise. An 88-degree computer-generated field of view using a projected image on a screen was the stimulus for the participants. The Molino et al. experiment was conducted in a dark environment with dark-adapted drivers, so the results cannot be generalized to lighted or high ambient illumination roads. In addition, there are limits in the contrasts that can be achieved using a simulator.

Table 4. Experimental design used by Molino et al. (34).

Number of Levels	Factor	Levels
36	Driver participant's age group, 12 in each age group, 6 male and 6 female per group	ages: 18-30 ages: 31-64 ages: 65 and older
4	Luminance levels for pavement markings	None Low Medium High
4	Luminance levels for pavement markers	None Low Medium High
2	Driving speed and road curvature	35 miles per hour on 10-degree curves 55 miles per hour on 6-degree curves
2	Scenarios of markings	Double yellow centerline with markers with single white edge Double yellow centerline with markers only
2	Lighting scenarios	Night scene (dark overcast, with texture) Black background only
2	Trials per condition	
36 × 4 × 4 × 2× 2× 2× 2 = 9216 Total trials		

Molino et al. (34) curve detection findings are in Figure 12, collapsed across all conditions except luminance. Figure 12 shows that as both the luminance of the markings and markers increased, the curve detection distance also increased. Other significant main effects found by Molino et al. included age with younger participants had the longest curve recognition distances. The presence of edgelines also contributed significantly toward improved lane-keeping performance. Molino et al. concluded that the trading ratio was 0.55 for yellow centerlines on non-freeway roads, which means pavement markings could degrade as much as 45% with the addition of pavement markers and still maintain the same overall curve detection distances.

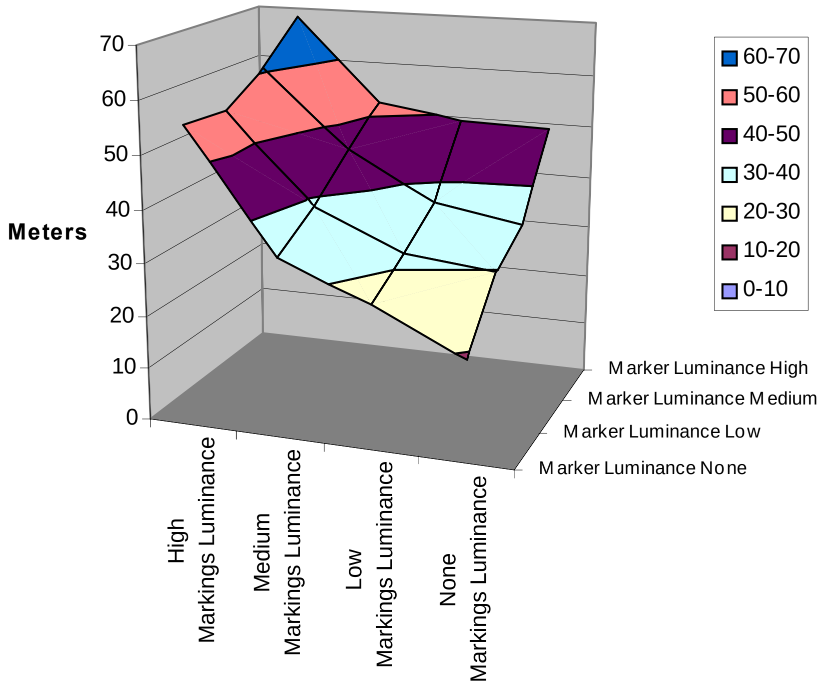


Figure 12. Mean curve recognition distances, from Molino et al. (34).

In a second simulator experiment, Molino et al. (36) investigated the interaction between centerline and edgelines luminance on driver curve recognition distances. Just as the addition of pavement markers increases road delineation luminance, the addition of edgelines to centerlines also increases the delineation luminance. In a parallel to their previous experiment, Molino et al. looked for the trading ratio for the addition of edgelines that would allow for degradation in centerline retroreflectivity while maintaining the same curve detection distance. The simulator task was very similar to the previous Molino et al. (34) experiment, except the experiment took 2.5 hours. The experimental design for investigating the interaction between centerlines and edgelines is shown in Table 5.

Table 5. Experimental design used by Molino et al. (36).

Number of Levels	Factor	Levels
18	Driver participant's age group, 6 in each age group, 3 male and 3 female per group	ages: 18-30 ages: 31-64 ages: 65 and older
4	Luminance levels for pavement markings	None Low Medium High
4	Luminance levels for pavement markers	None Low Medium High
2	Driving speed and road curvature	35 miles per hour on 10-degree curves 55 miles per hour on 6-degree curves
2	Scenarios of markings	Double yellow center with single white edge Double yellow center only
2	Lighting scenarios	Night scene (dark overcast, with texture) Black background only
1	Trial per condition	
18 × 4 × 4 × 2 × 2 × 2 × 1 = 2304 Total trials		

Results from the Molino et al. (36) simulator study are shown in Figure 13 and included an unintuitive finding. Figure 13 shows that edgelines of low luminance had a shorter curve recognition distance than the no-edgeline condition, circled in red. In other words, "edgelines of very low luminance (dim or faded edgelines) may be worse than no edgelines at all." The reasons for lower curve detection distances with faded edgelines than no edgelines are less than clear. Molino et al. explained this reversal in curve detection distances for faded edgelines by an interference or distraction hypothesis. By having incomplete visual information, the visual search task may require more eye saccades to identify the location of the pavement lines. Another possible explanation for poorer performance with faded edgelines compared with no edgelines may come from the concept of *optic flow*, or the translational motion of an observer over a flat surface (37). Mestre (37) explains that the way a driver steers a vehicle is akin to a tracking task, and the driver's task is to "maintain visual stability of edgelines". Optic flow in driving refers to using edgeline motion (Figure 14) as an effective visual cue for the control of heading and lateral control. According to Mestre (37), "delineation systems appear to be a privileged visual cue for facilitating driving". The possibility then exists that driving under conditions of faded edgelines becomes a signal detection task, thus complicating a driver's ability to maintain visual stability.

Addressing their initial experimental goal, Molino et al. (36) calculated a trading ratio between centerlines and edgelines to be 0.41, which means centerline luminance may be allowed to degrade by as much as 59% with the addition of edgelines while maintaining the same curve detection distances.

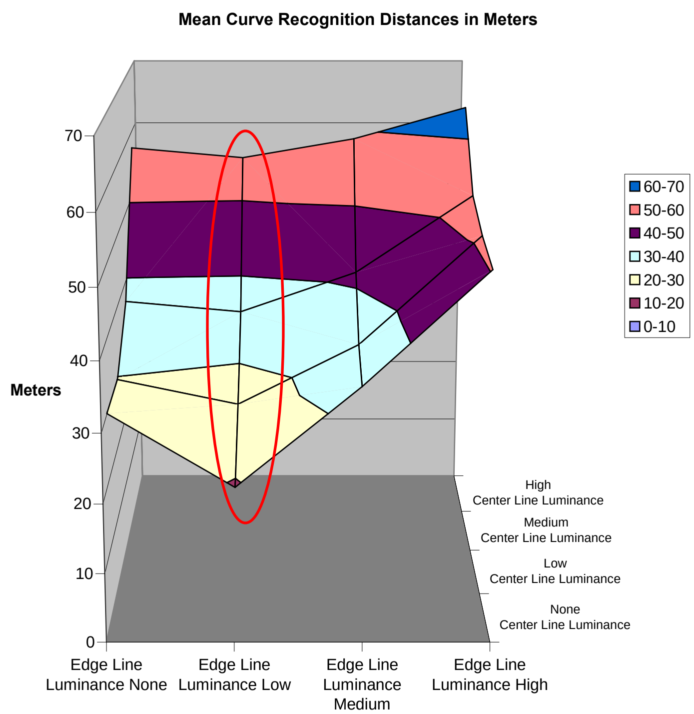


Figure 13. Mean curve recognition distances from Molino et al. (36).

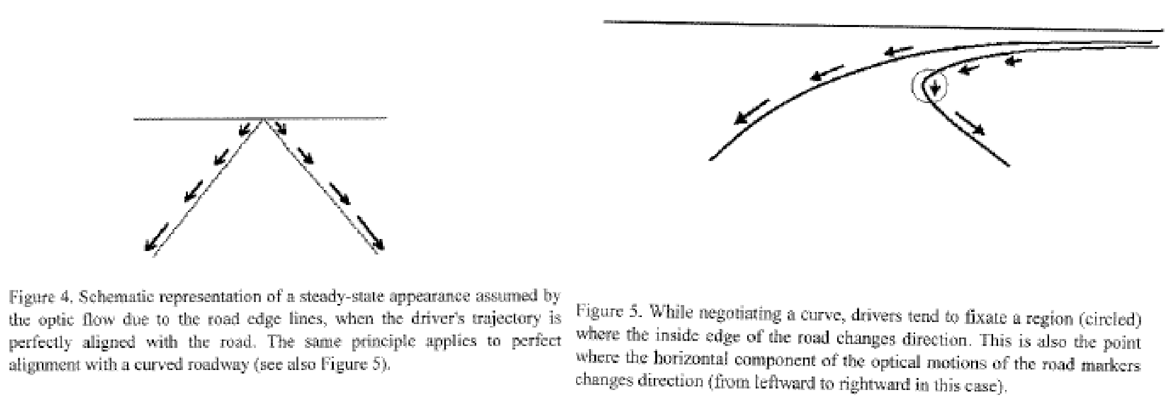


Figure 14. Depiction of optic flow, for a straight segment and a curve, from Mestre (37)

The limited contrasts available with their simulator in both Molino simulator experiments (34,36) were 150:1, which is “far below those likely to be experienced on a real roadway at night.” This limitation in contrasts emphasized the need for a field validation study. A field validation of the two previous experiments was conducted by Molino et al. (35), as described in Table 6. The field study was conducted on a newly constructed highway, not opened to other traffic, and delineated to look like a two-lane rural highway. Twelve-foot-wide lanes matched what were used in the two previous simulator studies. The road grade was a constant 0.84% downhill and there was no illumination by fixed roadway lighting. The closed road did have some ambient illumination from nearby buildings and other roads. Six trials were conducted, which took about 9 hours per participant over 7 nights.

Table 6. Experimental design used by Molino et al. (35)

Number of Levels	Factor	Levels
8	Driver participant's age group, 3 each in the younger age groups, 2 in the older age group	ages: 18-30 ages: 31-64 ages: 65 and older
3	Luminance levels for yellow pavement centerline markings adjusted by the mixture of glass beads	None 18 $mcd/m^2/lux$ Low 29 $mcd/m^2/lux$ High 172 $mcd/m^2/lux$
3	Luminance levels for white pavement edgelines markings adjusted by the mixture of glass beads	None 18 $mcd/m^2/lux$ Low 42 $mcd/m^2/lux$ High 370 $mcd/m^2/lux$
3	Luminance levels for pavement markers adjusted by filters [however, **only 20** of the 27 possible luminance scenarios were tested]	None 0.0001 cd/lux Low 0.012 cd/lux High 0.212 cd/lux
1	Driving speed and road curvature	35 miles per hour on 6-degree curves
2	Scenarios of markings	Double yellow center with single white edge Double yellow center only
1	Trial per condition	
8 × 20 × 1× 2× 1 = 320 Total trials in theory, actual data collected on only 268 trials due to equipment failures and participants not showing up		

The Molino et al. (35) field validation resulted in calling into question the use of simulators for pavement markings studies. Molino et al. found that because of the limited contrast ratios simulators can project, simulators are poor representations of real-world conditions. Molino et al. revised the previous simulator findings (34) to say that their trading ratios between centerline markers and markings is valid only for markers which are very faded or have low retroreflectivity. In the field, pavement markers were so much brighter than the pavement markings as to produce trading ratios that were practically zero (less than 0.001). In other words, the effect of pavement markers is so much more powerful than pavement markings in curve detection distances that yellow centerlines could be allowed to deteriorate by more than 99% in retroreflectivity if new pavement markers were added (35). Molino et al. therefore questioned the concept of a trading ratio in providing useful engineering information. In general, the issue of "trading" the retroreflectance of longitudinal lines with lines that have pavement markers is not entirely resolved or agreed upon by the research community. In addition, pavement markers themselves degrade very fast and can potentially lose 90% of their retroreflectivity within six months of installation (38). Findings from Molino et al.'s (35) second simulator study were validated in that low luminance edgelines combined with low luminance centerlines produced lower curve detection distances than low luminance centerlines alone, as shown in Figure 15.

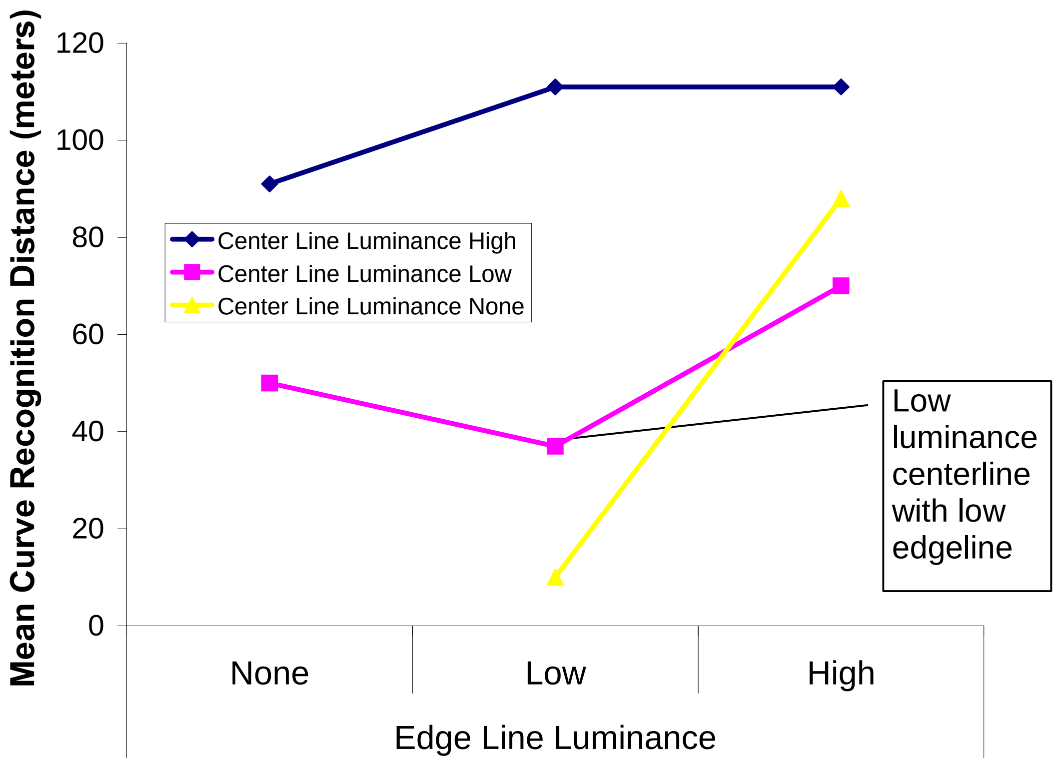


Figure 15. Mean curve recognition distance for edgeline tradeoffs from Molino et al. (35).

2.2.7. The Effects of Weather on the Performance of Pavement Markings

Most pavement marking materials do not provide equal visibility (and durability) under every roadway situation (10). Results from two studies conducted by Aktan and Schnell (39,40) demonstrate that the relative performances of different pavement marking materials vary under changing weather conditions. For example, wet-weather tape and profiled tape using mixed-index beads outperformed other pavement marking materials, such as profiled tape with high index beads, flat tape and paint with large beads in dry, wet and rainfall weather conditions. In both studies, the performances of the marking materials were evaluated using detection distances and subjective ratings assigned by participants in the study. Pavement marking materials that provided longer detection distances were given higher subjective ratings by evaluators and were considered superior. While the wet-weather tape and profiled tape with mixed-index beads clearly outperformed the other marking materials under all three weather conditions, results from comparisons between the other materials were less definitive. The researchers found that one material (other than wet-weather tape and profiled tape with mixed-index beads) would perform better than another under one weather condition, but vice-versa under another weather condition. For instance, pavement markings consisting of paint and large beads were found to provide longer detection distances, compared with profiled tape with high-index beads under wet conditions as prescribed by the American Society for Testing and Materials (ASTM) E-2177. However, when further tests were conducted using a modified version of the wet test (waiting 5 minutes instead of the 45 seconds prescribed in the ASTM standard), the average detection distances for the profiled tape with high-index beads were longer than those measured for the paint markings. Aktan and Schnell (39) concluded that the relationship between detection distances of pavement markings and the retroreflectivity measurements for those pavement markings is linear under similar weather conditions. Figure 16 illustrates this relationship for three types of pavement markings under dry, wet, and rainy conditions, while minimum retroreflectivity levels are shown in Table 7.

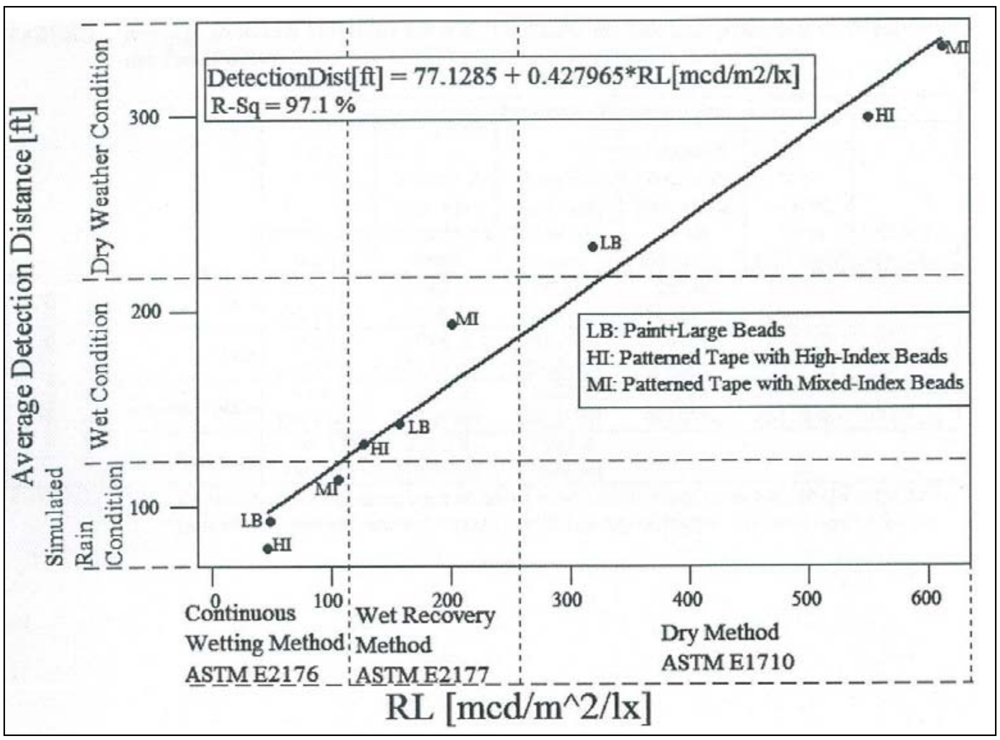


Figure 16. Detection distance versus retroreflectivity of marking, from Aktan and Schnell (39)

Table 7. Minimum required retroreflectivity levels (RL), from Aktan and Schnell (39)

Preview Time = 3.65 s, Paint and Beads (OUWHITE.PMM)			Minimum Required RL [mcd/m²/lx] for a Fully Marked Road Consisting of Two White Edgelines and a Dashed Yellow/White Center/Lane Line							
			GE H6054 Low Beam at 13.3V		GE H6054 High Beam at 13.3V		50% UMTRI Low Beam at 13.3V		25% UMTRI Low Beam at 13.3V	
			Driver Age [years]		Driver Age [years]		Driver Age [years]		Driver Age [years]	
Vehicle Speed [mph]	Vehicle Speed [km/h]	Preview Distance [m]	22	62	22	62	22	62	22	62
25	40.23	40.78	23	28.4	24.8	31.9	24.2	28.4	24.8	31.9
35	56.32	57.10	33.7	49.6	31.9	46.1	35.4	56.7	39.0	56.7
45	72.41	73.41	56.7	85.1	46.1	70.9	63.8	113.4	63.8	113.4
55	88.50	89.72	99.2	170.1	70.9	113.4	113.4	226.8	141.8	283.5
60	96.54	97.88	127.6	225.2	85.1	141.8	155.9	340.3	170.1	340.3
65	104.59	106.04	170.1	340.3	99.2	184.3	226.8	453.7	255.2	510.4
70	112.63	114.19	223.8	510.4	127.6	226.8	283.5	623.8	340.3	737.2
75	120.68	122.35	283.5	623.8	155.9	283.5	397.0	793.9	453.7	907.3

One of the major objectives of Aktan and Schnell (39,40) was to determine the performance of these various products in rain (1 in. of rain per hour of simulated rain) as well as their performance when the products were only wet. Aktan and Schnell (39,40) found that:

1. Paint with big beads and profiled product worked well when they and the roads were wet, but was inadequate or not visible in 1 in. of simulated rain. Therefore, markings which retroreflect while wet will not necessarily work when it is raining.
2. The wet weather tape and the profiled tape with mixed index beads were the only products visible in 1 in. of rain, with the wet weather tape being far superior to the latter.

Similar findings were reported by Gibbons et al. (41), who concluded that wet retroreflective tape (wet-weather tape) and raised markers perform much better than waterborne paint with glass beads. Gibbons et al. (41) also conducted test of six different technologies and found that the ATSM retroreflectivity measurement methods were suitable for flooding (static pool of water) and continuous wetting (raining conditions) testing compared with the subjective evaluations. In other words, ATSM retroreflectivity test results for wet road and raining conditions correspond well to subjective driver ratings of markings under identical wet weather conditions.

2.2.8. Snow-Removal Policy

Snow-removal methods include chemical anti-icing, chemical de-icing, abrasives, and snowplowing practices, and they have a detrimental effect on the visibility of pavement markings and markers. Currently, there is limited information on the quantification of the detrimental effect that the different techniques for snow removal have on pavement markings and markers. Snow-removal methods are closely tied to a jurisdiction's snow-removal policy. An example of one state's policy is in Section 95.6 of the California Streets and Highways Code:

> *"Snow removal and ice control shall be performed as necessary in order to facilitate the movement and safety of public traffic and shall be done in accordance with the best management practices outlined herein with particular emphasis given to environmentally sensitive areas."(42)*

In Minnesota, where it can snow seven months a year (October through April), quantitative performance targets have been set, as shown in Table 8. (Minnesota's performance targets are constant through 2023.) Minnesota's policy aims to clear pavements of snow and ice within 10 hours of accumulation for the entire highway system (43), with the highest-traffic routes cleared within 3 hours.

Table 8. Minnesota snow and ice removal performance targets (43)

Targets	2009	2013	2023
Super Commuter (hours) 30,000+ vehicles/day	1-3	1-3	1-3
Urban Commuter (hours) 10-30,000 vehicles/day	2-5	2-5	2-5
Rural Commuter (hours) 2-10,000 vehicles/day	4-9	4-9	4-9
Overall System (hours)	10	10	10

2.2.8.1. Chemical De-icing

The primary purpose of chemical de-icers is to clear the road of ice. However, chemicals used today often have detrimental effects on the pavement surface, including pavement markings and markers. In controlled experiments, Lee et al. (44) concluded that magnesium in any form was very damaging to concrete and found that Sodium Chloride (NaCl) solutions were the least damaging. Since chemical de-icers can damage the pavement surface, it is reasonable to expect damage to markings and markers on the pavement surface. Controlled studies on precisely how chemical de-icers damage pavement markers and markings are not available in the literature. In general, determining the effect of chemical de-icers on pavement marking and markers is considered low priority, which may explain why no published studies are available. For example, a recent Problem Statement considered but not selected is NCHRP Problem Number 2003-C-25, Guidelines for Using Magnesium Chloride ($MgCl_2$) as a De-icer. NCHRP Problem Number 2003-C-25 called for research on:

1. The effects of $MgCl2$ on reinforcing steel;
2. The effect of $MgCl2$ on the surface of a concrete pavement; and
3. The effect of $MgCl2$ on painted and durable traffic markings.

The costs for structural steel and concrete surfaces are in the billions of dollars, while costs for markings are in the millions. The lack of study of the effect of chemical de-icers on markings and markers is probably due to the high costs of studying deterioration over time.

2.2.8.2. Chemical Anti-icing

Anti-icing involves the use of chemicals distributed on the pavement surface to prevent a bond from forming between the pavement and snow or ice (45). According to Boselly (45), anti-icing includes activities such as pre-treatment using liquid chemicals before a winter snowfall, and the application of solid chemicals at the onset of a storm. The most commonly used chemical for anti-icing is Sodium Chloride (NaCl) (45).

2.2.8.3. Abrasives

Abrasives, such as sand, are distributed on roads and intended to increase friction between vehicles and the ice and snow covered pavement surface. Research on the use of abrasives in winter maintenance has shown that the abrasives "do not remain on the road surface under the action of (even low volumes of) traffic."(46) Alternatives to distribution of dry abrasives, as discussed by Nixon (46), include pre-wetting abrasives, and heated abrasives which have the effect of partially melting into the ice and snow and sticking out as individual abrasive particles. However, no research is available which quantifies the effect dry, wet, or heated abrasives have on pavement marking and marker visibility.

2.2.8.4. Snowplowing

Two fundamental snowplowing policies are in use; the first involves using slightly elevated plows on "shoes" and the second involves running the plow blade right on the bare pavement. A bare-pavement policy is more expensive in terms of wear on the pavement surface and markings but it does not leave a snow/ice residue behind, as does the elevated snowplow policy.

There has been limited research quantifying the amount of damage snowplowing has on pavement markings. Cottrell (47) investigated the impact of carbide-tipped snowplows on pavement markings. Cottrell and Hanson (3) collected retroreflectivity, durability, and color data from 22 study sites along interstate highways and principal arterial corridors. Between January and March, Cottrell and Hanson (3) measured a 39% decrease in retroreflectivity on white waterborne paint skiplines, a 24% decrease on white waterborne paint edgelines, and a 15% decrease in yellow waterborne paint centerlines. Through observations, Cottrell and Hanson (3) concluded that of the different winter maintenance activities (snowplows, chemicals, and abrasives), snowplows are likely the predominant cause of pavement marking damage. Cottrell and Hanson (3) collected data from only one season (1994-95 winter), which was relatively mild compared with a typical winter in Virginia. Therefore, for heavier winters with increased snowplowing, larger drops in retroreflectivity on pavement markings should be expected.

2.2.9. Pavement Surface Influence on Pavement Marking and Marker Visibility

Contrast is a ratio between the target object and the background, as previously described in Section 2.2.1. For nighttime driving, the target objects are pavement markings and markers, and the pavement surface represents the background. The standard methodology for calculating reflectance for pavement is the Commission Internationale de l'Eclairage (CIE) r-Tables (48). However, as noted in its European scanning tour, FHWA has found that several countries reported that luminance values measured in the field can vary significantly from the values predicted by the design calculations that use the r-Tables (49). North American research by Khan et al. (50) compared measured reflectance values with the r-Tables. Khan et al concluded that the difference between calculated and measured values is as high as 130%. In this research effort, Khan et al. (50) hypothesized that a relationship between cumulative traffic volume and pavement reflectance exists, however, they were unable to identify a clear quantitative relationship. Khan et al. (50) concluded that asphalt surfaces tend to increase their brightness with ages whereas Portland cement concrete surfaces tend to decrease their brightness.

In conclusion, the influence of pavement surface on the visibility of markings and markers, or the luminance of pavement surface as a function of variables such as material type, age, and traffic volume, is not well understood. Both FHWA (49) and Khan et al. (50) have recommended additional research be conducted on pavement reflectance. A recent proposal, NCHRP Problem 2002-G-48 (Development of New Bi-Directional Pavement Reflectance Distribution Functions for All Pavement Types), to evaluate all pavements and produce reflectance tables was not approved for study at this time.

2.2.10. Summary of Visibility and Retroreflectivity

To summarize, the performance of pavement markings in terms of retroreflectivity over time is understood to follow basic patterns that can be modeled. Driver preference is for markings to have retroreflectivity levels greater than 100 mcd/m^2/lux. What remains unknown is what effect the change in retroreflectivity has on driver safety.

2.3. Human Factors

Given the tendency for drivers to drive too fast at night under low-visibility conditions and "overdrive" low-beam headlights (51), Migletz et al. (52) defined the preview or visibility distance as the distance that the delineation provides the driver to see upcoming changes in the roadway. This distance must provide drivers with enough time to detect roadway features and changes in alignment ahead, and respond with steering and speed adjustments. The preview distance offered by pavement markings is particularly important when the view of the road ahead is limited and drivers are forced to depend on roadway and traffic information that is visible only from a short distance (8). In adverse weather conditions or during nighttime, this preview distance is dependent on the visibility of the pavement markings, which in turn is a function of the reflectivity of the markings and markers.

Many previous studies have attempted to determine driver requirements in terms of preview time for both short-range and long-range guidance (8). The consensus is that 2 seconds of preview time is required for short-range guidance in extreme situations during when a driver may be required to respond quickly to perceived hazards or changes in alignment. For long-range guidance, the general view is that a minimum of 3 seconds of preview time is required to allow for comfortable driving (8). Zwahlen and Schnell (51) investigated this concept further and recommended a preview time of 3.65 seconds (3.00 seconds of true preview time and 0.65 seconds of perception-reaction time) to accommodate drivers with a margin of safety and comfort. Consistent with the research conducted by Molino et al. (35), Zwahlen and Schnell (51) also showed that requirements for preview times could be substantially relaxed if markers were used along the centerline or lane line. In general, the concept of using a preview time implies a static view of the driving task rather than an adaptive one. Most driving simulator experiments, and even most field studies, assume a constant speed and use this constant speed as a base for preview time calculations. However, on the highway, drivers change their speed as a function of visibility and road conditions and do not maintain a constant speed.

Parker and Meja (17) found that driver age has a significant impact on the visibility (which was quantified using detection distances) of pavement markings at night. The field study found older drivers ($\geq$ 55 years) tended to assign lower scores to pavement markings compared with younger drivers (<55 years). This observation is expected given that visual acuity is likely to diminish with age. However, it has also been shown that older drivers may sometimes assign higher subjective visibility ratings to pavement markings simply because they are aware of their visual limitations and have lower expectations in regards to the brightness or visibility of the pavement markings (16). Regardless, pavement marking, signage, and other road features for roads may not work adequately for drivers of all ages. In some cases, drivers 65 years old and over may need as much as four times greater contrast to see as well as a 39-year-old driver (8).

2.3.1. Driver Behavior on Curves

Dewar and Olson (53) state, "The study of vehicle operations on horizontal curves has shown that speeds reduce on curves and that encroachment onto the edgeline occurs on right curves and onto the centerline on left curves." Johnston (54) has provided quantitative evidence that optimal driving behavior does not mean driving consistently within the center of the lane. Instead, what drivers actually do, and what, according to Johnston, should be considered proper driving, is to 'cut the corner' without departing from the lane (Figure 17). In Figure 17, the radius of the curve driven is larger than geometric curvature of the road.

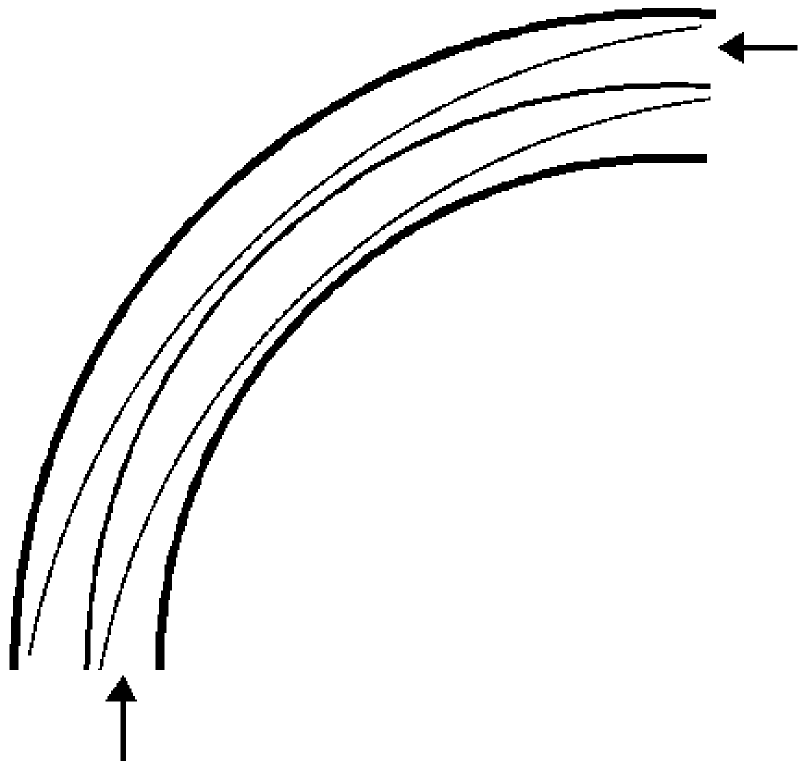


Figure 17. 90-degree curve showing the trajectory drivers actually drive.

2.3.2. Edgelines and Speed

Research by Zwahlen and Schnell (55) has shown that pavement marking retroreflectivity requirements increase exponentially with an increasing preview distance. Using a constant preview time of 3.65 seconds and 2.00 seconds for roadways without markers and with markers, respectively, Zwahlen and Schnell established the relationship between minimum retroreflectivity requirements and vehicle speeds for a 62-year-old driver (accounting for 95% of the nighttime driver population in the United States), as illustrated in Figure 18 below.

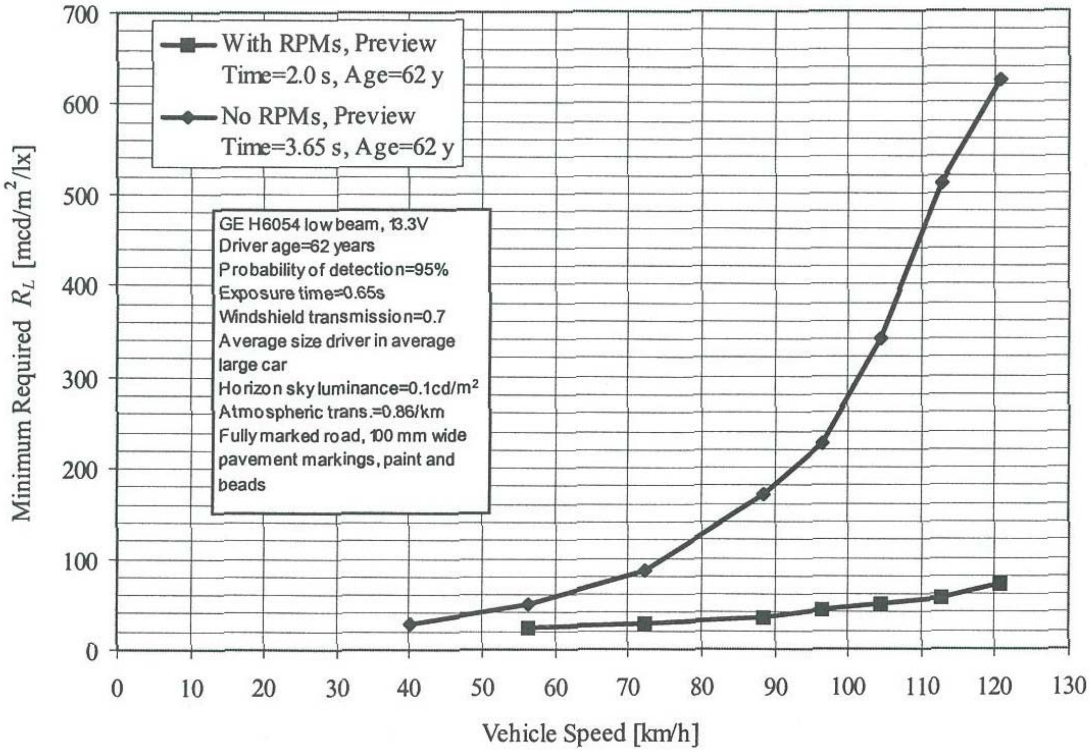


Figure 18. Retroreflectivity requirements by vehicle speed, from Zwahlen and Schnell (55)

In general, studies that have taken speed measures before and after the applications of markings and markers have reported a modest increase in operating speed immediately after installation. For reasons that are not clear, this speed change fades over time. For example, Willis et al. (56) collected daytime speed measures of traffic before-and-after the installation of both continuous and broken edgelines, and observed an average 1.9-km/h increase in speed one month after installation. However, 11 months later, the speed change was only a 0.5-km/h increase. A meta-analysis conducted by van Driel et al. (57) concluded that the application of an edgeline to a road without a centerline increases the road operating speed, whereas replacing a centerline by edgeline decreases the speed. According to van Driel et al. (57), the effects on speed of the addition of both a centerline and an edgeline remain unclear.

2.4. Safety Impact

Numerous safety evaluations of longitudinal marking have been published in the literature. Nearly all published studies evaluating the safety impact of marking have used variants of the before-and-after design, where the crash history of a road in a before period is compared with the period after a change (e.g., installation of edgelines, change in the type of pavement materials) has been made. Sometimes comparison or control locations are used to identify any existing crash trends over time.

A review of the literature reveals only two studies that examined the relationship between the visibility of markings and the number of crashes. In the first, Lee et al. (1) conducted a study of 50 locations in Michigan where the retroreflectivity of different types of markings over 3 years was measured and then compared with the number of nighttime crashes potentially associated with line visibility. One of the key difficulties in comparing visibility to the number of crashes is separating any seasonal effects from the delineation effects. There is no statistical methodology for separating the delineation and long-term effect from the yearly seasonal effect if, for example, all markings were installed on the same month each year. From an experimental design point of view, installation of markings and markers equally distributed throughout the year would be ideal. The reality is that northern states, such as Michigan, usually limit installation and restriping to the summer months, thus limiting the ability of statistical analysis to separate out the seasonal effect. Lee et al. (1) acknowledged this difficulty of seasonal bias but did not report what measures, if any, were taken. In the end, Lee et al. (1) were unable to identify any relationship between retroreflectivity and nighttime crashes.

The second study seeking to relate the visibility of markings to crashes, Abboud and Bowman (30), collected retroreflectivity readings on 520 miles of rural highways in Alabama over a 4-year period and compared them with the number of nighttime crashes potentially associated with line visibility. In their analysis, Abboud and Bowman (30) assumed linearity by using crash rates instead of frequency counts. However, expected crash frequency is not linearly proportional to traffic volume. In other words, the use of crash rates can be misleading and can produce conclusions that may be untrue. In addition, Abboud and Bowman (30) did not address seasonal effects or apply any analysis methods that could minimize a seasonal bias. Abboud and Bowman (30) compared the long-term crash rate to the average crash rate for the study period to identify 156 mcd/m^2/ls as the minimum acceptable retroreflectivity threshold for maintaining a crash rate below the study period's average. This conclusion was highly dependent up time of restriping of the markings in that one would expect that newly striped roads would have different crash rates than poorly maintained roads. Abboud and Bowman (30) admitted that the number of years of post-striping data for all roads was not equal, and therefore data from a road with only 1 year of post-striping data would have a different retroreflectivity average than data from a road of 3 years of post-striping data.

The use of longitudinal pavement markings is generally accepted as effective in reducing the number of crashes. Potters Industries (58) cited seven previous studies between 1955 and 1971 conducted in the United States that presented results ranging from 11.9% to as high as a 79% reduction in the number of crashes. Potters Industries conducted their own before-and-after study of replacing unreflectorized white centerlines with retroreflective centerlines and edgelines, although 4.6 of the total 18.3 miles treated had not been previously been marked. The Potters Industries study (58) was conducted to test the Manual on Uniform Traffic Control Devices (MUTCD), and the results are in Table 9.

Table 9. Summary of Potters Industries (58) findings of the safety effect of MUTCD marking guidelines for edgelines and centerlines,

<table>
<tr><th>Length of two-lane road</th><th>Before Condition May-August 1969 & 1970</th><th>After Condition May-August 1971</th><th>% Change in Total Number of Crashes</th><th>% Change in Single-Vehicle Crashes</th></tr>
<tr><td>4.6 miles</td><td>Unmarked</td><td rowspan="4">Double yellow lines and skip lines indicating passing zones</td><td>40% reduction</td><td>50% reduction</td></tr>
<tr><td>7.0 miles</td><td rowspan="3">Edgelines and single white center strip</td><td rowspan="3">15% reduction</td><td rowspan="3">32% reduction</td></tr>
<tr><td>4.1 miles</td></tr>
<tr><td>2.6 miles</td></tr>
<tr><td>All unstriped roads in West Milford</td><td colspan="2">Control group</td><td>18% increase in crashes over the previous 2 years</td><td>38% increase</td></tr>
</table>

The Potters Industries study (58), however, did not specify how the treated road segments were selected, leaving open the possibility that regression to the mean may have occurred. The Potters Industries study (58) was also limited to summertime data (May through August) to minimize the effect of severe weather on crashes.

Similar methodology has been applied in Great Britain to assess the safety impact of the addition of edgelines. In 1976 in South Yorkshire, the Road Marking Industry Group (59) conducted a before-and-after with control study by adding edgelines to two-lane, rural highways without edgelines. The study compared the 1 year after the application of edgelines with the previous 3 years of crash data. The Road Marking Industry Group (59) found a 13% reduction in the total number of crashes, compared with a 17% increase in the number of crashes in the control group. Again, this is a study which did not specify how roads were selected for treatment, leaving open the possibility that high-crash locations were purposely selected and thus potentially affected by regression-to-the-mean bias. Examining the data in more detail, the Road Marking Industry Group (59) found a 38% reduction in the number of nighttime crashes, compared with an increase on the control roads of 29%. Thus, the primary benefit of edgelines seems to be for reducing the number of nighttime crashes.

Also in Great Britain, Charnock and Chessell (60) conducted a thorough analysis using the before-and-after with control methodology to assess the safety impact of adding edgelines. Treatment and control locations were purposely selected so that the crash rate per mile, and the proportion of fatal/serious injuries and nighttime crash were comparable to other rural roads in Britain. Seven segments of 15 miles in total length were treated with edgelines, and the treated segments were matched up, based on crash rates, with 18 miles of untreated control segments without edgelines. All segments studied averaged 6,700 vehicles a day during their peak month. The before period looked at 2/3 of the previous 3 years of data, while the after period looked at results for the 2 years after edgelining. Charnock and Chessell (60) found a 12% and 37% reduction in injury crashes for daytime and nighttime crashes, respectively. The control roads showed a 10% reduction in the number of daytime injury crashes and a 6% increase in the number of nighttime injury crashes.

Given the limited number of 222 injury crashes from July 1972 to July 1975 in the County of East Sussex, Charnock and Chessell (60) were unable to demonstrate statistical significance. Nonetheless, the lack of statistical confidence is an indication of the uncertainty of the *magnitude* of the safety of edgelines and not the direction (increase or decrease) of safety. In fact, when looking at data from only the first 9 months of the 2-year study, the total reduction in crashes was 61% with a confidence level of 97.5%, leading Charnock and Chessell (60) to speculate that the *impact of edgelines was diminishing over time*. At 15 months after edgeline treatment, the results of a reflectance study using a standard photometer showed that the brightness of the edgelines during the daytime was 43% lower than when first installed. No retroreflectometer readings were reported for nighttime, but the expectation is that degradation of retroreflectivity would have been even greater.

Charnock and Chessell (60) also examined “Good Alignment” segments, which were defined as straight or virtually so down to a level where “no speed change would be necessary to negotiate the curve safely.” The road geometries that showed the maximum benefit from edgelines were those with “Good Alignment”. The authors also noted a reduction in severity in both daytime crashes and those involving drivers who resided locally. Note that all the conditions which received maximum benefits of edgelines were counter-intuitive, i.e., smooth curves, daylight, and local residents. Charnock and Chessell (60) wrote that:

> *“A significant reduction in accidents on bends might have been expected but the results indicate that as the bend “tightened” the lines have an adverse effect. This could be because the presence of the lines give the driver a false confidence on the approach to a bend.”*

Charnock and Chessell (60) further examined one section of road which consisted mostly of curves of sharp radii. They concluded that in the before period, 50% of crashes occurred on the curves, whereas after edgelining, 80% of crashes occurred on the curves.

The effect of markings and markers on curves appears to be dependent on the radii of the curve. In addition, the effect of markings and markers may be dependent on the road volumes. Glennon (61) conducted an analysis of (unpublished FHWA data) from six states where centerline and no-passing zone markings were added to previously unmarked roads. Glennon (61) found significant increases in crashes for roads with AADT of 500 vehicles a day or less, and for roads with AADT of 500-1,000 vehicles a day with less than a 10-foot-lane width. Lower volume roads are also the roads which are more likely to have lower design standards (e.g., narrower lanes, narrower shoulders, tighter horizontal curves, steeper vertical grades, and lower superelevation). Glennon (61) hypothesized that the addition of markings on lower-volume roads caused drivers to forget the need for more cautious driving as required on lower-design-standard roads. If this hypothesis is valid, then *the key to understanding the safety impact of marking delineation is understanding the interaction between driver response, delineation, road geometry, and traffic volumes*.

Glennon (61) found evidence that showed safety improvements with the installation of centerline and no-passing zone markings on roads with AADTs greater than 1,000 vehicles a day. Woods (62) used Glennon's findings to conduct a benefit-cost ratio of not providing markings on low traffic volume, no shoulder, 2-lane highways. Woods found the benefit-cost ratio to be 1.9 for centerline markings on lower-design-standard, low-volume, 2-lane roads.

More recent research from Bahar et al.(63) has also found the safety effect of delineators explicitly tied to key aspects of road geometry and traffic volumes. Bahar et al.(63) collected crash, roadway geometry, and traffic volume data from six states (Illinois, Missouri, Pennsylvania, New York, Wisconsin, and New Jersey) from various time periods from 1991 to 2001, depending on the state. Bahar et al. conducted a before-and-after study specifically "to assess the safety effects of permanent raised pavement markers"(63). The before period consisted of 2-lane roadways, 4-lane undivided freeways, and 4-lane divided expressways without pavement markers, while the after period consisted of the same roads with markers. The retroreflectivity of markers, just like for markings, deteriorates over time. A study by Ullman (38) found that the retroreflectivity of many pavement markers dropped below minimum threshold after less than 6 months. The retroreflectivity of the markers remaining constant is necessary for a before-and-after study. Given that the after periods for the Bahar et al. (63) study ranged from 1 to 5 years depending on the state, Bahar et al.

(63) selected states with careful monitoring and maintenance schedules. However, the Bahar et al. (63) survey results indicated that states replace markers in a cyclic pattern usually every 2 to 4 years, unless the field studies show 2 or more damaged permanent raised pavement markers in succession (38).

On 2-lane roadways, Bahar et al. (63) found that snowplowable pavement markers significantly *decreased* the occurrence of head-on crashes and wet-weather crashes. In addition, Bahar et al. (63) found that the safety benefit of snowplowable markers increased with higher traffic volumes. On the other hand, for 2-lane roadways, Bahar et al.(63) found that snowplowable pavement markers *increased* the number of nighttime crashes on sharp curves and roads with lower design standards, such as narrower pavement widths. On 4-lane freeways, Bahar et al. (63) found that snowplowable pavement markers *decreased* nighttime crashes and wet-weather crashes. An increased safety effect of snowplowable markers was also found with higher traffic volumes. In fact, Bahar et al.(63) found that snowplowable markers may not have been effective on 4-lane freeways with AADTs of less than 20,000 vehicles a day.

Delineation often is installed to improve visibility specifically for those situations where visibility is particularly poor, such as at night and in poor weather conditions (e.g., rain, snow, and fog). Certain pavement markings have somewhat improved performances under adverse weather conditions compared with conventional paint markings. In order to quantify the safety effect and service life of all-weather pavement markings, Migletz et al. (2) conducted a large-scale evaluation working with the FHWA.

Over a 3-year time period (1994-1996), 85 sites in 19 states installed all-weather pavement markings on freeways, multi-lane cross sections, and 2-lane highways. In general, the all-weather markings used in the Migletz et al. study (2) consisted of the more durable (and more expensive) pavement markings, which included epoxy, methyl methacrylate, profiled methyl methacrylate, polyester, profiled polyester, profiled tape, thermoplastic, profiled thermoplastic, as well as conventional and waterborne paint combined with permanent raised pavement markers. No criteria for selecting sites with average crash frequencies were used, so the possibility of regression-to-the-mean exists.

Using a before-and-after study design, Migletz et al. (2) made the assumption that the all-weather markings were replacing conventional and waterborne paint markings. Since FHWA was funding the installation costs, this would seem to be a reasonable assumption because the state would benefit from having more expensive marking installed at no additional cost. However, the Migletz et al. (2) study did not acquire the type of marking used in the before period. In fact, after the safety evaluation was completed, 7 sites, all from the same state, were discovered to have been marked with an epoxy marking, rather than conventional paint, prior to the installation of a variety of all-weather markings. For 28 sites of the remaining 55 used in the safety evaluation, the researchers were unable to confirm the type of markings used during the before period of the study.

In the Migletz et al. (2) study, the duration of the before period was between 22 and 46 months, whereas the after period ranged between 3 and 54 months. The safety evaluation considered all crash types except multiple-vehicle crashes at or related to intersections. The safety analysis was conducted for all crashes, thus combining fatal, injury, and property damage-only crashes. Migletz et al. (2) did not examine any potential interactions between markings and curves or other road characteristics. Even though a service life evaluation was conducted, resulting in a regression line of retroreflectivity performance over the life of the marking, the retroreflectivity of the marking was not used to assess the safety of pavement markings. The retroreflectivity of markings over time may not have been used because no retroreflectivity measurements or estimates were available for the markings in the before period.

Service life refers to the duration a marking from its installation until it reaches a minimum retroreflectivity level. Migletz et al.(2) conducted a service-life evaluation of all-weather markings. According to Migletz et al. (2):

> *"Daytime and nighttime visibility are closely related because as a marking is chipped or abraded by traffic action, there typically is not only loss of marking material, which decreases the daytime visibility of the marking, but also loss of beads, which reduces the nighttime visibility (retroreflectivity) of the marking."*

To assess the markings' expected service life, Migletz et al. (2) conducted 1,940 retroreflectivity measurements on the 362 all-weather pavement markings installed for the study over a period of 3.5 years. Using the retroreflectivity measurements, 179 unique combinations of, type of material, type of line, site, and severity of winter climate (such as profiled thermoplastic, yellow centerlines, on freeways, in mild weather locations) were modeled to produce 179 retroreflectivity models as a function of cumulative traffic passages. The regression analysis conducted by Migletz et al. (46) produced 120 first-order linear (straight lines) relationships (67%) and 45 exponential decay models (25%). The remaining 8% could not be modeled or could only be fitted using a second-order linear model, such as:

$$SL_{Months} = \frac{SL_{CTP}}{\left[\dfrac{CTP_{Final}}{Date_{Final} - Date_{Install}}\right]\left[\dfrac{365.25days}{12months}\right]}$$ *Equation 2*

where

SL_{Months}	= Service life in elapsed months,
SL_{CTP}	= Service life in cumulative traffic passages (millions of vehicles),
CTP_{Final}	= Cumulative traffic passages (millions of vehicles) at final field measurement date,
$Date_{Final}$	= Date of final field measurement, and
$Date_{Install}$	= Installation date of pavement marking.

Equation 2 defines expected service life expressed in elapsed months since marking installation, based on cumulative traffic passages from Migletz et al. (2). Migletz et al. (2) originally intended to incorporate four variables (color of line, roadway type, marking material, and severity of winter climate) in order to estimate the service life of markings. However, their analysis of variance found no statistically significant effect of climate severity on pavement service life, so climate severity was not used as a factor. Migletz et al. (2) also studied the effect of rain on the retroreflectivity of markings. Based on 424 sets of comparative dry and wet pavement measurements made at 60 of the 85 study sites, Migletz et al.(2) concluded that *the mean retroreflectivity of wet markings drops by 42% to 52% of the retroreflectivity under dry-pavement conditions*.

The Migletz et al. (2) study did examine daylight and nighttime crashes separately, with nighttime crashes including dawn and dusk crashes. In addition, dry and wet crashes were examined separately to assess the safety of all-weather pavement markings. However, crashes occurring under ice and snow conditions were excluded because "*pavement markings are often obscured from the driver's view and, therefore, cannot be expected to function properly under such conditions*." (Migletz et al. (2) p.71). To determine whether the number of wet-weather crashes was high, a model of wet-weather exposure was developed as a software program called WETTIME (64). WETTIME estimates exposure to various pavement conditions from the available weather data, which were obtained for each road segment from the nearest National Climatic Data Center.

Migletz et al. (2) used both a paired sign evaluation and a yoked-comparison evaluation for analyzing the before-and-after data. Both approaches make the explicit assumption that the all-weather markings have no effect on daytime crashes, which may not necessarily be true. No control or comparison sites were used. In the yoked-comparison analysis, the daytime crash experience was compared with the nighttime crash history at the same locations. Migletz et al. (2) concluded that while all-weather markings may be effective overall in reducing the number of crashes, they were unable to demonstrate this overall safety effect with statistical significance. No statistically significant data on nighttime wet-pavement crashes was found, and in fact the number of nighttime wet-pavement crashes increased by 15%. Nighttime dry-pavement crashes decreased by 11%. For all nighttime dry and wet crashes, the number of crashes decreased by 6%. The Migletz et al. (2) study considered all types of durable markings as “all-weather,” which included 10 different durable markings as well as waterborne paint with permanent marker, which in reality have very different properties under wet and raining conditions. Migletz et al. (2) did attempt to estimate service life by roadway type, pavement marking material, and color of line for sites without roadway lighting and permanent raised pavement markers, as shown in Table 10.

Another study on the safety effectiveness of pavement markings was recently completed by Cottrell and Hanson (3). Broad in scope, Cottrell and Hanson studied safety, motorist opinion, and the cost-effectiveness of pavement markings. For the safety evaluation of markings, Cottrell and Hanson identified 22 sites for remarking with either paint, thermoplastic, or tape. The Cottrell and Hanson study used a surprisingly small number of sites per pavement marking type (e.g., One marking type was installed in 5 locations, and all other marking types were installed in only 2 or 3 locations). Some of the sites were used as control study sites, whereas others were used to compare the effectiveness of different types of marking. Two sets of analyses were conducted. The first set consisted of sideswipe-in-the-same-direction and run-off-road crashes only in the first analysis and all crashes in the second analysis. Given the rarity of crashes, markings installed on about 80 miles of road over a 5-year period are insufficient to identify statistically significant differences between markings which differ primarily on the type of material. In fact, Cottrell and Hanson (3) was unable to statistically identify any significant differences in the frequency of crashes between different types of pavement markings.

In the motorist survey, Cottrell and Hanson (3) videotaped roadways at night when driven at the speed limit with low-beam headlights. Five scenes of 7 to 10 seconds in duration were used to survey motorists on the appearance of the edgelines. Even though significant effort was made to make the survey as realistic as possible, videotaped driving scenes have limitations in particular with respect to contrast and resolution of picture. The results of the survey were that motorists were more satisfied with retroreflectivity readings greater than 600 mcd/m^2/lux and less satisfied with retroreflectivity readings less than 300 mcd/m^2/lux.

Table 10. Estimated service life by roadway type, pavement marking material, and color for sites without roadway lighting and permanent raised pavement markers, from Migletz et al. (2)

Roadway type	Material	Number of pavement marking lines	Service life in: CTP (million vehicles) Average	Elapsed months Average	Elapsed months Range
WHITE LINES					
Freeway	Thermoplastic	14	7.5	22.6	7.4 - 49.7
	Polyester	2	9.6	20.8	14.7 - 27.0
	Profiled tape	5	6.3	19.6	11.7 - 27.3
	Profiled thermoplastic	7	6.5	18.4	4.7 - 35.6
	Profiled methyl methacrylate	6	7.9	14.0	7.8 - 33.5
	Epoxy	11	2.4	12.8	1.0 - 34.0
	Methyl methacrylate	6	3.7	11.9	6.8 - 17.5
	Waterborne paint	3	3.7	10.4	4.1 - 18.4
Non-freeway ≤40 mi/h	Profiled thermoplastic	1	25.1	55.7	-
	Profiled polyester	1	10.9	45.9	-
	Epoxy	2	4.5	39.4	29.2 - 49.7
	Profiled tape	2	7.6	26.9	22.3 - 31.6
Non-freeway ≥45 mi/h	Epoxy	5	8.8	38.8	26.1 - 56.0
	Profiled tape	4	5.3	37.3	22.9 - 60.0
	Thermoplastic	5	6.0	36.6	26.5 - 49.1
	Profiled methyl methacrylate	3	8.8	34.8	29.9 - 43.2
	Methyl methacrylate	1	3.4	29.3	-
	Polyester	3	2.7	27.4	18.8 - 34.1
	Profiled thermoplastic	6	3.7	24.9	23.8 - 26.2
YELLOW LINES					
Freeway	Polyester	1	11.1	39.7	-
	Profiled tape	3	6.9	25.8	19.6 - 29.8
	Thermoplastic	7	6.1	24.7	11.0 - 41.6
	Profiled thermoplastic	4	5.3	23.5	17.8 - 30.3
	Epoxy	7	4.7	23.2	12.6 - 47-5
	Profiled methyl methacrylate	3	6.2	21.1	18.1 - 24.4
	Methyl methacrylate	3	3.0	15.6	12.6 - 20.3
Non-freeway ≤40 mi/h	Profiled thermoplastic	1	11.4	50.7	-
	Epoxy	2	3.6	43.9	34.7 - 53.1
	Profiled polyester	1	4.7	39.6	-
	Profiled tape	1	3.5	19.6	-
Non-freeway ≥45 mi/h	Polyester	1	9.1	47.9	-
	Epoxy	6	8.9	44.1	35.8 - 57.8
	Profiled tape	3	5.1	38.9	25.4 - 53.4
	Thermoplastic	3	4.5	33.8	26.9 - 39.1
	Profiled methyl methacrylate	2	6.5	31.0	29.1 - 32.8
	Profiled thermoplastic	3	3.9	23.0	22.3 - 24.3
	Methyl methacrylate	1	4.8	20.5	-

Conversion: 1 mi = 1.6 km

2.4.1. Driver Response, Delineation and Safety Effects

Many researchers have hypothesized that if pavement markings are an effective safety treatment for sober drivers, then they should also be effective for impaired drivers. While the literature does not contain any studies which involve the use of crash data to study the effect of markings on impaired driving, several studies have used surrogate measures. These studies usually involve a before-and-after design involving participants driving under both normal and impaired conditions on either a closed road or in a simulator. Often studies on impaired driving consider the possibility that if pavement markings are good, then wider markings may be better.

One of the earlier studies on the effects of edgelines on impaired driving was conducted by Potters Industries (65). Potters Industries felt that edgelines were particularly effective as a safety device for several reasons: they provide a continuous message to the moving driver, they are located in a constant position from the viewpoint of the driver, they are located in an area easily visible to both sober and impaired drivers, and they provide a simple message. Potters Industries (65) used vehicle placement in a lane and vehicle speed as surrogate measures for safety. The explicit assumption made was that more consistent driving down the center of a lane equals safer driving.

Three groups with a total of 16 participants, aged 21 to 28, completed the study, out of an original 24 participants. A between-subject design of placebo (0.00 BAC) and 2 alcohol groups (0.05 and 0.08 BAC) drove a closed road 9.7 miles in length. Each participant drove the closed road twice, once dosed and once undosed. The rural 2-lane roads contained fourteen 2,000-foot sections of different edgeline treatments, although the design actually consisted of drivers driving through 7 of the sections and then returning on the outbound lane, thereby balancing the number of left and right curves. Ten of the sections were classified as “curved” and the other four as “tangent”. The sections were not treated at all or treated with edgelines of 4, 6, or 8 inches in width. The rural roads tested did not have superelevated curves or paved shoulders. Potters Industries (65) collected vehicle lane position and speed data.

Potters Industries (65) was unable to make any conclusions about the effect of edgelines on tangent sections. For both dosed and undosed participants, edgelines had the effect of shifting their positions from the right side of their paths towards the centerline. Participants used less and less of the road, drove within a more narrow width, as the edgeline width increased. Alcohol had the opposite effect of edgelines, causing drivers to use more of the road as the variability in their trajectory increased. Potters Industries (65) concluded “the presence of alcohol tends to increase positional variability, while the presence of edgelines serves to decrease this variability.” Potters Industries (65) did not look at left and right curves separately.

While the effect of widening edgelines on driving behavior has been documented based on field experiment, studies have yet to demonstrate a safety effect (e.g., fewer crashes). Some researchers, such as Hall (66), have argued that wider edgelines have no significant effect on the frequency of crashes.

Johnston (54) has argued that good curve driver performance has not been well-defined. “Is it better, for example, to drive consistently within the center of the lane than to ‘cut the corner’ (without departing from the lane)?” Generally, the most common measures of driver performance are:

- Frequency of lane departures;
- Lane position at fixed points in the curve;
- Mean lane position; and
- Variability of lane position.

Johnston (54) showed that drivers do not follow prescribed paths equal to the curve radius, and argued that “maintaining an average position close to the center of the lane is not obviously good driving”. In other words, Johnston (54) has argued that using lane position and position variability on curves as a performance indicator is flawed, stating, “Drivers generally use a corner-cutting strategy when negotiating horizontal curves, rendering many performance measures used in previous research invalid (54)”. Johnston claims that using a metric which defines good driving as a trajectory through the center of a lane is inappropriate since that is not how people drive. Nonetheless, center of a lane driving is still used by researchers to define good driving. For example, Cottrell (67), and McKnight, McKnight, and Tippetts (68), define “good” performance on curves as driving down the center of the lane. Driving down the center of the lane continues to be used as a performance metric most likely because such driving is expected to reduce sideswipes and run-off-road crashes.

Instead, Johnston proposed using the *instantaneous radius* of the driver’s trajectory to quantify drivers’ performance on curves. Johnston computed the instantaneous radius of the car at each point around a curve using the velocity and acceleration data, and the instantaneous radius was then divided by the geometric radius of the constructed curve to provide a measure of whether the instantaneous radius was above or below the geometric radius. The proportion of ratios less than 1.0 for a given driver on a given curve is the proportion of the curved path for which the driver is in the critical “sharper than geometry phase.”

Johnston cited previous research showing that the point of maximum lateral acceleration is a critical point for control when driving on a curve. Johnston's curve driving performance metric is based on the idea that:

- Higher instantaneous path radii indicates better performance; and
- Path radii below the geometric radii indicate undesirable performance.

Johnston's research also focused on understanding which countermeasures would make the roads safer for impaired drivers. Johnston (54) conducted a controlled experiment at the General Motors-Holden Proving Ground at Lang Lang, which made use of a closed track road. The experimental design, listed in Table 11, was a mixed model factorial design with repeated measures on alcohol and curve geometry. Alcohol and curve geometry were *within* subject tested, while delineation treated was *between* subject tested. Participants were tested on 2 separate nights, once under alcohol-effect and once under a placebo. On each night, participants drove the track twice, once in each direction. The experimental order (the order in which conditions were tested) for alcohol and direction runs were counter-balanced within each delineation treatment. Eighteen nights of experimentation were conducted over 9 weeks, which included the time required to change delineation treatments. Participants were told to treat the track as a normal rural road that they were driving for the first time, "to drive at a safe, comfortable speed". Participants were not told what aspect of their performance would be measured.

Table 11. Experimental design used by Johnston (54).

Number of Levels	Factor	Levels
6	Six curves below 600 m in radius, over a three-km track. Two of the curves were S-curves.	Six-meter-wide sealed pavement with the appearance typical of a minor two-lane road None of the curves was super-elevated
9	Nine types of roadway delineation	No delineation Post-mounted delineators (PMDs) Chevrons 80-mm edgelines 150-mm edgelines PMDs plus 80-mm edgelines PMDs plus 150-mm edgelines Chevrons plus 80 mm-edgelines Chevrons plus 150-mm edgelines
2	Two levels of BAC	zero BAC 0.05% BAC
4	Four participants per delineation type (for a total of 4X9= 36 participants)	All subjects were male and between ages 25 and –56 and regular drinkers
6 × 9 × 2 × 4 = 432 Total trials		

Johnston had two measures: the vehicle's forward speed profile from curve approach to curve exit, and the vehicle's lateral placement profile. Johnston found that curve geometry accounts for the vast majority of performance variance. Therefore, it is important that the same curve be used to compare different performance delineation treatments. Johnston also argued that it is not sufficient to match only for simple geometric features such as radius and length, but approach tangents also had to be included. If the tangents are short, the preceding curves should be included as part of the same curve. In other words, when one curve follows another curve closely, performance on the second curve is strongly influenced by the preceding curve or road section.

Johnston's conclusions on delineation treatments were that chevrons facilitate a corner-cutting strategy. However, chevrons also exacerbate the negative effects of alcohol, which means a greater number of lane encroachments and adoption of more extreme corner-cutting. Wider edgelines tend to offset the adoption of extreme lane positions. Therefore, Johnston concluded that the combination of wide edgelines and chevrons is to "gain the facilitation of corner-cutting without a disbenefit for alcohol-affected drivers."

In general, research has been less conclusive on the effect of edgelines on safety. Willis et al. (56) conducted a before-and-after study involving 600 kilometers of 2-lane rural roads in Great Britain. The roads were selected so that the crash rate (per 100 million vehicle kilometers) "compared favorably" with other 2-lane roads not selected for inclusion in the study. The 3-year before period consisted of roads without edgelines, and the 2-year after period included the same roads with edgelines. In the end, Willis et al. (56) were unable to conclude whether edgelines were a reliable crash prevention measure. A power analysis conducted by Willis et al. (56) showed that the study design was intended to identify safety effects of 20% or greater, which may explain why no conclusion was reached. Whatever the safety effect of markings may be, it is likely to be much smaller than 20%. In a review of the literature, Elvik and Vaa (7) have reported that the majority of road-marking studies have identified relatively small safety effects, in general not greater than +/- 5%, and often are not statistically significant. Significance should be achievable with larger sample sizes, however, no marking or marker research has been conducted to determine how much larger the experiments would need to be.

2.4.2. Climatological Information and Wet Pavement

Climatological data can be obtained from the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html). Information is available on hourly and daily weather patterns (e.g., rainfall and visibility) at a large number of weather stations in the United States. Weather dating back to 1948 is available by individual weather station, each of which can be searched via latitude/longitude, and state/division/county/city, by radar station name/alias (Figure 19). Such climatic data have been previously used by Harwood et al. (64). Harwood et al. have developed a model for estimating wet pavement exposure from available weather records which is presented based on NCDC data. By incorporating weather data into a safety model, the variability due to weather changes from year to year can be separated from the treatment effect, as was done by Migletz et al. (2). The WETTIME developed by Harwood et al. is essentially an expert system containing rules for translating climatological data into time wet-pavement conditions (Table 12). A recent review of available information on the effect of wetness on pavement was conducted by Comfort (69), who concluded that the WETTIME model is useful for general studies and evaluations. The WETTIME model, however, is considered inadequate for predicting or evaluating water build-up for real-time operations, according to Comfort (69).

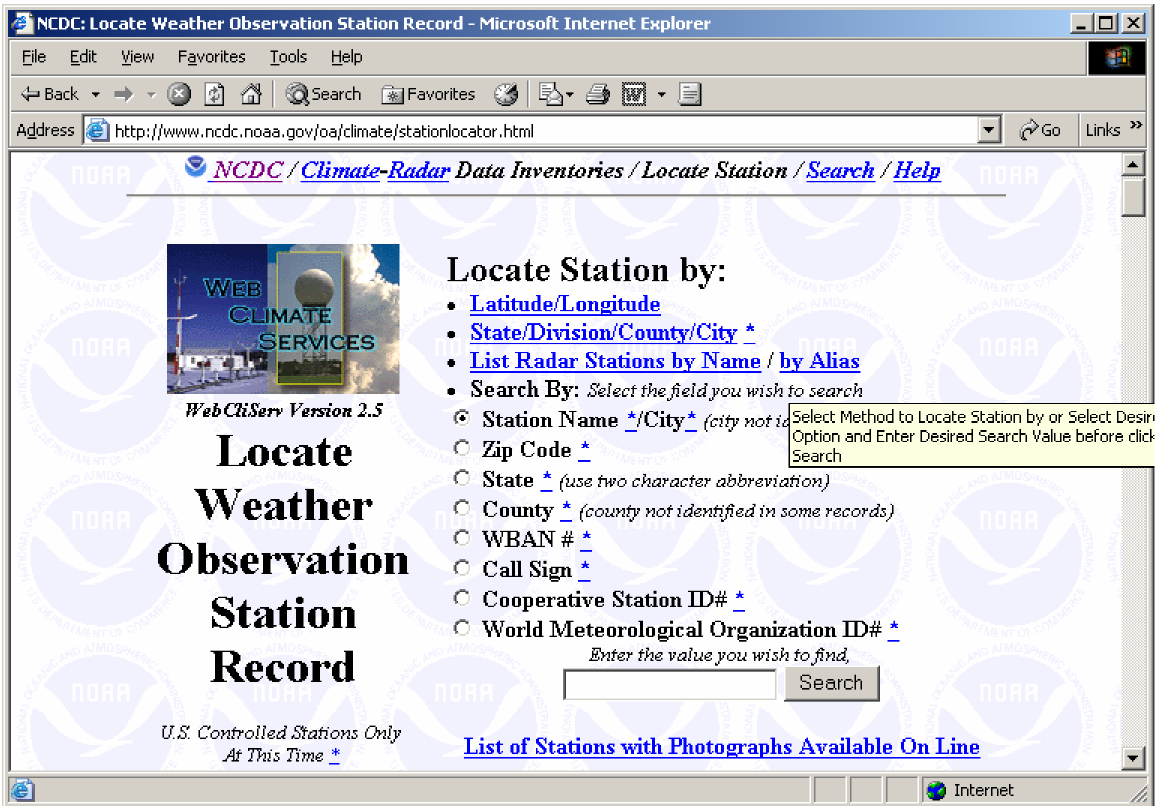


Figure 19. Screenshot of National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html)

Table 12. WETTIME model from Harwood et al. (64)

<table>
<tr><th>National Climatic Data Center Hourly Data</th><th>WETTIME Model Elements</th><th colspan="2">Expert system rules used in WETTIME</th></tr>
<tr><td rowspan="9">Air temperature

Dew point temperature

Relative humidity

Wind speed

Cloud cover

Occurrence of rain, snow, fog</td><td>Minimum level of wetness that reduces pavement surface friction</td><td colspan="2">0.001 inches of water on pavement surface can reduce the friction coefficient by 75%. Minimum level of wetness set at 0.01, smallest NCDC measurable amount</td></tr>
<tr><td rowspan="5">Rainfall intensity and duration</td><td>Hourly Rainfall Amount (in.)</td><td>Duration of Rainfall</td></tr>
<tr><td>0.01</td><td>15</td></tr>
<tr><td>0.02</td><td>30</td></tr>
<tr><td>0.03-0.04</td><td>45</td></tr>
<tr><td>0.05 and over</td><td>60</td></tr>
<tr><td>Pavement drying period following rainfall</td><td colspan="2">Rules based upon temperature, solar radiation, and wind speed. Solar radiation equivalent to a bright, cloudless day, or wind speeds of 1.5 mph or more.</td></tr>
<tr><td>Pavement wetness due to fog</td><td colspan="2">Pavement wetness due to fog occurs only when the NCDC hourly data indicates fog was observed and that the dew point temperature is within 2°F of the ambient air temperature</td></tr>
<tr><td>Estimation of exposure to ice and snow conditions</td><td colspan="2">Frozen precipitation treated as wet pavement exposure</td></tr>
</table>

2.5. State of Art in Materials Research and Development

In addition to using newer, more durable high-performance pavement marking materials, many highway agencies have also started testing and implementing alternative pavement marking application procedures to enhance the visibility of markings. Some of the most popular visibility-enhancing pavement marking application procedures include the use of profiled pavement markings and contrast pavement markings.

2.5.1. Profiled Pavement Markings

Profiled pavement markings have recently become more popular in the southern non-snowplow regions in the United States as a means of providing enhanced visibility under wet conditions at night (10). In Europe, these types of pavement markings are used more frequently, particularly in Belgium, Switzerland, Spain, the Netherlands, Germany, Denmark, France, Sweden, and the United Kingdom (19). Profiled pavement markings are most often constructed using thermoplastics (10), although other materials, such as epoxy, tape, polyester and methyl methacrylate, are also used. Profiled markings are sprayed or extruded onsite to produce an alternating elevated and recessed profile. In the case of profiled tape, the material is manufactured with the elevated and recessed profile. The purpose of this profile is to enhance the retroreflectivity of the marking material under wet conditions, and in cases where the profile pattern is pronounced enough, drivers can feel a rumble effect when driving over the markings. A number of application methods are used for the elevation and recessed pattern. Two of the most popular methods were identified by Gates et al. (10): inverted profile markings created by a cog rolling over fresh wet marking material, giving the line a corrugated appearance, and raised profile markings created by extruding a marking of normal thickness with a raised “bump” at uniform spacing. Filchek et al. (70) described an alternative method of creating profile pavement markings that was tested in Mississippi and Michigan and found to be highly successful when studied with respect to the resilience of pavement markings to winter-maintenance activities and enhanced wet-night retroreflectivity. This third method involves painting longitudinal markings with waterborne paint and glass beads on milled shoulder rumble strips. Filchek et al. (70) concluded that use of milled rumble strips was found to not only enhance the durability of the pavement markings against winter maintenance activities, but also provide improved retroreflectivity. One limitation, however, of Filchek et al. (70) was that the markings on rumble strips were placed further to right of the regular edgeline. This meant that the regular edgeline was potentially exposed to greater traffic wear when compared to the markings on the rumble strips, thus the improved durability and retroreflectivity may also be due to the lateral placement.

2.5.2. Contrast Pavement Markings

For the purposes of improving the visibility of pavement markings on light colored pavements during the day, some highway agencies have applied markings over top of compatible black marking material. In addition, marking materials manufacturers are now producing white preformed tape with black edges to emphasize the contrast. Many concrete and heavily oxidized asphalt pavements are so light in color that during the day, white pavement markings often appear to blend in with the pavement surface (10). These types of markings take advantage of the fact that human vision is tuned to detect edges of contrasting color or brightness. The underlying contrast material is often applied at a greater width than the actual marking (minimum of 1 in.) so that it provides a contrasting border around the marking. Alternatively, longitudinal leading or trailing sections of the black material of at least 12 inches in length can be applied. While contrast markings may be applied using most marking materials, both marking and contrast marking materials must be compatible because the actual marking is placed on top of the black marking. For example, thermoplastic markings cannot be applied over epoxy, polyester, or preformed tape (8).

2.6. Survey of Relevant Practices

This section documents relevant findings from a survey of selected states related to the application of longitudinal pavement markings and markers by their state Departments of Transportation (DOTs). The survey findings are from a 17-state survey conducted in the spring and summer of 2004, as well as the findings of a 29-state survey on the application of Permanent Raised Pavement Markers (PRPMs) carried out in 2002 as part of another NCHRP Project 5-17 (published Report 518) (63).

2.6.1. Installation/Application Policies and Procedures

States extensively use the MUTCD(71) and the FHWA's Roadway Delineation Practices Handbook (72) as guides for the implementation of pavement markings, markers, and other devices for highway delineation. Pavement markers, or more specifically PRPMs, were developed to provide delineation over a wider range of environmental conditions than could be achieved with standard pavement marking materials. Retroreflective PRPMs provide a clear, definitive outline of pavement markings even under adverse visibility conditions such as rain, fog, and darkness (73). As such, PRPMs are sometimes used as supplementary delineation devices in conjunction with pavement markings. Although there are differences in the policies related to the use of pavement markings and markers from state to state, all markings and markers in the United States are required to conform to the MUTCD.

The Roadway Delineation Practices Handbook (74) provides general guidelines and information on pavement marking and PRPM materials, installation, and maintenance procedures. The guidelines also cover the desired layout of PRPMs for various roadway infrastructure elements, and for different roadway types (e.g., curves, intersections, tangents, ramps, etc. on, for example, 2-lane roadways, 4-lane undivided roadways, and 4-lane divided roadways). According to these guidelines, the spacing between consecutive PRPMs on tangents should be 80 ft (24 m); a spacing of 40 ft (12 m) is recommended for horizontal curves between 3 and 15 degrees; and a spacing of 20 ft (6 m) is recommended for curves greater than 15 degrees. The guidelines note that centerline and edgeline PRPMs should not be used together because this may create confusion on some sharp curves (73).

As part of the NCHRP Project 5-17 in order to assess the safety effects of PRPMs and develop guidelines for their use, iTRANS Consulting conducted a survey of 29 states with known PRPM installations in 2002. The survey revealed that most states, in accordance with the guidelines in the MUTCD and Roadway Delineation Practices Handbook, install one 2-way yellow marker on the centerline of 2-lane roadways only. In some states, such as Illinois and Pennsylvania, a group of 2 markers can be used on the centerline of high volume, high speed, 2-lane roads. On divided multi-lane facilities, the most common practice among the states surveyed by iTRANS was to install 1-way white PRPMs on the lane lines only. An exception is New Jersey, where PRPMs are also installed on the left edgelines of multi-lane facilities (73).

In Ohio, Texas, and California, PRPMs are installed non-selectively on all state- maintained highways. Other states, such as Maryland, Massachusetts, Wisconsin, Pennsylvania, Illinois, Indiana and Kansas, have a combination of selective and non-selective implementation policies. PRPMs are implemented non-selectively on certain roadway types, such as freeways, and selectively on other roadway types based on one or a combination of the following parameters (73):

- Roadway type;
- Traffic volume;
- Illumination;
- Safety record;
- Speed limits; and
- Horizontal curves.

For example, Maryland implements PRPMs non-selectively on all Interstate highways and other freeways. Maryland, Massachusetts, and Wisconsin use the speed limit of a roadway as a primary criterion for deciding where to implement PRPMs. In Maryland, PRPMs are implemented on all 2-lane roadways with a speed limit exceeding 45 mph (72 km/h), regardless of traffic volume. In Massachusetts, PRPMs are installed on non-divided roadways with speed limits of 50 mph (80 km/h) or greater. In Wisconsin, PRPMs are installed on all roadways with a speed limit of more than 65 mph (100 km/h), which includes all multi-lane freeway facilities. Missouri, Pennsylvania, and Massachusetts implement PRPMs on all freeways. Michigan’s PRPM guidelines recommend implementation on all freeways without roadway illumination. The criteria for implementation of PRPMs in Illinois, Indiana, and Kansas relate to traffic volume thresholds for different roadway types. PRPMs are only installed on roadways where the Average Daily Traffic (ADT) volumes exceed these thresholds. Table 13 provides a summary of the ADTs thresholds for different roadway types.

Table 13. PRPM guidelines based on traffic volume for Illinois, Indiana, and Kansas

State	Roadway type	
	Rural 2-lane	Multi-lane
Illinois	ADT > 2,500 veh/day	ADT > 10,000 veh/day
Indiana	ADT > 2,500 veh/day	ADT > 6,000 veh/day
Kansas	ADT > 3000 veh/day and TADT > 450 veh/day	

ADT: Average Daily Traffic (both directions)

TADT: Truck Average Daily Traffic

Source: Bahar et al. (63)

2.6.2. Pavement Marking and Marker Management Systems

A survey conducted in 2000 (8) revealed that of the 51 (37 state, 5 provincial, 5 county and 4 city) highway agencies surveyed, only eight maintained pavement marking and marker management systems, with the majority consisting of spreadsheets and database program files. In the recent 2004 17 state survey conducted by iTRANS Consulting, the DOTs in Illinois, Iowa, Kansas, Michigan, Minnesota, Missouri, North Carolina, and Oregon indicated that they maintained pavement marking and marker management systems in electronic format (spreadsheets or database files). Although most state highway agencies also maintain databases that store data such as highway inventories, traffic volumes, and crash history, none of the agencies surveyed links those other databases to its respective pavement marking management system.

The Minnesota DOT, with the help of the FHWA, developed a PMMS. The PMMS provides a pool of data that can be developed and deployed to resolve complex problems facing transportation agencies, and is information technology, which can be viewed as putting in place a system that will allow its users to make data-driven decisions. This form of technology enables agencies to reduce costs by improving efficiency. Minnesota's comprehensive system tracks various data that give insight into the life of pavement markings. The current system tracks:

- Installation-location, date, line, type, and quantity of material;
- Inventory;
- Retroreflectivity;
- Recording of specific action steps;
- Costs-employee, equipment, material; and
- Suppliers.

The Oregon DOT maintains a database of maintenance activities by type of markings, costs of employee, equipment and material, and retroreflectivity readings. The database is reviewed by a pavement marking committee, which includes maintenance staff, striping crew staff, region traffic manager staff, and the traffic devices engineer. This work group meets monthly to share the best practices, with the goal of developing new practices and policies for maintenance and equipment. These initiatives allow a continuous update on the performance of pavement marking materials and products, and a proactive and informed process in making future purchasing decisions.

2.6.3. Performance Measures for Reapplication

Many agencies recognize the value of securing pavement marking and marker inventories that can facilitate the decision-making process for maintaining the long-term performance of pavement markings. However, all the agencies that responded to the 2004 iTRANS survey still rely on a combination of results from on-site inspections by maintenance personnel and simply applying the pavement markings at fixed-time intervals during their routine maintenance process. The on-site inspections typically consist of visual examinations of the markings; for 11of the state highway agencies (Illinois, Iowa, Kansas, Maryland, Minnesota, Missouri, Nevada, New York, Oregon, Pennsylvania, and Texas), the inspections may also include performance-based testing (e.g., retroreflectivity readings) of the pavement markings. In addition, agencies in Kansas, Maryland, Nevada, New York, and Oregon conduct benefit-cost analyses and/or safety analyses to determine whether to restripe their pavement markings. For example, Kansas DOT uses a benefit-cost analysis as one of its performance measures (in addition to on-site inspections and routine restriping schedules) to establish a restriping cycle, while the Maryland and Nevada DOTs use crash records for a similar purpose.

The New York and Oregon DOTs use both benefit-cost and safety performance measures, along with visual inspections, performance-based testing, and fixed-cycle restriping schedules, to maintain long-term pavement marking performance on their highway systems. As Migletz and Graham (8) pointed out, it is important to note that many highway agencies choose to re-apply pavement markings at fixed-time intervals for locations where the use of less durable marking materials (e.g., waterborne paints) is warranted. This is because the relatively low costs associated with the use of these materials far outweigh the resources that would have been required to conduct more vigorous testing, such as performance-based tests, visual inspections, and benefit-cost analyses. These types of tests are normally reserved for sites where durable pavement markings are used. Specifically, for California, the level of maintenance for pavement delineation, according to the state's maintenance manual, indicates that a formal night inspection is completed once each year.

The 2002 PRPM survey by iTRANS showed that the majority of states implement PRPMs at locations with actual or potentially poor safety records. In Maryland, PRPMs are implemented where the crash rate for "correctable" guidance-related crashes is significantly higher than the statewide average on similar road types. In Indiana, site selection for the implementation of PRPMs is based primarily on the need for additional alignment delineation in areas where there is frequent inclement weather (fog, smoke, and rain) and low roadway illumination, with evidence of vehicles leaving the roadway such as excessive wear of pavement markings or excessive skid marks. In Michigan, PRPMs are only installed on non-freeways where there is a concentration of crashes and only after other countermeasures, such as signing, pavement markings, and roadside delineation (e.g., chevrons and post-mounted delineators), have been unsuccessful in improving safety. Illinois and Maryland install PRPMs at horizontal curves where motorists must decrease their travel speed by more than 10 mph (16 km/h) in order to traverse the curve safely (Bahar et al. (75)).

Through a review of state policies and practices, Bahar et al. (75) found that some states implemented PRPMs at other cross-section elements. For example, Illinois installed PRPMs at lane reduction transitions, freeway gores, rural left-turn lanes, and 2-way left-turn lanes. Maryland had detailed standard design drawings for PRPM installations at 1-lane bridges, intersection approaches, 2-way left-turn lanes, left-turn lanes, acceleration lanes, deceleration lanes, and lane transitions.

In response to the iTRANS 2002 state practices survey, some states provided information on their PRPM maintenance practices and policies. Results from that effort revealed that Pennsylvania and Ohio replaced PRPM lenses on a fixed 2-and 3-year cycle, respectively. In general, the replacement cycles in some states depended on the roadway type and traffic volume. An example of the PRPM replacement policy for Indiana is shown in Table 14. Texas's Traffic Operations Manual for Signs and Markings provides guidelines for when to schedule the maintenance of PRPMs based on the results of a nighttime test inspection (Table 15).

The replacement cycle of PRPMs in Texas, based on ADT volumes, is summarized in Table 16. A review of state practices by Bahar et al. (75) found that Colorado and Iowa removed all existing PRPMs and implemented a moratorium on any future installations due to high maintenance costs.

A study conducted by Parker et al. (2002) on behalf of NJDOT found that the California Transportation Institute (Caltrans), where replacement policy is based on the number of missing RPMs, specifies that RPMs should be replaced when 8 or more non-retroreflective RPMs are missing in a 100-foot (30-meter) section, and when 2 successive retroreflective RPMs are missing. The policy used in Florida is similar, specifying replacement if 8 or more consecutive RPMs are missing. In Massachusetts, RPMs are replaced if 30% or more are missing in a section of roadway. On average, Caltrans replaces more than 1.6 million retroreflective and non-retroreflective RPMs annually, while Washington State DOT replaces more than two million RPMs annually.

Table 14. PRPM replacement cycle for Indiana, from Bahar et al. (75)

ADT Vehicular Volumes	Replacement Cycle
2 lanes	
Less than 5,000	4 years
5,000 to 15,000	3 years
Greater than 15,000	2 years
4 or more lanes	
Less than 10,000	4 years
10,000 to 30,000	3 years
30,000 to 75,000	2 years
Greater than 75,000 +	2 years

Note: + These roadways should be inspected at least once each year

Table 15. PRPM system maintenance schedule for Texas, nighttime inspections from Bahar et al. (75)

For Markers Spaced at…	Maintenance Should be Scheduled as Soon as Possible if…
80 ft (24 m)	Fewer than 2 markers are visible
40 ft (12 m)	3 or fewer markers are visible

Table 16. Suggested replacement cycles for raised pavement markers for Texas from Bahar et al. (75)

ADT Vehicular Volumes	Replacement Cycle
Greater than 50,000	1 year
Greater than or equal to 10,000	2-3 years
Less than 10,000	3-4 years

Once the decision to apply pavement markings or install pavement markers has been made, the process is normally carried out in the spring, summer, and fall (late March to November), depending on the location and prevailing climate conditions. Some states, such as Michigan, have narrower timeframes (May to August) to conduct their restriping and reinstallation operations, while states with warmer climates, such as Texas, have the opportunity of doing so year round.

2.6.4. Performance Evaluation

Many highway agencies use a variety of objective and subjective techniques to evaluate the performance of pavement markings and markers. These evaluations are typically carried out before, during, and after the pavement markings are placed as part of an agency's quality control program (8).

Performance measurements conducted before the application of pavement markings and markers include tests on the marking materials and the various components of the markers (such as the lens and casing) to ensure they are qualified to provide long-term performance. Such testing is done either in-house or by accepting results from national test laboratories, such as NTPEP. Once the pavement markings and markers have been applied, a variety of objective and/or subjective evaluations are conducted to ensure that they are performing as expected.

The majority of state respondents indicated that they take dry retroreflectivity readings, and very few respondents cited that they take wet retroreflectivity readings. To establish the retroreflectivity readings, the states use a range of equipment to meet their needs. Subjective ratings seemed less common in practice; pavement-marking durability was the evaluation stated most often. Table 17 provides a summary of the evaluation techniques used by the 17 states surveyed in 2004 to assess the performance of pavement markings and markers. There was also a range of minimum retroreflectivity requirements, confirming that a nationwide practice does not exist. Table 18 summarizes the performance-based specifications for the 17 states surveyed.

The greatest variance in state responses centered on the question about each agency's pavement marking and marker installation and maintenance budget. The significant range for pavement markings lies between $250,000 and $17,000,000. For pavement markers, the range is slightly less but equally significant at between $50,000 and $4,500,000.

Table 17. Summary of objective and subjective evaluations of pavement markings

Evaluation Methods		CA	IL	IA	KA	MD	MI	MN	MO	NV	NJ	NY	NC	OH	OR	PA	TX	UT
		States Surveyed																
Objective Evaluations using a Retroreflectometer																		
Dry retroreflectivity measurement of pavement markings		✔		✔	✔	✔	✔	✔	✔	✔	N/A	✔	✔	N/A	✔	✔	N/A	N/A
Wet retroreflectivity measurement of pavement markings		✔				✔					N/A			N/A			N/A	N/A
Luminance contrast ratio[1]								✔			N/A			N/A			N/A	N/A
Model of retroreflectometer used[2]:	Laserlux Van			✔				✔	✔		N/A			N/A			N/A	N/A
	LTL 2000	✔		✔	✔	✔		✔				✔	✔					
	LTL-X			✔		✔		✔		✔			✔					
	Mirolux					✔			✔						✔			
	MX-30				✔													
	Unspecified model						✔			✔						✔		
Subjective Evaluations																		
Dry measurement of pavement markings (e.g., using a 10-point scale)						✔		✔	✔		N/A	✔		N/A			N/A	N/A
Wet measurement of pavement markings (e.g., using a 10-point scale)						✔					N/A			N/A			N/A	N/A
Bead retention[3]			✔			✔					N/A	✔		N/A			N/A	N/A
Use of pocket microscope[4]						✔		✔			N/A	✔		N/A		✔	N/A	N/A
Pavement marking durability[5]			✔		✔	✔		✔	✔		N/A	✔		N/A		✔	N/A	N/A
Pavement marking color[6]			✔		✔	✔					N/A	✔		N/A			N/A	N/A

Note: N/A – Information not provided

1 - The relative difference in retroreflectivity between markings and the adjacent pavement surface.

2 - Some state DOTs allow the use of any 30-m geometry retroreflectometers on their respective qualified products lists.

3 - Use of sunlight-shadow techniques with a pass or fail rating.

4 - To conduct microscopic evaluation of bead distribution, embedment, and damage.

5 - Percentage of material remaining, typically using a 10-point scale for ratings.

6 - Use of color tolerance chart of standard colors and a 10-point scale for ratings.

Table 18. Minimum pavement marking retroreflectivity specifications

Type of Line	Standard Color of Line	Material Type	Minimum Retroreflectivity Requirements ($mcd/m^2/lux$)[1]																
			CA	IL[2]	IA	KA	MD	MI	MN	MO	NV	NJ	NY[3]	NC	OH	OR[4]	PA[5]	TX	UT
Centerline	Yellow	Paint	-		200 (100)	- (100)	150	- (140-160)	180 (80)	225	275 (125)	N/A	N/A	-	N/A	-	200 (175)	175	N/A
		Thermoplastic	150		-	275 (100)	150	- (140-160)	500 (80)	225	-	N/A	N/A	250 (100-150)	N/A	200 (125)	250 (200)	250	N/A
		Epoxy	150		-	275 (100)	-	-	200 (80)	225	275 (125)	N/A	N/A	250	N/A	200 (125)	250 (175)	-	N/A
Edgeline	Yellow	Paint	-		200 (100)	- (100)	150	- (130-165)	180 (80)	225	275 (125)	N/A	N/A	-	N/A	-	200 (175)	175	N/A
		Thermoplastic	150		-	275 (100)	150	- (130-165)	500 (80)	225	-	N/A	N/A	250 (100-150)	N/A	200 (125)	250 (200)	125	N/A
		Epoxy	150		-	275 (100)	-	-	200 (80)	225	275 (125)	N/A	N/A	250	N/A	200 (125)	250 (175)	-	N/A
	White	Paint	-		300 (150)	- (150)	250	- (220-270)	180 (80)	300	375 (175)	N/A	N/A	-	N/A	-	250 (175)	-	N/A
		Thermoplastic	250		-	- (150)	250	- (220-270)	500 (80)	300	-	N/A	N/A	375 (150)	N/A	250 (150)	300 (250)	-	N/A
Lane Line/Skip Lines	White	Paint	-		300 (150)	- (150)	250	- (240-260)	275 (100)	300	375 (175)	N/A	N/A	-	N/A	-	250 (175)	-	N/A
		Thermoplastic	250		-	325 (150)	250	- (240-260)	700 (100)	300	-	N/A	N/A	375 (100-150)	N/A	250 (150)	300 (250)	-	N/A
		Epoxy	250		-	325 (150)	-	-	300 (100)	300	375 (175)	N/A	N/A	375	N/A	250 (150)	300 (225)	-	N/A

Note:

1 - Minimum initial retroreflectivity specifications are shown; minimum in-service or acceptance retroreflectivity specifications are in parentheses.

2 - Illinois minimum retroreflectivity readings were provided in units not comparable to values shown in this table.

3 - NYDOT has established minimum retroreflectivity requirements for laboratory testing purposes only. Values not provided.

4 - Minimum in-service retroreflectivity specifications for Oregon are valid during specified warranty period for each marking material. ODOT uses Methyl Methcrylate instead of Epoxy.Thermoplastic which has three-year warranty period; Methyl Methacrylate has four-year warranty period.

5 - Minimum in-service retroreflectivity specifications for Pennsylvania have to be met at the end of a specified period of time after application for each material type. The duration is 90 days for paint, 180 days for Thermoplastic and Epoxy.

Discussions with industry experts and NTPEP RPM panel members indicated that few state highway agencies collect retroreflectivity data for pavement markers. This may be due to several reasons, including a lack of resources to collect the data and the need for special retroreflectometers that are restricted to measuring retroreflectivity of pavement markers only. Further, proposed minimum retroreflectivity standards by the FHWA are for pavement markings only. Although they take into account the presence or absence of pavement markers (as described in the following section), they do not specify minimum retroreflectivity thresholds for the markers themselves. Consequently, the collection of retroreflectivity data of pavement markers may not be a priority for many highway agencies.

2.6.4.1. Performance-Based Specifications

In recognition of the possibility of federal guidelines for minimum retroreflectivity standards for pavement markings, several state highway agencies have introduced their own minimum retroreflectivity specifications.

Draft minimum retroreflectivity guidelines introduced by the FHWA and similar guidelines recommended by state, county and city highway agencies in workshops sponsored by the FHWA are shown in Table 19 and Table 20. The performance-based specifications introduced by the state highway agencies all exceed draft federal guidelines. There are no proposed minimum retroreflectivity standards for pavement markers.

Material specifications directly affect the performance of markings and markers. For every construction/maintenance contract, material specifications form a part of the tender document. An example from California is cited below:

- Thermoplastic traffic stripes (traffic lines) and pavement markings shall be applied to conform with provisions in Section 84, “Traffic Stripes and Pavement Markings,” of the Standard Specification and these special provisions.
- Retroreflectivity of the thermoplastic traffic stripes and pavement markings shall conform to the requirements in ASTM Designation: D6359-99. White thermoplastic traffic stripes and pavement markings shall have a minimum initial retroreflectivity of 250 mcd/m^2/lux.
- Yellow thermoplastic traffic stripes and pavement markings shall have a minimum initial retroreflectivity of 150 mcd/m^2/lux.

The installation specifications affect the performance of the materials. For example, California specifies weather conditions (range of temperature and humidity) when striping should be conducted to achieve maximum service life. For markings, the temperature and humidity varies depending on the type of paint, while for markers, it varies with the type of adhesive used.

Minnesota has specifications for different pavement marking material. For example, the epoxy resin pavement marking specifications include the following information:

- Contractor qualifications;
- Material classifications (Type I or Type II);
- Epoxy and bead requirements (e.g., color, adhesion capabilities, abrasion resistance, hardness, tensile strength, and shelf life);
- Application and equipment procedures;
- Sampling rate and procedures;
- Certifications; and
- Acceptance of pavement markings (retroreflectivity).

Table 19. Minimum in-service retroreflectivity guidelines for pavement marking materials recommended by the FHWA (mcd/m²/lux)

	Speed Classification[a]			
		Non-Freeway	Non-Freeway	Freeway
	Option 1	≤40 mph	≥45 mph	≥55 mph
	Option 2	≤40 mph	≥45 mph	≥60 mph >10,000 ADT
Material	Option 3	≤40 mph	45–55 mph	≥60 mph
White		85	100	150
White with/RRPMs[b]		30	35	70
Yellow		55	65	100
Yellow with/RRPMs[b]		30	35	70

Note:
a - Retroreflectivity values are measured at 30-m (98.4-ft) geometry.
b - Levels of retroreflectivity for the material classifications “White with RRPMs” and “Yellow with RRPMs” are for roads with supplemental delineation aids, retroreflective raised pavement markers (RRPMs), and/or roadway lighting.

Source: Adapted from Migletz and Graham (8)

Table 20. Minimum in-service retroreflectivity guidelines for pavement marking materials recommended by state, county, and city agencies (mcd/m^2/lux)

Material	Speed Classification[a,b]		
	Local and Minor Collector 48.3 km/h (30 mph)	Major Collector and Arterial 56.3–80.5 km/h (35–50 mph)	Highways, Freeways and All Roads 88.5 km/h (55 mph)
White	Presence[c]	80	100
Yellow	Presence[c]	65	80

Note: 1 mph = 1.61 km/h.
a – Retroreflectivity values are measured at 30-m (98.4-ft) geometry.
b - Roads without RRPMs or roadway lighting.
c - Presence is a pavement marking visible at night, but with no retroreflectivity value.

Source: Adapted from Migletz and Graham (8)

2.6.4.2. Material Purchasing Policies

To produce functional, long-life pavement markings, it is essential that agencies use quality controlled materials and well-trained operators. To minimize application failures, some agencies develop approved product lists before a bidding process. For example, Minnesota's inventory lists the manufacturer, product name, and approval date, while California's inventory lists the manufacturer, model number, color, and dimension details where available.

In California, the contractor is responsible for ensuring that a Certificate of Compliance is provided by the manufacturer of all products on the list of Prequalified and Tested Delineation Materials. Materials and products may be added to the list in accordance with Caltrans procedures, which require that:

- The manufacturer submit a New Product Information Form;
- Sufficient samples are submitted to permit performance tests; and
- Compliance with Caltrans specifications be made to gain approval of materials or products.

2.7. Summary of the Relevant Findings from the Literature Review

There are agencies that operate a pavement management system (PMS), which incorporates pavement markings and markers as a minor item in a very large structure, but very few agencies have implemented an exclusive pavement markings and marker system (PMMS). Typical criteria used to evaluate the cost-effectiveness of pavement markings include: durability, retroreflectivity, and cost. Cost can become a critical factor when selecting pavement marking materials for installation. As a result, preventive maintenance and good budget planning become essential. Some state agencies have developed or integrated decision-making tools that assist in evaluating the multiple criteria regarding the life and serviceability of a pavement marking.

Pavement markings are considered by many to be a minor maintenance treatment (76) and as a result are not regarded as an integral part of many pavement management systems. Numerous reports that deal with pavement management systems (77,78,79,80,81), however are often too macro and give no additional insight into the area of pavement markings and markers. They illustrate that there is a need to improve the current management systems and promote the important role of markings in an adequate pavement management system.

Conventional paint (waterborne) is traditionally the least expensive pavement marking material when incorporating only material and installation costs in the life-cycle cost analysis. However, several other factors can have an impact on the economics of pavement markings, such as extent of inconvenience experienced by the traveling public during marking installation (cost of delay), tort liability, quality and extensiveness of installation, and cost of life of road users and work crews. As a result, more durable markings can become the most beneficial material alternative. A benefit-cost analysis incorporating all the aforementioned factors should assist in determining the true cost-effectiveness of the selected marking materials.

In the literature safety impacts of the visibility of markings and the number of crashes were limited in their documentation; but there were two specific studies that examined this relationship (30,82). One of the key difficulties identified in comparing visibility to the number of crashes is separating any seasonal effects from the delineation effects.

A thorough analysis of edgelines using a before-and-after methodology, where specific control locations were selected so the crash rates were directly comparable to other similar road types, concluded that crashes actually increased on curves after edgelining and that the effect of markings was dependant on curve radii (60). Another study (61) found that centerline and no-passing zone markings actually increased the amount of crashes on low-volume roads. A similar research study (63) found that the use of snowplowable pavement markers yielded the same results as the edgeline and centerline pavement markings.

Pavement markings are unlike many other engineering safety treatments in that the treatment is continuously changing. The nighttime retroreflectivity of markings drop over time and can be estimated by data collected by NTPEP based on their field test site. Agencies tend to specify levels of minimum retroreflectivity standards two ways: by recognizing that increased retroreflectivity equals increased visibility for drivers under nighttime conditions, and that increased visibility equals increased safety for road users. While the first assumption has been validated by field data, with visibility being defined as detection distance, increased detection distance has not always meant an increase in safety, especially for roads with lower design standards. The key to understanding the safety impact of marking delineation is to understand the interaction between driver response, delineation, road geometry, and traffic volumes.

The MUTCD provides guidance on the application of longitudinal pavement markings in terms of the color, width and patterns of the markings based on type of street or highway, travel width, and traffic volume (ADT). In addition to the requirements outlined in the MUTCD, many U.S. highway agencies also use internal guidelines to aid in the selection of pavement marking materials. These guidelines typically take into account factors such as pavement type, pavement age, service life, (or future reconstruction), pavement condition, whether or not the roadway is a bridge, and whether or not the stretch of roadway to be marked is in a snow-removal area. Although there is a wide variety of pavement marking materials on the market, in common practice not all existing types of pavement markings are equally used. The most common marking materials are waterborne paint, thermoplastic, and epoxy, which account for more than 80% of all existing marking materials in common use by total road mileage. Given the need for highly trained work crews and specialized equipment to apply the newer durable marking materials, many highway agencies are using private contractors to apply pavement markings and implementing performance-based and warranty provision specifications for the purpose of quality control. Furthering the use of newer marking materials, many agencies now determine their true life-cycle cost to properly evaluate the performance of marking materials using both objective and subjective evaluation methods. In addition, some agencies are investigating different methods of application, such as painting stripes over milled rumble strips, and using profiled markings and contrast markings.

3. Chapter 3 Study Methodology

This chapter presents the study methodology for *correlating the safety impact of pavement markings and markers with their retroreflectivity.* The methodology is based upon time-series approach as opposed to the traditional before-after design. This research study is not the first one designed to address the safety and cost effectiveness of pavement markings and markers, however previous studies have often been inconclusive on several key questions.

3.1. Vision of the Research Study

The overall vision of this research study is to provide agencies with the ability to make informed decisions regarding the use of pavement marking materials and markers, including their maintenance/construction activities based on the safety impacts and cost-effectiveness of different pavement marking and marker management policies. In this report, pavement markings (and materials) and markers refer to those in common use for longitudinal delineation of all road types.

A review of the literature has determined that the primary research gap concerning pavement markings and markers is a study of the relationship between *safety* and *visibility*. Safety is defined here as the number of crashes by severity (e.g., fatal, nonfatal injury, property damage only) per unit of time and distance during non-daylight conditions. Visibility at night is defined here as the retroreflectivity of the delineation. This research study did not explore the daytime relationship between safety and visibility.

The relationships between visibility, driver *performance* and driver *preference* have been studied (33,83,16,84,55). Previous research has also reviewed the overall safety effect of newly installed pavement markings (85,58,86,54,61,60) and markers (63,87,88,89,90). However, underlying previous studies of the overall safety effect of a marking or marker was the assumption that the visibility of markings and markers is constant throughout the evaluation period. Unfortunately, the reality is that the visibility of markers and markings degrades over time. As a result, t*he quantitative relationship between visibility and safety has yet to be determined*. In other words the question is, how do different levels of visibility of markings and markers affect the safety of highways?

Understanding the relationship between visibility and safety is important in:

- Establishing guidelines for the use of pavement marking material and markers; and
- Setting minimum retroreflectivity guidelines for pavement markings and markers.

Previous research that examined the relationship between visibility and safety has been inconclusive (1), or has failed to adequately address issues such as seasonality and the non-linearity of traffic data (30). Currently, recommended minimum retroreflectivity guidelines are based on driver performance and driver preference responses that were measured in the field or during simulator studies (29). Superior recommendations and guidelines for their use will be achieved when a cost analysis of pavement marking and markers include their safety effects. A comprehensive cost analysis requires a *formalized structure* which takes into account total costs and total benefits for assessing the effectiveness of markings and markers. The following variables have been included in the study methodology:

- **Road Type:**
    - Multi-lane freeways
    - Multi-lane highways
    - Two-lane highways
- **Time of Day:**
    - Non-daylight crashes (nighttime crashes, which includes dawn and dusk)
- **Crash Type:**
    - Non-intersection crashes
- **Crash Severity:**
    - All crashes combined (total)
    - Fatal and nonfatal injury crashes
- **Pavement Markings and Markers:**
    - Markings only
    - Markings and Markers
- **Pavement:**
    - Surface material type
- **Climate Region:**
    - As a function of precipitation and temperature
- **Snow Removal:**
    - Historical snowfall is used as a proxy measure for the amount of snow removal
- **Traffic Volume:**
    - Full range of traffic volumes by road type
    - By AADT bin ranges

The previous variables define the scope of the study. No distinction was made between roads based upon environment (rural or urban), roadway geometry (tangent or curve), or whether the surface condition (wet or dry). The analysis focused on retroreflectivity and its effect on non-daylight crashes at non-intersection locations.

3.2. Methodology Outline

The methodology adopted has five major steps. The first two steps involve data collection and preparation. The third step involves modeling the retroreflectivity of pavement markings and markers over time under different conditions. Using the resulting models, the fourth step allows all different markings and all different markers to be compared in terms of their retroreflectivity profiles over time. In the fifth step, the retroreflectivity profiles over time and the number of crashes by severity over time are analyzed in concert to determine the relationship between retroreflectivity of longitudinal markings and markers and crashes. In order to separate the cyclic pavement marking and marker safety effect from the seasonal effect, separate seasonal effect multipliers are estimated, where a constant seasonal effect for all roads of the same type is assumed. The full range of experimental conditions is shown in Figure 20.

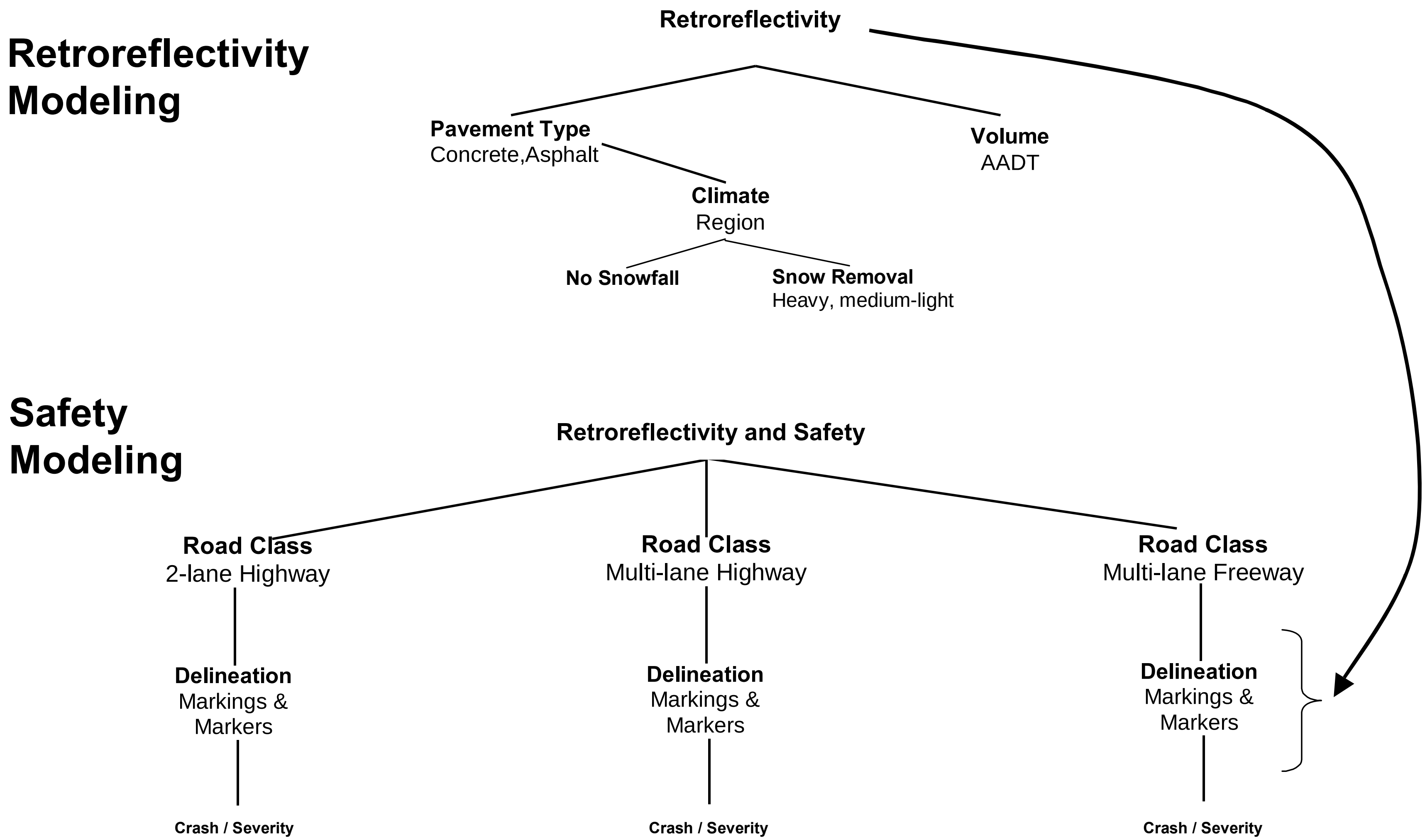


Figure 20. Full range of experimental conditions

3.3. Study Enhanced Methodology

There are three features of this research methodology that expands on what has been previously accomplished:

- The focus is on determining the direct relationship between retroreflectivity and crash frequency and severity (safety);
- The focus is on most materials in common use; and
- The focus is on the change in safety over time.

These three features of this study methodology are discussed in detail in the following sections.

3.3.1. Focus on the Relationship Between Visibility and Safety

Pavement markings and markers are unlike many other engineering safety treatments in that the treatment is continuously changing over time. Most treatments remain unchanged over time (for example, installing a dedicated left turn lane to deal with rear-end crashes). In contrast, pavement markings and markers change in a measurable/quantifiable way from the date of installation. The non-daylight retroreflectivity visibility of pavement markings and markers degrades over time as the markings and markers separate from and are worn off the pavement. This change in the condition of the markings and markers may affect their safety performance.

In addition, markings and markers are remarked on a regular basis whereas many other engineering treatments require little to no regular maintenance. Waterborne paint, for example, in many jurisdictions is remarked on a yearly basis, which results in a cyclic pattern for the retroreflectivity of the markings and markers. Other markings follow different cyclic patterns.

Nearly all variants of the before-after research design assume that the safety effect of a treatment remains constant during each time period. Because of this assumption, the safety of markings and markers as a function of visibility cannot be assessed using a traditional before-after design if time is not taken into account. Most previous studies have used the before-after design without including the changing performance of the markings and markers over time as a factor.

3.3.2. Focus upon Materials in Common Use

Not all types of pavement marking materials and markers are used to the same extent (Section 2.1). The most commonly-used marking material is waterborne paint which is applied on 65% of total road mileage in the U.S. Thermoplastic is second accounting for about 25% of total road mileage based upon industry panel sources (91). This research study focuses upon materials in common use. This focus optimizes the research design toward the application of the findings by the transportation agencies.

3.3.3. Focus on Safety Over Time

Hauer et al. (92) provide an example of research which examines changes in safety as a function of time, specifically the effect of resurfacing on safety. Hauer et al. (92) conducted a before-after study with the specific intent of understanding the effect of resurfacing on safety *over time*. Therefore, it is of critical importance to know *when* the treatment has occurred. Knowing when the treatment occurred would be important for the before period, the after period, or for any comparison sites, since the treatment is the variable of interest. In the Hauer et al. (92) study, only the date of the pavement resurfacing for the after period of the study was known, while the before period resurfacing date was unknown. Post-analysis, Hauer et al. (92) discussed their study design:

> *"There is one deficiency that became apparent only after the analysis was completed. The results indicate that as the pavement ages accidents diminish. Because all treated road sections were resurfaced within 1 year of each other* [treatment]*, their pavements must have been deteriorating approximately in tandem; they were all in need of repair just before resurfacing and in good shape 5 to 7 years earlier. If so there is a systematic factor that the analysis in Step 1* [estimating the expected number of accidents] *neglected. The net effect of this deficiency is that prediction of what would be expected without resurfacing has been produced as if a constant pavement condition prevailed during the entire before-resurfacing period." Hauer et al. (92) p37*

Hauer et al. (92) called the overlooking of the date of the treatment (resurfacing) during the before period a "logical deficiency". This type of logical deficiency is not limited to Hauer et al. (92) as both Migletz et al. (2) and Cottrell and Hanson (3) did not obtain or did not use the date of restriping in their analysis of the before period. In order to avoid this logical deficiency, the proposed design requires that it is necessary to know when striping has occurred for all time periods, and for all roads. Only by using the age of markings in an analysis of pavement markings can the relationship between restriping and safety be understood.

3.4. Methodology for Modeling Retroreflectivity

Since retroreflectivity measurements of pavement markings and markers are not usually conducted by state agencies in a systematic manner, it is not possible to attain observed retroreflectivity values when studying historical crash data for any particular locations. Therefore, there is a need to develop such models of retroreflectivity in order to estimate how retroreflectivity changes with time and road use. Retroreflectivity is used as a common metric to compare performance across material types, and where two materials result with the same retroreflectivity, these are assumed to have the same safety effect. As discussed in the literature review (Section 2.2.3), the National Transportation Product Evaluation founded in 1994 has been collecting retroreflectivity data from trafficked roads at test decks in various states. The retroreflectivity models based upon NTPEP data were developed by following top-down approach:

1. Examine the variables affecting retroreflectivity starting with the variable with the largest influence proceeding with the next most important variable to the variable with the smallest influence, based upon the test deck data available. So for example, the variable with the largest effect on retroreflectivity is age, and the second largest effect is color.
2. By setting on the largest effect variable, based upon graphs and model residuals, determine the most appropriate model form describing the relationship between the variable and retroreflectivity. Calibrate the model parameters to optimize the fit to the average retroreflectivity value for the data.
3. Once the most appropriate model form has been identified, subdivide the data by the next largest variable affecting retroreflectivity. So for example, after fitting a model as a function of marking age, the next models to fit would be for white and yellow markings over time.
4. Based upon graphs and model residuals determine the most appropriate model form for the data subset, and calibrate the model to optimize the fit.
5. If the subset model form is the same as the parent category, and the residuals show no pattern, collapse the subset variable data into one model. So if there is no pattern to the residuals for models of retroreflectivity collected on asphalt compared to concrete, for example, then the same model form is adopted for both types of pavement surface.
6. Repeat this analysis for each variable affecting retroreflectivity.

Once the retroreflectivity models are complete, they need to be linked to roadway and crash data in order to examine the relationship between safety and retroreflectivity as described in the next section.

3.5. Methodology for Examining the Relationship Between Safety and Retroreflectivity

As described, the methodology aims to quantify the relationship between the retroreflectivity of markings and markers and non-daylight, non-intersection crashes by severity (target crashes). The most likely cause-effect scenario is that pavement markings and markers affect perception and thereby may affect the probability of target crash occurrence and/or of crash severity (if perception affects speed choice).

From the time when a marking is freshly painted or a new marker installed, retroreflectivity (denoted as R) diminishes until new markings or markers are installed. This cyclical pattern of decline and restoration of R may be reflected in the corresponding time-series of reported non-daylight crash counts. In order to analyze the relationship between crashes and safety, the concept of retroreflectivity bins is introduced where there are 'n' retroreflectivity bins i=1, 2, ..., n. Thus, for example, i=1 when R>250, i=2 when 200<R≤250, i=3 when 150<R≤200 and i=4 when R≤150. In this example, n=4. On this basis there are n m*ultipliers* q_i , i=1, 2, ..., n. If a marking with R in category i reduces the probability of reported non-daylight crash occurrence relative to markings in category n by 5%, q_i /q_n=0.95; if the marking with R in category i increases the probability of target crash occurrence relative to markings in category n by 4%, q_i/q_n will be 1.04. This research study aims to estimate the magnitude of q_i, i=1, 2, ..., n and, if appropriate, fit a smooth function to these estimates. In other words, this research aims to estimate the magnitude of these multipliers as a function of the retroreflectivity of the pavement markings and markers over time.

Thus, data for the safety modeling of R will be in the form of:

- The monthly count of reported non-daylight, non-intersection crashes on roads segments;
- The dates of remarking without resurfacing for same roads; and
- A model that predicts R on these roads for each calendar month (based on models built from NTPEP data).

Data from several sources (Chapter 4) will be entered into a large database. Each row in this database corresponds to one road segment that all its attributes are the same and the markings were painted on the same calendar month, thus have the same R. That is, it has been remarked as a unit by the same materials and has the same traits that influence R. These are named "homogeneous segments" (Section 3.6). Thus, should it turn out in the course of modeling the relationship between R and safety, that, e.g., pavement surface type and AADT do not materially affect R, there is no need to discontinue a segment when pavement surface type or AADT change, and homogeneous segments will be redefined accordingly.

As an example consider apportioning retroreflectivity into one of four bin ranges as shown in Table 21. For a specific homogeneous segment, the monthly target crash counts for, say, the years 1998, 1999 and 2000 are grouped (Table 22), and indexed by year and month so that for January 1998 y=1, m=1 and for December 2000 y=3 and m=12. Assuming that this road segment has been remarked in May 1998, July 1999 and July 2000, the month of remarking will be indexed "0" and subsequent months as a (a=0,1,…A). Based on 'a' (and other traits of the road segment), and using the retroreflectivity model (Section 3.4), one can compute the estimated retroreflectivity R in year y and month m after each remarking ($R_{y,m}$)

Table 21. Example retroreflectivity bin ranges and numbers

Retroreflectivity Range	Retroreflectivity Bin Number
$R_{white}>300$	1
$250<R_{white}\leq300$	2
$200<R_{white}\leq250$	3
$R_{white}\leq200$	4

Table 22. Illustration of retroreflectivity table for analysis (months of remarking in bold)

Year	**Month**	**M**	**A**	$R_{y,m}$	**i Retroreflectivity Bin**	**Target Crash Counts**
1998	Jan	1	7	386	1	0
	Feb	2	8	335	1	3
	Mar	3	9	295	2	0
	Apr	4	10	264	2	1
	May	**5**	**0**	**386**	**1**	**1**
	Jun	6	1	335	1	0
	Jul	7	2	295	2	1
	Aug	8	3	264	2	1
	Sep	9	4	239	3	0
	Oct	10	5	218	3	1
	Nov	11	6	200	4	1
	Dec	12	7	186	4	2
1999	Jan	1	8	173	4	0
	Feb	2	9	162	4	2
	Mar	3	10	152	4	2
	Apr	4	11	143	4	3
	May	5	12	135	4	2
	Jun	6	13	129	4	2
	Jul	**7**	**0**	**386**	**1**	**0**
	Aug	8	1	335	1	3
	Sep	9	2	295	2	2
	Oct	10	3	264	2	1
	Nov	11	4	239	3	1
	Dec	12	5	218	3	3
2000	Jan	1	6	200	4	2
	Feb	2	7	186	4	3
	Mar	3	8	173	4	3
	Apr	4	9	162	4	0
	May	5	10	152	4	0
	Jun	6	11	143	4	3
	Jul	**7**	**0**	**386**	**1**	**1**
	Aug	8	1	335	1	3
	Sep	9	2	295	2	2
	Oct	10	3	264	2	0
	Nov	11	4	239	3	1
	Dec	12	5	218	3	1

It is assumed that each crash count (rightmost column in Table 22) is a realization of a Poisson random variable the mean of which is $\mu_{y,\,m,\,i}$ to indicate that it varies as a function of Year (y), Month of Year (m), and the retroreflectivity in bin 'i'. More specifically, it is assumed that $\mu_{y,\,m,\,i}$ can be represented as a product of three elements:

> $\boldsymbol{\mu_y}$ which represents how the annual mean number of target crashes for the road segment would change from year to year (because of changes in annual AADT, vehicle fleet, driver demography, annual precipitation etc.) if retroreflectivity was that of category 'n'.
>
> $\mathbf{p_m}$ which is the typical seasonal monthly proportion of yearly target crashes on the road segment (such that $\sum_{m=1}^{12} p_m = 1$) and represents the typical within-year variations in traffic, precipitation, kind of road use and condition.
>
> $\mathbf{q_i}$ which is the aforementioned multiplier representing the influence of retroreflectivity in bin i. As illustrated in Table 21, the retroreflectivity prevailing in year y and month m ($R_{y,m}$) determines the retroreflectivity bin. Since q_i changes with y and m, the notation $q_i(y,m)$ will be used.

Thus, the expected number of crashes in year y and month m in which the retroreflectivity is in bin 'i' is:

$$\boldsymbol{\mu}_{\mathbf{y,m,i}} = \boldsymbol{\mu}_{\mathrm{y}} \times \mathbf{p_m} \times \mathbf{q_i(y,m)} \qquad \textit{Equation 3}$$

For a road segment for which there are, for example, three years of data, there are three unknown values of μ_y, 11 unknown values of p_m, and n unknown values of q_i. For the road segment in Table 22, there are 36 crash counts. It is assumed that the unknown seasonal monthly proportions (p_m), and marking effect multipliers (q_i) are common to all road segments of the same kind (2-lane highways, etc). Thus, every additional road segment adds Y unknown μ_y's (depending on the number of years, Y) and 12×Y data points. Therefore, it is evident that estimation by least square or by maximizing likelihood would be feasible even if no model for μ_y is carried out.

The likelihood function can be derived as follows. Let $c_{y,m}$ the count of target crashes in year y and month m. By the Poisson assumption:

$$P(c_{1,1}, c_{1,2}, \ldots, c_{1,12}, \ldots, c_{Y,1}, c_{Y,2}, \ldots, c_{Y,12}) = \prod_{y=1}^{Y} \prod_{m=1}^{12} \frac{\mu_{y,m,i}^{\;c_{y,m}}}{c_{y,m}!} e^{-\mu_{y,m,i}}$$

Equation 4

Viewing this as the likelihood component for one road segment, and omitting the constant $c_{y,m}!$, the natural logarithm is:

$$\sum_{y=1}^{Y} \sum_{m=1}^{12} \mathbf{c_{y,m} \ln \mu_{y,m,i} - \mu_{y,m,i}} = \sum_{y=1}^{Y} \sum_{m=1}^{12} \mathbf{[c_{y,m}(\ln \mu_y + \ln p_m + \ln q_i(y,m)) - (\mu_y p_m q_i(y,m))]}$$

Equation 5

This study is interested in the estimated values of the multipliers q_i. The estimates of μ_y and p_m are of no direct interest - they are nuisance parameters. Therefore, it is advantageous to take the μ_y out of estimation by assuming that $\mu_y = \sum_{m=1}^{12} c_{y,m}$.

The methodology for determining the relationship between retroreflectivity and crashes involves maximizing Equation 5. Equation 5 is the maximum likelihood function and it can be solved by selecting values for the parameters u_y, p_m, q_r, which maximize the function. These values that maximize the function are the values which “make the observed data most probable or most likely” (93). The values for the parameters are selected in an iterative fashion using an optimization procedure, such as the Solver add-in tool in Microsoft Excel.

Suppose now that a road segment has yellow and white markings and that these differ in lifetime so that the remarking of each color follows its own cycle. Thus in any year and month the retroreflectivity bins of the white lines will be ‘i’ and the retroreflectivity bins of the yellow color will be ‘j’. Thus, a matrix of retroreflectivity bins might look like Table 23 and the number of parameters $q_{i,j}$ will vary, and in this illustration case there are 12 $q_{i,j}$. For example, for a certain month when R_{white}=172 and R_{Yellow}=212, then i=3 and j=1, their parameter is q_7. A road segment with markers will add another dimension to the matrix of retroreflectivity bins.

Table 23. Illustration of retroreflectivity bins

		$R_{Yellow}>200$	$150<R_{Yellow}\leq200$	$R_{Yellow}\leq150$
		j=1	j=2	j=3
$R_{white}>300$	i=1	q_1	q_2	q_3
$250<R_{white}\leq300$	i=2	q_4	q_5	q_6
$200<R_{white}\leq250$	i=3	q_7	q_8	q_9
$R_{white}\leq200$	i=4	q_{10}	q_{11}	q_{12}

By applying Equation 5 and simultaneously solving for p_m and q_r, the seasonal effect and the safety effect of retroreflectivity will be estimated. The values for p_m and q_r are multipliers may be thought of as crash or accident modification factors.

3.6. Homogeneous Segments

In order to allow comparisons between segments to be made the road segments must first be *homogeneous*. A homogeneous segment is defined as a segment in which the variables of interest (road identification, traffic volume, pavement material type, marking remarking or restriping dates, and marker installation dates) are either "all" consistent within the segment, or "some" are consistent based on their relevance toward the definition of the model form by means of the modeling as explained in Section 5.1. For example, consider a 5-mile segment of Sinclair Road (2-lane highway) that stretches from milepost (MP) 13.5 to 18.5, with the following variables of interest:

- **Road Identification:** California, District 12, 2-lane highway of Sinclair Rd, from milepost 13.5 to 18.5, data available from 1998 to 2000. (Table 24).
- **Pavement Surface:** MP 13.5-15.0 was reconstructed with concrete in January 1998. (Table 25).
- **Traffic Volume:** MP 13.5-17.2 experienced 8,000 AADT in years 1998-2000, MP 17.2-18.5 experienced 9,000 AADT in years 1998-2000. (Table 26).
- **Marker Installation Dates:** January 1998 makers were installed on all 5 miles. In January 2000, makers were reinstalled from between MP 13.5 to 15.5. (Table 27).
- **Marking Installation Dates:** January 1998, 1999, 2000 markings were restriped for all five miles. (Table 28).

Table 24 to Table 28 illustrate how the inclusion of more and more variables of interest causes the number of rows and columns increases. Table 28 illustrates a full table including all five classes of variables of interest.

Table 24. Variables: road identification

Year	State	District	2-lane Highway	Start MP	End MP
1998	California	12	Sinclair Rd	13.5	18.5
1999	California	12	Sinclair Rd	13.5	18.5
2000	California	12	Sinclair Rd	13.5	18.5

Table 25. Variables: pavement material type

Year	State	District	2-lane Highway	Start MP	End MP	Pavement
1998	California	12	Sinclair Rd	13.5	15.0	Concrete
1998	California	12	Sinclair Rd	15.0	18.5	Asphalt
1999	California	12	Sinclair Rd	13.5	15.0	Concrete
1999	California	12	Sinclair Rd	15.0	18.5	Asphalt
2000	California	12	Sinclair Rd	13.5	15.0	Concrete
2000	California	12	Sinclair Rd	15.0	18.5	Asphalt

Table 26. Variables: traffic volume

Year	State	District	2-lane Highway	Start MP	End MP	Pavement	Volume (AADT)
1998	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000
1998	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000
1998	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000
1999	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000
1999	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000
1999	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000
2000	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000
2000	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000
2000	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000

Table 27. Variables: marker installation dates

Year	State	District	2-lane Highway	Start MP	End MP	Pavement	Volume (AADT)	Last Marker Installation Date
1998	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 1998
1998	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 1998
1998	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998
1999	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 1998
1999	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 1998
1999	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998
2000	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 2000
2000	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 2000
2000	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998

Table 28. Variables marking restriping dates

Year	State	District	2-lane Highway	Start MP	End MP	Pavement	Volume (AADT)	Last Marker Installation Date	Last Marking Installation Date
1998	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 1998	Jan, 1998
1998	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 1998	Jan, 1998
1998	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998	Jan, 1998
1999	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 1998	Jan, 1999
1999	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 1998	Jan, 1999
1999	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998	Jan, 1999
2000	California	12	Sinclair Rd	13.5	15.0	Concrete	8,000	Jan, 2000	Jan, 2000
2000	California	12	Sinclair Rd	15.0	17.2	Asphalt	8,000	Jan, 2000	Jan, 2000
2000	California	12	Sinclair Rd	17.2	18.5	Asphalt	9,000	Jan, 1998	Jan, 2000

3.7. Data Requirements - Simulation

The research team conducted a comprehensive experimental design using simulated crash data as a function of pavement markings. An extensive effort was needed to generate artificial but credible data to validate the estimation procedure for pavement markings and *determine the amount of data required to achieve sufficiently accurate results*. This is believed to be the first time such approach has been applied for such a purpose. A detailed description of the simulation exercise may be found in Appendix E. Detailed simulation results are given in Appendix G. Appendix G presents in graphical format the results of 40 simulation exercises representing more than 5 million crashes. Since this is a simulation, generating millions of crashes is not as costly as collecting the real data. For smaller sample sizes, more advanced validation methods would have been necessary, such as bootstrapping or jackknife testing (e.g., (94)).The conclusions of the simulation exercise are summarized in the following paragraphs.

For this study one target crash represents one data point. To have a realistic probability of success, one must answer the question *how much data are needed to detect a nominal safety effect?* Specifically, this question may be rephrased as: *How many target crashes are needed to detect a 5% change in the safety effect of new pavement markings when compared to old markings?*

The simulation results give the minimal amount data needed to detect a 5% difference in safety (Table 29) for non-daylight, non-intersection locations. At least 50,000 target crashes are needed for 2-lane roads, 200,000 crashes for multi-lane highways, and 200,000 crashes for multi-lane freeways.

Table 29. Number of total target crashes required by road type

Road Type	Required number of target crashes to detect a 5% change in safety
2-lane roads	50,000
Multi-lane highway	200,000
Multi-lane freeway	200,000

Given a typical given crash rate, the total number of crashes can also be expressed in terms of miles of road and years of data (Table 31). Converting 50,000 crashes into a number of years of data and miles of road is equal to:

$$\text{Number of target crashes} \div \text{crash rate} \div \text{AADT} = 50{,}000 \div 0.00061 \div 3112 = 26{,}364\ mile \times years$$

Where the average ADT of 3112 and a non-daylight crash rate of 0.00061 for 2-lane highways is taken from HSIS data as shown in Table 31.

Table 30. HSIS volume and crash information for six states, and the values used in the simulation

								Simulation Values		
Road Class	Variable	MN	CA	NC	IL	UT	OH	**Average**	**Minimum**	**Maximum**
2-Lane Highways	Traffic Volume[a]	472,233	1,719,700	954,718	1,523,788	821574	1323218			
	Average ADT[b]	1,294	4,712	2,616	4,175	2,251	3,625	3112	1212	5012
	Crash Rate (All day)[c]	0.8219	2.3	1.63	3.08	2.11	2.57			
	Non-daylight Crash Rate [c]	0.22654	0.59	0.5	0.82	0.54	0.98	0.61	0.00024	0.00098
Multi-Lane Highways	Traffic Volume[a]	5,019,484	8,202,905	6,456,359	7,895,313	6494722	5431506			
	Average ADT[b]	13,752	22,474	17,689	21,631	17,794	14,881	18037	13537	22537
	Crash Rate (All day) [c]	10.53	14.9	12.83	33.11	27.38	6			
	Non-daylight Crash Rate [c]	2.55	3.56	2.64	7.59	5.99	1.86	4.03	0.00193	0.00613
Multi-Lane Freeways	Traffic Volume[a]	13,760,000	30,560,000	14,440,000	11,300,000	7,896,936	15250000			
	Average ADT[b]	37,699	83,726	39,562	30,959	21,635	41,781	42560	22560	62560
	Crash Rate (All day) [c]	12.73	30.11	10.35	10.13	7.97	7.07			
	Non-daylight Crash Rate [c]	3.71	8.23	2.75	3.41	2.21	2.41	3.79	0.00229	0.00529

[a] Traffic Volume = average annual traffic volume = (AADT * segment length * 365) / summation of segment lengths by road class
[b] Average ADT = traffic volume / 365, i.e., average vehicles / day
[c] Crash Rate = 1000 × crashes / miles

Thus, if 26,364 miles × years are divided by 2 years of data, it means that 13,182 miles of 2-lane rural roads over two years would be needed to detect a 5% change in the safety effect of pavement markings. Based on similar calculations, Table 31 was developed.

Table 31. Number years and miles of road per year required by road type

	Years of Data									
	2	3	4	5	6	7	8	9	10	12
2-lane highway										
50,000 Crashes										
Miles of Road	13182	8788	6591	5273	4394	3766	3296	2929	2636	2397
Multi-lane highway										
200,000 Crashes										
Miles of Road	1375	917	688	550	458	393	344	306	275	250
Multi-lane freeway										
200,000 Crashes										
Miles of Road	620	414	310	248	207	177	155	138	124	113

Previous pavement marking and marker studies have rarely collected data of this magnitude, which may explain why previous studies have often been inconclusive. These data requirement estimates would not have been known without conducting the simulation exercise.

4. Chapter 4 Data Collection and Preparation

This chapter describes the content of the data collected, and the steps involved in preparing a retroreflectivity-safety database to analyze the relationship between retroreflectivity and crashes. Based upon an extensive survey of the states, it was determined that the State of California contained a large database of historical marking and marker installation information. With its large range of temperatures and precipitation, high crash counts corresponding to a large population, and participation in the Highway Safety Information System (HSIS) database, California was selected as the source state for the study.

4.1. Data Collection

Several different sources were used to build the retroreflectivity-safety database which included retroreflectivity measurements, pavement marking and marker installation dates, capital pavement projects' information, roadway inventory, traffic volume, crash, climate region, and historical snowfall. A listing of the data sources and available years of data collected is given in Table 32. Each data type is described in greater detail in the following sections.

Table 32: Data sources and status

Data Type	Source	Available Years
Retroreflectivity	National Testing Product Evaluation Program (NTPEP)	Various
Pavement marking and marker installation dates	Caltrans	1992-1994 1997-2002
Capital pavement projects	Caltrans	1991-2002
Roadway inventory, traffic volume, crash variables	Highway Safety Information System (HSIS)	1992-2002
Climate region	U.S. Department of Energy	1990-2004
Historical snowfall	National Climatic Data Center	1990-2004

4.1.1. Retroreflectivity

The single largest publicly available source of retroreflectivity measurements of pavement markings and markers database is the National Transportation Product Evaluation Program (NTPEP), and is in the form of field and laboratory reports. All available NTPEP marking and marker reports were obtained (42 in all), and reviewed. Each report represents one year of published results from a NTPEP test deck. A NTPEP test deck refer to asphalt and concrete sections of road that have markings and markers applied for testing purposes, usually located within the same county in a state.

Many of the older NTPEP reports contain the results of measurements conducted using 15-meter geometry measures, and therefore are not usable due to their incompatibility with today's standards.

Several of the reports also contain data collected and analysed strictly on laboratories. Given the need for producing results that have direct applicability to today's practices, analysis of NTPEP data was limited to field measurements only. Of the 42 NTPEP reports, 21 reports contained data on 30-meter geometry field measurements for markings or for markers. Those NTPEP reports that were included for analysis of pavement markings contained data from the following states:

- Alabama (95,96);
- California (97);
- Minnesota (98,99);
- Mississippi (100,101);
- Pennsylvania (102,103,104,105);
- Texas (106,107);
- Utah (108); and
- Wisconsin (109,110).

NTPEP reports on pavement markers were also restricted to field reports only, which are measured using different technology than pavement markings. Unlike pavement markings, pavement markers are not tested in the field but instead must be removed and taken back to a lab for testing. The NTPEP reports contained data from the following states for pavement markers:

- Georgia (111)
- Maryland (112)
- Ohio (113,114,115)

One of the Ohio test deck (115) results was found to have results that were not usable due to "instrument recalibration". To summarize, 16 and 4 NTPEP reports were used to build databases of marking and marker retroreflectivity measurements, respectively.

4.1.2. Pavement Marking and Marker Installation

California has two pavement marking and marker data management systems. The current system is known as IMMS (Integrated Marking Management System), while the older system, no longer used, is known as MMS (Marking Management System). The older MMS system was the source of the historical pavement marking and marker installation data and it contains the following attributes:

- **District-County-Route**: District number, county and route information;
- **Post Mile From**: Starting milepost point of striping;
- **Post Mile To**: Ending milepost point of striping;
- **Part Description**: Description of work; and
- **Date**: Invoice date which is used as the completion date of striping.

An excerpt from the older California system is shown in Table 33 (data show striping data for District 1, Lake County, Route 20), which contains:

- **DIST**: District number;
- **FPH**: Type of maintenance work, where M1 is striping;
- **CORTE**: County and route information;
- **WRK-DTE**: Date of work;
- **FRM PM**: Starting milepost;
- **TO PM**: Ending milepost; and
- **CLASS**: Material type code.

Table 33. Excerpt of California's statewide MMS database, the older management system

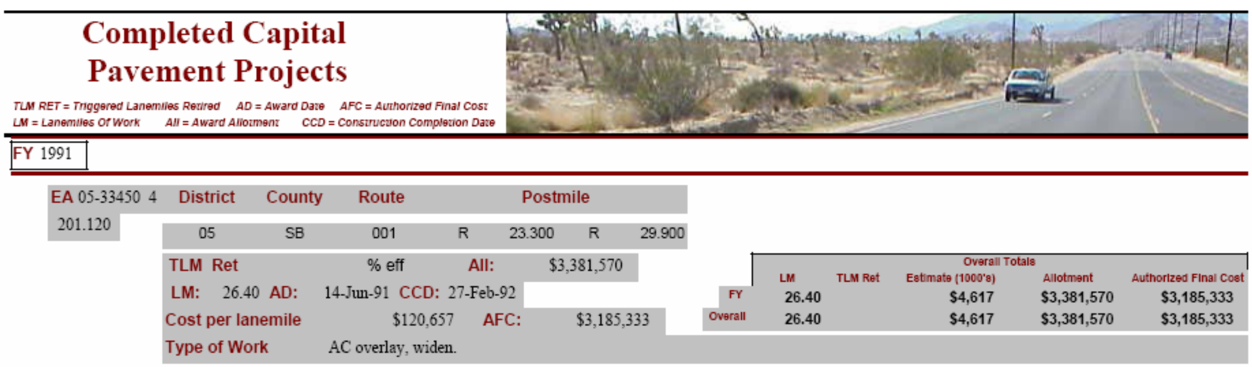
FY91-92						
				FRM	**TO**	
DIST	**FPH**	**CORTE**	**WRK-DTE**	**PM**	**PM**	**CLASS**
01	M1E	01101	01/08/1991	3.0	12.0	8010
01	M1E	01101	23/07/1991	4.0	27.0	8010
01	M1E	01101	09/03/1992	12.0	21.0	8010
01	M1E	01101	02/06/1992	12.0	21.0	8010
01	M1E	01101	02/06/1992	12.0	21.0	8010
01	M1E	01101	22/10/1991	15.0	24.0	8010
01	M1E	01101	22/10/1991	15.0	24.0	8010
01	M1E	01101	22/10/1991	15.0	24.0	8010
01	M1E	01101	09/03/1992	27.2	31.4	8010
01	M1E	01101	19/03/1992	37.0	46.5	8010
01	M1E	01101	17/09/1991	39.0	46.5	8010
01	M1E	01197	09/03/1992	0.0	7.0	8010
01	M1E	01197	09/03/1992	0.0	7.0	8010

The California MMS database contains maintenance records of Caltrans work related to markings and markers and is mostly used as an asset management inventory system. The MMS database does not contain records related marking and marker installation which is installed by contractors. For this study it was not possible to know what marking and marker materials were installed for capital pavement projects, it was only possible to identify those time period for which marking and marker data was unavailable. In California all large capital pavement projects are conducted by contractors, thus all marking and marking installations which accompanies new repair, resurfacing, and restoration (3R) work are carried out by contractors, and are found in a different source (Section 4.1.3).

4.1.3. Capital Pavement Projects

Marking and marker material installation data, conducted under contract and not done by the Caltrans, were not available for this study. This included all repair, resurfacing, and restoration (3R) work which in California is done by contractors. In order to know the time periods where 3R projects occurred it was necessary to incorporate the capital pavement projects data into the study. For the purpose of this study, segments undergoing 3R were treated as "blackout periods" for which no data were available for studying the relationship between retroreflectivity and crashes. Therefore, the retroreflectivity-safety database includes only data related to maintenance periods and not periods including or right after 3R projects. These periods of missing data had an inadvertent benefit to the study by removing any possibility of confounding the safety effect of resurfacing with the retroreflectivity of markings and markers.

An excerpt of completed capital pavement projects listing in California is shown in Figure 21. For each project the listing includes start and end construction dates, district, route, and milepost information.


Completed Capital Pavement Projects

TLM RET = Triggered Lanemiles Retired AD = Award Date AFC = Authorized Final Cost
LM = Lanemiles Of Work All = Award Allotment CCD = Construction Completion Date

FY 1991

EA 05-33450 4	District	County	Route		Postmile		
201.120	05	SB	001	R	23.300	R	29.900

TLM Ret % eff All: $3,381,570
LM: 26.40 AD: 14-Jun-91 CCD: 27-Feb-92
Cost per lanemile $120,657 AFC: $3,185,333
Type of Work AC overlay, widen.

	Overall Totals				
	LM	TLM Ret	Estimate (1000's)	Allotment	Authorized Final Cost
FY	26.40		$4,617	$3,381,570	$3,185,333
Overall	26.40		$4,617	$3,381,570	$3,185,333

Figure 21. Excerpt of capital pavement projects listing in California

4.1.4. Roadway Inventory, Traffic Volume, and Crash Variables

The Highway Safety Information System (HSIS) provided all roadway inventory, traffic volume, and crash variables used in this study. HSIS is a multistate database that contains crash, roadway inventory, and traffic volume data for a few States. The HSIS is operated by the University of North Carolina Highway Safety Research Center (HSRC) and LENDIS Corporation, under contract with FHWA. Additional information about HSIS is available from their website at www.hsisinfo.org.

Crash data was restricted to non-intersection related crashes during non-daylight (including dawn, night and dusk conditions). Variables of interest obtained from HSIS are summarized in Table 34.

Table 34. Roadway inventory, traffic volume, and crash variables

Category	**Variable**
Roadway inventory	Location (district, county, route, milepost) Road type
Traffic volume	AADT (Average Annual Daily Traffic)
Crash variables	Crash severity Crash date Crash time Light condition Location type (intersection vs. non-intersection) Location (milepost)

4.1.5. Climate Region

Assignment of counties to a specific climate region has been published by the U.S. Department of Energy (116) and is summarized for California in Table 35. The counties in California fall under one of four climate regions: marine (coastal), hot-dry (desert), mixed-dry (central), and cold (mountain).

Table 35. California climate regions

County Name	Climate Region	County Name	Climate Region
Alameda	Marine	Orange	Hot-Dry
Alpine	Cold	Placer	Hot-Dry
Amador	Mixed-Dry	Plumas	Cold
Butte	Hot-Dry	Riverside	Hot-Dry
Calaveras	Mixed-Dry	Sacramento	Hot-Dry
CoIusa	Hot-Dry	Santa Barbara	Marine
Contra Costa	Hot-Dry	San Bernardino	Hot-Dry
Del Norte	Marine	San Benito	Marine
El Dorado	Mixed-Dry	Santa Clara	Marine
Fresno	Hot-Dry	Santa Cruz	Marine
Glenn	Hot-Dry	San Diego	Hot-Dry
Humboldt	Marine	San Francisco	Marine
Imperial	Hot-Dry	Shasta	Hot-Dry
Inyo	Mixed-Dry	Sierra	Cold
Kern	Hot-Dry	Siskiyou	Cold
Kings	Hot-Dry	San Joaquin	Hot-Dry
Lake	Mixed-Dry	San Luis Obispo	Marine
Lassen	Cold	San Mateo	Marine
Los Angeles	Hot-Dry	Solano	Hot-Dry
Madera	Hot-Dry	Sonoma	Marine
Marin	Marine	Stanislaus	Hot-Dry
Mariposa	Mixed-Dry	Sutter	Hot-Dry
Mendocino	Marine	Tehama	Hot-Dry
Merced	Hot-Dry	Trinity	Mixed-Dry
Modoc	Cold	Tulare	Hot-Dry
Mono	Cold	Tuolumne	Mixed-Dry
Monterey	Marine	Ventura	Marine
Napa	Marine	Yolo	Hot-Dry
Nevada	Cold	Yuba	Hot-Dry

4.1.6. Historical Snowfall

On NTPEP test decks, snowfall is highly correlated to the amount of snow removal activities occurring, where greater snowfall means more snow removal. In California, Caltrans has adopted a snow removal policy which says *"Snow removal and ice control shall be performed as necessary in order to facilitate the movement and safety of public traffic and shall be done in accordance with the best management practices outlined herein with particular emphasis given to environmentally sensitive areas."(42)* There are four road maintenance classifications in California which range from bare pavement to removal only during normal daytime work shifts. Historical snowfall was used as a proxy for snow removal activities in California, where it was assumed that heavy snowfall meant heavy snow removal.

In order to apply the appropriate retroreflectivity models, counties in cold regions were classified into low-medium and heavy snowfall counties. Snowfalls over all the weather stations within each county was averaged for each year to get the average value of annual snowfall. Counties with annual snowfalls less than 50 inches were categorized as “low-medium” snowfall counties and counties with annual snowfalls greater than or equal to 50 inches were categorized as “heavy” snowfall counties.

Yearly snowfall for all recording stations in California was acquired from the National Climatic Data Center (www.ncdc.noaa.gov). Snowfalls were averaged over all weather stations within each county for each year to get the average value of annual snowfall for the county. The counties in cold regions (Alpine, Lassen, Modoc, Mono, Nevada, Plumas, Sierra and Siskiyou) were categorized by year as having either low to medium or heavy snowfalls.

4.2. Data Preparation

Data preparation consisted of five major subtasks:

1. Quality control;
2. Retroreflectivity database building;
3. Safety database building;
4. Retroreflectivity-safety database linking; and
5. Retroreflectivity-safety database manipulation.

Quality control refers to verifying the correctness of the data, database linking refers to using key identifiers to link data from different sources, and database manipulation refers to converting the data into the structure required for analysis. In terms of sequence, quality control occurred first and throughout the preparation phase. The retroreflectivity and safety database building, subtasks 2 and 3, occurred in parallel. The safety database contains the roadway inventory, traffic volume, and crash data. The retroreflectivity-safety database was built by linking the retroreflectivity and safety databases. In order to build the retroreflectivity-safety database, database linking and data manipulation occurred simultaneously. For the safety analysis, the retroreflectivity-safety database was manipulated into homogenous segments, which was described in Section 3.6.

4.2.1. Quality Control

Data quality was prime consideration in data collection, preparation, and analysis. In order to obtain the data needed for this study, the research team worked with HSIS, Caltrans, and the National Climate Center. Questions regarding the meaning or content of the data was resolved by contacting the data source directly.

The data were subjected to additional quality control processes, which were:

1. Are the data fields complete (are there any missing data elements)?
2. Are the available data correct and reasonable?

HSIS data were checked to confirm that all crashes were recorded on non-intersection locations and during non-daylight conditions. HSIS traffic volume was checked through histograms by miles of road versus AADT to learn about the volume ranges for different road types. Sample entries, for each year of data, were extracted from the final retroreflectivity-safety database and manually checked against the original data sources to confirm that pavement surface type, crash counts, resurfacing dates, road type, and marking and marker age had been entered and manipulated correctly.

4.2.2. Retroreflectivity Data Building

This section describes how a database of retroreflectivity database for both pavement markings and markers was built from NTPEP reports.

4.2.2.1. Converting Hardcopy NTPEP Reports into Electronic files

Four steps were carried out in order to convert the hardcopy NTPEP reports into an electronic format suitable for statistical modeling, they were:

Step 1: NTPEP field reports were scanned as image files using an Epson scanner.

Step 2: The scanned files were then converted to ASCII stripped.txt files by using computer software called *Text Bridge Pro* version 8.0. This software was used to convert image files into text files through the process of *optical character recognition* (OCR).

Step 3: The text files were imported into MS Excel.

Step 4: Quality controller checked the spreadsheets against the original NTPEP field reports, and make any necessary manual edits.

4.2.2.2. NTPEP Retroreflectivity Database Structure for Markings

The column headings of the NTPEP retroreflectivity database is shown in Table 36.

Table 36. NTPEP retroreflectivity database structure

Test Deck	Test Deck Year	Install Date	Surface	Reading Locator	AADT	Snow Removal	Color	Type	Climate Region	NTPEP	Age (months)	Value

1. **Test Deck:** Test deck refers to the name of the participating NTPEP state where representative pavement markings were installed for the subsequent testing for retroreflectivity.
2. **Test Deck Year:** Test deck year is the year when a participating state initiated the process of installing pavement markings for testing.
3. **Install Date:** The exact date of marking installation.
4. **Surface:** Surface refers to either concrete pavement or asphalt. Both types of pavement surface may be found at each test deck.
5. **Reading Locator:** Pavement markings are tested at two different locations, at the centreline and at the left wheel path.
6. **AADT:** AADT is Annual Average Daily Traffic and represents the traffic volume of the road sections where test decks were installed.
7. **Snow Removal:** Snow removal refers to the degree of snow ploughing during winters. Categorical descriptions were used based upon the amount of qualitative descriptions given in the NTPEP report. There are four possible values of snow removal namely; None, Low, Medium and Heavy.
8. **Color:** Refers to the color of the pavement marking material, either yellow or white.
9. **Type:** The type of binder material such as for example, epoxy, waterborne, or thermoplastic.
10. **Climate Region:** The climate conditions of the county where test decks were installed. Climate region values include; Cold, Hot – Humid, Mixed – Humid, Hot - Dry. Region values were determined by consulting a report by the Department of Energy (116).
11. **NTPEP:** Refers to the NTPEP number assigned to a product being tested for retroreflectivity.
12. **Age:** Number of months since installation, the time when a particular deck was tested for retroreflectivity measurement.
13. **Value**: Corresponding retroreflectivity value measured in $mcd/m^2/lx$

4.2.2.3. Database Cleanup for Markings

After scanning and converting the hardcopy NTPEP reports into an electronic format, the following types of data were removed from the database:

- **Black colored markings.** Black colored markings are not retroreflective.
- **Missing values.** Missing values could be due to a variety of reasons including weather, but mostly due to equipment failure.
- **Temporary, experimental, and other.** These markings are outside of the research focus of this project which is dedicated to permanent markings. Thus, temporary marking measurements were removed from the database. In addition, all materials labeled experimental or “other” were also removed.

A visual inspection of the retroreflectivity database was conducted to identify outlier values. Outliers refer to those values that for one reason or another are clearly in error. The visual inspection included plots of age vs. retroreflectivity were used to help identify unrealistic values of retroreflectivity measurements. Table 37 illustrates an excerpt of the retroreflectivity database showing a circled value (1607) which was investigated as a potential outlier, because its value is several hundred larger than most other readings for the same age. Possibilities for the error errors in the scanning process, errors in the database building process, or errors in the published NTPEP report. All potential sources of error were checked for each outlier identified. Determining whether a value is an outlier or not requires going back to the NTPEP source report. If the source report and the electronic data match, the retroreflectivity value is compared to the previous and subsequent month data to determine if the value is too large or too small to be considered a reasonable value. Unreasonable values were removed from the retroreflectivity database.

Table 37: Table 11 from NTPEP Report 98 (98) showing an outlier

TABLE 11: MONTHLY REFLECTIVITY DATA - LEFT WHEEL TRACK ASPHALT DECK (LTL 2000)

NTPEP #	Jul-97	Aug-97	Sep-97	Oct-97	Dec-97	Feb-98	Mar-98	Apr-98	May-98	Jun-98	Jul-98
1	164	24	34	22	17	19	20	13	11	OMIT	OMIT
2	200	230	222	270	246	368	258	296	221	316	175
3	123	113	131	164	147	223	154	178	122	192	115
4	288	289	308	390	302	357	272	312	226	329	206
5	280	262	256	330	245	258	204	228	179	222	93
6	282	230	157	189	141	249	164	170	121	178	112
7	129	94	67	72	35	60	43	45	34	57	43
8	105	96	83	108	90	61	33	43	25	41	33
9	371	355	316	417	318	297	180	160	105	137	79
10	337	340	317	372	235	224	149	171	115	191	137
11	336	327	315	375	289	322	197	176	107	128	67
12	247	220	224	212	203	212	212	187	144	133	148
13	227	192	162	170	161	149	162	127	105	96	93
14	218	182	152	160	153	145	156	124	97	95	90
15	331	282	274	252	268	271	235	194	138	136	109
16	300	280	224	221	238	217	208	163	106	124	132
17	319	228	194	180	190	158	164	132	98	106	87
18	241	228	206	201	198	198	194	147	117	120	99
19	196	119	99	97	104	108	101	81	54	61	58
20	143	123	105	108	119	123	120	91	65	72	75
21	150	149	127	125	137	130	127	111	79	93	77
22	84	99	102	170	95	139	155	103	69	71	65
23	181	139	135	113	101	113	104	64	46	44	44
24	141	127	181	106	101	104	99	237	59	46	38
25	134	107	125	93	67	56	57	35	39	25	21
26	119	110	129	90	70	49	48	32	49	21	22
27	265	250	232	228	230	203	216	167	118	130	139
28	261	229	202	202	209	175	163	137	104	118	116
29	111	89	75	80	90	82	93	71	50	65	67
30	229	297	282	349	287	225	220	253	155	228	141
31	171	207	184	227	194	194	153	[illegible]	100	155	95
32	173	394	451	463	523	453	385	1607	292	403	250
33	90	293	332	431	381	359	311	[illegible]	232	320	192

4.2.2.4. NTPEP Retroreflectivity Database Structure for Markers

The steps for building the marker retroreflectivity database are identical to the steps described for markings (Section 4.2.2.1), with only for small differences in the database structure described in this section. The column headings in Table 38 are as follows:

Table 38. Marker retroreflectivity database structure

Test Deck	Test Deck Year	Install Date	Surface	AADT	Snow Removal	Type	Climate	NTPEP	Date	Dirty Average	Age

1. **Test Deck:** Test deck refers to the name of the participating NTPEP state where representative pavement markers were installed for the subsequent testing for retroreflectivity.
2. **Test Deck Year:** Test deck year is the year when a participating state initiated the process of installing pavement markers for testing.
3. **Install Date:** The exact date of marker installation.
4. **Surface:** Surface refers to either concrete pavement or asphalt. Both types of pavement surface may be found at each test deck.
5. **AADT:** AADT is Annual Average Daily Traffic and represents the traffic volume of the road sections where test decks were installed.
6. **Snow Removal:** Snow removal refers to the degree of snow ploughing during winters. There are four possible values of snow removal namely; None, Low, Medium and Heavy.
7. **Type:** Type parameter shows the type of pavement markers used; there are two types that were used for testing, plowable and non-plowable markers.
8. **Climate Region:** Climate region shows the climate conditions of the county where test decks were installed. Climate region values include; Cold, Hot – Humid, Mixed – Humid, Hot - Dry.
9. **NTPEP:** NTPEP refers to the NTPEP number assigned to a product being tested for retroreflectivity.
10. **Date:** Date refers to the time when a particular deck was tested for retroreflectivity measurement. The different testing dates were tabulated in rows as opposed to pavement marking testing dates which were tabulated in separate columns.
11. **Dirty Average:** Dirty Average is a field measurement of luminous intensity of pavement markers taken before lens cleaning, expressed in cd/lux.
12. **Age**: Time elapsed in months at the testing day since the installation of markers.

4.2.2.5. Database Cleanup for Markers

Missing retroreflectivity values were removed from the database. Missing values could be due to a variety of reasons including weather, but mostly due to equipment failure.

4.2.3. Database Linking

In order to build the retroreflectivity-safety database, the different data sources (Table 32) are combined within a single database. Each separate data source was imported into a MySQL dabase (www.mysql.com) as a separate table, then the primary key identifiers were used to link the tables. The primary key identifiers usually consisted of year, district, county, begin milepost, and end milepost. With these five fields a unique segment can be identified for one year of data. The research team developed look-up tables so that tables from different sources could be cross-linked to each other (Table 39). For example, the codes used for county are different for the HSIS, NCDC, Caltrans resurfacing, and Caltrans marking and marker maintenance data.

Table 39. The look-up table used for linking counties in the retroreflectivity-safety database

NCDC County Names	HSIS County Codes	Caltrans Maintenance County Codes	Caltrans Resurfacing County Codes
Alameda	1	33	ALA
Alpine	2	31	ALP
Amador	3	26	AMA
Butte	4	12	BUT
Calaveras	5	30	CAL
Colusa	6	15	COL
Contra Costa	7	28	CC
Del Norte	8	1	DN
El Dorado	9	25	ED
Fresno	10	42	FRE
Glenn	11	11	GLE
Humboldt	12	4	HUM
Imperial	13	58	IMP
Inyo	14	48	INY
Kern	15	50	KER
Kings	16	45	KIN
Lake	17	14	LAK
Lassen	18	7	LAS
Los Angeles	19	53	LA
Madera	20	41	MAD
Marin	21	27	MAR
Mariposa	22	40	MAR
Mendocino	23	10	MEN
Merced	24	39	MER
Modoc	25	3	MOD
Mono	26	47	MNO
Monterey	27	44	MON
Napa	28	21	NAP

NCDC County Names	HSIS County Codes	Caltrans Maintenance County Codes	Caltrans Resurfacing County Codes
Nevada	29	17	NEV
Orange	30	55	ORA
Placer	31	19	PLA
Plumas	32	9	PLU
Riverside	33	56	RIV
Sacramento	34	24	SAC
Santa Barbara	35	51	SB
San Bernardino	36	54	SBD
San Benito	37	43	SBT
Santa Clara	38	37	SCL
Santa Cruz	39	36	SCR
San Diego	40	57	SD
San Francisco	41	34	SF
Shasta	42	6	SHA
Sierra	43	13	SIE
Siskiyou	44	2	SIS
San Joaquin	45	29	SJ
San Luis Obispo	46	49	SLO
San Mateo	47	35	SM
Solano	48	23	SOL
Sonoma	49	20	SON
Stanislaus	50	38	STA
Sutter	51	18	SUT
Tehama	52	8	THE
Trinity	53	5	TRI
Tulare	54	46	TUL
Tuolumne	55	32	TUO
Ventura	56	52	VEN
Yolo	57	22	YOL
Yuba	58	16	YUB

4.2.4. Database Manipulation

The structure of the data needed for safety analysis is different than the structure of the source data. In addition, each data source has its own unique database structure. Data manipulation refers to reconciling the different structures through transforming variable codes, addition of columns and rows, transposing columns to rows, and converting units. The process of database manipulation results in a single multi-attribute database of homogenous segments.

For example, consider a dataset in terms only of marker installation date. Formatting the marker age in month time windows produces an additional 12 columns. As seen in Table 40, each month column (Jan, Feb, Mar, etc.) contains a number equal to the age of the markers in months on the road segment.

Table 40. Marker age based upon installation date

							Marker Age in Months (Year+ Column Month – Installation Date)			
Year	State	District	2-lane Highway	Start MP	End MP	Last Marker Installation Date	Jan	Feb	Mar	…
1998	California	12	Sinclair Rd	13.5	18.5	Jan, 1998	0	1	2	…
1999	California	12	Sinclair Rd	13.5	18.5	Jan, 1998	12	13	14	…
2000	California	12	Sinclair Rd	13.5	15.5	Jan, 2000	0	1	2	…
2000	California	12	Sinclair Rd	15.5	18.5	Jan, 1998	24	25	26	...

The study methodology requires a database structure with rows representing homogeneous segments and columns representing the required variables. Table 41 contains an expanded schematic depiction of the Marker Age database structure, shown in Table 40. After retroreflectivity modeling took place, 12 additional columns of retroreflectivity readings are generated for the corresponding marker age columns, as shown in Table 42.

Table 41. Detailed illustration of 12 marker age columns

		Marker Age in Months											
"Segment"	**"Year"**	**MRA1**	**MRA2**	**MRA3**	**MRA4**	**MRA5**	**MRA6**	**MRA7**	**MRA8**	**MRA9**	**MRA10**	**MRA11**	**MRA12**
Sinclair Rd	1998	0	1	2	3	4	5	6	7	8	9	10	11
Sinclair Rd	1999	12	13	14	15	16	17	18	19	20	21	22	23
Sinclair Rd	2000	0	1	2	3	4	5	6	7	8	9	10	11
Sinclair Rd	2000	24	25	26	27	28	29	30	31	32	33	34	35
Main St	1999	8	9	10	11	0	1	2	3	4	5	6	7
Hwy 7	2000	6	7	8	9	10	11	0	1	2	3	4	5
…	1998	8	9	10	11	0	1	2	3	4	5	6	7
…	1997	4	5	6	7	8	9	10	11	0	1	2	3
…	1995	8	9	10	11	0	1	2	3	4	5	6	7
…	1995	8	9	10	11	0	1	2	3	4	5	6	7

Table 42. Detailed illustration of 12 marker luminance columns

Marker Coefficient of Luminous Intensity (cd/foot-candle) by Month

"Segment"	"Year"	MRL1	MRL2	MRL3	MRL4	MRL5	MRL6	MRL7	MRL8	MRL9	MRL10	MRL11	MRL12
Sinclair Rd	1998	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36	0.33	0.30	0.27	0.24
Sinclair Rd	1999	0.21	0.19	0.17	0.16	0.14	0.12	0.11	0.09	0.06	0.04	0.02	0.00
Sinclair Rd	2000	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36	0.33	0.30	0.27	0.24
Sinclair Rd	2000	0.22	0.21	0.19	0.18	0.17	0.15	0.14	0.12	0.11	0.10	0.08	0.07
Main St	1999	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36
Hwy 7	2000	0.39	0.36	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96	2.10	1.24
…	1998	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36
…	1997	2.10	1.24	0.39	0.36	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96
…	1995	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36
…	1995	0.33	0.30	0.27	0.24	5.53	4.67	3.81	2.96	2.10	1.24	0.39	0.36

The retroreflectivity-safety database, when completed, was structured into rows representing homogeneous segments and columns with the headings shown in Table 43.

Table 43. Retroreflectivity-safety database format and column headings.

District	District code
County	County code
Route	Highway number
BEGMP	Beginning milepost
ENDMP	End milepost
Climate region	Climatic region for the county
Surface type*	Surface is either concrete or asphalt
Road type	Road type as freeway, multilane highway, or two-lane highway.
AADT*	Annual Average Daily Traffic
Year	Year of the data
Snowfall	Year snowfall classified as either heavy or medium to low.
FI1 to FI12	Total number of non-intersection, non-daylight fatal + nonfatal injury crashes for Year by month where FI1 corresponds to the number of fatal + nonfatal injury crashes in the month of January and FI12 corresponds to that in December
PDO1 to PDO12	Total number of non-intersection, non-daylight PDO crashes for Year by month where PDO1 corresponds to the number of PDO crashes in January and PDO12 corresponds that in December
Yellow waterborne White waterborne Yellow thermoplastic White thermoplastic Yellow solvent White solvent Markers plowable Markers non-plowable	**Age** of markings or markers, by month for each material-color combination. Each material-color combination has 12 columns where the first column corresponds to January and the 12th column corresponds to December. A value of 0 means the markings were installed during that month. A value of 1 means the markings were installed the month before, a value of 2 means the markings were installed 2 months earlier, and so on.
Yellow retroreflectivity White retroreflectivity Marker retroreflectivity	Predicted **retroreflectivity** as a function of • Material type (waterborne, thermoplastic, solvent for markings, and plowable or non-plowable for markers) • Marking age or marker age • Marking color • Climate region • Snowfall
* Homogenous segments were eventually collapsed across surface type and AADT because they were not found to improve the retroreflectivity models' goodness of fit	

4.3. Summary of the Retroreflectivity-Safety Database

The retroreflectivity-safety database links the following information:

- Roadway inventory and traffic volume information as homogenous segments for all California state roads by road type:
  - 2-lane highways
  - Multilane highways
  - Multilane freeways
- The number of non-daylight crashes recorded for each homogeneous segment per month by severity:
  - Fatal + nonfatal injury crashes
  - Property damage only crashes
- The climate region for each county region in California as:
  - Cold
  - Hot-dry
  - Marine
  - Mixed-dry
- The yearly snowfall for cold region counties in California as:
  - heavy
  - low to medium
- The age of the pavement *markings* installed by Caltrans maintenance in terms of months. California uses only waterborne, thermoplastic, and solvent marking material types. The six different material-color combinations tracked in the retroreflectivity-safety database are:
  - Yellow waterborne
  - White waterborne
  - Yellow thermoplastic
  - White thermoplastic
  - Yellow solvent
  - White solvent
- The age of the pavement *markers* installed by Caltrans maintenance in terms of months. California's markers were classified as:
  - Marker plowable
  - Marker non-plowable
- The predicted retroreflectivity based upon the calibrated models as a function of:
  - Material type (waterborne, thermoplastic, solvent for markings, and plowable or non-plowable for markers)
  - Marking age or marker age
  - Marking color
  - Climate region
  - Snowfall
- Start and end periods for California state pavement projects where reconstruction or rehabilitation has occurred. In California, capital pavement projects do not maintain records of which marking and marker materials were installed. Therefore in the retroreflectivity-safety database construction periods are treated as blackout periods during which marking and marker retroreflectivity is unknown. Retroreflectivity is predicted using the next cycle of Caltrans maintenance activities in the period after resurfacing.

5. Chapter 5 Retroreflectivity Modeling and Safety Analysis

This chapter on retroreflectivity modeling and safety analysis has three major sections. The first section describes the retroreflectivity models of pavement markings and markers based upon NTPEP data. These models were subsequently applied to convert the age of different marker and marking materials in different climate regions into predicted retroreflectivity values, which were entered into the retroreflectivity-safety database. The second section gives an account of the data contained in the retroreflectivity-safety database. The third section explains how the number of target crashes was modeled as function of retroreflectivity by using retroreflectivity as a common metric.

5.1. Retroreflectivity Modeling

The goal of the retroreflectivity modeling is to develop equations that can be used to estimate an average retroreflectivity of pavement markings and pavement markers as a function of material type, time since application, traffic volume, climate and other variables. Retroreflectivity modeling of pavement markings is discussed in the next section followed by retroreflectivity modeling of pavement markers. NTPEP collects retroreflectivity data for 2 years. However in practice, markings and markers may be in the field for longer than two-year durations. The retroreflectivity models were later extended beyond 25 months to 48 months (Section 5.1.3).

5.1.1. Retroreflectivity Prediction Modeling of Pavement Markings

The retroreflectivity of pavement markings were examined as a function of:

- Age;
- Color;
- Material type;
- Traffic volume;
- Pavement surface;
- Climate region; and
- Snow removal.

5.1.1.1. Age Effect

The age of pavement markings is the most important variable in determining their retroreflectivity. Figure 22 shows the relationship between age and retroreflectivity across all pavement marking materials in the NTPEP data. As pavement markings age, their retroreflectivity decreases in a non-linear manner. Figure 22 also depicts the amount of variability in retroreflectivity for markings of the same age. Figure 23 shows the average retroreflectivity by age across all pavement marking materials in the NTPEP data.

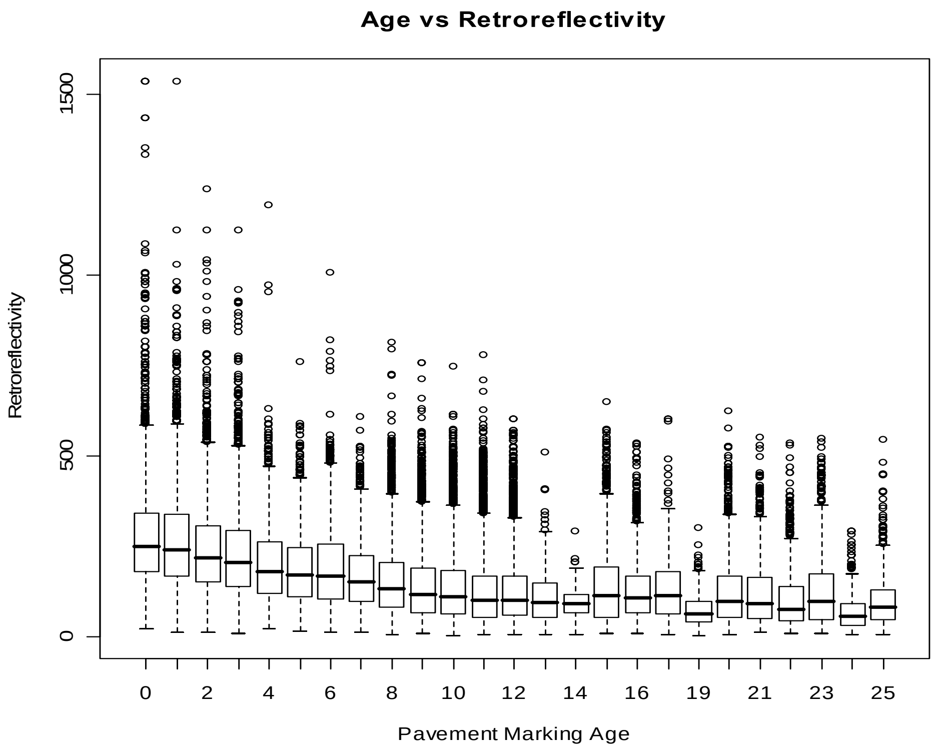


Figure 22. Marking age versus retroreflectivity (Source: NTPEP data)

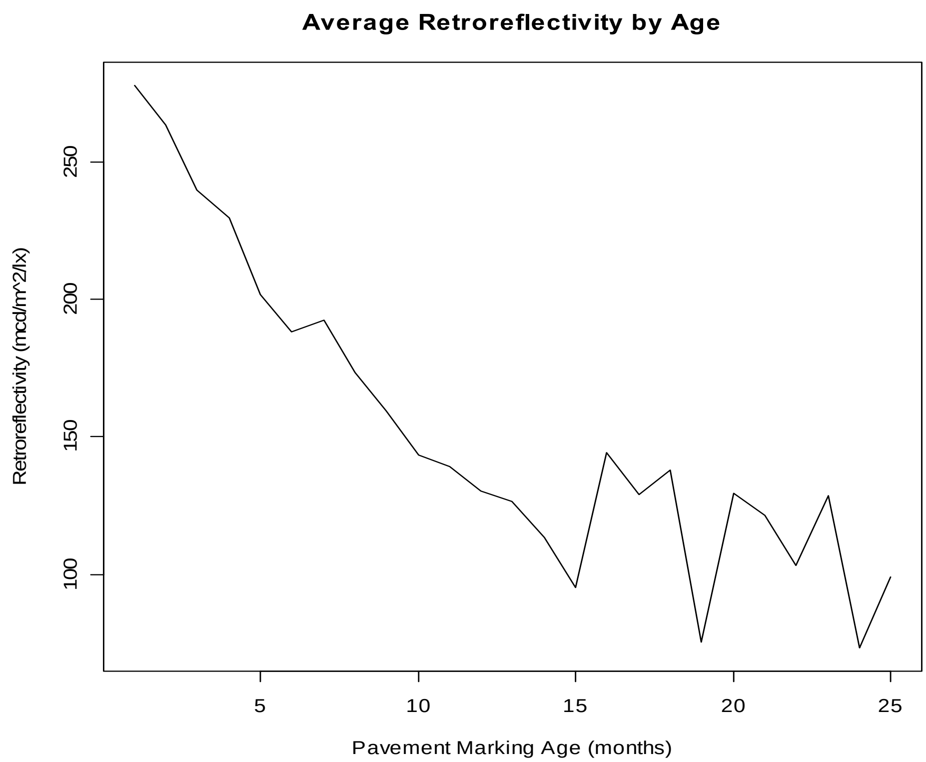


Figure 23. Average marking age versus retroreflectivity (Source: NTPEP data)

Through exploratory analysis, the relationship between age and retroreflectivity was determined to be best explained by the inverse polynomial model given in Equation 6.

Equation 6

$$R = \frac{1}{\beta_0 + \beta_1 * Age + \beta_2 * Age^2}$$

Where

R: retroreflectivity of pavement stripe ($mcd/m^2/lx$)

Age: age of pavement stripe (months)

β_0, β_1, β_2: model parameters to be estimated

5.1.1.2. Color Effect

Across all materials, white pavement markings are more retroreflective than yellow markings (Figure 24). Therefore, separate models were developed for white and yellow markings.

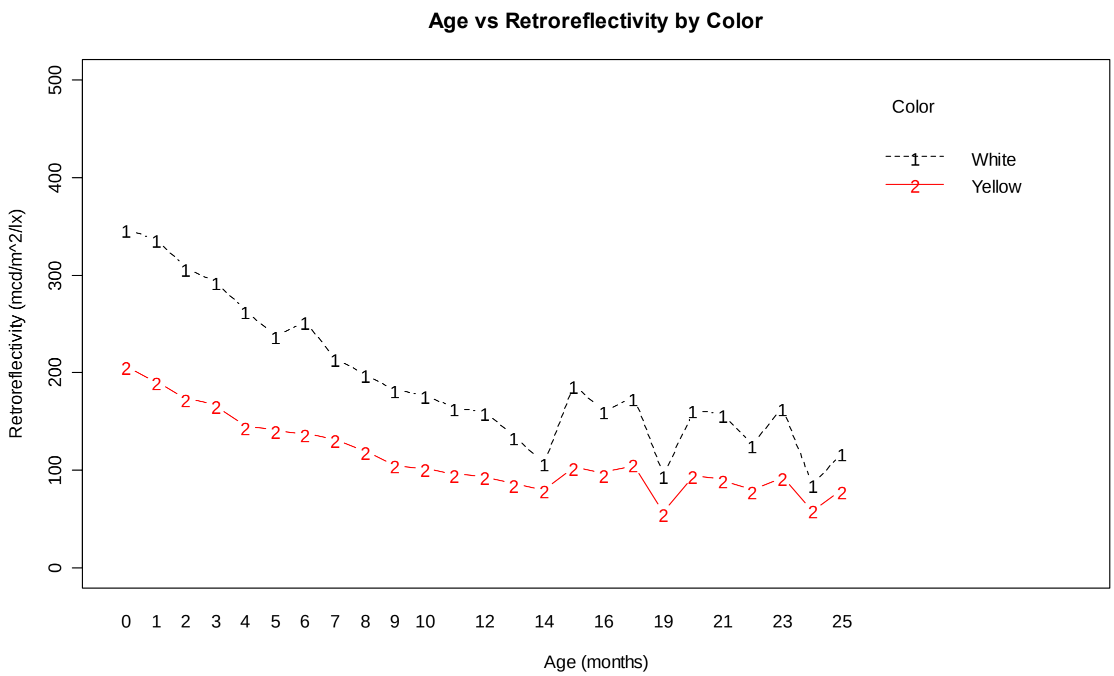


Figure 24. Marking age versus average retroreflectivity by color (Source: NTPEP data)

5.1.1.3. Material Type Effect

Table 44 shows the total number of NTPEP observations, after the removal of outliers, by material type, where an observation is a published NTPEP retroreflectivity reading for a given condition. Observations are taken at centerline, left wheel, on asphalt, and on concrete. For every 100 observations taken by NTPEP:

- 25% of the observations are centerline on asphalt;
- 25% of the observations are centerline on concrete;
- 25% of the observations are left wheel on asphalt; and
- 25% of the observations are left wheel on concrete.

Table 44. Total number of NTPEP observations by material type

Marking Material Type	Number of NTPEP Observations	Percent of NTPEP Observations
Cold Liquid Plastic	176	0.38%
Epoxy	3748	8.05%
Methyl Methacrylate	582	1.25%

Modified Urethane	40	0.09%
Permanent Tape	2452	5.27%
Poly-Cement	88	0.19%
Polyester	210	0.45%
Polyurea	40	0.09%
Solvent	1315	2.82%
Thermoplastic	18793	40.37%
Waterborne	19110	41.05%
Total	**46554**	**100%**

Based upon the number of available observations, epoxy, methyl methacrylate, permanent tape, solvent, thermoplastic and waterborne have sufficient data to be modeled. It was concluded, based upon the number of observations and the high variance of the data, that there were insufficient data to reliably model the remaining five material types:

1. Cold liquid plastic;
2. Modified urethane;
3. Poly-cement;
4. Polyester; and
5. Polyurea.

Waterborne, thermoplastic, epoxy and solvent represent about 95% of the materials tested by NTPEP.

A non-linear least square regression method was used to estimate the model parameters. A summary of the model parameters for color and material type is presented in Table 45.

Table 45. Summary of model parameters by color and material type for all climate regions and snow removal

	β_0	β_1	β_2
Epoxy White all Climate Regions and all Snow Removal	2.95E-03	6.96E-05	-6.01E-07
Epoxy Yellow all Climate Regions and all Snow Removal	4.22E-03	1.33E-04	-8.40E-07
Methyl Methacrylate White all Climate Regions all Snow Removal	2.65E-03	8.81E-05	3.00E-07
Methyl Methacrylate Yellow all Climate Regions all Snow Removal	5.56E-03	8.76E-05	6.57E-06
Permanent Tape White all Climate Regions all Snow Removal	1.82E-03	1.96E-04	7.40E-07
Permanent Tape Yellow all Climate Regions all Snow Removal	2.59E-03	4.01E-04	-1.10E-07
Solvent White all Climate Regions all Snow Removal	5.49E-03	3.35E-04	1.25E-05
Solvent Yellow all Climate Regions all Snow Removal	7.82E-03	4.30E-04	1.40E-05
Thermoplastic White Hot Humid and No Snow Removal*	2.42E-03	1.32E-04	-1.18E-06
Thermoplastic Yellow Hot Humid and No Snow Removal*	4.89E-03	1.85E-04	-8.00E-08
Waterborne White Hot Humid and No Snow Removal*	2.81E-03	2.19E-04	-4.14E-06
Waterborne Yellow Hot Humid and No Snow Removal*	4.20E-03	3.83E-04	-1.75E-06

* Note that snow removal models for waterborne and thermoplastic are not presented here since more detailed models for amount of snowfall are introduced later.

The goodness of fit of the models was examined graphically by plotting observed and predicted retroreflectivity and the corresponding cumulative residual (CURE) plot. In addition to using the CURE plot, the predicted models were required to meet requirements based upon known pavement marking properties. For example, the predicted retroreflectivity must not trend upwards over time during the second year since markings fade over time. This sometimes meant selecting a somewhat poorer fitting CURE plot in order to choose a model which did not show increasing retroreflectivity over time. A second requirement was that the white and yellow predicted values for the same material should not cross. White markings are always more retroreflectivity than yellow markings for the same material, and the prediction should reflect this. The CURE plots presented reflect the trade-off between best fitting models and models which fit known marking properties.

Figure 25 to Figure 30 show the observed and predicted retroreflectivity and corresponding CURE plots for the color, material and age models. Based upon the CURE plots, these models are considered good predictors of the average retroreflectivity as a function of color, material type, and age.

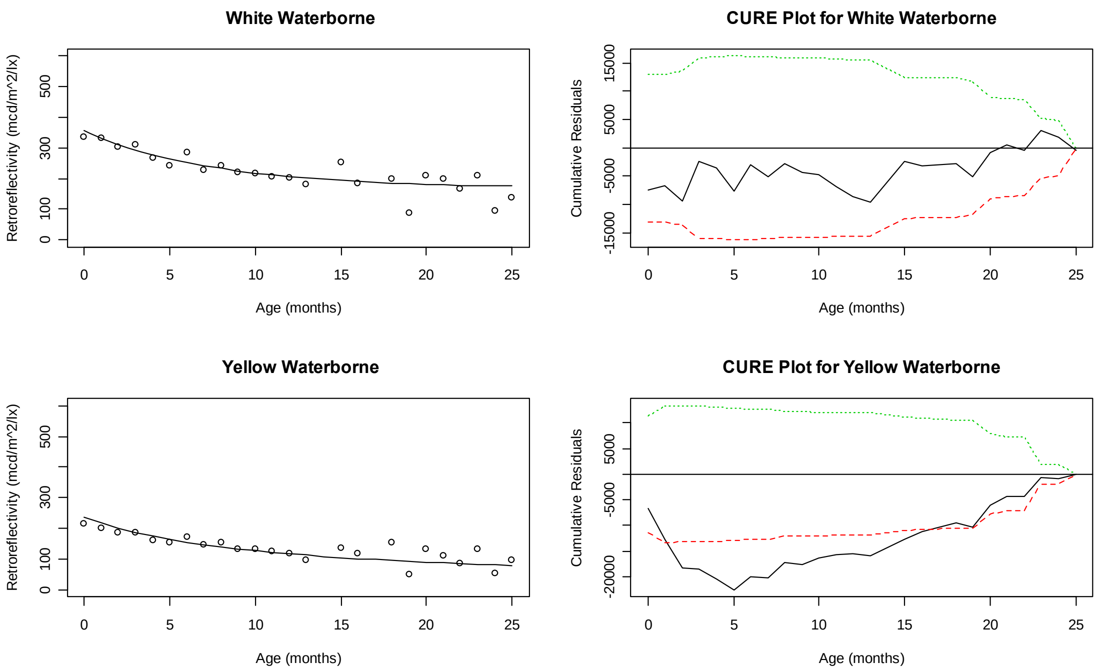


Figure 25. Observed and predicted average retroreflectivity for white and yellow waterborne and corresponding CURE plots (Source: NTPEP data)

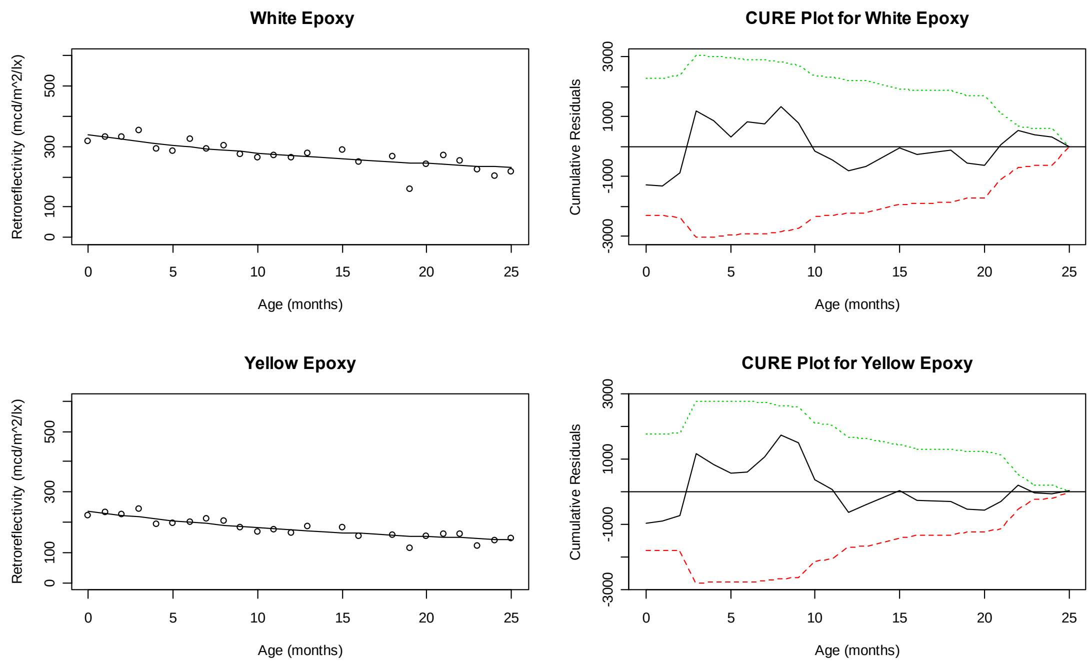


Figure 26. Observed and predicted average retroreflectivity for white and yellow epoxy and corresponding CURE plots (Source: NTPEP data)

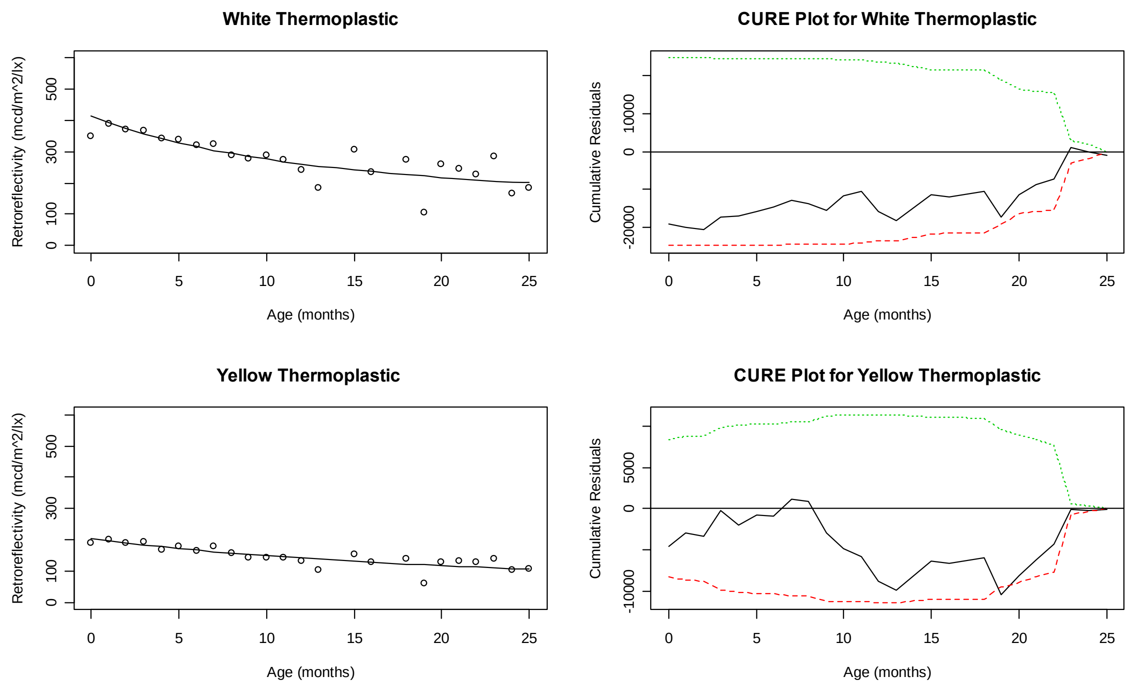


Figure 27. Observed and predicted average retroreflectivity for white and yellow thermoplastic and corresponding CURE plots (Source: NTPEP data)

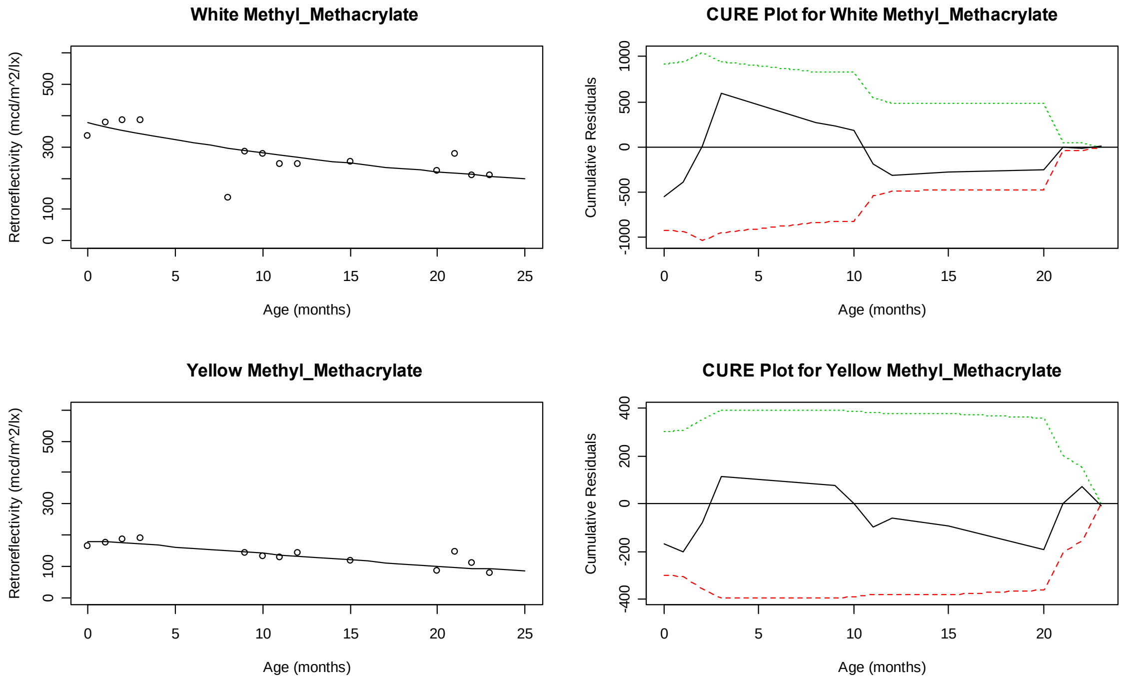


Figure 28. Observed and predicted average retroreflectivity for white and yellow methyl methacrylate and corresponding CURE plots (Source: NTPEP data)

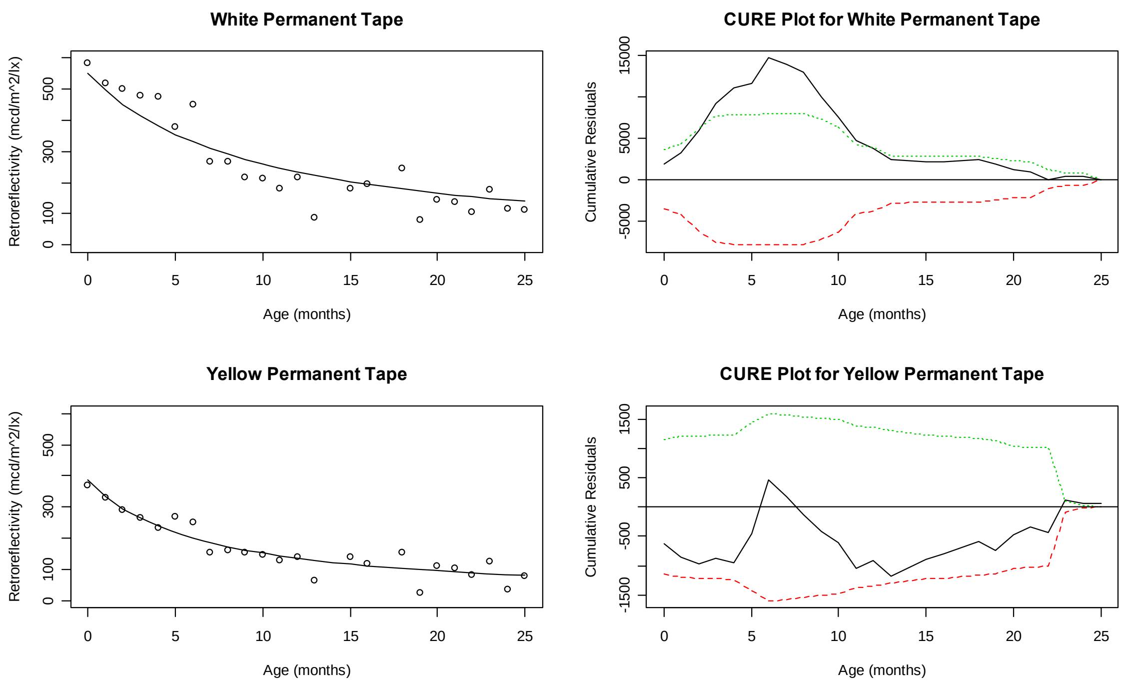


Figure 29. Observed and predicted average retroreflectivity for white and yellow permanent tape and corresponding CURE plots (Source: NTPEP data)

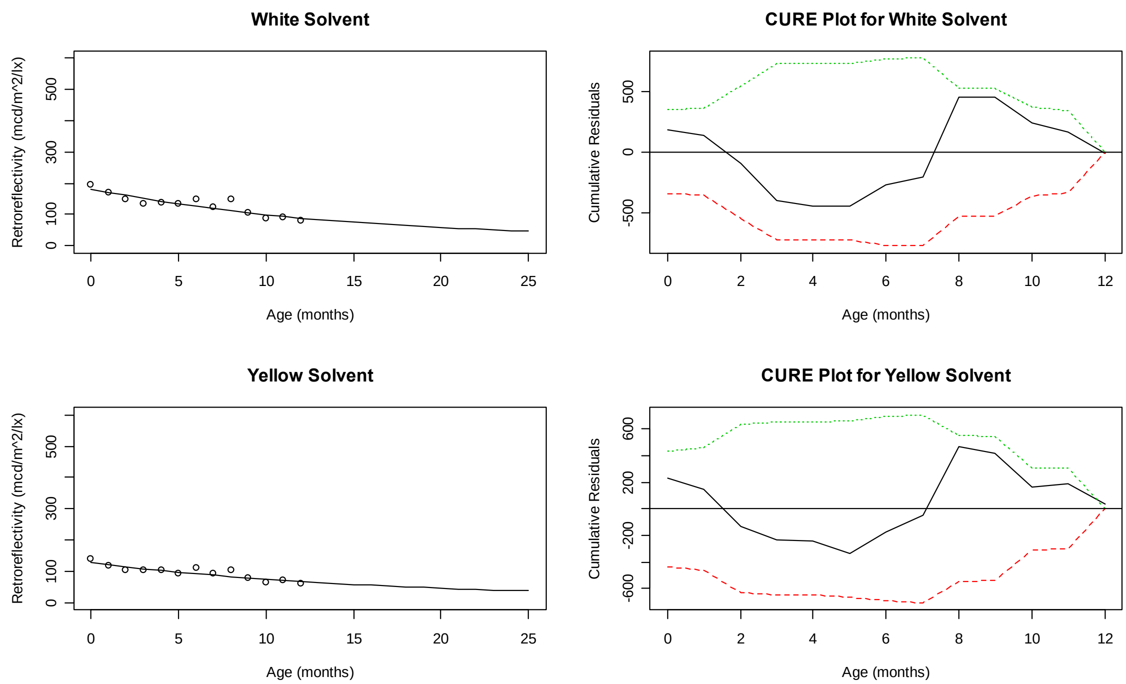


Figure 30. Observed and predicted average retroreflectivity for white and yellow solvent and corresponding CURE plots (Source: NTPEP data)

5.1.1.4. Traffic Volume Effect

The distribution of number of observations by AADT is given in Table 46. Traffic volume (AADT) data were apportioned into two roughly equal bins (or categories) in terms of the number of observations, with one bin having traffic volume less than or equal to 9,000 vehicles per day and the other having traffic volume greater than 9,000 vehicles per day. A scatter plot of the four major material types (waterborne, thermoplastic, epoxy and solvent) by AADT can be seen in Figure 31 and Figure 32.

Table 46. Number of observations by AADT for markings in NTPEP data

AADT	Number of NTPEP Observations	Percent of NTPEP Observations
5000	8034	17.26%
5500	2308	4.96%
8000	4196	9.01%
9000	4254	9.14%
10000	8268	17.76%
11600	2450	5.26%
12000	5680	12.20%
12195	2694	5.79%
13100	2478	5.32%
15000	2790	5.99%
20000	2742	5.89%
160000	660	1.42%
Total	46554	100.00%

In Figure 31, epoxy and solvent have randomly distributed observed values indicating that the AADT effect on the retroreflectivity is not useful for improving the prediction of retroreflectivity. In Figure 32, for thermoplastic and waterborne materials, the observed retroreflectivity is less than the predicted values in the case of low AADT and more in the case of high AADT. In other words, lower traffic volume areas indicated lower retroreflective levels while higher traffic volume areas indicated higher retroreflective levels. This contradicts the intuitive expectation that pavement markings fade faster with higher traffic volume. Given that the AADT effect is not consistent across different material types and unexplained for some, the research team decided not to use AADT for retroreflectivity prediction.

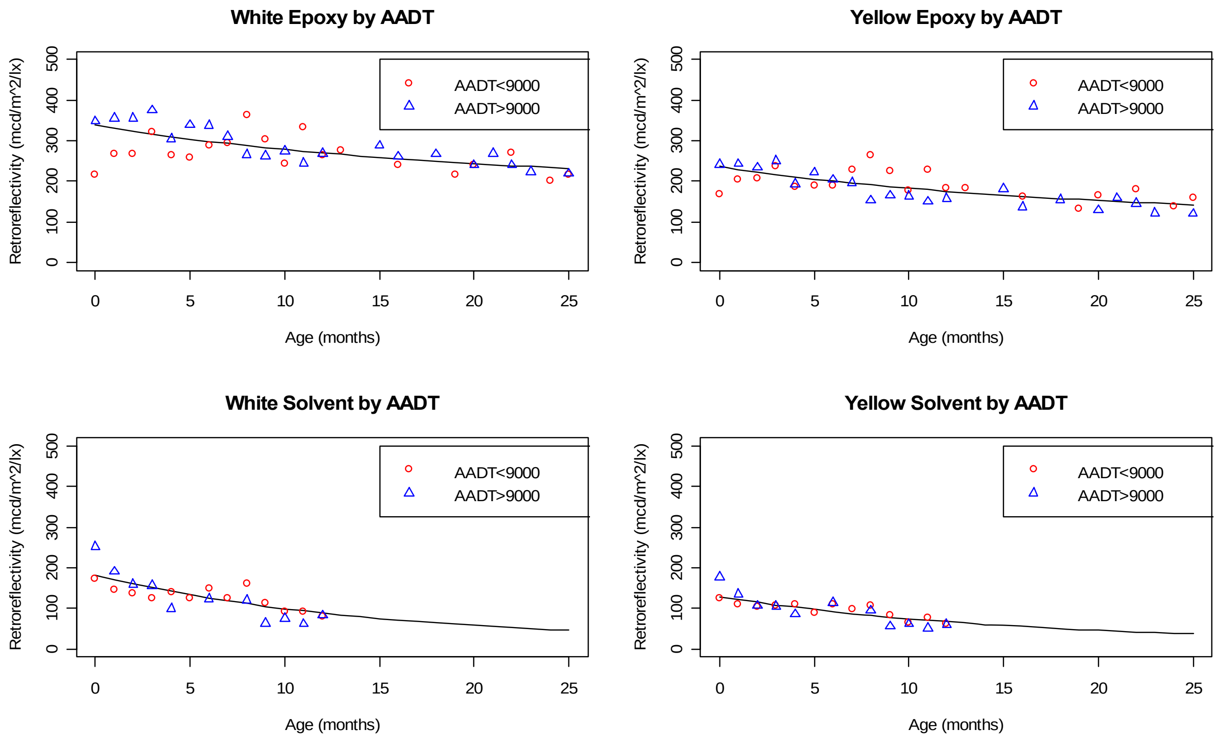


Figure 31. Distribution of AADT for white and yellow epoxy and solvent (Source: NTPEP data)

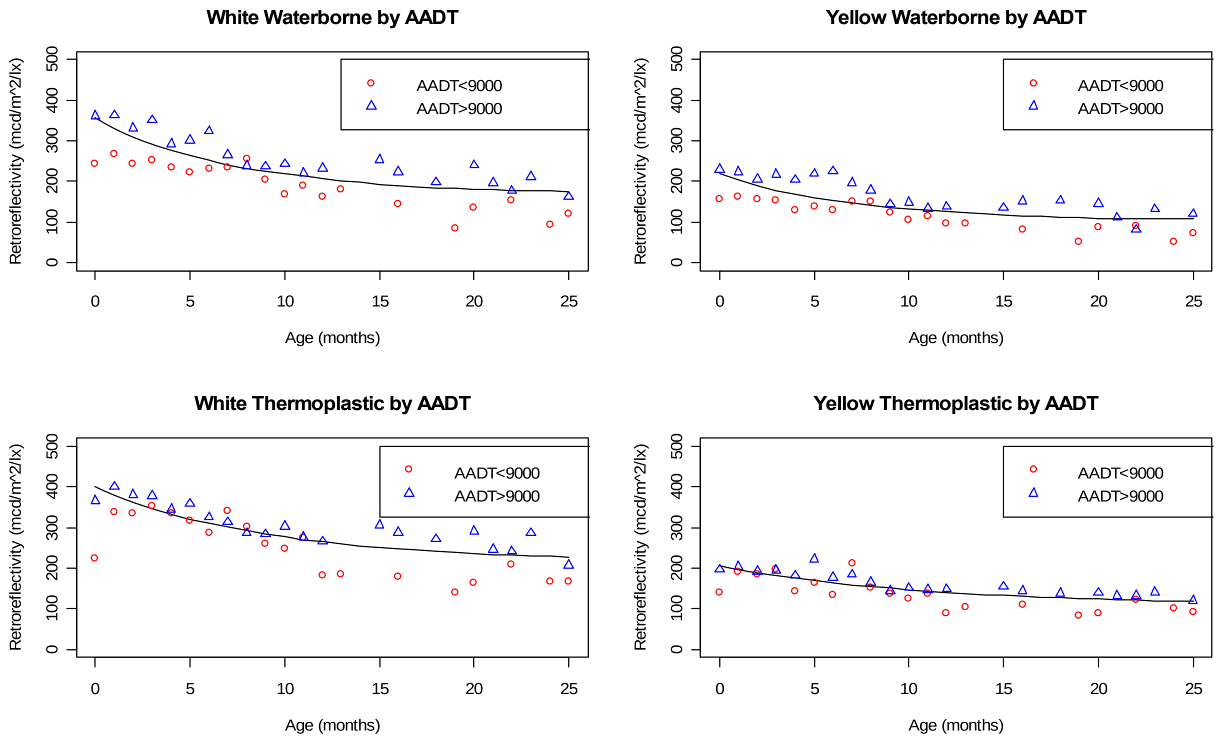


Figure 32. Distribution of AADT for white and yellow waterborne and thermoplastic (Source: NTPEP data)

5.1.1.5. Pavement Surface Type Effect

NTPEP markings are tested upon two different pavement surfaces: concrete and asphalt. The effect of pavement surface on retroreflectivity was examined through residual plots. The color scatter plot in Figure 33 of the observed retroreflectivity by surface type for white and yellow waterborne and thermoplastic versus the model shows no systematic residual pattern of the residuals. This leads to the conclusion that the effect of surface type on retroreflectivity is not useful for improving the prediction of retroreflectivity.

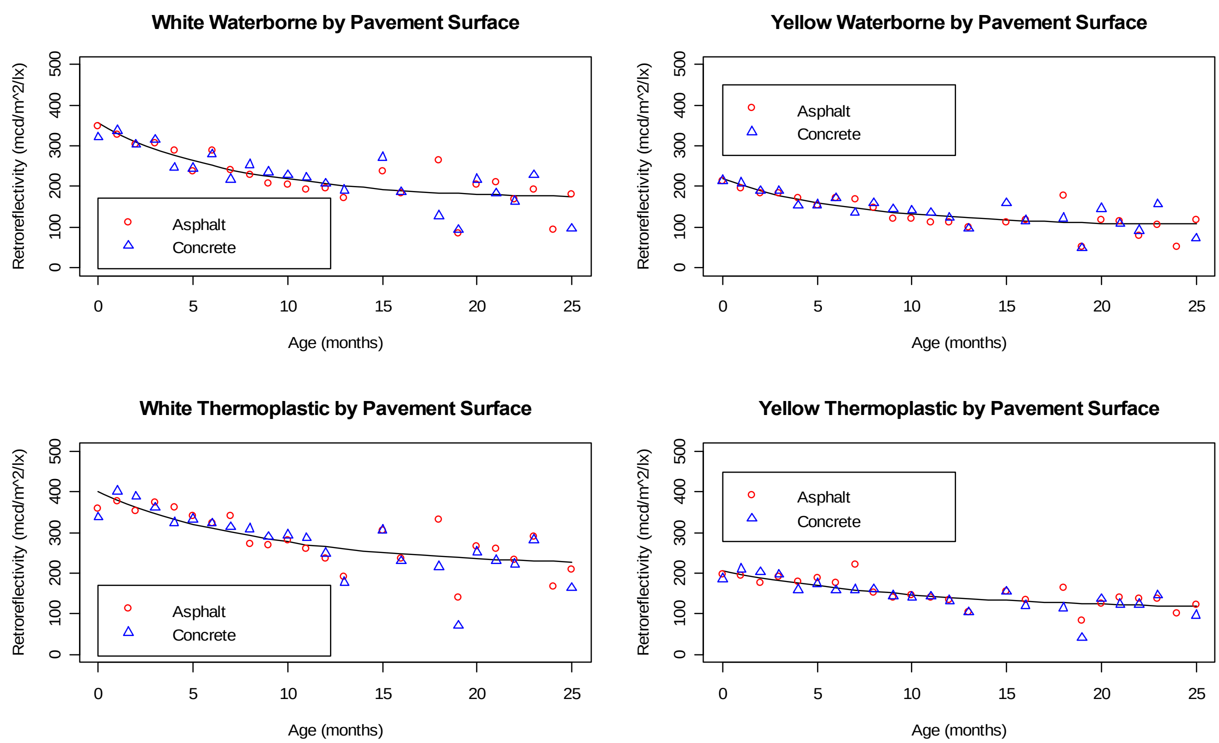


Figure 33. Marking age by pavement surface for white and yellow waterborne and thermoplastic (Source: NTPEP data)

5.1.1.6. Climate Region Effect

The available NTPEP data include retroreflectivity readings taken in four climate regions; cold, hot dry, mixed humid, and hot humid. Systematic patterns of residuals were noticed in the thermoplastic materials of both white and yellow markings for hot dry and mixed humid climate regions. For both white and yellow thermoplastic materials in hot-dry regions, the observed retroreflectivity values were consistently less than the predicted values. For thermoplastic and waterborne materials in mixed humid climate regions the observed retroreflectivity values were consistently higher than the predicted values.

For the climate region models, there are a total of 6 models combinations with sufficient data for separate models. Building separate models is based the availability of NTPEP data, which is shown in Table 47, and data which show a different prediction pattern. While all climate regions were explored, only 6 climate region material combinations were sufficiently distinct from the other climate region material combinations. If a climate region does not have a separate model for a particular material type, that means that prediction differences due to climate region could not be identified from the data. Four models are based on the combinations of white and yellow thermoplastic hot dry and mixed humid, and two models are based on white and yellow waterborne mixed humid.

Table 47. Number of NTPEP observations by climate region and material type

Material Type	Cold	Hot-Dry	Hot-Humid	Mixed-Humid
Cold Liquid Plastic	176	0	0	0
Epoxy	2670	0	568	510
Methyl Methacrylate	582	0	0	0
Modified Urethane	0	40	0	0
Permanent Tape	1464	100	616	272
Poly-Cement	88	0	0	0
Polyester	210	0	0	0
Polyurea	0	40	0	0
Solvent	929	0	386	0
Thermoplastic	9427	480	6290	2596
Waterborne	11438	0	5518	2154
Total	**26984**	**660**	**13378**	**5532**

The color, material and age model parameters for waterborne and thermoplastic materials were recalibrated to account for the effect of hot dry and mixed humid climate regions. The revised model parameters are shown in Table 48. The climate region predictions and corresponding CURE plots are shown in Figure 34to Figure 36. For the other two climate regions and materials, the research team concluded that the climate region would not bring enhancement to the previous models (Table 45).

Table 48. Summary of revised model parameters for color, material, climate region and age models

	β_0	β_1	β_2
Waterborne White Mixed-Humid Climate and No Snow Removal	2.99E-03	1.21E-04	1.00E-07
Waterborne Yellow Mixed-Humid Climate and No Snow Removal	4.25E-03	1.35E-04	-1.00E-09
Thermoplastic White Mixed-Humid Climate and No Snow Removal	2.52E-03	9.31E-05	-3.30E-07
Thermoplastic Yellow Mixed-Humid Climate and No Snow Removal	3.99E-03	1.79E-04	8.70E-07
Thermoplastic White Hot-Dry Climate and No Snow Removal	3.02E-03	1.79E-04	-2.48E-06
Thermoplastic Yellow Hot-Dry Climate and No Snow Removal	6.38E-03	2.58E-04	-1.30E-07

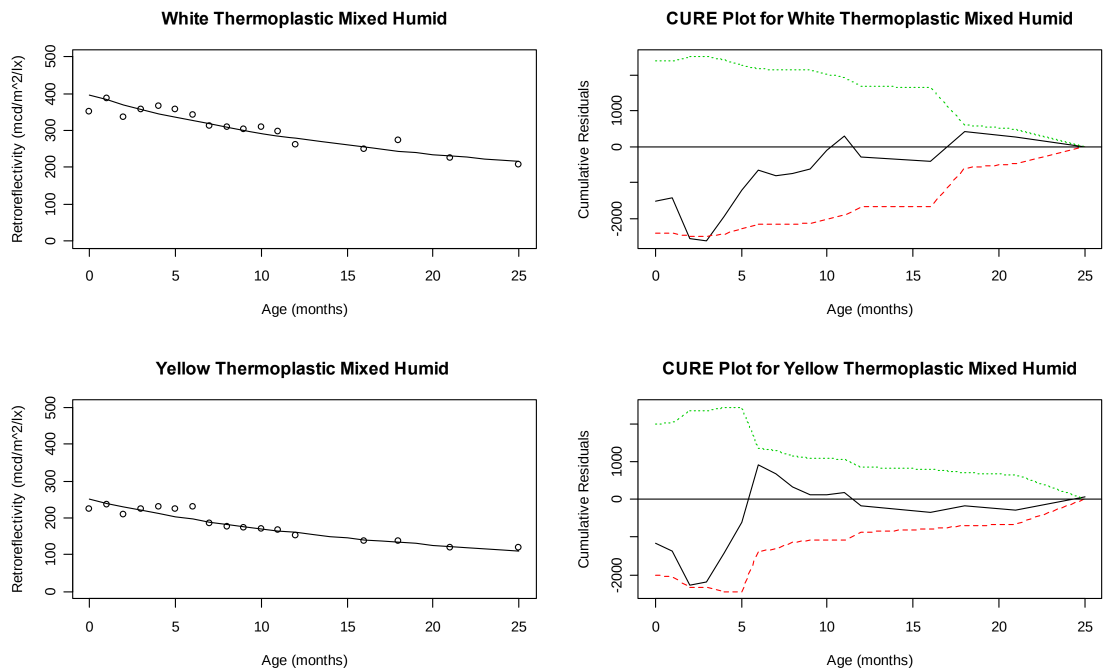


Figure 34. Marking age versus average retroreflectivity by white and yellow thermoplastic mixed humid and corresponding CURE plots (Source: NTPEP data)

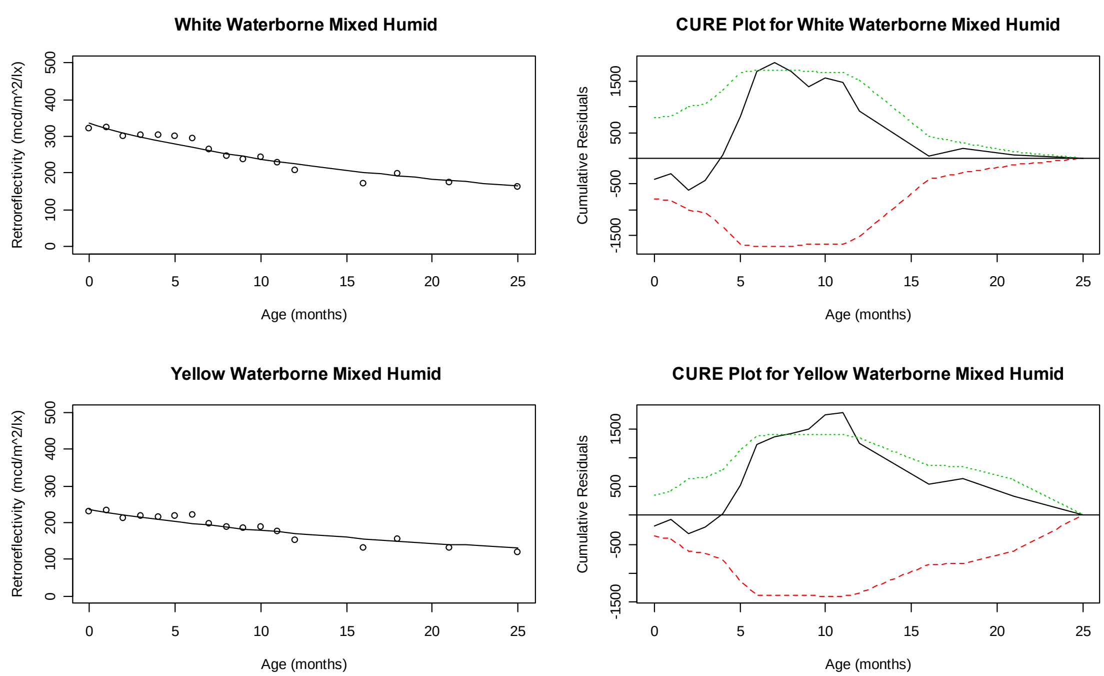


Figure 35. Marking age versus average retroreflectivity for white and yellow waterborne mixed humid and corresponding CURE plots (Source: NTPEP data)

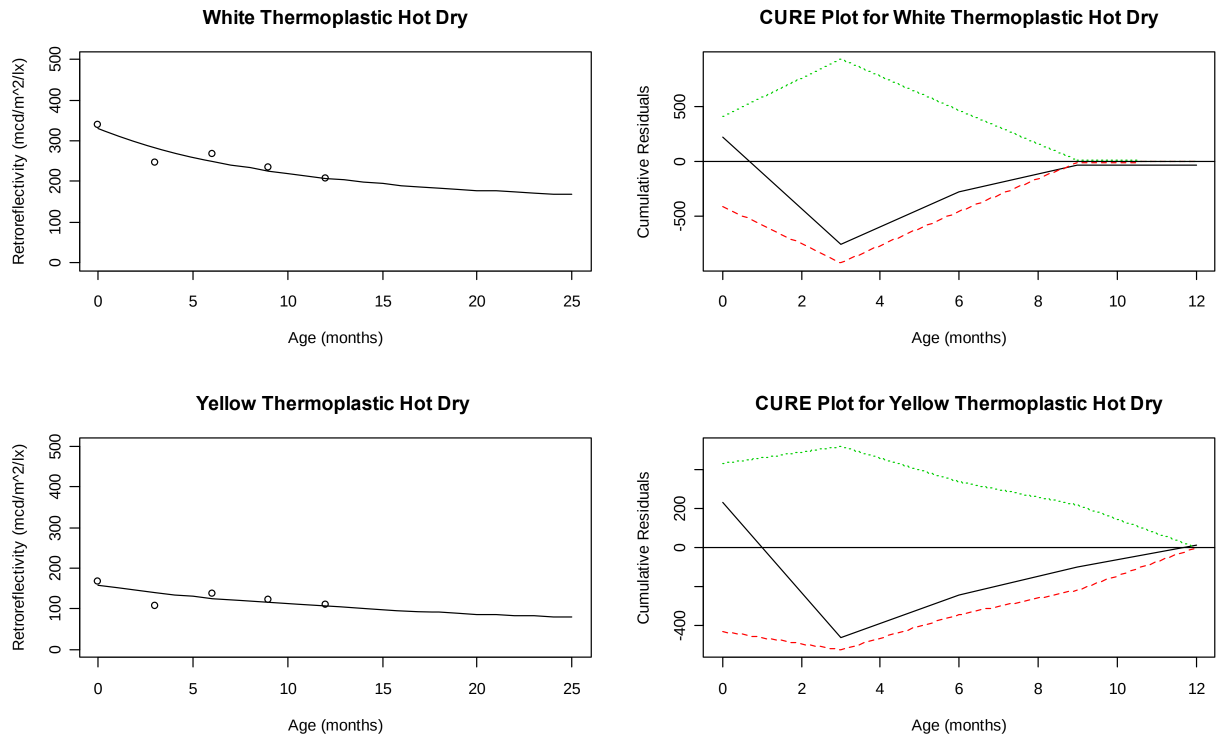


Figure 36. Marking age versus average retroreflectivity for white and yellow thermoplastic hot dry and corresponding CURE plots (Source: NTPEP data)

5.1.1.7. Snow Removal Effect

The amount of snow removal was determined based upon the number of snowplow events recorded at the NTPEP test deck. Snow removal categories of low to medium and heavy were developed based upon the recorded number of snowplow events, as given in Table 49. No snow removal occurs in climate regions hot dry, hot humid or mixed humid. Low to medium and heavy snow removal only occurs in cold climate regions. Only one test deck provided data the heavy snow removal category.

Table 49. Categories for snow removal

Snow Removal Category	Amount of Snow (inches)	Number of Snowplow Events
Low to Medium	27" – 50.3"	42- 95
Heavy	201"	401

Snowplow events have the effect of scrapping the retroreflective beads and binder material off of the pavement surface, thus reducing retroreflectivity. This snow removal effect was noticeable for waterborne and thermoplastic materials of both colors under heavy snow removal conditions.

In the case of heavy snow removal areas, the observed retroreflectivity values were consistently less than the predicted. In the case of low to medium snow removal areas, the observed retroreflectivity values were consistently higher than the predicted. The parameter estimates from Table 45 for waterborne and thermoplastic materials of both colors were recalibrated to account for the effect of snow removal. Table 50 shows the revised model parameters.

Table 50. Summary of revised parameters for white and yellow waterborne and thermoplastic by snow removal effect

	β_0	β_1	β_2
Waterborne White Cold Climate and Heavy Snow Removal	3.03E-03	-8.32E-05	6.80E-05
Waterborne Yellow Cold Climate and Heavy Snow Removal	4.78E-03	-9.95E-05	1.03E-04
Waterborne White Cold Climate and Low to Medium Snow Removal	2.92E-03	1.44E-04	-1.22E-06
Waterborne Yellow Cold Climate and Low to Medium Snow Removal	4.45E-03	3.01E-04	-4.76E-09
Thermoplastic White Cold Climate and Heavy Snow Removal	2.63E-03	-1.29E-05	3.92E-05
Thermoplastic Yellow Cold Climate and Heavy Snow Removal	4.72E-03	-8.33E-05	6.37E-05
Thermoplastic White Cold Climate and Low to Medium Snow Removal	2.37E-03	1.22E-04	-2.16E-06
Thermoplastic Yellow Cold Climate and Low to Medium Snow Removal	4.75E-03	1.53E-04	-1.60E-07

Figure 37 to Figure 40 display the observed and predicted values and corresponding CURE plots for the white and yellow thermoplastic, and white and yellow waterborne by snow removal.

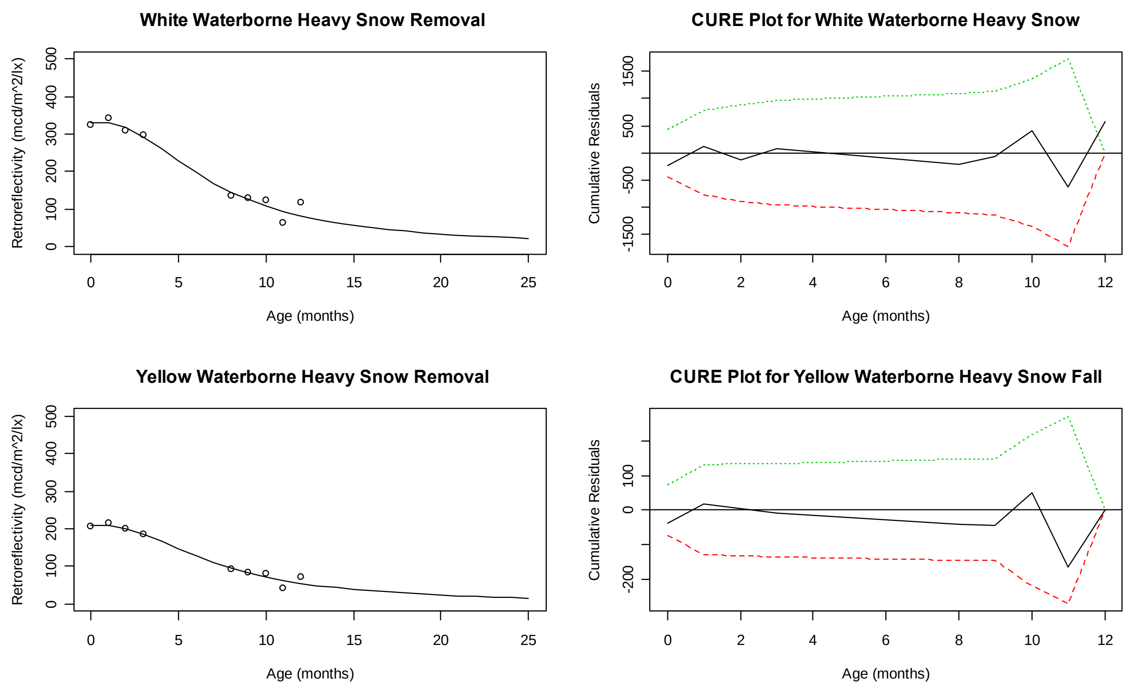


Figure 37. Pavement marking age for white and yellow waterborne by heavy snow removal (Source: NTPEP data)

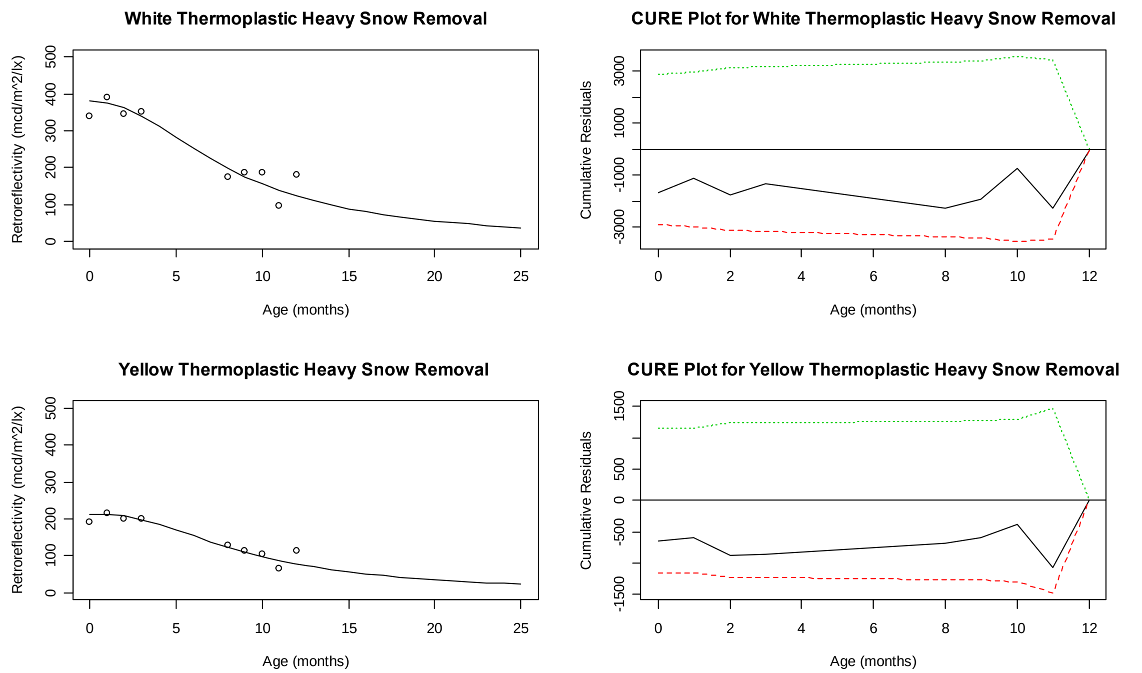


Figure 38. Pavement marking age for white and yellow thermoplastic by heavy snow removal (Source: NTPEP data)

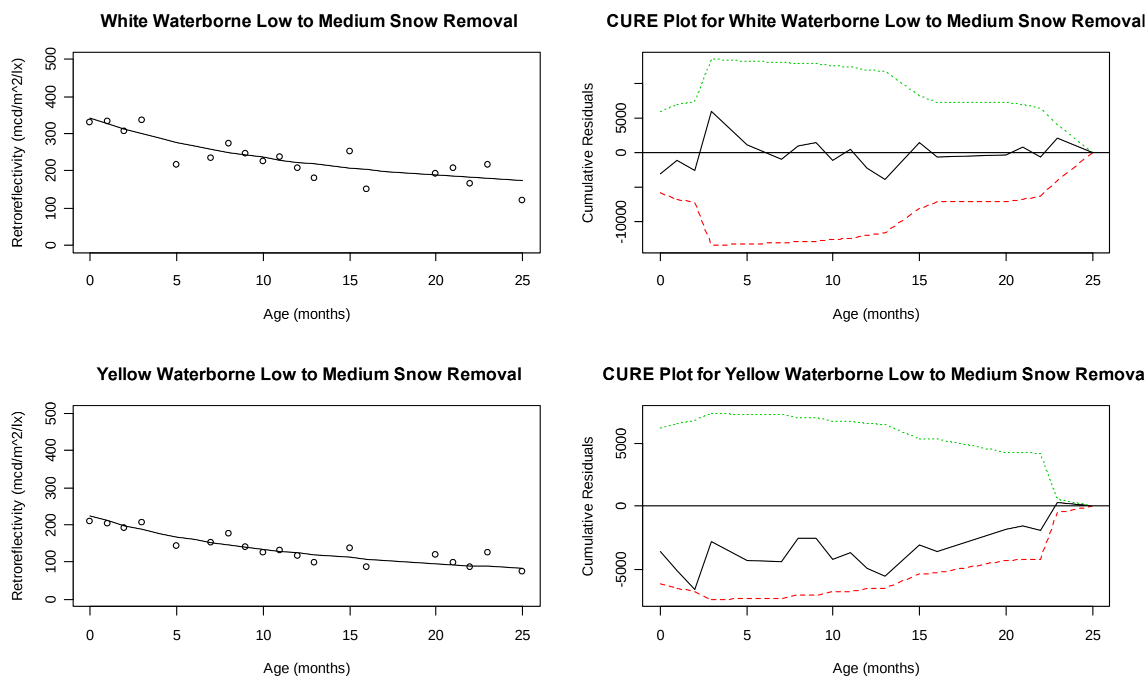


Figure 39. Pavement marking age for white and yellow waterborne by low to medium snow removal (Source: NTPEP data)

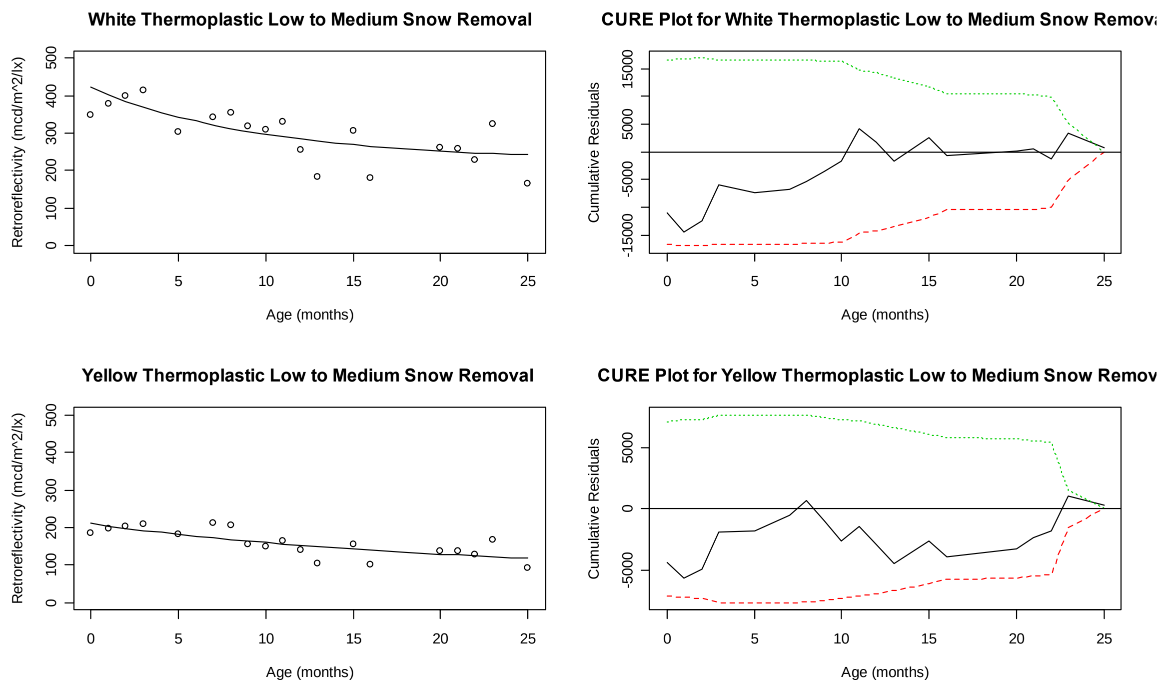


Figure 40. Pavement marking age for white and yellow thermoplastic by low to medium snow removal (Source: NTPEP data)

5.1.2. Retroreflectivity Modeling of Pavement Markers

The retroreflectivity of pavement markers were examined as a function of

- Age;
- Marker type;
- Pavement surface;
- Snow removal; and
- Traffic volume.

5.1.2.1. Age Effect

The goal of the retroreflectivity analysis is to develop statistical models that can be used to estimate the average retroreflectivity of pavement markers. The first step in developing a statistical model is to study the relationship between the different explanatory variables through visual inspection of main effect and interaction plots.

Figure 41 shows the relationship between age and retroreflectivity of pavement markers. As pavement markers age, their retroreflectivity decreases in a non-linear manner. The non-linear decrease can be seen by the line representing the average retroreflectivity at each age. Figure 41 also depicts the amount of variability in retroreflectivity for markers at the same age.

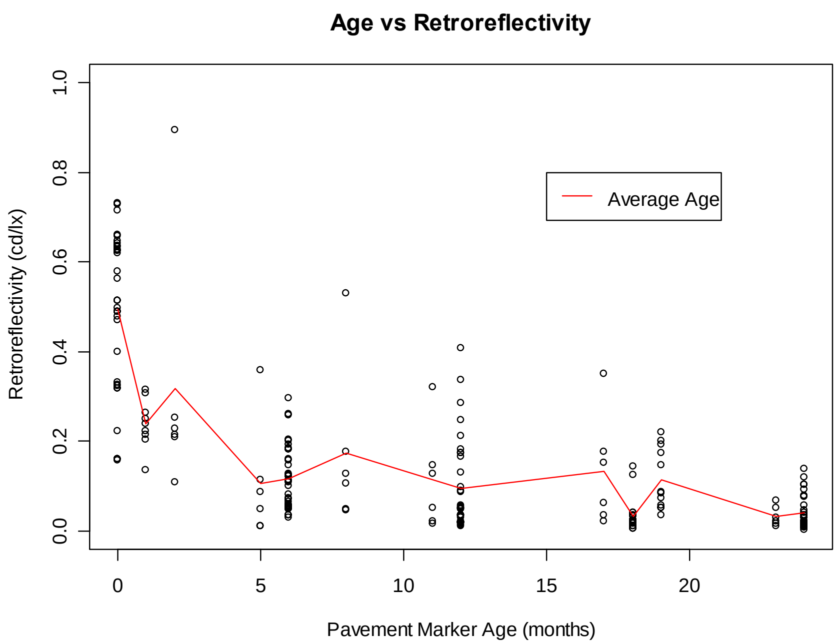


Figure 41. Marker age versus retroreflectivity (Source: NTPEP data)

Through exploratory analysis, it was determined that the relationship between age and average retroreflectivity is best explained by the same model form used for markings. Using Equation 6 the following inverse polynomial model was fit to the marker data:

Equation 6

$$R = \frac{1}{\beta_0 + \beta_1 * Age + \beta_2 * Age^2}$$

Where

R: retroreflectivity of pavement markers (cd/lx)

Age: age of pavement marker (months)

$\beta_0, \beta_1, \beta_2$: model parameters to be estimated

5.1.2.2. Marker Type Effect

Marker type refers to the marker being either plowable or non-plowable. After further exploratory data analysis, it was found that plowable markers are more retroreflective than non-plowable markers, as shown in Figure 42. As a result of the findings separate inverse polynomial models were developed for plowable and non-plowable markers.

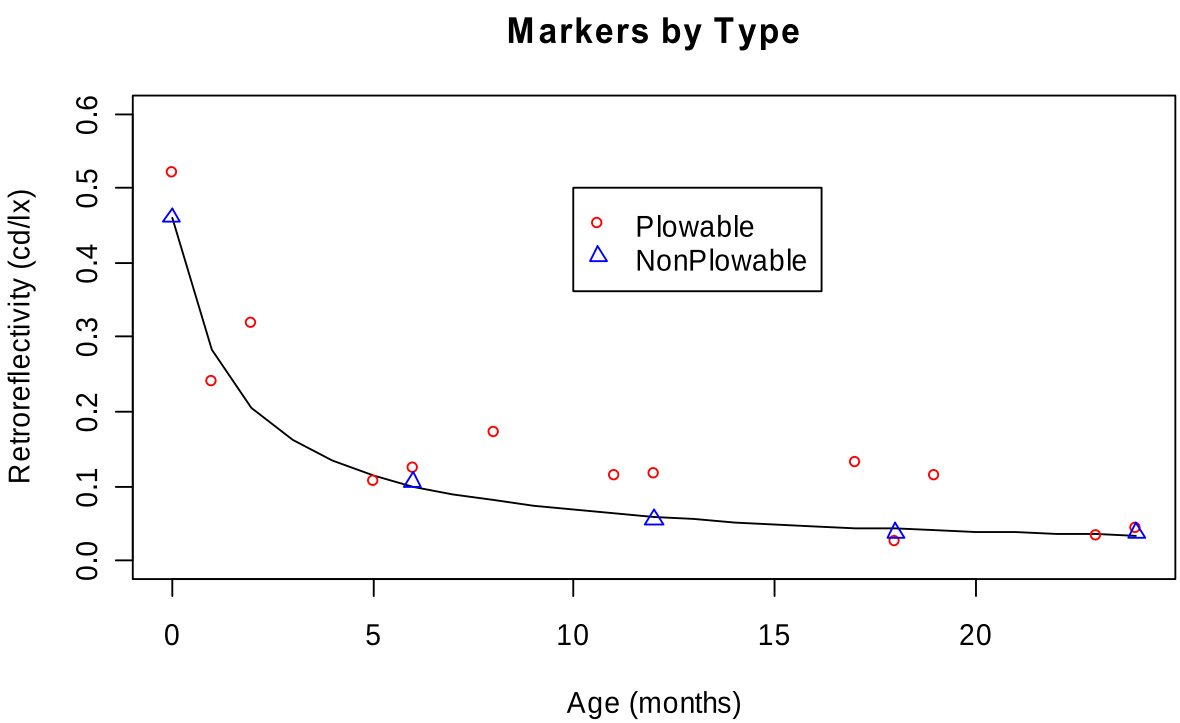


Figure 42. Distribution of marker type (Source: NTPEP data)

A non-linear least square regression method was used to estimate the model parameters. The goodness of fit of the models was examined graphically by plotting observed and predicted retroreflectivity and the corresponding cumulative residual (CURE) plots. The observed and predicted and corresponding CURE plots can be seen in Figure 43. A summary of model parameters for the inverse polynomial model of non-plowable and plowable markers can be found in Table 51. Based upon the CURE plots, these models are considered good predictors of the average retroreflectivity as a function of age and marker type.

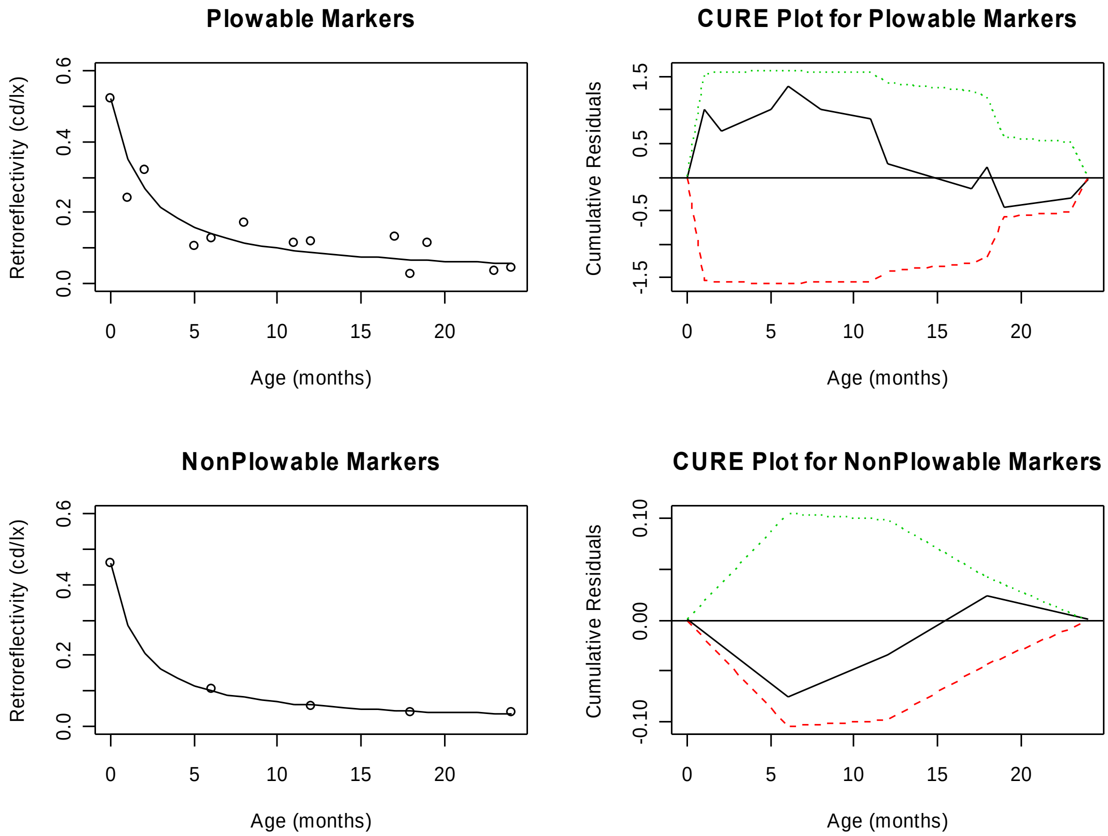


Figure 43. Observed and predicted average retroreflectivity for plowable and non-plowable markers and corresponding CURE plots (Source: NTPEP data)

Table 51. Summary of model parameters by type

	β_0	β_1	β_2
Non-plowable all colors, climate regions, and snow removal	2.17	1.36	-1.00E-02
Plowable all colors, climate regions, and snow removal	1.92	9.40E-01	-1.20E-02

5.1.2.3. Pavement Surface Type Effect

The inverse polynomial models of age non-plowable, and age plowable markers were used to evaluate the effects of the following variables:

- surface type;
- snow removal; and
- traffic volume (AADT).

The effect of pavement surface on retroreflectivity can be seen in Figure 44. No systematic pattern was noticed in the distributions of pavement surface for asphalt or concrete indicating that the effect of surface type on the retroreflectivity of pavement markers is not useful in improving the prediction of retroreflectivity.

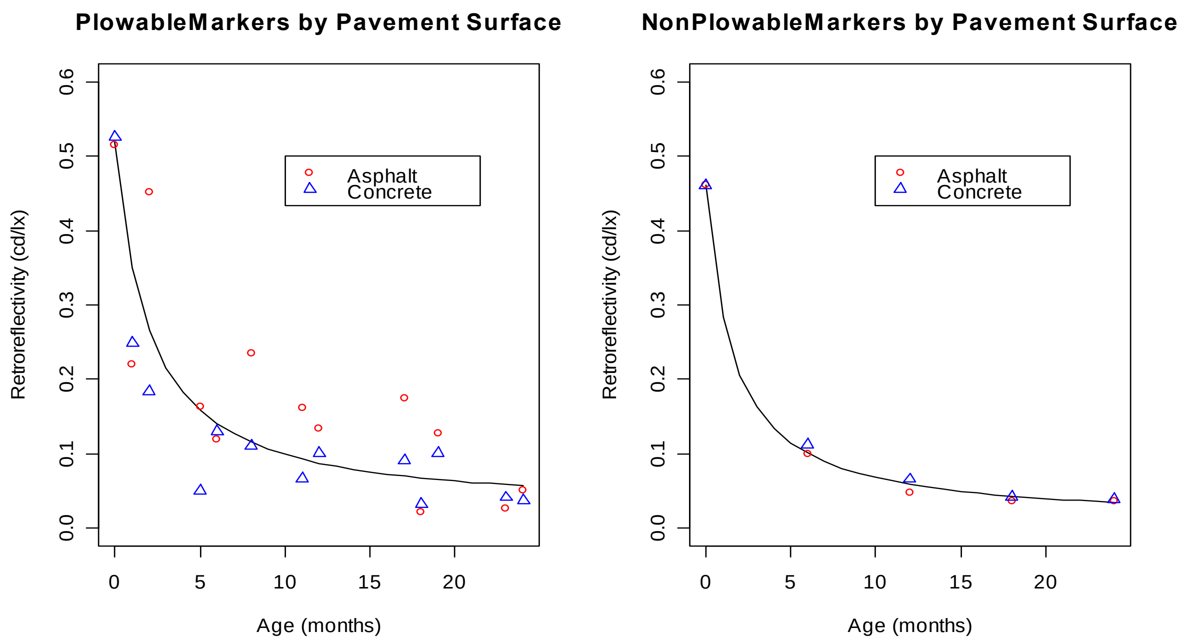


Figure 44. Distribution of pavement surface (Source: NTPEP data)

5.1.2.4. Snow Removal Effect

The amount of snow removal was determined based upon the number of snowplow events recorded at the NTPEP test deck. Snow removal categories were developed based on the recorded number of snowplow events taken place during the winter. These findings are summarized in Table 52.

The non-plowable marker model already considers the effect of no snow removal. As a result the effect of heavy and low to medium snow removal can be seen in Figure 45. Only one test deck provided data the heavy snow removal category.

Table 52. Categories for snow removal

Snow Removal Category	Amount of snow (inches)	Number of Snowplow Events
Low to Medium	24.3" – 25.7"	45-55
Heavy	58.2"	142

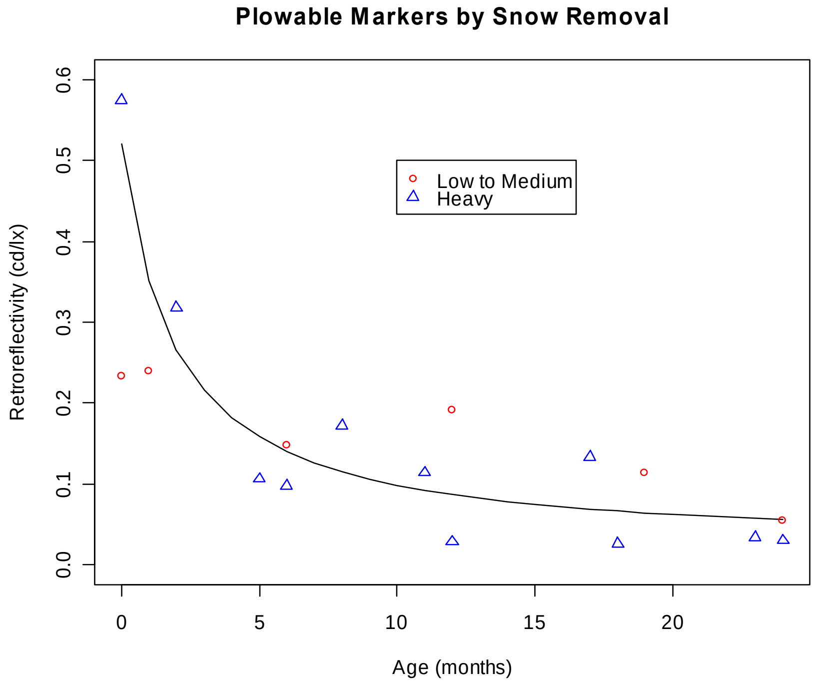


Figure 45. Distribution of snow removal (Source: NTPEP data)

In Figure 45, the effects of a low to medium snow removal and heavy snow removal are seen to be randomly distributed around the model. Thus, the effect of snow removal on markers retroreflectivity could not improve the prediction of average retroreflectivity.

5.1.2.5. Traffic Volume Effect

Traffic volume (AADT) data were apportioned into two separate bins (or categories) in order divide the number of observations roughly in half. The distribution of number of NTPEP observations for markers by AADT is shown in Table 53. Traffic volume less than or equal to 50,000 vehicles per day was defined as the lower volume bin, and the other bin having traffic volume greater than 50,000 vehicles per day was defined as the higher volume bin. The 50,000 cut-off was selected so that roughly the same number of NTPEP observations would occur in each bin. Figure 46 displays the distribution of lower AADT and higher AADT. The observed values of retroreflectivity are randomly distributed indicating that the traffic volume effect could not improve the prediction of average retroreflectivity.

Table 53. Number of observations by AADT for markers in NTPEP data

AADT	Number of NTPEP Observations	Percent of NTPEP Observations
37,200	30	14.29%
45,600	61	29.05%
61,800	30	14.28%
78,827	89	42.38%
Total	210	100.00%

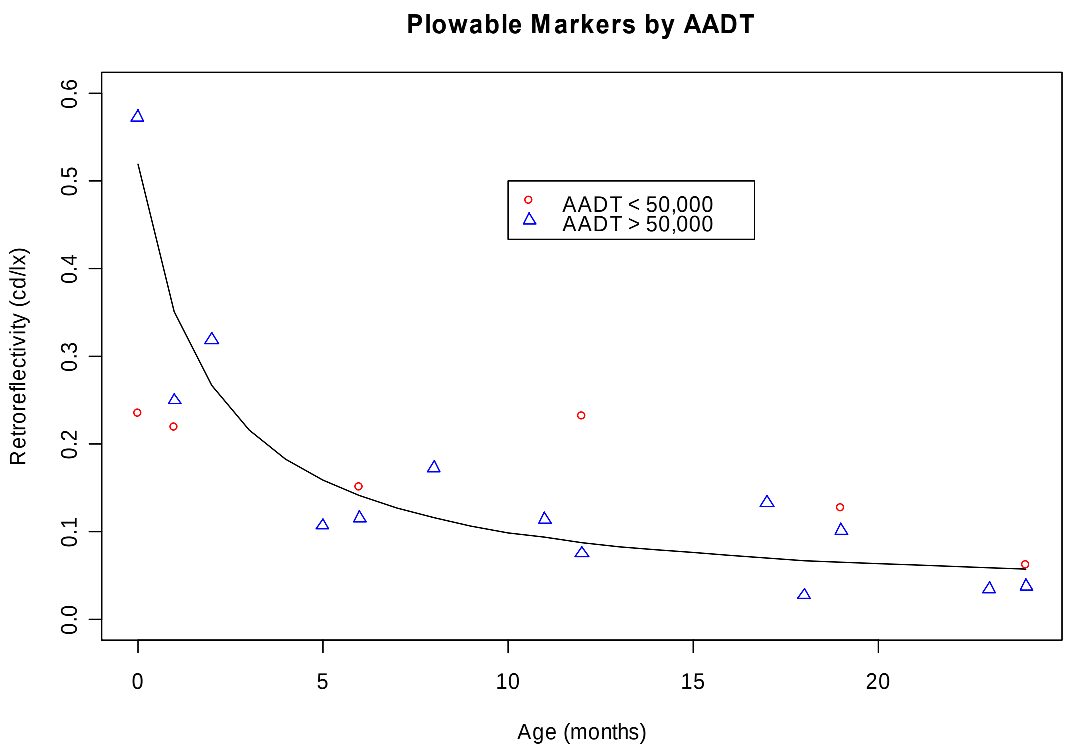


Figure 46. Distribution of AADT (Source: NTPEP data)

5.1.3. Retroreflectivity Prediction Beyond 25 Months

The retroreflectivity models for markings and markers were calibrated utilizing data from 0 to 25 months. NTPEP collects data for the first two years, after that the retroreflectivity of pavement markings is linear based upon observations from practitioners and industry (91,117). Using the parameters of the fitted inverse polynomial models (Table 45, Table 48, Table 50 and Table 51), it is possible to predict the retroreflectivity for 0 to 25 months. Beyond 25 month, retroreflectivity is assumed to be linearly decreasing with a constant decrement in each month. The constant decrement is equal to the difference between the 24th month and the 25th month. The models were used to predict retroreflectivity until 48 months.

In order to predict average retroreflectivity of markers and markings beyond 25 months, a linear extrapolation of the models for the first 25 months was used. The change in the predicted retroreflectivity from 25th to the 24th month was used to determine the slope of the prediction beyond 25 months. Equation 7 displays the formulation that was used.

$$R_N = -\lambda(Age - 25) + \delta$$ *Equation 7*

Where

R_N: retroreflectivity at month N

λ: $R_{24} - R_{25}$

R_{24}: retroreflectivity at 24th month

R_{25}: retroreflectivity at 25th month

δ: R_{25} - retroreflectivity at 25th month

Age: age of predicted marking

Using the age, color and material type marking models (Table 45), the retroreflectivity approaches zero at different times for each model. The predicted retroreflectivity from 0 to 48 months for white and yellow epoxy, methyl methacrylate, permanent tape and solvent can be seen in Figure 47.

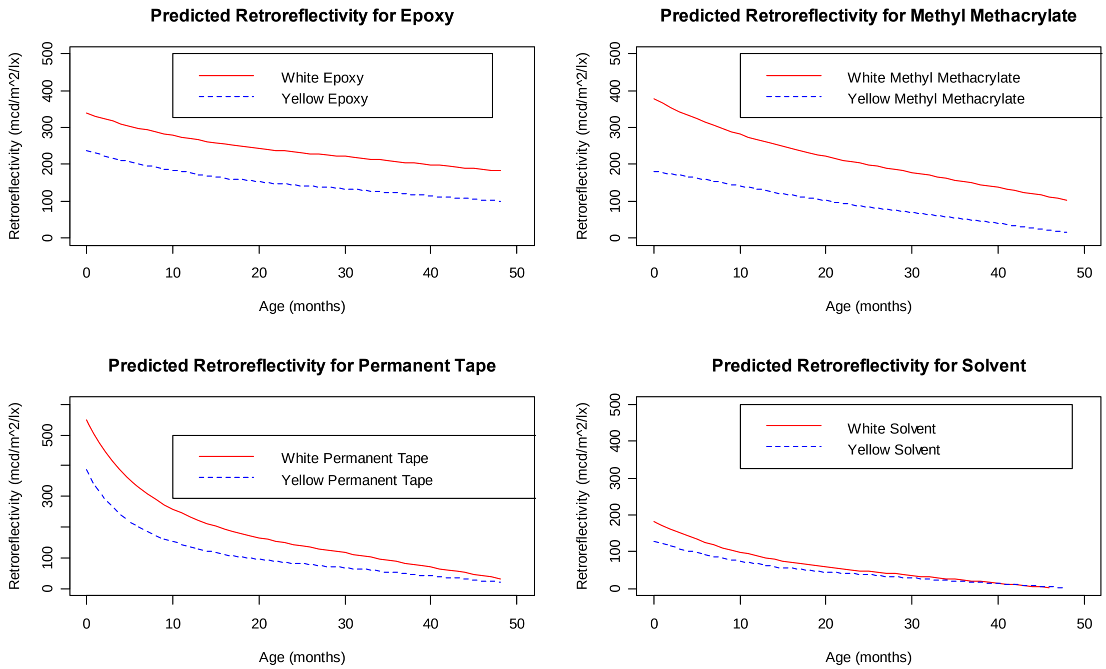


Figure 47. Predicted average retroreflectivity for epoxy, methyl methacrylate, permanent tape and solvent

White and yellow epoxy and white and yellow methyl methacrylate approach zero retroreflectivity after the projected 48 months. Permanent tape and solvent are approaching zero before 48 months.

Figure 48 displays the predicted retroreflectivity from 0 to 48 months for the four thermoplastic models and Figure 49 displays the predicted retroreflectivity from 0 to 48 months for the two waterborne models. The cold region models are confounded with the snow removal models and are discussed in a following section.

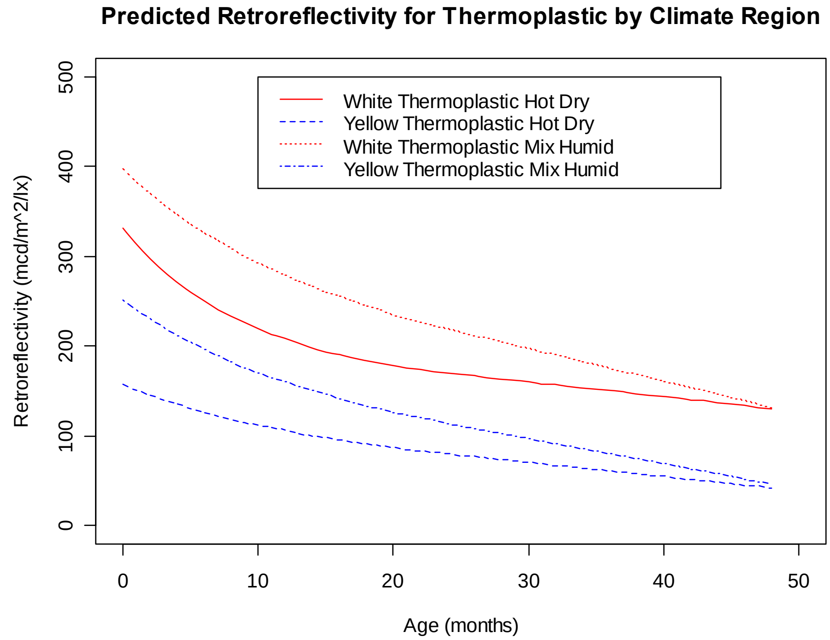


Figure 48. Predicted average retroreflectivity for thermoplastic by climate region

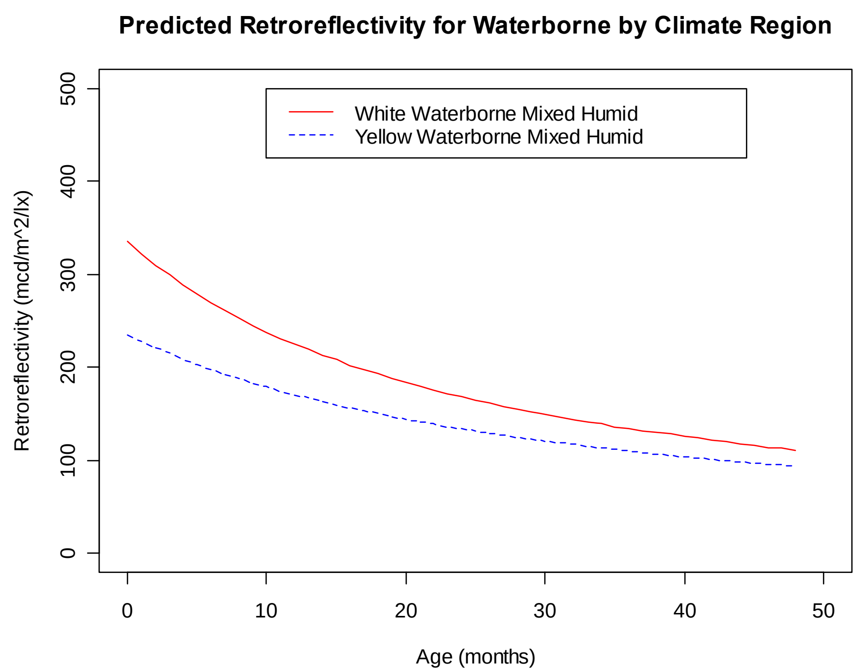


Figure 49. Predicted average retroreflectivity for waterborne for mixed humid climate region

Figure 50 displays the predicted average retroreflectivity for the yellow and white thermoplastic by heavy snow removal and low to medium snow removal. Heavy snow removal for white and yellow thermoplastic approaches zero retroreflectivity by the 38th month. White and yellow thermoplastic low to medium snow removal approaches zero retroreflectivity after the 48 months. The faster fading of the markings seen in the heavy snow removal is attributed to the snowplow effect.

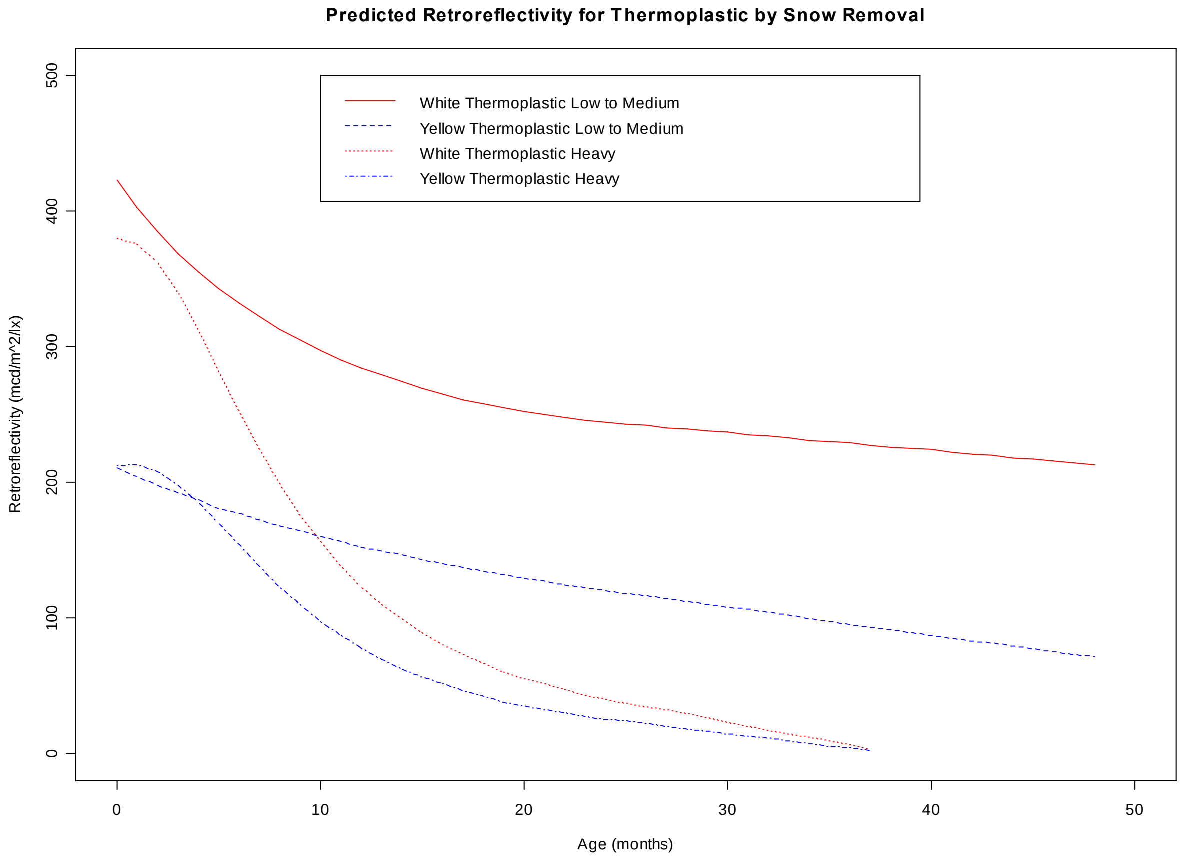


Figure 50. Predicted average retroreflectivity for white and yellow thermoplastic under heavy and low to medium snow removal

Figure 51 displays the predicted average retroreflectivity for white and yellow waterborne for low to medium and heavy snow removal.

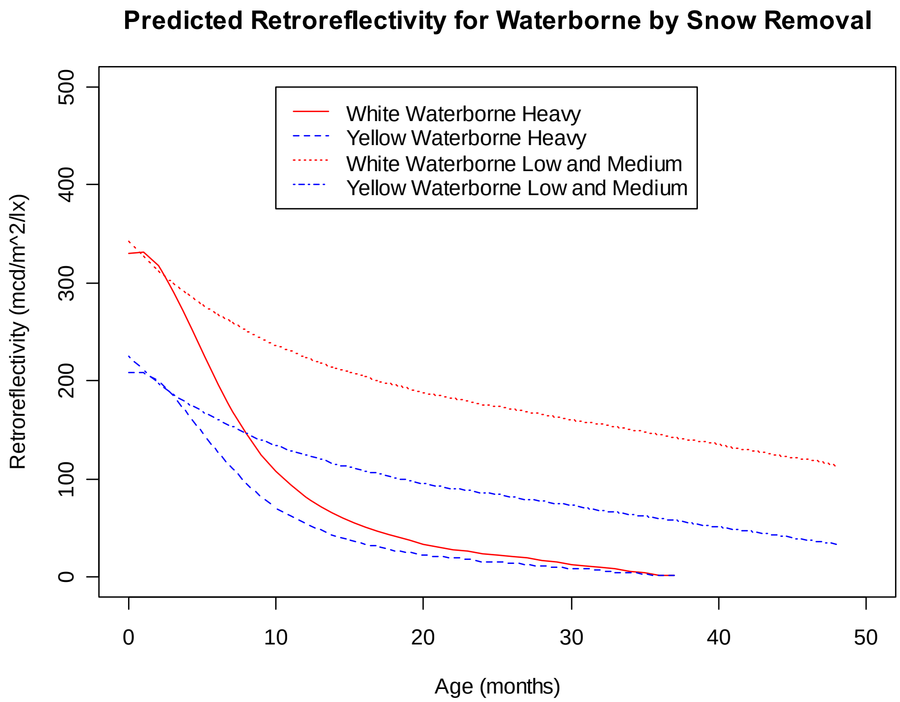


Figure 51. Predicted average retroreflectivity for waterborne by snow removal

Using the plowable and non-plowable models for the marker data, Figure 52 displays the predicted retroreflectivity from 0 to 48 months.

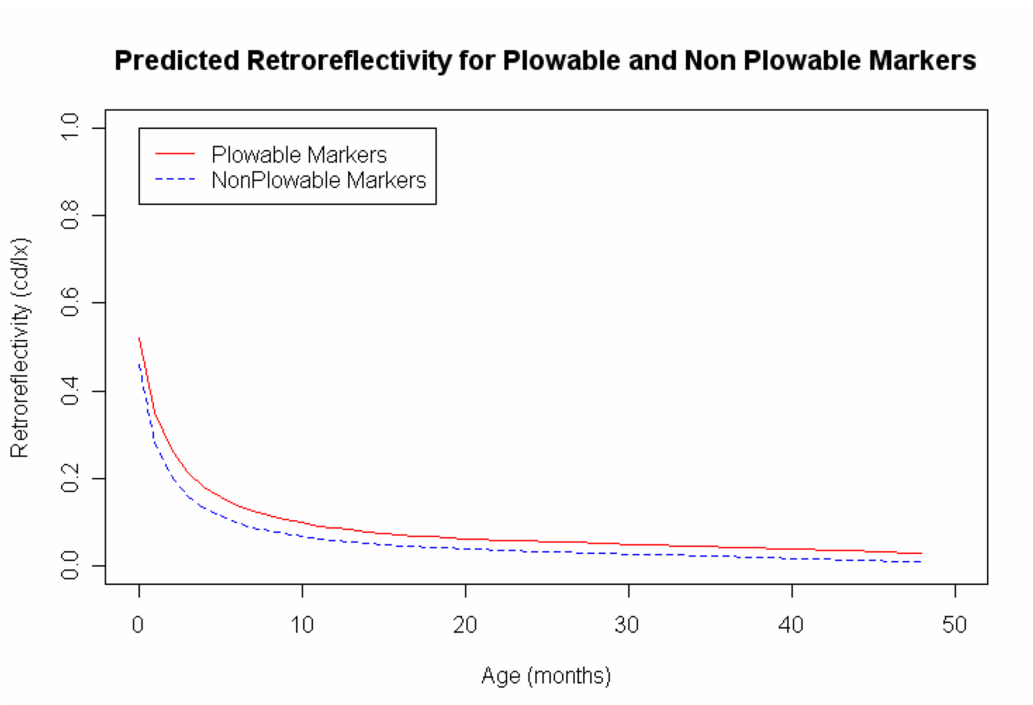


Figure 52. Predicted average retroreflectivity for plowable and non-plowable markers

Table 54 to Table 56 summarizes all twenty six marking models developed in this study and their calculated parameter estimates needed for Equation 7.

Table 54. Parameter estimates for color, material type and age models

Model	λ	δ
Epoxy White all Climates all Snow Removal	2.17	231.51
Epoxy Yellow all Climates all Snow Removal	1.89	142.49
Methyl Methacrylate White all Climates all Snow Removal	4.13	198.46
Methyl Methacrylate Yellow all Climates all Snow Removal	3.02	84.34
Permanent Tape White all Climates all Snow Removal	4.65	139.21
Permanent Tape Yellow all Climates all Snow Removal	2.60	79.78
Solvent White all Climates all Snow Removal	2.11	46.13
Solvent Yellow all Climates all Snow Removal	1.56	36.61
Thermoplastic White Hot Humid and No Snow Removal	3.03	200.51
Thermoplastic Yellow Hot Humid and No Snow Removal	2.06	105.61
Waterborne White Hot Humid and No Snow Removal	0.50	175.52
Waterborne Yellow Hot Humid and No Snow Removal	1.89	78.75

Table 55. Parameter estimates for color, material type, age, and climate region models

Model	λ	δ
Waterborne White Mixed-Humid Climate and No Snow Removal	3.49	164.99
Waterborne Yellow Mixed-Humid Climate and No Snow Removal	2.36	131.27
Thermoplastic White Mixed-Humid Climate and No Snow Removal	3.64	215.53
Thermoplastic Yellow Mixed-Humid Climate and No Snow Removal	2.80	111.00
Thermoplastic White Hot-Dry Climate and No Snow Removal	1.64	168.21
Thermoplastic Yellow Hot-Dry Climate and No Snow Removal	1.58	78.43

Table 56. Parameter estimates for color, material type, age, and snow removal models

Model	λ	δ
Waterborne White Cold Climate and Heavy Snow Removal	1.81	22.33
Waterborne Yellow Cold Climate and Heavy Snow Removal	1.20	14.99
Waterborne White Cold Climate and Low to Medium Snow Removal	2.58	173.77
Waterborne Yellow Cold Climate and Low to Medium Snow Removal	2.15	83.51
Thermoplastic White Cold Climate and Heavy Snow Removal	2.86	37.30
Thermoplastic Yellow Cold Climate and Heavy Snow Removal	1.82	23.56
Thermoplastic White Cold Climate and Low to Medium Snow Removal	1.30	243.10
Thermoplastic Yellow Cold Climate and Low to Medium Snow Removal	2.06	117.99

Table 57 summarizes the two proposed marker models and the calculated parameter estimates needed for Equation 7.

Table 57. Parameter estimates for type and age models

Model	λ	δ
Non-plowable	1.00E-03	3.30E-02
Plowable	1.12E-03	5.58E-02

5.1.4. Example Calculation of Retroreflectivity

5.1.4.1. Retroreflectivity of Pavement Markings Until 25 months

In order to predict the average retroreflectivity for white waterborne markings under heavy snow removal conditions at the 20^{th} month the parameter estimates are taken from Table 50. The model parameters are: β0 = 3.03E - 03, β1 = 8.32E - 05, β2 = 6.80E - 05. For the 20^{th} month, age = 20. Retroreflectivity can be calculated using Equation 6 as follows:

$$R_{20} = \frac{1}{3.03\text{E-}03 - -8.32\text{E-}05 * 20 + 6.80\text{E-}05 * 20^2} = 35\ \text{mcd/m}^2/\text{lx}$$

5.1.4.2. Retroreflectivity of Pavement Markings Beyond 25 months

Continuing with the previous example to predict the average retroreflectivity for white waterborne markings under heavy snow removal conditions at the 30th month the parameter estimates are taken from Table 56. The model parameters are: $\lambda = 1.81,\ \delta = 22.33$. For the 30th month, age = 30. The average retroreflectivity can be calculated using Equation 7 as follows:

$$R_{30} = -1.81\,(30-25) + 22.33 = 13\ \text{mcd/m}^2\,/\,\text{lx}$$

The predicted retroreflectivity for white waterborne markings under heavy snow removal from age 0 to 48 months is shown in Figure 53.

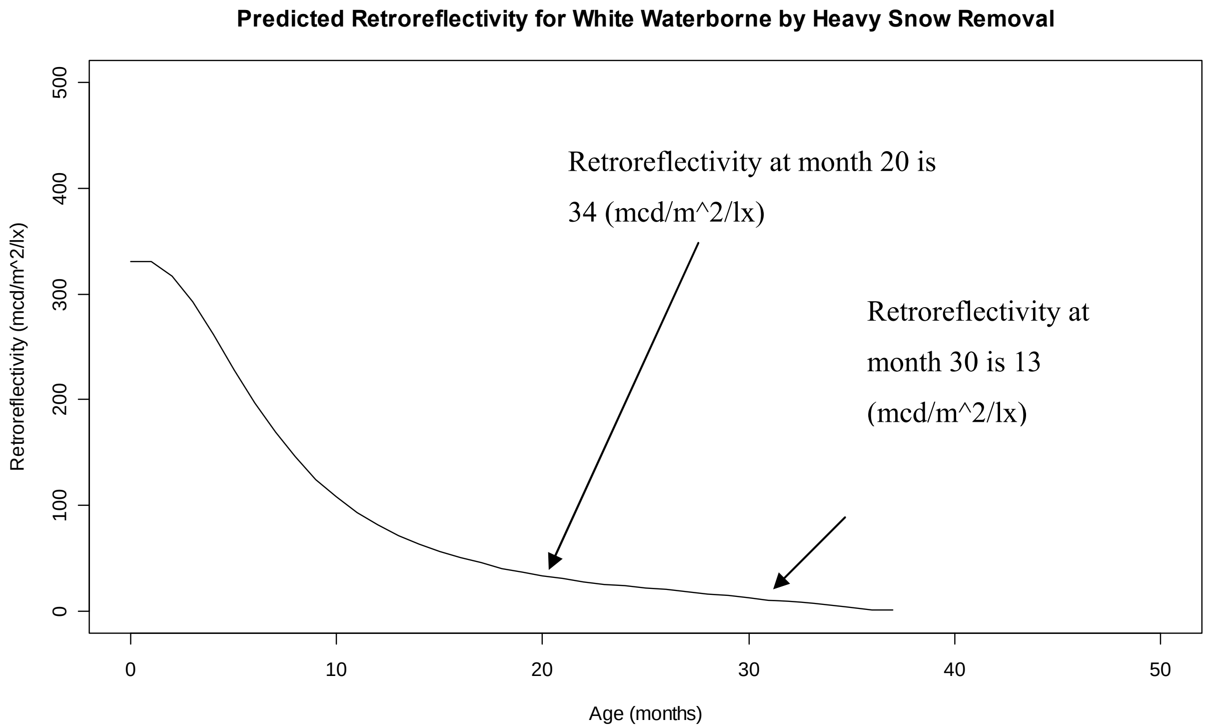


Figure 53. Predicted average retroreflectivity for white waterborne heavy snow removal

5.1.4.3. Retroreflectivity of Pavement Markers until 25 Months

In order to predict the retroreflectivity for plowable markers at the 20th month the parameters estimates are taken from Table 51. The model parameters are: $\beta_0 = 1.923,\ \beta_1 = 0.940,\ \beta_2 = -0.012$. For the 20th month, age = 20, retroreflectivity can be calculated using Equation 6 as follows:

$$R_{20} = \frac{1}{1.923 + 0.940 * 20 - 0.012 * 20^2} = 0.063 \text{ cd/lx}$$

5.1.4.4. Retroreflectivity of Pavement Markers beyond 25 Months

Continuing with the previous example to predict retroreflectivity for plowable markers at the 30th month, the parameter estimates are taken from Table 57. The model parameters are: $\lambda = 0.001$ and $\delta = 0.056$. For the 30th month, age = 30. The retroreflectivity can be calculated using Equation 6 as follows:

$$R_{30} = -0.001(30 - 25) + 0.056 = 0.051 \text{ cd / lx}$$

The predicted retroreflectivity for plowable markers from age 0 to 48 months is shown in Figure 54.

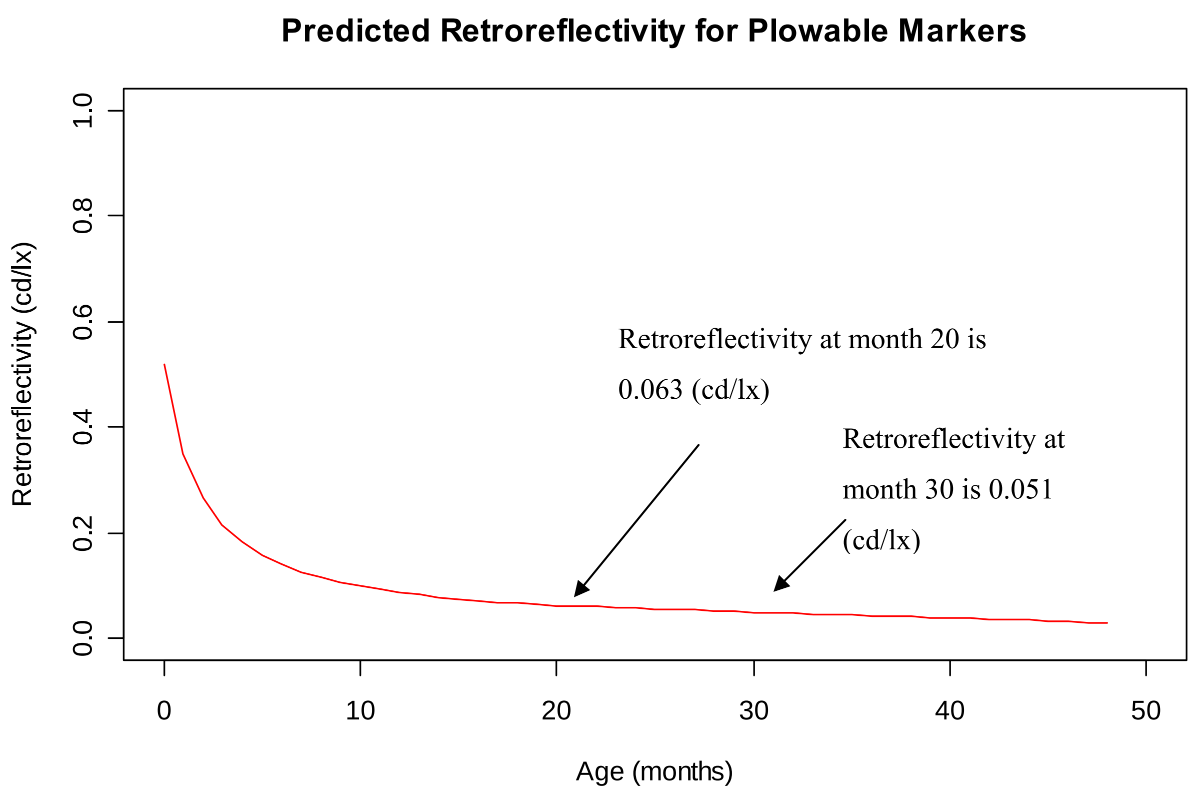


Figure 54. Predicted average retroreflectivity for plowable markers

5.1.5. Retroreflectivity Modeling Summary

As a result of the modeling process, it was found that the retroreflectivity of pavement markings decreases non-linearly over time. The variables pavement surface and traffic volume do not improve the prediction of average retroreflectivity and as a result were not included in the prediction models. Color, material type, climate region and snow removal all improve the prediction of retroreflectivity, thus separate models can be found for these variables.

In the initial modeling process of pavement markings, there was a total of twelve models. Two models for each material type, i.e., one model for yellow pavement markings and the one for white pavement markings for a given material. As the model building process continued, it was found that climate region and snow removal improved the prediction of retroreflectivity of pavement markings. This effect was dominant in two material types, namely, waterborne and thermoplastic. Consequently, white and yellow waterborne and white and yellow thermoplastic were further modeled based on these variables and the data that were available. The resulting separate models looked at white and yellow waterborne climate region (mixed humid) and snow removal (heavy and low to medium). Similarly, separate models for thermoplastic included white and yellow models for mixed humid and hot-dry climate regions, and white and yellow models for heavy and low to medium snow removal.

A total of 26 models were developed during this process. These models depend on age, color, material type, climate region and snow removal. The suggested parameters for these models can be found in Table 45, Table 48 and Table 50. Using these proposed models it is possible to predict retroreflectivity for 0 to 48 months with the assistance of the parameter estimates found in Table 54 to Table 59.

For markers, age was found to act similarly to markings and decrease in a non-linear manner. It can also be seen that marker type i.e., plowable or non-plowable, was the only other variable to improve the prediction of retroreflectivity. Variables such as surface, AADT, snow removal and climate region did not improve the prediction of retroreflectivity. Therefore, only two models, plowable and non-plowable, are available to model retroreflectivity for pavement markers.

5.2. Retroreflectivity-Safety Data Summary

The effect of pavement markings and marker on non-intersection, non-daylight crashes was estimated separately for three different road types using 8 years of HSIS California crash data. The three different road types were:

- Multilane freeways;
- Multilane highways; and
- 2-lane highways.

All roads in California are marked or striped according to the California Manual on Uniform Traffic Control Devices (CMUTCD), which is FHWA's MUTCD 2003 Edition Revision 1 Manual amended for use in California. For a summary of CMUTCD see Table 58.

Table 58. California Manual on Uniform Traffic Control Devices marking summary

Summary Application of Yellow and White Markings in California

In general:

- Yellow lines are used to separate the direction of travel
- White lines are used to separate the traffic flow in the same direction

Specifically, application of yellow markings:

1. Center line of roads without divider
2. Left edges of divided highways
3. Left edges of undivided highways where there is presence of a left turning lane at the center
4. Both edges of left turn lanes with limited storage
5. Left edge of approach taper
6. Left edge of entrance ramps
7. Left edges of lanes where the number of lanes change (1 lane to 2 lanes or vice versa)

Specifically, application of white markings:

1. Right edges of ramps, highways and passing lanes (climbing lanes)
2. Channelizing lines at islands, entrance and exit ramps
3. Lane divider lines (broken or solid)

http://www.dot.ca.gov/hq/traffops/signtech/mutcdsupp/pdf/CA-Chap3B.pdf

The state database includes data by segment by month. It is possible to have a segment with marking installation occurring midyear with no age information available for the first half of the year. This would occur when marking occurred in the period before data were available such that the exact date of marking installation is unknown. Table 59 illustrates how the ages were entered in the database if striping occurred in July and no installation data were available before. The null values correspond to no age data available, and a 0 corresponds to month of striping.

Table 59. Illustration of age entries by month for one segment.

Segment	Length	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
101	4.0	null	null	null	null	null	Null	0	1	2	3	4	5

For some road locations, only yellow striping installation data were available, and in others only white striping installation was available. Installation data were converted into marking and marker age.

Then for a given marking material, age, climate region, and snowfall, a retroreflectivity value was determined based upon the NTPEP retroreflectivity models.

The number of miles for each road type was calculated as follows. The total miles of road per year is the sum all the segment lengths with marking installation data available, times the number of months in a year (12). So for example, Table 60 shows three segments. Segment 101 has marking age information for the last six months of the year, and segment 102 has marking age information for all twelve months. Segment 103 has marking age information for only the first six months of the year because a reconstruction project took place in July and no marking material information was available since the project was contracted outside of the Caltrans. Each month per segment with marking installation is multiplied by the length of the segment. Therefore, segment 101 has 4*6 =24 miles-months, segment 102 has 3*12=36 mile-months, and segment 103 has 1.5*6=9 mile-months of data. The total number of mile-months in Table 60 is equal to 24+36+9 = 69 mile-months of data. Therefore, 69 mile-months divided by 12 months per year gives 5.75 miles of data per year.

Table 60. Illustration of three segments resulting in an average of 5.75 miles of data per year

Segment	Length	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
101	4.0	null	null	null	null	Null	Null	0	1	2	3	4	5
102	3.0	0	1	2	3	4	5	6	7	8	9	10	11
103	1.5	11	12	13	14	15	16	null	null	null	null	null	null

The total miles of road per year with white markings, yellow markings, markers, white and yellow markings combined and white markings and yellow markings and markers combined is given in Table 61. For example, for multilane freeways; total length of segments over all months for the 8 years of data that had restriping or marker information was 142,879. This number was divided by (12*8) to get 1448 representing the average mileage/year.

Table 61. Total average miles per year of road by road type

	Multilane Freeways	Multilane Highways	2-lane Highways
White	1488	622	3204
Yellow	1218	446	2577
Markers	256	140	587
White +Yellow	1071	383	2298
White+Yellow+Markers	74	51	263

The total number of non-daylight, non-intersection crashes for each road type with white markings, yellow markings, marker, white and yellow markings combined and white markings + yellow markings + markers combined is given in Table 62. The number of crashes is the sum of the fatal, nonfatal injury, and PDO over 8 years at those road segments that there was information about their markings and markers. An analysis for pavement markers was attempted, however, the sample for pavement markers available for California was too small to be conclusive regarding combinations of markers with markings.

Table 62. Total number of non-daylight, non-intersection crashes by road type

	Multilane Freeways	Multilane Highways	2-lane Highways
White	89,655	13,457	15,618
Yellow	81,334	8,956	11,921
Markers	16,153	3,189	3,642
White+Yellow	74,514	7,233	10,577
White+Yellow+Markers	870	515	1,177

5.3. Safety Analysis

Equation 8 represents the effect of different factors on crashes.

$$\mu_{y,m,r,x} = \mu_y \times p_m \times q_r \times w_x$$ *Equation 8*

Where,

μ_y : mean number of crashes per year

p_m : multiplier representing the safety effect of seasonal variation

q_r : multiplier representing the safety effect of retroreflectivity of pavement markings

w_x : multiplier representing the safety effect of retroreflectivity of markers

The maximum likelihood estimation methodology (Section 3.5), allows the simultaneous estimation of seasonal parameters p_m for different months of the year and of safety effect parameters q_r and w_x for different retroreflectivity bin ranges (a retroreflectivity bin range is for example, all markings with a retroreflectivity between 100 and 125 mcd/m^2/lux). The safety effect parameters are multipliers which modify the expected number of crashes. Thus, e.g., a ratio q_i/q_j=1.1 would indicate that a road segment with retroreflectivity belonging to retroreflectivity of bin i (Section 5.3.1) has, on the average 1.1 the number of crashes of an identical road segment with retroreflectivity belonging to bin j. Seasonal parameters are expected to be largest during the winter months where crashes are more frequent, while retroreflectivity parameters have never previously been determined, according to our literature review.

5.3.1. Retroreflectivity Bin Ranges

The retroreflectivity values contained in the state database derived from the NTPEP retroreflectivity models range from 21 to 413 mcd/m^2/lux for white pavement markings, and 15 to 238 mcd/m^2/lux for yellow pavement markings. One goal of this study is to identify the function which describes the relationship between retroreflectivity and crashes. It is not possible to estimate the safety effect for each individual retroreflectivity value between 15 and 413 mcd/m^2/lux, so instead points along the retroreflectivity continuum are estimated. The points along the continuum are referred to as bin ranges such that a bin range of 100 to 120 represents all markings with a retroreflectivity greater than or equal to 100 and less than or equal to 120. A safety effect parameter is then estimated for the 100-120 bin range, which may be thought of as an average safety effect of markings within that range.

The larger the bin range, the greater the number of segments, miles of road, and crashes which will fall within the range. The more data in terms of miles and crashes available, the greater the accuracy of the safety effect can be determined. In general, it is good practice to define bin ranges such that the data are distributed equally among all bin ranges, as much as possible, such that all safety effects can be estimated at the same reliability. Two methods were considered for apportioning the data into different bin ranges:

- Equal number of crashes per bin; and
- Equal number of miles of highway per bin.

The number of crashes and miles of highway are highly correlated to each other. If there is no safety effect of retroreflectivity on crashes, then apportioning the data by miles or by crashes should result in similar bin ranges. However, if retroreflectivity does have a safety effect, then the bin ranges will be different dependent upon the method used to divide the data. A safety effect of retroreflectivity will cause the safer retroreflectivity bins to become larger, and the less safe retroreflectivity bins to become smaller, when setting the bin ranges by the number of crashes.

For white markings, the bin ranges in terms of equal numbers of crashes or miles per bin for nine equal bin sizes is given in Table 63 for each road type. The bin ranges by equal numbers of crashes and miles per bin for yellow markings for each road type are given in Table 64.

Table 63. Retroreflectivity bins apportioned by crashes and by miles for white markings

Multilane Freeways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	25-175	176-187	188-207	208-225	226-248	249-268	269-292	293-328	329-413
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	25-183	184-204	205-225	226-250	251-263	264-292	293-314	315-341	342-413
Multilane Highways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	75-174	175-185	186-203	204-225	226-250	251-271	272-294	295-331	332-413
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	75-178	179-202	203-225	226-250	251-271	272-292	293-327	328-341	342-413
2-lane Highways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	21-184	185-204	205-225	226-250	251-263	264-292	293-328	329-341	342-413
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	21-183	184-204	205-225	226-250	251-267	268-291	292-312	313-341	342-413

Table 64. Retroreflectivity bins apportioned by crashes and by miles for yellow markings

Multilane Freeways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	15-70	71-82	83-93	94-106	107-122	123-140	141-165	166-187	188-238
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	15-79	80-94	95-108	109-126	127-139	140-154	155-174	175-204	205-238
Multilane Highways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	15-73	74-87	88-101	102-115	116-131	132-145	146-165	166-201	202-238
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	15-79	80-94	95-108	109-126	127-139	140-154	155-174	175-217	218-238
2-lane Highways									
Retroreflectivity Bins Apportioned by Equal Number of Crashes									
Retroreflectivity (mcd/m²/lux)	15-82	83-100	101-115	116-131	132-149	150-165	166-187	188-201	202-238
Retroreflectivity Bins Apportioned by Equal Number of Miles									
Retroreflectivity (mcd/m²/lux)	15-84	85-101	102-118	119-133	134-152	153-166	167-187	188-217	218-238

If retroreflectivity affects safety, then bin ranges based upon the number of crashes will change with the safety effect. Since the number of miles does not change as a function of the safety effect of retroreflectivity, retroreflectivity bins were apportioned by equal number of miles.

5.3.2. Safety Effect by Crash Severity

The multiplication factors were estimated separately for property damage only (PDO) crashes and fatal and nonfatal injury crashes for each road type and for each color of marking. Retroreflectivity bins apportioned by equal number of miles were used for estimating the multiplication factors. The seasonal factors were also estimated simultaneously for each category. The multiplication factors for white markings apportioned by severity and road type are summarized in Table 65.

Table 65. Estimation results of safety effects q_r for white markings by non-daylight, non-intersection crash severity

Multilane Freeways									
Retroreflectivity (mcd/m^2/lux)	25-183	184-204	205-225	226-250	251-263	264-292	293-314	315-341	342-413
Safety effect (PDO)	1.00	0.98	1.01	1.00	0.99	1.01	1.01	1.02	0.98
Safety effect (FI)	1.00	0.98	1.00	1.04	0.99	1.00	0.98	1.04	0.95
Multilane Highways									
Retroreflectivity (mcd/m^2/lux)	75-178	179-202	203-225	226-250	251-271	272-292	293-327	328-341	342-413
Safety effect (PDO)	0.99	1.04	1.00	1.01	0.99	1.01	0.95	1.01	0.97
Safety effect (FI)	1.02	0.99	0.99	1.04	0.98	0.97	1.02	1.06	0.98
2-lane Highways									
Retroreflectivity (mcd/m^2/lux)	21-183	184-204	205-225	226-250	251-267	268-291	292-312	313-341	342-413
Safety effect (PDO)	1.00	0.99	0.98	0.99	1.05	0.96	1.03	0.98	0.98
Safety effect (FI)	1.01	1.00	1.02	0.96	1.09	0.91	0.98	0.98	1.00

The seasonal factors for white markings simultaneously estimated with the multiplication factors are summarized in Table 66.

Table 66. Estimation p_m results of seasonal effect for white markings by non-daylight, non-intersection crash severity

Road Type and Crash Severity	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Multilane Freeways (PDO)	1.36	1.15	1.01	0.67	0.60	0.58	0.64	0.72	0.84	1.25	1.58	1.60
Multilane Freeways (FI)	1.20	1.08	0.99	0.77	0.74	0.70	0.76	0.84	0.91	1.20	1.39	1.41
Multilane Highways (PDO)	1.38	1.15	1.04	0.72	0.68	0.61	0.65	0.76	0.79	1.12	1.52	1.58
Multilane Highways (FI)	1.29	1.16	1.07	0.72	0.70	0.64	0.73	0.83	0.89	1.14	1.43	1.42
2-lane Highways (PDO)	1.31	1.09	0.93	0.71	0.66	0.66	0.74	0.84	0.92	1.17	1.47	1.50
2-lane Highways (FI)	1.14	0.98	0.95	0.76	0.76	0.76	0.85	1.02	0.98	1.15	1.35	1.30

The multiplication factors for yellow markings apportioned by non-daylight, non-intersection crash severity and road type are summarized in Table 67.

Table 67. Safety estimation results for yellow markings by non-daylight, non-intersection crash severity

Multilane Freeways									
Retroreflectivity (mcd/m²/lux)	15-79	80-94	95-108	109-126	127-139	140-154	155-174	175-204	205-238
Safety effect (PDO)	1.00	1.01	0.98	1.00	1.02	1.00	1.02	1.01	0.99
Safety effect (FI)	1.01	1.00	0.96	1.01	1.05	1.02	1.00	1.01	0.98
Multilane Highways									
Retroreflectivity (mcd/m²/lux)	15-79	80-94	95-108	109-126	127-139	140-154	155-174	175-217	218-238
Safety effect (PDO)	1.00	1.00	1.01	0.95	1.03	1.02	0.98	0.99	1.02
Safety effect (FI)	0.99	0.97	1.05	1.02	0.95	1.03	0.98	1.06	0.98
2-lane Highways									
Retroreflectivity (mcd/m²/lux)	15-84	85-101	102-118	119-133	134-152	153-166	167-187	188-217	218-238
Safety effect (PDO)	1.01	0.99	1.01	0.95	0.98	1.05	0.99	1.03	0.98
Safety effect (FI)	0.96	1.05	1.04	0.95	0.94	1.01	0.98	0.96	1.05

The seasonal factors for yellow markings simultaneously estimated with the multiplication factors are summarized in Table 68.

Table 68. Estimation p_m results of seasonal effect for yellow markings by non-daylight, non-intersection crash severity

Road Type and Crash Severity	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Multilane Freeways (PDO)	1.36	1.15	1.01	0.67	0.60	0.58	0.64	0.72	0.84	1.25	1.58	1.60
Multilane Freeways (FI)	1.20	1.08	0.99	0.77	0.74	0.70	0.76	0.84	0.91	1.20	1.39	1.41
Multilane Highways (PDO)	1.38	1.15	1.04	0.72	0.68	0.61	0.65	0.76	0.79	1.12	1.52	1.58
Multilane Highways (FI)	1.29	1.16	1.07	0.72	0.70	0.63	0.73	0.82	0.89	1.14	1.43	1.42
2-lane Highways (PDO)	1.31	1.09	0.93	0.71	0.66	0.66	0.74	0.84	0.92	1.17	1.47	1.50
2-lane Highways (FI)	1.14	0.98	0.95	0.76	0.76	0.76	0.85	1.02	0.98	1.15	1.35	1.30

The multiplication factors shown in Table 65 and Table 67 are very close to one and do not show any pattern. This indicated that there was no measurable safety effect of pavement marking retroreflectivity on any severity type of non-daylight, non-intersection crashes. In order to further investigate the safety effect of pavement markings, total non-daylight, non-intersection crashes were used. Total non-daylight, non-intersection crashes include all fatal, nonfatal injury, and PDO crashes. The analysis details and results are presented in the following sections.

5.3.3. Safety Effect on Total Non-daylight, Non-intersection Crashes

As the safety effect of pavement markings could not be detected for PDO and fatal + nonfatal injury non-daylight, non-intersection crashes, further analysis was done using the total non-daylight, non-intersection crashes. The multiplication factors were estimated for each road type separately. The effect of white markings, yellow markings, marker and white + yellow combined were estimated separately for each road type. Estimation results for white markings are given in Table 69.

Table 69. Estimation results of safety effects q_r for white markings by total non-daylight, non-intersection crashes

Multilane Freeways									
Retroreflectivity (mcd/m^2/lux)	25-175	176-187	188-207	208-225	226-248	249-268	269-292	293-328	329-413
Safety effect	1.01	1.00	0.98	1.00	1.01	0.99	1.01	1.00	0.99
Multilane Highways									
Retroreflectivity (mcd/m^2/lux)	75-174	175-185	186-203	204-225	226-250	251-271	272-294	295-331	332-413
Safety effect	1.01	0.98	1.04	0.99	1.02	0.98	0.99	1.00	0.98
2-lane Highways									
Retroreflectivity (mcd/m^2/lux)	21-184	185-204	205-225	226-250	251-263	264-292	293-328	329-341	342-413
Safety effect	1.01 (0.01)	0.99 (0.01)	0.99 (0.06)	0.98 (0.04)	1.07 (0.03)	0.97 (0.02)	1.01 (0.04)	0.96 (0.06)	0.99 (0.01)
	(standard error)								

Bootstrapping was used in order to provide an estimate of the accuracy (standard error) of the safety effect of retroreflectivity by first randomly dividing the data into three separate groups. Next, the maximum likelihood estimates of the safety effect and seasonal effects were separately calculated for each of the three groups. The standard error of the safety estimates was then calculated based upon the distribution of the three separate estimates. The standard error estimates were calculated for 2-lane highways, the road type with the least amount of data in order to generate the most conservative estimates of the standard error. For road types with more data (multilane freeways and highways), the standard errors should be smaller.

For white markings on 2-lane highways, the standard error estimates of the safety effect, for bin ranges based upon an equal distribution of miles, are shown in the parentheses in the last row in Table 69. The standard error estimates for white markings on 2-lane highways range from 0.01 to 0.06, which is a fairly tight range indicating that safety estimate of retroreflectivity is accurate. The safety effect of markings bin values are all at, or very close to a value of 1.0 indicating no measurable safety effect of white pavement markings. The safety effect of seasonal variation for white stripping is given in Table 70. It can be observed that the winter months contribute more crashes than the summer months. This pattern is consistent across all three road types.

Table 70. Estimation p_m results of seasonal effect for white markings by total non-daylight, non-intersection crashes

Highway Type	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Multilane Freeways	1.31	1.13	1.00	0.70	0.65	0.63	0.68	0.76	0.86	1.23	1.51	1.53
Multilane Highways	1.34	1.16	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.51
2-lane Highways	1.23	1.04	0.94	0.73	0.70	0.70	0.79	0.92	0.95	1.16	1.42	1.41

The safety effect of yellow pavement markings is given in Table 71. The safety effects of markings for all bin values are either at, or very close to a value of 1.0 indicating no measurable safety effect of yellow pavement markings. The standard error for 2-lane highways has been calculated via bootstrapping and may be found in the bottom row in Table 71.

Table 71. Estimation results of safety effects q_r for yellow markings by total non-daylight, non-intersection crashes

Multilane Freeways									
Retroreflectivity (mcd/m^2/lux)	15-70	71-82	83-93	94-106	107-122	123-140	141-165	166-187	188-238
Safety effect	1.01	0.98	0.99	0.97	0.99	1.01	1.02	1.01	0.99
Multilane Highways									
Retroreflectivity (mcd/m^2/lux)	15-73	74-87	88-101	102-115	116-131	132-145	146-165	166-201	202-238
Safety effect	0.99	0.99	1.05	1.01	0.95	1.02	1.00	1.02	0.99
2-lane Highways									
Retroreflectivity (mcd/m^2/lux)	15-82	83-100	101-115	116-131	132-149	150-165	166-187	188-201	202-238
Safety effect	0.99 (0.02)	1.01 (0.02)	1.01 (0.04)	0.97 (0.04)	0.95 (0.02)	1.03 (0.03)	0.99 (0.02)	1.00 (0.02)	1.01 (0.01)
	(standard error)								

The safety effect of seasonal variation for yellow stripping is given in Table 72. The seasonal pattern for yellow markings matches the seasonal pattern observed for white markings.

Table 72. Estimation results p_m of seasonal effect for yellow markings by total non-daylight, non-intersection crashes

Highway Type	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Multilane Freeways	1.31	1.13	1.00	0.70	0.65	0.63	0.68	0.76	0.86	1.23	1.51	1.54
Multilane Highways	1.34	1.16	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.51
2-lane Highways	1.23	1.04	0.94	0.73	0.70	0.70	0.79	0.92	0.95	1.16	1.42	1.41

The safety effect of markers, for which retroreflectivity is measured in cd/lux, is given in Table 73. The safety effect of markers for all bin values are at, or very close to a value of 1.0 indicating no measurable safety effect as a function of the retroreflectivity of markers. The safety effect of seasonal variation for markers is given in Table 74. The seasonal variation matches with the seasonal variation seen from the analysis of pavement markings.

Table 73. Estimation results of safety effects q_r for markers by total non-daylight, non-intersection crashes

Multilane Freeways									
Retroreflectivity (cd/lux)	0-0.028	0.029-0.036	0.037-0.048	0.048-0.058	0.059-0.072	0.073-0.099	0.1-0.126	0.127-0.206	0.207-0.52
Safety effect	1.01	1.07	0.94	1.06	0.98	0.94	1.01	1.03	0.99
Multilane Highways									
Retroreflectivity (cd/lux)	0-0.029	0.030-0.037	0.038-0.046	0.047-0.055	0.056-0.068	0.069-099	0.1-0.034	0.135-0.266	0.267-0.52
Safety effect	1.00	1.05	1.04	1.00	1.03	0.93	1.00	1.02	0.94
2-lane Highways									
Retroreflectivity (cd/lux)	0-0.028	0.029-0.037	0.038-0.048	0.049-0.058	0.059-0.072	0.073-0.089	0.09-0.126	0.127-0.181	0.182-0.52
Safety effect	1.03	0.98	0.96	1.05	1.02	0.99	0.93	1.02	0.99

Table 74. Estimation results p_m of seasonal effect for markers by total non-daylight, non-intersection crashes

Highway Type	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Multilane freeways	1.31	1.13	1.00	0.70	0.66	0.63	0.68	0.76	0.86	1.23	1.51	1.53
Multilane Highways	1.34	1.15	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.51
2-lane Highways	1.23	1.04	0.94	0.74	0.70	0.70	0.79	0.92	0.95	1.16	1.42	1.41

The next stage in the analysis is the consideration of those road segments that there are 2 pavement marking colors, i.e., white and yellow. The remarking of each color may follows a different striping cycle/ In order to address multiple safety effect of markings, a matrix of safety parameters are estimated simultaneously. In order to evaluate the effect of two types of markings, yellow and white, a matrix was applied as previously shown in Table 23 in Section 3.5.

Safety effect estimation results of white and yellow markings combined for multilane freeways are given in Table 75. The precision of individual safety parameters is lower when estimating the safety effect of yellow and white markings simultaneously within a matrix for two reasons. The first is simply because there are many more parameters being estimated. In the one dimensional maximum likelihood estimation for yellow or white markings alone, the total number of parameters estimated is 20 which is the sum of 9 (safety parameters) and 11 (monthly seasonal parameters). In Table 75, there are 92 parameters which is the sum of [9 (white) * 9 (yellow)] and 11 (monthly seasonal parameters). The second reason is that since the column and row bin ranges are fixed, the number of miles of segments occurring at each yellow and white marking retroreflectivity combination is not equal. Some yellow and white marking retroreflectivity combinations occur infrequently and therefore have fewer segments associated with these combinations. With fewer miles of segments, there are less data to estimate the safety effect parameter with precision.

The variability of the safety effect values in Table 75 show a much larger variance than in the individual color marking estimates. However, there is no systematic pattern in values of the safety parameters.

Table 75. Safety effect estimation results for white and yellow markings combined for multilane freeways for all non-daylight, non-intersection crashes

		Retroreflectivity of Yellow Markings (mcd/m^2/lux)								
		15-70	71-82	83-93	94-106	107-122	123-140	141-165	166-187	188-238
Retroreflectivity of White Markings (mcd/m^2/lux)	25-175	1.03	0.95	1.17	1.05	0.94	0.77	1.05	1.15	1.41
	176-187	0.96	1.00	1.02	1.00	0.90	1.16	0.87	0.93	1.08
	188-207	1.03	0.98	0.90	0.96	0.99	1.08	0.96	1.03	0.94
	208-225	1.01	1.02	1.05	0.96	1.00	1.01	1.00	1.23	1.03
	226-248	0.95	1.00	1.02	0.99	1.01	1.00	1.05	1.05	0.88
	249-268	1.01	1.00	0.89	0.94	0.99	1.05	1.00	0.90	1.00
	269-292	0.99	0.96	1.02	0.92	1.05	1.02	0.97	1.01	0.94
	293-328	0.92	1.07	0.96	0.97	1.04	1.05	0.99	0.95	0.99
	329-413	1.12	1.12	0.95	0.92	1.01	1.00	1.08	1.01	1.00

Safety effects estimation results of white and yellow markings combined for multilane highways are given in Table 76.

Table 76. Safety effect estimation results for white and yellow markings combined for multilane highways for non-daylight, non-intersection crashes

Retroreflectivity of White Markings(mcd/m²/lux)	Retroreflectivity of Yellow Markings (mcd/m²/lux)								
	15-73	74-87	88-101	102-115	116-131	132-145	146-165	166-201	202-238
75-174	1.02	1.01	0.97	0.98	0.91	0.77	0.79	0.55	0.50
175-185	0.71	0.92	1.01	1.10	0.85	1.01	0.67	0.64	0.50
186-203	1.14	0.95	1.09	1.14	0.93	0.97	0.90	0.61	0.63
204-225	1.00	1.17	0.98	0.65	0.97	0.98	0.82	0.60	0.61
226-250	1.00	1.05	1.05	0.88	0.97	1.08	1.08	1.10	1.04
251-271	0.71	1.19	1.26	1.12	1.01	0.97	0.96	0.93	0.64
272-294	0.84	1.35	0.83	1.30	0.82	1.08	1.17	1.02	0.78
295-331	1.00	0.97	1.01	0.98	1.27	0.91	0.98	1.05	0.95
332-413	0.94	0.96	1.15	1.01	0.90	1.07	0.95	0.88	1.13

Safety effect estimation results of white and yellow markings combined together for 2-lane highways are given in Table 77. Estimates of the standard error for the combined retroreflectivity safety effect of white and yellow markings for 2-lane highways were also computed. When computing the combined safety effect the data is apportioned into 9X9=81 bins, thus the amount of data per bin is much smaller than looking at one color safety effects. Therefore, the fluctuation in safety estimates is much larger, which is reflected in much larger standard error values given in parenthesis in Table 77. The larger standard error values correspond to those safety effects which are much smaller or larger than 1.0. This provides evidence that the safety effect as a function of retroreflectivity is effectively non-existent. Any variation in the safety effect values is due to the limitations of the accuracy of the data, corresponding to a high standard error measure, and is not a true safety effect.

Table 77. Safety effect estimation results for white and yellow markings combined for 2-lane highways for non-daylight, non-intersection crashes with standard error estimates

Retroreflectivity of White Markings ($mcd/m^2/lux$)	Retroreflectivity of Yellow Markings ($mcd/m^2/lux$)								
	15-82	83-100	101-115	116-131	132-149	150-165	166-187	188-201	202-238
21-184	1.01 (0.02)	1.04 (0.05)	1.08 (0.17)	0.99 (0.24)	1.07 (0.15)	0.91 (0.38)	0.97 (0.72)	0.83 (0.51)	1.08 (0.59)
185-204	1.03 (0.08)	1.07 (0.11)	0.95 (0.10)	0.94 (0.10)	1.13 (0.37)	1.01 (0.12)	0.84 (0.36)	0.69 (0.38)	0.97 (0.20)
205-225	0.97 (0.05)	0.85 (0.07)	1.05 (0.07)	1.00 (0.16)	0.93 (0.08)	1.02 (0.17)	0.95 (0.16)	1.05 (0.57)	0.79 (0.28)
226-250	0.89 (0.10)	0.98 (0.12)	1.07 (0.20)	0.92 (0.07)	0.95 (0.05)	1.21 (0.20)	0.95 (0.24)	1.30 (0.77)	1.12 (0.18)
251-263	1.02 (0.17)	1.27 (0.06)	1.05 (0.13)	1.01 (0.30)	1.09 (0.13)	1.06 (0.09)	1.35 (0.21)	0.97 (0.23)	1.39 (0.05)
264-292	1.09 (0.08)	0.96 (0.11)	0.93 (0.07)	0.93 (0.13)	0.81 (0.16)	0.98 (0.29)	1.00 (0.03)	0.81 (0.44)	1.05 (0.51)
293-328	0.91 (0.23)	0.97 (0.10)	1.13 (0.10)	0.87 (0.08)	1.10 (0.24)	1.24 (0.16)	0.91 (0.03)	1.05 (0.03)	0.95 (0.10)
329-341	0.72 (0.19)	0.87 (0.35)	1.22 (0.36)	0.85 (0.25)	0.85 (0.25)	0.93 (0.08)	0.82 (0.12)	0.84 (0.03)	1.01 (0.08)
342-413	1.01 (0.17)	1.07 (0.19)	0.94 (0.07)	1.19 (0.20)	0.76 (0.18)	0.90 (0.12)	0.94 (0.13)	1.06 (0.15)	0.99 (0.09)

Table 78. Estimation results of seasonal effect for white and yellow markings combined

Road Type	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Multilane freeways	1.31	1.12	1.00	0.70	0.65	0.62	0.68	0.76	0.86	1.23	1.51	1.53
Multilane Highways	1.34	1.16	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.52
2-lane Highways	1.24	1.03	0.94	0.73	0.71	0.70	0.79	0.92	0.95	1.16	1.42	1.41

Table 78 indicates that there is a significant safety effect of season variation throughout the year on all three road types. By examining the values of safety effects of markings in Table 69 through Table 77, there is no relationship of safety with the retroreflectivity. This indicates that no measurable safety effect was ascertained on multilane freeways, multilane highways, or 2-lane highways as a function of the relative retroreflectivity of either white or yellow pavement markings, or pavement markers.

5.3.4. Effect of the First Full Month of New Stripping

If there is a safety effect due to the retroreflectivity of pavement markings, one would expect that safety effect to be most apparent when comparing the first full month of new striping to all other months. If markings are striped in mid-May, then June as the second month would be the first full month of new striping. In order to quantify the effect of first full month of stripping, separate bins were created corresponding to the retroreflectivity of both white and yellow pavement markings during the first full month of new striping. For example, the retroreflectivity values of white markings for the first full month of new striping, are 313, 331 and 392, as shown in Table 79 extracted from **Appendix A**.

Table 79. Retroreflectivity of relevant marking materials on first full month after striping (Age = 1)

Age (month)	Thermoplastic White Hot-Dry Climate and No Snow Removal	Waterborne White Hot Humid and No Snow Removal	Thermoplastic White Hot Humid and No Snow Removal	Thermoplastic Yellow Hot-Dry Climate and No Snow Removal	Thermoplastic Yellow Hot Humid and No Snow Removal	Waterborne Yellow Hot Humid and No Snow Removal
1	313	331	392	151	197	218

To analyze the effect of white color, separate retroreflectivity bins were created to contain 313, 331 and 392, which were assumed to have same safety effect. The estimation results for white markings are given in Table 80, with their corresponding seasonal effects given in Table 81.

Table 80. Safety effect estimation results for white markings separating the effect of first full month of new stripping for all non-daylight, non-intersection crashes

Multilane Freeways							
Retroreflectivity (mcd/m^2/lux)	25-207	208-268	269-312	314-330	332-391	313, 331, 392	393-413
Safety effect	1.00	1.00	1.00	0.97	0.97	1.02	0.97
Multilane Highways							
Retroreflectivity (mcd/m^2/lux)	75-203	204-271	272-312	314-330	332-391	313, 331, 392	393-413
Safety effect	1.01	1.00	1.00	0.99	0.99	0.99	0.99
2-lane Highways							
Retroreflectivity (mcd/m^2/lux)	21-225	226-292	293-312	314-330	332-391	313, 331, 392	393-413
Safety effect	1.00	1.00	1.00	0.99	0.99	0.97	0.99

Table 81. Estimation results p_m of seasonal effect for white markings separating the effect of first full month of new stripping for all non-daylight, non-intersection crashes

	Months											
Highway Type	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Multilane freeways	1.31	1.12	1.00	0.70	0.65	0.63	0.68	0.76	0.86	1.23	1.51	1.54
Multilane Highways	1.34	1.16	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.51
2-lane Highways	1.23	1.04	0.94	0.74	0.70	0.70	0.79	0.92	0.95	1.16	1.42	1.41

Likewise, to analyze the effect of yellow color, separate retroreflectivity bins were created to contain 151, 197 and 218. Estimation results for yellow markings are given in Table 82, with the corresponding seasonal values given in Table 83.

Table 82. Estimation results for yellow markings separating the safety effect of first full month of new striping for all non-daylight, non-intersection crashes

Multilane Freeways							
Retroreflectivity (mcd/m^2/lux)	15-93	94-140	141-150	152-196	198-203	219-238	151,197 218,
Safety effect	1.00	0.99	1.03	1.01	1.01	1.01	0.99
Multilane Highways							
Retroreflectivity (mcd/m^2/lux)	15-101	102-145	146-150	152-196	198-217	219-238	151, 197, 218
Safety effect	1.01	0.99	1.06	1.01	1.01	1.01	0.95
2-lane Highways							
Retroreflectivity (mcd/m^2/lux)	15-115	116-150	152-165	166-196	198-203	219-238	151, 197, 218
Safety effect	1.00	0.98	0.98	1.00	1.00	1.00	1.01

Table 83. Estimation results p_m of seasonal effect for yellow markings separating the effect of first full month of new stripping for non-daylight, non-intersection crashes

	Months											
Highway Type	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Multilane freeways	1.31	1.12	1.00	0.70	0.65	0.63	0.68	0.76	0.86	1.23	1.51	1.54
Multilane Highways	1.34	1.15	1.05	0.72	0.69	0.62	0.68	0.79	0.83	1.12	1.48	1.51
2-lane Highways	1.23	1.04	0.94	0.73	0.70	0.70	0.79	0.92	0.95	1.16	1.42	1.41

5.3.5. Sensitivity Analysis

The purpose of this sensitivity analysis is to determine what number of crashes would have corresponded to a *measurable* marking safety effect. For this analysis the data set with the greatest number of crashes, freeway database with white stripping, was used in order to produce the most conservative estimate (smaller data sets are more easily influenced). In the database, the number of crashes was artificially increased in an incremental basis at segments during the first complete month of new striping (e.g., so if striping occurred in May, June would be the first complete month of new striping). The safety effect of markings was then re-estimated. Table 84 shows the change in safety effect with the change of number of crashes. The rightmost shaded column shows the effect of the artificial additional crashes. This change in safety effect with the change in number of crashes is also shown graphically in Figure 55.

Table 84. Safety effect with artificially increased number of crashes on multilane freeways

Additional Crashes	**Safety Effect**						
	25-207	208-268	269-312	314-330	332-391	393-413	313 331 392
0	1.00	1.00	1.00	0.97	0.97	0.97	1.02
200	1.00	1.00	1.00	0.97	0.97	0.97	1.04
400	0.99	1.00	0.99	0.96	0.96	0.96	1.06
600	0.99	1.00	0.99	0.96	0.96	0.96	1.08
800	0.99	1.00	0.99	0.95	0.95	0.95	1.09
1000	0.99	1.00	0.98	0.95	0.95	0.95	1.11
1200	0.99	0.99	0.98	0.95	0.95	0.95	1.13
1400	0.99	0.99	0.98	0.94	0.94	0.94	1.14
1600	0.99	0.99	0.97	0.94	0.94	0.94	1.16

The safety effect multiplier estimated for the current study for white markings on multilane freeways during the first full month of new striping is 1.02, shown in the first row of data, far right column in Table 84. The second data row in the table lists that if an addition 200 crashes had occurred during the first full month of new striping over the entire study period (8 years over 1488 miles of multilane freeways), the resulting safety effect multiplier would have been 1.04. In other words, that is a difference of 200 crashes out of approximately 90,000 crashes in total. An additional 400 crashes during the first full month of new striping over the entire study period would have resulted in a safety effect multiplier for the first full month of new striping of 1.06. A safety effect multiplier of 1.06 would have been large compared to the estimates of the standard error (Section 5.3.3), and therefore considered large enough to be significant.

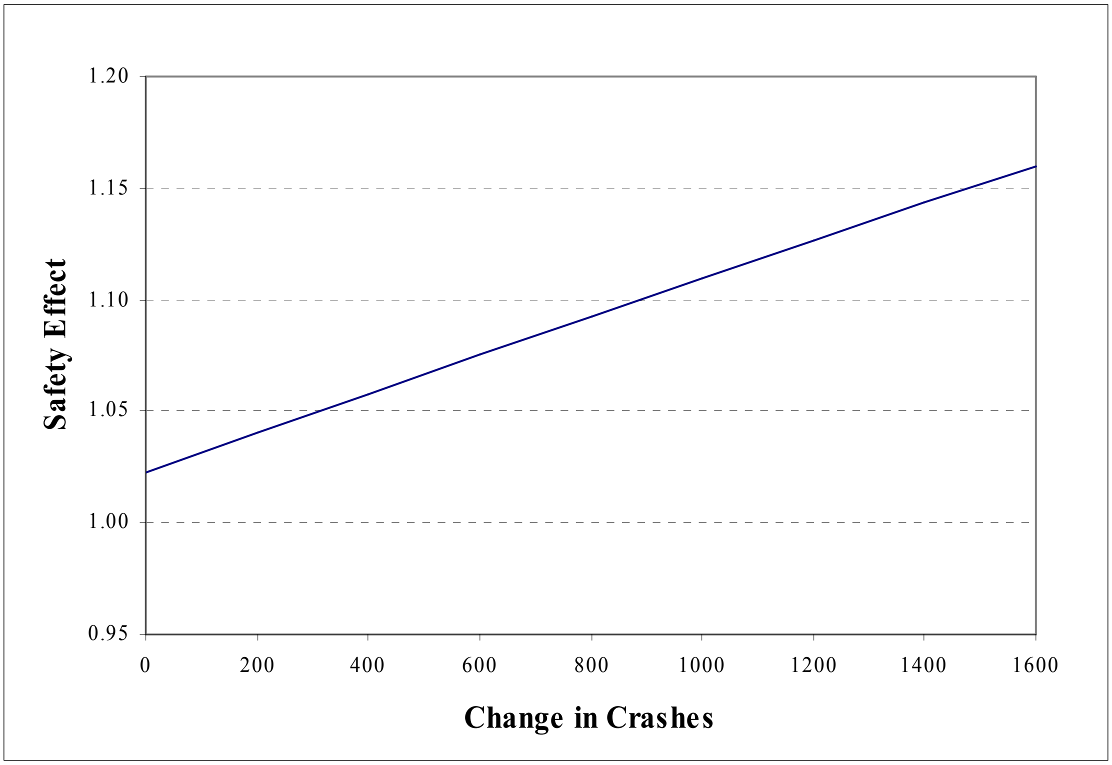


Figure 55. Change in safety with change in number of crashes for multilane highways

6. Chapter 6 Discussion of Study Results

This chapter discusses the results presented in Chapter 5 on retroreflectivity modeling and safety analysis in conjunction with related human factors issues.

A review of the literature on the safety effect of the retroreflectivity of markings and markers leads to the conclusions that:

1. The safety effect of pavement marking and marker retroreflectivity is very hard to detect.
2. The safety effect of pavement marking and marker retroreflectivity is most likely very small.

This study addressed the difficulty of measuring a hard to quantify safety effect by applying an innovate time series approach which allowed the use of historical data covering over 118,000 crashes and 5,000 miles of highways and freeways with known marking installation data over a period of eight years. Safety effect multipliers were computed for different retroreflectivity ranges that represent markings of different brightness. The scope of this study is believed to be larger than any previous work on the safety effect of the retroreflectivity of pavement markings and markers. The size of the present study, combined with the innovative time series methodology were used to look for a hard-to-find, overall average safety effect of retroreflectivity.

The retroreflectivity safety effects for the following conditions were estimated: marking and marker combinations, road type, and crash severity. *This study concludes that the difference in safety between new markings and old markings during non-daylight conditions on non-intersection locations is approximately zero.* No measurable safety effect was ascertained on multilane freeways, multilane highways, or 2-lane highways as a function of the relative retroreflectivity of either white or yellow pavement markings, or for pavement markers. The sample for pavement markers available for California was too small to be conclusive to examine combinations of markers and markings.

This study did not identify any change in safety with low marking or marker retroreflectivity, nor any change in safety with bright marking or marker retroreflectivity, with respect to non-daylight, non-intersection locations. The safety of pavement markings during non-daylight conditions for non-intersection locations appears to be independent of whether the markings are new or deteriorated to the level found on average on roads in California. Based upon the findings in the literature, the presence of lane lines is important. In addition, the literature also clearly identifies that there is a strong driver preference for brighter pavement markings, but do brighter markings, brighter than the retroreflectivity of old markings in California, lead to increases in safety? Based upon the current study, the answer appears to be “no”. While drivers prefer higher retroreflective markings and markers, and may therefore drive more confidently, the overall safety difference in the number of crashes when compared to driving with less bright markings is approximately zero.

As established by several studies, when sight detection distance is reduced, as it is during non-daylight, and adverse weather, lane control becomes more difficult and driver work load increases, causing drivers to compensate by reducing their speed. The increase in sight detection distance due to higher retroreflectivity of pavement markings and markers may cause drivers to maintain higher speeds, thereby increasing the possibility of a crash under certain geometric conditions. In other words, driver adaptation to road conditions may be minimizing any improvement in safety due to greater sight detection distances from retroreflectivity markings and markers. Based upon extensive analysis of pavement marking and marker data, roadway inventory data, and crash data, the best estimate of the joint effect of retroreflectivity and driver adaptation is approximately zero for non-intersection road segments during non-daylight.

Questions about the validity of the study and its limitations are discussed in the following sections.

6.1. How do We Know the Methodology is Correct?

The maximum likelihood estimate methodology simultaneously estimates the seasonal effects along with the pavement markings and markers effects. The seasonal effect refers to the fluctuations in crashes which occur from month to month but which repeat from year to year. The seasonal effect must be estimated in order to separate the safety effect due to markings and the effect due to the season. The season effect parameters obtained in this study are very similar even across road types. In every estimation of the safety effect of markings, the estimate of the seasonal effect is very reasonable with higher number of crashes during the winter months and lower crashes in the summer.

The seasonal effects are known to be reasonable because the values are very similar to other published seasonal effects. For example, the monthly seasonal factors found by Hauer et al. (92), for data from New York State are given in Table 85. One difference however is that the seasonal factors by Hauer et al (92), are 24 hour seasonal factors whereas this study focuses on *non-daylight* crashes only. The number of hours per month changes from a high of 14.8 hours in January to a low of 9.0 hours in July (based on sunrise and sunset times for Redding California (118)), as given in the third row of Table 85. A non-daylight crash modification factor (CMF) for California may be estimated by dividing the number of hours by the average number of non-daylight hours (11.9 hours) for Redding California, which is given in the fourth row of Table 85. The product of the New York seasonal factors and the California non-daylight

CMF is given in the fifth row of Table 85, and they range from a high of 1.7 to a low of 0.7. This last row of Table 85 can now be compared to the seasonal factors estimated in this study (Table 83). In both cases the magnitude of the seasonal effects are very similar and the highest number of non-daylight crashes occur during January, November, and December.

Table 85. New York State seasonal factors from Hauer et al. (92), and California non-daylight hours

Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
New York Seasonal Factors	1.25	0.97	0.97	0.79	0.84	0.89	0.96	0.98	0.85	0.95	1.15	1.40
California Non-daylight (hours)	14.8	13.9	12.4	11.2	10.0	9.1	9.0	9.8	11.0	13.0	13.3	14.7
California Non-daylight Hours/ California Average Non-daylight Hours (CMF)	1.2	1.2	1.0	0.9	0.8	0.8	0.8	0.8	0.9	1.1	1.1	1.2
New York Seasonal × California CMF	1.6	1.1	1.0	0.7	0.7	0.7	0.7	0.8	0.8	1.0	1.3	1.7

6.2. What if the Retroreflectivity Models are Inaccurate?

An analysis of the second month of installation (which is the first full month of new markings), the month where the retroreflectivity effect is supposed to be greatest still found no measurable effect on safety. Therefore, independent of what the on the road retroreflectivity may actually be, the safety difference between old and new markings is essentially zero. This result remains valid regardless of how accurate the retroreflectivity models may be.

6.3. How Small Might the Safety Effect of Pavement Markings be?

When crashes are artificially added to the data during the first full month of installation, the safety effect of markings is less than 300 crashes spread over eight years over 1388 miles of road on multilane freeways. This conclusion may be drawn from the graph in Figure 55 which shows that an additional 300 crashes occurring on roads with markings with the same retroreflectivity (markings within the same bin range) would have resulted in a safety effect of 1.05. A safety effect of 1.05 is large enough to have been detected as significant. In other words, the current study is sensitive to a difference of about 300 out of approximately 90,000 total crashes, or 0.3% sensitivity. The purpose of this sensitivity test is to demonstrate that the scope and design of this study is sufficiently large and robust to confidently conclude that the safety effect of retroreflectivity during non-daylight conditions on non-intersection locations is approximately zero.

6.4. Limitations of the Study

This study does not address the safety effect of pavement markings or markers themselves, rather the focus has been on the safety effect of retroreflectivity. This study can not be used to quantify the safety effect of the presence or absence of pavement markings and markers. This study also can not be used to quantify the safety effect of retroreflectivity greater or less than the ranges modeled for California.

There are associated limitations in defining precisely what the true retroreflectivity ranges are for California. The retroreflectivity values used in this study are estimates from models data based upon NTPEP test decks retroreflectivity measurements. The modeled retroreflectivity estimates have not been calibrated for California. This means that the true retroreflectivity of markings and markers in California may be different than the modeled NTPEP retroreflectivity. The applications of pavement markings and markers at NTPEP test decks may be more carefully applied than average highway installations where state department of transportation crews are under schedule and budget deadlines. On the other hand, state departments of transportation may be choosing marking and marker materials and types which perform above average NTPEP performance instead of selecting materials below average. The average retroreflectivity found on NTPEP test decks may be different than the average retroreflectivity found on state roads. It is not known if the retroreflectivity found on California highways and freeways is higher or lower than the retroreflectivity found on NTPEP test decks. So while there is certainty regarding that the difference in safety between new markings and old markings during non-daylight conditions on non-intersection locations is approximately zero, there is uncertainty regarding what is the value of retroreflectivity of new and old markings in California.

In addition, there are very few states which maintain a pavement marking management system like the one currently used in California. It may be that the very existence of a marking management system leads to an improved marking and marker program, thus producing very few roads with relatively low levels of retroreflectivity (below the proposed FHWA minimum of ~100 mcd/m^2/lux). A pavement marking management system may be a leading factor in having better than average pavement markings on the road. Therefore, it is possible that California is not representative state if in fact the condition of its markings are better than average. It may be that the absolute brightness level does not have a major effect on safety if the agency has a management system and the roads are maintained above a “minimum”. The only way to test this issue would be to compare the results for an agency that does a poor job of maintaining their system. Unfortunately, such an agency, if existent, would not have the data records to conduct the current study.

7. Chapter 7 Conclusions and Recommendations

This research study investigated the safety effect of the retroreflectivity of pavement markings and markers on state maintained multilane freeways, multilane highways, and 2-lane highways in California. An innovative analytical approach was developed which analyzed historical pavement marking and marker installation data over time, thereby making use of large quantities of data that otherwise could not be analyzed using traditional before-after methods. By converting the age of pavement markings into their corresponding retroreflectivity, different marking material types could be directly compared to one another by using retroreflectivity as a common metric. This approach is based on the assumption that different pavement marking material types at the same retroreflectivity, for example waterborne and thermoplastic both at 150 mcd/m^2/lux, have the same level of safety. Safety, defined as the number of crashes by severity per unit of time and distance, was examined as function of different ranges of retroreflectivity brightness.

Retroreflectivity performance of pavement markings and markers were based upon National Testing Product Evaluation Program (NTPEP) data. A database was built using published NTPEP retroreflectivity measurements, and mathematical models were built which compute retroreflectivity as a function of age, color, material type or marker type, climate region, and amount of snow removal. These retroreflectivity models provide average retroreflectivity performance for pavement markings and markers (look-up tables are provided in Appendix A). These models may be useful to jurisdictions seeking estimates of their pavement marking and marker retroreflectivity, or for comparing the performance of new products to the average performance of a particular material type. The retroreflectivity models were applied to convert California installation date data into retroreflectivity data. The safety effect of retroreflectivity of pavement markings (which also deteriorates over time) was studied by examining the change in the number of non-intersection, non-daylight crashes (nighttime, dawn, and dusk) over a period of eight years and over 118,000 crashes.

The analysis methodology used in this study solved for multipliers representing the safety effect for different retroreflectivity ranges (bin ranges). Because a time-series approach was used, it was necessary to separate out the monthly seasonal effect from the cyclic pattern of pavement marking and marker installation. Multipliers for the seasonal effect showing higher crash counts in January, November, and December provide support for the validity of the analysis methodology. No conclusions were drawn regarding the safety effect of the retroreflectivity of pavement markers because the sample size was too small. For pavement markings or markers, the difference in safety (measured during non-daylight and at non-intersection conditions) between time periods with between high retroreflectivity and low retroreflectivity markings is approximately zero, for roads that are maintained at the level implemented by California. California's level of maintenance appears to be frequent with pavement markings being installed on higher volume highways up to three times a year with waterborne paint, or every two years with thermoplastic markings.

What appears to be important is that markings are present and visible to drivers, but what is less important with respect to safety is whether the markings are "new marking bright" or "old marking bright". One hypothesis is that drivers compensate by reducing their speed under lower visibility conditions, and maintain higher speeds under higher visibility conditions. Therefore, any effect of the level of brightness of pavement markings may be minimized by driver adaptation to road conditions. In other words, the best estimate of the joint effect of retroreflectivity and driver adaptation is approximately zero for non-intersection road segments during non-daylight conditions.

Finally, the approach used in this study was found to be reliable and straightforward to implement and is recommended for safety treatments which change one way or another over time. The advantages of the approach used allowed for maximum inclusion of historical data and does not have the same sampling problems of traditional before-after studies.

7.1. Recommended Future Research

This report recommends the following issues be considered for future research.

- **Calibration of California retroreflectivity data.** The modeled retroreflectivity values based upon NTPEP data may not be the same as the retroreflectivity of pavement markings in California. Therefore, the ranges of retroreflectivity reported in this study may be higher or lower than the true retroreflectivity found on California roads. In order to accurately report the retroreflectivity bin ranges, the brightness of the markings need to be calibrated with measurements.
- **Study replication in other states.** The current study is based upon data from only one state and it is a state with an above average pavement marking and marker management system. Since California may not be representative of other state conditions and practices, this approach could be replicated in other states, particularly in states with poorer pavement marking and marker management systems. Though at this time it is unclear how the study approach could be executed in a state without installation data.
- **Examination of the effect of longitudinal markings and markers retroreflectivity on intersection related crashes.** The current study limited its scope to non-intersection related crashes on the belief that the effect of longitudinal markings and markers is greatest where they are applied, which is road segments. However, Musick (119) found that the addition of pavement marking edgelines led to a decrease in crashes not just on road segments but also at access points such as intersections, alleys, and driveways. Given that drivers' speed and performance on segments is related to their speed and performance at connecting intersections, it is therefore

reasonable that the retroreflectivity of longitudinal markings and markers has an influence on the safety of access points.

- **The human factors of marker and marking visibility.** How does driver behavior change as a function of the visibility of pavement markings and markers? How do driver speed, lane position, number of encroachments, and driver comfort change as a function of pavement markings and markers?
- **Traffic Operations.** Traffic operations often are influenced either positively or negatively by implementing strategies designed to improve safety. How are traffic operations affected even as safety remains unchanged with different retroreflectivity levels?
- **Examination of the effect of marking and marker retroreflectivity on crashes at curves.** The current study did not collect data on horizontal alignment. Previous research by Bahar et al. (63) found that the safety effect of snowplowable pavement markers is explicitly tied to key aspects of road geometry. It is reasonable to expect that the safety effect of retroreflectivity is not equal for all horizontal alignments.
- **Examination of the effect of marking and marker durability on daytime crashes.** The current study only examined the effect of retroreflectivity on non-daylight crashes and did not look at the effect of the visibility of markings on daytime crashes. Daytime visibility could be defined as the percentage of marking surface area or number of markers remaining on the road surface, e.g., the durability of the marking. NTPEP collects data on marking durability which could be used to model daytime visibility, and the same approach applied in this study could be extended to a daytime examination of the safety of the visibility of markings.
- **Examination of the effect of marking and marker retroreflectivity on crash impact type.** While the current study did examine the impact of crash severity, this study did not examine the effect of marking and marker retroreflectivity on different impact types (i.e., rear-end, sideswipe, head-on).
- **Improved retroreflectivity models.** While the models developed in this study are extensive, there are several areas of potential improvement for future models. Improved models are however dependent upon obtaining additional data, specifically data that were sparse in the current NTPEP data set. For example, only one test desk for marking and test deck for markers had observations during heavy snowfall years, so additional data on how snow removal affects retroreflectivity is needed. Another important limitation of using NTPEP data is reflected in the effort to model the effect of AADT. There is consensus that AADT should be a major influence on retroreflectivity degradation, but no research has yet been able to quantify it.
- **Examination of the benefit of pavement marking and marker management systems.** California is not a typical state in that it maintains a detailed pavement marking and marker management system, however, California conducts no retroreflectivity measurements. What are the costs and benefits of a pavement marking and marker management system? A marking and marker management system provides asset management benefits, allowing agencies to know what materials have been applied at which locations and at what times. In order to maintain a minimum retroreflectivity standard, is a pavement marking and marker management system a prerequisite in order to know which materials are in need of replacement, as opposed to regular retroreflectivity measurements?

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Appendix A. Retroreflectivity Look-up Tables for Markings and Markers

Table 86 displays the calculated predicted retroreflectivity for the proposed markings and marker models. The first column represents the ages from 0 to 48 months the remaining columns represent the modeled retroreflectivity values.

Table 86. Retroreflectivity look up tables for pavement markings

Age	Epoxy White all Climates all Snow Removal	Epoxy Yellow all Climates all Snow Removal	Methyl Methacrylate White all Climates all Snow Removal	Methyl Methacrylate Yellow all Climates all Snow Removal	Permanent Tape White all Climates all Snow Removal	Permanent Tape Yellow all Climates all Snow Removal	Solvent White all Climates all Snow Removal	Solvent Yellow all Climates all Snow Removal
0	338	237	377	180	549	386	182	128
1	331	230	365	177	496	335	171	121
2	324	223	354	174	451	295	161	115
3	317	217	343	170	414	264	151	108
4	310	211	333	166	382	239	142	102
5	304	206	323	162	355	218	134	97
6	298	200	314	158	331	200	126	92
7	293	196	305	154	310	186	118	87
8	288	191	296	150	291	173	111	82
9	283	187	288	145	274	162	105	78
10	279	183	281	141	259	152	99	74
11	274	179	274	137	246	143	94	70
12	270	176	267	132	234	135	88	67
13	266	172	260	128	223	129	84	63
14	262	169	254	124	212	122	79	60
15	259	166	248	120	203	117	75	57
16	255	163	242	116	194	111	71	55
17	252	160	236	112	186	107	68	52
18	249	158	231	108	179	102	64	50
19	246	155	226	104	172	98	61	48
20	244	153	221	101	166	95	58	45
21	241	151	216	97	160	91	55	43
22	238	148	211	94	154	88	53	42
23	236	146	207	90	149	85	50	40
24	234	144	203	87	144	82	48	38
25	232	142	198	84	139	80	46	37
26	229	141	194	81	135	77	44	35
27	227	139	190	78	130	75	42	33
28	225	137	186	75	125	72	40	32
29	223	135	182	72	121	69	38	30
30	221	133	178	69	116	67	36	29

Age	Epoxy White all Climates all Snow Removal	Epoxy Yellow all Climates all Snow Removal	Methyl Methacrylate White all Climates all Snow Removal	Methyl Methacrylate Yellow all Climates all Snow Removal	Permanent Tape White all Climates all Snow Removal	Permanent Tape Yellow all Climates all Snow Removal	Solvent White all Climates all Snow Removal	Solvent Yellow all Climates all Snow Removal
31	218	131	174	66	111	64	33	27
32	216	129	170	63	107	62	31	26
33	214	127	165	60	102	59	29	24
34	212	126	161	57	97	56	27	23
35	210	124	157	54	93	54	25	21
36	208	122	153	51	88	51	23	19
37	205	120	149	48	83	49	21	18
38	203	118	145	45	79	46	19	16
39	201	116	141	42	74	43	17	15
40	199	114	137	39	69	41	15	13
41	197	112	132	36	65	38	12	12
42	195	110	128	33	60	36	10	10
43	192	109	124	30	55	33	8	9
44	190	107	120	27	51	30	6	7
45	188	105	116	24	46	28	4	5
46	186	103	112	21	41	25	2	4
47	184	101	108	18	37	23	NA	2
48	182	99	103	15	32	20	NA	1

Age	Thermoplastic White Hot Humid and No Snow Removal	Thermoplastic Yellow Hot Humid and No Snow Removal	Waterborne White Hot Humid and No Snow Removal	Waterborne Yellow Hot Humid and No Snow Removal	Waterborne White Mixed-Humid Climate and No Snow Removal	Waterborne Yellow Mixed-Humid Climate and No Snow Removal	Thermoplastic White Mixed-Humid Climate and No Snow Removal	Thermoplastic Yellow Mixed-Humid Climate and No Snow Removal
0	413	204	356	238	335	235	397	251
1	392	197	331	218	322	228	383	240
2	373	190	309	201	310	221	370	230
3	356	184	292	187	299	215	358	221
4	341	178	276	175	288	209	347	212
5	328	172	263	165	279	203	336	204
6	315	167	252	155	269	198	326	196
7	304	162	242	147	261	192	317	189
8	294	157	233	140	253	188	309	183
9	284	153	225	133	245	183	300	176
10	276	149	218	127	238	179	293	170
11	268	145	212	122	231	174	286	165
12	261	141	207	117	225	170	279	160
13	254	137	202	112	219	167	272	155
14	248	134	197	108	213	163	266	150
15	242	131	194	105	208	159	260	146
16	236	128	190	101	202	156	255	141
17	231	125	187	98	197	153	250	137
18	226	122	185	95	193	150	245	133
19	222	119	183	92	188	147	240	130
20	218	117	181	89	184	144	235	126
21	214	114	179	87	180	141	231	123
22	210	112	178	85	176	139	227	120
23	207	110	177	83	172	136	223	117
24	204	108	176	81	168	134	219	114
25	201	106	176	79	165	131	216	111

Age	Thermoplastic White Hot Humid and No Snow Removal	Thermoplastic Yellow Hot Humid and No Snow Removal	Waterborne White Hot Humid and No Snow Removal	Waterborne Yellow Hot Humid and No Snow Removal	Waterborne White Mixed-Humid Climate and No Snow Removal	Waterborne Yellow Mixed-Humid Climate and No Snow Removal	Thermoplastic White Mixed-Humid Climate and No Snow Removal	Thermoplastic Yellow Mixed-Humid Climate and No Snow Removal
26	197	104	175	77	162	129	212	108
27	194	101	175	75	158	127	208	105
28	191	99	174	73	155	125	205	103
29	188	97	174	71	152	123	201	100
30	185	95	173	69	149	121	197	97
31	182	93	173	67	147	119	194	94
32	179	91	172	66	144	117	190	91
33	176	89	172	64	141	115	186	89
34	173	87	171	62	139	113	183	86
35	170	85	171	60	136	112	179	83
36	167	83	170	58	134	110	176	80
37	164	81	170	56	132	108	172	77
38	161	79	169	54	130	107	168	75
39	158	77	169	52	128	105	165	72
40	155	75	168	50	126	104	161	69
41	152	73	168	48	124	102	157	66
42	149	71	167	47	122	101	154	63
43	146	69	167	45	120	100	150	61
44	143	66	166	43	118	98	146	58
45	140	64	166	41	116	97	143	55
46	137	62	165	39	114	96	139	52
47	134	60	165	37	113	95	136	49
48	131	58	164	35	111	93	132	47

Age	Thermoplastic White Hot-Dry Climate and No Snow Removal	Thermoplastic Yellow Hot-Dry Climate and No Snow Removal	Waterborne White Cold Climate and Heavy Snow Removal	Waterborne Yellow Cold Climate and Heavy Snow Removal	Waterborne White Cold Climate and Low to Medium Snow Removal	Waterborne Yellow Cold Climate and Low to Medium Snow Removal	Thermoplastic White Cold Climate and Heavy Snow Removal	Thermoplastic Yellow Cold Climate and Heavy Snow Removal
0	331	157	330	209	343	225	380	212
1	313	151	331	209	327	211	376	213
2	297	145	317	200	312	198	362	208
3	283	140	292	185	299	187	340	198
4	271	135	261	166	288	177	312	185
5	260	130	228	146	277	168	282	170
6	250	126	197	127	268	160	252	154
7	241	122	169	110	259	153	224	138
8	233	119	146	95	251	146	199	123
9	226	115	125	82	243	140	176	110
10	219	112	108	71	236	134	156	97
11	213	109	94	62	230	129	138	87
12	208	106	82	54	224	124	123	78
13	203	103	72	48	218	120	110	69
14	198	100	64	42	213	115	99	62
15	194	98	57	38	208	112	89	56
16	191	95	51	34	204	108	80	51
17	187	93	46	30	199	105	73	46
18	184	91	41	27	196	101	66	42
19	181	89	37	25	192	98	60	38
20	178	87	35	23	188	96	55	35
21	176	85	31	21	185	93	51	32
22	174	83	28	19	182	90	47	30
23	172	82	26	18	179	88	43	27

Age	Thermoplastic White Hot-Dry Climate and No Snow Removal	Thermoplastic Yellow Hot-Dry Climate and No Snow Removal	Waterborne White Cold Climate and Heavy Snow Removal	Waterborne Yellow Cold Climate and Heavy Snow Removal	Waterborne White Cold Climate and Low to Medium Snow Removal	Waterborne Yellow Cold Climate and Low to Medium Snow Removal	Thermoplastic White Cold Climate and Heavy Snow Removal	Thermoplastic Yellow Cold Climate and Heavy Snow Removal
24	170	80	24	16	176	86	40	25
25	168	78	22	15	174	84	37	24
26	167	77	21	14	171	81	34	22
27	165	75	19	13	169	79	32	20
28	163	74	17	11	166	77	29	18
29	162	72	15	10	163	75	26	16
30	160	71	13	9	161	73	23	14
31	158	69	11	8	158	71	20	13
32	157	67	10	7	156	68	17	11
33	155	66	8	5	153	66	14	9
34	153	64	6	4	151	64	12	7
35	152	63	4	3	148	62	9	5
36	150	61	2	2	145	60	6	4
37	149	59	1	1	143	58	3	2
38	147	58	NA	NA	140	56	NA	NA
39	145	56	NA	NA	138	53	NA	NA
40	144	55	NA	NA	135	51	NA	NA
41	142	53	NA	NA	132	49	NA	NA
42	140	52	NA	NA	130	47	NA	NA
43	139	50	NA	NA	127	45	NA	NA
44	137	48	NA	NA	125	43	NA	NA
45	135	47	NA	NA	122	40	NA	NA
46	134	45	NA	NA	120	38	NA	NA
47	132	44	NA	NA	117	36	NA	NA
48	130	42	NA	NA	114	34	NA	NA

Age	Thermoplastic White Cold Climate and Low to Medium Snow Removal	Thermoplastic Yellow Cold Climate and Low to Medium Snow Removal	Markers Non-plowable All Colors, Climates and Snow Removals	Markers Plowable All Colors, Climates and Snow Removals
0	423	211	0.461	0.520
1	403	204	0.284	0.351
2	385	198	0.206	0.266
3	369	192	0.162	0.216
4	355	187	0.134	0.182
5	343	181	0.115	0.158
6	332	177	0.100	0.140
7	322	172	0.089	0.126
8	313	168	0.081	0.115
9	305	164	0.074	0.106
10	297	160	0.068	0.099
11	290	156	0.063	0.092
12	284	152	0.059	0.087
13	279	149	0.055	0.083
14	274	146	0.052	0.079
15	269	143	0.049	0.075
16	265	140	0.047	0.072
17	261	137	0.045	0.069
18	258	134	0.043	0.067
19	255	132	0.041	0.065
20	252	129	0.039	0.063
21	250	127	0.038	0.061
22	248	124	0.037	0.060
23	246	122	0.036	0.058
24	244	120	0.034	0.057
25	243	118	0.033	0.056
26	242	116	0.032	0.055
27	240	114	0.031	0.054
28	239	112	0.030	0.052
29	238	110	0.029	0.051
30	237	108	0.028	0.050
31	235	106	0.027	0.049
32	234	104	0.026	0.048
33	233	102	0.025	0.047
34	231	99	0.024	0.046
35	230	97	0.023	0.045
36	229	95	0.022	0.043
37	227	93	0.021	0.042
38	226	91	0.020	0.041

Age	Thermoplastic White Cold Climate and Low to Medium Snow Removal	Thermoplastic Yellow Cold Climate and Low to Medium Snow Removal	Markers Non-plowable All Colors, Climates and Snow Removals	Markers Plowable All Colors, Climates and Snow Removals
39	225	89	0.019	0.040
40	224	87	0.018	0.039
41	222	85	0.017	0.038
42	221	83	0.016	0.037
43	220	81	0.015	0.036
44	218	79	0.014	0.035
45	217	77	0.013	0.033
46	216	75	0.012	0.032
47	214	73	0.011	0.031
48	213	71	0.010	0.030