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An analysis of the safety effectiveness of pavement marking retroreflectivity

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An analysis of the safety effectiveness of pavement marking retroreflectivity

by

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Abstract

It has been shown in previous research that greater longitudinal pavement marking retroreflectivity levels increase drivers' visibility and detection distance. However, increased visibility may also cause drivers to feel too comfortable during nighttime conditions and drivers may then pay less attention and/or operate at unsafe speeds. Before-and-after studies have been conducted on pavement marking improvements such as repainting stripes or changing to a more durable marking material. Studies have also used models to estimate the retroreflectivity based on the date of installment, the vehicle exposure, or assumed a linear reduction in retroreflectivity over time. Only two studies have related measured pavement marking retroreflectivity to safety performance (crash) data. This study analyzes the relationship between 3 years of pavement marking retroreflectivity data collected by the Iowa DOT on all state primary roads and corresponding crash and traffic data. This study developed a spatial-temporal database using measured retroreflectivity data to account for the deterioration of pavement markings over time along with a statewide crash data to attempt to quantify a relationship. Three different sets of data were analyzed: the complete database, two-lane roads, and records with low retroreflectivity values (≤ 200 mcd/m^2/lx) only. The distributions and models of the entire database and the two-lane records did not show that poor pavement marking retroreflectivity correlating to a higher crash probability. When looking at records with low retroreflectivity values only, a statistically significant relationship was determined. However, the correlation was so small it does not have practical significance.

1.0 Introduction

Longitudinal pavement markings are a guidance tool used to delineate the traveled way. These markings include centerlines and edgelines. Longitudinal pavement markings help protect drivers by indicating where they should be on the road to prevent collisions with oncoming vehicles or vehicles traveling in the same direction, as well as run-off-the-road (ROR) crashes. At night time, when it is dark and roadway lighting is absent, pavement markings are especially important.

1.1 Retroreflectivity

A very important feature of a longitudinal pavement marking is the retroreflectivity. Reflective beads are implanted in pavement markings so that driver's can see them at night or in dark conditions. The light from a vehicle's headlights reflect off the beads and the amount of light that is reflected back to light source is defined as the retroreflectivity. Pavement marking retroreflectivity is measured in units of millicandelas per square meter per lux ($mcd/m^2/lx$).

1.2 Variability of Retroreflectivity

Pavement marking retroreflectivity can vary significantly by location. One spot may have a high retroreflectivity value while a spot just a few feet away may have a low value. Potential causes of this variability include environmental conditions and the consistency in which the pavement markings were applied and measured. The variability makes it difficult to measure pavement marking retroreflectivity which accurately represents a roadway segment.

1.3 Service Life Evaluation / Degradation of Pavement Markings

In Iowa, and other states with significant amounts of snowfall, the reflective beads imbedded in the paint get worn and are scraped up by snow plows. Pavement markings wear out over time and it is necessary for agencies to re-stripe and repair the condition of pavement markings on a regular basis. The question then is: How often should a marking be re-striped? Many studies have tested the visibility and subjective preferences of drivers against pavement markings with a known retroreflectivity. Others have compared crashes by location to either measured or modeled pavement marking retroreflectivity values. All of these studies are concerned with determining a relationship between pavement marking retroreflectivity and safety. With this relationship identified agencies can evaluate the service life of their pavement markings much more efficiently and improve their asset management programs and the allocation of their maintenance funding. The Iowa DOT currently uses 150 $mcd/m^2/lx$ for white markings and 100 $mcd/m^2/lx$ for yellow pavement markings as a minimum standard for re-striping state highways.

2.0 Literature Review

2.1 Variability of Pavement Marking Retroreflectivity

Kopf (2004) completed a study to determine degradation curves for waterborne and solvent-based paints in the state of Washington. The retroreflectivity data recorded in the study had a high variability. Potential causes of this variability were the application method of the pavement markings, the inherent variability in the Laserlux device (which was mounted to a vehicle) used to measure the retroreflectivity, the difficulty of calibrating the Laserlux device, a difference in environmental conditions, and the possibility of inconsistent retroreflectivity measurements. As a result of the high variability in the retroreflectivity data, many of the service life estimates were “questionable”. Using 100 mcd/m^2/lx as a minimum retroreflectivity threshold, the service life estimates were calculated with the formulas of trend lines developed from plots of average retroreflectivity by the number of days since last striping. The average coefficient of determination for the retroreflectivity degradation trend lines was 0.3059, with a range of 0.0335 to 0.7321. The main result of the study is that retroreflectivity is unpredictable. “Unfortunately, given the variability of the data observed to date, it may not be possible, even with the collection of more data, to create striping performance predictions that have a high level of statistical confidence. (Kopf, pg. 31)”

2.2 Pavement Marking Retroreflectivity & Driver Visibility

Graham and King (1991) performed a field test using 59 observers to evaluate the effectiveness of retroreflectivity for pavement markings. More than 98 percent of the tested observers rated a retroreflectivity value of 93 mcd/m^2/lx as adequate or more than adequate. However, many of the subjects in the study were relatively young and the study was conducted under ideal conditions. The authors recognized that “it is likely that an older driver, operating in a real-world driving situation, would require a retroreflectivity value higher than 93 mcd/m^2/lx. (Graham and King, pg. 23)”

Thirty-two state and local highway agencies throughout the United States participated in a pavement marking field survey conducted by Migletz et al. (1999). Field measurements were collected in the fall of 1994 and the spring of 1995 at sites in the jurisdiction of the 32 agencies. The study determined that the retroreflectivity of white markings is generally higher than that of yellow markings. The mean retroreflectivity of the white markings and yellow markings they measured was 203 and 133 mcd/m^2/lx, respectively. Durable (tape) marking materials were found to generally have a greater retroreflectivity than painted markings. The mean retroreflectivity values for white markings ranged from 158 mcd/m^2/lx for conventional paint markings to 330 mcd/m^2/lx for tape markings. The mean retroreflectivity values for yellow markings ranged from 117 mcd/m^2/lx for conventional paint markings to 327 mcd/m^2/lx for tape markings. The study also determined that white markings do not differ in retroreflectivity and luminance contrast ratio among edgelines and lane lines (the contrast ratio is the pavement marking retroreflectivity divided by the retroreflectivity of the pavement surface). When comparing the fall and spring retroreflectivity measurements from 2 states with relatively severe winter climates it was found that the mean retroreflectivity was 15 to 34 percent lower following the winter season.

Zwahlen and Schnell (1999) conducted a study to find the relationship between pavement marking visibility by driver age and the retroreflectivity of the pavement markings under low-beam and high-beam illumination at night. The study found that age has a significant effect on drivers' visibility and how well they can see pavement markings. The average end detection distance increased by about 55 percent when the younger group of drivers (average age 23.2 years) was compared to the older group (average age of 68.3 years). The end detection distance is the length of longitudinal pavement marking visible to the driver. The difference between high-beam and low-beam headlamp illumination was found to be insignificant and highly retroreflective pavement markings (average yellow R_L = 399 mcd/m^2/lx, average white R_L = 706 mcd/m^2/lx) allowed for a greater end detection distance than medium retroreflective markings (average yellow R_L = 222 mcd/m^2/lx, average white R_L = 268 mcd/m^2/lx). "Upgrading pavement markings from medium retroreflectivity to high retroreflectivity allows for a 13 to 14.9 percent increase in the end detection distance." (Zwahlen and Schnell, pg. 162)

Parker and Meja (2002) conducted a night time visibility study in New Jersey. Seventy-two test subjects were asked to rate the pavement markings at certain sites as they drove along a predetermined route where the retroreflectivity of the markings was known. The retroreflectivity of pavement markings along the test route ranged from 92 mcd/m^2/lx to 286 mcd/m^2/lx. The results of a survey showed no significant variation in ratings between genders and found a significant difference in pavement marking ratings by age. An older group, which included drivers age 55 and older, rated the yellow pavement markings significantly lower than the other age groups did.

In comparing the retroreflectivity to the drivers' visibility ratings, Parker and Meja (2002) found that a "curvilinear regression yielded a polynomial function of 4th order as the best fit." (Parker, pg. 7) A strong correlation between the measured retroreflectivity and the participants' night visibility ratings was confirmed. The lowest coefficient of determination for all of the line types was 0.97. The curvilinear regression fit is shown in Figure 1. "Results suggest that concentrating resources on re-striping pavement markings with a retroreflectivity below 125 mcd/m^2/lx would achieve a greater relative increase in driver satisfaction, than re-striping pavement marking with retroreflectivity above 125 mcd/m^2/lx." (Parker, pg. 7)

The limit between acceptable and unacceptable, as rated by the test subjects, was "consistent with conclusions reached by other investigators on similar research, with results generally ranging between 70-170 mcd/m2/lux." (Parker, pg. 9)

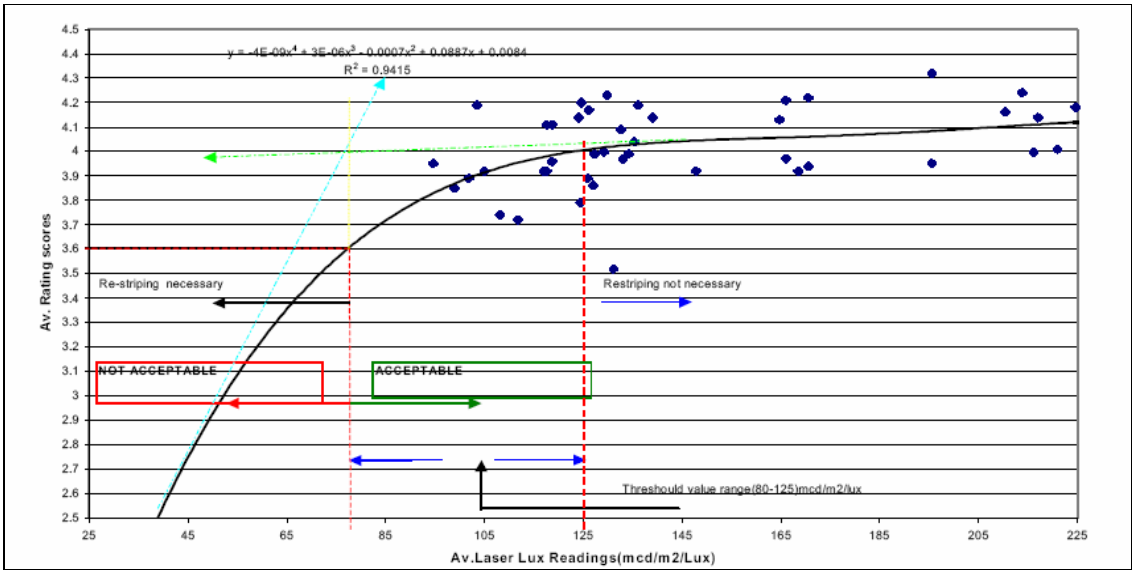

Figure 1: Curvilinear Regression for WEL, YCL and SPL.

2.3 Pavement Marking Improvements & Safety

A before-and-after study, FHWA (1981), of pavement marking improvement projects was conducted in six states (Iowa, Michigan, Montana, North Carolina, Virginia, and West Virginia). The before-and-after period was either 1-year or 2-years, depending upon the state. The study was conducted on two-lane rural roads with a posted speed limit of 40 miles per hour or more. Pavement marking improvements included the addition of a centerline and edgeline, centerline only, and edgeline only. It was assumed that pavement markings have minimal effect on crashes occurring during the day, so daylight crashes were used to control regression-to-the-mean. Since crash reporting systems for low volume rural roads were considered to be the least reliable, only fatal and injury crashes were used.

Overall, the FHWA (1981) study found that pavement marking improvements decreased fatal and injury crashes at night. The percent reduction in crashes was statistically significant for added edgelines (16 percent) and centerlines and edgelines (12 percent). A centerline improvement only resulted in a statistically insignificant reduction of 3 percent. The study determined that adding edgelines to roads with centerlines was the most cost effective pavement marking improvement to reduce fatal and injury crashes that occur at night.

Hall (1987) and Cottrell (1988) evaluated the effects of wide edgelines on ROR crashes. In Hall's study approximately 530 miles of rural 2-lane highway with high rates of ROR crashes were selected. Over 2 years 176 of these miles were re-striped with an 8-inch white edgeline. The remaining miles were used for comparison reasons. Cottrell (1988) conducted a "before-and-after study with a comparison group and a check for comparability" (Cottrell, pg. 35) on 60.7 miles of rural two-lane roadway. It was not stated as to how the treatment locations were chosen, but the comparison locations were selected because of similar roadway geometrics, traffic volumes, and crash frequencies. A duration of 3 years was used for the before period and a duration of 2 years was used for the after period. Both of these studies found that wide edgelines do not have a significant effect on the frequency of ROR crashes.

A before-and-after study based on the Bayesian approach was completed by Al-Masaeid and Sinha (1994) to evaluate the effectiveness of centerline and edge line pavement marking improvements. The study was performed on undivided rural roads in the state of Indiana. Al-Masaeid and Sinha (1994) selected 100 improved pavement marking sites. The ADT on the study sections ranged from 1,000 to 4,000 vehicles per day. The total number of crashes occurring along the selected sites over the 2-year before and 2-year after periods was used in the analysis. "For both before and after periods, the first-year accident rates were used to compute the prior parameters; and the second-year accident rates were used to update to prior knowledge to estimate posterior parameters at site level" (Al-Masaeid, pg. 726).

Al-Masaeid and Sinha (1994) estimated the pavement markings effectiveness as a crash reduction factor. A probabilistic approach was used to estimate an accident reduction factor due to pavement markings. When considering all of the selected sites the results of the analysis were not significant. When only hazardous sites were considered the pavement markings provided a significant accident reduction of 13.5%. Hazardous sites were defined as sites which had an expected accident rate greater than the mean expected accident rate in the before period.

Migletz and Graham (2002) completed a before-and-after study for the Federal Highway Administration (FHWA) to determine if "longer lasting more retroreflective materials reduced crashes" (Migletz, pg. 32). Multiple vehicle collisions at intersections and crashes on ice/snow covered pavements were excluded from the analysis. The before-period consisted of 48 sites with conventional solvent paint and 7 sites with epoxy based paint. The 55 sites were re-striped with durable markings for the after-period. At the all of the sites, five measures of exposure were considered. The measures included were: "site length, duration of study period (in days), average ADT, proportion of ADT under daytime and night time conditions, and proportion of ADT under dry and wet conditions" (Migletz, pg. 32).

The results of the analysis showed that night time crashes on dry pavement, adjusted by the measure of exposure, decreased significantly by an average of 11%. The night time wet pavement crashes increased by a statistically insignificant average of 15 % after adjustment for exposure. Random variation was given as a possible reason for this increase. When combined, the overall night time crash frequency at the 55 sites decreased by an average of 6%. This was not statistically significant.

The researchers also mentioned a survey completed in the year 2000 by the Washington State DOT that reported a decrease in crashes due to pavement markings. "A benefit-cost ratio of 1.9 for year-round pavement markings on a rural, two-lane, two-way arterial was achieved" (Migletz, pg. 32). The results were reported to be statistically significant at the 95th percentile level, but no documentation was given.

Bahar et al. (2004) evaluated the effects of permanent raised pavement markers (PRPMs) on safety. The study was done in six states: Pennsylvania, Illinois, Missouri, Wisconsin, New Jersey, and New York. Raised pavement markers are added to pavement markings to increase the visibility of roadway delineation. The study found that PRPMs "are less effective on roadways with a higher degree of curvature and lower roadway design standards" (Bahar, pg. 52). This finding is counterintuitive in that it is assumed that increased visibility and delineation on curves would have a safety benefit. The study found that drivers tended to move away from the PRPMs. Evidence was also found that PRPMs and increased visibility may be associated with drivers operating at higher speeds.

Tsyganov et al. (2006) performed a before and after study on rural two-lane highways in Texas where edgeline markings were added. Highway segments of 3 miles or greater consisting of uniform lane width, shoulder width (less than 4 feet), traffic volumes, and edge striping were analyzed in the study. Crash records from 1998-2001 were used to evaluate the safety benefits of adding edgelines. Work zone related crashes were removed from the analysis.

The safety analysis found that the addition of edgelines on rural two-lane highways may reduce accident frequency. The addition of edgelines had the greatest safety benefit on curved segments of roadways with narrow lane widths (9-10 feet). The researchers recommend that edgelines should be considered as a possible strategy to reduce ROR crashes at high crash horizontal curve locations and also where there are many older drivers. "Overall, for all lane widths, the frequency of ROR accidents is 11 percent higher on highways without edge lines than with edge lines". (Tsyganov, p.g. 4) The presence of edge lines also showed safety benefits during darkness conditions. The researchers suggested that this may be related to better driver perception of path and speed.

Tsyganov et al. (2004) also studied the effects of edglines on speed. The study found that speeds increased by an average of 5 mph on both straight and curved sections of highway after edgelines were applied. This change in average speed, however, is not considered significant.

2.4 Pavement Marking Retroreflectivity & Safety

Along with evaluating the retroreflectivity and durability of different pavement markings the study by Lee et al. (1999) looked at the relationship between retroreflectivity and traffic variables as well as retroreflectivity and night time accidents in Michigan. Five test areas were selected around the state with variations in traffic, speed limit, lighting, and snow fall. Three to eight retroreflectivity readings were taken at randomly selected locations along the test areas. Readings were collected at each location every three months, except for the Upper Peninsula where readings were taken every month.

An analysis showed no evidence that average daily traffic, speed limit, and commercial traffic percentage had an effect on the deterioration of longitudinal pavement marking retroreflectivity. The analysis did find that snowfall, and the consequential plowing of the road, was correlated to the decline of pavement marking retroreflectivity.

The researchers performed a linear regression analysis to determine the relationship between night-to-day accident ratios and corresponding retroreflectivity values. Table 1 shows the criteria in selecting the accidents relating to pavement marking visibility. The results showed no evidence that night time crash frequency is sensitive to pavement marking retroreflectivity levels. "However, very few reported reflectance measurements fell below the commonly accepted minimum value of 100 mcd/m^2/lux. A database that includes a wider range of retroreflectivity levels may reveal the effects of low retroreflectivity on traffic crashes or accidents" (Lee, pg. 49). The authors also suggested that a larger sample of night time accidents may allow the identification of a relationship between pavement marking visibility and night time accidents.

Table 1: Criteria to Select Accidents Associated with Line Visibility

Variables	Selected Values
Highway Area Type	Non-intersection and non-interchange area
Lighting Conditions	Dawn, dusk, darkness
Road Condition	Dry
Special Accident Tag	None (excluding school buses, emergency vehicles or animal collisions)
Accident Type	Miscellaneous one vehicle, overturn, fixed object, other object, head on
Driver Violation	No hazardous action and other or not known
Contributing Circumstance	None and other or not known (excluding driver's alcohol or drugs, careless, fatigued, defective equipment, lost control due to shifting load, skidding

Cottrell and Hanson (2001) completed a before-and-after analysis to determine the impact of white pavement marking materials on crashes. Two different analyses were done. The first involved only looking at sideswipe-in-the-same-direction and ROR crashes. Night time crashes were targeted and daytime crashes were used in comparison. The second analysis looked at all crashes occurring during the before and after periods.

Thirty-two crash analysis sites with an average length of 3.6 miles were selected for the study. Of the 32 sites, only 22 were used because there was no crash experience in the before period for 10 of the sites. The researchers estimated the average retroreflectivity of the white pavement markings by assuming that the retroreflectivity reduced linearly over time. Due to a lack of analysis sites and crash count data the final results of both analyses provided insufficient evidence that the improved retroreflectivity and visibility of the pavement markings reduced the number of crashes.

Abboud and Bowman (2002) conducted a study in the state of Alabama to determine a threshold for pavement marking retroreflectivity based on crash rates and traffic volumes. “This objective is achieved by establishing a retroreflectivity-crash relationship and identifying the minimum retroreflectivity value that corresponds to a maximum allowable crash rate (CR)” (Abboud and Bowman, pg. 2). Crashes considered in the analysis excluded: rear-end and angle type crashes; drug/alcohol, animal, and pedestrian related crashes; crashes occurring in rain, fog, snow, ice, sleet, and hail; crashes occurring when the road was icy; and daytime crashes. The rest of the crashes were considered striping-related. Both waterborne paint and thermoplastic pavement markings were tested. Yellow markings were excluded because research has found that drivers tend to use the white edgeline more for guidance. Highway segments were analyzed in units of 1 mile and a CR in crashes per million vehicle-miles was calculated for each segment. Crash records were collected for up to 3 years after the striping date and retroreflectivity readings were taken at 1-3 mile intervals for all striping projects.

A linear regression analysis was used to relate the CR of each segment to the vehicle exposure (VE), which was defined as the cumulative number of vehicles that traverse the highway segment. A plot of the CR-VE regression model determined that the CR increased with an increase in VE at an approximately the same rate for both paint and thermoplastic pavement markings. The plot also indicated that the thermoplastic lines provided safer traffic operation than the painted markings under the same VE.

A logarithmic regression analysis was used to determine the relationship between the retroreflectivity of the pavement markings and the VE of the highway segment. Lastly, using VE as a common factor, a relationship between retroreflectivity and crash rate was determined. A critical crash rate defined as the average crash rate or the overall number of crashes divided by overall sum of million vehicle miles was calculated. Based on the critical crash rate, the corresponding VE was calculated and then used to determine a minimum retroreflectivity threshold of 150 mcd/m^2/lx for white pavement markings. Pavement markings in colder weather regions suffer due to snow removal operations and deicing materials. The authors acknowledged that since the study was done in a warm weather region the results are applicable to regions with a similar climate.

Bahar et al. (2006) found that “the safety difference between high retroreflectivity and low retroreflectivity markings during non-daylight conditions on non-intersection locations was found to be approximately zero, for all roads that are maintained at the level implemented by California” (Bahar, pg.3). Retroreflectivity models based upon data collected by the National Transportation Product Evaluation Program (NTPEP) were used. Retroreflectivity of the pavement markings was estimated as a function of pavement marking age, color, material type, climate region, and amount of snow removal. Retroreflectivity models were applied to relate pavement marking installation date data into pavement marking retroreflectivity estimates. Seasonal multipliers were developed for the three road types (multi-lane freeways, multi-lane highways, two-lane highways) involved in the study to account for seasonal crash variation.

There are limitations to the results of this study. The authors acknowledge that the "study can not be used to quantify the safety effect of retroreflectivity greater or less than the ranges modeled for California" (Bahar, pg. 173). Another potential problem is that "the true retroreflectivity of markings and markers in California may be different than the modeled NTPEP retroreflectivity" (Bahar, pg. 173).

2.5 Gaps in Research

It has been shown in previous research that greater retroreflectivity levels increase drivers' visibility and end detection distance. However, a study of permanent raised pavement markers found that the increased visibility in roadway delineation actually had a negative effect on safety (Bahar et al. (2004)). Only two studies have collected pavement marking retroreflectivity measurements to determine a safety/crash impact. One of the studies determined a retroreflectivity threshold based upon crash rates (Abboud and Bowman (2002)) and the other had inconclusive results due to a lack of enough target crashes (Lee et al. (1999)). Before and after studies have been conducted for pavement marking improvements such as repainting the road or changing to a more durable marking material, but before-and-after analyses do not account for the deterioration of pavement markings over time. Other studies have used models to estimate the retroreflectivity based on pavement marking characteristics or assumed a linear reduction in retroreflectivity over time.

Previous research has not produced implementable results when evaluating the correlation between pavement marking retroreflectivity measurements and crashes. Therefore, a study utilizing measured retroreflectivity data accounting for the deterioration of pavement markings over time along with a sufficient amount crash data is needed to provide a relationship between pavement marking retroreflectivity and safety performance.

3.0 Problem Statement

Improving the safety of rural roadways is the major motivation behind determining a relationship between pavement marking retroreflectivity and crashes. It is assumed that lower retroreflectivity values are a contributing factor is some crashes (such as night time, single vehicle, ROR crashes), however a statistically significant relationship has not yet been determined. If a statistically reliable relationship can be identified, agencies can improve their pavement marking management programs and reduce the number of night time crashes where low pavement marking retroreflective values are a contributing factor.

A study of the safety effects of pavement marking retroreflectivity is complex. The fact that pavement marking retroreflectivity deteriorates non-linearly overtime and varies immensely by location, environmental condition, and other unidentified factors complicates a safety analysis. Assigning crashes spatially to a road segment seems simple, but multiple line types and directions at individual locations create difficulties in developing a database. A location may have a combination of white edgeline, yellow centerline or yellow edgeline pavement markings and the edgeline markings are in both directions of travel. Additionally, the data used were collected over 3 years. This creates a temporal factor. These different factors require that each record in a database be unique by location, line type, direction, and time. After that, each target crash record needs to be assigned to the appropriate record. This requires that each target crash is assigned a location, line type, direction, and time.

Because of the complexity involved in developing a large spatially and temporally accurate database, the development of such a database and the methodology required, may be, in themselves significant contributions. Therefore, this thesis sets out to design and develop such a database, and use that database to test the relationship between pavement marking retroreflectivity and safety performance in Iowa.

This study analyzes the correlation among 3 cumulative years of measured pavement marking retroreflectivity data collected by the Iowa DOT on state primary roads and corresponding crash, roadway, and traffic data. The retroreflectivity data for this study include retroreflectivity levels lower than what is typically recommended. Therefore a wide range of retroreflectivity levels were available for the analysis.

4.0 Database Preparation

The data used in this research required significant organization before they could be analyzed. The following section describes how the data were prepared for analysis.

4.1 Pavement Marking Retroreflectivity Data

Two separate pavement marking retroreflectivity databases were used in the analysis. A “spring/fall” database consists of retroreflectivity measurements collected by the Iowa DOT on state primary roads in both “spring” and “fall” periods from 2004 through 2006. The “spring” period includes data from approximately March through June and the “fall” period includes data from approximately July through November in each of the three years. The duration of each period varied some by year due to the availability of data collection crews. The beginning and end dates of each white edge line retroreflectivity data collection period is shown in Table 2 below.

Table 2: White Edgeline Retroreflectivity Data Collection Periods

Period	2004		2005		2006	
	Begin	**End**	**Begin**	**End**	**Begin**	**End**
Spring	March 2	May 3	February 28	June 29	March 16	May 9
Fall	September 8	November 23	July 6	November 28	September 12	December 5

A “paint” database contains the initial retroreflectivity values of corridors where pavement markings were re-striped. For each re-striping corridor a single initial retroreflectivity value was assigned to the entire corridor. For example, if the yellow centerline of a section of roadway between mileposts 5 and 25 were re-striped, the same initial retroreflectivity value was assigned to all of the mileposts from 5 to 25. The database also includes the date the re-striping occurred.

4.2 Data Collection

Two different types of devices were used by the Iowa DOT to collect pavement marking retroreflectivity data. Most of the data were collected using a handheld Retrometer LTL-X. The handheld retroreflectivity data were collected by taking 12 spot measurements over a distance of approximately 200 feet. The nearest milepost was then assigned the average of the 12 spot measurements. Figure 2 shows where the handheld retroreflectivity data were collected for the spring/fall database in 2006.

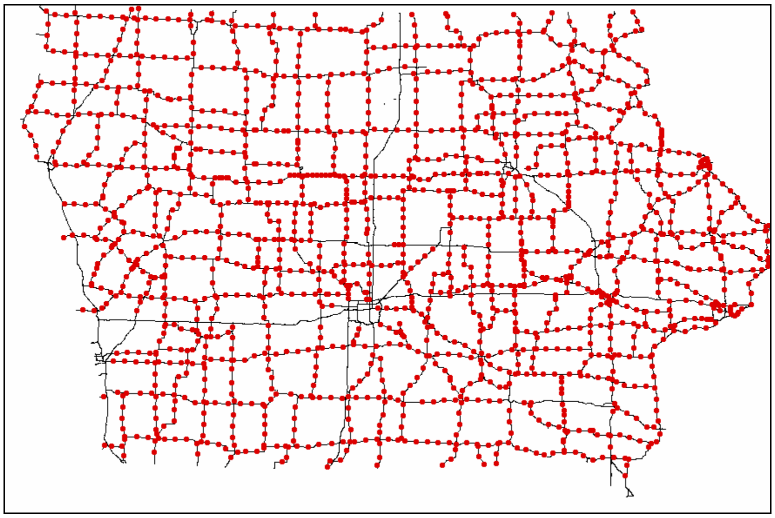

Figure 2: Spring/Fall Retroreflectivity Data Collected by Handheld Retrometer (LTL-X) in 2006

The paint data was collected using a handheld LTL-X as well. During the re-striping process, the retroreflectivity of the markings are checked at least two times per mile. The average of these readings is then entered into the paint database and assigned to every milepost along the section of road re-striped that day.

The Iowa DOT also collected pavement marking retroreflectivity data using a laserlux van. The laserlux van collects data every tenth of a mile and averages these reading every 1 mile. The laserlux van was used to collect pavement marking retroreflectivity data on the interstates and other high volume roads. Figure 3 shows where the laserlux van was used to collect the retroreflectivity data. Data for all of the interstates and several other high volume, limited access facilities were collected in this fashion. Using the handheld Retrometer LTL-X to collect data on these roads would be too dangerous.

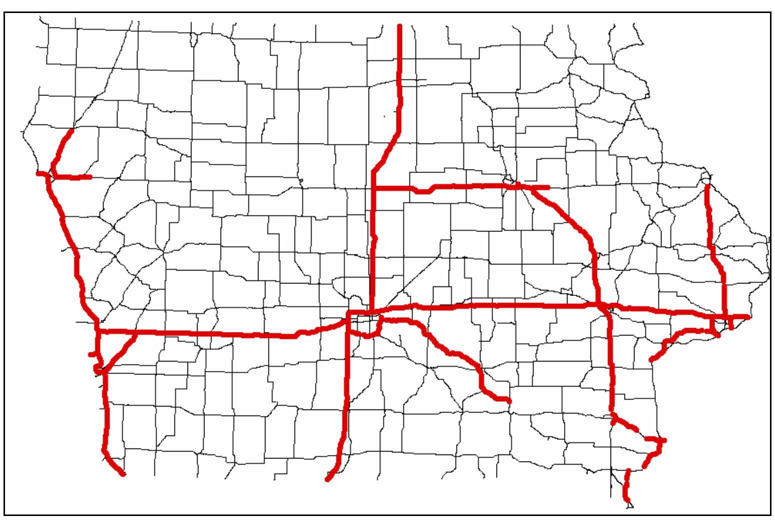

Figure 3: Spring/Fall Retroreflectivity Data Collected by the Laserlux Van from 2004-2006

The retroreflectivity database included the following information for each record:

- County (1 – 99)
- Route
- System (1, 2, or 3)
- Milepost
- Line Type (WEL, YCL, YEL, WDC)
- Direction (1 or 2)
- Retroreflectivity
- Date
- Year (2004, 2005, or 2006)
- Time of Year (Spring or Fall)
- Contractor
- Material Type
- Source (Handheld or Laserlux)
- District (1 - 6)
- Length (1 or 5 mile)

Where WEL = White Edgeline; YCL = Yellow Centerline; YEL = Yellow Edgeline; WDC = White Dashed Centerline; Direction 1 = Northbound or Eastbound; and Direction 2 = Southbound or Westbound.

4.3 Five Mile to One Mile Retroreflectivity Data Conversion

The retroreflectivity measurements taken by the Retrometer LTL-X were assumed to be representative of 5 mile sections. Therefore, retroreflectivity values were copied for 2 mileposts in each direction of the milepost the retroreflectivity measurements were assigned to. The original 5 mile section database had 32,160 records (mileposts) with retroreflectivity values. After assigning the data, the new 1 mile section database contained 155,758 records (some of the mileposts in the database had zero or only one existing milepost in either direction, so the resulting database was smaller than 32,160*5=160,800 records) The retroreflectivity assignment method is illustrated in Figure 4.

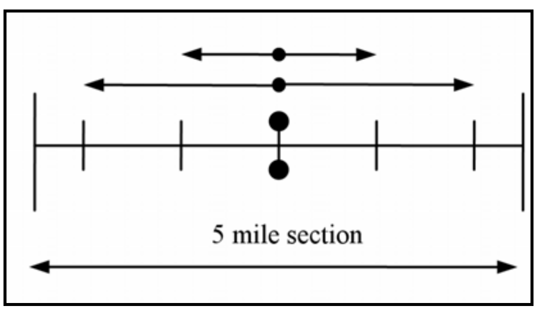

Figure 4: Retroreflectivity Data Assignment

4.4 Combining the Handheld & Laserlux Retroreflectivity Data

After converting the 5 mile handheld data to cover 1 mile sections of roadway the retroreflectivity data collected by the laserlux van was added. Combining the data increased the database to 174,525 records. Since only white edgeline, yellow center line, and yellow edgeline records were needed, the white dashed centerline retroreflectivity records were then removed (18,917). This reduced the combined database to a total of 155,608 records.

4.5 Retroreflectivity Time Periods

Because two or three retroreflectivity measurements were collected within a single year to represent a segment of roadway, multiple approaches could be used to estimate the pavement marking retroreflectivity at a specific time. This study used retroreflectivity time periods as the duration of time a retroreflectivity value is representative.

Retroreflectivity time periods were established assuming that there is very little change in retroreflectivity values during the non-winter months. Two retroreflectivity time periods were determined for each year. If a pavement marking was re-striped during the year (paint year), the first retroreflectivity time period is between April 1st and the date of re-striping (the paint date). The retroreflectivity value representing this time period is the spring measurement. The second retroreflectivity time period is between the paint date and December 1st. An average of the initial retroreflectivity of the pavement marking and the fall retroreflectivity measurement were used to represent the corresponding roadway segment during this time period.

If a pavement marking was not re-striped during the year, the first time period is considered to be April 1st through August 1st. The representative retroreflectivity value for this period is shown in Equation 1. The second retroreflectivity time period is considered to be August 1st through December 1st. The retroreflectivity value to represent this time period is calculated using Equation 2. The April 1st and December 1st dates were chosen because snowfall is not typical in Iowa after April 1st or before December 1st. Using these dates allows for the extrapolation of retroreflectivity readings before the spring after the fall measurement dates.

Equation 1: Time Period 3 Retroreflectivity

Representative Retroreflectivity = 0.75 * (Spring Retroreflectivity) + 0.25 * (Fall Retroreflectivity)

Equation 2: Time Period 4 Retroreflectivity

Representative Retroreflectivity = 0.25 * (Spring Retroreflectivity) + 0.75 * (Fall Retroreflectivity)

Figure 5 illustrates the different retroreflectivity time periods throughout a year and displays the corresponding retroreflectivity.

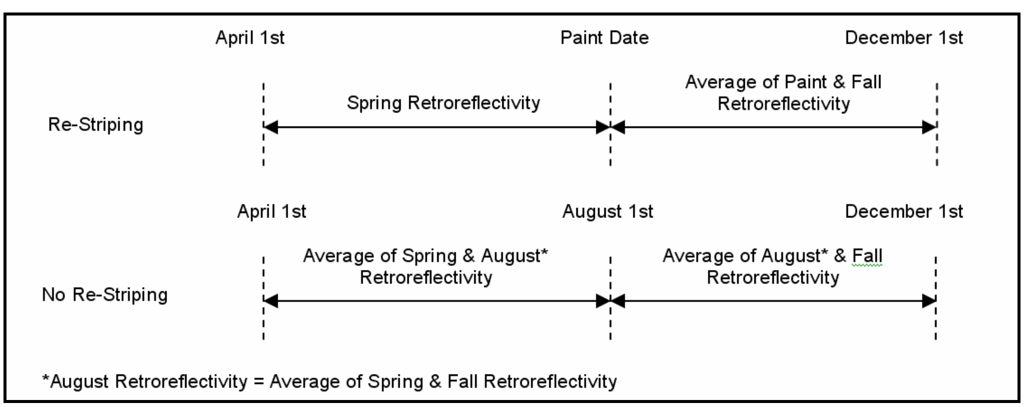

Figure 5: Retroreflectivity Time Periods & Corresponding Retroreflectivity

4.6 Target Crash Selection Procedure

The crash data used in this study were compiled by the Iowa DOT. It is important to note that due to availability the 2006 crash data used in the analysis are preliminary. If the completed 2006 crash data were used significantly different results would not be expected.

Crashes that are possibly related to the retroreflectivity of longitudinal pavement markings were identified as target crashes. Similar to Bahar et al. (2006), crashes during non-daylight conditions were considered target crashes. Unlike other studies, the target crashes were limited to ROR or cross centerline crashes only. ArcView GIS 3.3 (© ESRI) was used to query the target crashes. The following steps explain how target crashes were selected.

Step 1: Limited Time Period.

Crashes outside the established retroreflectivity time periods were eliminated. This does create a potential for biased results because wintertime crashes are excluded, but retroreflectivity readings would be difficult measure and unreliable. Only crashes occurring in April through November were selected as possible target crashes.

Step 2: Light Conditions.

Crashes occurring in daylight, lighted, or unknown conditions were eliminated. The retroreflectivity of a pavement marking is only important in dark conditions. Crashes during dawn, dusk, and dark conditions with no roadway lighting were therefore selected as possible target crashes.

Step 3: Crash Characteristics.

Lane departure crashes not caused by an animal or object in the roadway, a collision with another vehicle, avoiding a collision with another vehicle, or equipment problems were selected. Table 3 displays the three sets of crashes included in the selection. For the third set, both sequence of events characteristics were required in order to be selected.

Table 3: Target Crash Characteristics

1	**Major Cause**
	Crossed centerline
	Ran off road - right
	Ran off road - straight
	Ran off road - left
2	**Sequence of Events 1**
	Ran off road, right
	Ran off road, straight
	Ran off road, left
	cross centerline/median
	Collision with fixed object: Bridge/bridge rails/overpass
	Collision with fixed object: Underpass/structure support
	Collision with fixed object: Culvert
	Collision with fixed object: Ditch/embankment
	Collision with fixed object: Curb/island/raised median
	Collision with fixed object: Guardrail

	Collision with fixed object: Concrete Barrier (median or right side)
	Collision with fixed object: Tree
	Collision with fixed object: Poles (utility, light, etc.)
	Collision with fixed object: Sign post
	Collision with fixed object: Mailbox
	Collision with fixed object: Impact attenuator
	Collision with fixed object: Other fixed object
3	**Sequence of Events 1**
	Non-collision events: Overturn/rollover
	Non-collision events: Jackknife
	Non-collision events: Other non-collision
	Collision with: Parked motor vehicle
	Sequence of Events 2
	Ran off road, right
	Ran off road, straight
	Ran off road, left
	cross centerline/median

Step 4: Rural Locations.

Since many state primary roads in urban areas have curbs, a lot of turning traffic, and other road characteristics which can potentially complicate the crash data, the crashes within urban areas were eliminated. The definition of an urban area used in the analysis is any city with a population of more than 2,000. In GIS, the cities with a population of more than 2,000 are represented as polygons. All of the crashes within any of these polygons were eliminated from the target crash selection.

Step 5: State Primary Roads.

Since all of the retroreflectivity data used were measured on state primary roadways, crashes not occurring on these roadways were eliminated. The GIS database of crashes remaining was then spatially joined to each of two roads databases (state primary roads and all other roads). The spatial joins attached the characteristics of the nearest roadway link to each crash record. When the databases are spatially joined, a field is created which contains the distance between the crash and the nearest roadway link. Crashes where the distances to primary roadway links were less than the distances to non-primary roadway links were therefore selected as primary road crashes. Due to spatial accuracy limitations this methodology may have resulted in some crashes which actually occurred on non-primary roads near the intersection with a primary road to be selected as a primary road crashes; and vice versa. It was assumed that this error was minimal. To check this assumption, indicated route attributes from the crash data were compared to attributes from the roadway database.

4.7 Crash & Retroreflectivity Assignment Procedure

In order to compare retroreflectivity records with and without crashes, the crashes were assigned to a corresponding retroreflectivity time period record. The following steps explain how the crash assignment procedure was completed.

Step 1: Unique Retroreflectivity Locations.

The first step in assigning the target crashes to proper retroreflectivity data record was identifying the unique locations in the spring/fall retroreflectivity database. Most of the locations have many retroreflectivity records, others have just a few. These records vary by line type and by the date of measurement. ArcView 3.3 was used to identify the unique locations by combining the longitude and latitude coordinate fields into one field (*long-lat*). Utilizing the summarize field function in ArcView 3.3, a table containing all of the unique *long-lat* values was produced along with a count of how many times each value occurred in the database. Then, using Microsoft Excel the *long-lat* field from the unique locations table was separated back into longitude and latitude coordinate fields so the locations could be plotted in GIS. The resulting database contained one record for each unique location that was in the spring/fall retroreflectivity database.

Step 2: Assigning Unique Retroreflectivity Locations to the Crashes.

Target crashes were assigned to the nearest unique retroreflectivity location by a spatial join in ArcView 3.3. The spatial join resulted in some assignment errors. For example, as a result of the spatial join the crash on Route A in Figure 6 would be assigned retroreflectivity location number 4 on Route B. The crash should be assigned retroreflectivity location number 1.

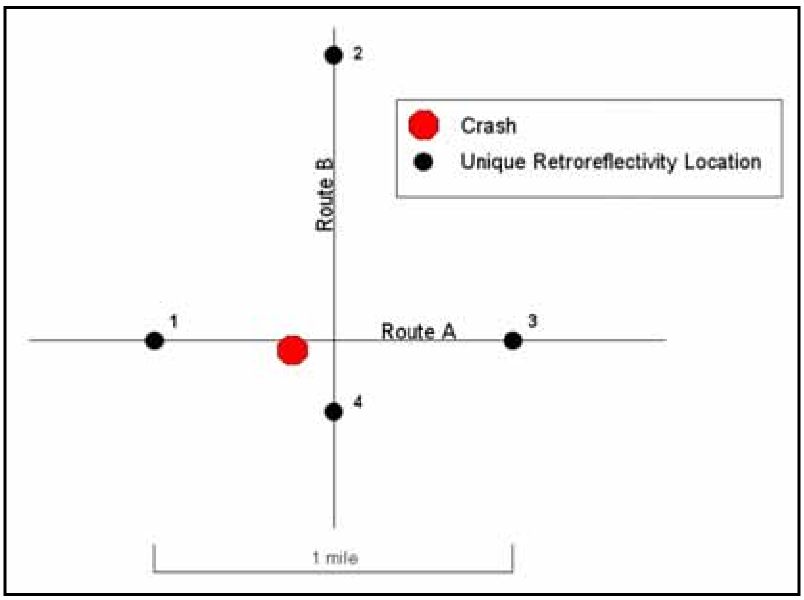

Figure 6: Example of Crash Assignment Error

To correct this error, the route fields from the unique retroreflectivity locations and the crashes were compared to identify crashes that were assigned the wrong retroreflectivity location. These crashes were then inspected and changed manually. The initial direction of the vehicle that lead to the identification of the crash as a target crash was also used to verify the correct route. There were only about 40 instances where this assignment error occurred out of 8,492 locations.

Step 3: Assigning Related Pavement Marking Type to the Target Crashes Records.

The related pavement marking type was determined by the target crash characteristics displayed in Table 3. ROR right and ROR straight crashes were assumed to potentially be white edgeline related. Cross centerline and ROR left crashes were assumed to potentially be yellow center line or yellow edgeline related. If a multiple vehicle crash had one vehicle with attributes indicating one pavement marking type and another vehicle indicating another pavement marking type, the crash was considered yellow center line or yellow edgeline related. This was assumed because a vehicle that crossed the centerline could cause an oncoming vehicle to ROR right, but a vehicle that runs-off-the-road right would not affect oncoming traffic. Table 4 shows the target crashes with their related pavement marking type.

Table 4: Related Pavement Marking Type by Target Crash Characteristic

1	**Major Cause**	**Related Line Type**
	Crossed centerline	YCL / YEL
	Ran off road - right	WEL
	Ran off road - straight	WEL
	Ran off road - left	YCL / YEL
2	**Sequence of Events 1**	**Related Line Type**
	Ran off road, right	WEL
	Ran off road, straight	WEL
	Ran off road, left	YCL / YEL
	cross centerline/median	YCL / YEL
	Collision with fixed object: Bridge/bridge rails/overpass	See Table Y
	Collision with fixed object: Underpass/structure support	See Table Y
	Collision with fixed object: Culvert	See Table Y
	Collision with fixed object: Ditch/embankment	See Table Y
	Collision with fixed object: Curb/island/raised median	See Table Y
	Collision with fixed object: Guardrail	See Table Y
	Collision with fixed object: Concrete Barrier (median or right side)	See Table Y
	Collision with fixed object: Tree	See Table Y
	Collision with fixed object: Poles (utility, light, etc.)	See Table Y
	Collision with fixed object: Sign post	See Table Y
	Collision with fixed object: Mailbox	See Table Y
	Collision with fixed object: Impact attenuator	See Table Y
	Collision with fixed object: Other fixed object	See Table Y
3	**Sequence of Events 1**	**Related Line Type**
	Non-collision events: Overturn/rollover	Depends on Sequence of Events 2
	Non-collision events: Jackknife	
	Non-collision events: Other non-collision	
	Collision with: Parked motor vehicle	
	Sequence of Events 2	**Related Line Type**
	Ran off road, right	WEL
	Ran off road, straight	WEL
	Ran off road, left	YCL / YEL
	cross centerline/median	YCL / YEL

For crashes where the first event was a collision with a fixed object it was less clear which pavement marking should be assigned. Therefore, each event in the sequence of events fields was examined. Table 5 shows the sequence of events for each of these crashes along with the pavement marking type assumed to be related to the crash. If the sequence of events did not clearly reveal which pavement marking could possibly be related to the crash, it was assumed to be the white edgeline.

Step 4: Assigning the Direction of Travel to the Target Crash Records.

Each target crash also required the assignment of a direction of travel. For a potential white edgeline or yellow egdgeline related crash, the corresponding pavement marking could for either direction of traffic. It is important to identify the direction of travel for each crash so it can be assigned to the pavement marking record. The direction for each crash was determined by the "Initial Direction of Travel" field in the vehicle records of the crash database.

Single vehicle target crashes were examined first. The initial direction of travel of each target crash was determined by linking the crash records to the vehicle records in ArcView 3.3. Multi-vehicle target crashes were next examined. This was required on an individual basis because multi-vehicle crashes could include vehicles traveling in opposite directions. For each multi-vehicle target crash, the sequence of events for each vehicle was examined. From the sequence of events fields it was verified which vehicles crash attributes were used to identify the crash as a target crash. Using a vehicle identification field, the initial direction of travel was then established from the vehicle records.

Step 5: Identifying Paint Year Target Crashes.

Since each target crash will be assigned to a pavement marking retroreflectivity value, it was important to identify which target crashes by location occurred during a year where the related pavement marking was re-striped. To identify the paint year crashes a manual selection method was used. Both the paint database and the crash database were restricted to a single year, line type, and direction combination. This allowed crash records to be compared to paint database records with the same combination. Then, using ArcView 3.3, the crashes that were located in areas of re-striping were manually selected. This was done for every year, line type, and direction combination. Figure 7 shows a screenshot of the manual selection process.

Step 6: Assigning the Paint Date to Crash Records.

The crashes occurring during a paint year were next assigned a paint date. The paint and crash databases were restricted to a single year, line type, and direction combination (as it was done in Step 5). Then the paint data were spatially joined to the crash data. All of the crash records then had a corresponding paint date attached to them.

Table 5: Pavement Marking Type Assignment by Sequence of Events

Collision with:				Most Likely Related Pavement Marking
Sequence of Events 1	Sequence of Events 2	Sequence of Events 3	Sequence of Events 4	
2004				
Bridge/bridge rails/overpass	Ditch embankment	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Vehicle in traffic	Not Reported	Not Reported	WEL
Ditch embankment	Overturn/rollover	Not Reported	Not Reported	WEL
Ditch embankment	Guardrail	Not Reported	Not Reported	WEL
Pole	Not Reported	Not Reported	Not Reported	WEL
Sign post	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Other fixed object	Not Reported	Not Reported	WEL
2005				
Bridge/bridge rails/overpass	Guardrail	Ran off road, left	Not Reported	YCL/YEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Bridge/bridge rails/overpass	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Bridge/bridge rails/overpass	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Bridge/bridge rails/overpass	Bridge/bridge rails/overpass	Bridge/bridge rails/overpass	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Ditch embankment	Overturn/rollover	Not Reported	Not Reported	WEL
Ditch embankment	Not Reported	Not Reported	Not Reported	WEL
Sign post	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Not Reported	Not Reported	Not Reported	WEL
Other fixed object	Not Reported	Not Reported	Not Reported	WEL
2006				
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Vehicle in traffic	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Not Reported	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Evasive action	Not Reported	Not Reported	WEL
Bridge/bridge rails/overpass	Vehicle in traffic	Not Reported	Not Reported	WEL
Ditch embankment	Tree	Not Reported	Not Reported	WEL
Ditch embankment	Overturn/rollover	Not Reported	Not Reported	WEL
Ditch embankment	Not Reported	Not Reported	Not Reported	WEL
Ditch embankment	Overturn/rollover	Not Reported	Not Reported	WEL
Curb/island/raised median	Cross centerline	Not Reported	Not Reported	YCL/YEL
Guardrail	Not Reported	Not Reported	Not Reported	WEL
Guardrail	Bridge/bridge rails/overpass	Overturn/Rollover	Vehicle in traffic	WEL
Other fixed object	Evasive action	Bridge/bridge rails/overpass	Not Reported	WEL

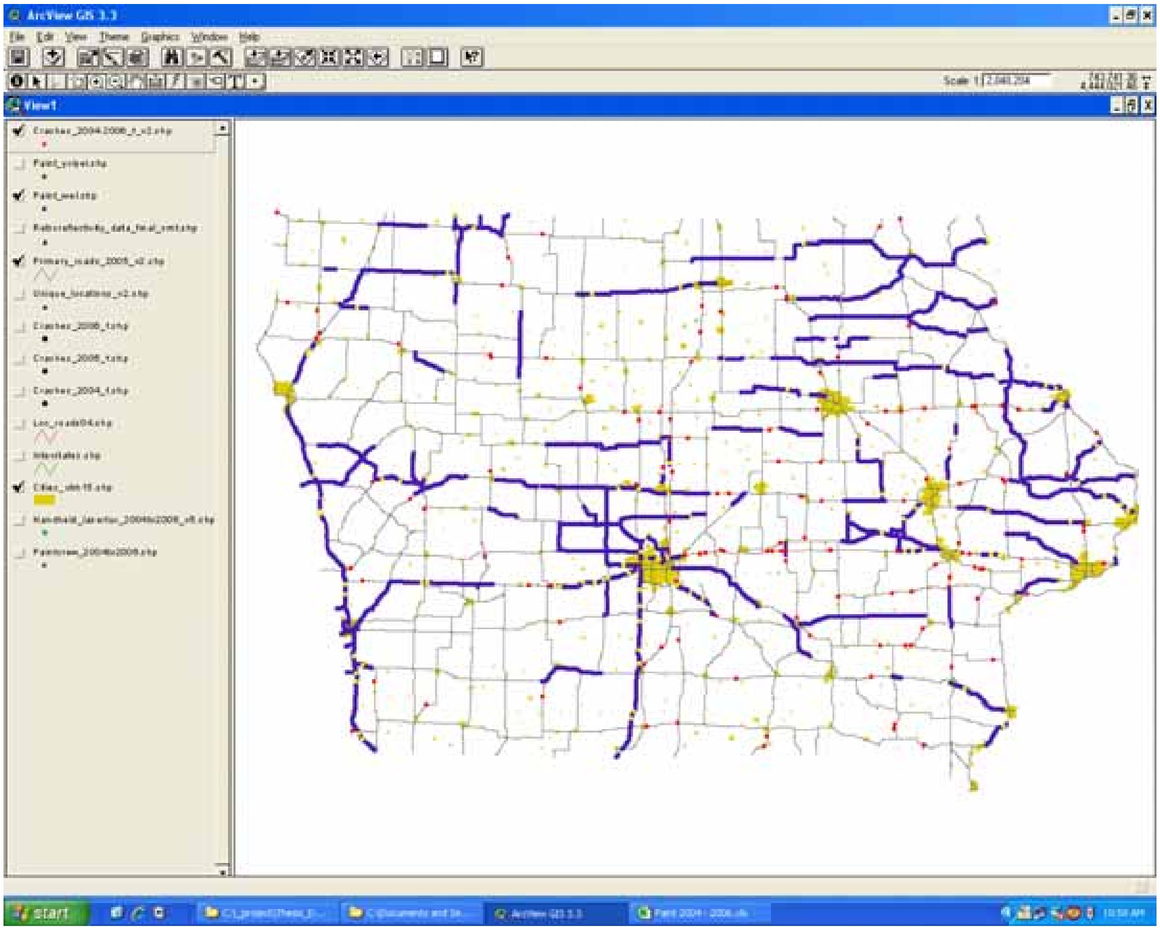

Figure 7: Screenshot of Paint Year Target Crash Selection

Step 7: Assigning a Retroreflectivity Time Period to the Crash Records.

In order to assign the crashes to the retroreflectivity database, the time period of each crash must be known. Figure 8 shows the different retroreflectivity time periods as defined previously. Each time period was numbered 1-4. Time periods 1 and 2 occur when the pavement marking is re-striped. Time period 1 is from April 1st to the paint date and time period 2 is from the paint date till December 1st. Time periods 3 and 4 occur when the pavement marking is not re-striped. Time period 3 is from April 1st to August 1st and time period 4 is from August 1st till December 1st.

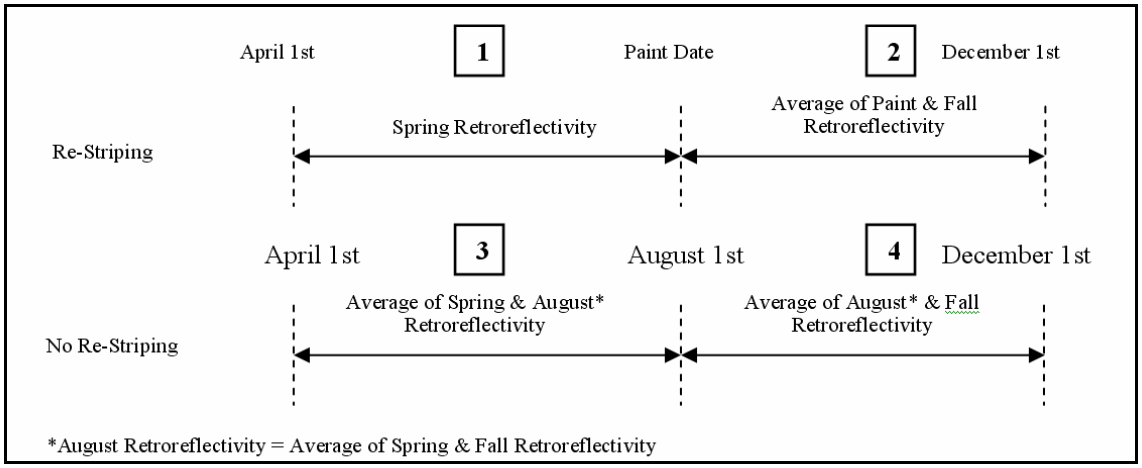

Figure 8: Numbered Retroreflectivity Time Periods & Corresponding Retroreflectivity

Crashes occurring during a paint year where assigned a retroreflectivity-time-period 1 if the crash date was prior to the paint date. If the crash date was after the paint date the crash was assigned retroreflectivity-time-period 2. The remaining crashes (occurring during years where the related pavement marking was not re-striped) were assigned a time period based on crash date only. If the crash date was before August 1st the crash was assigned retroreflectivity-time-period 3; if after August 1st the crash was assigned retroreflectivity-time-period 4.

Step 8: Assigning a Retroreflectivity ID to Target Crashes.

Each crash and retroreflectivity roadway segment needs to be assigned a retroreflectivity identification number. For the crash database this number specifies 1) the year in which the crash occurred, 2) the pavement marking type potentially related to the crash, 3) the retroreflectivity time period encompassing the crash, and 4) the initial direction of travel of the vehicle that identified the collision as a target crash. For the retroreflectivity database the retroreflectivity identification number specifies 1) when the retroreflectivity measurement was taken, 2) the pavement marking type related to the retroreflectivity, 3) the time period the retroreflectivity values are representative of the roadway segment, and 4) the appropriate pavement marking associated with the direction of traffic. Table 6 lists the retroreflectivity identification numbers and shows the corresponding year, pavement marking type, retroreflectivity time period, and direction. All of the information needed to select crashes based upon the characteristics of each retroreflectivity identification number was established in previous crash assignment steps. Retroreflectivity identification numbers were assigned in ArcView 3.3 by querying the characteristics and designating the appropriate number. The field containing the retroreflectivity identification numbers was labeled "Time_Line" in ArcView 3.3. Table 7 shows the number of crashes by retroreflectivity identification number.

Table 6: Retroreflectivity Identification Numbers

ID #	Year	Line Type	Retroreflectivity Time Period	Dir.	ID #	Year	Line Type	Retroreflectivity Time Period	Dir.	ID #	Year	Line Type	Retroreflectivity Time Period	Dir.
1	2004	wel	1	1	21	2005	wel	1	1	41	2006	wel	1	1
2	2004	wel	1	2	22	2005	wel	1	2	42	2006	wel	1	2
3	2004	wel	2	1	23	2005	wel	2	1	43	2006	wel	2	1
4	2004	wel	2	2	24	2005	wel	2	2	44	2006	wel	2	2
5	2004	wel	3	1	25	2005	wel	3	1	45	2006	wel	3	1
6	2004	wel	3	2	26	2005	wel	3	2	46	2006	wel	3	2
7	2004	wel	4	1	27	2005	wel	4	1	47	2006	wel	4	1
8	2004	wel	4	2	28	2005	wel	4	2	48	2006	wel	4	2
9	2004	yel	1	1	29	2005	yel	1	1	49	2006	yel	1	1
10	2004	yel	1	2	30	2005	yel	1	2	50	2006	yel	1	2
11	2004	yel	2	1	31	2005	yel	2	1	51	2006	yel	2	1
12	2004	yel	2	2	32	2005	yel	2	2	52	2006	yel	2	2
13	2004	yel	3	1	33	2005	yel	3	1	53	2006	yel	3	1
14	2004	yel	3	2	34	2005	yel	3	2	54	2006	yel	3	2
15	2004	yel	4	1	35	2005	yel	4	1	55	2006	yel	4	1
16	2004	yel	4	2	36	2005	yel	4	2	56	2006	yel	4	2
17	2004	ycl	1	X	37	2005	ycl	1	X	57	2006	ycl	1	X
18	2004	ycl	2	X	38	2005	ycl	2	X	58	2006	ycl	2	X
19	2004	ycl	3	X	39	2005	ycl	3	X	59	2006	ycl	3	X
20	2004	ycl	4	X	40	2005	ycl	4	X	60	2006	ycl	4	X

Table 7: Crashes by Retroreflectivity Identification Number

ID #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	
Number of Crashes	32	11	13	7	32	33	41	49	8	10	4	2	11	10	9	22	35	59	4	11	
ID #	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	
Number of Crashes	20	26	51	40	19	19	33	26	0	0	1	2	16	19	30	33	21	37	23	56	
ID #	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**TOTAL**
Number of Crashes	13	12	11	9	43	28	46	49	1	0	1	1	21	21	19	28	24	53	8	13	1276

Step 9: Identifying Paint Year Retroreflectivity Records.

Similar to the target crashes in Step 5, the retroreflectivity measurements that were taken in a re-striping year were identified. In ArcView 3.3 the retroreflectivity database was restricted to a single year, line type, and direction combination and spatially joined to the paint database which was restricted to the same combination. Then the retroreflectivity database was linked to the paint database using a unique identifier in the retroreflectivity database. Finally, all of the records in the paint database were selected and subsequently (because of the database link) all of the paint year records were selected in the retroreflectivity database.

The distance field due to the join was checked to identify any errors. Because both the retroreflectivity and the paint databases were created using the same reference post file any selected record with a distance field greater than zero was erroneous and deselected. The selected retroreflectivity records were then marked (1 if paint year, 0 if not) as paint year records. This process was repeated for all combinations of year, line type, and direction.

Step 10: Eliminating Double & Multiple Records in the "Spring/Fall" Retroreflectivity Database.

The "spring/fall" retroreflectivity database had several double and multiple records. Double records had the same retroreflectivity, date, time of year (spring or fall), and location. Multiple records had the same time of year and location. For the analysis, only a single retroreflectivity record was desired for each time of year and location to determine the representative retroreflectivity of each retroreflectivity time period. These double and multiple records would cause assignment problems if they were not removed. It was assumed that of the double and multiple records the earliest record (by date) would be most appropriate for analysis. All of the other records were not needed. To eliminate the unwanted records, the retroreflectivity data was sorted in Microsoft Excel. Upon sorting the records in the order shown in Table 8, all of the double and multiple records are sequential by measurement date. The unwanted crashes were eliminated by first assigning an ID to the records. All of the double and multiple records received the same ID number. With this ID field in place, the "advanced filter" function in Excel filtered though the database leaving the first record with a unique id alone and hiding all of the unwanted records. The filtered data were then copied and pasted into a new file and the elimination process was complete. Table 9 shows the number of records eliminated by line type.

Table 8: Sorting Order to Eliminate Unwanted Retroreflectivity Records

Sorting Order	Field
1	Retroreflectivity Measurement Date
2	Unique Location ID
3	Direction
4	Time of Year
5	Year
6	Line Type

Table 9: Number of Unwanted Duplicate Retroreflectivity Records

Line Type	Number of Records Before Elimination	Number of Records After Elimination	Number of Unwanted Duplicate Records
WEL	92,225	83,157	9,068
YCL	46,600	35,814	10,786
YEL	16,783	15,289	1,494
TOTAL	155,608	134,260	21,348

Step 11: Assigning a Retroreflectivity Identification Number to the Retroreflectivity Records.

In order to assign crashes to the retroreflectivity records, the same retroreflectivity identification number used in Step 8 was assigned to them. A retroreflectivity time period field was added and populated based upon whether or not the record was a paint year record (determined in Step 9) and on the time of year field. Table 10 shows the resulting retroreflectivity time periods which are also displayed in Figure 8.

Table 10: Retroreflectivity Time Period Determination for Retroreflectivity Records

Paint Year Record	Time of Year	Retroreflectivity Time Period
Yes	Spring	1
Yes	Fall	2
No	Spring	3
No	Fall	4

With the retroreflectivity time period field created, the retroreflectivity records were assigned a retroreflectivity identification number using the same process in as in Step 8 where the crash records were assigned a retroreflectivity identification number. Table 11 shows the number of retroreflectivity records by retroreflectivity identification number.

Table 11: Retroreflectivity Records by Retroreflectivity Identification Number

ID#	Number of Retroreflectivity Records	ID#	Number of Retroreflectivity Records	ID#	Number of Retroreflectivity Records
1	1478	21	3797	41	1940
2	1167	22	3548	42	1602
3	1462	23	3537	43	1919
4	1194	24	3305	44	1586
5	5034	25	3787	45	5795
6	5332	26	3994	46	6065
7	4351	27	3299	47	5345
8	4549	28	3445	48	5626
9	160	29	402	49	732
10	155	30	335	50	698
11	142	31	352	51	567
12	116	32	287	52	608
13	704	33	1266	53	873
14	724	34	1245	54	911
15	462	35	1206	55	852
16	398	36	1226	56	868
17	5607	37	2975	57	5417
18	5236	38	2655	58	5439
19	603	39	3090	59	736
20	557	40	2759	60	740

Step 12: Combine The Retroreflectivity Identification Number with Unique Location Number.

In Arcview 3.3 the retroreflectivity identification number and the unique location numbers were chained together in a new "final_id" field. The two numbers were separated by a tilde in the newly created identification field. For example, if the retroreflectivity identification number was 5 and the unique location number was 5555 then the "final_id" field would be 5~5555. This field represents a unique value for all retroreflectivity data by year, line type, retroreflectivity time period, direction, and location.

Step 13: Assigning the Unique Location Identification to the Paint Database.

In order to assign the paint data to the retroreflectivity records a common location field was necessary. Using a spatial join the unique location identification numbers of the retroreflectivity database were assigned to the nearest paint records. The resulting distance field was checked and invalid records were removed. The invalid records were reference posts where paint data was assigned but no spring/fall retroreflectivity measurements were ever taken. This check removed 1,786 paint records, reducing the database to 44,204 records. The irrelevant line type records (such as white dashed centerline) were then removed as well. This reduced the paint database to 37,560 records of only white edgline, yellow centerline, and yellow edgeline line types.

Step 14: Assigning a Paint Identification Numbers to the Paint & Retroreflectivity Records.

Since retroreflectivity time periods do not apply to the paint data, a paint identification number was needed. Each paint identification number represents the combination of year, line type, and direction of a re-striped pavement marking. Table 12 presents the paint identification numbers. The numbers were assigned to the paint database by querying the year, line type, and direction fields. The paint identification numbers were assigned to the retroreflectivity database by querying the related retroreflectivity identification numbers. Table 13 illustrates this relationship.

Step 15: Assigning Paint Data to the Retroreflectivity Records.

The paint data (paint date and paint retroreflectivity) were assigned to the retroreflectivity records by creating a unique id number. Like in Step 12, the paint identification number was combined with the location identification number. This was done in both the paint and retroreflectivity databases. Using this common field in both databases the paint records were joined to the retroreflectivity records.

Table 12: Paint Identification Numbers by Year, Line Type, and Direction

ID#	Year	Line Type	Direction	ID#	Year	Line Type	Direction	ID#	Year	Line Type	Direction
1	2004	wel	1	6	2005	wel	1	11	2006	wel	1
2	2004	wel	2	7	2005	wel	2	12	2006	wel	2
3	2004	yel	1	8	2005	yel	1	13	2006	yel	1
4	2004	yel	2	9	2005	yel	2	14	2006	yel	2
5	2004	ycl	X	10	2005	ycl	X	15	2006	ycl	X

Table 13: Retroreflectivity Identification Numbers with Corresponding Paint Identification Numbers

Retroreflectivity #	Paint #	Retroreflectivity #	Paint #	Retroreflectivity #	Paint #
1	1	21	6	41	11
2	2	22	7	42	12
3	1	23	6	43	11
4	2	24	7	44	12
5	---	25	---	45	---
6	---	26	---	46	---
7	---	27	---	47	---
8	---	28	---	48	---
9	3	29	8	49	13
10	4	30	9	50	14
11	3	31	8	51	13
12	4	32	9	52	14
13	---	33	---	53	---
14	---	34	---	54	---
15	---	35	---	55	---
16	---	36	---	56	---
17	5	37	10	57	15
18	5	38	10	58	15
19	---	39	---	59	---
20	---	40	---	60	---

Retroreflectivity

Identifies unique records by year, line type, retroreflectivity time period, and direction in retroreflectivity database.

Paint

Identifies unique paint year records by year, line type, and direction in retroreflectivity database

Step 16: Assigning Spring/Fall Retroreflectivity Values to the Temporal Retroreflectivity Database.

Following Step 10 the retroreflectivity database included records by year, time of year (spring or fall), line type, direction, and location. In order to analyze the data, the retroreflectivity database was converted into a retroreflectivity-time-period database. This will be called the temporal retroreflectivity database.

Specifically, the “spring” records were converted into either retroreflectivity-time-period 1 or 3 and the “fall” records were converted into either retroreflectivity-time-period 2 or 4. The spring and fall retroreflectivity values were joined to the retroreflectivity records because many records needed both in order to determine the representative retroreflectivity value of the time period. To accomplish this, another identification field was created. The new spring/fall identification numbers were created from the retroreflectivity identification numbers. The spring and fall combinations by year, line type, direction, and paint or no paint were given a single identification number. Table 14 shows the retroreflectivity identification numbers with the corresponding spring/fall identification numbers.

Table 14: Retroreflectivity Identification Numbers with Corresponding Spring/Fall Identification Numbers

Retroreflectivity #	Spring/Fall #	Retroreflectivity #	Spring/Fall #	Retroreflectivity #	Spring/Fall #
1	1	21	13	41	25
2	2	22	14	42	26
3	1	23	13	43	25
4	2	24	14	44	26
5	3	25	15	45	27
6	4	26	16	46	28
7	3	27	15	47	27
8	4	28	16	48	28
9	5	29	17	49	29
10	6	30	18	50	30
11	5	31	17	51	29
12	6	32	18	52	30
13	7	33	19	53	31
14	8	34	20	54	32
15	7	35	19	55	31
16	8	36	20	56	32
17	9	37	21	57	33
18	10	38	22	58	34
19	11	39	23	59	35
20	12	40	24	60	36

After the spring/fall identification numbers were created, they were combined with the unique location numbers into a field called “Final_ID3”; as in steps 12 and 15. In order to join the spring and fall retroreflectivity fields the temporal retroreflectivity database was copied. The copied records were then limited by time of year. First, the spring records only (from the copied database) were joined to the temporal retroreflectivity database using the “Final_ID3” field. Second, the same was done with the copied data limited to the fall records only. With this procedure complete, spring and fall retroreflectivity values were assigned to the corresponding retroreflectivity time periods.

Step 17: Assigning Representative Retroreflectivity Values for each Retroreflectivity Time Period.

As explained previously, there are 4 retroreflectivity time periods represented by different retroreflectivity values. All of the representative retroreflectivity values are derived from a combination of the spring, paint, and fall retroreflectivity values. The retroreflectivity value for time period 1 is the spring retroreflectivity and is already a field in the database (Step 16). The retroreflectivity value for time period 2 is the average of the paint and fall retroreflectivity. The retroreflectivity value for time periods 3 and 4 are calculated using Equations 1 and 2, respectively (see Retroreflectivity Time Periods section). A field for each retroreflectivity value was added to the database and calculated from the spring, paint, and fall retroreflectivity fields.

Step 18: Creating a Time Period Duration Field.

The duration of each retroreflectivity time period was calculated in order to estimate the amount of traffic on the road segment over that period of time. To calculate the duration an April 1st (beginning date) and a December 1st (end date) field were added to the records. Each field was then populated with the appropriate date corresponding to the year of the retroreflectivity time period. The duration of time period 1 records were calculated as the paint date minus the beginning date. Retroreflectivity-time-period 2 records were calculated as the end date minus the paint date. Retroreflectivity-time-periods 3 and 4 were assigned a duration of 122 days, the number of days between April 1st and August 1st as well as between August 1st and December 1st.

Step 19: Assigning the Target Crashes to the Temporal Retroreflectivity Database.

The retroreflectivity identification numbers ("final_id" field) were used to assign crashes to the proper location by retroreflectivity time period. When the "final_id" field was summarized in ArcView 3.3 it was found some of the retroreflectivity identification numbers were assigned to multiple crashes. That means more than one crash with the same retroreflectivity identification number occurred at a locations during a single retroreflectivity time period. In order to assign the correct number of crashes to the retroreflectivity time period records with the corresponding retroreflectivity identification numbers, each number was inserted manually. Only 21 crash records, as shown in Table 15, had a common "final_id" value.

Table 15: Number of Retroreflectivity Identification Numbers by the Number of Crashes

Number of Crashes	Number of Retroreflectivity IDs	
	Crash Database	Temporal Retroreflectivity Database
0	---	133,446
1	1233	797
2	20	16
3	1	1

After entering the number of crashes in the temporal retroreflectivity records where multiple crashes occurred, the records where a single crash occurred were assigned. This was done by selecting all of the single crash records in the retroreflectivity identification numbers summary table and linking the temporal retroreflectivity database to it using the “final_id” field. Table 15 shows that only 832 out of the 1,276 target crashes were assigned to the temporal retroreflectivity database. Some crashes were eliminated because not all of the retroreflectivity locations were measured by line type and direction every year. Figure 9 shows a screenshot of ArcView3.3 depicting the direction 1, white edgeline potentially related crashes in the year 2004 (red), and the segments of state primary road were direction 1, white edgeline retroreflectivity measurements were taken in the year 2004 (blue).

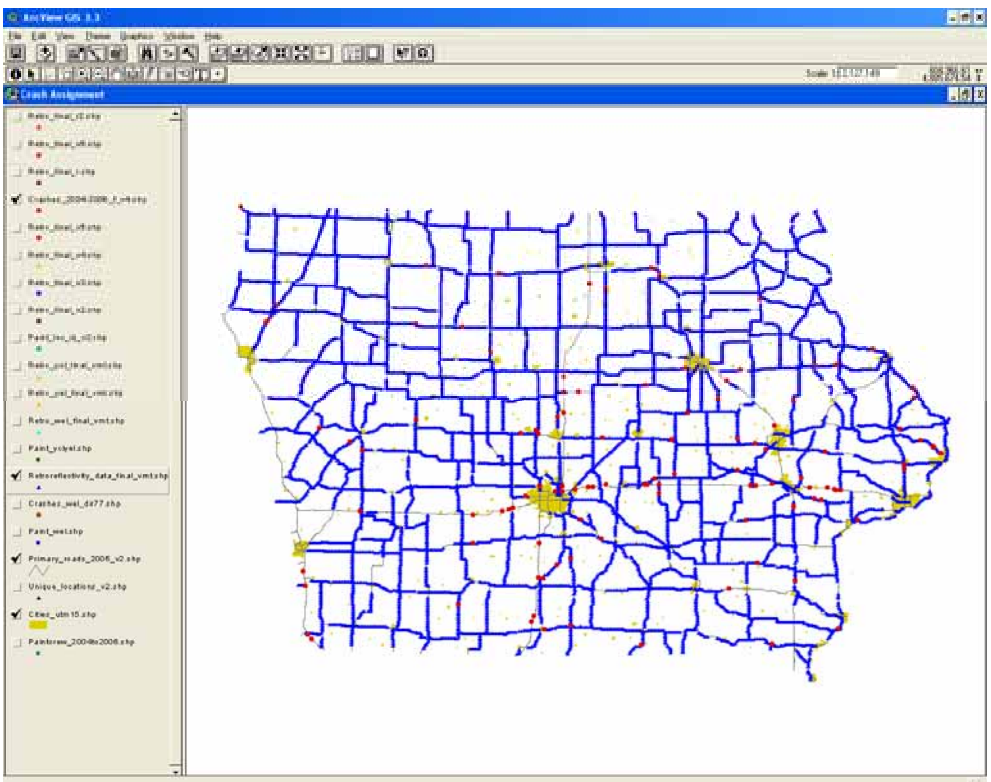

Figure 9: ArcView 3.3 Screenshot Explaining Reduction in Target Crashes During Crash Assignment

4.8 Database Modifications

Empty Retroreflectivity Values

After the temporal retroreflectivity database was constructed, some modifications were necessary. Many of the records in the “representative retroreflectivity” field were empty. This occurred for three reasons.

First, some of the paint retroreflectivity values for retroreflectivity-time-period 2 were empty (359 records). The reason for the empty records was either the paint database did not include them or the records were misidentified as paint records. For these records, the paint and fall retroreflectivity values could not be averaged to find the representative retroreflectivity value (as other records were in Step 17). To fix this problem, it was assumed that the fall retroreflectivity value only would be suitable to represent these retroreflectivity-time-period 2 records.

Second, some of the retroreflectivity-time-period 3 records did not have a fall retroreflectivity value (11,400 records). This resulted as only spring measurements were taken at these locations. For these records, it was assumed that the spring retroreflectivity values alone were representative of the retroreflectivity time period. This assumption was based general assumption that retroreflectivity levels do not change significantly in the non-winter months.

Third, some of the retroreflectivity-time-period 4 records did not have a spring retroreflectivity value (6,924 records) for the same reason some of the time period 3 records did not have a fall retroreflectivity value. For these records, it was assumed that the fall retroreflectivity value alone was suitable to represent the retroreflectivity for time period 4. Table 16 displays the modifications made to resolve the issue empty retroreflectivity values.

Table 16: Modification Made to Records with Empty Retroreflectivity Values

Retroreflectivity Time Period	Retroreflectivity Values Not Present	Number of Records	Modified Representative Retroreflectivity Value
2	Paint	359	Fall
3	Fall	11,400	Spring
4	Spring	6,924	Fall

Unreasonable Retroreflectivity Values

Another issue with the database that needed to be addressed was unreasonable retroreflectivity values. Some of the spring and fall retroreflectivity values were extremely high. It was assumed that any retroreflectivity values greater than 600 mcd/m^2/lux were either measured or entered into the database incorrectly. Other records had a retroreflectivity value of 0 mcd/m^2/lux. It was assumed that these records were incorrect as well. To eliminate the effect of these errors all of the records with a representative retroreflectivity value that was calculated using a retroreflectivity value greater than 600 or equal to 0 were either removed from the database or modified.

The representative retroreflectivity values for time periods 2, 3, and 4 are calculated using two retroreflectivity values, which will be called paired retroreflectivity values. For retroreflectivity time period 2 the paired values are the paint and fall retroreflectivity values and for time periods 3 and 4 the paired values are the spring and fall retroreflectivity values.

The records that were removed from the database did not have a paired retroreflectivity value to modify the representative retroreflectivity assignment with. For example, the representative retroreflectivity value for time period 2 is the average of the paint and fall retroreflectivity. In this case the paired retroreflectivity values are the paint and the fall retroreflectivity values. If the fall retroreflectivity is greater than 600 and the paint retroreflectivity value is empty then the record is removed. If the paint retroreflectivity value is present then the representative retroreflectivity value for the record is modified to equal the paint retroreflectivity.

The records that were removed were done so in a 7 step process. Table 17 summarizes the removal process. First, the records with retroreflectivity-time-period 1 and a spring retroreflectivity value greater than 600 were removed. The representative retroreflectivity value for time period 1 is the spring retroreflectivity, so these records were removed because there was no retroreflective pair value to use for modification. Second, the records with a spring retroreflectivity value greater than 600 and no pair value were removed. Third, the records with a fall retroreflectivity value greater than 600 and no pair value were removed. Fourth, the records with a retroreflectivity-time-period 1 and a spring retroreflectivity value of zero were removed. Fifth, the records with a retroreflectivity-time-period of 2, a paint retroreflectivity value of zero, and a fall retroreflectivity value of zero were removed. Sixth, the records with a retroreflectivity-time-period of 3, a spring retroreflectivity value of zero, and a fall retroreflectivity value of zero were removed. Lastly, the records with a retroreflectivity-time-period of 4, a spring retroreflectivity value of zero, and a fall retroreflectivity value of zero were removed. This process eliminated a total of 298 records. Only 2 crashes were assigned to these records. The total number of crashes therefore was reduced to 830.

Table 17: Summary of Process Removing Records with Invalid Retroreflectivity Values

Step	Retroreflectivity Time Period	Invalid Retroreflectivity Value			Records Removed	Crashes Removed
		Spring	Fall	Paint		
1	1	> 600	---	---	10	0
2	3 and 4	> 600	empty	---	3	0
3	2*, 3**, and 4**	empty**	> 600	empty*	9	0
4	1	0	---	---	144	1
5	2	---	0	0	5	0
6	3	0	0	---	85	1
7	4	0	0	---	42	0

After removing some of the invalid records, the records that could be modified were done so in a 6 step process. Table 18 summarizes the modification process. The modification process reassigned the pair of the invalid retroreflectivity value as the representative value. First, the records with a retroreflectivity time period of 3 or 4 and a spring retroreflectivity of greater than 600 were assigned the fall retroreflectivity as the representative value. Second, the records with a retroreflectivity time period of 2 and a fall retroreflectivity of greater than 600 were assigned the paint retroreflectivity as the representative value. Third, the records with a retroreflectivity time period of 3 or 4 and a fall retroreflectivity of greater than 600 were assigned the spring retroreflectivity as the representative value. Fourth, the records with a retroreflectivity time period of 2 and a paint retroreflectivity of zero were assigned the fall retroreflectivity as the representative value. Fifth, the records with a retroreflectivity-time-period of 3 or 4 and a spring retroreflectivity of zero were assigned the fall retroreflectivity as the representative value. Lastly, the records with a retroreflectivity time period of 3 or 4 and a fall retroreflectivity of zero were assigned the spring retroreflectivity as the representative value. This process modified 2,139 records containing 7 crashes.

Table 18: Summary of Process Modifying Records with Invalid Retroreflectivity Values

Step	Retroreflectivity Time Period	Invalid Retroreflectivity			Records Modified	Crashes Affected
		Spring	Fall	Paint		
1	3 and 4	> 600	---	---	32	1
2	2	---	> 600	---	13	0
3	3 and 4	---	> 600		12	1
4	2	---	---	0	1582	4
5	3 and 4	0	---	---	416	1
6	3 and 4	---	0	---	84	0

Durations of Zero or Less than Zero

Records with a time period duration of zero or less were also sometimes an issue. There were 19 records where the time period duration was a negative value. This occurred because the paint date was before April 1st. There were 707 records where the time period duration was zero. This occurred because the paint date field was empty. Empty paint date records resulted from an error during the crash assignment procedure because all records in the paint database include a paint date. Since these records could not be modified and are useless without a positive time period duration, they were removed from the database. This reduced the total number of records in the time period database to 133,236 and the number of target crashes to 829.

Creating a Road Type Field

Creating a road type field was another modification made to the temporal retroreflectivity database. Instead of analyzing the roadway segments in the database by the number of lanes, median type, median width, access control, and federal function characteristics as individual variables, they were combined into a road type characteristic field. This simplified the analysis considerably without eliminating the effects of roadway characteristics.

The majority of data records were assigned a road type using the road classifications developed in the Iowa pilot study of the research done by the Center for Transportation Research and Education (2006). The Iowa pilot study classified roads into four road types which were based on access control, median type, and the number of lanes. The four road types were: freeway, multi-lane divided, multi-lane undivided, and two-lane. The roads in the study were limited to state primary roads and excluded highways within cities of a population of 2,000 or more as well as freeways within metropolitan areas with a population of 50,000 or more. The road types were joined to the retroreflectivity-time-period database using a common “mslink” field which is a unique identifier for Iowa road segments. Since some of the road segments included in this study were excluded from the usRAP study, the remaining road segments were assigned based upon the characteristics in the time period retroreflectivity database.

Roadway characteristics were used to assign a road type in the following order. First, the remaining records with federal function classified as "interstate" and access control classified as "interstate and freeway" were assigned the road type "INTERSTATE/FREEWAY". Second, all of the remaining records with 2 lanes were assigned to the road type "TWO-LANE". Third, the remaining records with more than 2 lanes and a median width equal to zero were assigned the road type "MULTI-LANE UNDIVIDED". Fourth, the remaining records with more than 2 lanes and median width greater than zero were assigned the road type "MULTI-LANE DIVIDED". Fifth, the remaining records were all labeled as having 1 lane. A visual inspection of these records showed that the assigned segments were interchange ramps. In order to assign the mainline roadway characteristics the to the time period retroreflectivity records the ramp segments were removed from the road file in GIS using the function field (function < 50). With the ramps eliminated the road file was spatially joined to the records that were mislabeled with ramp characteristics. All of these records were then assigned the road type "TWO-LANE" for records with 2 lanes and "MULTI-LANE DIVIDED" for records with more than 2 lanes, a median width greater than 0, and access control not equal to "interstate and freeway".

Selecting Rural Records

A further modification made to the database was to eliminate non-rural records, as target crashes were limited to rural crashes only. All of the records which had corresponding milepost coordinates that were within a polygon representing a city of 2,000 or more were eliminated in ArcView 3. This reduced the number of records from 133,236 to 124,094 and the number of crashes from 829 to 821. The 8 crashes eliminated were all just outside the cities polygon, but assigned to a retroreflectivity segment which crossed into a city polygon.

Creating a VMT Field

A final modification made to the temporal database was creating a vehicle miles traveled (VMT) field. The VMT field was calculated as the product of half the "AADT" field and the "duration" field. Assuming that the directional split is even, one half of the AADT is the daily VMT since each record represents a 1 mile section. Then by multiplying the daily VMT and the duration (number of days) the result is the VMT for the entire retroreflectivity time period. In the analysis the VMT field is labeled as the "traffic" parameter.

4.9 Database Error

Records with Incongruent "Spring/Fall" & "Paint" Data

The sections of roadway with incongruent "spring/fall" and "paint" data are erroneous. The "spring/fall" measurements were collected every 5 miles and assigned to the roadway within 2.5 miles in both directions. When a roadway was re-striped, sometimes the re-striping ended in the middle of one of the 5-mile "spring/fall" sections; causing the retroreflectivity assigned to be invalid. Figure 10 illustrates the problem.

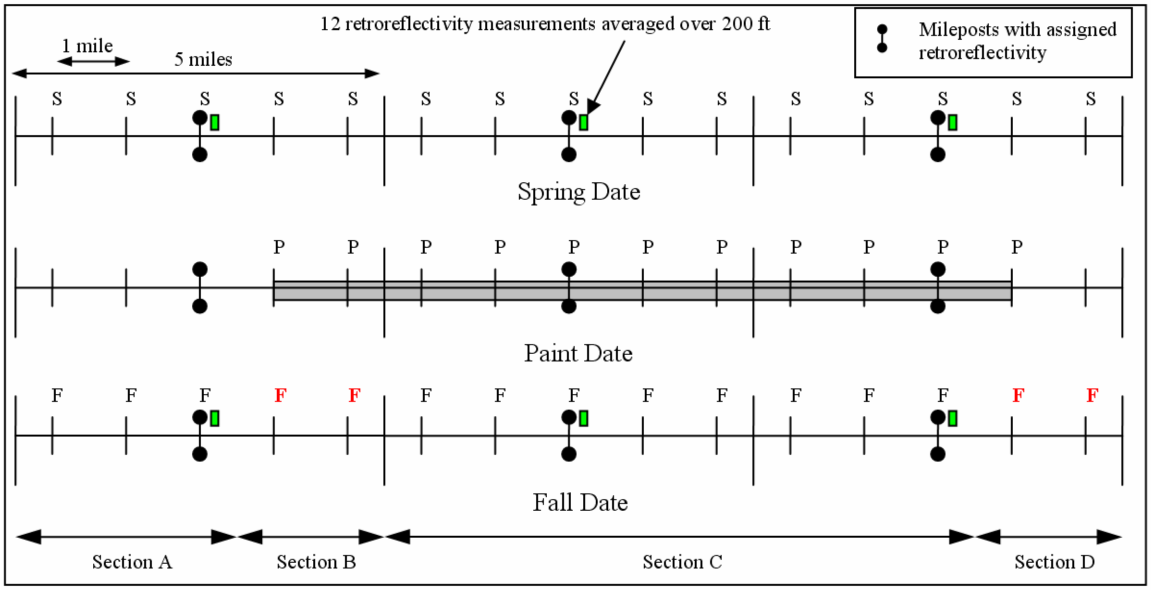

Figure 10: Illustration of Incongruent Sections

For Sections A and C, in the figure, all of the 1-mile segments are either re-striped or not re-striped just as the milepost where the retroreflectivity measurements were collected. For these sections the fall retroreflectivity value is valid. For Sections B and D the 1-mile segments are either re-striped or not re-striped opposite of the location where the retroreflectivity was measured. For these sections the fall retroreflectivity is invalid, as well as any "spring/fall" retroreflectivity values assigned afterwards.

Eliminating this error would be difficult and time intensive. The estimated maximum number of records that could be invalid due to this error is 10,512 or about 8.5% of the database. This maximum value was estimated by multiplying the number of roadway sections re-striped (2,628) by 4, the maximum number of invalid segments per re-striping section.

Records with Crashes Occurring During Wet Conditions

When water covers pavement markings the visibility and retroreflectivity are significantly reduced. Migletz and Graham (2002) found that the average dry-to-wet pavement marking retroreflectivity ratio was 2.17. That means if a marking has a retroreflectivity of 200 mcd/m^2/lx during dry pavement conditions the retroreflectivity under wet conditions is around 92 mcd/m^2/lx.

This effect creates a retroreflectivity assignment error in the data where target crashes occurred during wet conditions. Because all of the retroreflectivity measurements were taken during dry conditions, all of the data records containing crashes which occurred during wet conditions were assigned a retroreflectivity value that is too high. In the database, 75 of the 821 (9.1%) target crashes occurred during rainy weather conditions. Table 19 shows the representative retroreflectivity values in three bin ranges for the records containing the 75 rainy weather crashes.

Table 19: Retroreflectivity Distribution of Crashes Occuring During Wet Conditions

Line Color	**Retroreflectivity Bin**			**Total**
	< 150	**150 - 300**	**> 300**	
White	17	25	4	46
	< 100	**100 - 200**	**> 200**	
Yellow	10	10	9	29

5.0 Analysis

5.1 Data Distributions

Before modeling and analyzing the data, basic descriptive statistics and distributions of the data were investigated. The first point of interest was the number of crashes that were assigned to records. Table 20 shows the total number of records that were assigned 0, 1, 2, or 3 crashes by year and retroreflectivity time period. Tables 21 and 22 depict white edgeline and yellow centerline or edgeline records separately.

Table 20: Number of Records by Year, Number of Crashes, and Retroreflectivity Time Period

Year	Number of Crashes	Retroreflectivity Time Period				Total
		1	2	3	4	
2004	0	7,828	7,508	11,356	9,572	36,264
	1	49	57	40	49	195
	2	1	0	1	0	2
2005	0	10,180	9,373	12,223	10,766	42,542
	1	51	83	58	109	301
	2	2	5	0	3	10
	3	0	1	0	0	1
2006	0	9,582	9,360	13,199	12,344	44,485
	1	44	66	83	97	290
	2	2	0	1	1	4

Table 21: Number of White Edgeline Related Records by Year, Number of Crashes, and Retroreflectivity Time Period

Year	Number of Crashes	Retroreflectivity Time Period				Total
		1	2	3	4	
2004	0	2,264	2,353	9,672	8,350	22,639
	1	16	7	29	45	97
	2	1	0	1	0	2
2005	0	6,767	6,330	7,187	6,159	26,443
	1	33	58	27	43	161
	2	1	4	0	1	6
	3	0	1	0	0	1
2006	0	3,245	3,253	11,024	10,219	27,741
	1	23	18	62	69	172
	2	1	0	0	1	2

Table 22: Number of Yellow Centerline and Yellow Edgeline Related Records by Year, Number of Crashes, and Retroreflectivity Time Period

Year	Number of Crashes	Retroreflectivity Time Period				Total
		1	2	3	4	
2004	0	5,564	5155	1684	1222	13,625
	1	33	50	11	4	98
2005	0	3413	3043	5036	4607	16,099
	1	18	25	31	66	140
	2	1	1	0	2	4
2006	0	6337	6107	2175	2125	16,744
	1	21	48	21	28	118
	2	1	0	1	0	2

By examining the above tables it is evident that the overwhelming majority of the records have zero crashes assigned to them. It is also apparent that very few records have more than 1 crash assigned (only 17). For analysis purposes, and because there are so few multiple crash records, a new field was created in the database and records were labeled “0” if zero crashes were assigned and “1” if one or more crashes were assigned to the record, facilitating the use of the field as a dummy variable for statistical modeling purposes.

The second point of interest was the retroreflectivity values. It is important to differentiate the markings by color. The white edgline retroreflectivity classification range is larger because white pavement markings are naturally more retroreflective than yellow pavement markings.

Figure 11 shows a graph of the number of records by white edgeline retroreflectivity. Figure 12 shows a bar chart of the same general distribution, but includes a relative distribution of records that were assigned one or more target crashes. The retroreflectivity distribution of the white edgeline records with one or more crashes peaks at a higher retroreflectivity class than the distribution of all of the white edgeline records. This observation is not expected, as lower retroreflectivity values were expected to increase crash risk. However, the values may be correlated with some other factor which in fact decreases crash risk, such as low traffic levels.

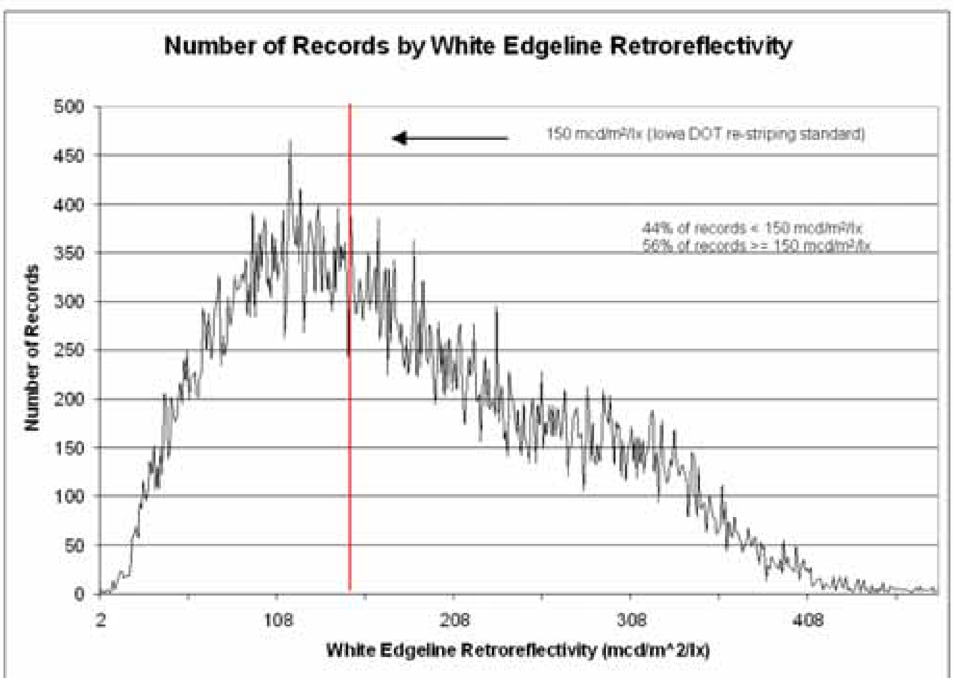

Figure 11: Graph of White Edgeline Records by Retroreflectivity

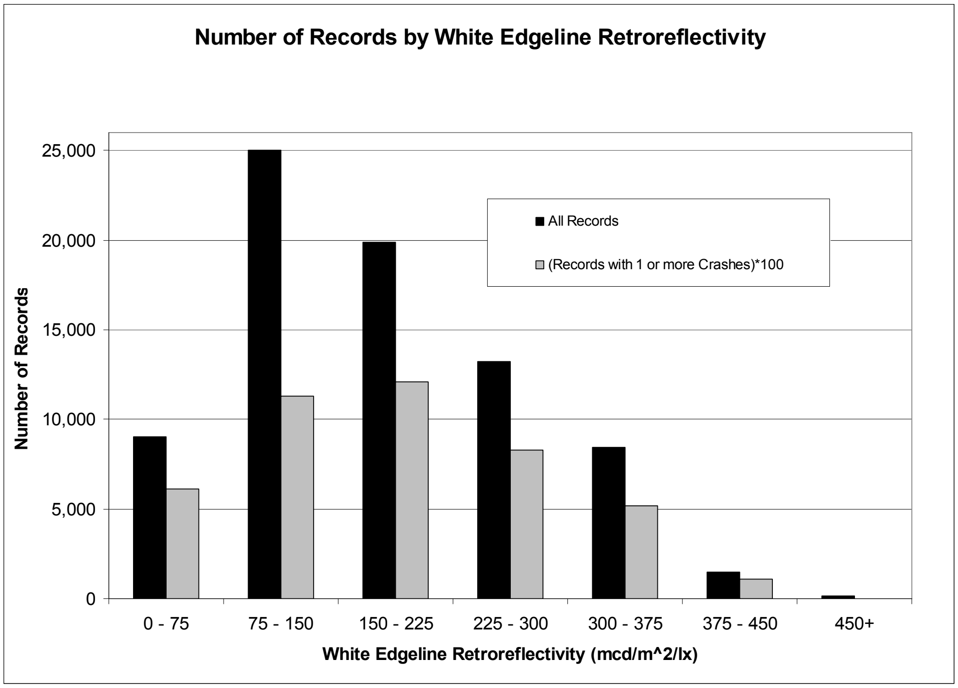

Figure 12: Bar Chart of White Edgeline Records by Retroreflectivity

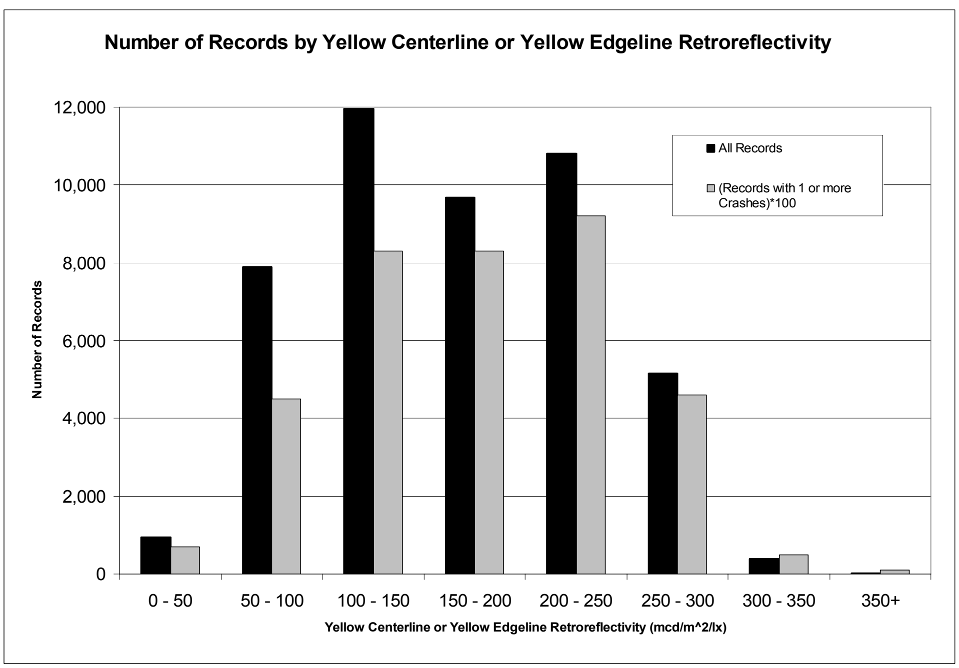

Figure 13: Bar Chart of Yellow Centerline or Yellow Edgeline Records by Retroreflectivity

The distribution of the yellow longitudinal pavement markings as shown in Figure 13 is different than that for white markings. The number of records peaks at the retroreflectivity class of 100-150 mcd/m^2/lx then it drops down, but increases again at the retroreflectivity class of 200-250 mcd/m^2/lx. An explanation for this is that the yellow centerline markings for most state primary roads were re-striped in 2004 and 2006. The re-striping of these markings probably caused the second peak in the yellow longitudinal pavement marking distribution. Figure 14 shows a similar distribution for yellow centerline records only, while Figure 15 shows yellow edgelines have a distribution more similar to white edgelines. These figures also show the percentage of records above and below the Iowa DOT re-striping standard. As with the retroreflectivity distribution of white edgeline records with one or more crashes, the retroreflectivity distribution of yellow pavement marking records with one or more crashes is also counterintuitive. The yellow pavement marking distribution of records with a one or more crashes peaks at the retroreflectivity class of 200-250 mcd/m^2/lx.

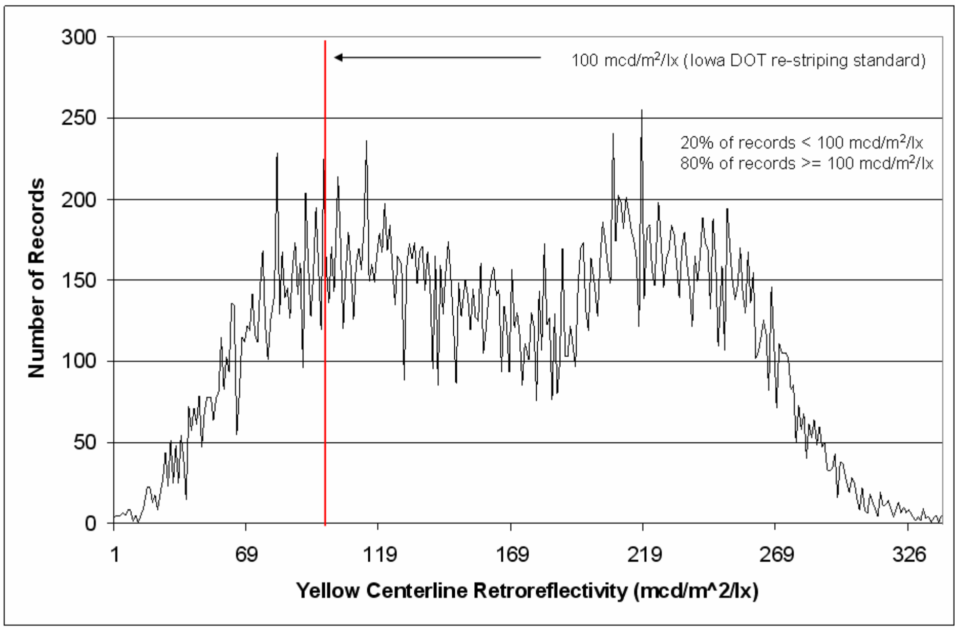

Figure 14: Graph of Yellow Centerline Records by Retroreflectivity

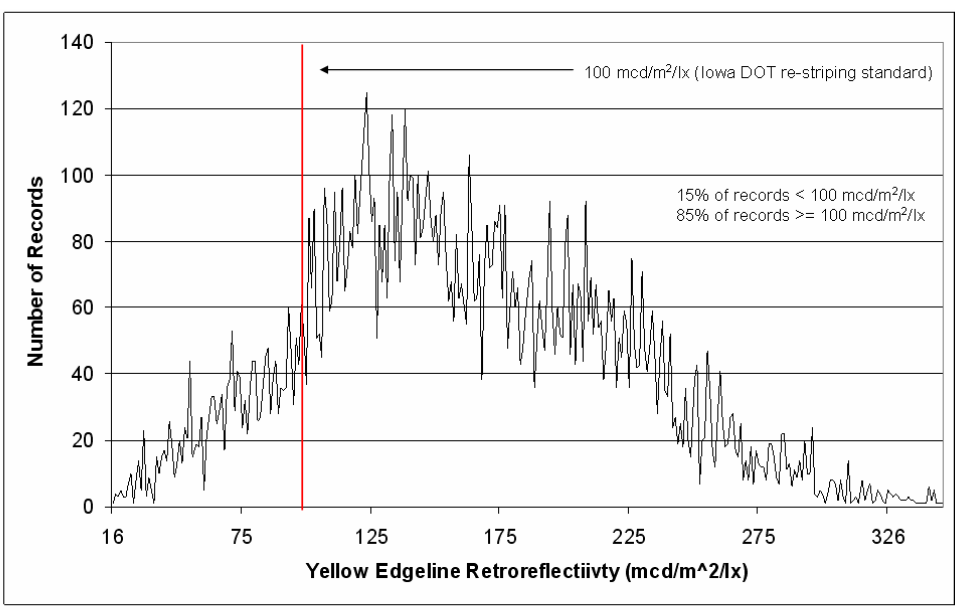

Figure 15: Graph of Yellow Edgeline Records by Retroreflectivity

Data records with low representative retroreflectivity values (≤ 200 mcd/m^2/lx) were also examined. Figure 16 shows the data distribution of white markings with low retroreflectivity values. Unlike the distribution of the complete database, the distribution of records with one or more crashes peaks at a lower retroreflectivity bin that all of the records. This distribution does suggest that lower retroreflectivity values could be correlated with higher crash frequency.

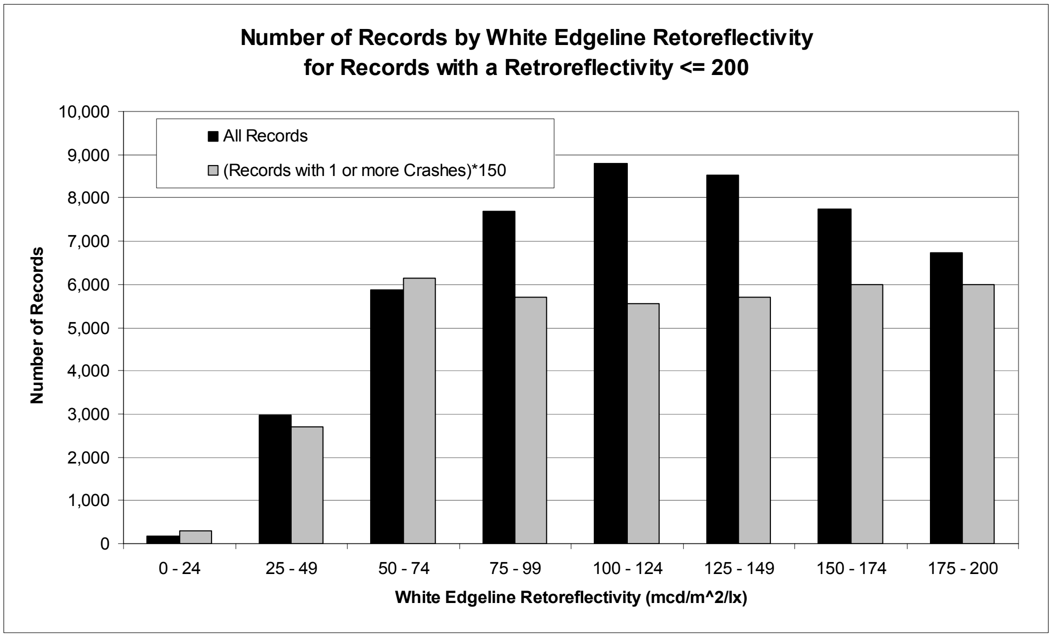

Figure 16: Number of Records by White Edgeline Retroreflectivity for Records with a Low Retroreflectivity Value

Figure 17 shows the distribution for yellow pavement marking records with a low retroreflectivity value (≤ 200 mcd/m^2/lx). The distribution of yellow markings with low retroreflectivity values does not suggest a negative correlation between retroreflectivity and crashes. The distribution of records with one crash or more seems to increase as retroreflectivity increases.

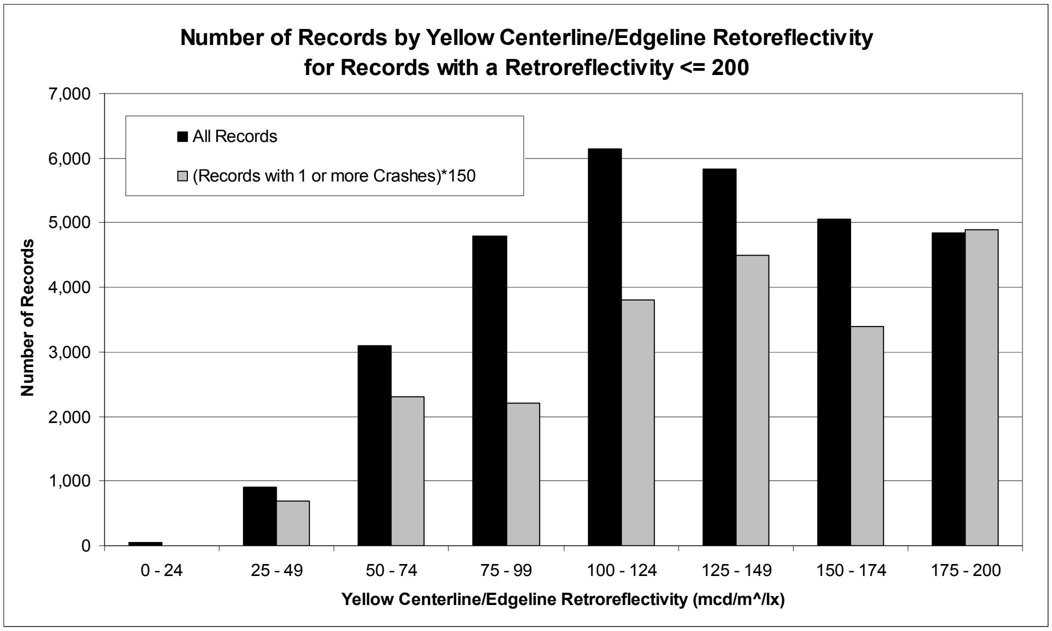

Figure 17: Number of Records by Yellow Centerline/Edgeline Retroreflectivity for Records with a Low Retroreflectivity Value

Box plots are another useful tool to examine data distributions. The box plots presented represent the complete database and are not restricted by road type or retroreflectivity value. Figure 18 shows a graph with two retroreflectivity box plots. The first box plot presents the retroreflectivity distribution of the records with no crashes and the second box plot shows records with one or more crashes. In Figure 18, the median retroreflectivity of the records with crashes is greater than the median retroreflectivity of the records with no crash. As with the bar charts in Figure 12 and Figure 13 this finding contradicts the intuition that lower retroreflectivity values contribute to certain crashes.

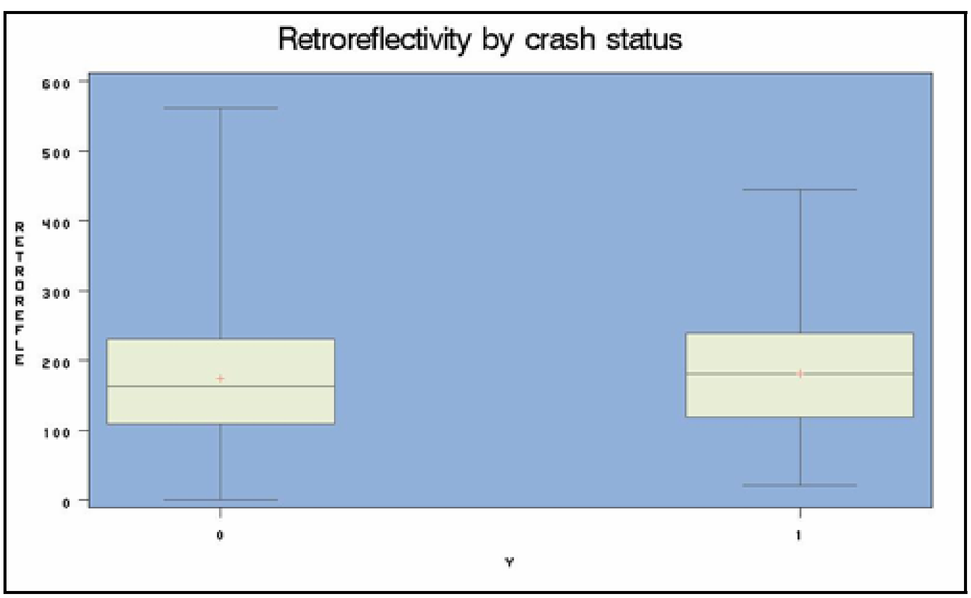

Figure 18: Retroreflectivity Box Plots by Crash Status

The box plots in Figure 19 show the retroreflectivity distributions by both crash status and line type. Just as in Figure 18, they show no evidence that lower retroreflectivity values contribute to more target crashes.

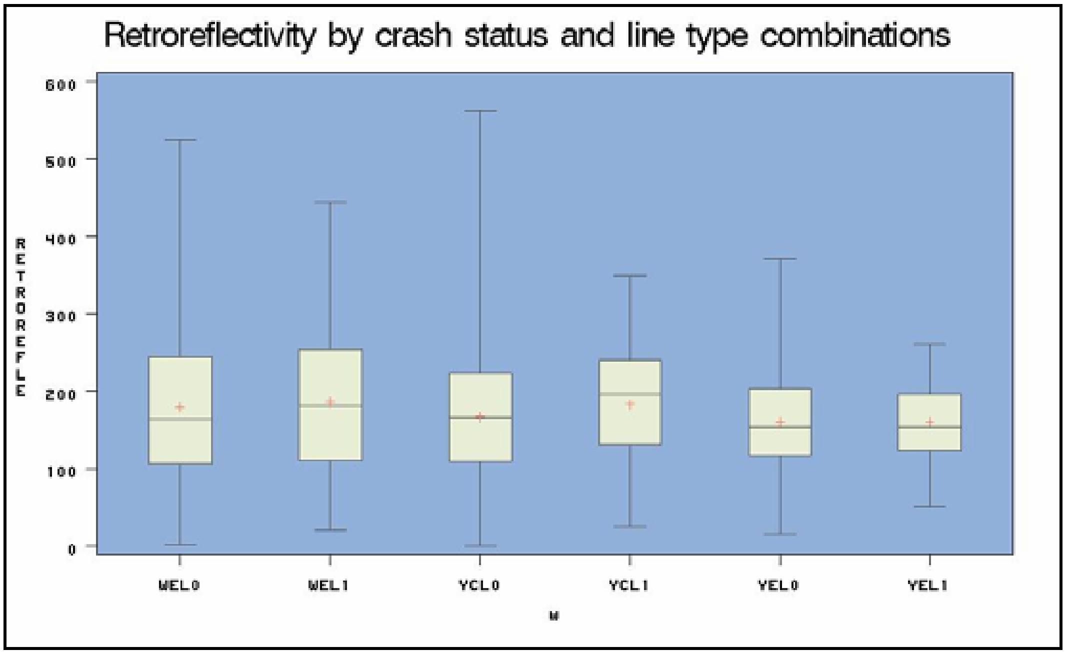

Figure 19: Retroreflectivity Box Plot by Crash Status & Line Type

A set of box plots for retroreflectivity by crash status and road type was also prepared and is shown in Figure 20. The crash status and road type combinations are labeled as follows:

D0	Multi-lane divided road with zero crashes
D1	Multi-lane divided road with one or more crashes
F0	Freeway with zero crashes
F1	Freeway with one or more crashes
T0	Two-lane road with zero crashes
T1	Two-lane road with one or more crashes
U0	Multi-lane undivided road with zero crashes
U1	Multi-lane undivided road with one or more crashes

The only road type with a lower crash record retroreflectivity distribution is multi-lane undivided. For all of the other road types the retroreflectivity distribution of the crash records is higher than the records with no crashes.

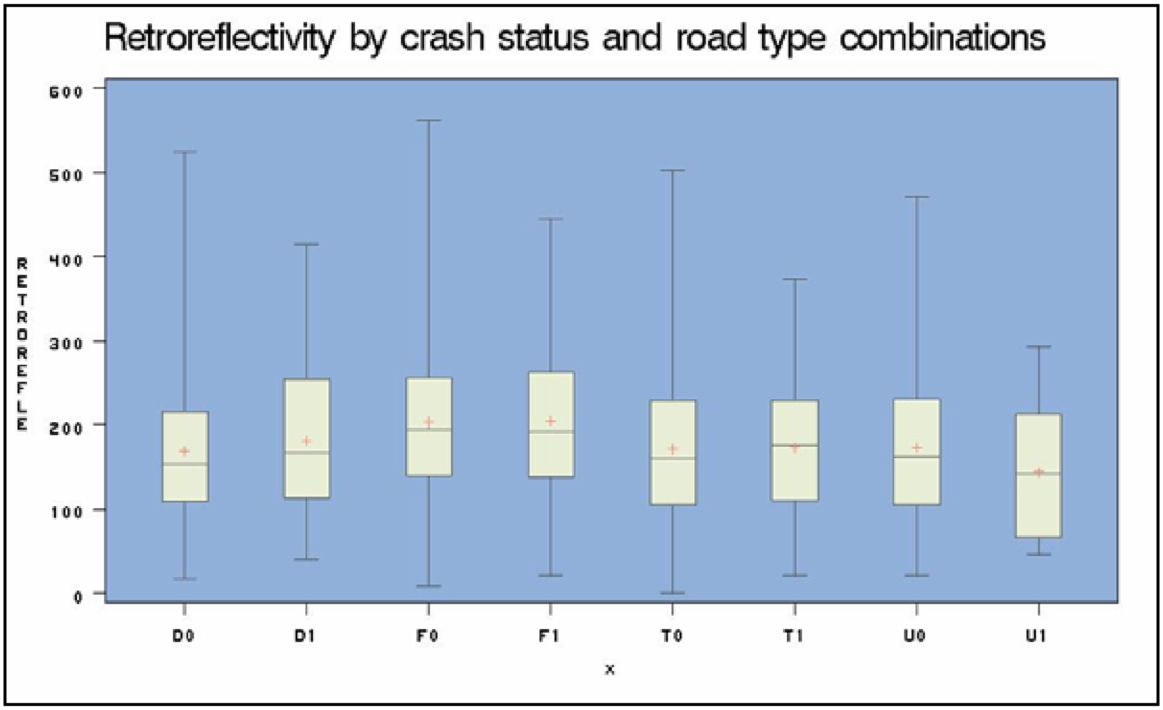

Figure 20: Retroreflectivity by Crash Status and Road Type

A third point of interest was the VMT field. It is known that the greater the amount of traffic the more likelihood for a crash. This is verified by the VMT data in the following figures. Figure 21 through Figure 24 shows that greater VMT leads to more target crashes. The figures also display the expected finding that VMT would decrease from freeway to two-lane road types.

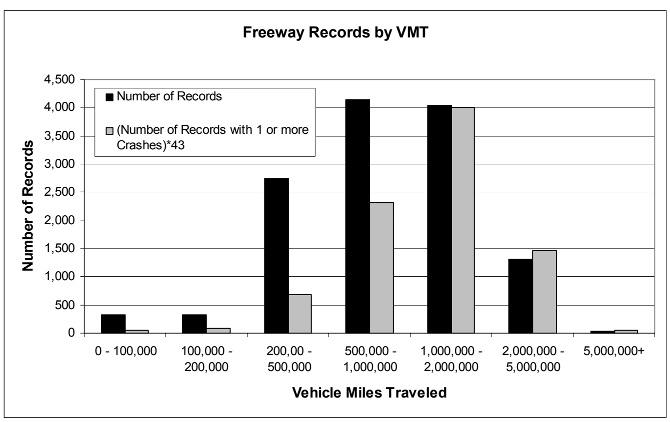

Figure 21: Freeway Records by VMT

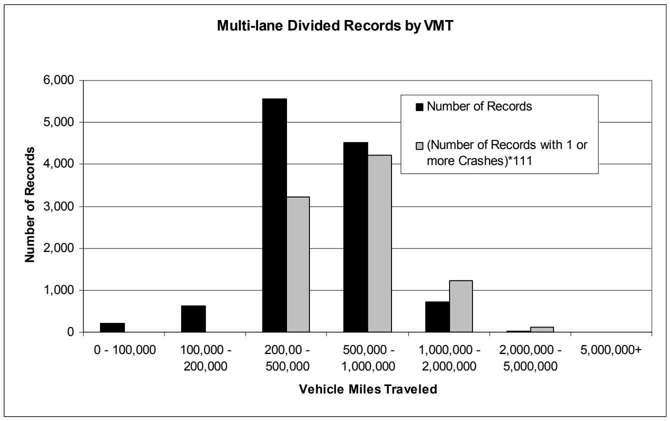

Figure 22: Multi-lane Divided Records by VMT

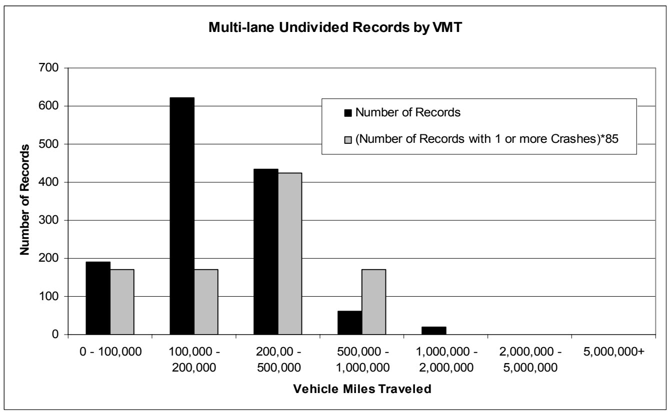

Figure 23: Multi-lane Undivided Records by VMT

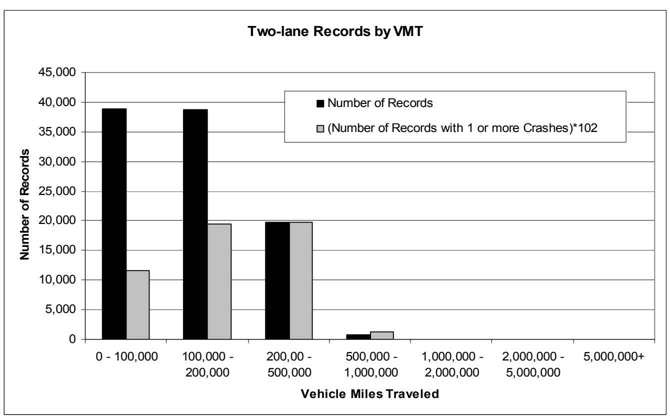

Figure 24: Two-lane Records by VMT

Another point of interest was road type. Figure 25 shows a bar chart of all the records and records with one or more crashes by road type. The number of records with crashes assigned to them was multiplied by 50 so that the distribution could be seen in the figure. It is evident from the bar chart that the majority of rural state primary roads are two-lane. The road type distribution by line type was checked to see if they differed. The road type distribution was very similar for both line types and each resembled the combined distribution in Figure 25.

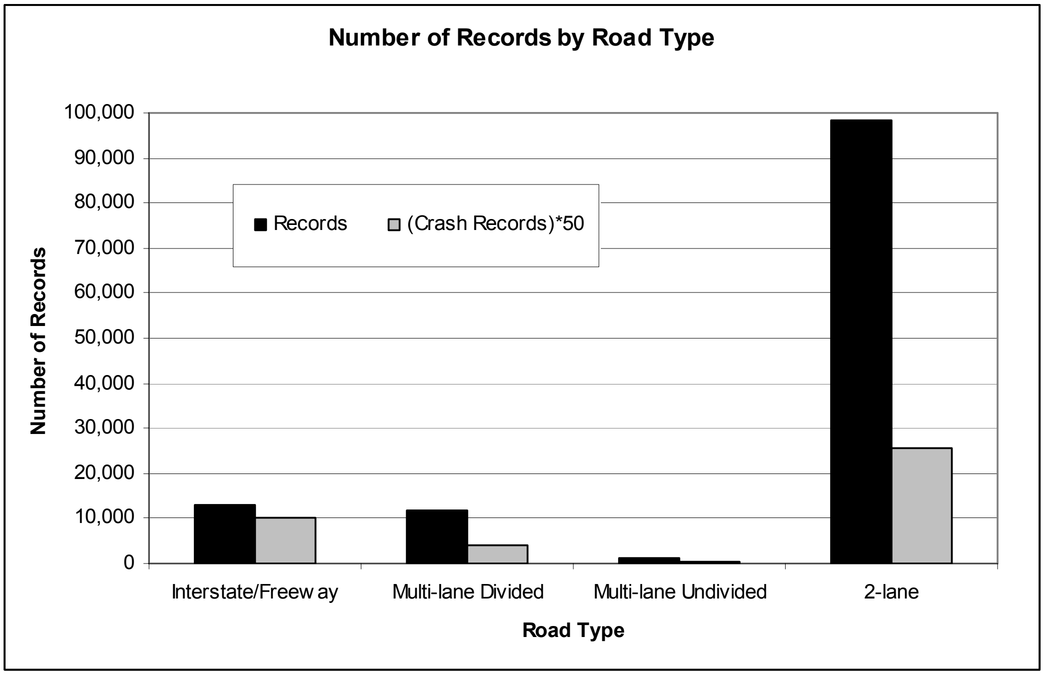

Figure 25: Number of Records by Road Type

5.2 Modeling the Data

The data were modeled in SAS 9.1. The entire database and records with low retroreflectivity values (≤ 200 mcd/m^2/lx) were modeled using a logistic regression model. A logistic regression model allows for the prediction of a discrete outcome, crash or no crash, from a set of variables that included both continuous (retroreflectivity and traffic) and discrete (line type and road type) variables. The 4 variables and 10 parameters used in the model are displayed in Figure 26.

```
                        Parameter Information

    Parameter        Effect         ROADTYPE          LINETYPE

    Prm1             Intercept
    Prm2             RETROREFLE
    Prm3             LINETYPE                         wel
    Prm4             LINETYPE                         ycl
    Prm5             LINETYPE                         yel
    Prm6             ROADTYPE       freeway
    Prm7             ROADTYPE       multidivided
    Prm8             ROADTYPE       multiundivided
    Prm9             ROADTYPE       twolane
    Prm10            TRAFFIC
  Retroreflectivity by crash status and line type combinations
```

Figure 26: Logistic Regression Model Parameter Information

The logistic regression model estimates the logit, which is the log of the crash probability. Equation 3 shows the equation used in the model. The baseline categorical parameters were yellow edgeline for line type and two-lane for road type.

Equation 3: Logistic Regression Equation

$$\log it[P(crash)] = \log\left(\frac{P(crash)}{1-P(crash)}\right)$$
$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9$$

Where:	β_0	= Intercept	*P(crash)*	= Probability of a Target Crash
	β_1	= Retroreflectivity Coefficient	x_1	= Retroreflectivity Value
	β_2	= White Edgeline Coefficient	x_2	= 1 or 0
	β_3	= Yellow Centerline Coefficient	x_3	= 1 or 0
	β_4	= Yellow Edgeline Coefficient	x_4	= 0
	β_5	= Freeway Coefficient	x_5	= 1 or 0
	β_6	= Multi-lane Divided Coefficient	x_6	= 1 or 0
	β_7	= Multi-lane Undivided Coefficient	x_7	= 1 or 0
	β_8	= Two-lane Coefficient	x_8	= 0
	β_9	= Traffic Coefficient	x_9	= Traffic Value (VMT)

To determine the probability of a crash, the model output was converted to the probability Equation 4.

Equation 4: Crash Probability Equation

$$P(crash) = \frac{e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4}}{1 + e^{\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4}}$$

The two-lane data only were also modeled in SAS 9.1. This was done to eliminate the effect that high volume freeways had on the database. A logistic regression model was used, but excluded the road type variable. Since there was only one categorical variable in the two-lane model the logistic regression equation was a little different. Equation 5 shows the equation used in the two-lane model.

Equation 5: Logistic Regression Equation (Two-Lane Only)

$$\text{logit}[P(crash)] = \log\left(\frac{P(crash)}{1-P(crash)}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5$$

Where:	β_0	= Intercept	*P(crash)*	= Probability of a Target Crash
	β_1	= Retroreflectivity Coefficient	x_1	= Retroreflectivity Value
	β_2	= White Edgeline Coefficient	x_2	= 1 or 0
	β_3	= Yellow Centerline Coefficient	x_3	= 1 or 0
	β_4	= Yellow Edgeline Coefficient		
		= $-(\beta_2 + \beta_3)$	x_4	= 1 or 0
	β_5	= Traffic Coefficient	x_5	= Traffic Value (VMT)

6.0 Results

6.1 Model of Complete Database

The results of modeling the complete database suggest that pavement marking retroreflectivity does not have a statistically significant effect on crash probability. Table 23 below shows the parameter estimates (β values) and the p-values for each parameter in the logistic regression model.

Table 23: Parameter Estimates and P-Values

Parameter	Estimate (β value)	p-value
Intercept	-5.8085	< 0.0001
Retroreflectivity	-0.0005	0.2400
Line Type: White Edgeline	0.4646	< 0.0001
Line Type: Yellow Centerline	0.8950	< 0.0001
Line Type: Yellow Edgeline	0.0000	---
Road Type: Freeway	1.2381	< 0.0001
Road Type: Multi-lane Divided	0.4885	< 0.0001
Road Type: Multi-lane Undivided	0.5006	0.0438
Road Type: Two-lane	0.0000	---
Traffic	0.0000	< 0.0001

The p-values indicate that all of the parameters are statistically significant except for retroreflectivity. The p-value for the retroreflectivity parameter is 0.24 (a p-value of ≤ 0.05 is required for the 95% confidence level). The β value for the retroreflectivity parameter is only -0.0005. The negative sign indicates a negative correlation between retroreflectivity and crash probability. This means that as retroreflectivity increases the crash probability decreases. However, because the retroreflectivity β value is so small it has little effect.

The least squares means for the probability of no crashes for each categorical parameter was calculated using the Delta Method. Table 24 shows the probability of no target crash occurring by line type and road type, all other variables being equal.

Table 24: Least Squares Means of Categorical Parameters

Variable	Parameter	Least Squares Mean (Probability of NO Crash)
Line Type	White Edgeline	0.9919
Line Type	Yellow Centerline	0.9875
Line Type	Yellow Edgeline	0.9949
Road Type	Freeway	0.9842
Road Type	Multi-lane Divided	0.9925
Road Type	Multi-lane Undivided	0.9924
Road Type	Two-lane	0.9954

The least squares means for the 4 road type parameters suggest that, everything else being equal, the probability of no crashes is highest for two-lane roads. The other categorical parameters were compared using a t-test. The results revealed an order of safety for each categorical variable, all other variables being equal. The order of safety and whether or not the differences are statistically significant are shown in Table 25.

Table 25: Order of Safety for Categorical Parameters

Order (Safest to Least Safe)	Parameter	Statistically Significant Difference?
1	Two-lane	
		Yes
2	Multi-lane undivided	
		No
3	Multi-lane divided	
		Yes
4	Freeway	
1	Yellow Edgeline	
		Yes
2	Yellow Centerline	
		Yes
3	White Edgeline	

The order of safety for the road type parameters would be very different if traffic was factored in. The order of safety for the line type show that there are more ROR right or ROR straight crashes than cross centerline or ROR left crashes. The line type order also show that there are more cross centerline or ROR left crashes on undivided roads (yellow centerline) than on divided roads (yellow edgeline).

The parameter estimate for traffic is not zero as shown in Table 23. The estimate value is just smaller than $1\text{x}10^{-4}$. The SAS output did not display the true value; the program just rounded the number to the nearest 4^{th} decimal place. With the traffic values ranging up to nearly 10 million, the estimate does make a difference. If the traffic parameter was divided by a large constant then the parameter estimate would be larger.

The goodness of fit of the model can be judged by the deviance value divided by the degrees of freedom. The value for this model was 0.0064. If the data were modeled differently this value could be compared to see which model fit the data better. This value is later compared to the corresponding low retroreflectivity model value.

6.2 Model of Two-lane Records

The results of only the two-lane records are similar. Table 26 shows the parameter estimates and p-values for the two-lane model.

Table 26: Parameter Estimates and P-Values for Two-lane Roads

Parameter	Estimate (β value)	p-value
Intercept	-6.1898	< 0.0001
Retroreflectivity	0.000596	0.2803
Line Type: White Edgeline	-0.0348	0.8611
Line Type: Yellow Centerline	0.5442	0.0062
Traffic	3.914 E-6	< 0.0001

The continuous variables traffic (VMT) and retroreflectivity were graphed using Equation 4 to calculate the probability of a crash (with one of the continuous variables fixed) versus the other continuous variable. Figures 27 and 28 show the crash probability versus VMT for white edgelines and yellow centerlines, respectively. Figures 29 and 30 show the probability of a target crash versus pavement markings retroreflectivity.

Figures 27 and 28 show the expected trend that the probability of a crash increases as VMT increases. These figures also show that the probability of a crash increases a small amount as pavement marking retroreflectivity increases. Like the box plots in Section 5.1, this finding contradicts the intuition that lower retroreflectivity values are contributing factors for target crashes. Figures 29 and 30 reiterate the previous results. These figures show crash probability to have a positive correlation with both VMT and pavement marking retroreflectivity. The correlation is much stronger with VMT however.

The goodness of fit of the two-lane model can be judged by the percent of concordant pairs. All of the records are compared to each other and are said to be concordant if the record with the lowered ordered response (0 for no crashes, 1 for one or more crashes) has a lower ordered predicted response (the predicted likelihood of a crash). A pair is discordant if the record with a crash has a predicted crash probability lower than that of a record not containing a crash. For the two-lane model, 52.2 percent of the pairs were concordant, 24.4 percent were discordant, and 23.5 percent tied.

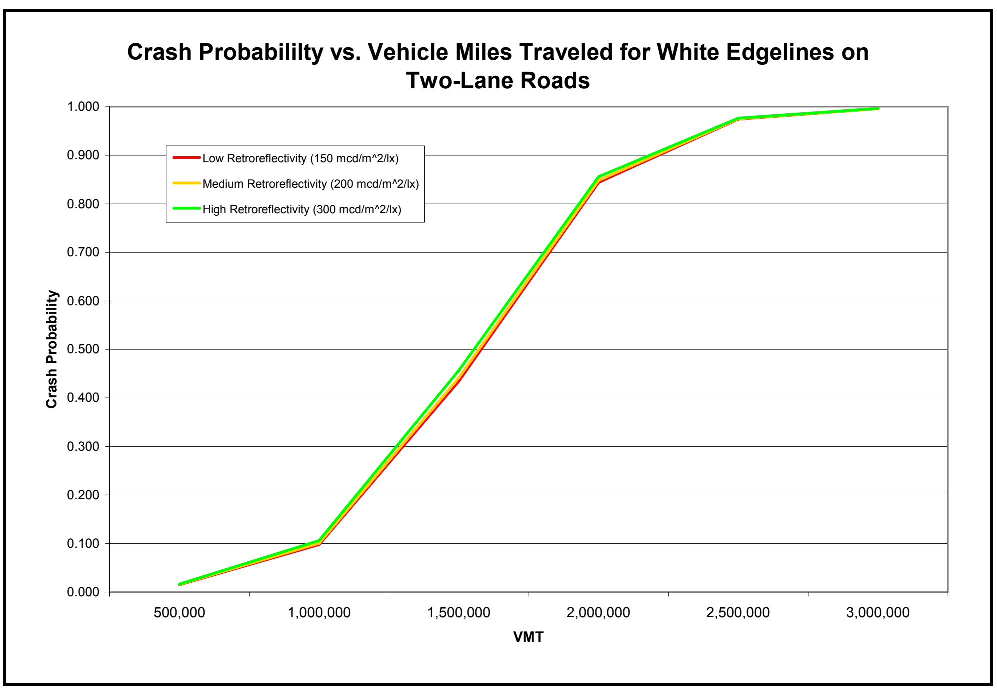

Figure 27: Crash Probability vs. VMT for White Edgelines on Two-lane Roads

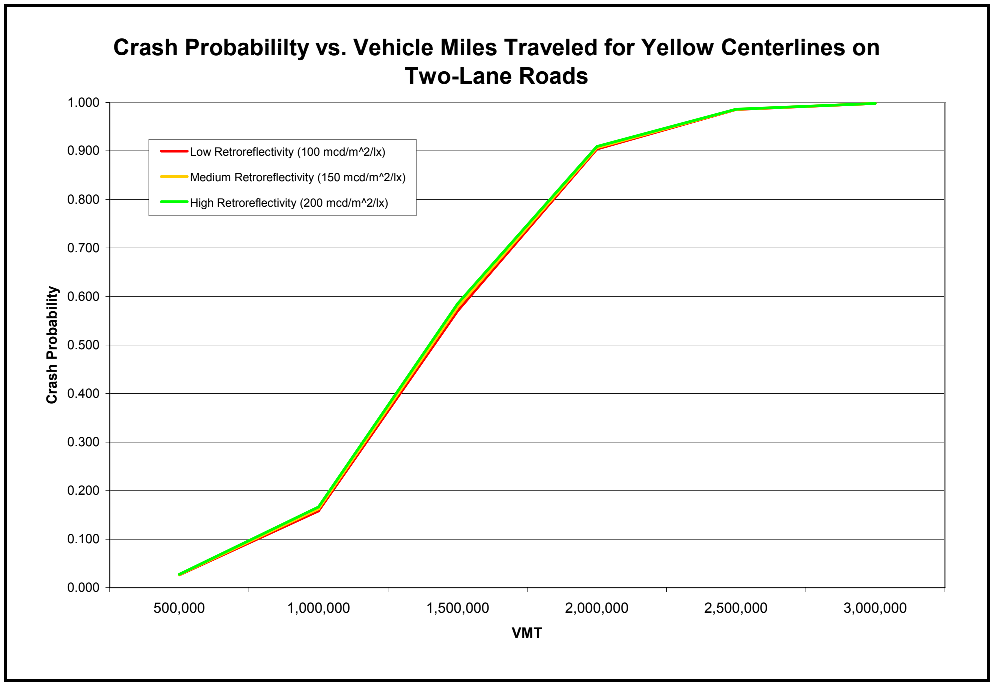

Figure 28: Crash Probability vs. VMT for Yellow Centerlines on Two-lane Roads

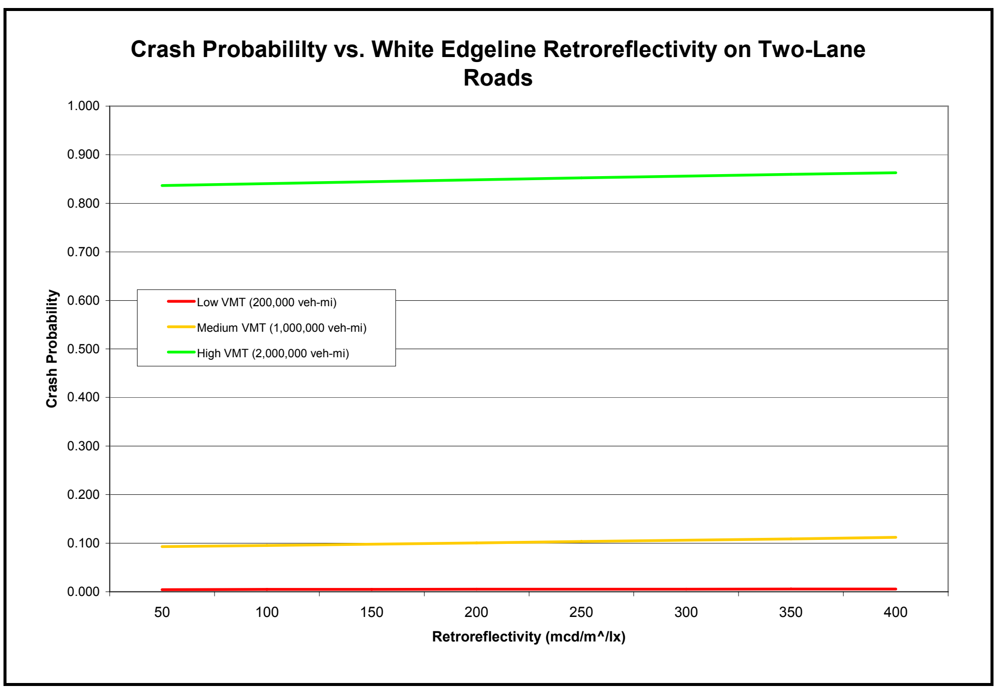

Figure 29: Crash Probability vs. White Edgeline Retroreflectivity on Two-lane Roads

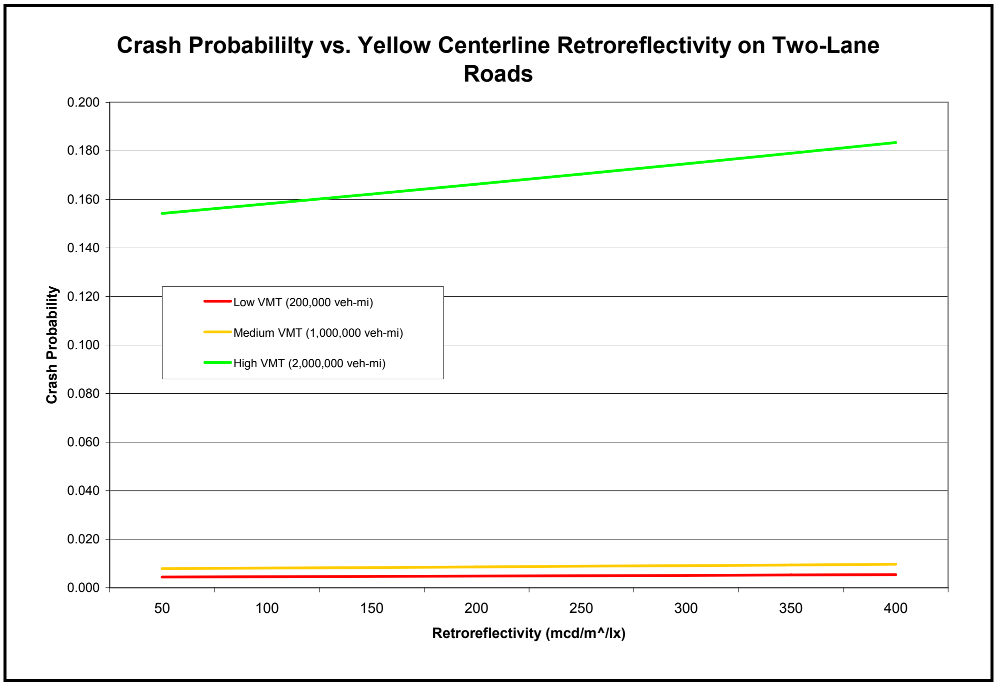

Figure 30: Crash Probability vs. Yellow Centerline Retroreflectivity on Two-lane Roads

6.3 Model of Low Retroreflectivity Records

A model was developed for the low retroreflectivity records (≤ 200 mcd/m^2/lx) because no statistically significant relationship was found for all records. This model found a statistically significant correlation between retroreflectivity and crash probability. Table 27 shows the parameter estimates and p-values for the low retroreflectivity model.

Table 27: Parameter Estimates and P-Values for Low Retroreflectivity Records

Parameter	Estimate (β value)	p-value
Intercept	-5.7401	< 0.0001
Retroreflectivity	-0.0021	0.0406
Line Type: White Edgeline	0.5088	< 0.0001
Line Type: Yellow Centerline	0.8112	< 0.0001
Line Type: Yellow Edgeline	0.0000	---
Road Type: Freeway	1.1701	< 0.0001
Road Type: Multi-lane Divided	0.3936	0.0080
Road Type: Multi-lane Undivided	0.7205	0.0052
Road Type: Two-lane	0.0000	---
Traffic	4.87E-7	< 0.0001

For low retroreflectivity records, a negative correlation between retroreflectivity and crash probability was found to be statistically significant. The retroreflectivity parameter estimate is -0.0021. According to the model, as retroreflectivity increases crash probability decreases by a very small amount. From retroreflectivity level 100 mcd/m^2/lx to 200 mcd/m^2/lx the crash probability decreases by only thousandths of a percent. Since the crash probability is so small, the relative change -19% (see Figures 31-34).

The goodness of fit of the model was better for low retroreflectivity records than it was for the entire database. The deviance value divided by the degrees of freedom was 0.0059, while the value for the whole database was 0.0064.

A possible explanation for this finding is that pavement marking visibility increases considerably for positive changes in retroreflectivity at low levels than it does at high retroreflectivity levels. Once retroreflectivity values exceed an adequate pavement marking visibility threshold, the rate at which visibility improves flattens out (see Figure 1). By removing the records with a retroreflectivity value greater than 200 mcd/m^2/lx the effects of a visibility threshold were reduced.

Eliminating all records with a retroreflectivity value greater than 200 mcd/m^2/lx reduced the database to 79,228 records, a 36% reduction. The number of records with one or more crashes was reduced from 803 to 472, a reduction of 41%. With this many crashes occurring at locations with a high corresponding retroreflectivity value it is clear why the model of the complete database found no statistically significant correlation between retroreflectivity and crash probability.

Figures 31 through 34 show the crash probability from the low retroreflectivity model by line type and road type (freeway or two-lane). The crash probability in all of these figures is on a very small scale; less than 3 hundredths of a percent. Although the negative correlation between low retroreflectivity values and crash probability was found to be statistically significant, the practical implications are minimal.

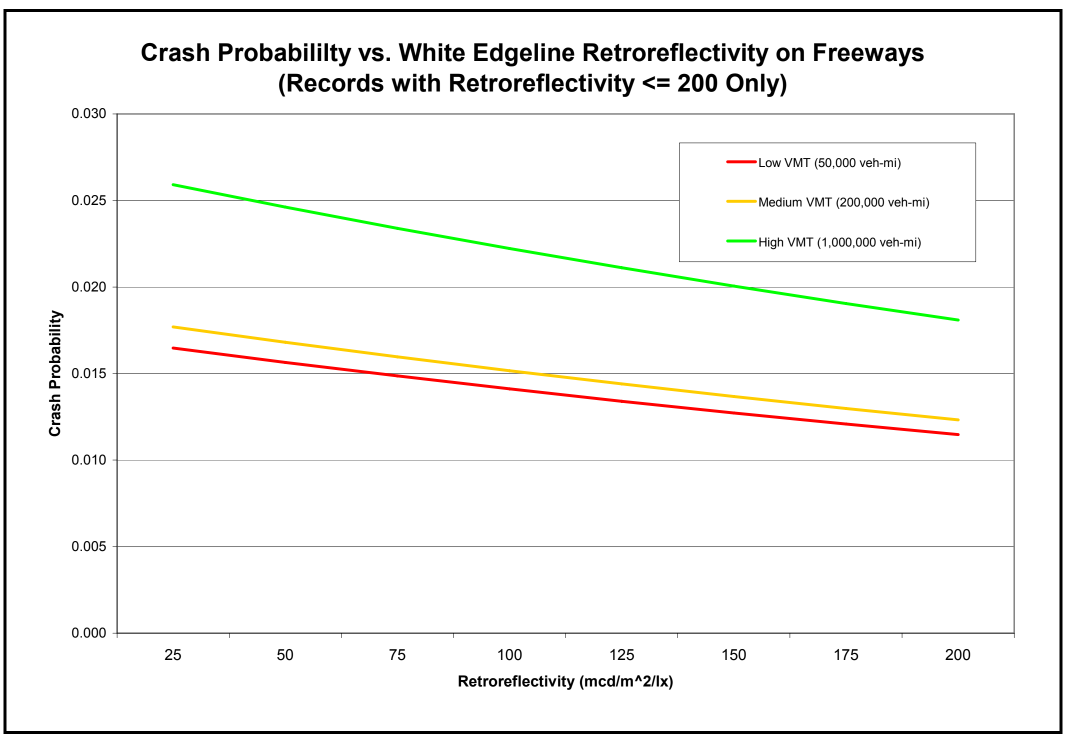

Figure 31: Crash Probability vs. WEL Retroreflectivity on Freeways (Records with Retroreflectivity <= 200)

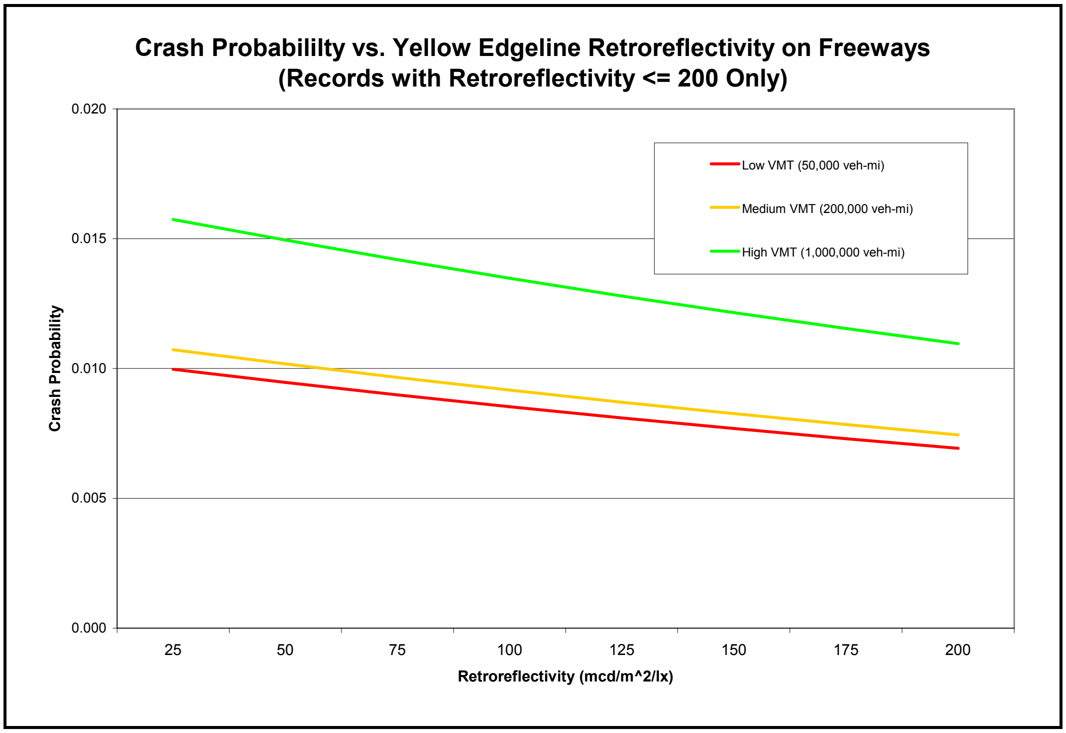

Figure 32: Crash Probability vs. YEL Retroreflectivity on Freeways (Records with Retroreflectivity <= 200)

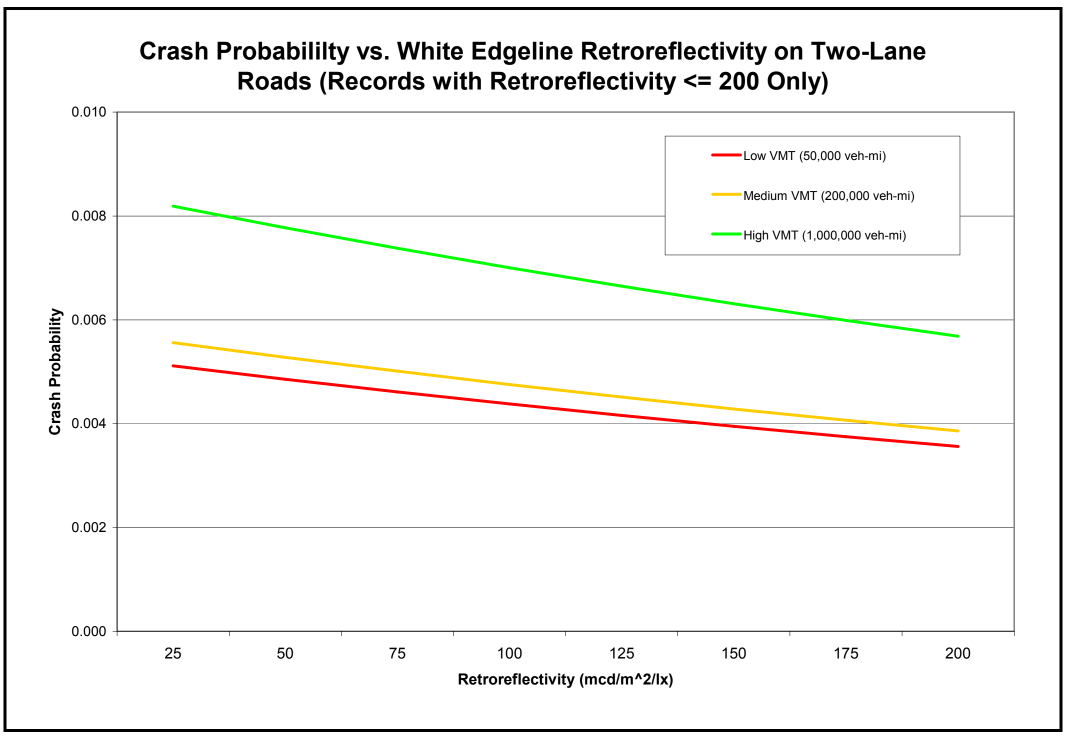

Figure 33: Crash Probability vs. WEL Retroreflectivity on Two-Lane Roads (Records with Retroreflectivity <=200)

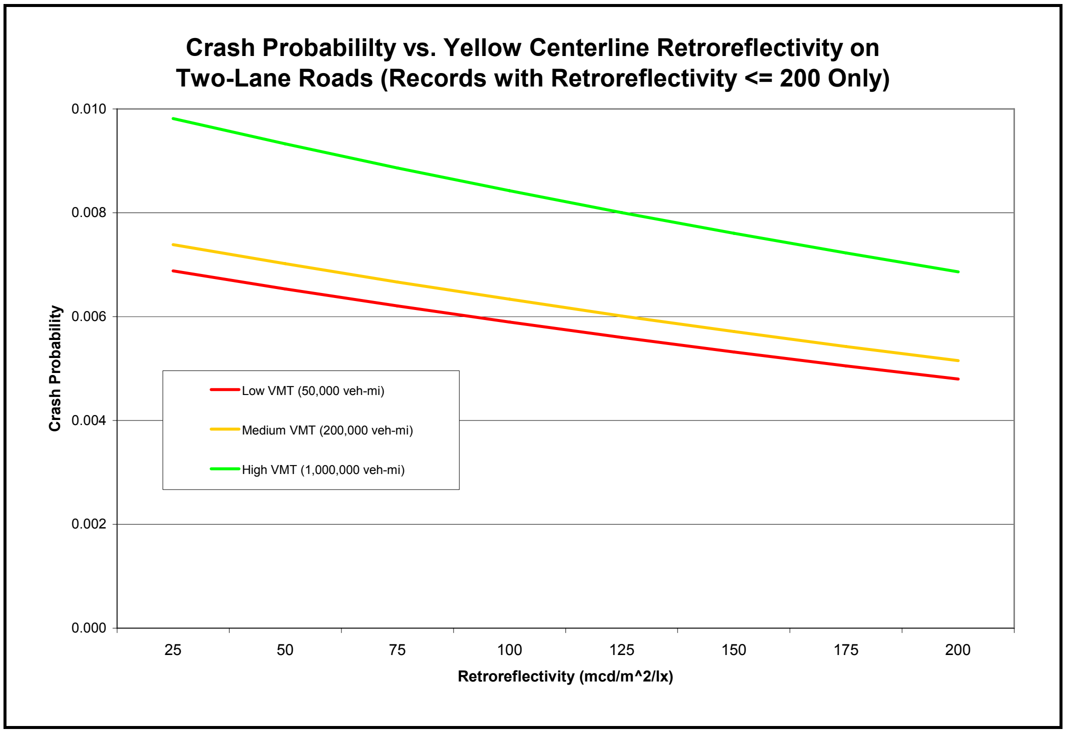

Figure 34: Crash Probability vs. YCL Retroreflectivity on Two-Lane Roads (Records with Retroreflectivity <= 200)

7.0 Conclusion

GIS is a valuable tool for evaluating roadway safety performance. In GIS it is relatively easy to manage crash, roadway, and numerous other types of spatial data. Based upon spatial proximity, in GIS, crashes can be subjectively assigned roadway characteristics. Or vice versa, roadway segments can be assigned crashes. In GIS, database records store any type of information which can be queried and dissected. GIS also makes it simple for data to be rearranged and for the addition of future data. Temporal data can also be included within the spatial data records. However, managing both spatial and temporal data can be complicated as shown in this study.

The database developed in this study is an example of how dynamic roadway characteristics can be tested against crash performance over time. This type of spatial-temporal database has the potential to be applied elsewhere such as sign management or investigations of the effects of weather.

This study focused on testing the correlation between longitudinal pavement marking retroreflectivity and safety performance. It has been shown in previous studies that the presence of edgelines, compared to no edgelines, significantly increases safety performance. From this, intuition leads one to assume that pavement marking visibility and retroreflectivity would also have a positive effect on safety performance. The distribution and models of the entire database and the two-lane records did not show that poor pavement marking retroreflectivity correlating to a higher crash probability. Upon examination of low retroreflectivity values only ($\leq$ 200 mcd/m^2/lx), a negative correlation was found to be statistically significant. However, the correlation was so small it does not have practical significance.

There are some limitations in the crash and retroreflectivity data. The target crashes selected were assumed to be related to pavement marking retroreflectivity. A sufficient amount of information in the crash data was not available to determine a retroreflectivity-safety relationship. The retroreflectivity data were collected on a mile basis over only 200 feet or so. These spot measurements were assumed to be representative of an entire 5 mile segment. The recognized fact that pavement marking retroreflectivity can vary significantly makes this a problematic assumption.

This study identified a general relationship between low pavement marking retroreflectivity levels and safety performance. Future research should be conducted to further define the correlation between pavement marking retroreflectivity and safety. With additional knowledge agencies can expectantly improve their pavement marking management programs and reduce the number of night time crashes where low pavement marking retroreflective values are a contributing factor.

8.0 Recommendations for Future Research

In order to better understand the relation between pavement marking retroreflectivity and safety performance the follow research is recommended for the future.

- **Analysis of future data**
  The addition of future data to the database developed in this study would help further define the correlation between pavement marking retroreflectivity and safety performance.
- **Replication of this study in other states.**
  A replication of this study in other states would help verify the results and/or identify differences among states. Similar data resources would be necessary.
- **Investigation of retroreflectivity variability**.
  The level of inconsistency in pavement marking retroreflectivity should be known in order to achieve a certain level of accuracy in assigning retroreflectivity values to more than a single spot location. How much does the retroreflectivity a typical pavement marking vary over a certain distance? What causes this variation? How much does the angle at which the retroreflectivity is measured effect the resulting value?
- **Study of pavement marking retroreflectivity related crashes**.
  An examination of the types of crashes retroreflectivity levels affect would allow for more accurate results. The database created in this study could be used to test crash types, other than ROR and cross centerline which were tested in this study, versus pavement marking retroreflectivity.
- **Examination of the effects of paint cycle on crash performance.**
  If determining when to re-stripe a road is the driving force behind determining a relationship between pavement marking retroreflectivity and crash performance, a comparison of two homogeneous roadway segments with different striping cycles could offer a solution.
- **A human factors study on the impact of pavement marking retroreflectivity and speed**.
  Does speed increase due to drivers feeling more comfortable with higher retroreflectivity values; especially at night or during other poor visibility conditions? Previous research has suggested this possibility.
- **A study analyzing the effect of retroreflectivity on safety performance at high crash locations or on horizontal curves**.
  Does limiting a retroreflectivity-crash analysis to certain crash locations affect the results?

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