Pavement Markings and Safety

Final Report
November 2010

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16. Abstract

Previous research on pavement markings from a safety perspective tackled various issues such as pavement marking retroreflectivity variability, relationship between pavement marking retroreflectivity and driver visibility, or pavement marking improvements and safety. A recent research interest in this area has been to find a correlation between retroreflectivity and crashes, but a significant statistical relationship has not yet been found.

This study investigates such a possible statistical relationship by analyzing five years of pavement marking retroreflectivity data collected by the Iowa Department of Transportation (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 statewide crash data to attempt to quantify a relationship between crash occurrence probability and pavement marking retroreflectivity.

First, logistic regression analyses were done for the whole data set to find a statistical relationship between crash occurrence probability and identified variables, which are road type, line type, retroreflectivity, and traffic (vehicle miles traveled). The analysis looked into subsets of the data set such as road type, retroreflectivity measurement source, high crash routes, retroreflectivity range, and line types.

Retroreflectivity was found to have a significant effect in crash occurrence probability for four data subsets—interstate, white edge line, yellow edge line, and yellow center line data. For white edge line and yellow center line data, crash occurrence probability was found to increase by decreasing values of retroreflectivity.

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EXECUTIVE SUMMARY

Objective

This study explores the statistical relationship between crash occurrence probability and longitudinal pavement marking retroreflectivity. For this purpose, a spatial-temporal database was developed that combines the representative retroreflectivity values for nonwinter months and for each available milepost on primary roads of Iowa based on the retroreflectivity readings by the Iowa Department of Transportation (DOT) and the statewide crash data for selected target crashes. Crashes that occurred in daylight, under good lighting conditions or unknown conditions, were not included in the data set since the study was interested in the effect of retroreflectivity under dark conditions. Crashes during dawn, dusk, and dark conditions with no roadway lighting were therefore selected as possible target crashes. Target crash selection was finalized by selecting only the 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. The target crash data were then matched with the retroreflectivity data by location. The final data set contained representative retroreflectivity values for each available milepost with accompanying variables like vehicle miles traveled, line type, direction of reading, road type, route number, and crash information when available.

Analysis

A series of logistic regression analyses was completed for various subsets to investigate the significance of parameters in the probability of crash occurrence—retroreflectivity being the main parameter of interest. Of 83,539 records (per milepost, year, and direction), only 1,343 crash records are in the data set, which constitutes approximately 1.61% of all records statewide. This small sample size creates a challenge for the statistical analyses since the occurrence is a rare event within the whole data set.

Results

Retroreflectivity was found to be a significant parameter in the probability of crash occurrence when only data from the interstate roads were analyzed and when the data was divided into three subsets by line type (white edge lines, yellow edge lines, and yellow center lines). Dividing the data by line type into three subsets enabled the inclusion of a subject effect for routes into the logistic regression model. Including the routes as a subject effect addresses the autocorrelation from the readings that come from the same route. In this final set of analyses for white edge lines and yellow center lines, crash occurrence probability was found to increase by decreasing values of longitudinal pavement marking retroreflectivity.

Conclusion

The statistical results from this study and the several cases explained above where retroreflectivity was significant in crash occurrence probability are valid only for the mentioned data subsets. While the extent of the study and the data set is not sufficient for identifying a causal relationship, results represent a potential relationship to be explored in future research.

Future Research

Addressing the data from the same routes by a subject effect is an addition to the previous work in the literature, and future research may be extended to model the possible autocorrelation from sequential retroreflectivity readings. These additions to the model in simple terms let us model these known relationships within the bigger logistic regression model and enable an improved investigation of the other parameters (such as the retroreflectivity or traffic) in effect in crash occurrence.

INTRODUCTION

Longitudinal pavement markings provide guidance through delineating the traveled way. 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. Pavement markings are especially important at night.

Retroreflectivity

A very important feature of a longitudinal pavement marking is the retroreflectivity. Reflective beads are recessed into the pavement markings so that drivers can see them at night. The light from a vehicle's headlights reflects off the beads, and the amount of light that is reflected back to the 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).

Variability of Retroreflectivity

Pavement marking retroreflectivity can vary significantly by location. One segment may have a high retroreflectivity value, while a segment just a few feet away may have a low value. Potential causes of this variability include damage due to traffic or winter maintenance, environmental conditions, and the consistency in which the pavement markings were applied and measured. The variability makes it difficult to summarize pavement marking retroreflectivity by roadway segment.

Service Life Evaluation/Degradation of Pavement Markings

In Iowa and other states with significant amounts of snowfall, the reflective beads embedded in the paint get worn and are scraped up by snowplows. Pavement markings wear out over time, and it is necessary for agencies to restripe and repair the condition of pavement markings on a regular basis. The question then is: How often should a marking be restriped? 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 Department of Transportation (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 restriping state highways.

LITERATURE REVIEW

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 the 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 2004).

Pavement Marking Retroreflectivity and 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% 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 1991).

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 edge lines 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 two states with relatively severe winter climates, it was found that the mean retroreflectivity was 15 to 34% 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% when the younger group of drivers (average age of 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 1999).

Parker and Meja (2003) conducted a nighttime 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 of 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 (2003) found that a "curvilinear regression yielded a polynomial function of 4th order as the best fit." 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 and Meja 2003).

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/m^2/lx" (Parker and Meja 2003).

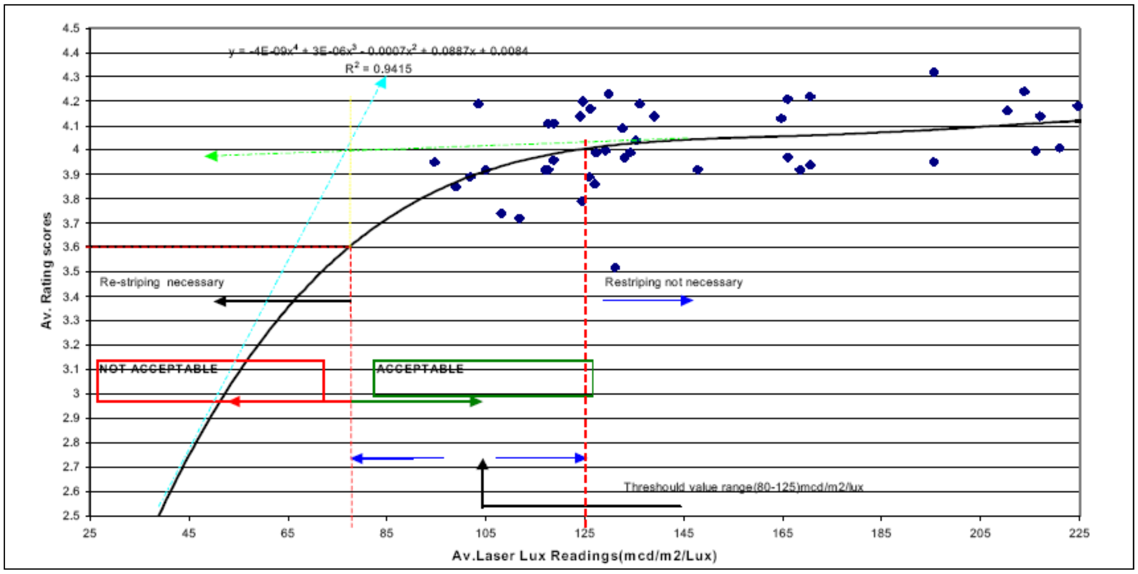

Figure 1. Curvilinear regression for WEL, YCL, and SPL

Pavement Marking Improvements and Safety

A before-and-after study (Federal Highway Administration [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 one year or two 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 center line and edge line, center line only, and edge line 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 1981 FHWA study found that pavement marking improvements decreased fatal and injury crashes at night. The percent reduction in crashes was statistically significant for added edge lines (16%) and center lines and edge lines (12%). A center line improvement only resulted in a statistically insignificant reduction of 3%. The study determined that adding edge lines to roads with center lines 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 edge lines on ROR crashes. In Hall's study, approximately 530 miles of rural two-lane highway with high rates of ROR crashes were selected. Over two years, 176 of these miles were restriped with an eight-inch white edge line. 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" 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 three years was used for the before period, and a duration of two years was used for the after period. Both of these studies found that wide edge lines 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 center line 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 average daily traffic (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 two-year-before and two-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 and Sinha 1994).

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 that 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 FHWA to determine if "longer lasting more retroreflective materials reduced crashes" (Migletz and Graham 2002). 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 restriped with durable markings for the after period. At 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 nighttime conditions, and proportion of ADT under dry and wet conditions (Migletz and Graham 2002).

The results of the analysis showed that nighttime crashes on dry pavement, adjusted by the measure of exposure, decreased significantly by an average of 11%. The nighttime 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 nighttime 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 and Graham 2002). 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: Illinois, Missouri, New Jersey, New York, Pennsylvania, and Wisconsin. 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 et al. 2004). 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 edge line markings were added. Highway segments of three miles or greater consisting of uniform lane width, shoulder width (less than four feet), traffic volumes, and edge striping were analyzed in the study. Crash records from 1998 to 2001 were used to evaluate the safety benefits of adding edge lines. Work zone-related crashes were removed from the analysis.

The safety analysis found that the addition of edge lines on rural two-lane highways may reduce accident frequency. The addition of edge lines had the greatest safety benefit on curved segments of roadways with narrow lane widths (9–10 feet). The researchers recommend that edge lines 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% higher on highways without edge lines than with edge lines" (Tsyganov et al. 2006). The presence of edge lines also showed safety benefits during dark conditions. The researchers suggested that this may be related to better driver perception of path and speed.

Tsyganov et al. (2006) also studied the effects of edge lines on speed. The study found that speeds increased by an average of 5 mph on both straight and curved sections of highway after edge lines were applied. This change in average speed, however, is not considered significant.

Pavement Marking Retroreflectivity and 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 nighttime accidents in Michigan. Five test areas were selected around the state with variations in traffic, speed limit, lighting, and snowfall. 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 ADT, 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 nighttime 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/m2/lx. A database that includes a wider range of retroreflectivity levels may reveal the effects of low retroreflectivity on traffic crashes or accidents" (Lee et al. 1999). The authors also suggested that a larger sample of nighttime accidents may allow the identification of a relationship between pavement marking visibility and nighttime accidents.

Table 1. Criteria to select accidents associated with line visibility

Variables	Selected Values
Highway Area Type	Nonintersection and noninterchange area
Lighting Condition	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. Nighttime 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 2002). 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 edge line more for guidance. Highway segments were analyzed in units of one mile and a CR in crashes per million vehicle-miles was calculated for each segment. Crash records were collected for up to three years after the striping date, and retroreflectivity readings were taken at one- to three-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 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 the 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 cold-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 et al. 2006). 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, and material type, as well as 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 (multilane freeways, multilane 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 cannot be used to quantify the safety effect of retroreflectivity greater or less than the ranges modeled for California” (Bahar et al. 2006). Another potential problem is that “the true retroreflectivity of markings and markers in California may be different than the modeled NTPEP retroreflectivity” (Bahar et al. 2006).

Highway Tort Liability Claims and Asset Conditions

Transportation agencies are interested in the impacts of pavement markings on their systems in several areas such as safety and nighttime visibility as discussed in the previous sections. Asset conditions in general also represent a legal concern for the transportation agencies as they may be subjected to tort liability claims due to asset condition. This section briefly reviews the relationship between tort liability claims and asset conditions and presents some statistics on the subject.

The early 1970s marked a new phase of maturation in the United States highway system with the shift from construction to operation of the highway assets (Lewis 1983). A growth in tort liability litigation is also observed in this era. Since the early 1970s, states have experienced an increasing number of cases and claims in tort liability due to the modern concept of social justice and "snowballing effect of litigation" (Lewis 1983). The purpose of a tort liability claim lawsuit is to "seek repayment for damages to property and injuries to individuals" (Lewis 1983). For a tort action to be valid, a breach of duty by the defendant must be the proximate cause of the accident, the defendant (e.g., state transportation agency) must owe a legal duty to the plaintiff, and the plaintiff must have suffered damages as a result. A majority of the tort claims are dismissed since they do not have substantial grounds. Even when a state is found grossly negligent in a lawsuit (failed to exercise a duty), contributory negligence by the plaintiff (sharing the responsibility for the accident) may result in a dismissed tort claim. The fact that a majority of these tort claims are dismissed does not change the statistics, and state transportation agencies are subject to many new claims each year and dedicate time and personnel for the management of these cases.

The Iowa Department of Transportation received 1,159 tort claims during the 2006–2010 period with an average of 232 cases per year. The total sum of these tort claims was over $60 million in categories such as administration, bridge related, construction zone, design, or roadway surface to name a few. Tort claims due to problems with traffic control assets such as pavement markings, signals, signs, and lighting are grouped under one category as traffic control. During 2006–2010 there were on average three claims per year in this category and the total claims were over $4.62 million. These claims were dismissed, as many such claims are at the national level.

A recent report by the FHWA regarding traffic sign visibility indicates that while such tort claims have not historically been a problem, having proper assessment and management programs provides adequate defense to the agencies (Opiela and Andersen 2007). Another report on minimum retroreflectivity values on sign replacement practices has a similar comment on the benefits of having a sign inventory management system (SIMS) and discusses that having a SIMS reduces the likelihood of tort liability claims and provides documentation of conditions of assets and agencies' efforts to determine and improve problems (Hawkins et al. 1996). Vereen et al. (2002)investigated alternatives for the North Carolina DOT for compliance with the proposed minimum in-service retroreflectivity levels, and they also looked into sign inventory and liability interaction in this context. As in previously reported literature, they emphasized the value of having a SIMS since it provides evidence of the existence of a particular sign at a particular location and related inspection and maintenance activities.

Highway assets, including pavement markings and traffic signs, have increasing maintenance needs that state transportation agencies are challenged to respond to. While agencies try to spend available funds in the best possible way to maintain their assets, limited funds for the needs typically cause backlogs. The intention to keep up with every possible maintenance need and keep the highway assets at optimum conditions is ideal but very difficult to attain. Substantial or not, lawsuits are going to occur since anyone involved in an accident has the right to sue. What is critical for an agency is to be aware of the risk of lawsuits, plan for costs related to manage the claims, and have the proper documentation and data for the assets to prove accountability as an agency.

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 PRPMs 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 of crash data is needed to provide a relationship between pavement marking retroreflectivity and safety performance.

PROBLEM STATEMENT

For this study, 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 in some crashes (such as nighttime, single vehicle, and 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 strategies to reduce the number of nighttime crashes where low pavement marking retroreflectivity values are a contributing factor.

A study of the safety effects of pavement marking retroreflectivity is complex. The fact that pavement marking retroreflectivity deteriorates nonlinearly over time 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 edge line, yellow center line, or yellow edge line pavement markings, and the edge line markings are in both directions of travel. Additionally, the data used were collected over five 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 study 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 five cumulative years of measured pavement marking retroreflectivity data collected by the Iowa DOT on state primary roads and corresponding crash, roadway, and traffic data. A wide range of retroreflectivity levels were available for the analysis.

DATABASE PREPARATION

The data used in this research required a significant organizational effort prior to analysis, as described below.

Pavement Marking Retroreflectivity Data

Two separate pavement marking retroreflectivity databases were used in the analysis. The 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 2008. 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 five years. The duration of each period varied slightly each year due to staff scheduling and weather. The beginning and end dates of each white edge line retroreflectivity data collection period is shown in Table 2 below.

Table 2. Typical retroreflectivity data collection periods

		Period	
		Spring	**Fall**
2004	Begin	March 2	September 8
	End	May 3	November 23
2005	Begin	February 28	July 6
	End	June 29	November 28
2006	Begin	March 16	September 12
	End	May 9	December 5
2007	Begin	March 16	June 4
	End	May 9	November 26
2008	Begin	April 2	June 16
	End	May 28	November 27

The “paint” database contains the initial retroreflectivity measurements for roadway segments that were restriped (a single initial retroreflectivity value was assigned to the entire segment). For example, if the yellow center line of a section of roadway between mileposts 5 and 25 was restriped, the same initial retroreflectivity value was assigned to all of the mileposts from 5 to 25. The database also includes the date each restriping occurred.

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 retroreflectometer

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 2008 (each red square represents the average of 12 measurements).

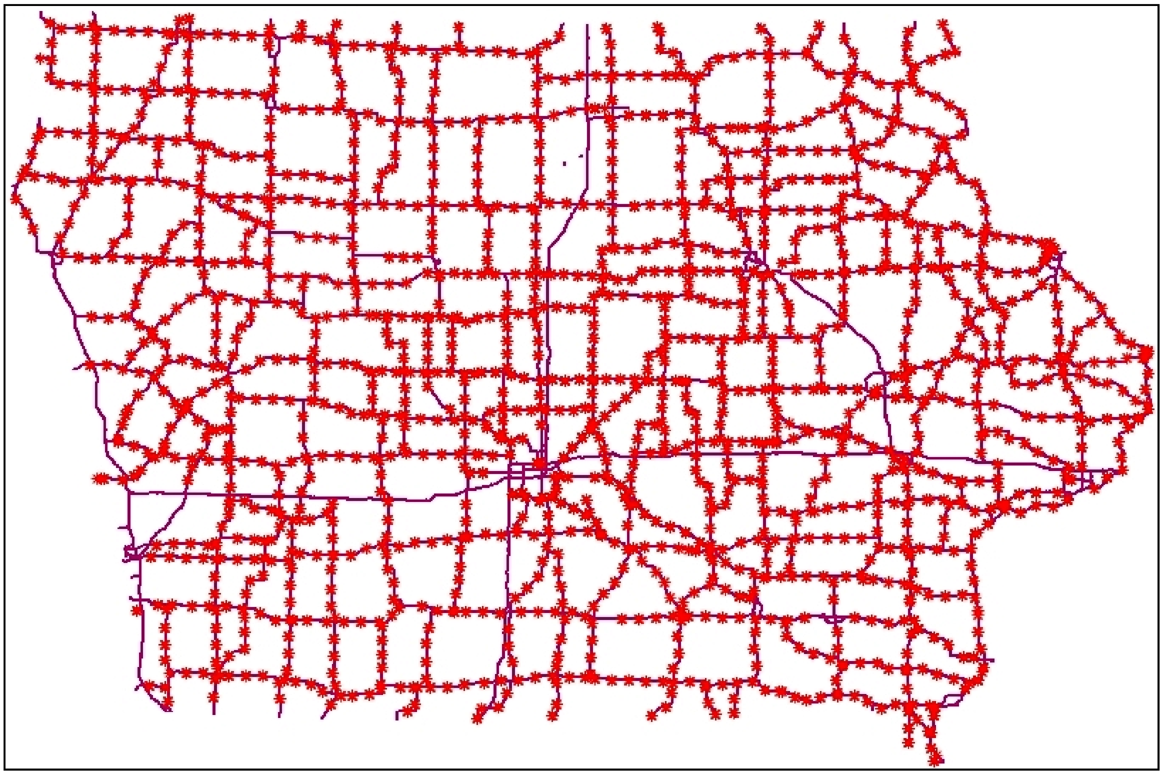

Figure 2. Spring/Fall retroreflectivity data collected by handheld retroreflectometer (LTL-X) in 2008

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

The Iowa DOT also collects pavement marking retroreflectivity data using a Laserlux van. The Laserlux van collects data every tenth of a mile and averages these readings every one mile. The Laserlux van is 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 (collection routes are represented by a bold red line).

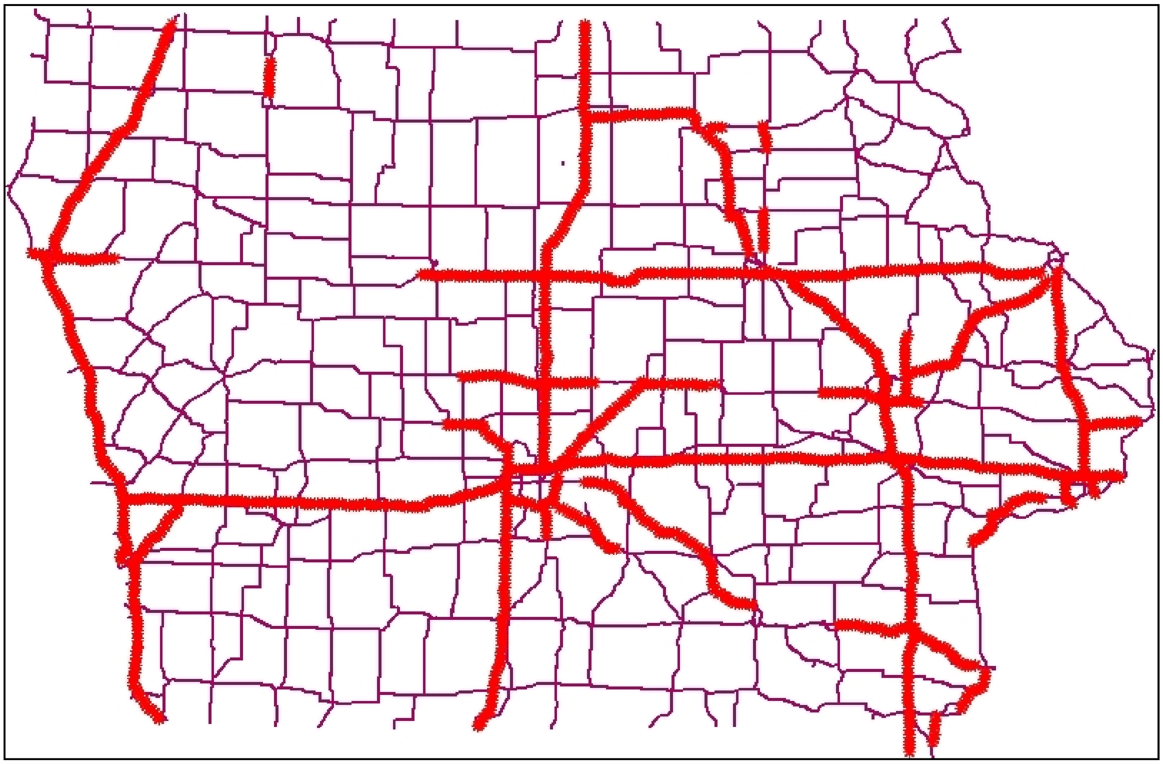

Figure 3. Spring/Fall retroreflectivity data collected by the Laserlux van in 2008

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 edge line, YCL = yellow center line, YEL = yellow edge line, WDC = white dashed center line, Direction 1 = northbound or eastbound, and Direction 2 = southbound or westbound.

Five-Mile to One-Mile Retroreflectivity Data Conversion

The retroreflectivity measurements taken by the retroreflectometer LTL-X were assumed to be representative of five-mile sections. Therefore, retroreflectivity values were copied for two mileposts in each direction of the milepost the retroreflectivity measurements were assigned to. The retroreflectivity assignment method is illustrated in Figure 4.

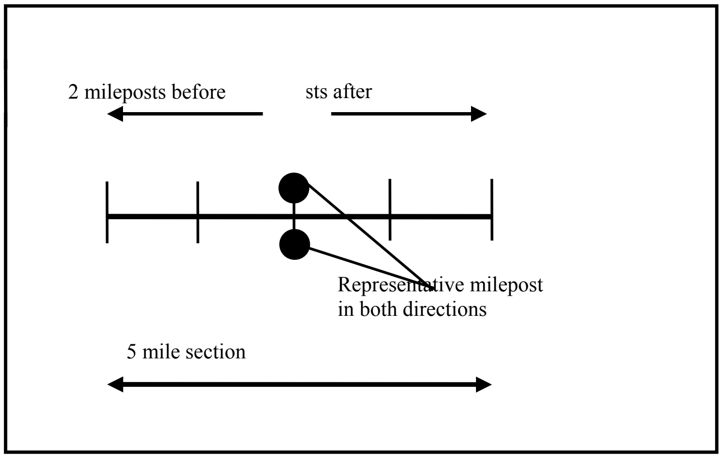

Figure 4. Retroreflectivity data assignment

Combining the Handheld and Laserlux Retroreflectivity Data

After converting the five-mile handheld data to cover one-mile sections of roadway, the retroreflectivity data collected by the Laserlux van was added. Since only white edge line, yellow center line, and yellow edge line records were needed, the white dashed center line retroreflectivity records were then removed.

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 nonwinter months. Two retroreflectivity time periods were determined for each year. If a pavement marking was restriped during the year (paint year), the first retroreflectivity time period is between April 1st and the date of restriping (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 segments during this time period.

If a pavement marking was not restriped 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.

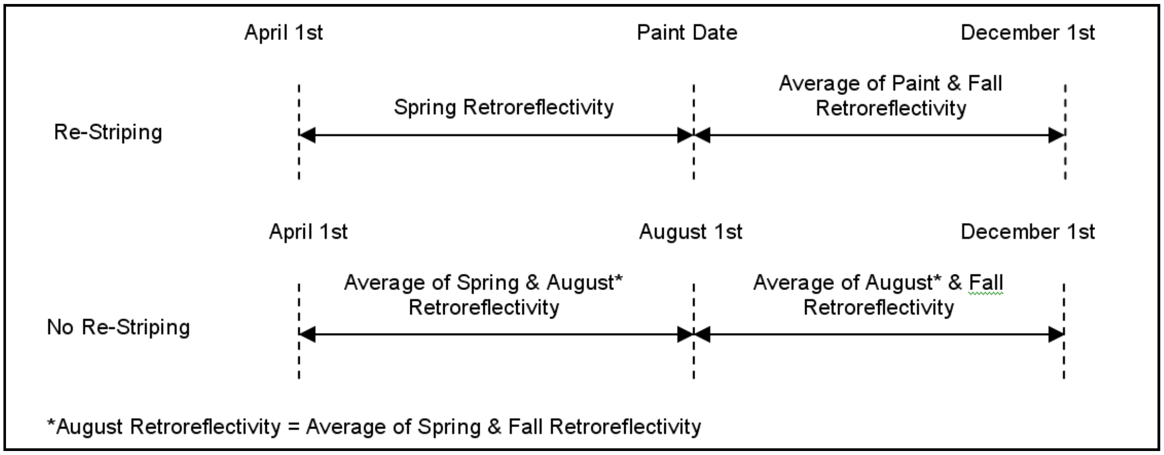

Figure 5. Retroreflectivity time periods and corresponding retroreflectivity

Target Crash Selection Procedure

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 nondaylight conditions were considered target crashes. Unlike other studies, the target crashes were limited to ROR or cross-center line crashes only. ArcGIS 9.3 (© 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 (December 1st to April 1st) were eliminated. This does create a potential for biased results because wintertime crashes are excluded, but retroreflectivity readings would be difficult to measure and unreliable.

Step 2: Light Conditions

Crashes occurring in daylight, lighted, or unknown lighting conditions were eliminated. Crashes identified during dawn, dusk, and dark conditions, with no roadway lighting, were selected as possible target crashes.

Step 3: Crash Characteristics

Potential target crashes were further filtered by crash characteristic. Lane departure crashes *not* caused by the following were included:

- An animal or object in the roadway
- A collision with another vehicle
- Avoiding a collision with another vehicle
- Equipment problems

Table 3 displays the two sets of crashes included in the selection. For the second set, at least one sequence of event characteristics needed to be an ROR in order to be selected.

Table 3. Target crash characteristics

1	**Major Cause**
	Crossed center line
	Run off road, right
	Run off road, straight
	Run off road, left
2	**Sequence of Events 1, 2, 3, or 4**
	Run off road, right
	Run off road, straight
	Run off road, left
	Cross center line/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
	Noncollision events: Overturn/rollover
	Noncollision events: Jackknife
	Noncollision events: Other noncollision
	Collision with: Parked motor vehicle

Step 4: Rural Locations

Since many state primary roads in urban areas have curbs, a lot of turning traffic, and other road characteristics that 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, and the crashes within any of these polygons were eliminated from the target crash selection.

Step 5: State Primary Roads

Retroreflectivity data were only measured on state primary roadways; therefore, any crash not occurring on these roadways was eliminated. The GIS database of crashes remaining was then spatially joined to each of two road 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 that 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 nonprimary roadway links were therefore selected as primary road crashes. Due to spatial accuracy limitations, this methodology may have resulted in some crashes that actually occurred on nonprimary roads near the intersection with a primary road being selected as 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.

Crash and 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 records was to identify 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. ArcGIS 9.3 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 ArcGIS 9.3, 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. Each record also contained route and milepost information.

Step 2: Assigning Unique Retroreflectivity Locations to the Crashes

Target crashes were assigned to the nearest unique retroreflectivity location by a spatial join in ArcGIS 9.3. 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.

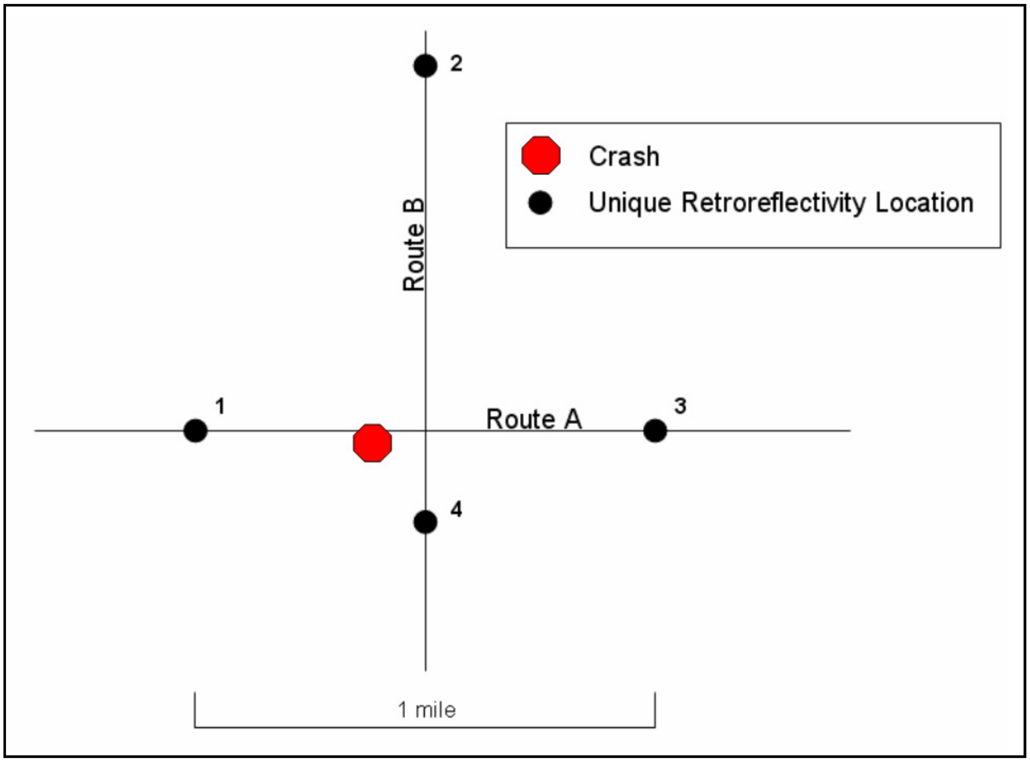

Figure 6. Example of crash assignment error

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 led to the identification of the crash as a target crash was also used to verify the correct route.

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

The related pavement marking type was determined by the target crash characteristics displayed in Table 3. Runs-off-the-road right and ROR straight crashes were assumed to potentially be white edge line related. Cross-center line and ROR left crashes were assumed to potentially be yellow center line or yellow edge line 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 edge line related. This was assumed because a vehicle that crossed the center line 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 types.

Table 4. Related pavement marking type by target crash characteristic

1	**Major Cause**	**Related Line Type**
	Crossed center line	YCL/YEL
	Run off road, right	WEL
	Run off road, straight	WEL
	Run off road, left	YCL/YEL
2	**Sequence of Events 1, 2, 3, or 4**	**Related Line Type**
	Run off road, right	WEL
	Run off road, straight	WEL
	Run off road, left	YCL/YEL
	Cross center line/median	YCL/YEL
	Collision with fixed object: Bridge/bridge rails/overpass	See Table 5
	Collision with fixed object: Underpass/structure support	See Table 5
	Collision with fixed object: Culvert	See Table 5
	Collision with fixed object: Ditch/embankment	See Table 5
	Collision with fixed object: Curb/island/raised median	See Table 5
	Collision with fixed object: Guardrail	See Table 5
	Collision with fixed object: Concrete barrier (median or right side)	See Table 5
	Collision with fixed object: Tree	See Table 5
	Collision with fixed object: Poles (utility, light, etc.)	See Table 5
	Collision with fixed object: Sign post	See Table 5
	Collision with fixed object: Mailbox	See Table 5
	Collision with fixed object: Impact attenuator	See Table 5
	Collision with fixed object: Other fixed object	See Table 5
	Noncollision events: Overturn/rollover	Depends on if at least one sequence of events can be attributed to an ROR-right or ROR-left
	Noncollision events: Jackknife	
	Noncollision events: Other noncollision	
	Collision with: Parked motor vehicle	

The assumption with the sequence of events was that they did not always happen in a sequential order. 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 edge line.

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 edge line- or yellow edge line-related crash, the corresponding pavement marking could account 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 ArcGIS 9.3. Multivehicle target crashes were also examined. This was required on an individual basis because multivehicle crashes could include vehicles traveling in opposite directions. For each multivehicle 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.

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 restriped. 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, route, milepost, line type, and direction combination. This allowed crash records to be compared to paint database records with the same combination. Then, the crashes that had the same combination that were located in areas of restriping were selected. This was done for every year, route, milepost, line type, and direction.

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, route, milepost, line type, and direction combination (as in Step 5). Then the paint data were spatially joined to the crash data. Each crash record was assigned the paint date of the nearest paint record based on the year, route, milepost, line type, and direction.

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**	
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	Other fixed object	Not Reported	Not Reported	WEL
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
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 center line	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

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 7 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 restriped. Time period 1 is from April 1st to the paint date, and time period 2 is from the paint date until December 1st. Time periods 3 and 4 occur when the pavement marking is not restriped. Time period 3 is from April 1st to August 1st, and time period 4 is from August 1st until December 1st.

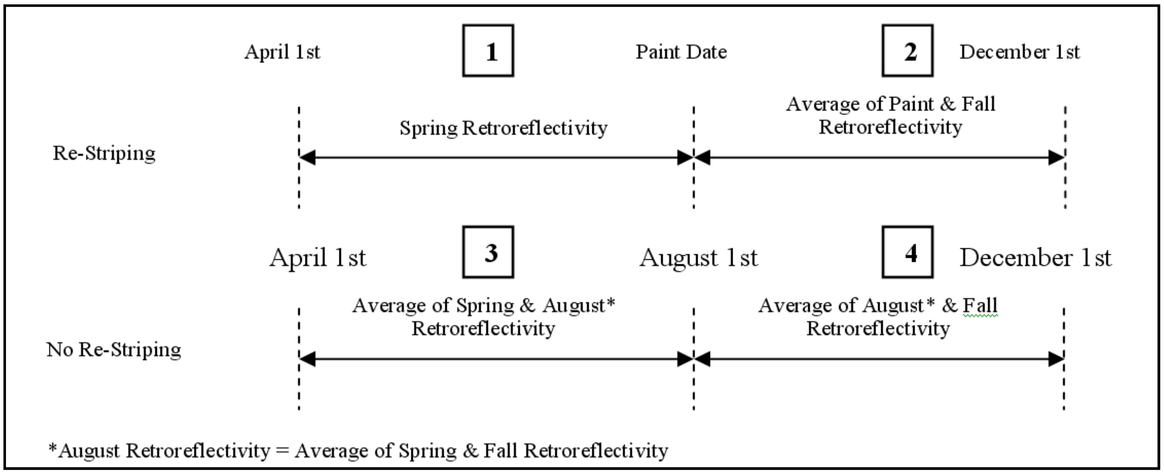

Figure 7. Numbered retroreflectivity time periods and corresponding retroreflectivity

Crashes occurring during a paint year were 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 when the related pavement marking was not restriped) 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 was assigned a retroreflectivity identifier. For the crash database, this identifier specifies (1) the year in which the crash occurred, (2) the route and nearest milepost where the crash occurred, (3) the pavement marking type potentially related to the crash, (4) the retroreflectivity time period encompassing the crash, and (5) the initial direction of travel of the vehicle that identified the collision as a target crash. For the retroreflectivity database, the retroreflectivity identification identifier specifies (1) the route and milepost where the retroreflectivity measurement was taken, (2) when the retroreflectivity measurement was taken, (3) the pavement marking type related to the retroreflectivity, (4) the time period the retroreflectivity values are representative of the roadway segment, and (5) the appropriate pavement marking associated with the direction of traffic. All of the information needed to select crashes based upon the characteristics of each retroreflectivity identifier was established in previous crash assignment steps. Retroreflectivity identifiers were assigned in ArcGIS 9.3 by concatenating the route, milepost, year, line type, direction, and time period.

Step 9: Identifying Paint Year Retroreflectivity Records

Similar to the target crashes in Step 5, the retroreflectivity measurements that were taken in a restriping year were identified. In ArcGIS 9.3, the retroreflectivity database was restricted to a single year, route, milepost, line type, and direction combination and joined to the paint database, which was restricted to the same combination. Finally, all of the records in the paint database were selected and subsequently all of the retroreflectivity records that had a paint record associated with it were selected.

The selected retroreflectivity records were then marked as paint year records (1 if paint record, 0 if not). This process was repeated for all combinations of year, route, milepost, line type, and direction.

Step 10: Eliminating Double and 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, for the sake of consistency, that of the double and multiple records the earliest record (by date) would be most appropriate for analysis and therefore all of the other records were removed.

Step 11: Assigning a Retroreflectivity Identifier to the Retroreflectivity Records

In order to assign crashes to the retroreflectivity records, the same retroreflectivity identifier 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 6 shows the resulting retroreflectivity time periods, which are also displayed in Figure 7.

Table 6. 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

Step 12: Assigning Paint Data to the Retroreflectivity Records

The paint data (paint date and paint retroreflectivity) were assigned to the retroreflectivity records. Records in both databases that had the same year, route, milepost, line type, direction of travel, and time period were joined together. At this stage, the irrelevant line type records (such as white dashed center line) were then removed as well. This reduced the combined database to line types of only white edge line, yellow center line, and yellow edge line.

Step 13: Assigning Spring/Fall Retroreflectivity Values to the Temporal Retroreflectivity Database

Following Step 10 the retroreflectivity database included records by year, route, milepost, 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 both needed in order to determine the representative retroreflectivity value of each time period. To accomplish this, another identification field was created. The new spring/fall identifiers were created from the retroreflectivity identifiers. The spring and fall records with the same year, route, milepost, line type, direction, and paint or no paint were given a single identification. Based on this, spring and fall retroreflectivity values were assigned to the corresponding retroreflectivity time periods.

Step 14: Assigning Representative Retroreflectivity Values for Each Retroreflectivity Time Period

As explained previously, there are four 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 13). 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 15: 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 was 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 16: Assigning the Target Crashes to the Temporal Retroreflectivity Database

Crashes were finally assigned to the retroreflectivity records in the same way that they were assigned to the paint data (Step 6), except in this case care was taken to ensure that each crash was assigned to the correct retroreflectivity time period. This was necessary to be able to estimate a representative retroreflectivity value at the time of the crash. Some crashes were eliminated because not all of the retroreflectivity locations were measured by line type and direction every year.

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 four reasons.

First, some of the paint retroreflectivity values for retroreflectivity-time-period 2 were empty. 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 14). To fix this problem, it was assumed that the fall retroreflectivity value alone 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. This resulted in only spring measurements being 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 on the general supposition that retroreflectivity levels do not change significantly in the nonwinter months.

Third, some of the retroreflectivity-time-period 4 records did not have a spring retroreflectivity value 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 6 displays the modifications made to resolve the empty retroreflectivity values.

Fourth, some of the retroreflectivity-time-period 1 and 2 records did not have a valid spring/fall retroreflectivity value. To resolve this, the representative retroreflectivity value was assumed to be the paint reading and was assigned to a time period 3 or 4, depending on whether the paint date was before August 1 or not. If the paint date was before August 1, it was assigned a time period 3, otherwise it was assigned a time period 4. In addition the time duration in Step 15 for time periods 3 and 4 was reduced to 61 days, again assuming the retroreflectivity levels do not change significantly in the nonwinter months. The reduction to 61 days from 122 days that Step 15 recommends occurs because the representative retroreflectivity value will be based on one reading instead of two readings.

Table 7. Modification made to records with empty retroreflectivity values

Retroreflectivity Time Period	Retroreflectivity Values Not Present	Modified Representative Retroreflectivity Value
2	Paint	Fall
3	Fall	Spring
4	Spring	Fall
1 or 2	Fall and Spring	Paint

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/lx were either measured or entered into the database incorrectly. Other records had a retroreflectivity value of 0 mcd/m^2/lx. 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 as shown in Table 7.

The representative retroreflectivity values for time periods 2, 3, and 4 are calculated using two retroreflectivity values, 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 with which to modify the representative retroreflectivity assignment. 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 seven-step process. Table 8 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.

Table 8. Summary of process removing records with invalid retroreflectivity values

		Invalid Retroreflectivity Value		
Step	**Retroreflectivity Time Period**	**Spring**	**Fall**	**Paint**
1	1	> 600	---	---
2	3 and 4	> 600	empty	---
3	2*, 3**, and 4**	empty**	> 600	empty*
4	1	0	---	---
5	2	---	0	0
6	3	0	0	---
7	4	0	0	---

After removing some of the invalid records, the records that could be modified were done so in a six-step process. Table 9 summarizes the modification process, which 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 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 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.

Table 9. Summary of process modifying records with invalid retroreflectivity values

Step	Retroreflectivity Time Period	Invalid Retroreflectivity		
		Spring	Fall	Paint
1	3 and 4	> 600	---	---
2	2	---	> 600	---
3	3 and 4	---	> 600	
4	2	---	---	0
5	3 and 4	0	---	---
6	3 and 4	---	0	---

Durations of Zero or Less Than Zero

Records with a time period duration of zero or less were also sometimes an issue. This occurred either because the paint date was before April 1st or 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.

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 that were based on access control, median type, and the number of lanes. The four road types were freeway, multilane divided, multilane 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.

Roadway characteristics were used to assign a road type in the following order. First, the remaining records 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 two lanes were assigned to the road type “TWO-LANE.” Third, the remaining records with more than two lanes and a median width equal to zero were assigned the road type “MULTILANE UNDIVIDED.” Fourth, the remaining records with more than two lanes and median width greater than zero were assigned the road type “MULTILANE DIVIDED.” Fifth, the remaining records were all labeled as having one lane. A visual inspection of these records showed that the assigned segments were interchange ramps. In order to assign the mainline roadway characteristics to the time period retroreflectivity records, the ramp segments needed to be 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 two lanes and “MULTILANE DIVIDED” for records with more than two 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 nonrural records, as target crashes were limited to rural crashes only. All of the records that had corresponding milepost coordinates that were within a polygon representing a city of 2,000 or more were eliminated in ArcGIS 9.3.

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 (annual average daily traffic) 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 one-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.

Database Error

Records with Incongruent Spring/Fall and Paint Data

The sections of roadway with incongruent spring/fall and paint data are erroneous. The spring/fall measurements were collected every five miles and assigned to the roadway within two-and-a-half miles in both directions. When a roadway was restriped, sometimes the restriping ended in the middle of one of the five-mile spring/fall sections, causing the retroreflectivity assigned to be invalid. Figure 8 illustrates the problem.

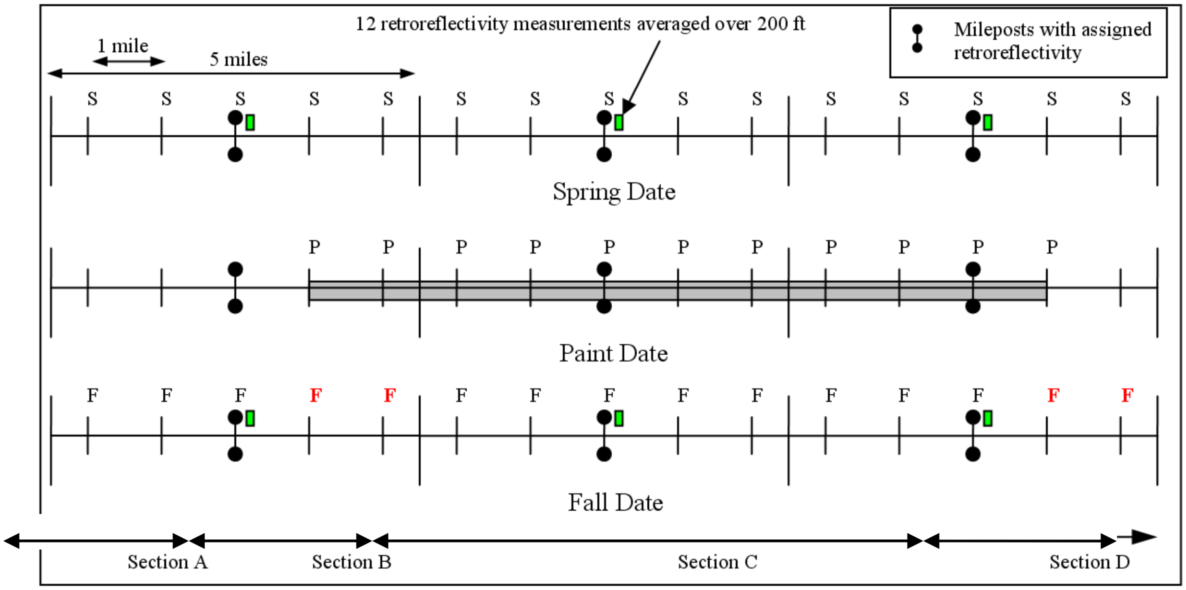

Figure 8. Illustration of incongruent sections

For Sections A and C in the figure, all of the one-mile segments are either restriped or not restriped 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 one-mile segments are either restriped or not restriped 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 afterward.

Eliminating this error would be difficult and time intensive.

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 that occurred during wet conditions were eliminated. Only crashes occurring in dry conditions were used.

ANALYSIS

General Statistics on the Data Set

The data set covers retroreflectivity records for each available milepost from 2004 to 2008 and selected crash records matched with representative retroreflectivity records. The matching crash records are minor in number of observations when compared with records with no crash observations. Of 83,539 records; only 1,343 records are in the data set, which is approximately 1.61% of all records. There are four road types in the data set: interstate, multilane divided, multilane undivided, and two-lane roads (Table 10). More than 68% of the data set comes from two-lane roads, 13.3% comes from interstate roads, 14.61% comes from multilane divided roads, and only 3.22% comes from multilane undivided roads. The distribution of the data per road type for different years is quite similar as can be seen in Figure 9.

Table 10. Number of records by road type

Year	Interstate	Multilane Divided
2004	787	1,447
2005	2,616	2,368
2006	2,625	1,580
2007	2,541	3,398
2008	2,541	3,416
Total	(13.30%)	(14.61%)
	11,110	12,209

Figure 10 shows the number of crashes by road type and year. The ratio of records with targeted crashes to all observations is highest for interstate roads, second highest for multilane undivided roads, and lowest for two-lane roads (Table 11). Figure 11 shows the number of crash records to all records by road type.

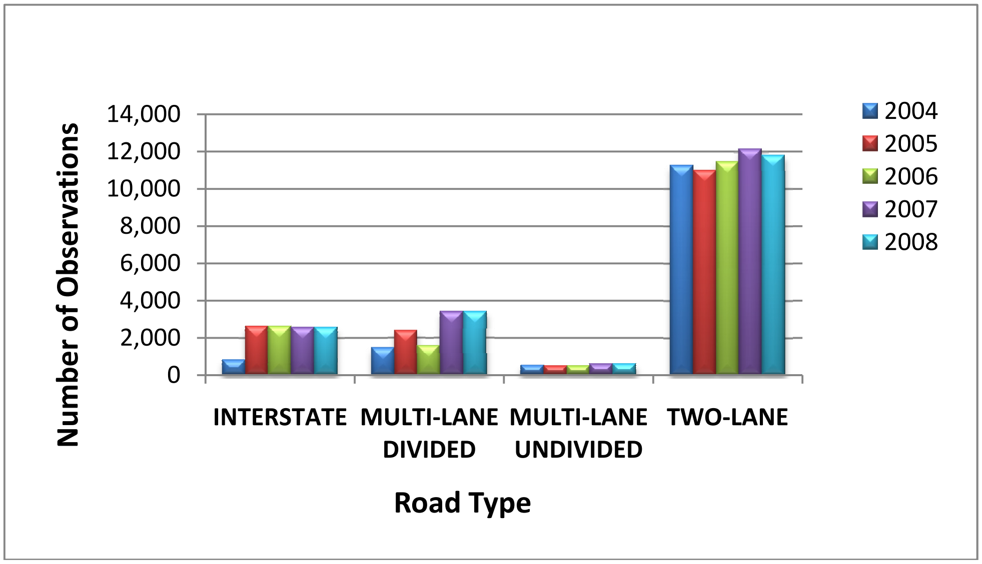

Figure 9. Observations by road type

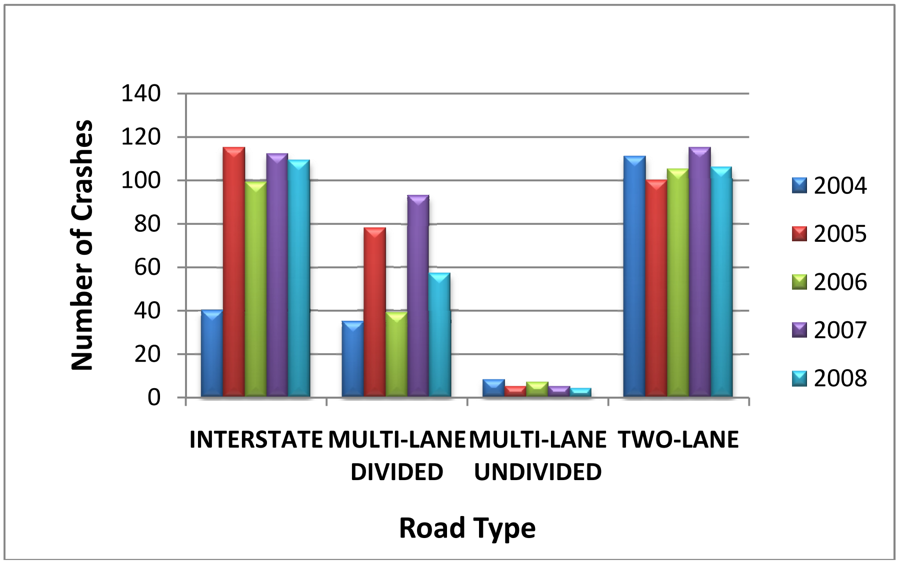

Figure 10. Crash records by road type

Table 11. Number of crashes and ratios of crash records to all observations by road type

Road Type	# Observations	# Crashes	Ratio
Interstate	11,110	475	4.28%
Multilane divided	12,209	302	2.47%
Multilane undivided	2,692	29	1.08%
Two-lane	57,528	537	0.93%

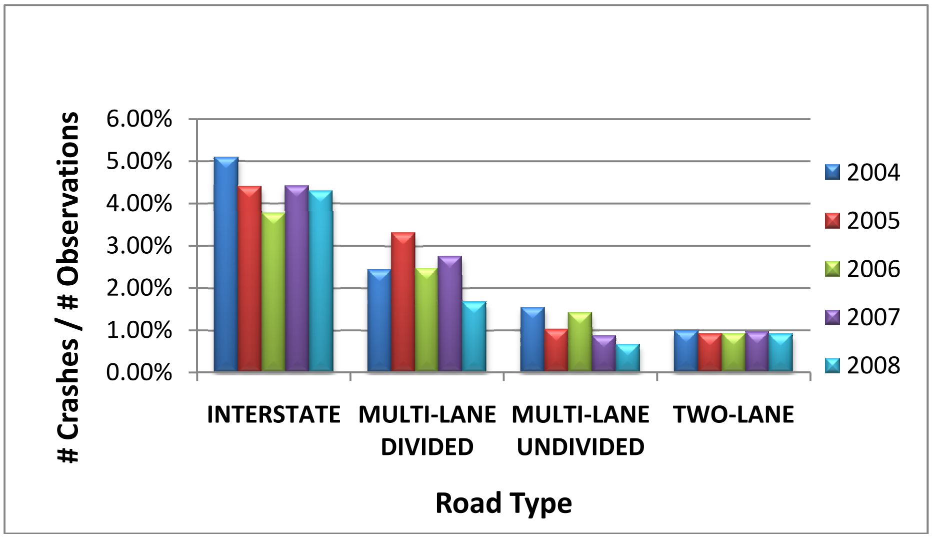

Figure 11. Crash records to all records ratio by road type

The representative retroreflectivity records in the data set come from three line types, which are white edge line (wel), yellow edge line (yel), and yellow center line (ycl). Interstate and multilane roads do not have yellow center lines but have yellow edge lines, while multilane undivided and two-lane roads have yellow center lines. Table 12 gives a summary of the number of records per road type and by line type. White edge lines, which are common for all types of roads, constitute almost half of the data records, while 14.34% of the data comes from yellow edge lines and the remaining 36% comes from yellow center lines. Figure 12 shows the distribution of the data by line type and over the years. Although there are discrepancies in the number of observations from year to year, the overall trend is consistent. Looking at the subset of data with matching crash records (Figure 13), it can be seen that although yellow edge lines have the least overall observations they have higher number of crash records versus yellow center lines.

Figure 14 emphasizes the higher number of crash observations with respect to records with no crashes for yellow edge lines. In this histogram, no crash records are plotted next to the ratio of crash records to no-crash records. This ratio is multiplied by 100,000 to increase the scale and in order to visually compare the ratio for three different line types.

Table 12. Records by line and road type

	Interstate	Multilane Divided	Multilane Undivided	Two-lane	Percentage
WEL	5,619	5,717	1,329	28,837	49.68%
YEL	5,491	6,492			14.34%
YCL			1,363	28,691	35.98%

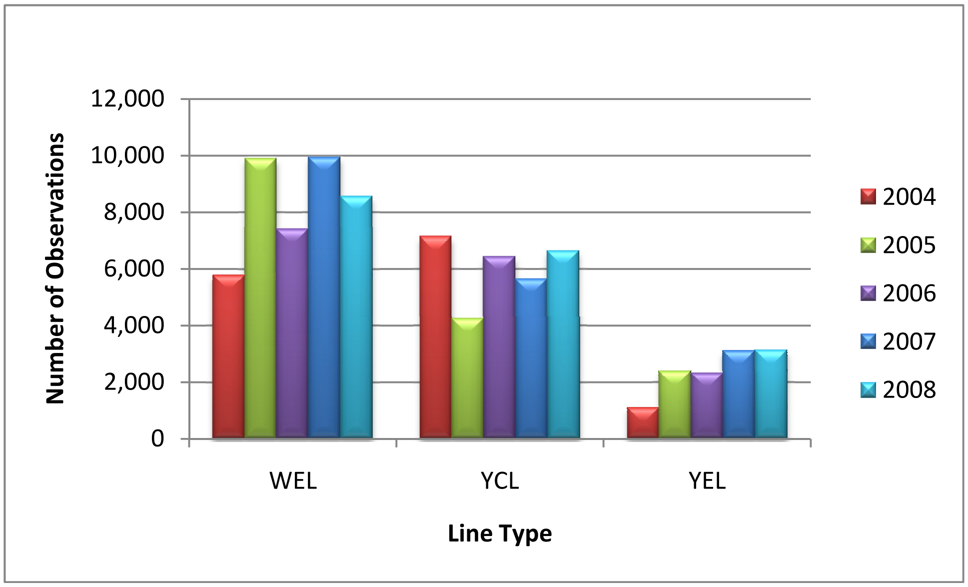

Figure 12. Observations by line type

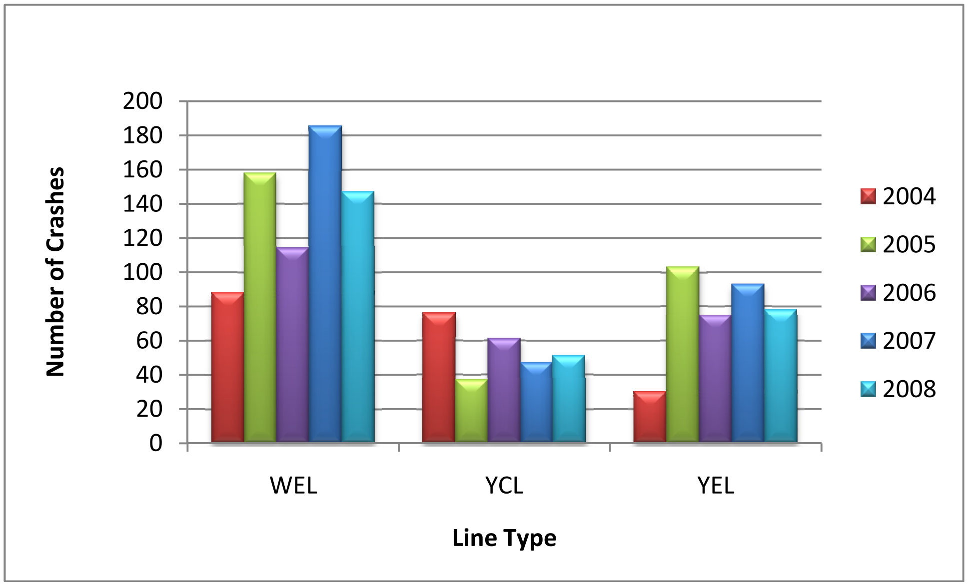

Figure 13. Crashes by line type

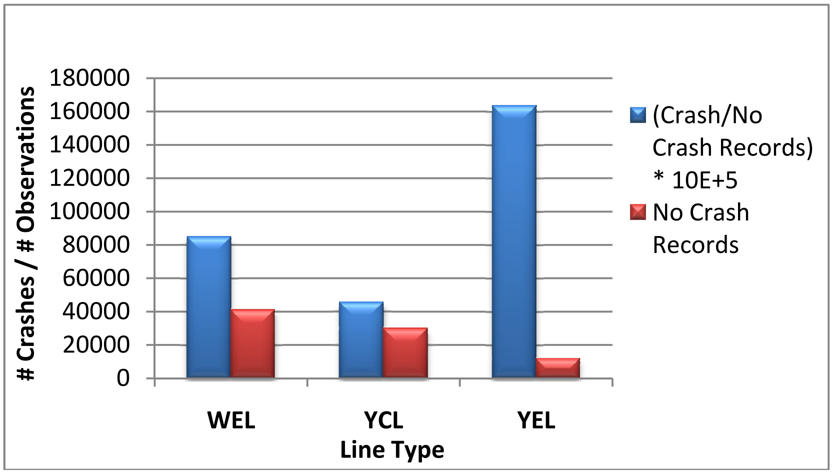

Figure 14. Crash to overall observations ratio by line type

Figures 9–14 show the frequencies by line and road types and help understand the general dimensions of the data. Figures 15–20, which follow, are a series of box plots that give information on the dispersion of the data subsets for other attributes of the data such as retroreflectivity values (represented with RR) and vehicle miles traveled (represented by VMT).

Figure 15 and Figure 16 show the dispersion of VMT and RR for the crash and no-crash records[1]. For crash records, the VMT records are more dispersed with a higher mean (almost five times at 1,392,274) than no-crash records (284,210) (Figure 15). The box plots for RR are more similar for crash and no-crash records with closer mean values (Figure 16); the mean retroreflectivity value for crash records is 174.1 mcd/m^2/lx and 161.44 mcd/m^2/lx for no-crash records. Figure 17 and Figure 18 are similar box plots but plotted separately for each year. The higher mean and more dispersed VMT values behavior for crash records is consistent for each year as in Figure 17 however, the behavior of retroreflectivity values is slightly different from year to year. The dispersions are slightly different but overall very close, and the mean values also change in a small interval of 110–175 1 mcd/m^2/lx.

Figures 19 and 20 are again for crash and no-crash data subsets but also plotted for each road type separately to see the variation of retroreflectivity values and VMT within road type. In Figure 19, it can be seen that the dispersion of the VMT values for each road type is expectedly very similar within road type for crash and no-crash records and no-crash records have slightly higher mean VMT values. The dispersion of retroreflectivity values is pretty similar across all road types with similar mean values for both crash and no-crash records (Figure 20). The mean retroreflectivity value for interstate and multilane undivided roads is slightly higher for crash records, while it is slightly lower for two-lane and multilane divided roads.

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[1] Crash records refer to the pavement marking retroreflectivity values (by year, location, direction, and line type) with observed crashes in the same period and at the same location. No-crash records are the observations with no crashes.

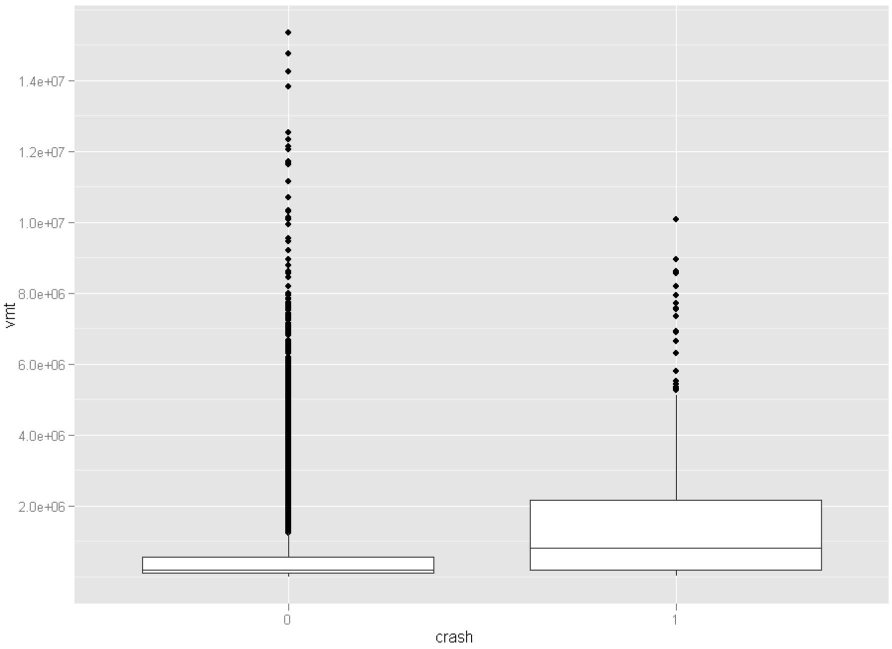

Figure 15. Box plots for VMT for crash and no-crash records

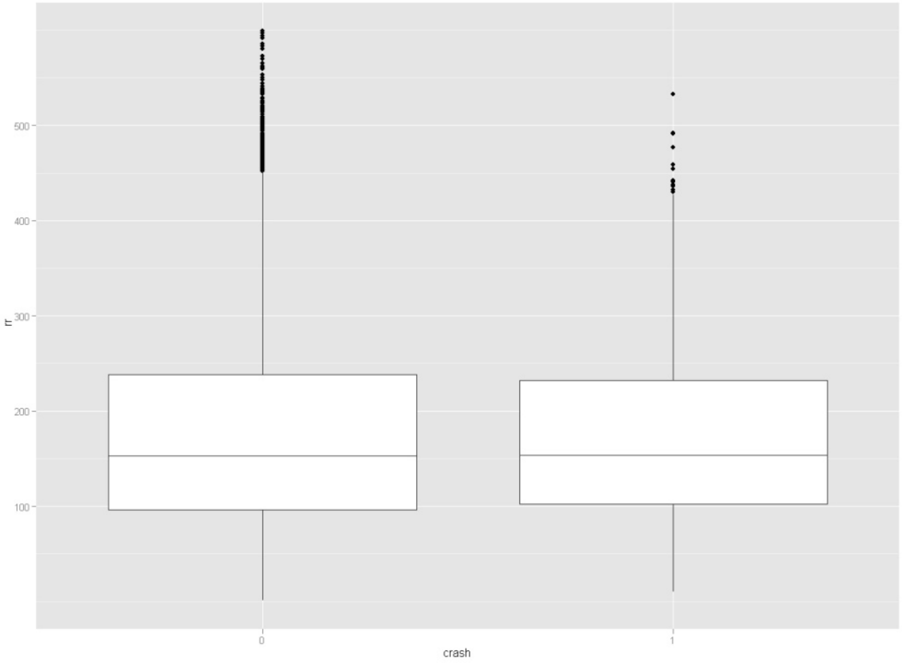

Figure 16. Box plots for retroreflectivity values for crash and no-crash records

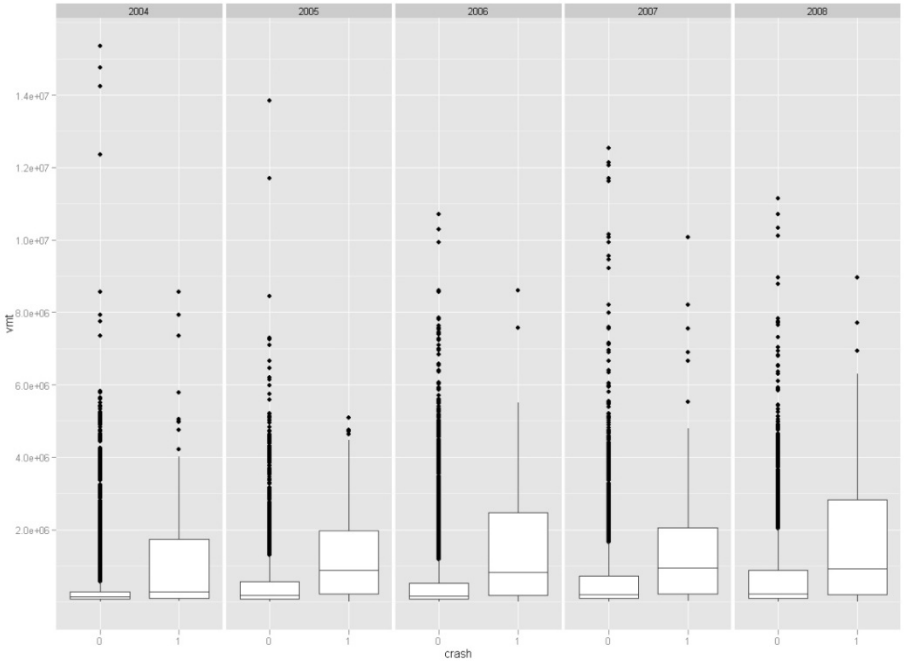

Figure 17. Box plots for VMT for crash and no-crash records by year

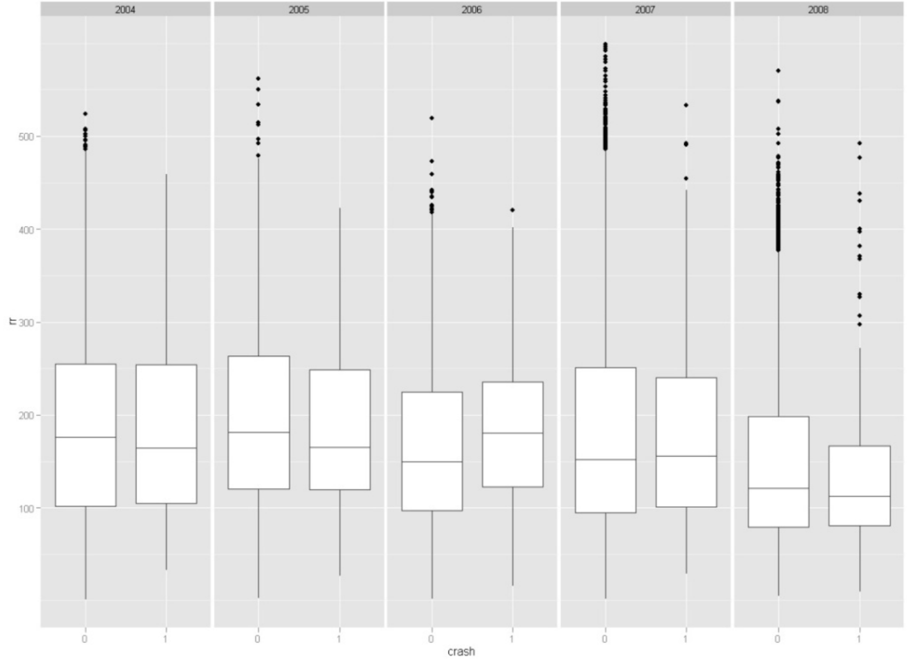

Figure 18. Box plots for RR for crash and no-crash records by year

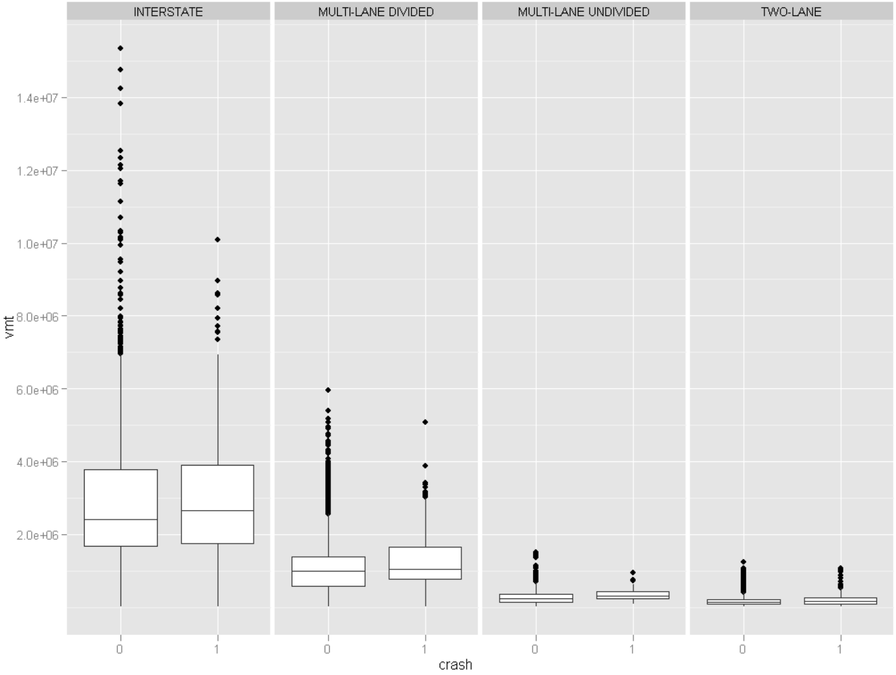

Figure 19. Box plots for VMT for crash and no-crash records by road type

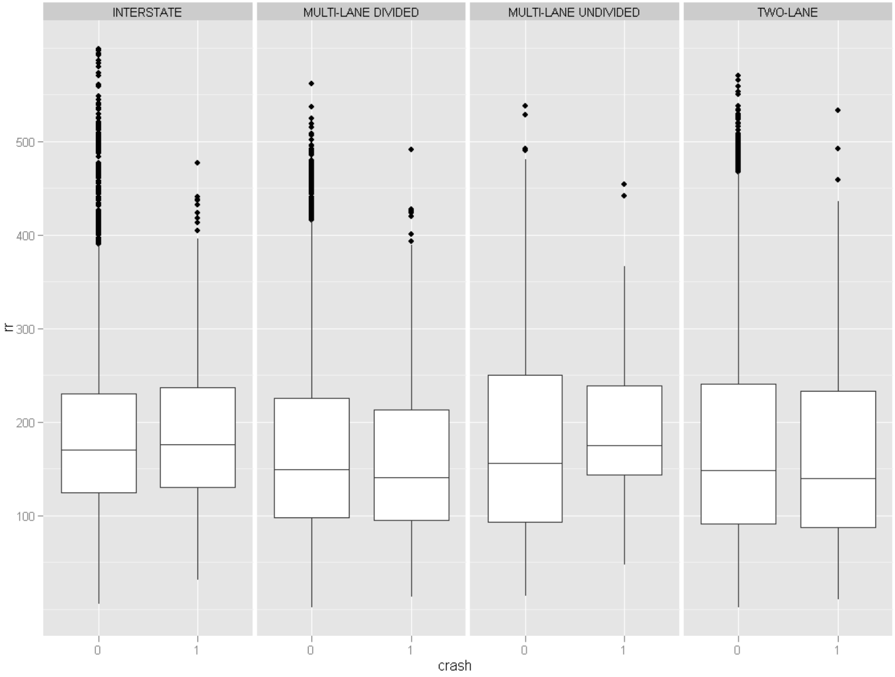

Figure 20. Box plots for RR for crash and no-crash records by road type

Logistic Regression

For the statistical analysis, logistic regression analyses were modeled in SAS 9.2 Software. Logistic regression is a generalized linear model for binomial regression and is used for prediction of the probability of occurrence of an event (in our case, crash occurrence) by fitting data to a logit function logistic curve. Analyses were run for different subsets of the data. In these analyses logistic regression model estimates the logit, which is the log of the crash probability. General model variables used in the analyses are as follows:

> Crash: Binomial response variable (0 for no-crash and 1 for crash)
> Road type: Discrete categorical variable with four levels (interstate, multilane divided, multilane undivided, and two-lane)
> Line type: Discrete categorical variable with three levels ("wel" for white edge line, "yel" for yellow edge line, and "ycl" for yellow center line)
> RR: Continuous numeric variable, representative retroreflectivity value
> VMT: Continuous numeric variable, vehicle miles traveled (traffic on the mile segment)

The general logistic regression equation used in the analysis is given below:

Equation 3**.** Logistic regression equation

$$\log it[p(crash)] = \ln(\frac{p(crash)}{1-p(crash)}) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots\dots\dots\dots + \beta_n x_n$$

Where:

β_0 =Intercept

β_i = Parameter estimate for parameter *i*

x_i = Parameter (e.g., road type, VMT, or RR)

For all analyses, VMT was divided by 1,000 due to the larger scale of this variable when compared with other variables. Results of individual analyses with parameter estimates are given in the following sections. The ratio (p[crash])/(1-p[crash]) is referred to as the odds ratio. The GENMOD procedure in SAS was used for the logistic regression analyses, and route values were assigned as subject effects to address the autocorrelation from the retroreflectivity values within each route. Responses within a subject (in our case, route) are assumed to be correlated when subject effects are defined in the GENMOD procedure and generalized estimating equations (GEE) modeling were used for the analysis. Autocorrelation plots (e.g., Figure 21) for a number of routes confirmed that retroreflectivity values along a route are autocorrelated, which justifies the modeling approach.

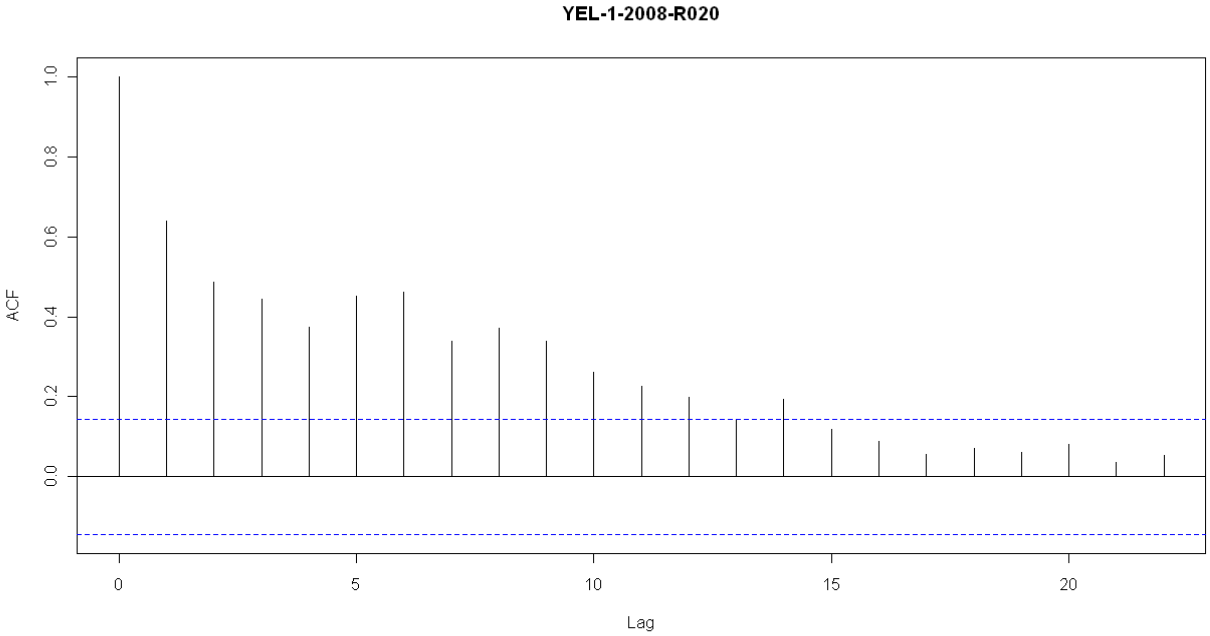

Figure 21. Autocorrelation plot for Route 20 yellow edge line

Logistic Regression for the Whole Data Set

The whole data set (83,539 records for each mile, direction, line type, and year combination) was modeled and Table 13 shows the logistic regression parameter estimates, confidence intervals for these estimates, and Z-scores for the parameters. Neither retroreflectivity nor VMT is significant with high p-values; only road type interstate and multilane divided are significant with p-values lower than 0.05 at 95% confidence level.

Table 13. Parameter estimates from LR for the whole data set

Analysis of GEE Parameter Estimates

Empirical Standard Error Estimates

Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.7013	0.1040	-	-	-	<.0001
				4.9051	4.4974	45.20	
Road type	Interstate	1.3354	0.1846	0.9735	1.6972	7.23	<.0001
Road type	Multilane Divided	0.9196	0.1350	0.6550	1.1841	6.81	<.0001
Road type	Multilane Undivided	0.1384	0.2197	-	0.5689	0.63	0.5286
				0.2921			
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	0.0929	0.0800	-	0.2497	1.16	0.2458
				0.0640			
Line type	ycl	0.0124	0.1024	-	0.2131	0.12	0.9034
				0.1883			
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0002	0.0004	-	0.0005	-0.49	0.6217
				0.0009			
VMT		0.0001	0.0001	-	0.0002	1.36	0.1752
				0.0000			

Logistic Regression by Road Type

A second set of logistic regression analyses data from four different road types was modeled separately. Table 14 gives the parameter estimates from the logistic regression analysis for the interstate observations only for 11,110 total observations and 475 crashes. In this analysis, retroreflectivity is significant at 90% confidence level with a p-value of 0.0989 and it is the only significant factor. The positive parameter estimate for retroreflectivity indicates that the odds ratio increases if the retroreflectivity increases; however, this increase is very small as the parameter estimate is 0.001. Table 15 summarizes the parameter estimates for two-lane roads. Fifty-seven thousand five hundred and twenty-eight observations with 537 crashes were used in this analysis, and only VMT was a significant parameter. The positive parameter estimate indicates increasing an odds ratio by increasing traffic. Logistic regression parameter estimates for multilane undivided roads only are given in Table 16. Observations from multilane undivided roads constitute only 3.22% of the data set with 2,692 observations and 29 crashes. For the two-lane roads the only significant parameter is VMT and again the odds ratio increases by increasing traffic.

Table 14. Parameter estimates for interstate roads only

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-3.4163	0.2227	-3.8527	-2.9799	-15.34	<.0001
Line type	wel	-0.0501	0.0992	-0.2446	0.1444	-0.51	0.6135
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		0.0010	0.0006	-0.0002	0.0021	1.65	0.0989
VMT		0.0001	0.0001	-0.0001	0.0002	0.98	0.3289

Table 15. Parameter estimates for two-lane roads only

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.9874	0.1091	-5.2014	-4.7735	-45.70	<.0001
Line type	wel	0.0506	0.0810	-0.1082	0.2094	0.62	0.5321
Line type	ycl	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0005	0.0004	-0.0014	0.0003	-1.23	0.2185
VMT		0.0022	0.0003	0.0016	0.0027	7.89	<.0001

Table 16. Parameter estimates for multilane undivided roads only

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-5.4392	0.5066	-6.4321	-4.4463	-10.74	<.0001
Line type	wel	-0.1912	0.3576	-0.8919	0.5096	-0.53	0.5929
Line type	ycl	0.0000	0.0000	0.0000	0.0000	.	.
RR		0.0019	0.0020	-0.0020	0.0058	0.96	0.3352
VMT		0.0022	0.0006	0.0011	0.0032	3.85	0.0001

Estimated logistic regression parameters for multilane divided roads are given in Table 17. Once again VMT is significant, while retroreflectivity is not. Line type is another significant parameter for multilane divided roads. The higher positive parameter estimate for the white edge line indicates a higher odds ratio estimate for white edge lines for this type of road.

Table 17. Parameter estimates for multilane divided roads only

Analysis of GEE Parameter Estimates Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.0030	0.2389	-4.4713	-3.5347	-16.75	<.0001
Line type	wel	0.2783	0.0949	0.0923	0.4643	2.93	0.0034
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0008	0.0007	-0.0021	0.0006	-1.09	0.2776
VMT		0.0003	0.0001	0.0001	0.0004	3.89	<.0001

Logistic Regression by Retroreflectivity Measurement Source

The retroreflectivity measurements in the data set were taken by two different devices—a handheld retroreflectometer and a Laserlux van. The retroreflectivity values from the handheld retroreflectometer were scarce with respect to the available measurements from the Laserlux van for the same length of road segments. Therefore, the autocorrelation of retroreflectivity values by measurement source was different. To address this difference, two separate logistic regression analyses for 63,142 (649 crashes) observations from handheld retroreflectometer and 20,397 (694 crashes) observations from the Laserlux van were done. While road type and VMT were significant parameters for the data subset from handheld retroreflectometer measurements (Table 18), only road type was significant for the data subset from Laserlux van measurements (Table 19).

Table 18. Parameter estimates for handheld retroreflectometer measurements only

Analysis of GEE Parameter Estimates Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.9732	0.2722	-5.5066	-4.4398	-18.27	<.0001
Road type	Interstate	1.3763	0.1914	1.0012	1.7514	7.19	<.0001
Road type	Multilane Divided	0.8912	0.2340	0.4325	1.3498	3.81	0.0001
Road type	Multilane Undivided	0.1362	0.2199	-0.2947	0.5672	0.62	0.5356
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	0.4083	0.2519	-0.0854	0.9020	1.62	0.1050
Line type	ycl	0.3186	0.2589	-0.1888	0.8261	1.23	0.2185
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0005	0.0004	-0.0012	0.0003	-1.12	0.2641
VMT		0.0001	0.0001	-0.0000	0.0003	1.74	0.0819

Table 19. Parameter estimates for Laserlux van measurements only

Analysis of GEE Parameter Estimates Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-3.7530	0.1586	-4.0639	-3.4421	-23.66	<.0001
Road type	Interstate	0.3957	0.1515	0.0988	0.6926	2.61	0.0090
Road type	Multilane Divided	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	0.0365	0.0721	-0.1049	0.1779	0.51	0.6128
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		0.0001	0.0006	-0.0010	0.0012	0.22	0.8234
VMT		0.0001	0.0001	-0.0000	0.0002	1.26	0.2078

Logistic Regression for High Crash Routes

Since retroreflectivity measurements from every available milepost and for each line type and direction were included in the data set; the number of observations with matched crashes in the whole data set is quite small. Only 1,346 crashes were matched with the data set, which constitutes roughly 1.6% of the total observations. Since the occurrence of the event is low, it is hard to see the effect of other variables to event occurrence in a logistic regression. Table 20 shows the logistic regression analyses for only routes with a high crash to total number of observations ratio. The data from high crash routes is approximately 14% (11,927 observations) of the whole data set. The data from these routes were grouped by year, and five logistic regression analyses were completed for each year cluster. The information about these subsets is given in Table 21. In the high crash data subset there was only one milepost from multilane undivided roads, so this data was eliminated from the data set to have reasonable parameter estimates for the other road types.

Table 20. High crash routes

Route	Observations per Route	Crashes per Route	Ratio # Crashes/ # Observations
35	3187	152	4.77%
80	4387	195	4.44%
29	2415	97	4.02%
380	812	29	3.57%
316	57	2	3.51%
67	230	8	3.48%
163	858	26	3.03%

Table 21. Number of crashes and total observations by year for high crash data

Year	# Crashes	# Observations
2008	115	2709
2007	116	2740
2006	107	2756
2005	123	2740
2004	47	982

Parameter estimates for high crash data sets of each year are given in tables below (Tables 22–26). For three of the five data subsets, retroreflectivity is significant in the logistic regression. For years 2008 and 2006, retroreflectivity values are significant at 95% confidence level, and for 2004 it is significant at 90% confidence level. Also, parameter estimates for these three data subsets are positive, which indicates an increasing odds ratio by increasing retroreflectivity values when other variables are held constant.

Table 22. Parameter estimates for high crash routes, 2008

Analysis of Maximum Likelihood Parameter Estimates (High Crash, 2008)								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	-4.5024	1.1199	-6.6974	-2.3075	16.16	<.0001
Road type	Interstate	1	0.5106	1.0595	-1.5660	2.5872	0.23	0.6298
Road type	Multilane Divided	1	0.2085	1.1351	-2.0162	2.4333	0.03	0.8542
Road type	Two-lane	0	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	1	0.3025	0.1952	-0.0802	0.6851	2.40	0.1213
Line type	ycl	1	0.3713	1.4566	-2.4836	3.2261	0.06	0.7988
Line type	yel	0	0.0000	0.0000	0.0000	0.0000	.	.
RR		1	0.0033	0.0014	0.0004	0.0061	5.11	0.0238
VMT		1	0.0001	0.0001	-0.0000	0.0002	2.22	0.1364
Scale		0	1.0000	0.0000	1.0000	1.0000		

Table 23. Parameter estimates for high crash routes, 2007

Analysis of Maximum Likelihood Parameter Estimates (High Crash, 2007)								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	-25.4148	0.5799	-26.5513	-24.2783	1921.02	<.0001
Road type	Interstate	1	22.1539	0.5198	21.1351	23.1727	1816.42	<.0001
Road type	Multilane Divided	0	21.3834	0.0000	21.3834	21.3834	.	.
Road type	Two-lane	0	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	1	0.0422	0.1910	-0.3321	0.4165	0.05	0.8251
Line type	ycl	1	0.0465	55241.75	-108272	108271.9	0.00	1.0000
Line type	yel	0	0.0000	0.0000	0.0000	0.0000	.	.
RR		1	-0.0000	0.0009	-0.0019	0.0018	0.00	0.9587
VMT		1	0.0001	0.0001	-0.0000	0.0002	2.14	0.1438
Scale		0	1.0000	0.0000	1.0000	1.0000		

Table 24. Parameter estimates for high crash routes, 2006

Analysis of Maximum Likelihood Parameter Estimates (High Crash, 2006)								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > Chi Sq**
Intercept		1	-25.7525	0.4663	-26.6664	-24.8386	3050.41	<.0001
Road type	Interstate	1	22.0986	0.3774	21.3590	22.8382	3429.27	<.0001
Road type	Multilane Divided	0	22.5975	0.0000	22.5975	22.5975	.	.
Road type	Two-lane	0	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	1	-0.3686	0.2287	-0.8169	0.0796	2.60	0.1070
Line type	ycl	1	-0.3195	60752.02	-119072	119071.5	0.00	1.0000
Line type	yel	0	0.0000	0.0000	0.0000	0.0000	.	.
RR		1	0.0038	0.0019	0.0001	0.0074	3.97	0.0462
VMT		1	-0.0000	0.0001	-0.0002	0.0001	0.41	0.5199
Scale		0	1.0000	0.0000	1.0000	1.0000		

Table 25. Parameter estimates for high crash routes, 2005

Analysis of Maximum Likelihood Parameter Estimates (High Crash, 2005)								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	-2.2460	1.0813	-4.3653	-0.1268	4.31	0.0378
Road type	Interstate	1	-0.7169	1.0583	-2.7911	1.3574	0.46	0.4982
Road type	Multilane Divided	1	-1.6174	1.1983	-3.9660	0.7312	1.82	0.1771
Road type	Two-lane	0	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	1	-0.2471	0.1960	-0.6312	0.1370	1.59	0.2073
Line type	ycl	1	0.2994	1.1825	-2.0181	2.6170	0.06	0.8001
Line type	yel	0	0.0000	0.0000	0.0000	0.0000	.	.
RR		1	-0.0004	0.0012	-0.0028	0.0021	0.09	0.7675
VMT		1	0.0000	0.0001	-0.0001	0.0002	0.35	0.5536
Scale		0	1.0000	0.0000	1.0000	1.0000		

Table 26. Parameter estimates for high crash routes, 2004

Analysis of Maximum Likelihood Parameter Estimates (High Crash, 2004)								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > Chi Sq**
Intercept		1	-26.3725	0.8602	-28.0584	-24.6865	939.98	<.0001
Road type	Interstate	1	22.5480	0.8088	20.9628	24.1332	777.24	<.0001
Road type	Multilane Divided	1	21.9657	0.8906	20.2201	23.7113	608.27	<.0001
Road type	Two-lane	0	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	1	0.0038	0.3253	-0.6337	0.6413	0.00	0.9907
Line type	ycl	0	22.7577	0.0000	22.7577	22.7577	.	.
Line type	yel	0	0.0000	0.0000	0.0000	0.0000	.	.
RR		1	0.0034	0.0020	-0.0004	0.0073	3.02	0.0820
VMT		1	0.0000	0.0001	-0.0001	0.0002	0.48	0.4894
Scale		0	1.0000	0.0000	1.0000	1.0000		

Logistic Regression by Retroreflectivity Range

A separate set of logistic regression analyses was done according to the range of retroreflectivity values. Three data subsets were formed as “low retroreflectivity,” where retroreflectivity values are equal to and smaller than 200 mcd/m^2/lx; “high retroreflectivity,” where retroreflectivity values are greater than 200 mcd/m^2/lx ; and finally “RRLT100,” where retroreflectivity values are smaller than 100 mcd/m^2/lx. Logistic regression parameter estimates are given in Tables 27–29. While road type and line type are significant parameters, retroreflectivity is not significant in this set of logistic regression models.

Table 27. Parameter estimates for low retroreflectivity data set

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.8297	0.1484	-5.1206	-4.5388	-32.54	<.0001
Road type	Interstate	1.3341	0.1882	0.9653	1.7029	7.09	<.0001
Road type	Multilane Divided	1.0045	0.1516	0.7073	1.3017	6.62	< .0001
Road type	Multilane Undivided	0.0585	0.2923	-0.5145	0.6315	0.20	0.8414
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	0.2544	0.0596	0.1376	0.3712	4.27	<.0001
Line type	ycl	0.1986	0.1107	-0.0183	0.4155	1.79	0.0727
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0001	0.0009	-0.0017	0.0016	-0.08	0.9336
VMT		0.0001	0.0001	-0.0001	0.0002	1.14	0.2529

Table 28. Parameter estimates for high retroreflectivity data set

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-5.1349	0.2647	-5.6538	-4.6160	-19.40	<.0001
Road type	Interstate	1.5089	0.2402	1.0382	1.9796	6.28	<.0001
Road type	Multilane Divided	1.3050	0.1651	0.9814	1.6286	7.90	<.0001
Road type	Multilane Undivided	-0.9286	0.5891	-2.0833	0.2261	-1.58	0.1150
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	0.5309	0.1017	0.3317	0.7302	5.22	<.0001
Line type	ycl	0.6734	0.1789	0.3227	1.0241	3.76	0.0002
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0016	0.0031	-0.0077	0.0044	-0.53	0.5982
VMT		0.0001	0.0001	-0.0000	0.0002	1.55	0.1200

Table 29. Parameter estimates for retroreflectivity values less than 100 mcd/m^2/lx

Analysis of GEE Parameter Estimates							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.7448	0.2666	-5.2674	-4.2222	-17.80	<.0001
Road type	Interstate	1.3299	0.1925	0.9527	1.7071	6.91	<.0001
Road type	Multilane Divided	0.7784	0.1902	0.4055	1.1512	4.09	<.0001
Road type	Multilane Undivided	0.2767	0.3697	-0.4479	1.0013	0.75	0.4542
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
Line type	wel	-0.2692	0.1599	-0.5826	0.0442	-1.68	0.0923
Line type	ycl	-0.3676	0.2067	-0.7728	0.0375	-1.78	0.0753
Line type	yel	0.0000	0.0000	0.0000	0.0000	.	.
RR		0.0009	0.0006	-0.0003	0.0020	1.51	0.1317
VMT		0.0001	0.0001	-0.0000	0.0002	1.94	0.0519

Logistic Regression by Line Type

The final set of regression analyses was done for all line types, which are white edge line, yellow edge line, and yellow center line. The number of crashes and total number of observations are given in Table . Half of the observations come from white edge lines, while around 36% comes from yellow edge lines. The remaining 14% of the data are from yellow center line observations.

Table 30. Number of crashes and total number of observations by line type

Line Type	# Crashes	# Observations
WEL	692	41502 (49.68%)
YEL	379	11983 (14.34 %)
YCL	272	30054 (35.98%)

For all logistic regression analyses done for the three data subsets by line type, retroreflectivity was a significant parameter. For white edge lines, retroreflectivity was significant at 90% confidence level with a negative parameter estimate (Table 31). A negative parameter estimate indicates increasing probability of crash occurrence by decreasing retroreflectivity values. For yellow edge lines, retroreflectivity was significant in logistic regression with a positive parameter estimate at 95% confidence level (Table 32). For yellow center lines, retroreflectivity was significant again at 99% confidence level with again a negative parameter estimate (Table 33). Vehicle miles traveled was another significant parameter for yellow center lines.

Table 31. Parameter estimates for white edge line observations

Analysis of GEE Parameter Estimates (WEL)							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.5507	0.0987	-4.7442	-4.3573	-46.10	<.0001
Road type	Interstate	1.2767	0.1902	0.9040	1.6495	6.71	<.0001
Road type	Multilane Divided	1.0025	0.1334	0.7411	1.2639	7.52	<.0001
Road type	Multilane Undivided	0.0808	0.2733	-0.4549	0.6164	0.30	0.7676
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0005	0.0003	-0.0010	0.0001	-1.67	0.0940
VMT		0.0001	0.0001	-0.0000	0.0002	1.50	0.1347

Table 32. Parameter estimates for yellow edge line observations

Analysis of GEE Parameter Estimates (YEL)							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.2143	0.2302	-4.6655	-3.7631	-18.31	<.0001
Road type	Interstate	0.5333	0.1677	0.2047	0.8620	3.18	0.0015
Road type	Multilane Divided	0.0000	0.0000	0.0000	0.0000	.	.
RR		0.0021	0.0010	0.0002	0.0040	2.16	0.0308
VMT		0.0001	0.0001	-0.0000	0.0002	1.18	0.2369

Table 33. Parameter estimates for yellow center line observations

Analysis of GEE Parameter Estimates (YCL)							
Empirical Standard Error Estimates							
Parameter		**Estimate**	**Standard Error**	**95% Confidence Limits**		**Z**	**Pr > |Z|**
Intercept		-4.8046	0.1387	-5.0765	-4.5327	-34.64	<.0001
Road type	Multilane Undivided	-0.1003	0.2718	-0.6330	0.4324	-0.37	0.7120
Road type	Two-lane	0.0000	0.0000	0.0000	0.0000	.	.
RR		-0.0022	0.0008	-0.0038	-0.0006	-2.67	0.0076
VMT		0.0025	0.0004	0.0018	0.0032	6.84	<.0001

CONCLUSION

This research study investigated a statistical relationship between crash occurrence and pavement marking retroreflectivity by analyzing data that combine representative pavement marking retroreflectivity values on state primary roads with possibly related crash data. Retroreflectivity was found to be a statistically significant factor in crash probability occurrence at a 90% confidence level for the interstate data subset, but the positive parameter estimate suggested increasing crash probability with increasing retroreflectivity values.

Two types of logistic regression analyses were completed for this study—standard logistic regression and logistic regression with a subject effect. When the data was divided by line type, the data structure for the resulting four subsets allowed the second type of analysis, where a subject effect for each route could be assigned. This subject effect in the model recognizes the observations from the same route and the correlation between these observations since they come from the same subject (same route for our analysis). This change in the model improves the model because it separates the variation within each route from the overall variation in the data, and, therefore, the statistical relationship between crash occurrence and pavement marking retroreflectivity can be better analyzed.

For this set of logistic regression analyses, retroreflectivity was found to be a significant parameter for all line types—at 90% confidence level for white edge lines, at 95% confidence level for yellow edge lines, and at 99% confidence level for yellow center lines. For white edge lines and yellow center lines, crash occurrence probability was found to increase by decreasing values of longitudinal pavement marking retroreflectivity. Future additions to the data set as available may improve the modeling to address the autocorrelation between consequent retroreflectivity values on a road.

These findings provide a statistical link between pavement marking retroreflectivity levels and crash history. Along with the FHWA proposed minimum retroreflectivity standards, these findings support increased investment in marking application and maintenance and also serve as a foundation for future research on this critical safety asset.

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