An Investigation of Longitudinal Pavement Marking Retroreflectivity and Safety

FHWA Final Report

Paul J. Carlson
Eun Sug Park
Dong Hun Kang

Texas Transportation Institute

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INTRODUCTION

This research was initiated to determine whether a correlation between pavement marking retroreflectivity and safety can be established. Previous research on this topic has provided mixed results and sometimes counterintuitive findings. This report includes a summary of the previous work as well as a description of the latest research attempting to link pavement marking retroreflectivity and safety.

BACKGROUND

There have been several attempts to evaluate the safety benefits of pavement marking retroreflectivity. A significant challenge has been that pavement marking retroreflectivity levels fluctuate over time. Attempts to model pavement marking retroreflectivity degradation curves have not been widely successful (1,2). While there is some predictability to pavement marking retroreflectivity (it is generally accepted that AADT is a significant predictor variable), it can change unpredictably and substantially as a function of frequency and intensity of rain (to clean markings), quality of installation, or even the condition of the pavement. Therefore, it is difficult to know the retroreflectivity levels of the pavement markings at the exact time and location of each crash. While crash data are available, researchers have had to make assumptions regarding the retroreflectivity levels for their analyses. Some researchers model retroreflectivity using various sources of measured data, while others make assumptions about the retroreflectivity without measurements.

In 2006, researchers in New Zealand studied the safety impacts of brighter pavement markings and concluded that there was not a conclusive improvement in safety (3). This study took advantage of a policy change in New Zealand in 1997 that required a minimum maintained retroreflectivity level of 70 mcd/m^2/lx. Using a before–after approach, the authors compared crash rates before the change in policy. They assumed that markings were brighter during the after period. It should also be pointed out that, in New Zealand, all state roadways are delineated as a function of traffic volume. As volumes increase, they progressively apply the following treatments: delineators, centerlines, edge lines, and then RRPMs. Therefore, roadways with centerlines had delineators too. Previous research in the United States has shown that supplemental delineation treatments, such as delineators or RRPMs, overpower the potential effect of pavement markings (4).

The results of an NCHRP study were published in 2006 with the following conclusions: ". . . the difference in safety between new markings and old markings during non-daylight conditions on non-intersection locations is approximately zero" (5). While the study incorporated large amounts of crash data and utilized the latest statistical techniques, there were significant limitations. For instance, the research only included crashes from California and modeled retroreflectivity (no measurements were made). While the study included efforts to overcome the possible limitations in modeling retroreflectivity, these efforts presuppose that markings in California reach a value where there is an adverse impact on safety. The pavement marking maintenance policy of California is such that higher-volume highways are restriped up to three times a year with paint, or every two years with thermoplastic markings. As a result, there is only the occasional roadway with retroreflectivity levels below100 mcd/m^2/lx.

Overlooking the concerns regarding the modeled retroreflectivity levels, the researchers also binned the retroreflectivity levels. The binning thresholds were derived linearly, which by itself is a limitation since the performance of retroreflectivity has been repeatedly shown to be best modeled logarithmically rather than linearly (6,7). In addition, the lowest bins for the edge lines included retroreflectivity levels from 21 to 183 mcd/m^2/lx, thus including both inadequate levels and near-desired levels in the same bin (according to a synthesis of perception studies reported elsewhere (8)). Eight additional bins included retroreflectivity levels up to 413 mcd/m^2/lx. Therefore, all binning used in the analyses included levels deemed to be acceptable or at least above previously recommended minimum retroreflectivity levels. These concerns limit acceptability of the quoted concluding remarks shown above.

In 2007, researchers reported results from an effort to develop a statistical association between measured pavement marking retroreflectivity and traffic crash frequency (9). For this research, data from North Carolina were used. The results suggest that increased levels of the average pavement marking retroreflectivity on multi-lane highways may be associated with lower expected target crash frequencies; however, the association was small in magnitude and not statistically significant. On two-lane highways, the association between pavement marking retroreflectivity and crash frequency was larger in magnitude and marginally significant. While this study used measured retroreflectivity levels (recorded once per year), it should be noted that all the retroreflectivity data were well above what might be considered minimum levels, and even near what might be considered desired levels (all data were above 100 mcd/m^2/lx with an overall average of 240 mcd/m^2/lx).

In 2008, a similar effort was reported that included 3 years of measured retroreflectivity (measured once per period) in Iowa (*10*). These data were analyzed along with crash records from the same year. The distributions and models of the entire database, and a subset including only two-lane highways, did not show that pavement marking retroreflectivity correlated to crash probability. When truncating the data to only records with retroreflectivity values less than 200 mcd/m^2/lx, a statistically significant relationship was determined. However, the correlation was small.

The four studies summarized here present the latest information regarding the relationship between pavement marking retroreflectivity and safety. Two of the studies conclude that there is no relationship, but both studies appear to have significant limitations. The remaining two studies point to some possible relationships with statistical significance but the findings are small and not consistent.

OBJECTIVE AND APPROACH

The objective of this research was to evaluate relationships between crashes and longitudinal pavement marking retroreflectivity. The retroreflectivity data consist of the measurements of pavement markings representing white edge lines (WEdge), white lane lines (WLane), yellow edge lines (YEdge), and yellow center lines (YCntr). The retroreflectivity data are from Michigan DOT road segments from 2002 to 2008. The research team combined the geometric and crash data from Michigan rural two-lane roadways and freeways (obtained during a previous project (*11*)) with the retroreflectivity data. Only nighttime crashes that occurred at nonintersection and noninterchange segments during the nonwinter months (between April and October) were considered (wet crashes were also excluded). The following specific types of crashes were initially identified as target crashes for this study: nighttime, single vehicle nighttime, fatal plus injury nighttime, and single vehicle nighttime fatal plus injury.

DATABASE PREPARATION

The data used in this research were compiled from the tables with many different formats and contents. Major source tables consist of retro data tables, crash report tables, roadway segment tables and other supporting tables collected from 2002 through 2008. Since the source tables were originally created with different purposes, there is no direct way to connect the retro values with crash records by road segments by time period. Hence, it required significant database development efforts to produce the final crash-retroreflectivity and retroreflectivity-crash tables prior to analysis as described in the sections below.

Retroreflectivity Data Table

The initial retroreflectivity table includes 24,862 retroreflectivity values from 3,553 sites for seven years (2002 – 2008) for four major line types (WEdge, WLane, YCntr, and YEdge). Michigan DOT restripes about 85 percent of their system with paint each year. They commission retroreflectivity measurements on about 15 percent of their system each year. The retroreflectivity measurements have been made with mobile technologies that produce data every 0.1 mile interval. Each 0.1 mile interval contains roughly 50 readings.

As shown in Figure 1, most of the retroreflectivity values were recorded in the late summer after Michigan DOT completed their annual striping program. During the spring period about 6 percent of the retroreflectivity values were collected in April and May in the given data set.

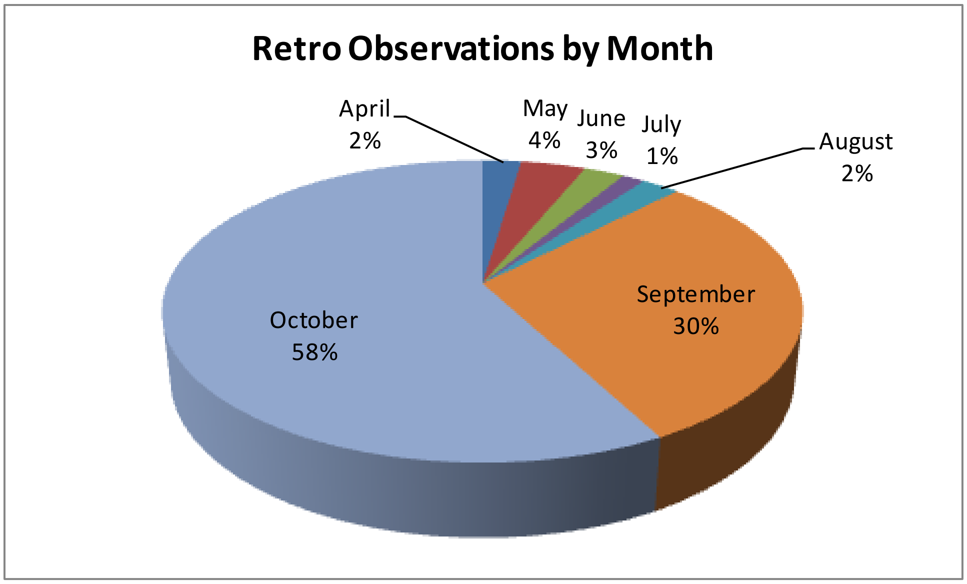


Figure 1. Percentage of retroreflectivity observations by month

An initial review of retroreflectivity values by line type shown in Figure 2 indicates that the yellow markings are mostly between 150 and 250 mcd/m^2/lx. In contrast, most of the white markings have measurements between 250 and 350 mcd/m^2/lx. The average retroreflectivity value of YCntr is 177.1 mcd/m^2/lx and YEdge for 197.6 mcd/m^2/lx. WEdge has the highest average value of 310 mcd/m^2/lx followed by WLane with 297.1 mcd/m^2/lx. Table 1 shows the actual numbers of Figure 2.

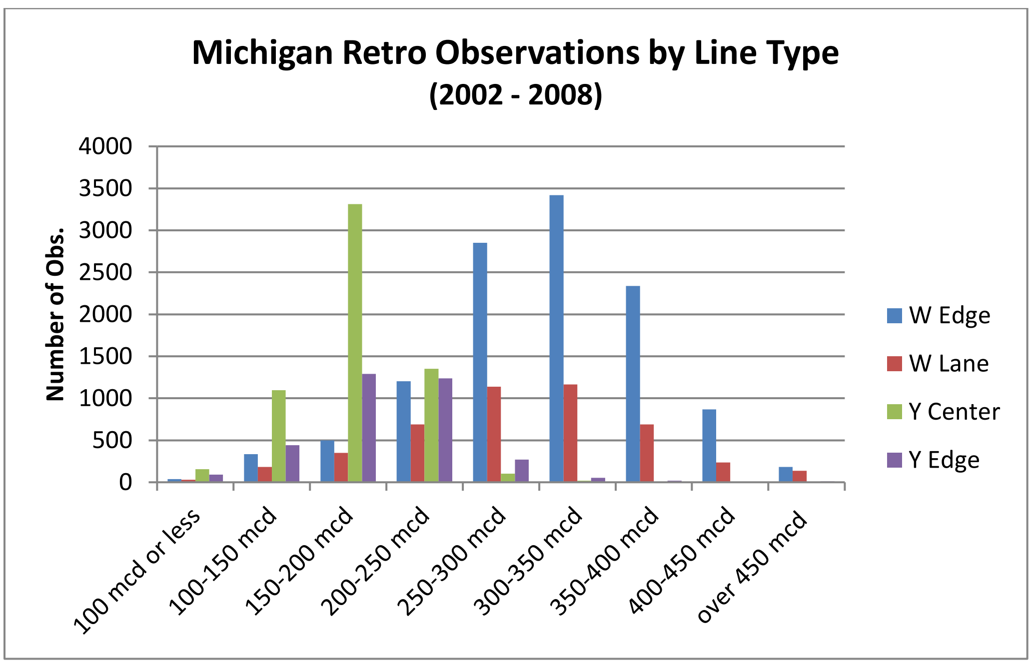


Figure 2. Distribution of retroreflectivity values by line type

Table 1. Number of retroreflectivity values by line type

MI Retro (02-08)	100 mcd or less	100-150 mcd	150-200 mcd	200-250 mcd	250-300 mcd	300-350 mcd	350-400 mcd	400-450 mcd	over 450 mcd	Total by Line Type
W Edge	37	326	461	1146	2770	**3337**	2289	865	179	11410
W Lane	28	180	324	642	1088	**1123**	663	231	129	4408
Y Center	155	1090	**3217**	1302	101	18	3	0	0	5886
Y Edge	93	423	**1179**	1126	253	50	14	8	12	3158
Total by mcd	313	2019	5181	4216	4212	4528	2969	1104	320	24862

Crash Data Table

The crash data table contains detailed information about accidents such as crash id, crash location, severity, accident type, weather, light condition, traffic control present, and road condition. For the accuracy and convenience of the database management they are coded as predefined parameter values as shown in Table 2. Since not all the variables are necessary for this research, the research team went through the filtering and cleaning process before building actual crash record databases. The crash records were filtered to exclude the ones with the following conditions:

- winter crashes: January, February, March, November, and December
- intersection crashes
- interchange crashes
- wet, ice/snow, debris crashes
- daytime crashes.

Actual location of a crash consists of primary milepost and PR (physical reference) number based on the Michigan Geographic Framework. However, this alone is not enough information to merge databases so the beginning milepost and end milepost values of the PR number were added to make connection to retroreflectivity data table.

Table 2. Crash data characteristics

Category	Accident Code Name	Parameter Value	Remarks
Crash Location & Roadway Information	report_yr		2002 - 2008
	cnty_rte_pr		County-Route-PR number
	pr_beg_mp		PR beginning milepost
	pr_end_mp		PR end milepost
	seg_lng		Segment length
	aadt		AADT
	comm_vol		Commercial vehicles volume
	lanewid		Lane width
	r_shdr_wid		right shoulder width
	r_shdr_pvd		right shoulder paved width
	spd_limt		Speed limit
Severity	fatl_crsh_ind	0 or 1	Fatal
	injy_crsh_ind	0 or 1	Injury
	prop_damg_crsh_ind	0 or 1	Property Damage Only
Accident Type	crsh_type_cd	1	Single Vehicle
	crsh_type_cd	2	Head-on
	crsh_type_cd	3	Head On - Left Turn
	crsh_type_cd	4	Angle
	crsh_type_cd	5	Rear End
	crsh_type_cd	6	Rear End - Left Turn
	crsh_type_cd	7	Rear End - Right Turn
	crsh_type_cd	8	Sideswipe Same Direction
	crsh_type_cd	9	Sideswipe Opposite Direction
	crsh_type_cd	10	Other
Weather	wthr_vis	1	Clear
	wthr_vis	2	Wet
	wthr_vis	3	Snow
	wthr_vis	4	Unknown
Light Condition	light_cd	1	day
	light_cd	2	dawn-dusk
	light_cd	3	dark light
	light_cd	4	dark
	light_cd	5	light cond. Unknown
Night Crash	night	1	night
Traffic Control Present	traf_cont	1	Signal
	traf_cont	2	Stop/ Yield
	traf_cont	3	No traffic control
	traf_cont	4	Unknown
interchange	interch_cd	0 or 1	Interchange
intersection	intersec_cd	0 or 1	Intersection
Road Condition	road_cond	1	Dry road
	road_cond	2	Wet road
	road_cond	3	Ice, snow road
	road_cond	4	debris
	road_cond	5	Unknown

Development of Databases

Because of the inherent limitation of the retroreflectivity data such that the measurements were available only at certain locations and times, the research team put significant effort into preparation of the database that can be used in the statistical analysis. After an initial review of the available data on retroreflectivity and crashes, there seemed to be two possible ways for constructing a database that can be used to analyze the crash-retroreflectivity relationships based on the Michigan data:

1. Using road segments from the crash database as basic spatial units and filling in retroreflectivity values for the segments in the database. This technique was employed and is referred to Database A.

2. Using road segments from the retroreflectivity database and filling in crash values for the segments in the database. This technique was also employed as is referred to as Database B.

Database A: Crash-Retroreflectivity Database

This database uses the segments of the crash database as basic spatial units. From a previous study, the research team used a Michigan crash database with 243 segments for rural 2 lane roadways and 508 segments for freeways. The research team first added retroreflectivity values to the crash segments with monthly crash frequencies for 49 months corresponding to 7 years (7 nonwinter months for each year) for rural 2 lane roadways and freeways. Figure 3 shows the schematic of the matching process.

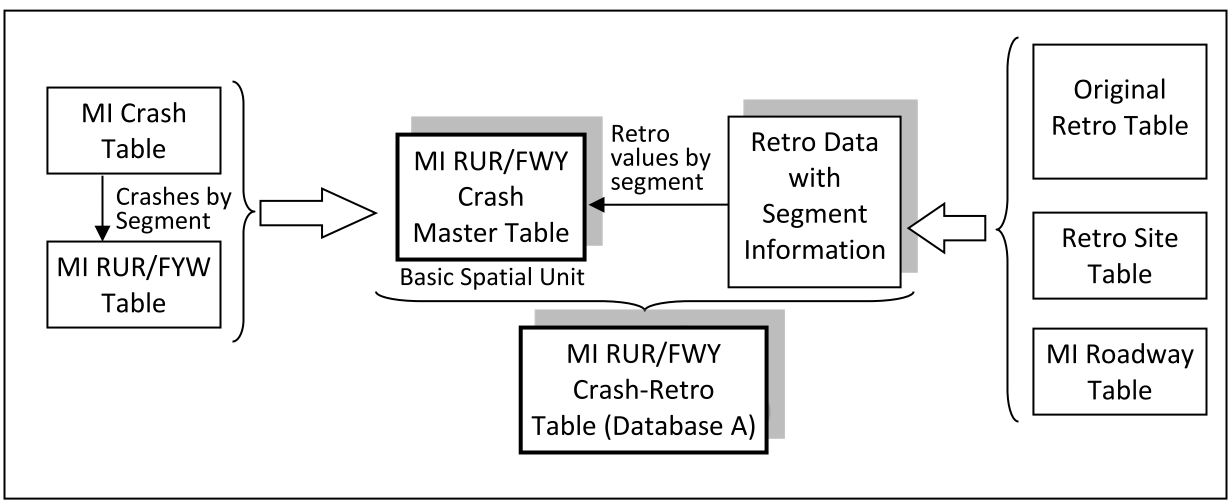


Figure 3. Schematic diagram of crash-retroreflectivity Database A

In Figure 3 the basic spatial unit of crash database is illustrated with thicker lines. During the matching process, many retroreflectivity segments in the retroreflectivity database were left out because they could not be matched with the segments in the crash database. For example only 116 segments out of 243 rural segments have one or more matched WEdge retroreflectivity values over the 49-month period. Among those 116 WEdge segments, there were no retroreflectivity measurements for many time periods since Michigan typically surveys about 15 percent of their system each year. There can be 11,907 rows (observational units) when all of 49 months and 243 segments are considered for rural 2 lane roadways and 24,892 rows (considering 49 months at each of 508 segments) for freeways of Database A. Table 3 shows the number of matched segments and rows over the 49-month period by line type.

Table 3. Number of segments and rows with one or more matched retroreflectivity values (monthly crash-retroreflectivity Database A)

Line Type	Rural 2-lane		Freeway	
	Segments	Observational Units	Segments	Observational Units
WEdge	116	421	250	845
YCntr	120	338	N/A	N/A
WLane	N/A	N/A	269	808
YEdge	N/A	N/A	262	784
Total	243	11,907	508	24,892

Before any imputation was applied, retroreflectivity measurements exist only for 338 YCntr rows out of 11,907 rows for rural 2 lane roadways, and for 808 WLane rows out of 24,892 rows for freeways, which corresponds to only 3 percent of the observational units. Note that those percentages (of rows with the actual retroreflectivity measurements) can change depending on temporal resolution of the database. For example if two periods (instead of 7 months) within each year are used, then the total number of possible rows for rural 2 lane roadways will be 3,402 and the percentage of rows with the original retroreflectivity measurements might be as high as 9.3 percent. For the initial matching process, the research team used monthly data as a basis. To increase the number of observations that can be included in the negative binomial regressions, the research team had to fill in missing retroreflectivity values for those segments and months with no retroreflectivity measurements in Database A. This spatial-temporal imputation of the retroreflectivity values is a critical step in the retroreflectivity-crash evaluation because the imputed values can significantly affect the retroreflectivity-crash relationship considering the proportion of the actual retroreflectivity measurements is small compared to the total number of rows in the database. The research team has explored several different options for imputation to come up with a most reasonable way. The final option chosen for imputation of monthly retroreflectivity values is as follows:

(Step 1) *Temporal Imputation*

- If there is no observation in April, then the retroreflectivity value is estimated from the last year's October (or September) value with the monthly degradation rates in table 4. These values were obtained through analysis of the Michigan retroreflectivity database considering only those road segments that included data from both fall and immediate spring. These winter degradation rates are similar to those reported in more recent work including 6 states snow plow states and 3 non-snow plow states (*12*).
- An unobserved value during the nonwinter months is imputed from the available preceding month in the same year with the degradation rate of zero.
- An unobserved value between September and October is imputed from the same month of the last year. This is to follow the actual practices performed by MDOT every year. MDOT is restriping 80 to 85 percent of their system each year. Therefore the retroreflectivity values of September or October are supposed to have higher values than the ones between April and May.

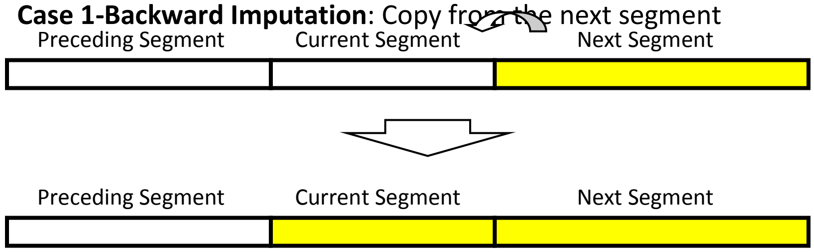
Table 4. MI retroreflectivity monthly degradation rates (over-winter period)

	W Edge	W Lane	Y Cntr	Y Edge
Average Monthly Degradation Rate	**-22.0**	**-22.3**	**-8.9**	**-10.7**
Standard deviation	7.799	7.439	4.350	4.541

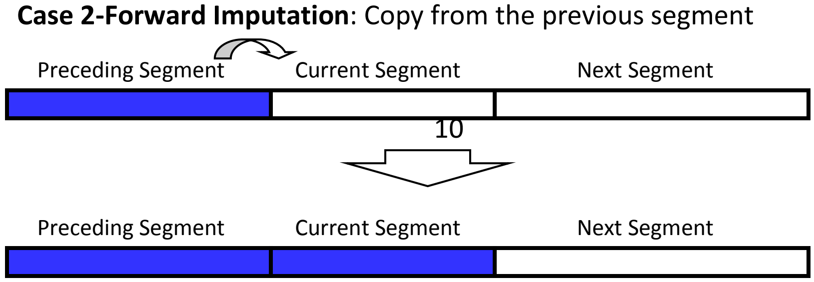
(Step 2) *Spatial Imputation*

- If the current segment has no retroreflectivity value, find the retroreflectivity value from the neighboring segments within 2 mile range from the beginning or the ending mile posts of the current segment. There are three possible cases for spatial imputation as shown below.

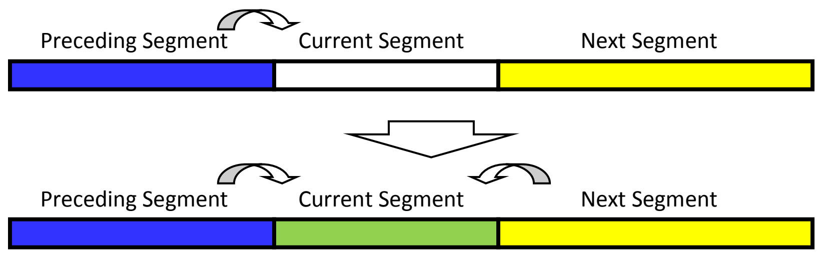
    - **Case 1-Backward Imputation**: Copy from the next segment



    - **Case 2-Forward Imputation**: Copy from the previous segment



- **Case 3-Combined Imputation**: Copy from the previous and next segments and average them



Many blank rows were populated with retroreflectivity values after the temporal and spatial imputations. As shown in Table 5 more than 40 percent of the rural retroreflectivity values and about 50 percent of freeway retroreflectivity values are filled after the two step imputation process.

Table 5. Proportion of usable retroreflectivity values after imputation (monthly crash-retroreflectivity Database A)

Line type	Rural 2-lane			Freeway		
	Original	After temporal imputation (Step 1)	After spatial imputation (Step1 +Step 2)	Original	After temporal imputation (Step 1)	After spatial imputation (Step1 +Step 2)
WEdge	4%	35%	44%	3%	33%	48%
YCntr	3%	34%	41%	N/A	N/A	N/A
WLane	N/A	N/A	N/A	3%	35%	52%
YEdge	N/A	N/A	N/A	3%	35%	53%

Figures 4 and 5 show the range of retroreflectivity levels after the imputation tasks were performed for Database A and Database B, respectively. Overall the retroreflectivity values are shifted down as expected. Imputation considers degradation during winter months. All of the imputed values are less than or equal to the immediate past observational values. The temporal degradations are spread to the neighboring segments which have no observations.

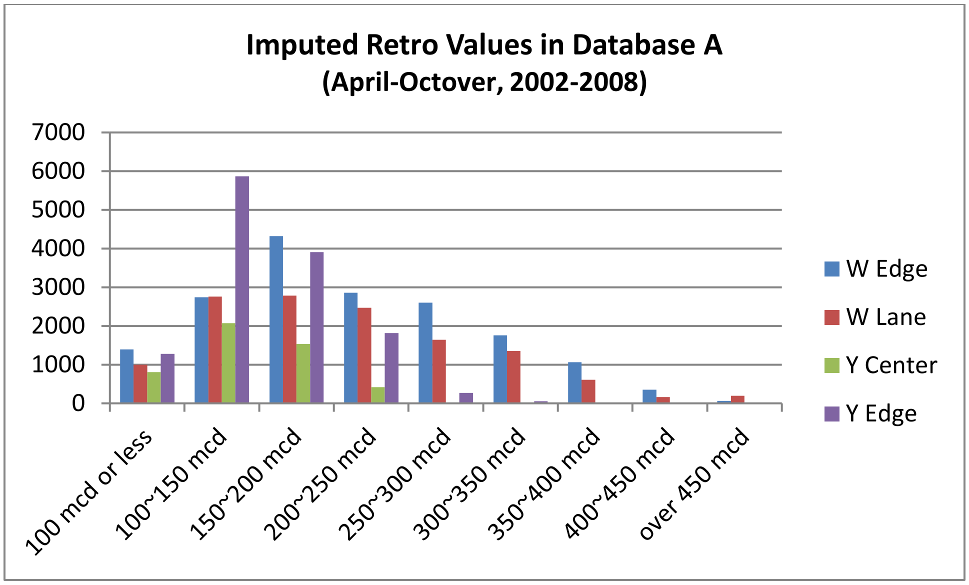


Figure 4. Distribution of all imputed retroreflectivity values in Database A

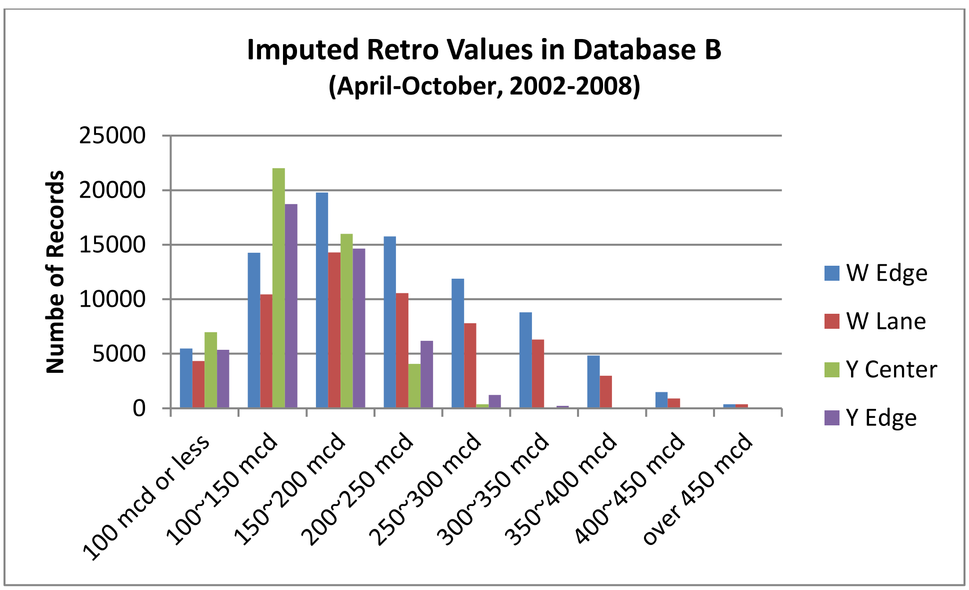


Figure 5. Distribution of all imputed retroreflectivity values in Database B

The final imputed monthly data is then grouped by two periods of April-May and September-October and the crash records and retroreflectivity values are averaged for those two periods for statistical analysis. The groupings avoid the summer months when most of the restriping occurs (the actual restriping dates were not available).

Database B: Retroreflectivity-Crash Database

This database uses the segments of the retroreflectivity database as basic spatial units. As shown in Figure 6, using the retroreflectivity site table and MI roadway table, the research team added roadway segment data to the original retroreflectivity table to build a basic spatial unit of retroreflectivity segments. Then Michigan crash data by segment was attached to the retroreflectivity database. The resulting retroreflectivity database consists of 933 rural 2-lane roadways and 1,103 freeway segments for 49 months (non winter months during 2002 through 2008).

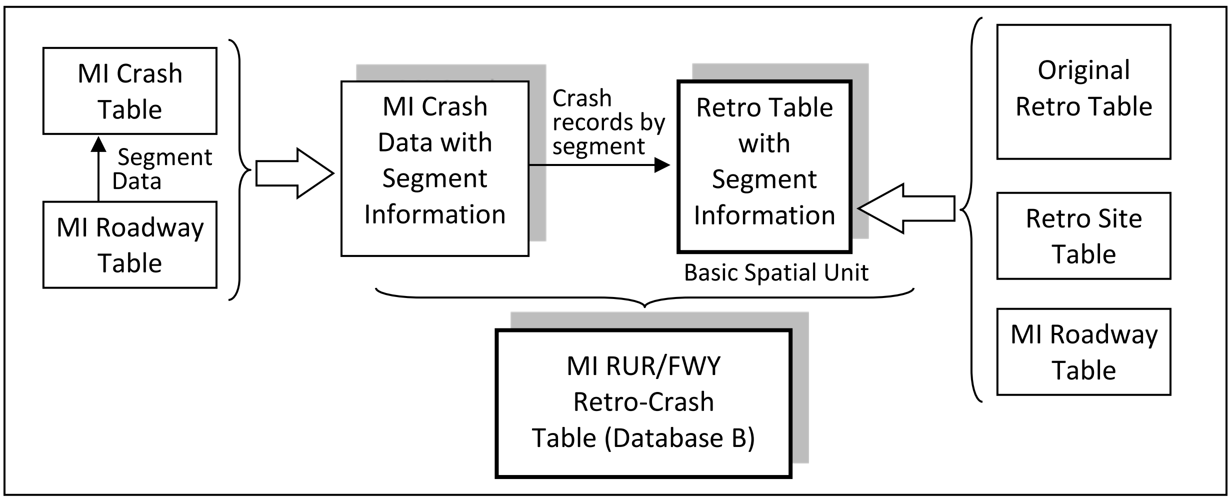


Figure 6. Schematic Diagram of retroreflectivity-crash Database B

Even though the roadway segments used in Database A provide very precise representation of rural 2-lane and freeway segments, they yield very small number of matched crash-retroreflectivity pairs and majority of the retroreflectivity values are not used for analysis. In order to increase the number of matched retroreflectivity-crash pairs, the research team used following criteria for Database B from the MI Roadway Table to define rural 2-lane roadways and freeway segments:

- *Rural 2-lane roadway*
  - Road type code = 9 (two-way undivided),
  - Number of lanes = 2 (two lanes)
  - National functional class (NFC) ≠ 8 (minor collector), 17 (collector)
- *Freeway*
  - Road type code = 1 (freeway) or 2 (divided),
  - NFC = 1 (rural principal arterial-interstate) or 5 (rural principal arterial-other freeways) or 11 (urban principal arterial-interstate) or 12 (urban principal arterial-other freeways)

During the matching process, multiple retroreflectivity measurements for the same line type were taken for the same segment during the same month and year, an average over those multiple measurements was included in the final table for analysis.

Table 6 shows the number of segments with at least one pair of retroreflectivity and crash data for 49 months after the initial matching process. Compared to the case of Database A in Table 3, they show much improved results. Now, 80 to 90 percent of the rural and freeway retroreflectivity segments are matched with crash data. However, they still have only 5 to 6 percent of matched values in terms of observational units. For example, 828 segments out of 933 rural segments have one or more matched WEdge retroreflectivity values over the 49-month period, while 2,793 out of 45,290 observational units have matched WEdge retroreflectivity values in rural segments.

Table 6. Number of Segments and Rows with One or More Matched Retroreflectivity Values (monthly retroreflectivity-crash Database B)

Line Type	Rural 2-lane		Freeway	
	Segments	Observational Units	Segments	Observational Units
WEdge	828	2,793	870	2,480
YCntr	804	2,296	N/A	N/A
WLane	N/A	N/A	883	2,394
YEdge	N/A	N/A	906	2,435
Total	933	45,290	1,103	53,466

The imputation logic for Database B is the same as Database A. It goes through temporal imputation with the same monthly degradation rates in Table 4 and completes with the same spatial imputation steps. However, thanks to more initial matched in segments, Database B shows much improved results in terms of final imputed percentages. As shown in Table 7 most of the line types have about 70 percent of observational units after the imputations, compared to about 50 percent of the observational units populated by imputations in Database A.

Table 7. Proportion of usable retroreflectivity values after imputation (monthly retroreflectivity-crash Database B)

Line type	Rural 2-lane			Freeway		
	Original	**After temporal imputation** (Step 1)	**After spatial imputation** (Step1 +Step 2)	**Original**	**After temporal imputation** (Step 1)	**After spatial imputation** (Step1 +Step 2)
WEdge	6%	61%	71%	5%	50%	67%
YCntr	5%	56%	69%	N/A	N/A	N/A
WLane	N/A	N/A	N/A	4%	53%	71%
YEdge	N/A	N/A	N/A	5%	53%	70%

In addition to a monthly crash frequency at each of retroreflectivity segments, the research team added a variable 'crash occurrence' taking a value 1 (if a crash/crashes occurred) or 0 (if no crash occurred) for each crash type. Like Database A, the team also added geometric variables (segment length, right shoulder width, lane width, and terrain) and AADT to Database B.

The final imputed monthly data is then grouped by two periods of April-May and September-October and the crash records and retroreflectivity values are averaged for the two periods for statistical analysis. The groupings avoid the summer months when most of the restriping occurs (the actual restriping dates were not available).

STATISTICAL ANALYSIS

The research team first conducted separate analyses of databases A and B to find the relationship between crashes and retroreflectivity. Each of the analyses are presented separately below.

Analysis of Database A

Database A contained 243 segments of rural 2-lane roadways (corresponding to 819.4 miles) and 508 segments of freeways (corresponding to 1067.4 miles). For rural 2-lane roadways, the retroreflectivity values exist mainly for WEdge and/or YCntr, and for freeways mainly for WEdge, WLane, and/or YEdge. The retroreflectivity data and crash data were available for 7 years (2002-2008) for segments in Database A. While annual striping in Michigan is mostly done during summer (June-August), the exact application date is usually unknown. For the missing retroreflectivity values during the summer in Database A, it could not be determined whether they were subject to striping or not, and so the imputed retroreflectivity values during the summer were somewhat questionable. To avoid any potential confounding between crash-retroreflectivity relationship and striping, only the crash data for two periods (Period 1: April-

May and Period 2: September-October) were analyzed (with the assumption that most if not all of the restriping occurs in June through August). Table 8 contains the summary statistics for the variables in Database A. Note that the temporal unit for crashes in Table 1 is a period (e.g., Average is the average period crash frequency).

Table 8. Descriptive statistics for variables in Database A.

Variable name	243 rural 2-lane segments (819.4 mi)			508 freeway segments (1067.4 mi)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Crashes						
Nighttime crashes	0	8	0.556	0	6	0.251
Single vehicle nighttime crashes	0	8	0.534	0	6	0.211
Nighttime fatal injury crashes	0	2	0.035	0	2	0.032
Single vehicle nighttime fatal injury crashes	0	2	0.027	0	2	0.020
Retroreflectivity variables (imputed)						
WEdge	58	465.5	252.7	50	501	245.5
YCntr	50	272	153.7			
WLane				50	643	240.9
YEdge				50	360	167.9
Segment variables						
Length (mi)	0.04	12.69	3.37	0.07	8.91	2.10
Average daily traffic	196	18,597	4,474	1,508	100,650	24,543
Lane width (ft)	10	12	11.51	11	12	11.99
Shoulder width (ft)	3	12	8.14	9	13	10.06
Rolling terrain (1=yes)	0	1	0.354	0	1	0.015

In order to separate out the effect of retroreflectivity from other important roadway characteristics, the Negative Binomial regression models were applied to the crash data. The general form of the expected number of crashes in a Negative Binomial regression model can be given as follows:

$$\mu_i = \exp\left(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki}\right)$$

where μ_i is the expected number of crashes at segment i, $X_{1i}, \ldots, X_{ki}$ are the covariates/predictors corresponding to roadway characteristics of segment i, and β_0, β_1, $\beta_2, \ldots$, β_k are the regression coefficients. After exploring various negative binomial regression model forms with different predictors, the model including with year, period (Period 1: April-May, Period 2: September-October), retroreflectivity values for different line types (WEdge and YCntr for rural 2 lane roadways and WEdge, WLane, and YEdge for freeways), lane width, right shoulder width, rolling terrain (1: Yes, 0: No), and log(AADT) as predictors and log(segment length) as an offset variable seemed to be most appropriate for these data. The crash data from rural 2-lane roadways and freeways were fitted separately. Generalized estimating equations (GEE) were used for estimation to account for correlations in repeated observations from the same segment over time. The GENMOD procedure in SAS was used for the NB regression analyses with GEE.

Negative binomial regression for the data from rural 2-lane roadways in Database A

Table 9 contains the results of fitting the NB model to nighttime crashes and single vehicle nighttime crashes from rural 2-lane roadways. Because there were almost no nighttime fatal plus injury crashes and single vehicle nighttime fatal plus injury crashes (97% of observations in the database A have no nighttime fatal plus injury crashes and 98% of observations have no single vehicle nighttime fatal plus injury crashes), models for nighttime fatal plus injury crashes and single vehicle nighttime fatal plus injury crashes could not be estimated reliably and not presented in the Table 9. As can be observed from Table 9, neither of WEdge retroreflectivity nor YCntr retroreflectivity turned out to be statistically significant at α=0.1.

Table 9. Estimates of regression coefficients of negative binomial regression models applied to crash data from 243 rural 2-lane roadway segments in Database A.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		**-6.7384 (<.0001)**	**-6.3865 (<.0001)**
Year	2002	−0.1432 (0.4470)	−0.1552 (0.4142)
	2003	0.0363 (0.8203)	0.0265 (0.8713)
	2004	−0.0842 (0.5468)	−0.0743 (0.6018)
	2005	−0.1237 (0.3037)	−0.1139 (0.3423)
	2006	−0.1852 (0.1424)	−0.1771 (0.1757)
	2007	−0.0120 (0.9033)	0.0088 (0.9305)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	-**0.4139 (0.0098)**	-**0.4131 (0.0133)**
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		0.0007 (0.4905)	0.0007 (0.4999)
YCntr		-0.0004 (0.7928)	-0.0000 (0.9725)
Lane Width		0.0365 (0.7691)	0.0150 (0.9064)
Shoulder Width		−0.0075 (0.8969)	−0.0082 (0.8886)
Rolling Terrain		0.0591 (0.6599)	0.0682 (0.6169)
Log(AADT)		**0.5783 (<.0001)**	**0.5538 (<.0001)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

To determine whether the effect of retroreflectivity on crashes is different for a different range of retroreflectivity values, NB models were also fitted using a subset of the data having YCntr retroreflectivity values satisfying a certain threshold (<=200 mcd/m^2/lx, <=150 mcd/m^2/lx, or <=100 mcd/m^2/lx). Applying the same threshold to WEdge retroreflectivity values did not leave enough data for model fitting, so was not pursued. When YCntr values were <=200 mcd/m^2/lx, the results were similar to those of Table 9, i.e., neither WEdge nor YCntr was statistically significant at α=0.1. When YCntr values were <=150 mcd/m^2/lx, the effects of YCntr on nighttime crashes and single vehicle night crashes were statistically significant at α=0.1 (actually at α=0.05 also). Table 10 presents the estimates of regression coefficients of NB models applied to the subset of the data corresponding to YCntr<=150 mcd/m^2/lx. The estimated coefficient for YCntr retroreflectivity for nighttime and single vehicle night crashes are -0.0066 and -0.0061, respectively, which can be associated with the percent crash reduction of 0.7% (=(1-e$^{-0.0066}$)×100) and 0.6% (=(1-e$^{-0.0066}$)×100) as retroreflectivity increases by 1 (unit). If retroreflectivity increases by 10 mcd/m^2/lx, the percent reduction in nighttime and single vehicle night crashes are 6.4% (=(1-e$^{-0.066}$)×100) and 5.9% (=(1-e$^{-0.061}$)×100), respectively. If retroreflectivity increases by 100 mcd/m^2/lx (e.g. from 50 mcd/m^2/lx to 150 mcd/m^2/lx), the associated percent reduction in nighttime and single vehicle night crashes are 48.3% (=(1-e$^{-0.66}$)×100) and 45.7% (=(1-e$^{-0.61}$)×100), respectively. It needs to be emphasized that the relationship is only associative, not causative, which is a limitation of any observational study. Note also that the range of the data used for Table 10 was from 50 mcd/m^2/lx to 150 mcd/m^2/lx, and extrapolation beyond this range should be avoided because the relationship between crash and retroreflectivity could change outside the data used for developing the model. Models for the subset of the data when YCntr<=100 mcd/m^2/lx could not be fitted due to insufficient data.

Table 10. Estimates of regression coefficients of negative binomial regression models applied to crash data from rural 2-lane roadway segments with YCntr<=150 $mcd/m^2/lx$ in Database A.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		**-4.1155 (0.0670)**	-3.5252 (0.1339)
Year	2002	**−1.2411 (0.0536)**	**−1.1834 (0.0704)**
	2003	-0.1842 (0.5168)	-0.1664 (0.5869)
	2004	−0.2213 (0.3228)	−0.1669 (0.4871)
	2005	−0.1270 (0.4954)	−0.0982 (0.6138)
	2006	−0.2370 (0.1592)	−0.2138 (0.2453)
	2007	−0.1186 (0.5337)	-0.0426 (0.8308)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	-**0.4836 (0.0728)**	-0.4763 (0.1041)
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		0.0014 (0.2587)	0.0016 (0.2466)
YCntr		**-0.0066 (0.0159)**	**-0.0061 (0.0406)**
Lane Width		-0.1018 (0.6309)	-0.1588 (0.4770)
Shoulder Width		−0.0440 (0.4855)	−0.0451 (0.4961)
Rolling Terrain		-0.0720 (0.7022)	0.0656 (0.7352)
Log(AADT)		**0.5776 (<.0001)**	**0.5627 (<.0001)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

Negative binomial regression for the data from freeways in Database A

For freeway crashes, reliable models for fatal plus injury nighttime crashes and single vehicle nighttime fatal plus injury crashes could not be developed, again due to an extremely small number crashes for those crash types. Table 11 contains the results of fitting the NB model to nighttime crashes and single vehicle nighttime crashes from freeways in Database A. As can be seen from the table, for nighttime crashes and single vehicle nighttime crashes, none of the effects of WEdge, WLane, and YEdge on crashes were statistically significant when all three retroreflectivity values WEdge, WLane, and YEdge were included in the model simultaneously. This is also the case regardless of whether all the data are used or a subset of the data (satisfying a threshold, <=200 $mcd/m^2/lx$, <=150 $mcd/m^2/lx$, or <=100 $mcd/m^2/lx$ for any line type) is used.

Table 11. Estimates of regression coefficients of negative binomial regression models applied to crash data from 508 freeway segments in Database A.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		5.3650 (0.3054)	7.1266 (0.1658)
Year	2002	**–0.8598 (0.0010)**	**–1.0186 (0.0003)**
	2003	**-0.2666 (0.0631)**	**-0.3208 (0.0432)**
	2004	–0.1356 (0.3006)	–0.1768 (0.2035)
	2005	–0.0060 (0.9624)	–0.0691 (0.6091)
	2006	–0.1675 (0.1416)	**–0.2491 (0.0367)**
	2007	0.0307 (0.7723)	0.0418 (0.7036)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	**-0.4282 (0.0355)**	**-0.4307 (0.0315)**
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		-0.0001 (0.9369)	0.0000 (0.9989)
WLane		0.0005 (0.5442)	0.0004 (0.6512)
YEdge		-0.0006 (0.6643)	-0.0006 (0.6488)
Lane Width		-0.6623 (0.1245)	**-0.6984 (0.0949)**
Shoulder Width		**–0.2693 (0.0136)**	**–0.3059 (0.0211)**
Rolling Terrain		**-0.3840 (0.0880)**	**-0.3925 (0.0840)**
Log(AADT)		**0.3690 (<.0001)**	**0.2603 (<.0001)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

Because the number of non-missing observations that can be used for the analysis when the retroreflectivity values for all three line types are considered simultaneously is smaller (n=2974 when no threshold is used) compared to when one line type is considered at a time, the team also conducted a separate analysis for each line type. While the effect of retroreflectivity of each of WEdge, WLane, or YEdge on freeway crashes was observed to be negative (i.e., the corresponding coefficient was negative, which implies that higher retroreflectivity was associated with lower crashes) whether all the data are used or a subset of the data (satisfying a threshold, <=200 mcd/m^2/lx, <=150 mcd/m^2/lx, or <=100 mcd/m^2/lx for any line type) is used, none of them was statistically significant at α=0.1.

Analysis of Database B

Database B contained 933 segments of rural 2-lane roadways (corresponding to 3095.5 miles) and 1103 segments of freeways (corresponding to 2065.0 miles). The retroreflectivity data and crash data were available for 7 years (2002-2008) for segments in Database B. Because Database B contained many more retroreflectivity values (even before imputation) than Database A, monthly crash and retroreflectivity data were also utilized for the analysis in addition to the period (corresponding to April-May and September-October periods) crash and retroreflectivity data. Table 12 and Table 13 contain the descriptive statistics for the variables in Database B with monthly crashes and retroreflectivity values and Database B with period crashes and retroreflectivity values, respectively.

Table 12. Descriptive statistics for variables in Database B with monthly crashes and retroreflectivity values.

Variable name	933 rural 2-lane segments (3095.5 mi)			1103 freeway segments (2065.0 mi)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Monthly Crashes						
Nighttime crashes	0	8	0.260	0	6	0.113
Single vehicle nighttime crashes	0	8	0.247	0	5	0.090
Nighttime fatal injury crashes	0	2	0.019	0	3	0.018
Single vehicle nighttime fatal injury crashes	0	2	0.014	0	2	0.011
Retroreflectivity variables (imputed)						
WEdge	50	490	218.1	50	556	216.0
YCntr	50	335.5	140.3			
WLane				50	778	209.9
YEdge				50	448	154.7
Segment variables						
Length (mi)	0.019	21.744	3.317	0.038	9.349	1.891
Average daily traffic	196	32,720	5,494	1,508	111,047	27,156
Lane width (ft)	9	12	11.64	11	16	12.00
Shoulder width (ft)	0	12	7.72	0	13	10.12
Rolling terrain (1=yes)	0	1	0.333	0	1	0.017

Table 13. Descriptive statistics for variables in Database B with period crashes and retroreflectivity values.

Variable name	933 rural 2-lane segments (3095.5 mi)			1103 freeway segments (2065.0 mi)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Period crashes						
Nighttime crashes	0	11	0.615	0	6	0.265
Single vehicle nighttime crashes	0	11	0.586	0	5	0.215
Nighttime fatal injury crashes	0	3	0.037	0	3	0.039
Single vehicle nighttime fatal injury crashes	0	2	0.029	0	2	0.024
Retroreflectivity variables (imputed)						
WEdge	50	490	250.0	50	556	247.5
YCntr	50	335.5	152.8			
WLane				50	761	238.9
YEdge				50	409	169.4
Segment variables						
Length (mi)	0.019	21.744	3.317	0.038	9.349	1.890
Average daily traffic	196	32,720	5,494	1,508	111,047	27,156
Lane width (ft)	9	12	11.64	11	16	12.00
Shoulder width (ft)	0	12	7.72	0	13	10.12
Rolling terrain (1=yes)	0	1	0.333	0	1	0.017

The crash data (nighttime crashes and single vehicle nighttime crashes) from rural 2-lane roadways and freeways were fitted separately using the NB regression models. Generalized estimation equations (GEE) were used again for estimation to account for correlations in repeated observations from the same segment over time. Because there were almost no nighttime fatal plus injury crashes and single vehicle nighttime fatal plus injury crashes, models for nighttime fatal plus injury crashes and single vehicle nighttime fatal plus injury crashes could not be estimated reliably.

Negative binomial regression for the data from rural 2-lane roadways in Database B

Table 14 contains the results of fitting NB models with year (2002-2008), month (4-10), WEdge retroreflectivity value, YCntr retroreflectivity value, lane width, right shoulder width, rolling terrain, and log(AADT) as predictors and log(segment length) as an offset variable to monthly nighttime crashes and monthly single vehicle nighttime crashes from rural 2-lane roadways. It can be observed from the table that the effects of WEdge on nighttime crashes and single vehicle night crashes were statistically significant at α=0.1. The estimated coefficient for WEdge retroreflectivity for nighttime and single vehicle night crashes is -0.0006, which can be associated with the percent crash reduction of 0.06% (=$(1-e^{-0.0006})\times100$) as retroreflectivity increases by 1 (unit). If retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the percent reduction in monthly nighttime and single vehicle night crashes are 0.6% (=$(1-e^{-0.006})\times100$) and 5.8% (=$(1-e^{-0.06})\times100$), respectively. Note again that the relationship is only associative and not causative.

Table 14. Estimates of regression coefficients of negative binomial regression models applied to monthly crash data from 933 rural 2-lane roadway segments in Database B.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		**-5.1321 (<.0001)**	**-4.9388 (<.0001)**
Year	2002	**−0.1765 (0.0334)**	**−0.1696 (0.0435)**
	2003	0.0490 (0.4062)	0.0727 (0.2279)
	2004	−0.0765 (0.1202)	**−0.0853 (0.0957)**
	2005	**−0.1951 (<.0001)**	**−0.2032 (<.0001)**
	2006	**−0.1969 (0.0188)**	**−0.0986 (0.0191)**
	2007	−0.0254 (0.5111)	−0.0314 (0.4305)
	2008	0.0000 (.)	0.0000 (.)
Month	4	**-1.0031 (<.0001)**	**-1.0005 (<.0001)**
	5	**-0.9565 (<.0001)**	**-0.9558 (<.0001)**
	6	**-0.9273 (<.0001)**	**-0.9213 (<.0001)**
	7	**-1.1313 (<.0001)**	**-1.1511 (<.0001)**
	8	**-1.3108 (<.0001)**	**-1.3292 (<.0001)**
	9	**-0.7551 (<.0001)**	**-0.7677 (<.0001)**
	10	0.0000 (.)	0.0000 (.)
WEdge		**-0.0006 (0.0879)**	**-0.0006 (0.0773)**
YCntr		-0.0006 (0.3343)	-0.0005 (0.4469)
Lane Width		-0.0149 (0.7795)	-0.0202 (0.7109)
Shoulder Width		**0.0403 (0.0047)**	**0.0454 (0.0022)**
Rolling Terrain		**-0.1358 (0.0054)**	**-0.1259 (0.0117)**
Log(AADT)		**0.4373 (<.0001)**	**0.4110 (<.0001)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

Next, NB models with year (2002-2008), period (Period 1: April-May, Period 2: September-October), WEdge retroreflectivity value, YCntr retroreflectivity value, lane width, right shoulder width, rolling terrain, and log(AADT) as predictors and log(segment length) as an offset variable are fitted to period nighttime crashes and period single vehicle nighttime crashes from rural 2-lane roadways. The dataset consisting of only spring and fall crashes (period 1 and period 2 crashes) might be free from the issue of striping during the summer, and the effects of retroreflectivity on crashes might be identified more clearly based on the period crash data. Table 15 contains the results of fitting the NB models to the period data. It can be observed from the table that the effects of WEdge on nighttime crashes and single vehicle night crashes were statistically significant at α=0.1. The estimated coefficient for WEdge retroreflectivity for nighttime and single vehicle night crashes is -0.0010, which correspond to the percent crash reduction of 0.1% (=(1-$e^{-0.001}$)$\times$100) as retroreflectivity increases by 1 (unit). This implies that the 10 mcd/m^2/lx increase and 100 mcd/m^2/lx increase of WEdge retroreflectivity can be associated with the 1% (=(1-$e^{-0.01}$)$\times$100) and 9.5% (=(1-$e^{-0.1}$)$\times$100) reduction in period nighttime and single vehicle nighttime crashes, respectively. To determine whether the effect of retroreflectivity on crashes is different for a different range of retroreflectivity values, NB models were also fitted using a subset of the data with YCntr retroreflectivity values <=200 mcd/m^2/lx and a subset of the data with YCntr<=150 mcd/m^2/lx. The results were similar to those of Table 15 in both cases.

Table 15. Estimates of regression coefficients of negative binomial regression models applied to period crash data from 933 rural 2-lane roadway segments in Database B.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		**-5.5830 (<.0001)**	**-5.3805 (<.0001)**
Year	2002	**–0.2941 (<.0001)**	**–0.2957 (<.0001)**
	2003	-0.0561 (0.3878)	-0.0683 (0.3009)
	2004	**–0.1222 (0.0324)**	**–0.1259 (0.0329)**
	2005	**–0.2002 (0.0001)**	**–0.2075 (0.0001)**
	2006	**–0.1557 (0.0029)**	**–0.1530 (0.0038)**
	2007	–0.0582 (0.2136)	–0.0621 (0.1914)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	-**0.7290 (<.0001)**	-**0.7220 (<.0001)**
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		**-0.0010 (0.0201)**	**-0.0010 (0.0169)**
YCntr		-0.0007 (0.3377)	-0.0005 (0.4855)
Lane Width		0.0392 (0.5043)	0.0298 (0.6187)
Shoulder Width		**0.0436 (0.0048)**	**0.0495 (0.0023)**
Rolling Terrain		**-0.1709 (0.0017)**	**-0.1580 (0.0045)**
Log(AADT)		**0.4799 (<.0001)**	**0.4561 (<.0001)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

Negative binomial regression for the data from freeways in Database B

For freeway crashes, reliable models for fatal plus injury nighttime crashes and single vehicle nighttime fatal plus injury crashes could not be developed, again due to an extremely small number crashes for those crash types. Table 16 contains the results of fitting the NB model to monthly nighttime crashes and monthly single vehicle nighttime crashes from freeways in Database B. It can be observed from the table that the effect of WEdge retroreflectivity on single vehicle night crashes was statistically significant at α=0.1. The estimated coefficient for WEdge retroreflectivity for single vehicle night crashes is -0.0009, which correspond to the percent crash reduction of 0.09% (=(1-$e^{-0.0009}$)$\times$100) as retroreflectivity increases by 1 (unit). If WEdge retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the associated percent reduction in period single vehicle night crashes can be expected to be 0.9% (=(1-$e^{-0.009}$)$\times$100) and 8.6% (=(1-$e^{-0.09}$)$\times$100), respectively.

Table 16. Estimates of regression coefficients of negative binomial regression models applied to monthly crash data from 1103 freeway segments in Database B.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		-3.1181 (0.1793)	-0.5180 (0.8236)
Year	2002	**−0.7264 (<.0001)**	**−0.8814 (<.0001)**
	2003	**-0.2585 (0.0004)**	0.3910 **(<.0001)**
	2004	−0.0050 (0.9368)	**−0.1198 (0.0707)**
	2005	**−0.1038 (<.0718)**	**−0.1943 (0.0019)**
	2006	**−0.1568 (0.0029)**	**−0.1963 (0.0005)**
	2007	−0.0534 (0.2933)	−0.0834 (0.1157)
	2008	0.0000 (.)	0.0000 (.)
Month	4	-**1.3162 (<.0001)**	-**1.4605 (<.0001)**
	5	**-0.6676 (<.0001)**	**-0.6602 (<.0001)**
	6	**-0.8182 (<.0001)**	**-0.8156 (<.0001)**
	7	**-1.3271 (<.0001)**	**-1.4122 (<.0001)**
	8	**-1.4048 (<.0001)**	**-1.6928 (<.0001)**
	9	**-0.9905 (<.0001)**	**-1.0824 (<.0001)**
	10	0.0000 (.)	0.0000 (.)
WEdge		-0.0006 (0.2100)	**-0.0009 (0.0671)**
WLane		0.0003 (0.4867)	0.0003 (0.5492)
YEdge		-0.0008 (0.2259)	-0.0007 (0.3371)
Lane Width		-0.1326 (0.4984)	-0.2255 (0.2506)
Shoulder Width		0.0058 (0.9076)	0.0280 (0.6173)
Rolling Terrain		-0.1910 (0.2387)	-0.2135 (0.2121)
Log(AADT)		**0.3092 (<.0001)**	**0.1318 (0.0002)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

For period nighttime crashes and period single vehicle nighttime crashes from freeways, NB models with year (2002-2008), period (Period 1: April-May, Period 2: September-October), WEdge retroreflectivity value, YCntr retroreflectivity value, lane width, right shoulder width, rolling terrain, and log(AADT) as predictors and log(segment length) as an offset variable were fitted. Table 17 contains the results of fitting the NB models to the period freeway crash data. It can be observed from the table that the effect of YEdge retroreflectivity on nighttime crashes and the effect of WEdge retroreflectivity on single vehicle night crashes were statistically significant at α=0.1. The estimated coefficient for YEdge retroreflectivity for nighttime and WEdge retroreflectivity for single vehicle night crashes are -0.0013 and -0.0009, respectively, which correspond to the percent crash reduction of 0.13% (=$(1-e^{-0.0013})\times100$) and 0.09% (=$(1-e^{-0.0009})\times100$), respectively, as retroreflectivity increases by 1 (unit). If YEdge retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the associated percent reduction in period nighttime crashes are estimated to be 1.3% (=$(1-e^{-0.013})\times100$) and 12.2% (=$(1-e^{-0.13})\times100$), respectively. If WEdge retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the associated percent reduction in period single vehicle night crashes are estimated to be 0.9% (=$(1-e^{-0.009})\times100$) and 8.6% (=$(1-e^{-0.09})\times100$), respectively.

Table 17. Estimates of regression coefficients of negative binomial regression models applied to period crash data from 1103 freeway segments in Database B.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		-0.9739 (0.6717)	1.3921 (0.5451)
Year	2002	**–0.6530 (<.0001)**	**–0.8109 (<.0001)**
	2003	**-0.2571 (0.0018)**	-0.3974 **(<.0001)**
	2004	–0.0581 (0.4440)	**–0.1777 (0.0262)**
	2005	–0.0541 (0.4246)	**–0.1374 (0.0614)**
	2006	–0.2867 **(<.0001)**	**–0.3082 (<.0001)**
	2007	–0.0403 (0.4995)	–0.0630 (0.3243)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	-**0.6395 (<.0001)**	-**0.6672 (<.0001)**
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		-0.0006 (0.2197)	**-0.0009 (0.0937)**
WLane		0.0000 (0.9680)	-0.0001 (0.8625)
YEdge		**-0.0013 (0.0740)**	-0.0013 (0.1087)
Lane Width		-0.2625 (0.1762)	**-0.3296 (0.0899)**
Shoulder Width		0.0091 (0.8575)	0.0364 (0.5230)
Rolling Terrain		**-0.4008 (0.0427)**	**-0.4625 (0.0294)**
Log(AADT)		**0.2984 (<.0001)**	**0.1083 (0.0031)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

To determine whether the effect of retroreflectivity on crashes is different for a different range of retroreflectivity values, NB models were also fitted using a subset of the data with retroreflectivity values for all three line types (WEdge, WLane, and YEdge) are less than or equal to 200 mcd/m^2/lx. The results are presented in Table 18. It can be observed from the table that the effects of WLane retroreflectivity on both of nighttime crashes and single vehicle night crashes became statistically significant at α=0.1 when retroreflectivity values are low (<=200 mcd/m^2/lx). The estimated coefficient for WLane retroreflectivity for nighttime and for single vehicle night crashes is -0.0027 in both cases, which corresponds to the percent crash reduction of 0.27% ($=(1-e^{-0.0027})\times 100$), as retroreflectivity increases by 1 (unit). If WLane retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the associated percent reduction in period nighttime crashes and single vehicle night crashes are estimated to be 2.7% ($=(1-e^{-0.027})\times 100$) and 23.7% ($=(1-e^{-0.27})\times 100$), respectively.

Table 18. Estimates of regression coefficients of negative binomial regression models applied to period crash data from freeway segments with WEdge <=200 mcd/m^2/lx, WLane<=200 mcd/m^2/lx, and YEdge <=200 mcd/m^2/lx in Database B.

Variable		Nighttime crashes	Single vehicle nighttime crashes
Intercept		**4.8650(0.0711)**	**7.0493(0.0127)**
Year	2002	-1.1523(0.1282)	-1.0763(0.1638)
	2003	-0.2056(0.2174)	-0.2583(0.1506)
	2004	-0.0068(0.9648)	-0.0925(0.5728)
	2005	0.0284(0.8592)	-0.0298(0.8674)
	2006	-0.2130(0.1832)	-0.1769(0.2874)
	2007	-0.2032(0.1808)	-0.2176(0.1709)
	2008	0.0000 (.)	0.0000 (.)
Period	Apr-May	**-1.1423(<.0001)**	**-1.2330(0.0002)**
	Sep-Oct	0.0000 (.)	0.0000 (.)
WEdge		-0.0008(0.5925)	-0.0019(0.2666)
WLane		**-0.0027(0.0455)**	**-0.0027(0.0674)**
YEdge		0.0001(0.9655)	0.0016(0.4620)
Lane Width		**-0.6351(0.0077)**	**-0.7352(0.0031)**
Shoulder Width		-0.0724(0.5284)	-0.0133(0.8995)
Rolling Terrain		-0.4305(0.3277)	-0.5866(0.1990)
Log(AADT)		**0.3092(<.0001)**	**0.1381(0.0500)**

Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.1 are denoted in bold.

FINDINGS

The relationship between crashes and retroreflectivity was explored based on two databases developed in this project. Nighttime crash frequencies and single vehicle nighttime crash frequencies were analyzed by the Negative Binomial regression models having retroreflectivity of different line types and roadway characteristics variables as predictors. To account for possible correlations in the repeated observations from the same segment over time, the

Generalized Estimating Equations (GEE) method was used in the estimation. Crashes from rural 2-lane road segments and freeways were analyzed separately.

The effect of YCntr retroreflectivity (while controlling for the effect of WEdge retroreflectivity as well as other roadway characteristics variables in the model) on nighttime crashes and single vehicle nighttime crashes on rural 2-lane road segments with low YCntr retroreflectivity (YCntr<=150 mcd/m^2/lx) in Database A was found to be statistically significant. The negative YCntr coefficient estimate suggested that expected crash frequency decreases as the YCntr retroreflectivity increases, specifically in the low range (YCntr<=150 mcd/m^2/lx).

The effect of WEdge retroreflectivity (while controlling for the effect of YCntr retroreflectivity as well as other roadway characteristics variables in the model) on nighttime crashes and single vehicle nighttime crashes on rural 2-lane road segments in Database B was found to be statistically significant. The negative WEdge coefficient estimate suggested that expected crash frequency decreases as the WEdge retroreflectivity increases.

The effects of YEdge retroreflectivity (while controlling for the effect of WEdge and WLane retroreflectivity as well as other roadway characteristics variables in the model) on nighttime crashes and WEdge retroreflectivity (while controlling for the effect of WLane and YEdge retroreflectivity as well as other roadway characteristics variables in the model) on single vehicle nighttime crashes on freeway segments in Database B were also found to be statistically significant. The negative coefficients suggested that expected nighttime crash frequency decreases as the YEdge retroreflectivity increases, and expected single vehicle nighttime crash frequency decreases as the WEdge retroreflectivity increases.

The effects of WLane retroreflectivity (while controlling for the effect of WEdge and YEdge retroreflectivity as well as other roadway characteristics variables in the model) on both nighttime crashes and single vehicle night crashes on freeway segments with low retroreflectivity values for WEdge, WLane, and YEdge in Database B were also found to be statistically significant. The negative coefficients suggested that expected nighttime crash frequency and single vehicle nighttime crash frequency decrease as the WLane retroreflectivity increases at the freeway segments with low retroreflectivity values.

CONCLUSIONS

The findings presented above lend support to the positive safety effects of maintaining retroreflectivity of pavement markings. There was not attempt here to develop or validate thresholds of retroreflectivity. However, the findings here provide the most compelling evidence demonstrating that maintenance of pavement markings retroreflectivity can have a positive effect on safety. It needs to be noted that throughout the report the relationship between crashes and retroreflectivity is only associative and should not be interpreted as a cause-effect relationship.

The inherent limitation of the current retroreflectivity data such that the measurements are available only at certain locations and times hinder establishing the relationship between crashes and retroreflectivity without extensive imputation of the original retroreflectivity data. Regularly scheduled measurements (e.g., each month) of retroreflectivity of pavement markings at road segments that can be easily connected to the crash database as well as maintaining the crash-retroreflectivity database will greatly aid the evaluation of relationships between crash and longitudinal pavement marking retroreflectivity.

CAVEATS

To date, this study included the most comprehensive set of retroreflectivity data for safety analyses. Michigan DOT has been measuring and recording their statewide pavement markings retroreflectivity levels probably longer than any other agency in the US. Despite the availability of the retroreflectivity data, limitations existed. For instance, the restriping dates were not always available which leads to some uncertainty regarding the age of the markings. In addition, it would be ideal but impractical to have retroreflectivity data for each segment for each month in order to avoid the imputation efforts.

Based on their long standing pavement marking retroreflectivity measurement program, the Michigan DOT is devoted to maintaining their pavement markings. The average retroreflectivity values were 177 mcd/m^2/lx for YCntr, 198 mcd/m^2/lx for YEdge, 310 mcd/m^2/lx for Wedge, and 297 mcd/m^2/lx for WLane. Before imputation, only a small portion all the readings were below 100 mcd/m^2/lx. Since most of the measurements are made late in the season, they are made on restriped highways before the winter months. The imputation efforts included typical degradation rates generated from the Michigan DOT data when readings were available on the same segments before and after a winter season. Initial implementation of the degradation rates through the winters resulted in some negative spring time retroreflectivity levels, particularly when the pre-winter retroreflectivity level was unusually low. In these cases, a rule was established in the imputation algorithm that minimized imputed retroreflectivity to a level of 50 mcd/m^2/lx.

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