Nighttime Safety and Pavement Marking Retroreflectivity on Two-Lane Highways: Revisited with North Carolina Data

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ABSTRACT

The relationship between pavement marking retroreflectivity and nighttime safety has been a topic of research for past decade or more but consistent findings have been elusive despite the intuitive nature of having bright markings. This paper builds from previous work that used Michigan retroreflectivity and crash data to demonstrate that pavement marking retroreflectivity relates to the nighttime safety on rural two-lane highways in a meaningful way. In this paper, new data from North Carolina were obtained and used. The North Carolina data were used to test the robustness of the statistical models derived from the Michigan data. Additional analyses were also explored and described in this paper. Using results from this paper, previous research, and state of the practice, recommendations and their implications are presented for safety-derived minimum retroreflectivity levels for pavement markings.

Keywords:

Safety modeling, retroreflectivity, pavement markings, night crashes

INTRODUCTION

During the 2014 TRB Annual Meeting, research results were shared that included new findings regarding the understanding of nighttime safety and pavement marking retroreflectivity (*1*). Those results indicate that, in general, retroreflectivity relates to the nighttime safety on rural two-lane highways in a meaningful way. The results showed that sites with high retroreflectivity values are associated with fewer crashes than sites with low retroreflectivity. After accounting for other influential factors, the analysis found that retroreflectivity of both white edge and yellow center jointly contribute to explaining crashes.

As the results of the aforementioned research presented during the 2014 TRB Annual Meeting were being shared and discussed throughout the country, the interest level quickly grew. It was not long after the results were made public that a new opportunity to expand the effort with additional data developed. Through a joint effort between the American Traffic Safety Services Association (ATSSA) and the Federal Highway Administration (FHWA), the researchers were able to expand the analysis by including data from the North Carolina Department of Transportation. This data was used to supplement the previous work which was developed entirely with data from the Michigan Department of Transportation (1-2). Having another set of data from a different region of the country was particularly valuable since Michigan DOT is primarily a paint state (i.e., they use waterborne paint for most of their markings and they re-stripe most roads annually) and North Carolina is primarily a thermoplastic state (i.e., they use a pavement marking material that typically provides multiple years of service). There was considerable interest to see if the results from Michigan could be repeated with the North Carolina data.

This paper continues to build from the previous results briefly described above. In this paper, new data and additional analyses techniques were employed to better understand the combined effects of edge line and center line pavement marking retroreflectivity levels on rural two-lane highways.

BACKGROUND

On April 22, 2010, the Federal Highway Administration (FHWA) published in the Federal Register a Notice of Proposed Amendment (NPA) to amend the Manual on Uniform Traffic Control Devices (MUTCD). This amendment included standards, guidance, options, and supporting information related to maintaining minimum levels of retroreflectivity for pavement markings. The NPA was issued in response to section 406 of the Department of Transportation and Related Agencies Appropriations Act, 1993 (Pub. L. 102-388; October 6, 1992). Section 406 of the Act directed the Secretary of Transportation to “revise the Manual on Uniform Traffic Control Devices to include – (a) a standard for a minimum level of retroreflectivity that must be maintained for pavement markings and signs, which shall apply to all roads open to public travel.” Improving safety throughout the transportation network is the primary goal of the Department of Transportation. The FHWA’s intent in regard to including minimum retroreflectivity levels in the MUTCD is to advance safety by meeting the nighttime visibility needs of the driver on our Nation’s roads. The comment period for the NPA related to pavement marking retroreflectivity closed on August 20, 2010. The FHWA received 105 letters that were submitted to the docket containing about 700 individual comments on the NPA. As of August 2014, the FHWA has not responded to the comments.

It should be noted that the FHWA minimum retroreflectivity levels proposed in the NPA were developed based on the visibility needs of nighttime drivers. This is different from safety-derived minimum retroreflectivity levels, which is the focus of the work described in this paper.

DATABASE DEVELOPMENT

The data used in this research consist of retroreflectivity data tables, crash report tables, roadway segment tables collected from 2001 through 2009. The retroreflectivity data were received from the NCDOT. Crash data and roadway segment data were received from the HSIS (Highway Safety Information System) database. Since the source tables contain different types of data attributes and formats, significant database development efforts were needed to link and combine the tables to create the final retroreflectivity-crash-road table prior to statistical analysis as described in the sections below.

Retroreflectivity Data Table

The initial two-lane retroreflectivity (RL) table received from NCDOT includes Retro ID number, Project Number, Run Length, Travel Direction, Begin Milepost, End Milepost, Type of Line, Date of RL Reading, RL Readings, and so on. The bidirectional RL readings taken at the same month-year at the same segment were averaged during the database process so that the final monthly retro table could be combined with monthly crash values by road segments. After the initial cleaning and preprocess, the base retroreflectivity table includes total 1,229 retroreflectivity values for two major line types (YCntr, and WEdge) from 283 retroreflectivity segments before matching with crash data. As shown in Figure 1, most of the retroreflectivity values were recorded from April through July with highest percentage at June.

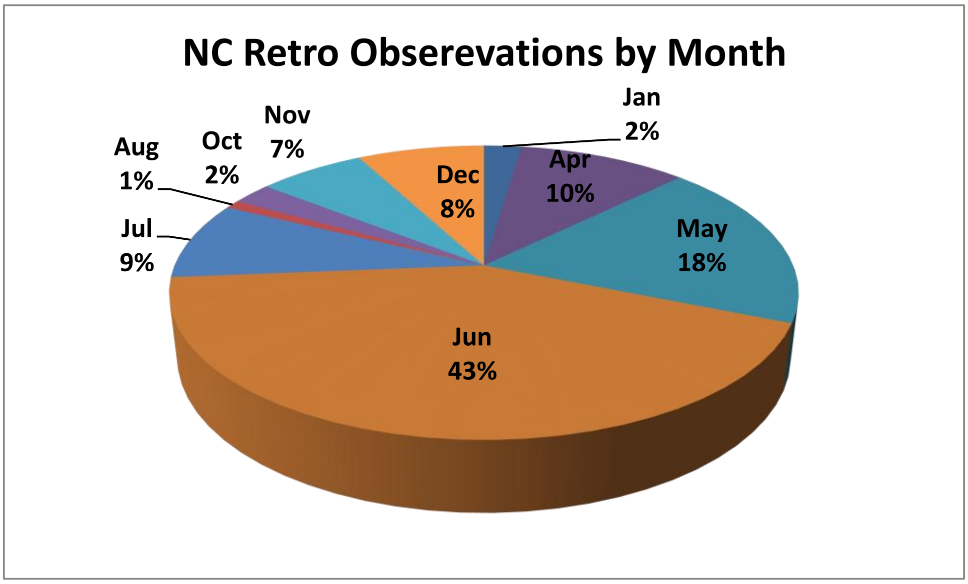

Figure 1. Percentage of retroreflectivity observations by month

An initial review of retroreflectivity values by line type is shown in Figure 2 and indicates that the yellow center markings are mostly between 150 and 250 mcd/m^2/lx. In contrast, most of the white edge markings have measurements between 250 and 400 mcd/m^2/lx. The average retroreflectivity value of YCntr is 196 mcd/m^2/lx and WEdge 328 mcd/m^2/lx. For Michigan, the average retroreflectivity of the YCntr was 177 mcd/m^2/lx and the average value of the WEdge was 310 mcd/m^2/lx.

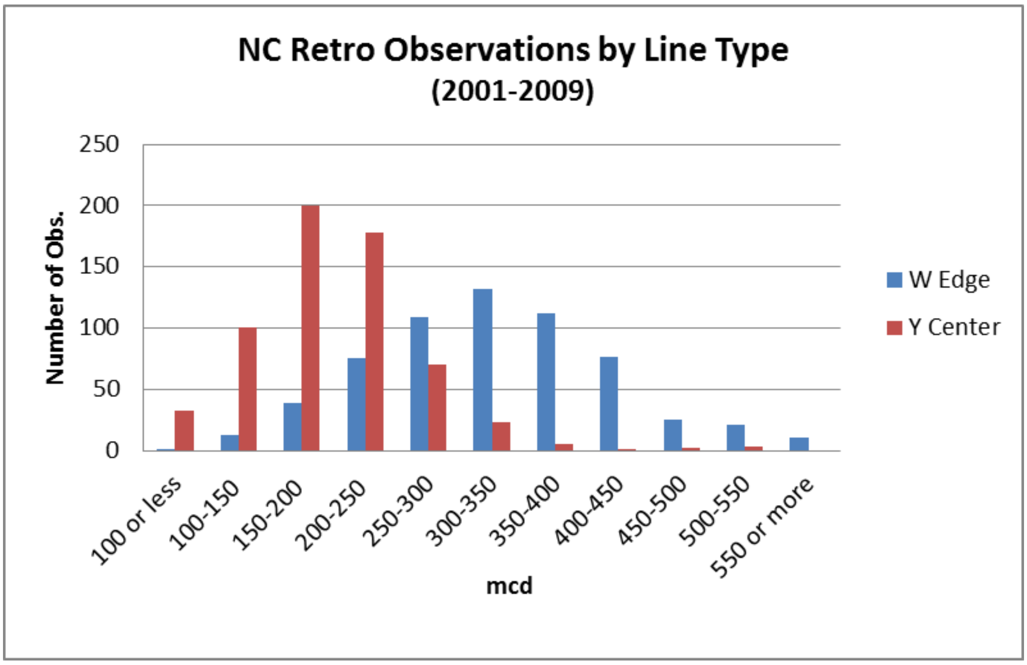

Figure 2. Distribution of retroreflectivity values by line type

Crash and Road Data Tables

The crash data and road data tables obtained from the HSIS database contains detailed information about crashes and roadway segments where crashes occurred such as crash id, crash location, severity, accident type, light condition, and road condition. Table 1 shows the major field names by category imported into the retro database for joining.

Table 1. Major field names of crash and road database

Category	Field Names
Crash Location & Roadway Information	Accident date
	County-Route number
	Beginning milepost of a road segment
	End milepost of a road segment
	Accident milepost
	AADT
	Number of lanes
	Right shoulder width
	Speed limit
	Total percent trucks
Severity	Fatal
	Injury
	Property Damage Only
Accident Type	Single Vehicle
	Head-on
	Sideswipe Same Direction
	Sideswipe Opposite Direction
	Ran-off-road accidents
Light Condition	day
	night

Development of Databases

To maximize the use of retroreflectivity readings researchers selected the retroreflectivity table as basic spatial and temporal units where the crash records and the road records were matched. As shown in Figure 3 monthly crash records were joined to the retroreflectivity table by retroreflectivity segment and crash year-month values. Similarly yearly road records were joined to the retroreflectivity table by retroreflectivity segment and year values. In the database all urban retro segments were excluded before joining so that the final retroreflectivity -crash-road table includes only rural two-lane roads.

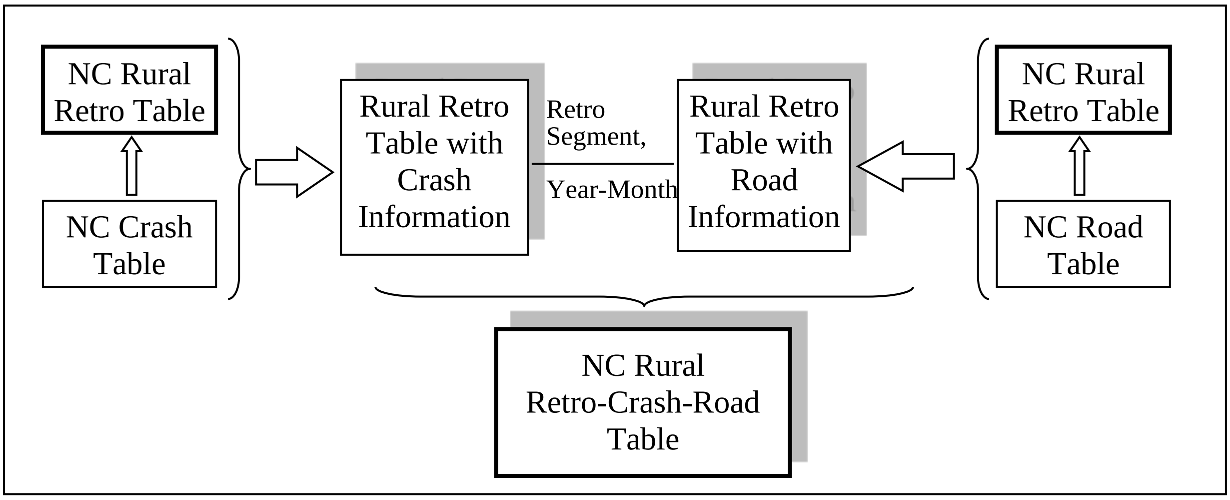

Figure 3. Schematic Diagram of retroreflectivity-crash-road database

STATISTICAL ANALYSIS USING GENERALIZED ESTIMATING EQUATIONS

The objective of this analysis is to evaluate the relationships between crashes and retroreflectivity levels on rural 2-lane roadways in North Carolina. The following types of crashes were initially identified as target crashes for this study: nighttime, nighttime single vehicle, nighttime fatal plus injury, and nighttime single vehicle fatal plus injury. The North Carolina retroreflectivity dataset originally contained 572 data points with actual measurements of both WEdge and YCntr representing 264 segments (680.7 miles).

The retroreflectivity measurement data were available for 9 years (2001-2009). When the monthly crashes and roadway characteristic variables were combined with the retroreflectivity measurement data, 30 of the original 264 segments did not have the corresponding AADT values, which reduced the number of usable data points for the analysis down to 507 points corresponding to 234 segments (616.8 miles).

contains the descriptive statistics for the variables in the North Carolina dataset.

Table 2 Summary statistics for 234 segments (616.8 miles) in North Carolina

Variable	Minimum	Maximum	Average	Std Dev	Total
Monthly crashes					
Nighttime crashes (NtAcc)	0	4	0.168	0.531	85
Nighttime single vehicle crashes (NtSV)	0	4	0.144	0.467	73
Nighttime fatal plus injury crashes (NtFatInj)	0	2	0.051	0.254	26
Nighttime single vehicle fatal plus injury crashes (NtSVFatInj)	0	2	0.041	0.218	21
Retroreflectivity variables					
WEdge	88	597	327.54	92.62	
YCntr	65	515	196.35	60.85	
Segment variables					
Segment Length (mi)	0.1	25.13	2.64	2.58	
Annual Average Daily Traffic	30	13,000	2,811	3,138	
Percent truck	0	36.4	8.3	3.3	
Right Shoulder width (ft)	0	12	5.60	1.88	

During the course of data analysis, it was discovered that the relationship between crash and retroreflectivity could be significantly confounded by seasonal variation throughout the year. The researchers designated a variable named “Summertime” to account for this variation.

Error! Not a valid bookmark self-reference. shows the average monthly crashes and average retroreflectivity two levels of variable Summertime (defined to be 1 for March-October and 0 for November-February). As this table shows, the average number of crashes is much higher (four times higher for nighttime crashes, for example) during the wintertime period as compared to the summertime period while the retroreflectivity values are higher during the wintertime period. This difference may reflect increased nighttime exposure (i.e. longer nighttime during non-summertime months), seasonal changes in traffic patterns, the influence of weather, among various possible explanations. Failing to accounting for this difference in exposure may result in masking the true effects of pavement marking retroreflectivity. Researchers, therefore, added ‘Summertime’ to the list of predictors in modeling crash-retro relationship.

Table 3 Averages for monthly crashes and retroreflectivity values for each of summertime and wintertime periods

Variable	**Average**	
	Summertime (March-October)	**Wintertime (November-February)**
Monthly crashes		
Nighttime crashes (NtAcc)	0.102	0.457
Nighttime single vehicle crashes (NtSV)	0.082	0.415
Nighttime fatal plus injury crashes (NtFatInj)	0.044	0.085
Nighttime single vehicle fatal plus injury crashes (NtSVFatInj)	0.034	0.074
Retroreflectivity variables		
WEdge	318.94	365.29
YCntr	188.98	228.71

The Negative Binomial (NB) regression models were fitted to the monthly crash data from North Carolina . These models include retroreflectivity values for edge line pavement marking (WEdge) and center line pavement marking (YCntr), percent truck, log(AADT), and Summertime (1: March-October, 0: November-February) as predictors and log(segment length) as an offset variable. Generalized Estimating Equations (GEE) were used to account for potential correlations in repeated observations from the same segment over time. The GENMOD procedure in SAS was used for the NB regression analyses with GEE. Table 4 presents the estimated model coefficients for each of four crash types considered.

Table 4 Coefficient Estimates of Negative Binomial Regression Models on Monthly Nighttime Crash Data in North Carolina (234 Rural 2-Lane Roadway Segments)

Variable	**NtAcc**	**NtSV**	**NtFatInj**	**NtSVFatInj**
Intercept	**-4.0887 (<.0001)**	**-3.5295 (0.0001)**	**-7.1592 (0.0029)**	**-6.6329 (0.0063)**
WEdge	-0.0024 (0.2837)	-0.0032 (0.1535)	-0.0039 (0.3466)	-0.0054 (0.2326)
YCntr	0.0030 (0.3454)	0.0039 (0.2530)	0.0037 (0.5836)	0.0066 (0.3123)
Percent truck	0.0206 (0.5475)	0.0201 (0.5371)	-0.0236 (0.5930)	-0.0270 (0.5487)
Log(AADT)	**0.2765 (0.0313)**	0.2001 (0.1219)	**0.5383 (0.0242)**	0.4385(0.0622)
Summertime	**-1.6947 (<.0001)**	**-1.7610 (<.0001)**	-0.7642 (0.1495)	-0.8291 (0.1443)
Notes: 1. P-values are given in parentheses 2. Statistically significant effects at α=0.05 are denoted in bold.				

It can be observed from Table 4 that the coefficients of WEdge are consistently negative for all four crash types (indicating that the expected crash frequency decrease as the WEdge retroreflectivity increases) although none of them are statistically significant at α=0.05. In the study of the Michigan data (2) the estimated coefficient for WEdge retroreflectivity for nighttime and nighttime single vehicle crashes was approximately -0.0010, which corresponds to a percent crash reduction of 0.1% and 9.5% for each increase in the retroreflectivity level of WEdge by 1 mcd/m^2/lux and by 100 mcd/m^2/lux, respectively, over the range from 150 to 450 mcd/m^2/lux.

In the case of Table , the estimated coefficients for WEdge retroreflectivity for nighttime and nighttime single vehicle crashes are -0.0024 and -0.0032, respectively, which can be associated with the percent crash reduction of approximately 0.2% (0.86=(1-$e^{-0.0024}$)×100) and 0.3% (1.28=(1-$e^{-0.0032}$)×100) as retroreflectivity increases by 1 mcd/m^2/lux and 21.3% (0.86=(1-$e^{-0.24}$)×100) and 27.4% (1.28=(1-$e^{-0.32}$)×100) as retroreflectivity increases by 100 mcd/m^2/lux, over the range from 176 to 597 mcd/m^2/lux. Although the effect size of WEdge retroreflectivity on crashes in North Carolina are somewhat larger than that of Michigan, they are still of the same order of magnitude. This may be explained by the inclusion of wintertime crashes in the current analysis, since those crashes were not included in the Michigan evaluation (2).

To see if the effects of WEdge and YCntr on crashes are different (in magnitude) for each of summertime and wintertime, researchers also fitted the model to each of summertime crash data and wintertime crash data, separately. Table 5 contains the results of fitting NB models with WEdge retroreflectivity value, YCntr retroreflectivity value, percent truck, and log(AADT) as predictors and log(segment length) as an offset variable to monthly nighttime crashes and monthly nighttime fatal plus injury crashes for wintertime data. Because of insufficient data, models for nighttime single vehicle crashes and nighttime single vehicle fatal plus injury crashes could not be estimated reliably.

Table 5 Coefficient Estimates of Negative Binomial Regression Models Applied to Wintertime Monthly Nighttime Crash Data (November-February)

Variable	**NtAcc**	**NtFatInj**
Intercept	**-3.2095 (0.0110)**	**-5.0234 (0.0217)**
WEdge	**-0.0086 (0.0084)**	*-0.0129 (0.0795)*
YCntr	0.0053 (0.1020)	0.0005 (0.9459)
Percent truck	**-0.1037 (0.0036)**	**-0.1901 (0.0049)**
Log(AADT)	**0.5001 (0.0027)**	**0.9118 (0.0003)**
Notes: 1. P-values are given in parentheses; 2. Statistically significant effects at α=0.05 are denoted in bold; 3. Statistically significant effects at α=0.1 are denoted in italic.		

Table shows that the effects of WEdge on wintertime nighttime crashes and nighttime fatal plus injury crashes were much stronger than those in Table 4 and also statistically significant (at α=0.05 for nighttime crashes and at α=0.1 for nighttime fatal plus injury crashes). The estimated coefficients for WEdge retroreflectivity for nighttime and nighttime fatal plus injury crashes are -0.0086 and -0.0129, respectively, which can be associated with the percent crash reduction of approximately 0.9% (0.86=(1-$e^{-0.0086}$)×100) and 1.3% (1.28=(1-$e^{-0.0129}$)×100) as retroreflectivity increases by 1 (unit). If retroreflectivity increases by 10 mcd/m^2/lx and by 100 mcd/m^2/lx, the associated percent reduction in wintertime nighttime crashes are estimated to be 8.2% (=(1-e$^{-0.086}$)×100) and 57.7% (=(1-e$^{-0.86}$)×100), respectively. For wintertime nighttime fatal plus injury crashes, the associated percent reduction correspond to 12.1% (=(1-e$^{-0.129}$)×100) and 72.5% (=(1-e$^{-1.29}$)×100), respectively. Table 6 contains the results of fitting the NB models with WEdge retroreflectivity value, YCntr retroreflectivity value, percent truck, and log(AADT) as predictors and log(segment length) as an offset variable to monthly crash data for summertime data.

TABLE 6 Coefficient Estimates of Negative Binomial Regression Models applied to Wintertime Monthly Nighttime Crash Data (March-October)

Variable	NtAcc	NtSV	NtFatInj	NtSVFatInj
Intercept	**-6.4870 (<.0001)**	**-5.7933 (<.0001)**	**-8.6955 (0.0032)**	**-8.3537 (0.0049)**
WEdge	0.0015 (0.5621)	0.0009 (0.6998)	-0.0015 (0.7504)	-0.0027 (0.5701)
YCntr	0.0019 (0.6500)	0.0026 (0.6073)	0.0046 (0.5428)	0.0077 (0.2691)
Percent truck	**0.0881 (0.0109)**	**0.1030 (0.0029)**	0.0271 (0.5646)	0.0279 (0.5558)
Log(AADT)	0.1469 (0.3744)	0.0152 (0.9194)	0.4558 (0.1398)	0.3508 (0.2443)

Notes:
1. P-values are given in parentheses; 2. Statistically significant effects at α=0.05 are denoted in bold.

Unlike wintertime crashes, no statistically significant effects of retroreflectivity levels on crashes are observed. The estimated coefficient for WEdge retroreflectivity for summertime nighttime fatal plus injury crashes is -0.0015, which is an order of magnitude smaller than that for wintertime nighttime fatal plus injury crashes. The insignificant results for the summertime data may again be partly explained by the much less number of crashes on average during the summertime as compared to wintertime.

STATISTICAL ANALYSIS USING GENERALIZED MIXED MODELS

The researchers performed additional analyses on the North Carolina data in order to contrast with the model specification recently proposed by Avelar and Carlson using Michigan data (1). That research proposed a model to characterize the safety association of retroreflectivity markings. Instead of using WEdge and YCntr, that research used the sum and the difference of these two retroreflectivity values as an effort to control for the inherent correlation between them. It is of interest, therefore, to examine if that specification succeeds in explaining the same relation in the data from another state.

This evaluation fitted the same model specification from the Michigan data to the North Carolina data obtained for this paper. Only total nighttime crashes were used for this comparison. The results are summarized in Table 7, with fitted individual random effects each month (which is different from the GEE analyses above). Regardless of these minor differences, the retroreflectivity values are very comparable in Table using GEE and

Table using GLMM. The sets of coefficients in these columns show the same signs, except for speed limit (which is not statistically significant).

Table 7 Mixed-Effects Models on Retroreflectivity Data from Michigan and North Carolina

Variable	MI Sum-Delta Model	NC Sum-Delta Model	NC WEdge-YCntr Model
(Intercept)	-9.692 (1.6250)***	-4.969 (1.785)**	-5.263 (0.9400)***
Ln(AADT)	0.6052 (0.07112)***	0.3048 (0.1083)**	0.3452 (0.1080)**
Ln(Segment Length)	0.9047 (0.06666)***	0.7603 (0.1512)***	0.7670 (0.1554)***
Speed Limit	0.05885 (0.02718)*	-0.03373 (0.02428)	
White.Retro			-0.00368 (0.00196)o
Yellow.Retro			0.004156 (0.002671)
Delta_Retros	0.00460 (0.00145)**	0.01326 (0.008033)*	
Sum_Retros	0.000521(0.0006572)	0.003334(0.001668)*	
Sum_Retros x Delta_Retros	-1.775×10^{-5} (6.799×10^{-6})**	-2.899×10^{-5} (1.319E-5)***	
Segment[a]	0.6083	0.5744	0.6093
Month[a]		0.628	0.601
Route[a]	0.09306		
Residual[a]	0.9201	0.8545	0.8638
NB2	18.5108	6.7483	3.6045
Number of data points	1955	507	507
Number of segments	513	234	234
Number of Parameters	10	10	9
AIC		418.83	418.98
BIC		461.12	452.81
Significance values are as follows: º p<0.1; * p < 0.05; ** p < 0.01; and *** p < 0.001			
Empty cell = not applicable [a] Variance of Random Effect			

In the case of the intercepts, the difference is not surprising since the NC data correspond to monthly crashes, whereas the MI analysis utilized periods of two months. However, in other instances, the differences in magnitude and significance have deeper implications in the meaning of the estimates. Particularly for the three coefficients for the retroreflectivity, the constituent terms for sum and delta are larger for NC, about three times for delta, about six times for sum. The interaction term in the NC model is almost twice as large compared to the MI model as well. What is disconcerting is the change in statistical significance of the constituent term of sum of retroreflectivity. For the MI Sum-Delta model, the significance of the marginal effect of sum emerges from the statistical significance of the interaction, which is negative. Therefore, in that model, sum had a negative association with number of crashes whenever the joint effect Sum-Delta is statistically significant. That is not the case for the NC Sum-Delta model coefficients in

Table . Since the constituent estimate for sum is statistically significant, as well as the intercept estimate, this set of coefficients imply that an increasing sum variable could associate with increasing number crashes and be statistically significant, a situation that presents a challenge for interpretation.

The researchers moved to find the simplest model that uses the original retroreflectivity values, WEdge and YCntr whose coefficient estimates are shown in the last column

Table . The coefficient for WEdge is statistically significant for NC WEdge-YCntr Model. Truck percentage was not found among the meaningful regressors for any of the GLMM models. These differences with Table may find explanation in part because models in Table utilized the indicator variable Summertime, whereas models in

Table fitted individual random effects each month. Regardless of these small differences, the retroreflectivity values are very comparable inTable using GEE and in

Table using GLMM.

Moving forward, the research team deemed the NC WEdge-YCntr model as the most appropriate in terms of parsimony and compatibility with other research. The monthly random effect from this model showed that crashes tend to be higher in the months of November, December and January, as it was noted in the examination of the raw data in a previous section. The researchers also noted from the raw data that there is more amplitude in the cyclical variation of WEdge than YCntr. Perhaps this characteristic contributes to explain the lack of significance of WCntr in the previous analyses.

Sensitivity Analysis of Safety Association of Retroreflectivity in North Carolina

This section explores the implications of the safety association of retroreflectivity found in

Table . It is of interest to estimate how safety is expected to vary regarding its association with the typical variation cycle of the retroreflectivity variables. Researchers collected retroreflectivity statistics by site with at least four retroreflectivity readings to assess the the ranges of their cyclical variation. Retroreflectivity datasets from 42 sites were examined in this way. Table 8 shows summary statistics for this group of sites.

Table 8 Retroreflectivity Variation Statistics by Site in 42 NC Database Segments

Retro Variable	Mean	Std.Dev	Min	Max
Min WEdge	230.39	67.16	88	342
Max WEdge	390.80	104.84	226	597
Min YCntr	136.81	42.87	65	223
Max YCntr	242.45	65.25	114	352
Delta YCntr	105.64	52.59	12	227
Delta WEdge	160.40	68.61	46	304

The last two rows in **Error! Reference source not found.** indicate the difference between the maximum and the minimum retroreflectivity values for a given site. The researchers developed scenarios of WEdge and YCntr varying realistically, considering the observed variation in Table 8. The researchers then constructed

Table 9 to examine the implications of four different restriping scenarios. The scenarios are paired; each pair contains an aggressive restriping policy and a relaxed restriping policy. The difference between the pairs of scenarios is the minimum in-service retroreflectivity level. The last column shows the average crash reduction, using the coefficient estimates from the last model from

Table and taking as reference the minimum In-Service RL values from Scenario 1.

Table 9 Implications of Results for Various Restriping Scenarios

	Minimum In-Service R_L (mcd/m²/lx)		**Minimum Installed R_L** (mcd/m²/lx)				
	W Edge	**Y Cntr**	**W Edge**	**Y Cntr**	**Delta W[b]**	**Delta Y[b]**	**Average Yearly Crash Reduction**
Scenario 1 [a]	100	100	300	200	200	100	11.9%
Scenario 2	100	100	400	200	300	100	22.4%
Scenario 3	150	150	300	200	200	100	12.3%
Scenario 4	150	150	400	200	300	100	23.8%

Notes:

a The Minimum In-Service R_L for this scenario was used as a reference to calculate the estimated Average Yearly Crash Reductions for all scenarios in this table.

b These deltas are computed with respect to Minimum In-Service R_L from Scenario 1.

Table 9 indicates that, consistent with expectation, a more aggressive restriping policy is expected to associate with higher crash reductions (e.g., 22.4% versus 11.9% for the scenarios with minimum retroreflectivity of 100 mcd/m2/lx).   Maintaining a slightly higher minimum in-service retroreflectivity level (150 mcd/m2/lx versus 100 mcd/m2/lx) only has a small impact on the associated crash reduction. However, the difference between the aggressive and relaxed restriping policy is nearly the same. The impact of installing pavement markings with high retroreflectivity levels and maintaining the retroreflectivity is clearly evident from the results in Table 9.

Two observations about Table 9 should be noted:

1. For the scenarios in
2. Table 9, minimum installed R_L values were selected such that recommended WEdge and YCntr values are as those typically observed in practical applications. Particularly, the relation to one another of these variables is instrumental for results to be consistent. The statistical analyses in this paper showed statistically insignificant results for the effect of YCntr. This effect was not removed from the calculations in
3. Table 9 because it tends to make the yearly projections more conservative. The projected yearly crash reductions associated with retroreflectivity values are mostly driven by the effect of WEdge, being this the significant result in the model selected from

4. Table . In practical applications, WEdge and YCntr tend to vary together, which is typically observed in restriping and maintenance activities of such markings. Caution is advised when examining their independent variation using the models in this paper, since the observed co-dependency is latent in the model results.
5. Some assumptions were made when estimating a practical crash reduction associated with retroreflectivity values, as these values change relatively quickly over time. A large crash reduction is expected in the following months after restriping because of the large increase in retroreflectivity levels. The crash reduction for subsequent months is expected to decrease as the markings wear and their retroreflectivity decreases. The last column of
6. Table 9 represents the average crash reduction over a year assuming that the restriping cycle is 12 months, and that retroreflectivity values decrease in an exponential fashion. Furthermore, this calculation assumes the exponential decrease being such that pavement markings are restriped at the Minimum Installed R_L indicated in
7. Table 9 on month 1 of a yearly cycle, and that 12 months later both retroreflective markings reach their Minimum In-Service R_L.

SUMMARY OF FINDINGS AND CONCLUSIONS

A database of roadway characteristics from the Highway Safety Information System (HSIS), and retroreflectivity records was assembled using data provided by the North Carolina DOT. Various types of nighttime crashes were collected for rural two-lane highway segments represented in that database.

Two analyses of these data are presented in this paper. One analysis utilized Generalized Estimating Equations (GEE) and the other used Generalized Linear Mixed Models GLMMs, both adequate techniques to deal with time-resolution and data structure correlations. The results from these analyses were compared to previous research using the same techniques but data provided by the Michigan DOT.

From the GEE analyses, the effect of YCntr on the NC data was not statistically significant. For the Michigan data, YCntr was statistically significant for retroreflectivity of 150 mcd and less.

The GEE analyses of the NC data showed that WEdge retroreflectivity (while controlling for YCntr retroreflectivity as well as other roadway characteristics) was statistically significant and of the same order of magnitude as found with the Michigan data. The effect of the WEdge retroreflectivity was strongest during the winter months. The negative coefficients of WEdge suggest that expected nighttime crash frequency and nighttime fatal plus injury crash frequency decrease as the WEdge retroreflectivity increases.

Regarding the GLMM analyses, the Sum-Delta model that was generated with the Michigan data did not provide consistent results with the North Carolina data. However, using the GLMM analyses on WEdge and YCntr instead provided similar results to the GEE analyses.

RECOMMENDATIONS

One of the highest-level objectives of the research described in this paper is the development of safety-derived minimum retroreflectivity levels for pavement markings. Using the available information from this paper, previous research, and state of the practice, Table 10 was generated as a point of reference for safety-derived recommended minimum retroreflectivity levels for pavement markings.

From the Sum-Delta model of the Michigan data, there appears to be a safety-derived minimum retroreflectivity level for yellow center line pavement markings at a value of 175 mcd/m^2/lx. Therefore, this value was set as the minimum in-service level for both scenarios. Scenario A uses the same minimum in-service level for both white and yellow markings. This is similar to the FHWA's recommended visibility-derived minimum in-service retroreflectivity levels.

Scenario B uses a white minimum in-service level consistent with practice when yellow is 175 mcd/m^2/lx. The installed levels are quite different. For Scenario A, the criteria are based on commonly specified minimum retroreflectivity levels for newly installed markings. For Scenario B, the retroreflectivity criteria are more aggressive but not impractical. The average yearly crash reduction associated are shown in the last column of Table 10.

Table 10 Recommendations safety-derived recommended minimum R_L levels

	Minimum In-Service R_L (mcd/m^2/lx)		**Minimum Installed R_L** (mcd/m^2/lx)				
	W Edge	**Y Cntr**	**W Edge**	**Y Cntr**	**Delta W^b**	**Delta Y^b**	**Average Yearly Crash Reduction**
Scenario A	175	175	350	225	250	125	14.8%
Scenario B	250	175	500	350	400	250	28.3%

Notes:

For consistent comparisons, the average yearly crash reductions are estimated with respect to Minimum In-Service R_L from Scenario 1 from Table 9

The results in this paper provide the tools to consider various scenarios of expected safety benefit associated with retroreflectivity of pavement markings. The scenarios shown in Table 10 provide examples of the potential benefits of maintaining retroreflectivity of pavement markings, as such practice is expected to associate with fewer crashes on two-lane rural highways.

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