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NSTSCE

National Surface Transportation Safety Center for Excellence

Rural Intersection Lighting Safety Analysis

Final Report

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ABSTRACT

Under the sponsorship of the National Surface Transportation Safety Center for Excellence (NSTSCE), this research studied the relationship between lighting level and the night-to-day (ND) crash ratio at rural intersections in the state of Virginia. Most existing research on intersection lighting indicates that the presence of lighting reduces night crashes. This study aimed to quantify the effect of lighting level and lighting quality on ND crash ratios at rural intersections.

Lighting data were collected from 131 rural intersections in Virginia, and crash data for the intersections were obtained from the Virginia Department of Transportation (VDOT). Lighting data were collected using a Roadway Lighting Mobile Measurement System (RLMMS). Out of the 131 intersections, data from 99 intersections were used for the comparative analysis. Data from 32 intersections could not be used because of issues with lighting data (e.g., Global Positioning System, illuminance data dropouts). Negative binomial regression was used to model the crash and lighting data.

The results showed that increasing the average horizontal illuminance at all the intersections (both lighted and unlighted) by one unit (1 lux) decreased the ND crash ratio by 7%. For the lighted intersections, the same increase in average horizontal illuminance decreased the ND crash ratio by 9%. The largest decrease in the ND crash ratio was for unlighted intersections, where a 1-lux increase in the average horizontal illuminance decreased the ND crash ratio by 21%. The average roadway luminance also had negative parameter estimates, indicating that an increase in average roadway luminance results in a lower ND crash ratio. Stop-controlled intersections had smaller ND crash ratios compared to signalized intersections. Intersections with a posted speed limit of less than or equal to 40 mph had lower ND crash ratios compared to intersections with a posted speed limit higher than 40 mph. Results also showed that most lighting levels at most rural intersections did not meet the standards recommended by the Illuminating Engineering Society of North America (IESNA).

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LIST OF ABBREVIATIONS AND SYMBOLS

CI	confidence interval
fps	frames per second
ft.	feet
GPS	Global Positioning System
IESNA	Illumination Engineering Society of North America
mph	miles per hour
ND	night to day
NSTSCE	National Surface Transportation Safety Center for Excellence
RLMMS	Roadway Lighting Mobile Measurement System
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

PROBLEM

Most of the research on lighting at intersections shows that the number of night crashes and the ratio of night-to-day (ND) crashes are lower at lighted intersections when compared with unlighted intersections (Bullough, Donnell, & Rea, 2013; Green, Agent, Barrett, & Pigman, 2003; Isebrands et al., 2006; Smadi, Hawkins, & Aldemir-Bektas, 2011; Robert Hilton Wortman, Lipinski, Fricke, Grimwade, & Kyle, 1972). While this research shows that there is a safety benefit in the presence of lighting at rural intersections, in all of these analyses, the presence of lighting was used as a binary variable: lighting was either present or absent. Consequently, the studies mentioned above did not account for the lighting level, which is defined as the amount of light incident on the roadway surface (illuminance) or reflected from the roadway surface (luminance) from the roadway lighting system or stray light from surrounding businesses (parking lots, gas stations, malls, etc.). To better understand the importance of lighting at rural intersections, the relationship between lighting levels and night crashes at these locations needs to be studied.

PROJECT SCOPE AND OBJECTIVES

In order to understand the effect of lighting level and quality on the number of night crashes at rural intersections, a comparative statistical analysis was conducted on lighting and crash data. This study analyzed rural intersections in the state of Virginia in terms of the level of lighting and crash information. Lighting data from rural intersections were collected via a Roadway Lighting Mobile Measurement System (RLMMS). Rural intersection (lighted and unlighted) crash data were obtained from the Virginia Department of Transportation (VDOT) crash database for the years 2003 to 2007. Lighting data were added to crash data to enhance the quality and understanding of rural intersection lighting.

The objectives of the study were to:

1. Collect lighting data (illuminance and luminance) from a sample of rural intersections in the state of Virginia.
2. Quantify the effect of lighting level on the number of night crashes at the rural intersections from which the data were collected.

CHAPTER 2. REVIEW OF EXISTING LITERATURE

EFFECT OF LIGHTING ON CRASHES/CRASH FREQUENCY AT INTERSECTIONS

Multiple studies over the last 50 years have shown that roadway lighting at intersections helps reduce night crash frequency. Lighting at intersections mitigates night crashes by increasing visibility, augmenting vehicles' headlamps, and providing more information about the surrounding area (Hasson & Lutkevich, 2002). Wortman et al. (1972) concluded that lighting could significantly help in reducing nighttime accidents at intersections. An analysis of lighted and unlighted rural intersections in Illinois found that illumination had a significant impact on reducing nighttime accidents; the number of accidents was reduced by about 30% (R. H Wortman & Lipinski, 1974). In a study conducted in Iowa, Walker and Roberts (1976) reported that the accident frequency at intersections was reduced by almost 49% after the installation of lighting. A meta-analysis conducted by Elvik (1995) of 37 published studies from 1948 to 1989 in 11 different countries indicated a reduction of 65% in nighttime fatal accidents, a 30% reduction in injury accidents, and a 15% reduction in property-damage-only accidents when lighting was installed on both intersections and road segments (rural, urban, and freeway). A study conducted by the Minnesota Local Road Research Board indicated that lighting at rural intersections not only reduces nighttime crashes, but is also a cost-effective countermeasure against crashes (Preston & Schoenecker, 1999). A before-and-after study conducted in Kentucky by Green et al. (2003) also concluded that after the installation of lighting, crashes that occurred at night were reduced by 45%. A before-and-after study conducted by Isenbrands et al. (2006) on 48 intersections in Minnesota to determine the effectiveness of lighting on nighttime crashes showed that increased lighting resulted in a 13% reduction in the nighttime crash frequency. In a comparative analysis performed in the same study on 3,622 rural stop-controlled intersections, the nighttime to total crash ratio for unlighted intersections was 7% higher than lighted intersections and this result was statistically significant. These and other previous lighting- and crash-related studies provide a great deal of evidence that lighting is an effective countermeasure against nighttime crashes at intersections.

EFFECT OF LIGHTING LEVEL ON CRASHES/CRASH FREQUENCY AT INTERSECTIONS

Various studies have shown that crash rates can be reduced and intersection safety therefore improved by increasing lighting levels. Oya et al. (2002) reviewed the effect of illuminance in reducing accidents at intersections, finding that an average road surface illuminance of 20 lux or higher serves as an effective countermeasure against crashes. Moreover, average road surface illuminance of 30 lux yielded statistically significant results in the reduction of crashes. The results of a study conducted in Japan indicated that an average road surface illuminance of 10 lux or more is required to make pedestrians more visible to drivers approaching intersections. This study also recommended using an average road surface illuminance of 30 lux or more to reduce accidents more efficiently (Minoshima, Oka, Ikehara, & Inukai, 2006). In addition, the same study conducted a survey of intersections where accidents occurred frequently by analyzing their optical properties. The results indicated that a uniformity ratio of illuminance of 0.4 makes intersections safer.

While the aforementioned studies examined road surface illuminance, very few studies have looked at the relationship between road surface luminance and crashes at intersections. In one study (Scott, 1980) that was trying to establish a relationship between lighting factors and accident frequency, it was found that average road surface luminance had a strong effect on reducing accidents. It was estimated that about a 1 cd/m^2 increase in the average road surface luminance would reduce the crash rate by approximately 35%. More recently, a study conducted at rural intersections in Iowa where lighting levels (illuminance and luminance) were measured concluded that it was difficult to quantify the effect of lighting on intersection safety. However, the study did state that intersections with the presence of fixed overhead lighting were safer than unlighted intersections (Smadi et al., 2011).

There is overwhelming evidence to support the notion that the presence of lighting reduces nighttime crashes or lowers crash frequency. However, few studies have actually looked at the relationship between lighting level and night crashes. An important point to consider is the fact that lighting level is not only dependent on the presence of roadway lighting but also the unplanned/unaccounted for light from the surrounding business establishments, homes, etc. If the roadway lighting is removed from an intersection, only the planned component of the lighting level is being eliminated; the unplanned light is still incident on the roadway surface. By using lighting as a binary variable (present vs. absent), a critical aspect of lighting—lighting level—is completely ignored. In order to accurately understand the effect of lighting on crashes, we should understand the relationship between lighting level and crashes. This study not only aims to understand this relationship but also makes an effort to quantify the effect of lighting level on nighttime crashes.

CHAPTER 3. VIRGINIA RURAL INTERSECTION LIGHTING DATA

LIGHTING DATA COLLECTION

Equipment

Lighting data (illuminance and luminance) were collected by the RLMMS, which was developed by the Lighting Infrastructure Technology group at the Virginia Tech Transportation Institute (VTTI) for collecting roadway lighting data without having to stop the vehicle. The RLMMS system has three main components: an illuminance measurement system, a Global Positioning System (GPS), and a luminance camera system.

A specially designed “Spider” apparatus (as shown in Figure 1) with four waterproof Minolta illuminance detector heads was mounted horizontally onto the vehicle’s roof in such a way that two detectors were positioned over the right and left wheel paths and the other two detectors were placed along the centerline of the vehicle. An additional vertically mounted illuminance meter was positioned in the vehicle’s windshield as a method to measure the vertical illuminance from the lighting installations at rural intersections. The waterproof detector heads and windshield-mounted Minolta head were connected to separate Minolta T10 bodies that sent data to the data collection computer positioned in the trunk of the vehicle.

Figure 1. Photo. RLMMS system’s “Spider” apparatus with four Minolta illuminance heads and NovaTel GPS device in the center.

A NovaTel GPS device was positioned at the center of the four roof-mounted illuminance meters and attached to the “Spider” apparatus. The GPS device was connected to the data collection box via Universal Serial Bus, and the vehicle’s latitude and longitude position data were incorporated into the overall data file.

Figure 2. Photo. RLMMS system showing the luminance cameras and the Minolta illuminance head that measures the vertical illuminance.

Two separate cameras were mounted on the vehicle's windshield (as shown in Figure 2); both collected luminance-only information of the forward driving scene at different shutter speeds and apertures to account for the varying light levels at rural intersections. Each camera was connected to a stand-alone computer (not shown in Figure 3) that was then connected to the data collection computer (data acquisition system [DAS] or laptop in Figure 3). The data collection computer was responsible for collecting illuminance and GPS data and synchronized the camera computer images with a common timestamp.

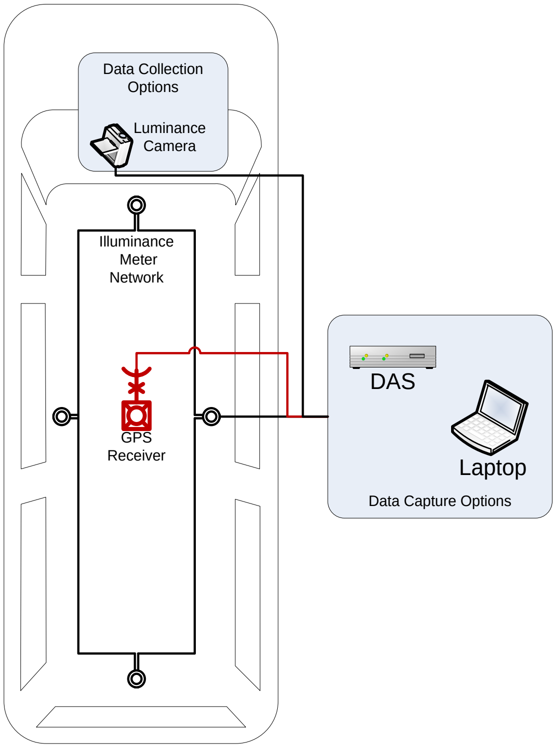

Figure 3. Diagram. Block diagram of the RLMMS system.

Each component of the RLMMS was controlled by a specialized software program created in LabVIEW. The entire hardware suite was synchronized through the software program, and data collection rates were set at 20 Hz. Video image capture rate was set at 3.75 frames per second (fps). The final output file used during the analysis contained a synchronization stamp, GPS information (e.g., latitude, longitude), individual images from each of the luminance cameras inside the vehicle, vehicle speed, vehicle distance, and the illuminance meter data from each of the Minolta T-10s (five total including the vertical illuminance from the windshield).

Method

For collecting the lighting data, a 2002 Cadillac Escalade equipped with the RLMMS system was used. At every intersection, the vehicle entered from every approach and made every possible turn. For example, Figure 4 shows the approach patterns with GPS coordinates at two different types of intersections (cross and "T").

Figure 4. Illustration. Approach patterns at two sample intersections.

Data Reduction

After data collection, the RLMMS output file from each intersection provided the illuminance measurements from every approach, the GPS coordinates, and the relevant luminance camera images. Illuminance and luminance data needed to be reduced (i.e., cleaned up) so that they could be used in conjunction with the crash data for the analysis. The following two subsections describe the reduction process for illuminance and luminance data in detail.

Illuminance Data

The illuminance level of an intersection was determined by calculating the mean of all the data points that were within a 100-ft. radius from the center of the intersection. A 100-ft. radius was used because most rural intersections are isolated and the luminaires that provide illumination are located solely at the intersection. The 100-ft. radius satisfied the Illumination Engineering Society of North America (IESNA) RP-8 specification that illumination of isolated traffic conflict areas (rural intersections) should be measured at the largest area between the stop bars. Moreover, since the illuminance data were averaged for each intersection, taking longer radius measurements reduced the average illuminance of the intersection. To accomplish the collection of data within the 100-ft. radius, the GPS coordinates from the RLMMS output file were plotted on a map using ArcMap. Using ArcMap, the center of the intersection was located, and all the data points within a 100-ft. radius were selected. These data points were output into a new file that contained only the lighting data within a 100-ft. radius from the center of the intersection. Figure 5 shows a sample of two intersections with plotted GPS coordinates in ArcMap; the red dots show all the data that were collected for the intersection, and the green dots indicate the data within 100 ft. of the center of the intersection.

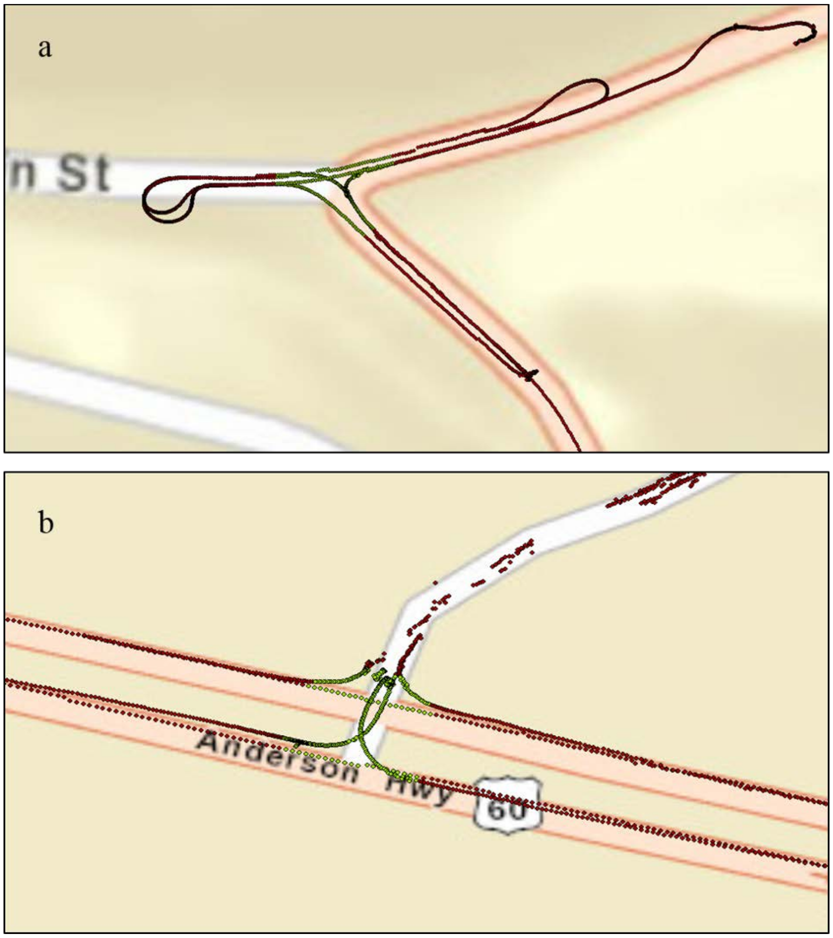

Figure 5. Map. Two sample intersections with GPS coordinates plotted. Red dots indicate all data collected and green dots indicate the data within a 100-ft. radius from the center of the intersection.

Luminance Data

The luminance camera images were extracted from the new ArcMap output file, which contained all the data within a 100-ft. radius from the center of the intersection. The luminance image data reduction process utilized a program created in MATLAB. Previously, a luminance reduction program for MATLAB was created as part of a National Surface Transportation Safety Center of Excellence (NSTSCE) project (Gibbons et al., 2009). To identify and obtain the luminance of the section of the roadway at the intersection, the reduction effort used the luminance images generated using the GPS coordinates of the intersections. Once these images were appropriately identified and placed in a reduction folder, the MATLAB program could be used. The MATLAB program displayed the image to a reductionist, who then manually identified the section of the roadway within the image and extracted that section from the image by "tracing" it with an image-cropping tool. Once the reductionist had successfully traced the image and accepted the cut-out image as valid, as shown in Figure 6, the luminance of the roadway section was calculated.

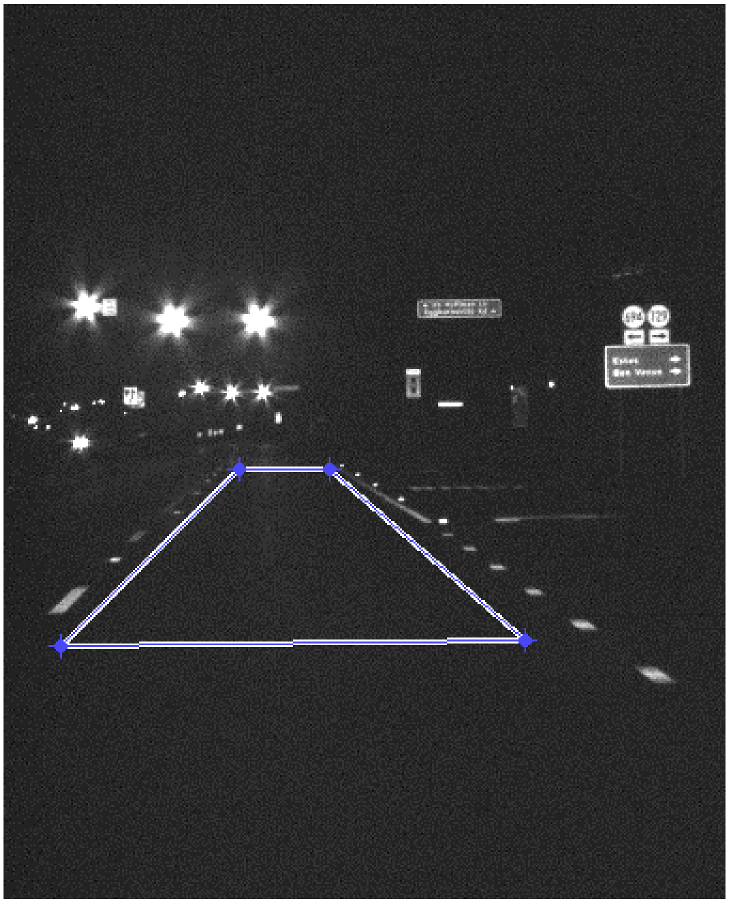

Figure 6. Screen capture. Reductionist-traced section of the road for luminance calculations.

DATA

Virginia Crash Database

The intersection data used for these analyses were provided by VDOT. For the purpose of this study, a rural intersection was defined as an intersection for which all the approaching roads were classified as rural by VDOT. The Virginia crash database contains information about all the intersections and roads in Virginia. This database consists of several tables that can be linked to each other by the intersection node number. These tables contain various attributes of the intersections that could be used in the analysis. Table 1 lists the information available in the intersection database tables.

Table 1. Intersection attributes available from the Virginia crash database.

Document Number	Shoulder width	Collision Type	Lane Type
Route prefix	Lane count	Impact Zone	Lane Number
Route number	Facility	Major Factor	Latitude
Route suffix	Intersection Type	Severity	Longitude
Node	Traffic Control	Fatal Count	Work Zone
Node type	Alignment	Pedestrian Fatal Count	Traffic Control Working
Crash Date	Weather	Injury Count	Speed Limit
Crash Hour	Surface Condition	Pedestrian Injury Count	Speed Limit Code
Surface Type	Road Defect	Traffic Count	
Surface Width	Lighting	Lane Direction	

The database was queried to select intersections based on the attributes shown in Table 1. After a review of the data, the research team cleaned and verified the data such that intersection locations of interest were checked for appropriate lighting, approach configurations, collision counts, collision types, etc. Some intersections were found to contain conflicting information regarding the presence or absence of lighting near the intersection. A total of 131 rural intersections were selected to include a broad spectrum of crash frequencies, intersection types and geometries, and lighted and unlighted intersections.

Out of the 131 intersections, data from 99 intersections had usable lighting metrics (good, continuous data without any GPS or illuminance data dropouts) and were used for analysis. These intersections were stop- or signal-controlled and were either lighted or unlighted. Different kinds of intersection classes were selected depending on the configuration. These were crossing (four approaches [“+”]), right angle (three approaches [“T”]), offset (four approaches), and branch (three approaches), as illustrated in Figure 7. Table 2 and Table 3 break this information down further and also show the maximum and the minimum values of the attributes used in the analyses.

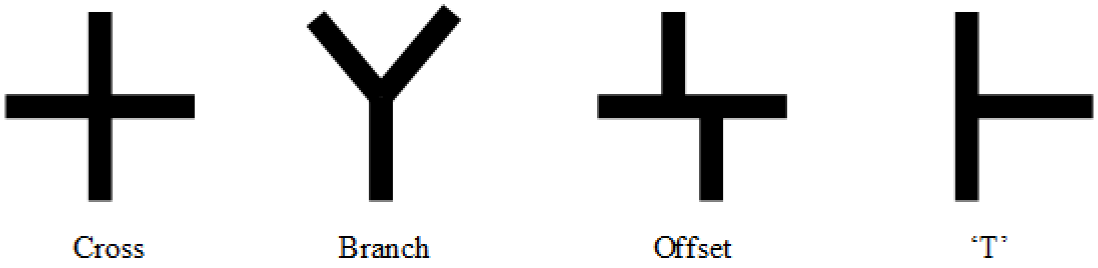

Figure 7. Diagram. Types of intersection geometries illustrated.

Table 2. Distribution of lighted and unlighted intersections.

		Lighted	Unlighted	Total
Number of Intersections		56	43	99
Intersection Type	**Stop**	29	18	47
	Signal	27	25	52
Intersection Classification	**Crossing**	26	15	41
	“T”	20	19	39
	Branch	6	9	15
	Offset	4	0	4
Approaches	**3**	30	15	45
	4	26	28	54

Table 3. Range of intersection attributes.

Intersection Attributes	Lighted		Unlighted	
	Min	Max	Min	Max
Posted Speed (mph)	25	55	25	55
Surface Width (ft.)	16	86	16	54
Shoulder Width (ft.)	0	9	0	10
Lane Count	2	5	2	5

Crash Data

The crash data were provided by VDOT from the Virginia crash database. The database was queried to find crashes that occurred exclusively at intersections over a 5-year period from 2003 to 2007. The crash data also yielded information about the number of fatalities/injuries and vehicles involved in a crash, the time and day of the crash, and the weather/surface conditions at the time of the crash. Information about the type of crash (e.g., rear end, angle, fixed object, etc.), crash location within the intersection, road name and number, and speed limit on the road were also available from the database. Each crash was identified by a distinct “Document Number.” Crash data for each Document Number also contained the intersection node information, which was used to locate the intersection information.

Combining both the crash data and intersection data on intersection nodes resulted in a complete list of night crash count data for use in analyses.

SUMMARY STATISTICS

The following sections summarize the Virginia intersection and crash data in an attempt to understand how night crashes were distributed across multiple intersection types and geometries. This section also compares crash ratio, type, and severity across lighted and unlighted intersections at night. Finally, the distributions of average illuminance and luminance across lighted and unlighted intersections are briefly discussed.

Crash Frequency

As previously mentioned, the crash data used for this study were from 2003 to 2007. From Table 4 and Figure 8, it is apparent that unlighted intersections had a higher number of crashes overall. Unlighted intersections also had a higher number of day crashes. This latter observation is interesting and care should be taken in statistical modeling to account for the number of day crashes.

Unlighted intersections also had higher crashes per year compared with lighted intersections. At almost three crashes per intersection per year, this rate was the highest for nighttime crashes and was approximately 84% higher than the rate for lighted intersections. Both dawn and dusk crashes at unlighted intersections had higher crashes per intersection per year. Overall, the crash rate per intersection per year at unlighted intersections was 48% higher than at lighted intersections.

Table 4. Crash frequency by time of day.

2002–2007	Lighted	Unlighted	Total	Lit/Int/Year	Unlit/Int/Year
Day	1,186	1,251	2,437	4.24	5.82
Night	433	611	1,044	1.55	2.84
Dawn	65	62	127	0.23	0.29
Dusk	63	61	124	0.23	0.28
Total Crashes	1,747	1,985	3,732	6.24	9.23

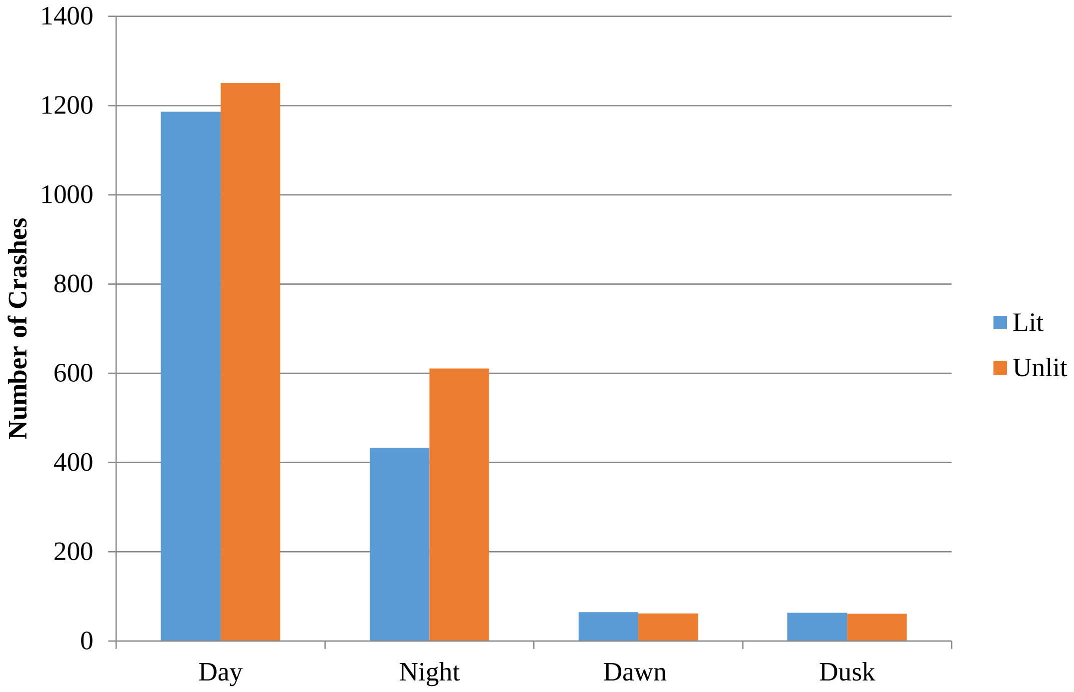

Figure 8. Graph. Number of crashes by time of day.

Crash Ratio

Table 5 illustrates that unlighted intersections also had higher night-to-total crash ratios than lighted intersections. The night-to-total crash ratio for unlighted intersections was 33% higher than at lighted intersections. The same trend was also evident with the ND crash ratio, which was approximately 32% higher at unlighted intersections than at lighted intersections.

Table 5. Crash ratios at rural intersections.

	Lit	Unlit
Night-to-total Crash	0.12	0.16
Night-to-day	0.37	0.49

Crash Ratio Rate

Hourly traffic volumes were not available for the intersections used in this study. Traffic count data were available, however. A crash ratio rate metric was created taking into account ND crash ratio and the traffic count at each intersection. For this study, traffic count at an intersection was considered the sum of the traffic count of the two intersecting roads. Thus, crash rate at each intersection was calculated using the following formula:

$$Crash\ Rate_i = \left(\frac{\left(\frac{NC_i}{DC_i}\right)}{TC_i}\right) \times 1000000 \tag{1}$$

where

i is the Intersection ID

NC_i = Number of night crashes at intersection i

DC_i = Number of day crashes at intersection i

TC_i = Traffic count at intersection i

This crash rate formula measured ND crash ratio per million traffic count. As shown in Figure 9 and Table 6, lighted intersections have a lower average crash ratio rate (33% lower) compared to unlighted intersections.

Table 6. Crash ratio rate at rural intersections.

	Lit	**Unlit**
Avg. Crash Ratio Rate (per million traffic count)	82.16	108.90

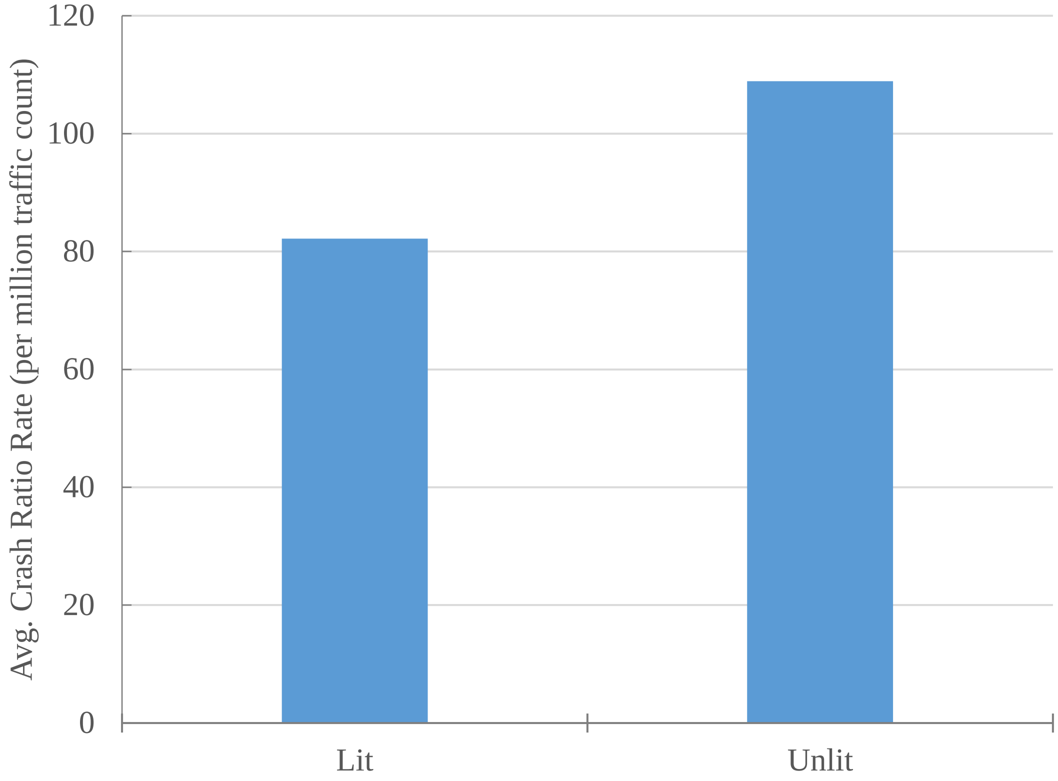

Figure 9. Graph. Average crash ratio rate at lighted and unlighted intersections.

Effect of Intersection Type

As shown in Table 7, the crash numbers indicate that unlighted intersections had a higher number of crashes than lighted intersections at both signalized and stop-controlled locations. Compared to stop-controlled intersections, signalized intersections had a significantly higher number of crashes.

The ND crash ratios, however, tell a different story. Even though signalized intersections had a higher number of crashes, the ND crash ratios at both lighted and unlighted locations were lower than those at stop-controlled intersections, as shown in Table 8 and Figure 10. The largest difference in ND crash ratios between stop-controlled and signal intersections was at unlighted locations. Lighted intersections had lower ND ratios than unlighted intersections by 49% and 18% at stop-controlled and signalized intersections respectively.

Table 7. Number of crashes by intersection type.

Intersection Type	**Lit**		**Unlit**	
	Day	**Night**	**Day**	**Night**
Stop	278	113	209	165
Signal	908	320	1042	446

Table 8. ND crash ratios by intersection type.

Intersection Type	**Lit**	**Unlit**
Stop	0.41	0.79
Signal	0.35	0.43

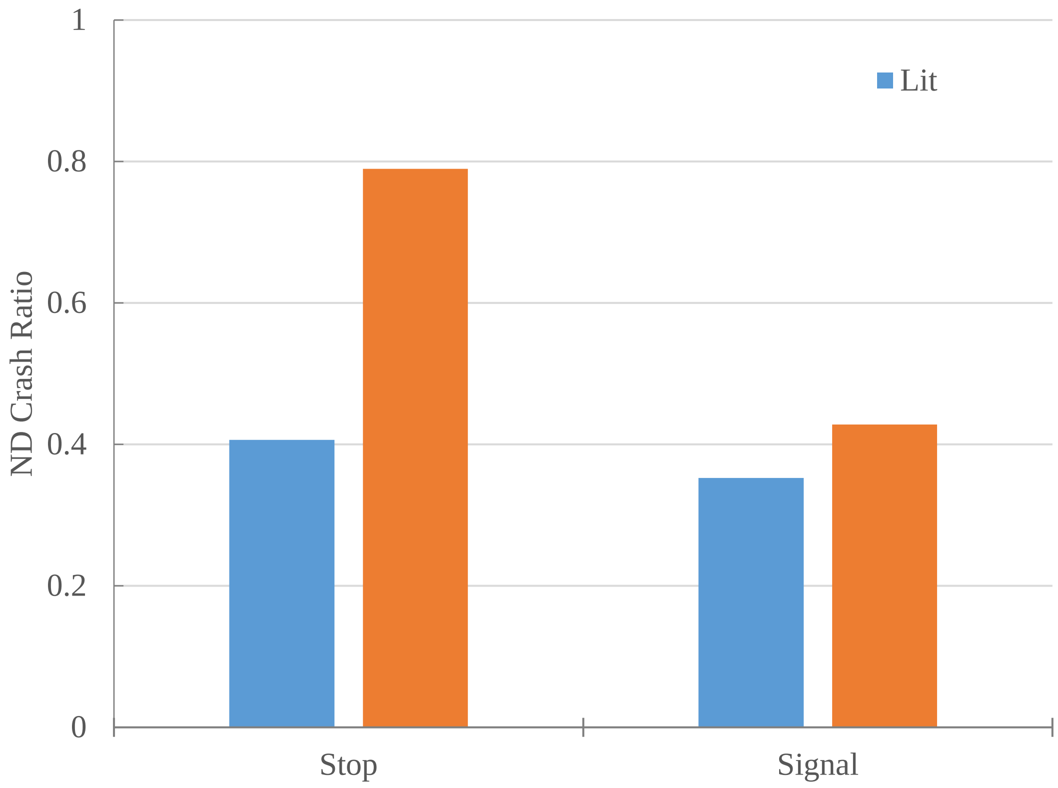

Figure 10. Graph. ND crash ratio by intersection type.

The crash ratio rates for signalized and stop-controlled intersections at both lighted and unlighted locations are displayed in Table 9 and Figure 11. The crash ratio rates exhibited different trends at stop-controlled and signalized intersections. At stop-controlled intersections, lighted locations had lower crash ratio rates compared to unlighted intersections, but at signalized intersections the opposite was true. However, both lighted and unlighted stop-controlled intersections had higher crash ratio rates compared to correspondingly lighted signalized intersections by 210% and 890% respectively.

Table 9. ND crash ratio rates at signalized and stop-controlled intersections.

	Lit	**Unlit**
Stop	121.95	228.12
Signal	39.42	23.06

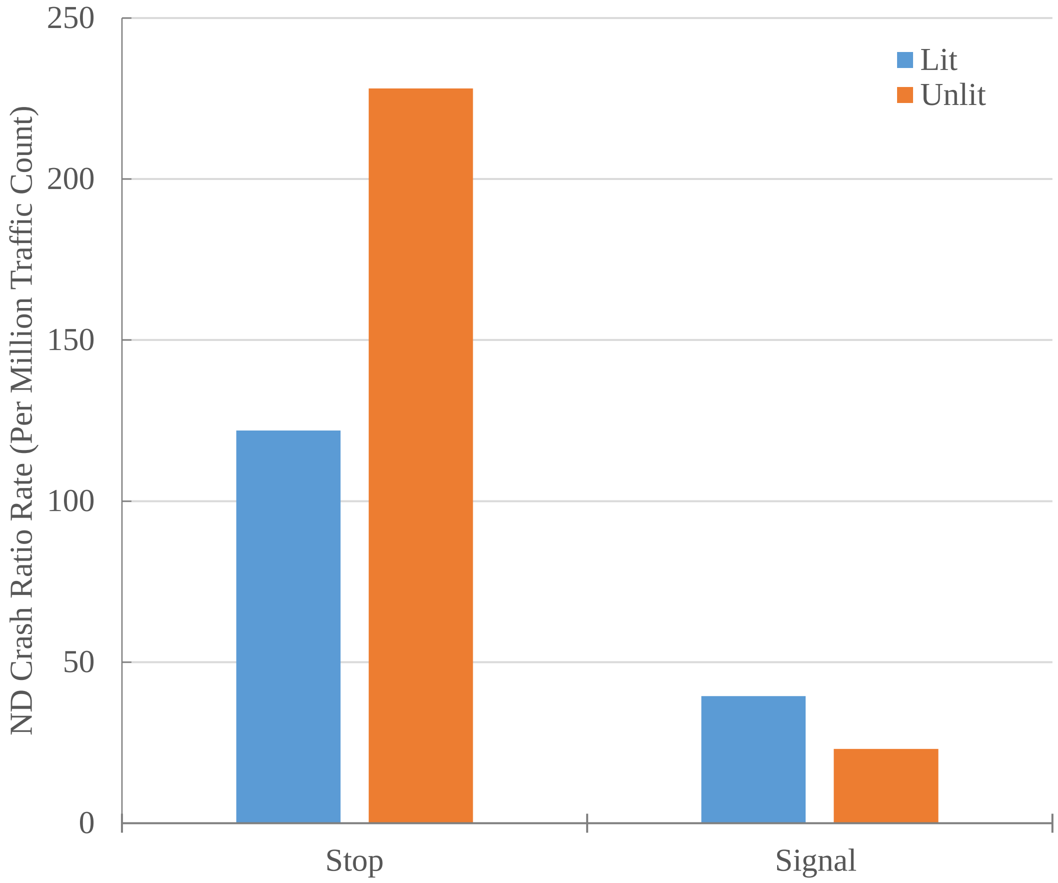

Figure 11. Graph. ND crash ratio rate at stop and signalized intersections.

Effect of Intersection Geometry

Table 10 clearly shows that both unlighted “T” and branch geometries had more than twice as many night crashes as lighted “T” and branch geometries. These geometries also had a higher number of day crashes, though the increase was not as high as the increase for night crashes. Night crashes at crossing intersections were almost equal at unlighted and lighted intersections.

ND crash ratios and ND crash ratio rates at unlighted geometries were consistently higher than at lighted geometries, as seen in Figure 12 and Table 11. Unlighted branch and crossing intersections had higher ND crash ratios and ND crash ratio rates.

Table 10. Number of crashes by intersection geometry.

Intersection Geometry	Lit		Unlit	
	Day	Night	Day	Night
Crossing	798	275	603	266
“T”	259	111	428	254
Branch	118	41	220	91

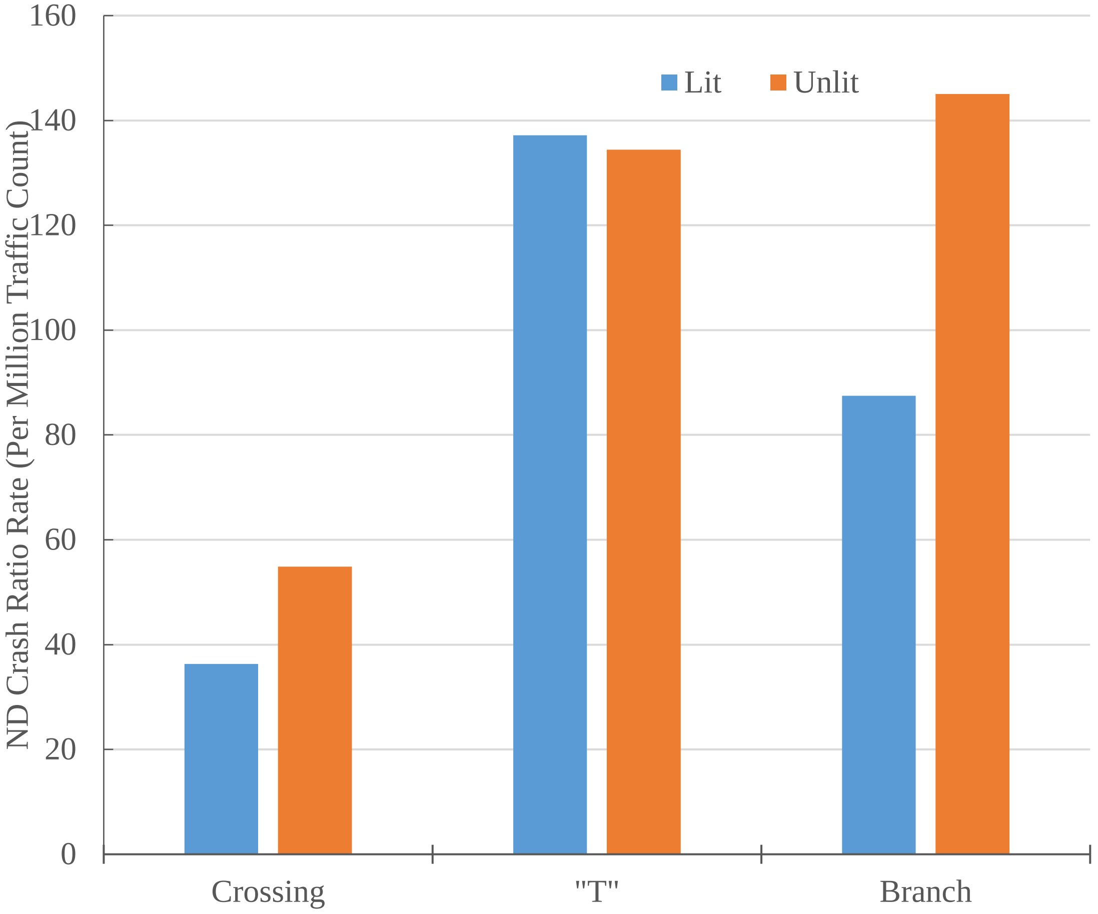

Figure 12. Graph. ND crash ratio rates at different intersection geometries.

Table 11. ND crash ratio rates by intersection geometries.

	ND Crash Ratio		ND Crash Ratio Rate	
	Lit	**Unlit**	**Lit**	**Unlit**
Crossing	0.345	0.441	36.323	54.885
“T”	0.429	0.593	137.140	134.409
Branch	0.347	0.414	87.487	145.067

Crash Type

Night crashes at intersections mostly involve the following crash types: rear end, angle, sideswipe–same direction of travel, fixed object off road, and deer. Of these, angle, fixed object off road, and deer crashes had a higher number of night crashes at unlighted intersections, and angle and fixed object off road crashes had a higher number of day crashes at unlighted intersections. Table 12 and Figure 13 illustrate crash types at lighted and unlighted intersections, showing that ND crash ratios for crashes involving deer are about twice as high at unlighted intersections. Further, results show that unlighted intersections have higher ND crash ratios in general.

Table 12. Crash types at lighted and unlighted intersections.

Crash Type	Lit			Unlit		
	Day	**Night**	**ND**	**Day**	**Night**	**ND**
Rear End	529	125	0.27	475	121	0.26
Angle	414	133	0.32	467	213	0.46
Sideswipe–Same direction of travel	82	30	0.37	99	33	0.33
Fixed Object Off Road	77	75	0.97	133	139	1.055
Deer	15	24	1.60	21	65	3.10

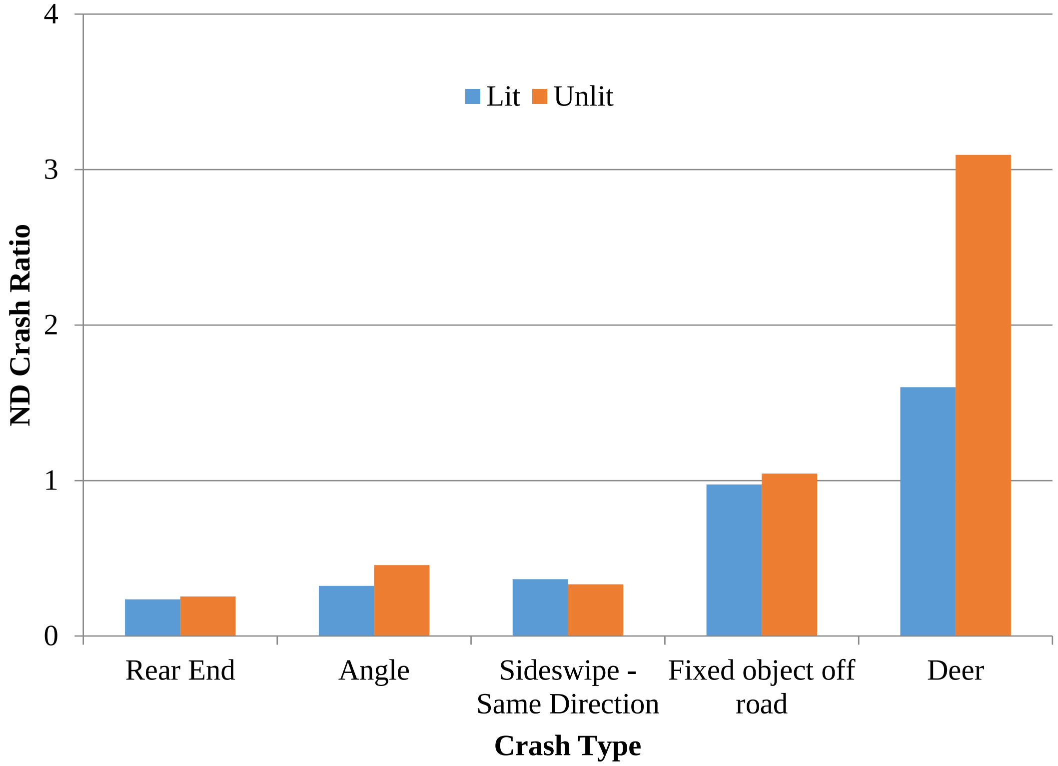

Figure 13. Graph. Rear end, angle, sideswipe, fixed object, and deer collisions types had higher ND crash ratios at unlighted intersections.

Crash Severity

In general, night crashes at unlighted intersections had a higher number of fatalities. Night crashes at unlighted intersections was also the only crash category to have pedestrian fatalities. In addition, night crashes at unlighted intersections resulted in a higher number of injuries compared to night crashes at lighted intersections. Day crashes at unlighted intersections also had higher injury counts than day crashes at lighted intersections. Nighttime pedestrian injury counts were the highest at unlighted intersections, as were nighttime vehicle crashes. These are clearly illustrated in Table 13 and Figure 14.

Table 13. Fatality, injury, and vehicle count at lighted and unlighted intersections.

Crash Severity	Lit		Unlit	
	Day	Night	Day	Night
Fatal Count	5	2	6	6
Pedestrian Fatal Count	0	0	0	2
Injury Count	667	214	707	357
Pedestrian Injury Count	5	8	3	6
Vehicle Count	2,454	781	2,498	1,034

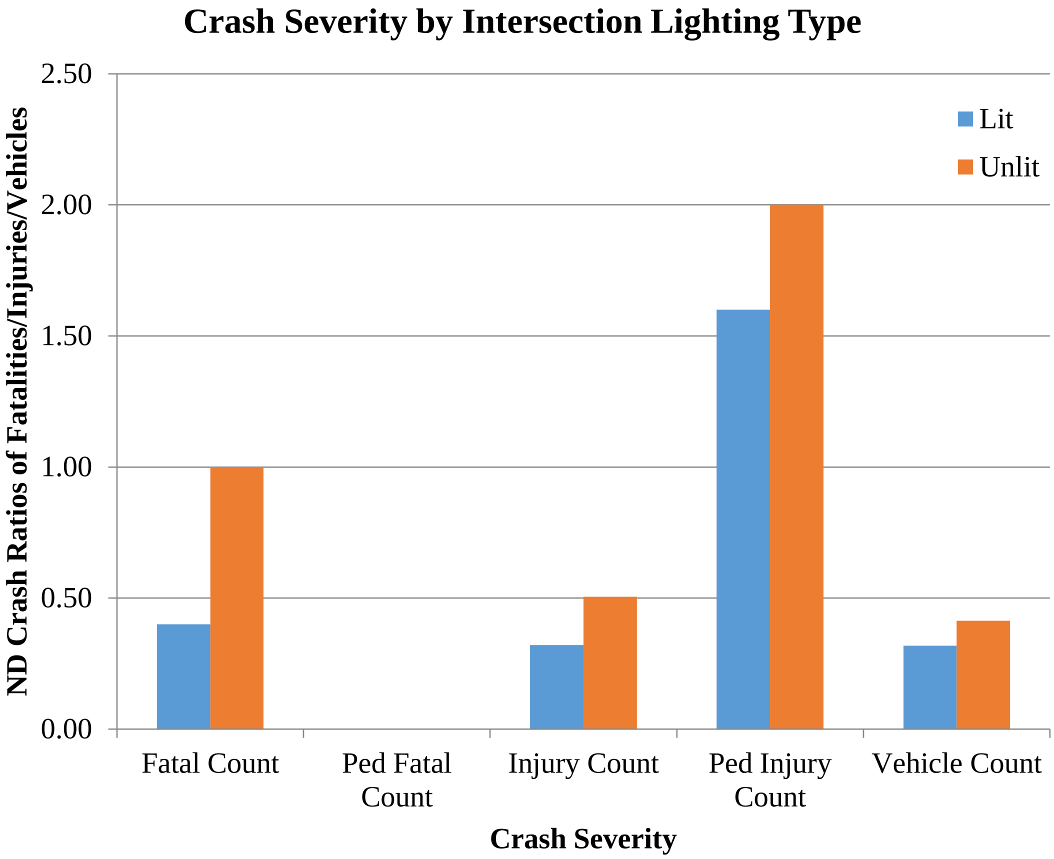

Figure 14. Graph. ND crash ratios for pedestrian injury, fatality, and vehicles at lighted and unlighted intersections.

Average Horizontal Illuminance

For this study, the average illuminance of the intersection was defined as the mathematical mean of the illuminance incident on the roadway area within a 100-ft. radius from the center of the intersection. For the lighted intersections, the average illuminance was 5.21 lux, and the values ranged from 0.42 lux to 31.60 lux, as shown in Table 14. Unlighted intersections had an average illuminance of 1.16 lux with values that ranged from 0.28 lux to 5.90 lux. It is important to remember that unlighted intersections have a certain amount of unplanned light levels (rather than having no light) as result of stray light from gas stations, business parking lots, etc. Lighted intersections had a wider range of illuminance values, as shown in Figure 15.

Table 14. Mean and range of values of horizontal illuminance.

	Lit			Unlit		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Average Horizontal Illuminance (lux)	5.21	0.42	31.60	1.16	0.28	5.90

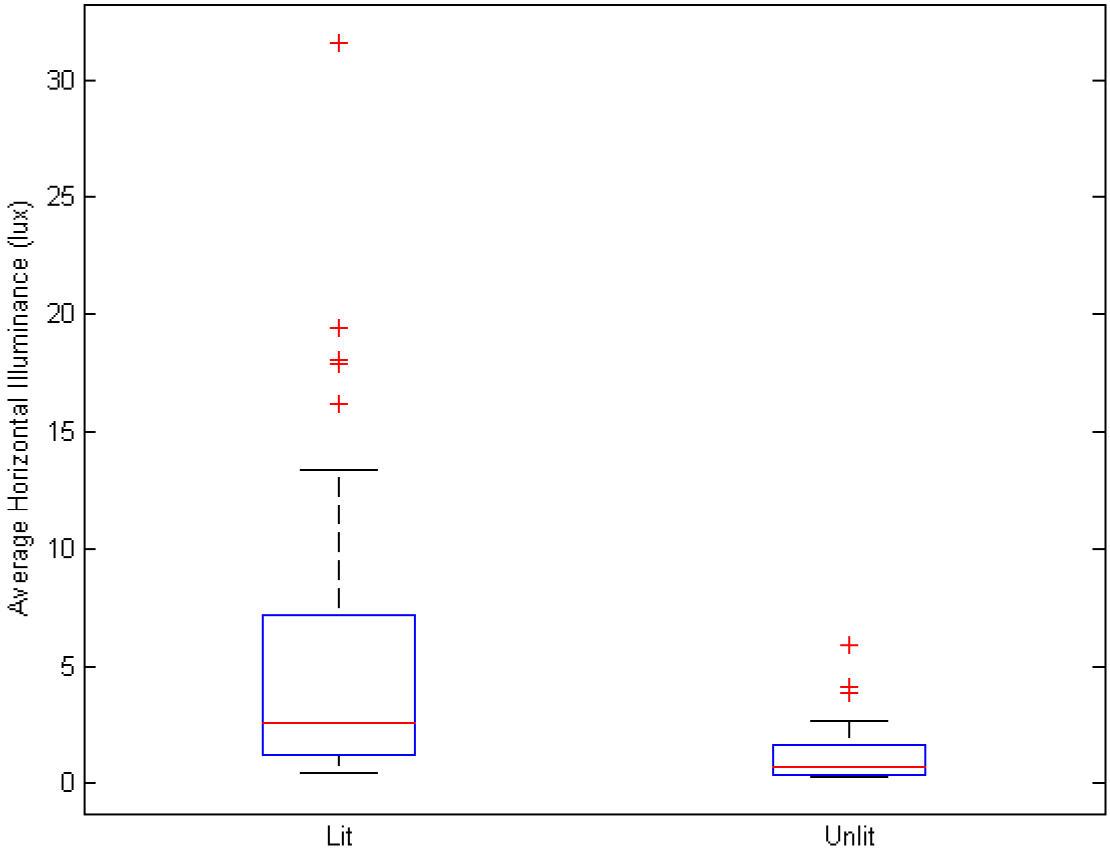

Figure 15. Graph. Distribution of illuminance across lighted and unlighted intersections.

Average Vertical Illuminance

Average vertical illuminance was defined as the mathematical mean of the vertical component of the illuminance incident on the eyes of the driver within a 100-ft. radius from the center of the intersection. The mean vertical illuminance of lighted intersections was 6.28 lux, and the illuminance values ranged from 4.02 lux to 15.91 lux. The mean vertical illuminance of unlighted intersections was 4.52 lux and had minimum and maximum values of 3.14 lux and 7.29 lux, respectively. Box plots of the distribution of the vertical illuminance values are illustrated in the Figure 16.

Table 15. Mean and range of values of vertical illuminance.

	Lit			Unlit		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Average Vertical Illuminance (lux)	6.28	4.02	15.91	4.52	3.14	7.29

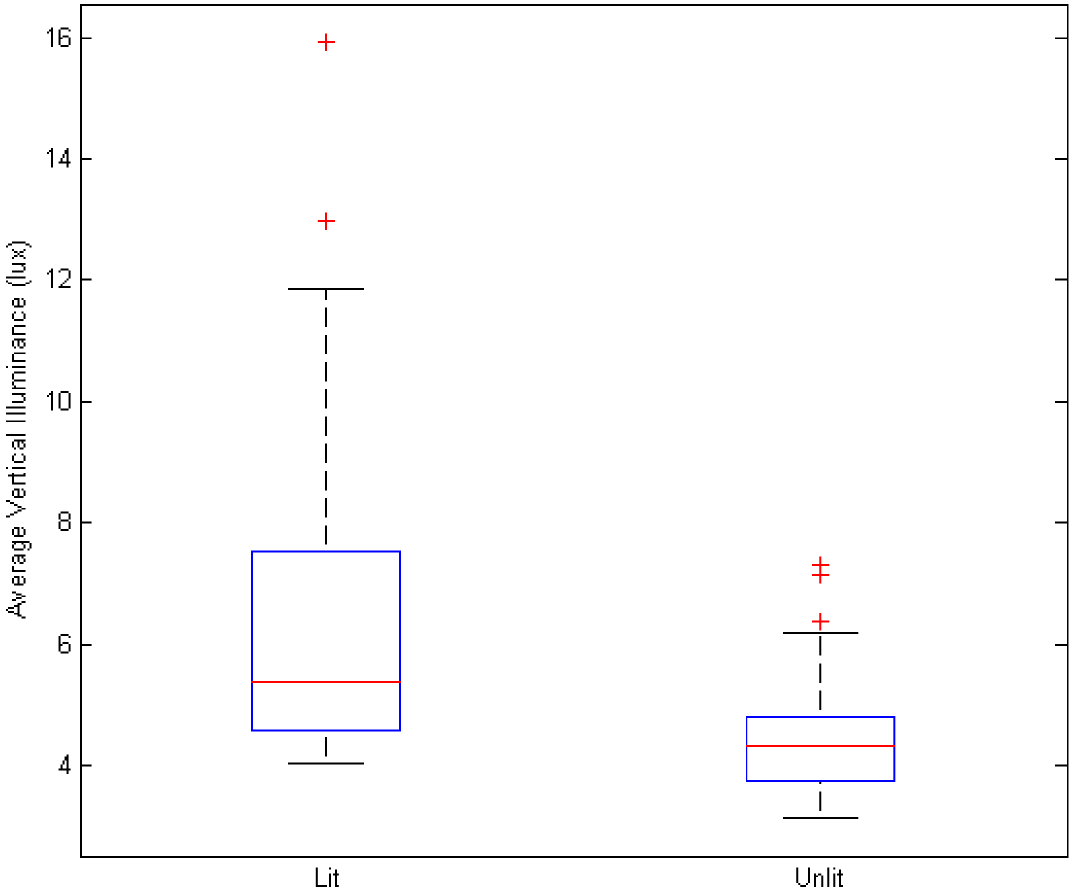

Figure 16. Graph. Distribution of vertical illuminance across lighted and unlighted rural intersections.

Average Luminance

Average luminance was defined as the mathematical mean of the luminance values of the roadway area within a 100-ft. radius from the center of the intersection. Lighted intersections had an average luminance of 0.38 cd/m^2, and the values ranged from 0.14 to 0.64 cd/m^2. Unlighted intersections had an average luminance of 0.20 cd/m^2, and the values ranged from 0.16 to 0.68 cd/m^2. Even though the ranges for lighted and unlighted intersections were similar, their distributions were completely different, as is illustrated in Figure 17.

Table 16. Mean and range of values of luminance.

	Lit			Unlit		
	Mean	**Min**	**Max**	**Mean**	**Min**	**Max**
Average Roadway Luminance (cd/m^2)	0.38	0.14	0.64	0.20	0.16	0.68

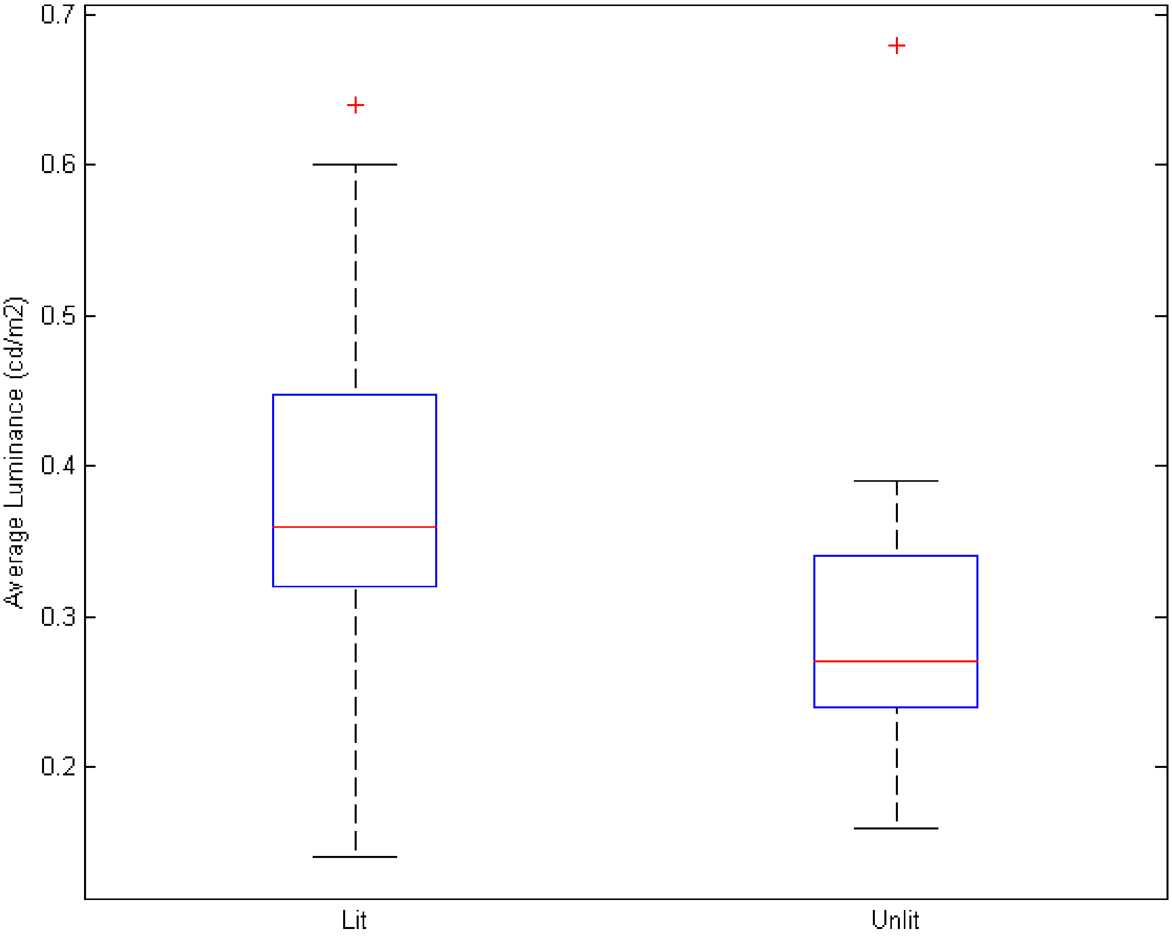

Figure 17. Graph. Distribution of luminance across lighted and unlighted intersections.

CHAPTER 4. VIRGINIA RURAL INTERSECTION LIGHTING DATA ANALYSIS

NEGATIVE BINOMIAL REGRESSION

In order to understand the causes of nighttime crashes at intersections, it is important to study the factors that affect the frequency of these crashes. Research has shown that negative binomial regression can be used to model intersection crash frequency (Bullough et al., 2013; Donnell, Porter, & Shankar, 2010; Lord & Mannering, 2010). Negative binomial regression accounts for the overdispersion that is widely prevalent in crash data. Overdispersion occurs when variance exceeds the mean of the crash counts (Lord & Mannering, 2010). The functional form of a negative binomial regression is shown below:

$$ln\,Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n. \quad (2)$$

In the above equation,

- Y_i is the expected number of night crashes at intersection i,
- $x_1, x_2, \ldots x_n$ are the explanatory variables, and
- $\beta_1, \beta_2, \ldots \ldots, \beta_n$ are the regression coefficients that are to be estimated.

Most of the studies that modeled the effect of lighting at intersections had ND traffic count data. For the data collected in this study, separate ND traffic count data were not available; instead, only a single traffic count was available for every intersection. The unavailability of the ND traffic counts made it impossible to calculate ND crash frequencies. If the number of night crashes alone was used as a dependent measure, the models would ignore the number of day crashes at the intersections, resulting in overestimation or underestimation of the other explanatory measures. For example, say that intersection “A” has 10 night crashes and 100 day crashes and that intersection “B” has 10 night crashes and 5 day crashes. If the model ignores the day crashes, then intersections A and B have the same number of night crashes and the ND crash ratio at intersection “B” is grossly underestimated. This lack of equivalence in the number of night crashes at intersections can be solved by using the number of day crash counts as an offset variable. The use of an offset variable allows the data to still be modeled as count data without changing the underlying distribution. In negative binomial regression, an offset variable is forced to have a regression coefficient of 1. The use of the offset variable transforms the form of the negative binomial as follows:

$$\ln Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \ln(DC_i), \quad (3)$$

where DC_i is the number of day crashes at intersection i.

Risk ratio is a measure of the percent change in the dependent variable for a one-unit increase in a continuous independent variable. For categorical variables, the risk ratio is defined as the percent change in the dependent variable when the value of the categorical value changes from one level to the next. The expected change in the number of night crashes for a one-unit change in the independent variable x_n is given by the following formula:

$$RR = \exp(\beta_n) - 1. \quad (4)$$

If the risk ratio is less than 1, it indicates that the expected number of night crashes decreases for a unit increase in the dependent variable when keeping the other variables constant. If the risk ratio is greater than 1, then it indicates that the expected number of night crashes increases for a unit increase in the dependent variable.

MODELS

Three major lighting parameters were collected for this study: average illuminance, average vertical illuminance, and average luminance. Since average vertical illuminance and average roadway luminance are dependent on average illuminance, using all three in the same model will result in multicollinearity and the effect of the independent variable cannot be accurately understood. In order to avoid multicollinearity, the three following negative binomial regression models were used, one with each lighting parameter as a predictor variable.

1. Horizontal Illuminance Model
2. Vertical Illuminance Model
3. Luminance Model

VARIABLES

For the negative binomial regression model, the number of night crashes was used as the dependent variable. As previously noted, the log of the number of day crashes was used as the offset variable. The explanatory variables commonly used in the three models mentioned above were intersection type, number of approaches, number of lanes, speed limit, and the log of the traffic count. Table 17 shows the variables and levels used in the negative binomial regression models.

Table 17. Response and explanatory variables used in negative binomial regression models.

Variable	Definition	Parameter	Levels
Response Variable	Number of Night Crashes	NightC	
Offset Variable	Log of Number of Day Crashes	DC	
Explanatory Variables Unique to the 3 Models	Average Horizontal Illuminance	E_h	
	Average Vertical Illuminance	E_v	
	Average Luminance	AvgLum	
Common Explanatory Variables in all 3 Models	Intersection Type	IntType	0 – Stop 1 – Signal
	Intersection Approach	IntC	1 – 4 Approaches 2 – 3 Approaches
	Number of Lanes	NOL	1 – ≤ 3 2 – > 3
	Speed Limit	SpeedL	1 – ≤ 40 mph 2 – > 40 mph
	Log of Traffic Count	logTC	

INTERSECTION TAXONOMY

General analysis taxonomy for rural intersections in Virginia is shown in Figure 18. The data from the lower levels of the taxonomy were included in the higher levels. Using taxonomy helps explain how lighting metrics affect different types of intersections: lighted versus unlighted, stop versus signal, etc.

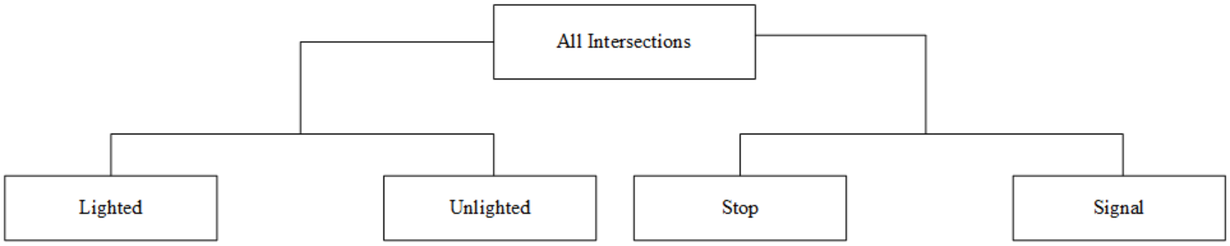

Figure 18. Diagram. Virginia rural intersection taxonomy.

ALL INTERSECTIONS

Effect of Average Horizontal Illuminance (E_h)

Table 18. Significant parameter estimates and risk ratios for E_h model.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
E_h	−0.07	0.93	0.017
IntType (Stop vs. Signal)	−0.39	0.68	0.012
SpeedL (≤ 40 mph vs. > 40 mph)	−0.42	0.66	0.012
AvgIllum*SpeedL	0.08	1.08	0.016

In this model, the effect of E_h on the ND crash ratio is evaluated.

Table 18 shows the parameter estimates and the risk ratios of the explanatory variables significant at an α level of 0.05. The average horizontal illuminance was significant, and a 1-lux increase in E_h was associated with a 7% decrease in the ND crash ratio. It is important to understand that this relationship is only valid within the range of the illuminance values recorded at the intersections used in the study. For this study, E_h ranged from 0.28 lux to 31.6 lux. Additionally, the ND crash ratio at stop-controlled intersections was 32% lower than its corresponding value at signalized intersections. Intersections with a posted speed limit of less than or equal to 40 mph had an ND crash ratio 34% lower than the ND crash ratio at intersections with a speed limit greater than 40 mph. The effect of the interaction between posted speed limit and E_h was also significant. However, the risk ratio of the interaction cannot be calculated by the exponentiation of the estimate of the interaction term. It is calculated using the following formula:

$$RR_{SpeedL*AvgIllum} = \exp(\beta_{SpeedL} + \beta_{SpeedL*AvgIllum}\,(AvgIllum)). \tag{5}$$

The variance is calculated using the following formula:

$$Var_{SpeedL*AvgIllum} = Var\left(\beta_{SpeedL}\right) + (AvgIllum)^2 Var\left(\beta_{SpeedL*AvgIllum}\right) + 2(AvgIllum)Cov(\beta_{SpeedL}, \beta_{SpeedL*AvgIllum}), \tag{6}$$

where Var is the variance and Cov is the covariance.

Finally, the confidence interval (CI) is calculated using this formula:

$$\mathrm{CI} = \left[\beta_{SpeedL} + \beta_{SpeedL*AvgIllum}\,(AvgIllum)\right] \pm Z_{1-\alpha/2} * \sqrt{V_{SpeedL*AvgIllum}}\,. \tag{7}$$

If the unexponentiated CI includes 1, the interaction is not significant and vice versa. Table 19 shows the risk ratios calculated at different levels of illumination at speed limits less than 40 mph. As E_h increases, the risk ratio of the ND crash ratio increases exponentially at intersections with a posted speed limit less than 40 mph. These risk ratios for the interaction term are interesting because they are the opposite of the expectation that ND crash ratios would decrease at the lower posted speed limits as the illuminance level increases.

Table 19. Risk ratios of the number of night crashes for the interaction between speed limit and E_h at intersections with posted speed limit ≤ 40 mph.

E_h (lux)	Interaction Parameter	Variance	Standard Error	Low CI	High CI	Risk Ratio
0	0.66	0.03	0.17	0.33	0.98	1.93
5	0.98	0.07	0.27	0.44	1.51	2.66
10	1.45	0.17	0.42	0.64	2.27	4.28
15	2.17	0.33	0.57	1.04	3.29	8.72
20	3.22	0.54	0.73	1.79	4.66	25.13
25	4.80	0.80	0.90	3.05	6.56	121.56
30	7.15	1.12	1.06	5.07	9.22	1270.36

Effect of Average Roadway Luminance (L_{avg})

Table 20. Significant parameter estimates and risk ratios for luminance model.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgLum	−3.47	0.03	0.001
IntType	−0.44	0.64	0.017
SpeedL	−1.50	0.22	0.004
AvgLum*SpeedL	3.90	49.30	0.003

Table 20 displays the significant explanatory variables in the luminance model. Average roadway luminance was significant, and the risk ratio indicates that a 1 cd/m^2 increase in the average roadway luminance decreased the ND crash ratio by 97%. However, it is important to understand that the sample size of the intersections for which luminance metrics were available is relatively small. This small sample size may have inflated the parameter estimates for the average roadway luminance. The effect of intersection type was also significant, which shows that the ND crash ratio at stop intersections is lower than those at signalized intersections by 36%. Furthermore, intersections with a posted speed limit of less than or equal to 40 mph had a ND crash ratio 78% lower than the ND crash ratio at intersections with a posted speed limit greater than 40 mph. The interaction between average roadway luminance was also significant, but only at average roadway luminance values of 0 cd/m^2 and 0.05 cd/m^2. The risk ratios at these levels of average roadway luminance are shown in the Table 21. These results are counterintuitive, as an increase in luminance should result in a decrease in the ND crash ratio at lower posted speed limits.

Table 21. Risk ratios of the number of night crashes for the interaction between speed limit and L_{avg} at intersections with posted speed limit ≤ 40 mph.

L_{avg} (cd/m^2)	Interaction Parameter	Variance	Standard Error	Low CI	High CI	Risk Ratio
0.00	0.22	0.00	0.06	0.11	0.34	1.25
0.05	0.27	0.07	0.27	−0.26	0.80	1.31

LIGHTED INTERSECTIONS

Effect of Average Horizontal Illuminance (E_h)

Table 22. Significant parameter estimates and risk ratios for horizontal illuminance model at lighted intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgIllum	−0.10	0.91	0.008
SpeedL	−0.68	0.51	0.008
AvgIllum*SpeedL	0.11	1.11	0.007

Table 22 displays the significant factors in the horizontal illuminance model for lighted intersections. The main effects of average horizontal illuminance, posted speed limit, and the interaction between horizontal illuminance and posted speed limit were significant. For a 1-lux increase in the average horizontal illuminance, there was a 9% decrease in the ND crash ratio at lighted intersections. Intersections with a posted speed limit of less than or equal to 40 mph had a ND crash ratio 49% lower than those intersections with a higher posted speed limit. The interactions between average horizontal illuminance and posted speed limit exhibited tendencies similar to the interactions seen in the overall analysis. There was an exponential increase in the risk ratio with an increase in the level of illuminance. Interactions were significant for illuminance levels greater than 15 lux, as shown in Table 23.

Table 23. Risk ratios of the number of night crashes for the interaction between speed limit and E_h at intersections with posted speed limit ≤ 40 mph.

E_h (lux)	Interaction Parameter	Variance	Standard Error	Low CI	High CI	Risk Ratio
15.00	2.53	0.19	0.44	1.67	3.39	12.57
20.00	4.32	0.39	0.62	3.10	5.55	75.50
25.00	7.39	0.66	0.81	5.79	8.98	1614.60
30.00	12.62	1.02	1.01	10.64	14.59	302233.26

Effect of Average Roadway Luminance (L_{avg})

Table 24. Significant parameter estimates and risk ratios for luminance model at lighted intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgLum	−4.82	0.01	0.009
AvgLum*SpeedL	4.40	81.79	0.053

The significant factors in the average luminance roadway model are shown in Table 24. As noted before, the average roadway luminance is highly inflated. A 1 cd/m^2 increase in the average roadway luminance decreased the ND crash ratio at lighted intersections by 99%. This is very unlikely, and the underlying data distributions need to be studied in more detail. Also, the high parameter estimate of the interaction term indicates that the risk ratios will be extremely high.

UNLIGHTED INTERSECTIONS

Effect of Average Horizontal Illuminance (E_h)

Table 25. Significant parameter estimates and risk ratios for horizontal illuminance model at unlighted intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgIllum	−0.23	0.79	0.048
IntType	−0.53	0.59	0.017

In the illuminance model at unlighted intersections, average horizontal illuminance and intersection type were significant, as shown in the Table 25. For a unit (cd/m^2) increase in the average roadway illuminance, the ND crash ratio at unlighted intersections was reduced by 21%. The ND crash ratio at stop-controlled intersections was 41% lower than at signalized intersections.

Effect of Average Roadway Luminance (L_{avg})

Table 26. Significant parameter estimates and risk ratios for luminance model at unlighted intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
NOL	−0.44	0.64	0.013
SpeedL	−1.32	0.27	0.039
LogTC	−0.31	0.73	0.007

In the luminance model at unlighted intersections, average roadway luminance was not significant. The number of lanes, the posted speed limit, and the log of the traffic count were significant. Intersections with less than or equal to three lanes had an ND crash ratio 36% lower than the ND crash ratio at intersections with greater than three lanes. Intersections with a lower posted speed limit (≤ 40 mph) had a 73% lower ND crash ratio, and for a one-unit increase in the log of the traffic volume, the ND crash ratio decreased by 27%.

SIGNAL INTERSECTIONS

Effect of Average Horizontal Illuminance (E_h)

Table 27. Significant parameter estimates and risk ratios for horizontal illuminance model at signal intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgIllum	−0.06	0.94	0.050

The only significant factor in the average horizontal illuminance model was average horizontal illuminance, as shown in the Table 27. For one cd/m^2 increase in the average horizontal illuminance at signalized intersections, the ND crash ratio decreased by 6%. Interestingly, posted speed limit was not significant.

Effect of Average Roadway Luminance (L_{avg})

Table 28. Significant parameter estimates and risk ratios for luminance model at signal intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
AvgLum	−3.36	0.03	0.002
NOL	−0.32	0.72	0.050
SpeedL	−1.38	0.25	0.021
AvgLum*SpeedL	3.54	34.38	0.013

Table 28 shows the factors that were significant in the luminance model at signalized intersections. As expected, the estimates of average roadway luminance are inflated. An increase in the average roadway luminance by 1 cd/m^2 decreased the ND crash ratio by 97%. Intersections with fewer lanes (≤ 3) and lower posted speed limits (≤ 40 mph) had 28% and 75% lower ND crash ratios respectively. Even though the interaction term was significant, further analyses revealed that, within the available range of luminances, interactions were not significant, as the confidence intervals include 1.

STOP INTERSECTIONS

Effect of Average Horizontal Illuminance (E_h)

Table 29. Significant parameter estimates and risk ratios for horizontal illuminance at stop intersections.

Parameter	Estimate	Risk Ratio	Pr > ChiSq
NOL	−0.81	0.44	0.007
SpeedL	−0.91	0.40	0.003
AvgIllum*SpeedL	0.17	1.19	0.003
LogTC	−0.42	0.66	0.006

Average horizontal illuminance was not significant for stop-controlled intersections. Table 29 displays the factors that were significant. Intersections with fewer lanes and a lower posted speed limit had 56% and 60% lower ND crash ratios, respectively, compared to intersections with more lanes and a higher posted speed limit. Interestingly, a one-unit increase in the log of traffic resulted in a 34% decrease in the ND crash ratio. The interactions between average horizontal illuminance and posted speed limit display a pattern similar to the patterns seen above: the risk ratios increased exponentially as the illuminance level increased, and for higher levels of illumination (≥ 20 lux), risk ratios reached infinity, as shown in Table 30.

Table 30. Risk ratios of number of night crashes for the interaction between speed limit and E_h at stop intersections with posted speed limit ≤ 40 mph.

E_h (lux)	Interaction Parameter	Variance	Standard Error	Low CI	High CI	Risk Ratio
0	0.94	0.10	0.31	0.33	1.54	2.55
5	2.22	0.07	0.26	1.72	2.72	9.17
10	5.24	0.20	0.45	4.36	6.12	188.25
15	12.38	0.51	0.71	10.98	13.77	237457.45
20	29.25	0.98	0.99	27.31	31.19	∞
25	69.12	1.62	1.27	66.63	71.62	∞
30	163.35	2.43	1.56	160.30	166.41	∞

Effect of Average Roadway Luminance (L_{avg})

None of the factors were significant in this model.

CHAPTER 5. DISCUSSION

HORIZONTAL ILLUMINANCE

The effect of average horizontal illuminance was significant overall for both lighted and unlighted intersections. For all intersections, the ND crash ratio decreased by 7% for a one-unit increase (1 lux) in the average horizontal illuminance. In lighted intersections, the decrease in the ND crash ratio rose to 9%. The increase was greatest in the unlighted intersections at 21%, as illustrated in Figure 19. Unlighted intersections had the highest benefit in crash reduction for a 1-lux increase in the average horizontal illuminance. This can be attributed to the increase in the visual information that can be extracted from the surrounding environment.

However, the 1-unit increase in the illuminance did not lead to the same reduction in the number of night crashes across all intersections, but depended rather on the ambient illuminance level of the intersections. A 1-lux increase in the average horizontal illuminance level provided a greater benefit for an intersection with low ambient illumination than for one with higher ambient illumination. This is because the amount of increase in the visual information extracted depends largely on the ambient illumination. By increasing the ambient illumination, more information can be extracted from a poorly lighted intersection than from a relatively well-lighted intersection. Therefore, increasing the average horizontal illumination of an intersection with more ambient light has a marginal benefit in reducing the number of nighttime crashes.

This can be clearly observed by the percentage of reduction in the nighttime crashes at lighted intersections; the average horizontal illuminance at lighted intersections was 5.21 lux compared with unlighted intersections at 1.16 lux. Consequently, the unlighted intersections had a higher ND crash ratio reduction (21%) compared with the lighted intersections (9%) for the same increase in the average horizontal illuminance of 1 lux. Furthermore, this relationship is only valid within the range of the illuminance values (0.28 lux to 31.6 lux) recorded at the intersections used in the study. It is important to understand that this benefit of reduction in the ND crash ratio will decrease with the increase in the intersection's ambient light level. Crashes often have multiple causal factors, and determining the light level at which the effect of lighting ceases to have an impact on the causation of the crash will help in determining the safe level of light for an intersection.

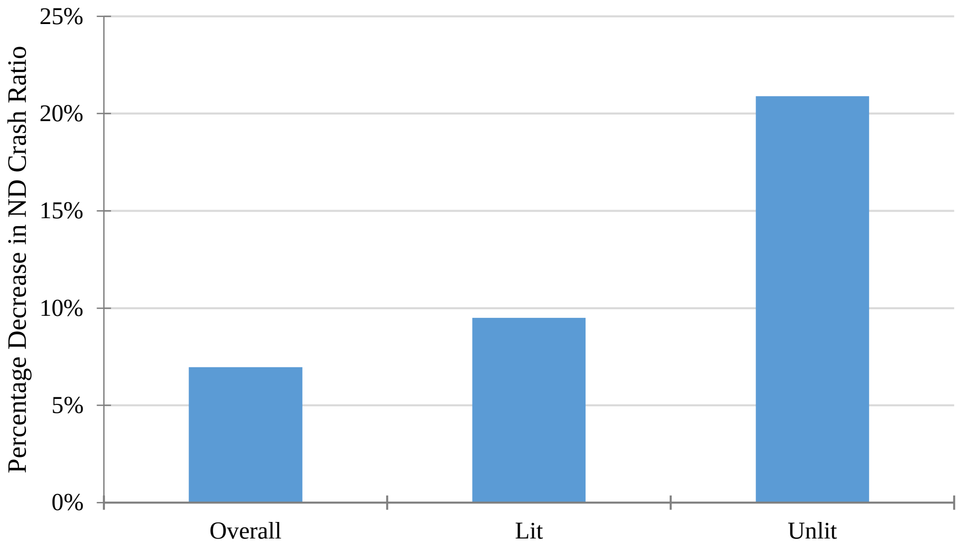

Figure 19. Graph. Decrease in the percentage of ND crash ratio with a 1-lux increase in the average horizontal illuminance.

Even though intersections that were unlighted or had low ambient illuminance levels seem to have received the greatest benefit in the reduction of ND crash ratio, lighted intersections also benefited from the increase in the illuminance level. Although the reduction in ND crash ratio at lighted intersections was not as great as that obtained at unlighted intersections, it was still a significant reduction.

VERTICAL ILLUMINANCE

Lighted intersections had higher average vertical illuminance levels compared with unlighted intersections. This increase in vertical illuminance did not translate to a statistically significant reduction in the ND crash ratio. However, an interesting observation was made during the comparison of the number of night crashes and the average horizontal illuminance. Three lighted intersections (all signalized) with high average horizontal illuminance levels had a high number of night crashes. These three intersections also saw high traffic volumes. Vertical illuminance at these intersections was also the highest measured in the study, as shown in Table 31 and Figure 20. These results indicate that vertical illuminance can increase discomfort and disability glare at intersections, in turn potentially making the intersections unsafe.

Table 31. Intersections with high number of night crashes had high average vertical and horizontal illuminance levels and high traffic volume.

Intersection ID	Night Crashes	Day Crashes	ND Crash Ratio	Avg. Horizontal Illuminance	Avg. Vertical Illuminance	Traffic Volume
62	54	151	0.36	9.81	9.18	49,781
63	34	87	0.39	5.67	7.13	53,327
29	31	101	0.31	31.60	15.91	31,596

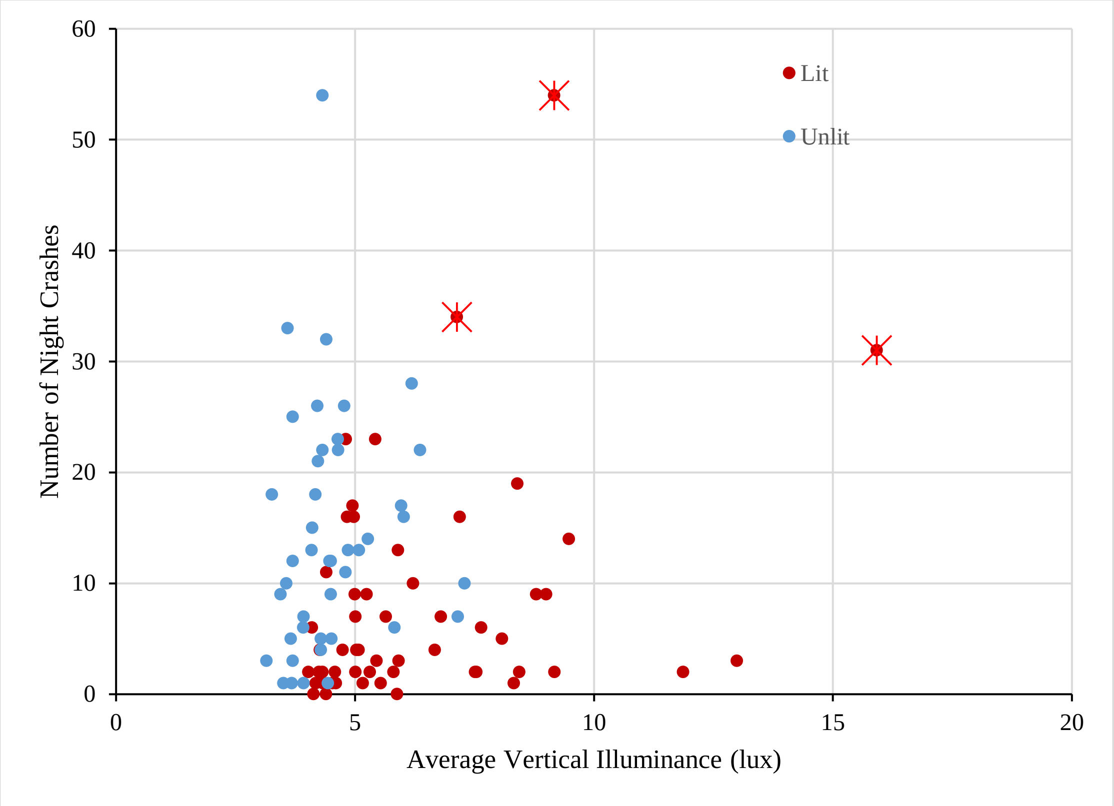

Figure 20. Graph. Scatter plot of number of night crashes vs. average vertical illuminance.

LUMINANCE

The luminance models yielded extremely high parameter estimates. According to the models, a 1-cd/m^2 increase in the average roadway luminance reduced the ND crash ratio by 97% and 99% for all intersections and at lighted intersections, respectively. The parameter estimates were highly inflated for two reasons. The first reason is that some intersections had a high number of day crashes and zero or a relatively low number of night crashes; since the number of day crashes was used as an offset variable, this caused high parameter estimates. The second reason is separation in the posted speed limit data. The data included only four unlighted intersections with posted speed limits less than or equal to 40 mph versus 20 intersections with posted speed limits greater than 40 mph. The distribution of posted limits for lighted intersections was almost equal, as shown in Table 32. The luminance model had an interaction term with posted speed limits that caused the parameter estimates to be very high. In spite of having high parameter estimates for average roadway luminance, the negative parameter estimates indicate that, for a unit increase in the average roadway luminance, the number of night crashes decreased.

Table 32. Distribution of different posted speed limits across lighted and unlighted intersections.

Posted Speed Limit (mph)	Lighted Intersections	Unlighted Intersections
≤ 40	18	4
> 40	17	20

INTERSECTION TYPE

In the overall intersection illuminance and luminance models, stop-controlled intersections had 32% and 36% lower ND crash ratios, respectively, compared with intersections that were signalized. The effect of intersection type was also significant in the illuminance model at unlighted intersections, where stop-controlled intersections had a 41% lower ND crash ratio compared with intersections that were signalized. Stop-controlled intersections are visually and attentively not as complex as signalized intersections. Visual and attentional demands are high for drivers approaching signalized intersections, as they involve complex decision-making, such as taking into account the higher traffic volume, the phase of the signal, the speed of the vehicle, the distance to the intersection, and so forth. Absence of lighting at signalized intersections increases the complexity to a higher degree, as the amount of information the driver gets from the intersection is significantly lower. Therefore, drivers have a higher chance of making errors at signalized intersections, especially at night. This can contribute to signalized intersections having a higher ND crash ratio compared with stop-controlled intersections.

POSTED SPEED LIMIT

Intersections with a posted speed limit less than or equal to 40 mph had statistically lower ND crash ratios compared with intersections that had a posted speed limit higher than 40 mph. Intersections with lower posted speed limits seem to have lower ND crash ratios because the lower vehicle speed enables drivers to take proper evasive actions to avoid a crash. At higher speeds, the absence of lighting makes the intersections more dangerous, as the visual information obtained from the areas is greatly reduced, giving the driver approaching the intersection far less time to react to take evasive action. The effect of lower posted speed limits was significant in both the illuminance and luminance models for all intersections, the illuminance model at lighted intersections, the luminance model at unlighted intersections, the illuminance model at stop intersections, and the luminance model at signalized intersections. Figure 21 shows the percentage reduction in ND crash ratios in the models where the posted speed limit was significant. In the luminance models, the separation in the data at unlighted intersections gave rise to higher parameter estimates and, consequently, higher reductions in the ND crash ratios. Therefore, the reductions in ND crash ratios as a result of lower posted speed limits are inflated.

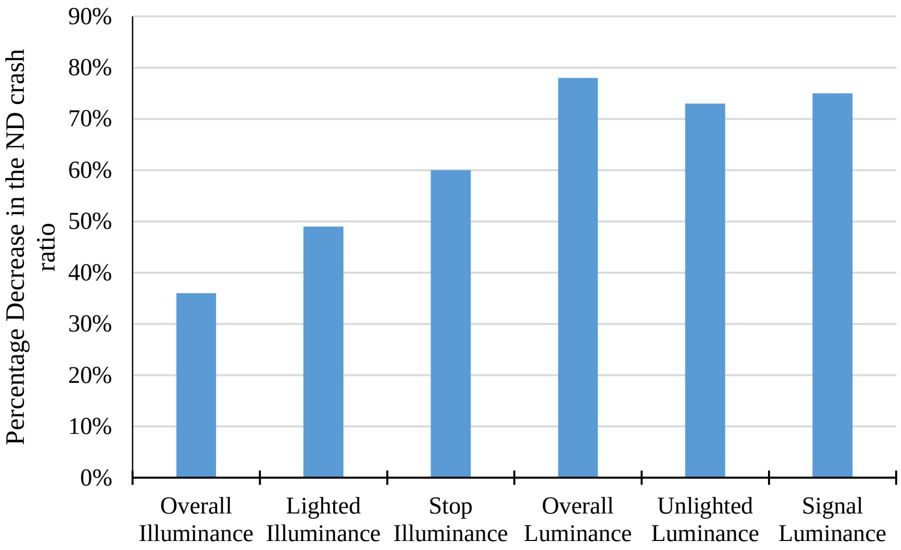

Figure 21. Graph. Percentage reduction in the ND crash ratio at intersections with posted speed limit ≤ 40 mph compared with intersections with higher posted speed limits.

INTERACTION OF AVERAGE HORIZONTAL ILLUMINANCE/ROADWAY LUMINANCE AND POSTED SPEED LIMIT

It was expected that, as the average horizontal illuminance/roadway luminance increased, the ND crash ratio would decrease at lower posted speed limits (≤ 40 mph). Not only did the opposite occur, but the increase in the ND crash ratio as the illuminance/luminance increased was exponential, as shown in Table 21. This was unexpected, as it is contrary to the existing literature about the relationship between speed and lighting level. Research (Economopoulos, 1978) has shown that as speed increases, a higher level of luminance is required to maintain the same level of contrast. These unexpected and intriguing effects of interaction between average horizontal illuminance/roadway luminance and posted speed limit could be attributed to separation of posted speed limit data (see Table 32). Also, use of the posted speed limit assumes that all the vehicles approaching an intersection are traveling at the same speed, but in reality, the approach speeds of individual vehicles vary. Using the actual vehicle speed instead of the posted speed limit might result in a better understanding of the interaction between speed and lighting level.

COMPARISON OF MEASURED LIGHTING LEVELS TO IESNA-RECOMMENDED MAINTAINED VALUES

Average Horizontal Illuminance

IESNA recommends a maintained value of 9 lux at isolated traffic conflict areas with an asphalt road surface (IESNA, 2005). On comparison, it was we found that only 10 intersections out of the 57 lighted intersections met the IESNA-recommended maintained value of average illuminance. Figure 22 shows lighted intersections in relation to ND crash ratios. A majority of the intersections that met the IESNA-recommended values had ND crash ratios lower than 1, indicating that they had a lower number of night crashes compared with day crashes. However, a strong majority (~72%) of intersections that did *not* meet IESNA-recommended levels also had an ND ratio of less than 1 (lower number of night crashes than day crashes). The fact that lower ND crash ratios were observed at intersections with lower light levels could imply that IESNA-recommended values for rural intersections are too high.

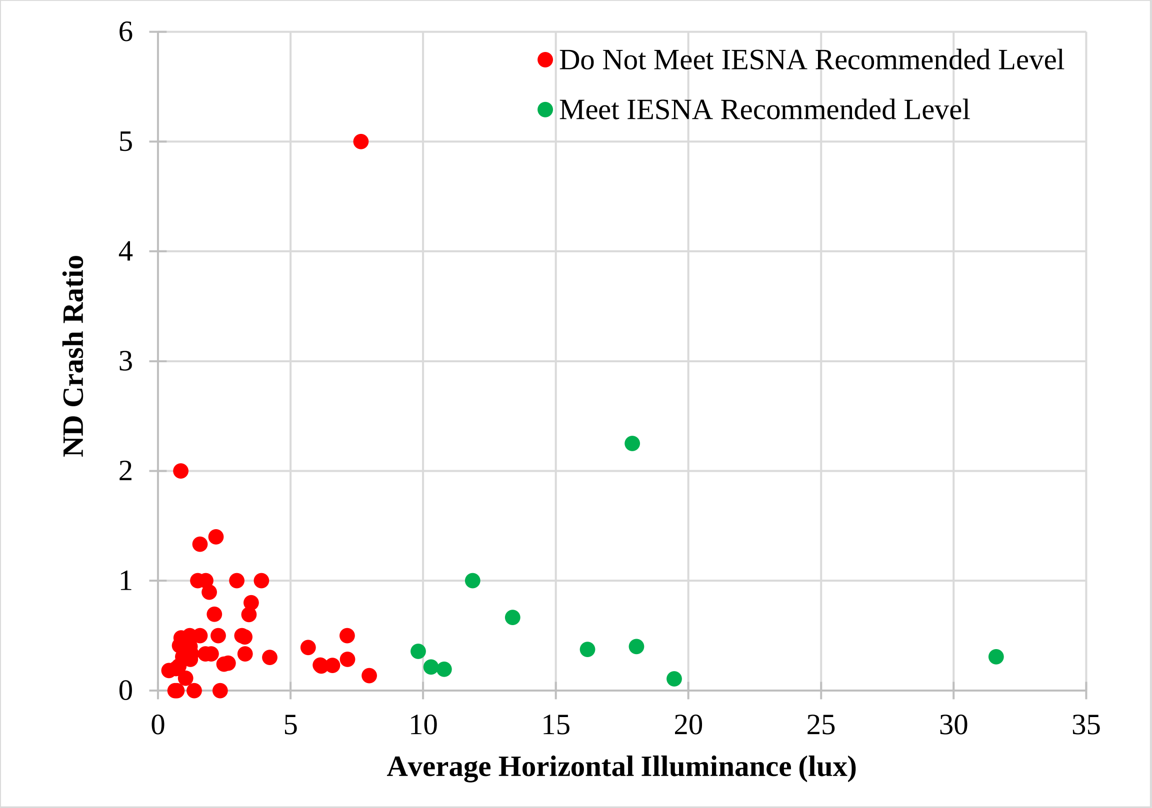

Figure 22. Graph. Scatter plot of lighted intersections that met IESNA-recommended lighting level vs. those that did not meet the recommended levels.

Average Roadway Luminance

IESNA recommends a maintained value of 0.6 cd/m^2 at isolated traffic conflict areas. As with average horizontal illuminance, average roadway luminance values for most of the lighted intersections did not meet the maintained values recommended by IESNA. Only 2 out of the 35 lighted intersections met the IESNA-recommended roadway luminance value, as illustrated in Figure 23.

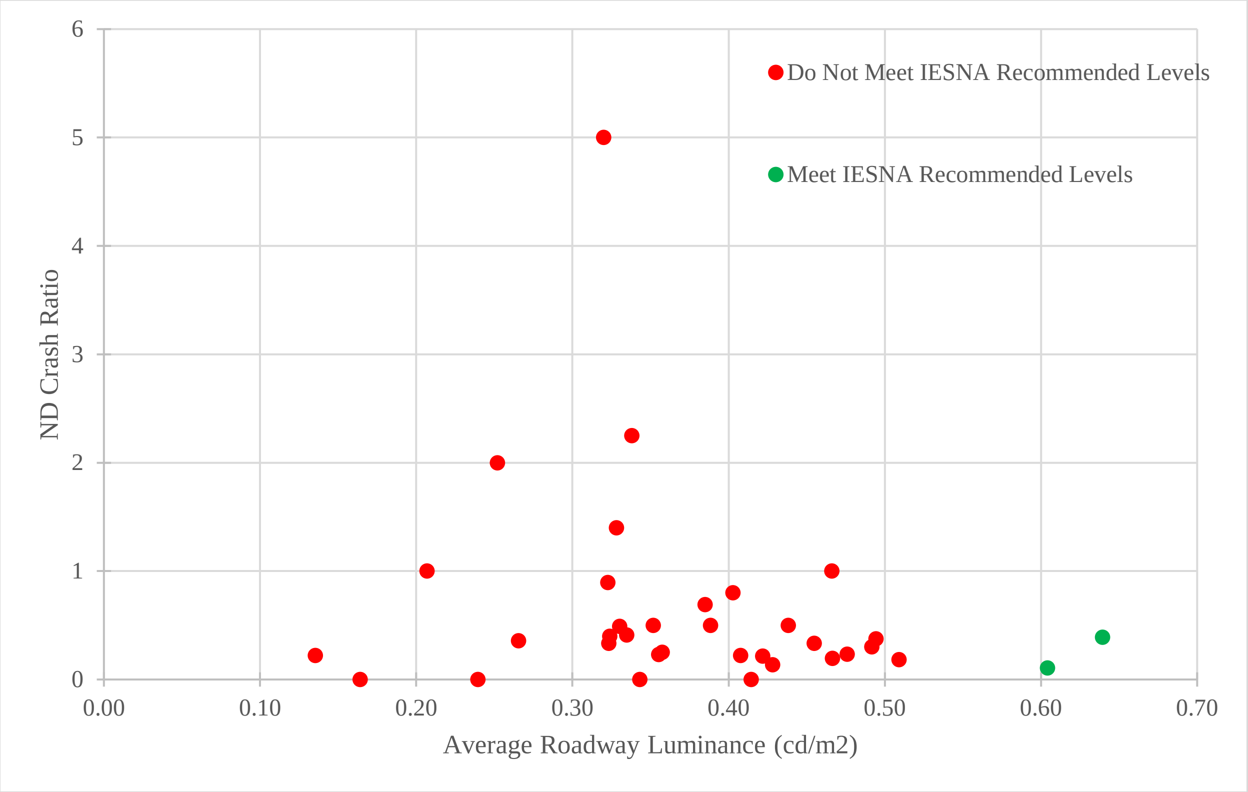

Figure 23. Graph. Scatter plot of lighted intersections that met the IESNA maintained average luminance values (without taking windshield transmissivity into consideration) vs. those that did not meet them.

From the above scatter plots, it is clearly evident that most of the rural intersections were underlit and did not meet the IESNA-recommended maintained values. Although the number of intersections for which luminance data were measured is small, those intersections that met the IESNA-recommended luminance values also had lower ND crash ratios compared with intersections that did not meet the recommended values. However, as with the illuminance levels for the intersections discussed above, 80% of the rural intersections that did not meet the IESNA-recommended levels had ND crash ratios less than 1. This observation again raises the question about whether IESNA-recommended levels are too high. More research is required to address this issue.

CHAPTER 6. CONCLUSIONS

SUMMARY OF FINDINGS

The main purpose of this study was to collect lighting data and quantify the effect of lighting level on night crashes at 56 lighted and 43 unlighted rural intersections in Virginia. Based on the summary statistics from crash data and the results of the data analysis, the following conclusions can be made:

- In general, unlighted intersections have higher night crashes per intersection per year and higher ND and night-to-total crash ratios compared with lighted intersections.
- Unlighted locations have higher ND crash ratios at both stop and signalized intersections compared to lighted locations. While signalized intersections have a higher number of night crashes, the ND crash ratios and ND crash ratio rates at signalized intersections were lower than those at stop-controlled intersections.
- Unlighted "T" intersection geometries have higher ND crash ratios compared to their respective lighted counterparts.
- Night crashes at unlighted intersections have a higher number of fatalities and injuries compared with night crashes at lighted intersections.
- A one-unit (1 lux) increase in average horizontal illuminance decreased the ND crash ratio at rural intersections by 7%. For the same increase in the average horizontal illuminance, the decrease in the ND crash ratios at lighted and unlighted intersections was 9% and 21%, respectively. Unlighted intersections or intersections with low ambient illuminance levels benefited most in ND crash ratio reduction resulting from increased illuminance; an increase in horizontal illuminance also resulted in a lower ND crash ratio overall. However, the ND crash ratio reduction associated with an increase in illuminance is not consistent across the entire range of illuminance; as the ambient illuminance level increases, any additional increase in the illuminance will result in a lesser reduction of ND crash ratio. Furthermore, these relationships are only valid in the range of illuminance levels measured at intersections selected for this study (0.28 lux to 31.6 lux).
- An increase in average vertical illuminance did not translate to a statistically significant effect on the ND crash ratio.
- The parameter estimates for models incorporating average roadway luminance were highly inflated, but the negative sign of the parameter estimates indicates that a unit increase (1 cd/m^2) in the average roadway luminance results in a decrease in the ND crash ratio.
- Even though stop-controlled intersections had fewer night crashes compared with signalized intersections, they had higher ND crash ratios compared to signalized intersections. Interestingly, both the illuminance and luminance models indicated that ND crash ratios at stop-controlled intersections were lower by 32% and 36%, respectively.

ND crash ratios at stop-controlled intersections were 41% lower at unlighted intersections compared to signalized intersections.

- Intersections with a posted speed limit of less than or equal to 40 mph had significantly lower ND crash ratios compared to intersections with a posted speed limit greater than 40 mph.

- Out of 56 lighted intersections, only 10 intersections met the illumination levels recommended by IESNA. In the 35 lighted intersections where luminance was measured, only two intersections met the luminance levels recommended by IESNA. In both cases, intersections conforming to IESNA-recommended lighting levels had lower ND crash ratios compared with those intersections whose lighting levels did not meet the recommended levels. However, most of the intersections that did not meet the recommended illuminance levels also had ND crash ratios that were less than 1 (indicating a lower number of night crashes than day crashes). This could imply that the recommended light levels (illuminance and luminance) for rural intersections may be too high, as lower ND crash ratios were observed with lower illuminance and luminance levels.

RECOMMENDATIONS

The following recommendations are based on the data analysis results of the current study:

- Increasing the average illuminance and roadway luminance of rural intersections is an effective measure for reducing ND crash ratios. Unlighted intersections that generally have low ambient illumination levels will benefit greatly from the resulting increase in illuminance and luminance levels. Even an increase in the average horizontal illuminance of 1 lux results in a significant decrease in the ND crash ratios at both lighted and unlighted intersections. Results of this study also show that the intersections meeting the IESNA-recommended illuminance and luminance levels have lower ND crash ratios.

  However, studying the effect of lighting level on the number of ND crash ratios might not completely reveal the relationship between lighting level and crashes, as crashes are extreme scenarios. It is extremely difficult to single out the one factor that led to a crash. Therefore, to truly understand the effect of lighting level on roadway safety, it should be studied in terms of the visual performance of drivers in a controlled environment.

- Signalized intersections that are unlighted have higher night crashes compared with stop-controlled intersections. Taking the high attentional and visual demands of drivers into consideration, increasing the illuminance and luminance levels at signalized intersections will definitely result in reducing the number of night crashes at these locations. Increased lighting levels will provide more information about the visual scene to drivers approaching the intersection, helping them make better decisions sooner.

LIMITATIONS

As mentioned earlier, annual average daily traffic data for the intersections used in the study were not available. As a result, ND crash rates could not be directly computed. A negative binomial regression with crash rates would have been more powerful, as the true crash rates would be compared.

Furthermore, lighting may be installed at intersections for a number of reasons. An intersection with high crash rates based on historical crash data may be selected for lighting installation. Not taking this relationship into account may bias the negative binomial parameter estimates. This is called endogeneity and it is a complex problem that has not been addressed by this report. Additional research is required to overcome the complexities associated with endogeneity.

DIRECTION OF FUTURE RESEARCH

The results of this study show that increasing the average horizontal illuminance level results in decreasing the ND crash ratio by 7% at rural intersections. However, this reduction in ND crash ratio will taper as the illuminance level is increased and plateau at a certain level of illuminance, as shown in Figure 24. Determining the level at which the effect of lighting is not significant will result in energy savings without compromising the safety of vehicles and pedestrians at intersections. Future research efforts should be directed toward determining this level of illuminance. Further, it is important to determine this level in a controlled environment, such as a test track, rather than through modeling based on crash data.

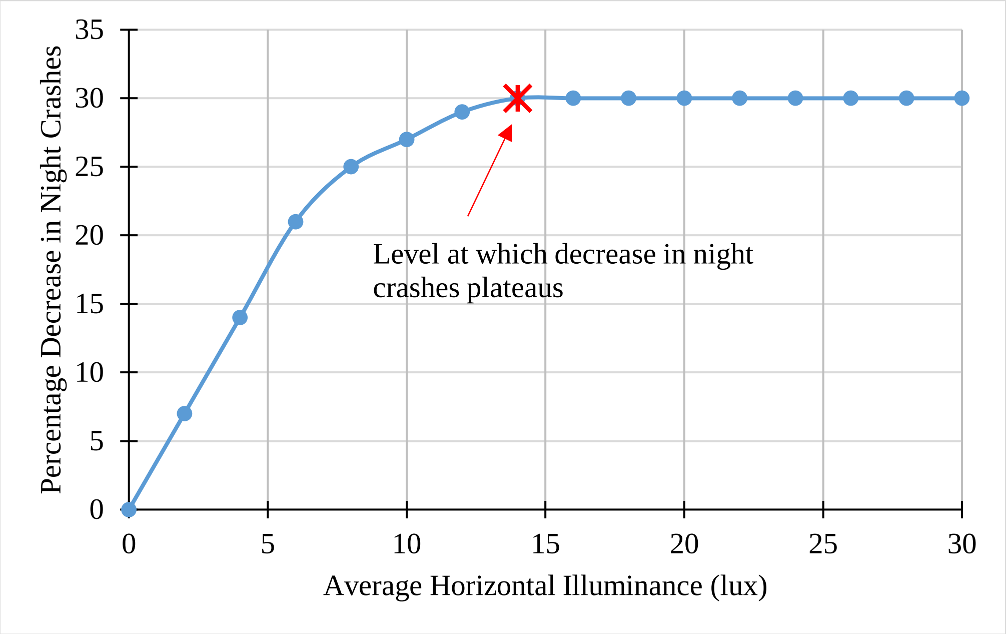

Figure 24. Graph. Illuminance level at which the decrease in night crashes remains constant even with increasing illuminance level.

The effect of vertical illuminance on the visual performance of drivers at intersections should also be studied under controlled scenarios. Vertical illuminance can provide more information to drivers about the intersection, but it can also produce glare that is disabling and discomforting to drivers. It is crucial to establish the level at which vertical illuminance transitions from providing visual information into causing disability and discomfort so that lighting at intersections can be designed in the most effective way in terms of providing information without producing glare.

The effect of the interaction between lighting level and posted speed limit did not yield any conclusive answers about reduction in ND crash ratios at intersections. More research should be conducted to understand the effect of speed and lighting level (both illuminance and luminance) on night crashes. Understanding this relationship can help in recommending the appropriate lighting level for an intersection depending on its posted speed limit.

Finally, current intersection lighting standards are based on luminance and illuminance criteria rather than designed in consideration of the human visual system’s response. This could introduce the potential for an inefficient design methodology, which may result in over lighting intersections without reducing crash risk.

APPENDIX A. NBR SAS OUTPUT OVERALL INTERSECTIONS ILLUMINANCE

Model Information	
Data Set	WORK.RURALOVERALL
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	99
Number of Observations Used	98
Missing Values	1

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	5	0 1 2 3 4
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	90	118.2647	1.3141
Scaled Deviance	90	118.2647	1.3141
Pearson Chi-Square	90	169.9695	1.8885
Scaled Pearson X2	90	169.9695	1.8885
Log Likelihood		1785.9421	
Full Log Likelihood		-281.8609	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AIC (smaller is better)		581.7219	
AICC (smaller is better)		583.7674	
BIC (smaller is better)		604.9866	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	1.0201	0.9416	-0.8254	2.8656	1.17	0.2786
AvgIllum		1	-0.0722	0.0302	-0.1313	-0.0130	5.72	0.0168
IntType	0	1	-0.3917	0.1550	-0.6955	-0.0880	6.39	0.0115
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	-0.1609	0.1377	-0.4308	0.1090	1.37	0.2426
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.1911	0.1467	-0.4786	0.0963	1.70	0.1925
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-0.4213	0.1668	-0.7483	-0.0943	6.38	0.0116
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgIllum*SpeedL	1	1	0.0796	0.0330	0.0150	0.1442	5.84	0.0157
AvgIllum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.1088	0.0971	-0.2991	0.0815	1.26	0.2623
Dispersion		1	0.1788	0.0512	0.1020	0.3134		

APPENDIX B. NBR SAS OUTPUT OVERALL INTERSECTIONS LUMINANCE

Model Information	
Data Set	WORK.RURALOVERALL
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	99
Number of Observations Used	58
Missing Values	41

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	4	1 2 3 4
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	50	74.3078	1.4862
Scaled Deviance	50	74.3078	1.4862
Pearson Chi-Square	50	100.2822	2.0056
Scaled Pearson X2	50	100.2822	2.0056
Log Likelihood		1193.4352	

Criteria for Assessing Goodness of Fit

Criterion	DF	Value	Value/DF
Full Log Likelihood		-165.5487	
AIC (smaller is better)		349.0975	
AICC (smaller is better)		352.8475	
BIC (smaller is better)		367.6415	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	2.4368	0.9684	0.5388	4.3348	6.33	0.0119
AvgLum		1	-3.4708	0.9990	-5.4289	-1.5127	12.07	0.0005
IntType	0	1	-0.4389	0.1837	-0.7989	-0.0790	5.71	0.0168
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	-0.1059	0.1720	-0.4429	0.2311	0.38	0.5380
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.2875	0.1666	-0.6140	0.0391	2.98	0.0844
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-1.5026	0.5204	-2.5227	-0.4826	8.34	0.0039
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgLum*SpeedL	1	1	3.8979	1.3266	1.2977	6.4980	8.63	0.0033
AvgLum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.1583	0.0928	-0.3401	0.0234	2.91	0.0878
Dispersion		1	0.1181	0.0517	0.0501	0.2784		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX C. NBR SAS OUTPUT LIGHTED INTERSECTIONS ILLUMINANCE

Model Information	
Data Set	WORK.RURALLIT
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	56
Number of Observations Used	55
Missing Values	1

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	5	0 1 2 3 4
Lighting	1	LIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	47	65.2874	1.3891
Scaled Deviance	47	65.2874	1.3891
Pearson Chi-Square	47	112.8905	2.4019
Scaled Pearson X2	47	112.8905	2.4019
Log Likelihood		666.3076	
Full Log Likelihood		-137.4216	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AIC (smaller is better)		292.8432	
AICC (smaller is better)		296.8432	
BIC (smaller is better)		310.9092	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	-0.5344	1.3210	-3.1234	2.0547	0.16	0.6858
AvgIllum		1	-0.0998	0.0379	-0.1742	-0.0255	6.94	0.0084
IntType	0	1	-0.3286	0.2121	-0.7442	0.0870	2.40	0.1212
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	-0.1913	0.2110	-0.6049	0.2222	0.82	0.3645
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.0564	0.2318	-0.5107	0.3978	0.06	0.8076
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-0.6778	0.2564	-1.1804	-0.1752	6.99	0.0082
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgIllum*SpeedL	1	1	0.1071	0.0394	0.0299	0.1843	7.40	0.0065
AvgIllum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	0.0568	0.1340	-0.2058	0.3193	0.18	0.6718
Dispersion		1	0.1282	0.0692	0.0445	0.3695		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX D. NBR SAS OUTPUT LIGHTED INTERSECTIONS LUMINANCE

Model Information	
Data Set	WORK.RURALLIT
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	56
Number of Observations Used	34
Missing Values	22

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	4	1 2 3 4
Lighting	1	LIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	26	42.4448	1.6325
Scaled Deviance	26	42.4448	1.6325
Pearson Chi-Square	26	61.2154	2.3544
Scaled Pearson X2	26	61.2154	2.3544
Log Likelihood		515.7423	
Full Log Likelihood		-90.5480	

Criteria for Assessing Goodness of Fit

Criterion	DF	Value	Value/DF
AIC (smaller is better)		199.0960	
AICC (smaller is better)		206.5960	
BIC (smaller is better)		212.8332	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	1.9730	1.6647	-1.2897	5.2357	1.40	0.2359
AvgLum		1	-4.8195	1.8564	-8.4579	-1.1811	6.74	0.0094
IntType	0	1	-0.5088	0.3071	-1.1107	0.0932	2.74	0.0976
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	-0.1178	0.3554	-0.8145	0.5789	0.11	0.7403
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.2508	0.3075	-0.8535	0.3518	0.67	0.4146
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-1.5513	0.9318	-3.3775	0.2749	2.77	0.0959
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgLum*SpeedL	1	1	4.4042	2.2803	-0.0651	8.8735	3.73	0.0534
AvgLum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.0582	0.1378	-0.3283	0.2119	0.18	0.6728
Dispersion		1	0.1733	0.0973	0.0577	0.5210		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX E. NBR SAS OUTPUT UNLIGHTED INTERSECTIONS ILLUMINANCE

Model Information	
Data Set	WORK.RURALUNLIT
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	43
Number of Observations Used	43

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	2	1 3
Lighting	1	UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	35	53.7324	1.5352
Scaled Deviance	35	53.7324	1.5352
Pearson Chi-Square	35	59.8817	1.7109
Scaled Pearson X2	35	59.8817	1.7109
Log Likelihood		1125.2054	
Full Log Likelihood		-138.8683	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AIC (smaller is better)		295.7366	
AICC (smaller is better)		301.1912	
BIC (smaller is better)		311.5874	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	2.3774	1.3022	-0.1749	4.9296	3.33	0.0679
AvgIllum		1	-0.2343	0.1183	-0.4661	-0.0024	3.92	0.0477
IntType	0	1	-0.5291	0.2220	-0.9642	-0.0941	5.68	0.0171
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	0.0565	0.1944	-0.3245	0.4375	0.08	0.7714
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.3168	0.1792	-0.6680	0.0344	3.13	0.0771
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	0.1375	0.3636	-0.5752	0.8502	0.14	0.7053
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgIllum*SpeedL	1	1	0.0938	0.1585	-0.2168	0.4045	0.35	0.5538
AvgIllum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.2310	0.1353	-0.4961	0.0342	2.92	0.0877
Dispersion		1	0.1530	0.0625	0.0687	0.3409		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX F. NBR SAS OUTPUT UNLIGHTED INTERSECTIONS LUMINANCE

Model Information	
Data Set	WORK.RURALUNLIT
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	43
Number of Observations Used	24
Missing Values	19

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	2	0 1
Alignment	2	1 3
Lighting	1	UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	16	29.8736	1.8671
Scaled Deviance	16	29.8736	1.8671
Pearson Chi-Square	16	34.1273	2.1330
Scaled Pearson X2	16	34.1273	2.1330
Log Likelihood		682.1292	

Criteria for Assessing Goodness of Fit

Criterion	DF	Value	Value/DF
Full Log Likelihood		-70.5644	
AIC (smaller is better)		159.1289	
AICC (smaller is better)		171.9860	
BIC (smaller is better)		169.7314	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		1	3.2510	1.1853	0.9278	5.5742	7.52	0.0061
AvgLum		1	-1.2416	1.4946	-4.1710	1.6877	0.69	0.4061
IntType	0	1	-0.2636	0.2064	-0.6681	0.1410	1.63	0.2016
IntType	1	0	0.0000	0.0000	0.0000	0.0000	.	.
IntC	1	1	-0.1301	0.1702	-0.4636	0.2034	0.58	0.4445
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.4404	0.1781	-0.7896	-0.0913	6.11	0.0134
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-1.3167	0.6363	-2.5638	-0.0695	4.28	0.0385
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgLum*SpeedL	1	1	2.2717	1.8437	-1.3418	5.8853	1.52	0.2179
AvgLum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.3081	0.1144	-0.5322	-0.0839	7.26	0.0071
Dispersion		1	0.0357	0.0327	0.0059	0.2157		

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX G. NBR SAS OUTPUT STOP INTERSECTIONS ILLUMINANCE

Model Information	
Data Set	WORK.RURALSTOP
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	47
Number of Observations Used	46
Missing Values	1

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	1	1
Alignment	5	0 1 2 3 4
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	39	60.2369	1.5445
Scaled Deviance	39	60.2369	1.5445
Pearson Chi-Square	39	110.3989	2.8307
Scaled Pearson X2	39	110.3989	2.8307
Log Likelihood		317.0958	
Full Log Likelihood		-115.1594	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AIC (smaller is better)		246.3188	
AICC (smaller is better)		250.2107	
BIC (smaller is better)		260.9479	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	4.3635	1.5127	1.3986	7.3284	8.32	0.0039
AvgIllum		1	-0.0641	0.0464	-0.1550	0.0268	1.91	0.1667
IntC	1	1	-0.3498	0.2708	-0.8806	0.1811	1.67	0.1966
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.8123	0.3034	-1.4070	-0.2177	7.17	0.0074
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-0.9099	0.3095	-1.5164	-0.3033	8.64	0.0033
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgIllum*SpeedL	1	1	0.1721	0.0579	0.0585	0.2856	8.82	0.0030
AvgIllum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.4215	0.1521	-0.7196	-0.1235	7.68	0.0056
Dispersion		1	0.1716	0.1027	0.0531	0.5547		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX H. NBR SAS OUTPUT STOP INTERSECTIONS LUMINANCE

Model Information	
Data Set	WORK.RURALSTOP
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	47
Number of Observations Used	41
Missing Values	6

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	1	1
Alignment	5	0 1 2 3 4
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	34	47.8052	1.4060
Scaled Deviance	34	47.8052	1.4060
Pearson Chi-Square	34	68.1554	2.0046
Scaled Pearson X2	34	68.1554	2.0046
Log Likelihood		308.6295	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Full Log Likelihood		-106.0364	
AIC (smaller is better)		228.0728	
AICC (smaller is better)		232.5728	
BIC (smaller is better)		241.7814	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	0.2211	2.5567	-4.7899	5.2322	0.01	0.9311
AvgLum		1	6.4851	3.7471	-0.8591	13.8293	3.00	0.0835
IntC	1	1	-0.5830	0.3196	-1.2095	0.0434	3.33	0.0681
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	-0.8711	0.4155	-1.6854	-0.0569	4.40	0.0360
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	3.1469	2.8834	-2.5045	8.7983	1.19	0.2751
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgLum*SpeedL	1	1	-5.7712	4.9206	-15.4153	3.8729	1.38	0.2408
AvgLum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.3723	0.1885	-0.7417	-0.0029	3.90	0.0482
Dispersion		1	0.2864	0.1260	0.1209	0.6783		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX I. NBR SAS OUTPUT SIGNAL INTERESECTIONS ILLUMINANCE

Model Information	
Data Set	WORK.RURALSIGNAL
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	52
Number of Observations Used	52

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	1	0
Alignment	2	1 3
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	45	54.9779	1.2217
Scaled Deviance	45	54.9779	1.2217
Pearson Chi-Square	45	58.9693	1.3104
Scaled Pearson X2	45	58.9693	1.3104
Log Likelihood		1480.5230	
Full Log Likelihood		-155.0248	
AIC (smaller is better)		326.0495	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AICC (smaller is better)		329.3984	
BIC (smaller is better)		341.6595	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	-0.8186	1.0554	-2.8872	1.2500	0.60	0.4380
AvgIllum		1	-0.0631	0.0322	-0.1262	0.0001	3.83	0.0504
IntC	1	1	-0.0539	0.1332	-0.3149	0.2071	0.16	0.6858
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	0.0158	0.1356	-0.2501	0.2816	0.01	0.9075
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-0.1362	0.1700	-0.4694	0.1969	0.64	0.4228
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgIllum*SpeedL	1	1	0.0466	0.0339	-0.0198	0.1131	1.89	0.1691
AvgIllum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	0.0139	0.1039	-0.1897	0.2176	0.02	0.8934
Dispersion		1	0.0931	0.0346	0.0450	0.1928		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

APPENDIX J. NBR SAS OUTPUT SIGNAL INTERESECTIONS LUMINANCE

Model Information	
Data Set	WORK.RURALSIGNAL
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	NightC
Offset Variable	DC

Number of Observations Read	52
Number of Observations Used	51
Missing Values	1

Class Level Information		
Class	**Levels**	**Values**
IntC	2	1 2
IntType	1	0
Alignment	2	1 3
Lighting	2	LIT UNLIT
SpeedL	2	1 2
NOL	2	1 2

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
Deviance	44	56.8340	1.2917
Scaled Deviance	44	56.8340	1.2917
Pearson Chi-Square	44	62.2269	1.4142
Scaled Pearson X2	44	62.2269	1.4142
Log Likelihood		1452.4565	
Full Log Likelihood		-149.5862	

Criteria for Assessing Goodness of Fit			
Criterion	**DF**	**Value**	**Value/DF**
AIC (smaller is better)		315.1725	
AICC (smaller is better)		318.6011	
BIC (smaller is better)		330.6271	

Algorithm converged.

Analysis of Maximum Likelihood Parameter Estimates								
Parameter		**DF**	**Estimate**	**Standard Error**	**Wald 95% Confidence Limits**		**Wald Chi-Square**	**Pr > ChiSq**
Intercept		1	3.8912	1.5971	0.7609	7.0216	5.94	0.0148
AvgLum		1	-6.0041	1.8872	-9.7030	-2.3052	10.12	0.0015
IntC	1	1	0.0145	0.1325	-0.2453	0.2742	0.01	0.9130
IntC	2	0	0.0000	0.0000	0.0000	0.0000	.	.
NOL	1	1	0.0003	0.1270	-0.2487	0.2492	0.00	0.9984
NOL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
SpeedL	1	1	-3.3487	1.2854	-5.8681	-0.8293	6.79	0.0092
SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
AvgLum*SpeedL	1	1	5.5094	2.1230	1.3483	9.6704	6.73	0.0095
AvgLum*SpeedL	2	0	0.0000	0.0000	0.0000	0.0000	.	.
LogTC		1	-0.1204	0.0929	-0.3025	0.0617	1.68	0.1949
Dispersion		1	0.0692	0.0308	0.0289	0.1655		

Note: The negative binomial dispersion parameter was estimated by maximum likelihood.

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