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Safety Benefits and Best Practices for Intersection Lighting

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Nighttime safety continues to be a major concern for transportation agencies across the country. Roadway lighting has been widely used as a countermeasure for nighttime crashes. However, safety engineers and researchers frequently lack effective tools when determining exactly how lighting should be optimized to maximize safety while conserving energy. This project involved an extensive effort to investigate traffic safety lighting impacts at intersections. Based on the results, the project identified optimal lighting levels for different types of intersections and developed guidelines to facilitate lighting needs analysis and design at the Virginia Department of Transportation. During this study, a crash analysis showed a 2.9% reduction in night-to-day crash ratio for each 1-lux increase of minimum illuminance at intersection boxes. Additionally, the project team found a benefit-cost ratio between 2.6 and 5.6 for unsignalized intersections and between 2.8 and 7.9 for signalized intersections, assuming one injury nighttime crash per year at such locations and depending on whether existing poles can be used.

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FINAL REPORT

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ABSTRACT

Nighttime safety continues to be a major concern for transportation agencies across the country. Roadway lighting has been widely used as a countermeasure for nighttime crashes. However, safety engineers and researchers frequently lack effective tools when determining exactly how lighting should be optimized to maximize safety while conserving energy. This project involved an extensive effort to investigate traffic safety lighting impacts at intersections. Based on the results, the project identified optimal lighting levels for different types of intersections and developed guidelines to facilitate lighting needs analysis and design at the Virginia Department of Transportation. During this study, a crash analysis showed a 2.9% reduction in night-to-day crash ratio for each 1-lux increase of minimum illuminance at intersection boxes. Additionally, the project team found a benefit-cost ratio between 2.6 and 5.5 for unsignalized intersections and between 2.8 and 7.9 for signalized intersections, assuming one injury nighttime crash per year at such locations and depending on whether existing poles can be used.

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INTRODUCTION

Nighttime safety continues to be a major concern for transportation agencies across the country. Roadway lighting has been widely used as a countermeasure for nighttime crashes. However, safety engineers and researchers frequently lack effective tools when determining exactly how lighting should be optimized to maximize safety while conserving energy consumption, operations, and maintenance costs. Previous research on the safety impacts of roadway lighting has mostly focused on the effects of lighting by comparing highways with and without lighting. While the results of those studies varied, many pointed to a positive safety impact due to the presence of lighting.

Two main aspects are involved in the design of lighting systems for intersections and midblock crosswalks: (1) the decision to install lighting, which is based on warrants; and (2) deciding what level of lighting is needed. The Federal Highway Administration (FHWA) in the current *FHWA Lighting Handbook*[1] specifies that a lighting need can be justified based on a warrant analysis showing that lighting is an effective safety feature. However, warranting guidelines for intersections and midblock crosswalk lighting are limited. While the *FHWA Roadway Lighting Handbook* provides some information, it primarily refers to the Transportation Association of Canada's (TAC's) *Guide for the Design of Roadway Lighting*.[2] In both documents, warranting conditions include geometric configurations (e.g., sight distances, angle of intersection, and number of legs), operational factors (e.g., annual average daily traffic and speed), and environmental and collision factors, all of which lead to a recommendation for the type of lighting to be installed. Note that these warrants have never been field validated and are mostly based on practitioner best practices.

In addition to the use of lighting, the amount of light emitted is another important component of roadway lighting. The latest national lighting design standard (ANSI/IES RP-8-18 *Recommended Practice for Roadway Lighting*) includes criteria for roadway lighting at interchanges and intersections.[3] However, these design criteria are consensus based and derived from practitioner experience rather than scientific results. The basic premise is that the intersection is lighted to the sum of the lighting levels on the intersecting roadways. This leads to what some users perceive as high lighting requirements. Virginia Tech Transportation Institute (VTTI) research on lighting at rural intersections in Virginia indicated a reduction in crashes and crash severity with increased lighting levels.[4] The study demonstrated that a 1 lux increase in lighting level can reduce crashes by as much as 9%. The results, however, also showed diminishing benefits in crash reductions as light levels exceeded a threshold, indicating a critical need for exploring the boundaries of lighting's impact. An earlier FHWA evaluation of adaptive lighting found that lighting levels slightly lower than the current standards might be just as beneficial based on crash and field lighting data.[5] Note that the use of signaling at both intersection and midblock crosswalks should also be considered in this analysis.

This report details the research activities conducted during this project, along with the findings and recommendations. The project team also developed intersection lighting guideline recommendations, which are included in the Recommendations section.

PURPOSE AND SCOPE

The objectives of this project were as follows:

1. Investigate lighting's traffic safety impacts at intersections and midblock pedestrian crossings.

2. Develop guidelines for intersection lighting and, to the extent feasible, midblock pedestrian crossing lighting design and warrants for use by the Virginia Department of Transportation (VDOT). These guidelines should consider both the presence of lighting and the lighting level.

3. Develop Crash Modification Factors (CMFs) for intersection lighting based on the crash analyses utilizing field-measured lighting data.

This research was mainly focused on intersection lighting. As feasible, the project team also discussed the design and safety impacts of lighting at midblock pedestrian crossings.

METHODS

During the project, the research team conducted a number of activities, as follows, towards developing an in-depth understanding of the lighting safety benefits at intersections:

- Review current lighting practices at intersections and midblock crosswalks. This activity included an extensive literature review and agency interviews. The agency interviews involved six state agencies with representative lighting practices and five VDOT districts.

- Collect data at sample intersections. The project team selected approximately 242 intersections across the state based on location, nighttime crash history, and intersection configurations at which they collected detailed field lighting measurements. In addition, the team also compiled detailed crash, roadway, and traffic data for the intersections based on a variety of sources.

- Conduct crash data analysis to understand lighting-safety correlations at the studied intersections. The project team conducted an in-depth analysis of 2014–2018 crash data using negative binomial regression to identify and quantify the significant correlations between night-to-day (ND) crash ratio and lighting variables. In addition, the project team developed three-parameter exponential curves for different types of intersections to identify optimal lighting levels.

- Carry out CMF development. Based on the crash data analysis, the project team developed CMFs for unit changes in minimum intersection box illuminance and intersection box lighting uniformity.

- Conduct a safety benefit-cost analysis to quantify the benefit cost ratios (BCRs) associated with intersection lighting. A detailed benefit-cost analysis estimating the BCRs for adding lighting at different types of intersections was also conducted.

- Develop intersection lighting guidelines. Based on the findings of this project, the project team developed a guideline document to facilitate the use of lighting at Virginia intersections.

The following sections describe the methods used for this project's major activities.

Summarize Current Lighting Practices

The research team reviewed and summarized current practices at international, national, and VDOT district levels for lighting at intersections and midblock pedestrian crossings. In addition to an in-depth literature review, the project team conducted telephone interviews with a number of states and VDOT districts and divisions to understand the current state of practice in intersection and midblock lighting design. The findings of the literature review are presented in Appendix A.

During the state interviews, the project team first solicited a number of candidate states for interview based on panel recommendations, past research experience, and known lighting practices. The selection of the candidate states considered a number of factors, such as varying lighting policies (e.g., wider use of lighting versus limited use of lighting), location (e.g., states representing different regions of the country), and known best lighting practices. The identified state contacts were first sent a request to participate in a telephone interview. Upon approval, the project team then sent out an interview consent form meeting all Internal Review Board requirements. This was followed by a list of nine general interview questions that was distributed to participants prior to each scheduled interview to guide the discussions (Figure 1).

At the end of the process, the project team interviewed representatives from five U.S. states (Arizona, Florida, Illinois, New York, and North Carolina) and Ontario, Canada. Each interview lasted between 1 and 2 hours, depending on how much interviewees had to share, with most lasting around 1.5 hours.

The District interviews followed a similar process. The project team interviewed representatives (e.g., District Traffic Engineers, District Maintenance officials, and traffic safety/lighting personnel) from the Traffic Engineering Division and five districts (Culpeper, Hampton Roads, Northern Virginia, Richmond, and Salem) via conference calls. Each interview lasted around 1 hour. Figure 2 shows the District interview questions asked during this project.

To collect first-hand information on lighting design practices at municipalities, the project team also conducted telephone interviews with representatives from the City of Alexandria and lighting designers at Dominion Energy® and AEP Energy™ who had experience in lighting designs for Virginia municipalities.

Review Data Availability and Data Collection

During the District interviews, the project team also asked about the availability of data items required to develop a comprehensive understanding of the lighting safety impacts at intersections and midblock pedestrian crosswalks, including the following:

- Lighting project data for the identification of lighted intersections, lighting system installation dates, and cost of initial installation of lighting systems
- Traffic counts, including hourly counts of turning movements, pedestrians, and bicycles
- Land use data showing land use types, such as commercial and residential
- 2014–2018 statewide crash data
- Roadway network with historical average daily traffic (ADT) data
- Statewide intersection inventory

Based on the district interviews, the project team learned that most Districts did not have wide scale traffic counts or pedestrian counts. VDOT also did not have an intersection inventory with basic intersection information. For safety projects relevant to intersections, districts generally used ADT data developed by the Central Office. The state also did not have wide scale databases tracking intersection lighting projects. At the end of this process, the project team was able to obtain detailed data on statewide crashes, roadway network, and yearly ADT. The team collected detailed roadway and land use information manually in addition to manual collection of the field lighting measurement data.

INTERVIEW QUESTIONS

VDOT Research Project: Safety Benefits and Best Practices for Intersection Lighting

1) What are your agency's responsibilities regarding intersection and mid-block crosswalk lighting?
    a) Who typically makes the decision on lighting needs for these areas?
    b) Based on what considerations?

2) What is the procedure to identify lighting **needs** at intersections and midblock crosswalks?
    a) What warranting conditions are used for intersection and midblock crosswalk lighting? *(e.g., traffic volume, pedestrian/bicyclist activity, crash history, geometry, location of intersection/crosswalk, cost, benefit-cost analysis, etc.)*

3) What is the process for lighting **design** at intersections and mid-block crosswalks?
    a) Does your agency have lighting design guidelines?
    b) Which national lighting standards are the guidelines based on? *(e.g., AASHTO Roadway Lighting Design Guide, ANSI/IES RP-8-14, ANSI/IES RP-8-00, FHWA Lighting Handbook, etc.)*
    c) What are the variations in lighting design within different districts/regions/municipalities in your state?
    d) How is lighting typically designed? *(e.g., in-house, contractors, design software, etc.)*
        i) **If by contractors:** How is your agency involved in the design process?
    e) How are minimum and maximum lighting design levels determined?
    f) What types of considerations influence the design? *(e.g., design area, roadway features, geometric layout, etc.)* How are these considerations prioritized?
    g) After implementation, are there inspections to ensure the lighting meets the design requirements?
    h) Where lighting design is in the overall project development/delivery process?

4) How is lighting maintained at intersections and mid-block crosswalks?

5) What is your agency's take or opinion regarding LED lighting at intersections? Midblock crosswalks? How are LEDs implemented?

6) What are some limitations or issues in the current lighting design practices in your opinion?
    a) How could the current lighting design practices be improved?

7) Do you know other best lighting design practices at other states or agencies?

8) Are you aware of previous, ongoing, or planned research efforts on intersection lighting at your agency?

9) Is your agency familiar with adaptive lighting?
    (i.e., changing lighting levels based on real traffic/environmental conditions)
        i) **If yes:** Has your agency implemented or any plans to implement adaptive lighting?

Figure 1. State Interview Questions

INTERVIEW QUESTIONS

VDOT Research Project: Safety Benefits and Best Practices for Intersection Lighting

1) What are the district's responsibilities regarding intersection and mid-block crosswalk lighting?
    a) Who typically makes the decision on lighting needs for these areas?
    b) Based on what considerations?
2) What is the procedure to identify lighting **needs** at intersections and midblock crosswalks?
    a) What warranting conditions are used for intersection and midblock crosswalk lighting? *(e.g., traffic volume, pedestrian/bicyclist activity, crash history, geometry, location of intersection/crosswalk, cost, benefit-cost analysis, etc.)*
3) What is the process for lighting **design** at intersections and mid-block crosswalks?
    a) How close does VDOT follow the latest IES RP-8 (i.e., RP-8-14) during lighting design in general and for intersections/midblock crosswalks?
    b) Are other lighting design guides used? *(e.g., AASHTO Roadway Lighting Design Guide, FHWA Lighting Handbook, etc.)*
    c) What are the variations in lighting design within different districts/regions/municipalities you are aware of?
    d) How is lighting typically designed? *(e.g., in-house, contractors, design software, etc.)*
        i) **If by contractors:** How is the district involved in the design process?
    e) How are minimum and maximum lighting design levels determined?
    f) What types of considerations influence the design? *(e.g., design area, roadway features, geometric layout, etc.)* How are these considerations prioritized?
    g) After implementation, are there inspections to ensure the lighting meets the design requirements?
    h) Where lighting design is in the overall project development/delivery process?
4) How is lighting maintained at intersections and mid-block crosswalks?
5) What is the district's take or opinion regarding LED lighting at intersections? Midblock crosswalks? How are LEDs implemented?
6) What are some limitations or issues in the current lighting design practices in your opinion?
    a) How could VDOT improve the current lighting design practices?
7) Do you know other best lighting design practices at other districts or agencies?
8) Is your district familiar with adaptive lighting?
    (i.e., changing lighting levels based on real traffic/environmental conditions)
    a) What's your take on adaptive lighting at intersections and mid-block crosswalks?
9) Data needs and sources:
    - Project data: intersection-related projects (2013-2018), district wise or for selected intersections. VTTI will identify data availability and contacts during district interviews.
    - Land use data. Zoning maps can be obtained at cities. Does VDOT have zoning/land use data for intersections on non-state maintained roadways and state maintained roadways?
    - Crash data including state wide 2013-2017 crashes (both on- and off- system roadways) with location information.

Figure 2. VDOT District Interview Questions

The project team was, however, able to obtain preexisting detailed 2014–2018 statewide crash data, historical ADT information, and the latest VDOT roadway network files. In addition, the project team also collected 2014–2018 Virginia Highway Performance Monitoring System data.

Intersection Sampling and Selection

The process for selecting study intersections for study considered the following factors:

- Presence of lighting at intersections. The purpose of this research was to identify the safety effects of lighting, and therefore it was necessary to include both lighted and unlighted intersections for study.

- Safety records of intersections. Crash history at each intersection was a major consideration for the selection of study sites. While intersections with higher nighttime crash frequency were important, the project team also considered sites with relatively lower crash frequencies for comparison purposes.

- Location of intersections. During the selection process, the project team made sure that sample intersections were selected from all nine districts to represent different conditions across the entire state.

- Type of intersection. The project team considered a balanced representation of intersections within different areas (e.g., urban, suburban, residential, commercial, and industrial areas), at different roadway types based on the functional classifications of the intersecting roadways, with different lane configurations (i.e., different combinations of turning and through lanes), speed limits, and different intersection layouts (i.e., number of legs and intersection angle).

- Field lighting data collection effort. The data collection effort was a major constraint for the number of intersections that could be analyzed. During this project, the team needed to drive the instrumented data collection vehicle to all sites to collect the lighting measurements. To ensure the data collection efforts were within budget and time limits, the project team made an effort to select clusters of intersections instead of randomly located individual intersections.

- Recommendations from district officials. During the district interviews, some officials suggested particular intersections for analysis due to factors such as high nighttime crash frequencies, complex roadway geometries, and/or challenging intersection configurations.

To address the aforementioned factors, the project team used the following procedures to select the intersections:

- Generate a statewide intersection inventory. The project team used the VDOT intersections feature class contained in the VDOT quarterly releases of the statewide Linear Referencing System package. The intersection layer, however, contained point features generated using a simple intersecting operation based on the route layer in the Linear Referencing System package. As a result, using this procedure caused the intersection layer to contain duplicate points for many intersections (e.g., at intersections along divided roadways that are represented by double lines in the route layer). To reduce the duplicate points for individual intersections, the project team simply applied a merge function in ArcGIS^{TM} to merge all intersection points within a 100-foot radius. At this point, the team decided not to process the intersection layer further, believing the resulting dataset would meet the needs of the initial intersection sampling process.

- Select initial sample intersections based on crash history. The project team performed a spatial join between the 2014–2018 crash data and the statewide intersections to join each intersection with all crashes within a 250-foot radius. Based on the joined data, the project team developed nighttime crash counts for the intersections, which were then grouped into three categories by nighttime crash frequency: high (i.e., five or more), medium (i.e., two to four), and low (i.e., one or zero). Within each category, the project team initially randomly selected 50 intersections, resulting in a total of 150 sample intersections. Nighttime crashes during this project were identified as the crashes that occurred when the sun was at least 12 degrees lower than the horizon. Solar angles for each crash were determined based on their time and location using the National Oceanic and Atmospheric Administration (NOAA) method.[6]

- Manual selection of additional intersections. During this step, the project team manually selected a varying number of suitable intersections near each initially sampled intersection to increase the total sample size while controlling the field lighting data collection efforts. During this process, the project team also added the intersections recommended by the district officials. Additionally, the team verified each initial sample intersection and deleted the ones that were not suitable for analysis (e.g., small intersections involving driveways, rural intersections with extremely low traffic, or intersections on freeway off ramps).

- Refine intersection selection to ensure balanced representation of different types and locations. During this step, the project team conducted a quick frequency analysis based on key variables such as functional class, speed limit, area type, and ADT to ensure each major variable was well represented. This step included further deleting intersections in each overrepresented category and adding additional intersections in each underrepresented category.

At the end of this process, the project team selected 300 intersections. However, during data collection and lighting data processing, this number was further reduced to 242 due to field verification of intersection conditions and lighting measurement equipment malfunctioning. Figure 3 and Figure 4 show the location and the intersections' distribution.

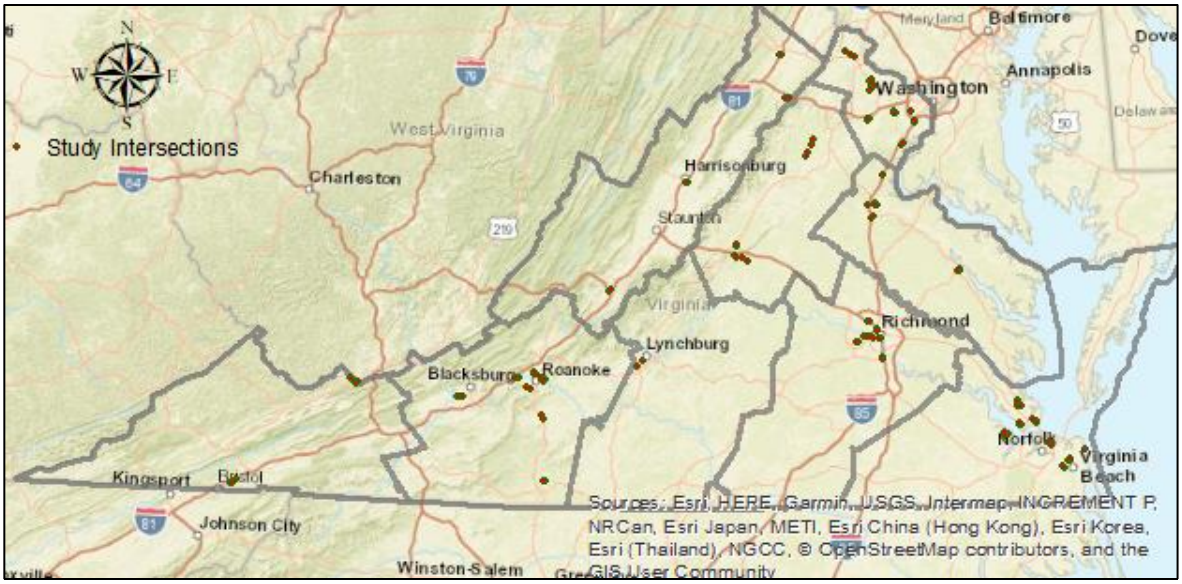


Figure 3. Selected Intersections for Study

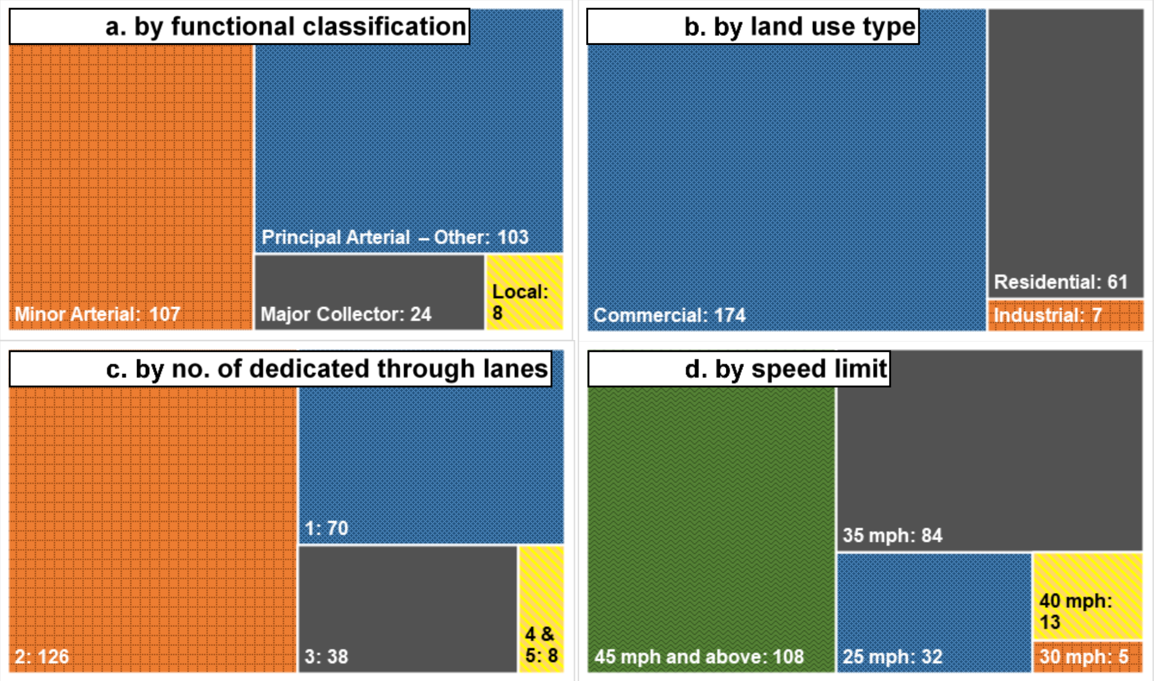


Figure 4. Distribution of the Selected Intersections

Additional Roadway Data Collection

For each intersection, the project team collected detailed roadway and traffic information for the intersection, major legs, and minor legs (Table 1). The variables were collected from a number of sources:

- VDOT roadway and traffic data. Variables such as area type, number of lanes, speed limit, and functional class were collected automatically by matching the identified intersections with the traffic and roadway datasets provided by VDOT (e.g., ADT, roadway centerline, and Highway Performance Monitoring System datasets).

- Satellite images from Google® Maps and ArcGIS satellite imagery. Most variables were collected from this source, including the detailed lane and median configuration, presence of lighting, traffic control, presence of sidewalk/crosswalk, and distances to next intersections.

- Engineering judgement combined with site conditions identified during data collection and based on satellite images. Due to the lack of pedestrian counts from VDOT, the research team estimated the level of pedestrian activities using this method. Researchers measured the pedestrian volumes at three levels for this purpose:
    - High – there are multiple or large commercial developments within 500 ft. of intersection and all legs have crosswalks
    - Medium – there are small commercial developments or large residential developments near intersection and at least one approach has crosswalks
    - Low – there are no visible commercial developments or limited residential units nearby

Table 1. Variables Collected for the Studied Intersections

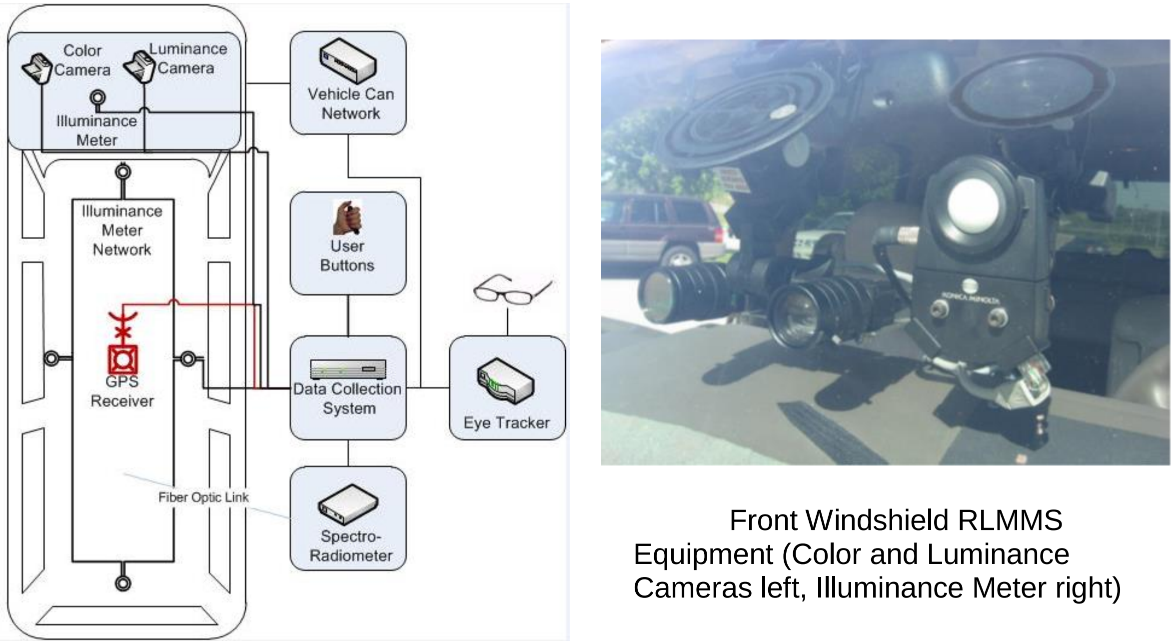
Intersection	Major Legs	Minor Legs
Area Type	Major Functional Classification	Minor Functional Classification
Land Use	Major Traffic Control	Minor Traffic Control
Total Number of Legs	Major Number of Through Lanes	Minor Number of Through Lanes
Intersection Geometric Alignment	Major Number of Right Turn Lanes	Minor Number of Right Turn Lanes
Roadway Alignment	Major Number of Left Turn Lanes	Minor Number of Left Turn Lanes
Pedestrian Activity Level	Major One Way Indicator	Minor One Way Indicator
-	Major Median Type	Minor Median Type
-	Major Median Width	Minor Median Width
-	Major Speed Limit (mph)	Minor Speed Limit (mph)
-	Major Sidewalk Indicator	Minor Sidewalk Indicator
-	Major Crosswalk Indicator	Minor Crosswalk Indicator
-	Major Street Lighting Indicator	Minor Street Lighting Indicator
-	Major Bike Lane Indicator	Minor Bike Lane Indicator
-	Major Street Parking Indicator	Minor Street Parking Indicator
-	Major ADT	Minor ADT
-	Major Distance to Next Intersection (ft)	Minor Distance to Next Intersection (ft)
-	Major Distance to Next Signalized Intersection (ft)	Minor Distance to Next Signalized Intersection (ft)

Intersection Lighting Data Collection

The field lighting measurements at the selected intersections were carried out using the VTTI Roadway Lighting Mobile Measurement System (RLMMS). In the RLMMS, a four-armed apparatus was placed on top of a 2001 Cadillac Escalade with four waterproof Minolta illuminance detector heads. Each head was positioned on the end (facing upward) of each of the four arms of the apparatus; this is also known as the “spider” configuration. This arrangement allows roadway illuminance to be measured at three positions in each lane with a redundant measurement (front and rear are redundant). These positions correspond to the left track, center of the lane, and the right track, and are approximately 32 inches apart across the lane. The system conceptual layout is shown in Figure 5.

In addition to the four-way spider on top of the vehicle, for this research effort, the system was expanded to include more Minolta illuminance detector heads to capture light incidence on the sides of the vehicle. One illuminance meter was positioned on each side of the vehicle’s rear window and a third was placed on the hood of the vehicle, facing forward. The purpose of these additional sensors was to attempt to capture potential light trespass. Positioned in the center of the four arms was a NovaTel GPS. A fifth Minolta was mounted to the forward windshield of the vehicle to detect oncoming traffic (Figure 5). A controller area network reader was utilized to collect the vehicle speed, throttle, and engine revolutions per minute from the On-Board Diagnostics II port. Additional modules included a spectro-radiometer and an eye-tracker.

Data collection trips were designed so that several clusters of corridors could be measured on each specific trip. Two research personnel were present for each data collection assignment. As one experimenter drove the research vehicle, the other provided directions for the next turn required in order to efficiently navigate the intersections and ensure each and every possible turn was made. All data collection occurred at night between the hours of 9 and 10 p.m., depending on traffic and sunset, until the early morning hours of 4 to 5 a.m. For each trip, the selected series of intersections were grouped into interlinked corridors. At each intersection, the vehicle made every possible turn legally allowable at an intersection, including straight through passes in each lane, to ensure the greatest coverage of lighting at the intersection. Figure 6 shows the lighting measurements at a sample intersection.



Front Windshield RLMMS Equipment (Color and Luminance Cameras left, Illuminance Meter right)

Figure 5. Key Components of Roadway Lighting Mobile Measurement System (RLMMS)

Figure 6. Examples of Intersection Lighting Measurement Points. Measurements are color-coded based on horizontal illuminance values, with red indicating higher illuminance and blue indicating lower illuminance.

Conduct Safety Analysis

Negative Binomial Regression Overview

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.[4-9] 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.[9] The functional form of a negative binomial regression is shown below:

$$\ln Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

In the above equation,

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

Note that for the data collected in this study, the project team were not able to obtain separate nighttime and daytime traffic counts; instead, the project team obtained ADT data from VDOT for all major roadways. The unavailability of the nighttime and daytime traffic counts made it impossible to calculate nighttime and daytime crash rates. If the number of nighttime crashes alone were used as a dependent measure, the models would ignore the number of daytime crashes at the intersections, resulting in overestimation or underestimation of the other explanatory measures. For example, say that intersection "A" had 10 nighttime crashes and 100 daytime crashes and that intersection "B" had 10 nighttime crashes and 5 daytime crashes. If the model ignores the daytime crashes, then intersections A and B had the same number of nighttime crashes and the night-to-day (ND) crash ratio at intersection "B" would be grossly underestimated. This lack of equivalence in the number of nighttime crashes at intersections can be solved by using the number of daytime 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.[4]

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:

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

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 1-unit change in the independent variable x_n is given by the following formula:

$$RR = \exp(\beta_n) - 1$$

If the risk ratio is less than one, 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, the expected number of night crashes increases for a unit increase in the dependent variable.

Lighting Variables

Lighting variables were calculated for three distinct parts of the intersection: intersection box, intersection major approach, and intersection minor approach. The lighting parameters that were collected are shown in Table 2. The illuminance uniformity calculation was changed and does not reflect the Illuminating Engineering Society method of calculation (average illuminance/minimum illuminance). This calculation does not account for the range of the illuminance because it does not account for the maximum illuminance. The illuminance uniformity in the current study is calculated to account for the maximum illuminance and is given by the following equation:

$$Unifomity = \frac{Maximum\ Illuminance - Minimum\ Illuminance}{Average\ Illuminance}$$

Table 2. Light Variables Used in the Study

Intersection Location	Lighting Parameter
Intersection Box (area enclosed by the stop bars or stop lines)	Average Illuminance
	Minimum Illuminance
	Illuminance Uniformity
	Standard Deviation of Illuminance
Major Approach (250 ft. radius from the center of intersection excluding the intersection box)	Average Illuminance
	Minimum Illuminance
	Illuminance Uniformity
	Standard Deviation of Illuminance
Minor Approach (same as the major approach)	Average Illuminance
	Minimum Illuminance
	Illuminance Uniformity
	Standard Deviation of Illuminance

Models

Three negative binomial regression models were conducted based on the lighting parameters. The first model used average illuminance and minimum illuminance as its lighting parameters. The second and third models used illuminance uniformity and standard deviation of illuminance, respectively.

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. Table 3 shows the common explanatory variables and levels used in the three negative binomial regression models. Each of the levels of the categorical variables was defined based on data distribution to ensure that none of the categories had too few crashes. In some instances, continuous variables such as median width and speed limit were also converted to categorical variables for ease of modelling. The conversion of a continuous to a categorical variable was conducted by analyzing the distribution of the variable such that each level did not have too few crashes.

Table 3. Common Explanatory Variables in the Three Negative Binomial Regression Models

Explanatory Variables	Levels	Type of Variable	Night Crashes	Day Crashes
Number of Legs	Four or Five	Categorical	603	1361
	Three		193	483
Intersection Geometry	Right angle		411	1006
	Skewed		385	838
Roadway Alignment	Curve		237	552
	Straight		559	1292
Major Function Class	Principal Arterial		357	843
	Minor Arterial		332	793
	Major Collector, Local, and others		107	208
Major Traffic Control	Not Signal		153	418
	Signal		643	1426
Major Number of Through Lanes	One or less		189	449

Explanatory Variables	Levels	Type of Variable	Night Crashes	Day Crashes
	Two or more		607	1395
Major Number of Right Turn Lanes	None		391	985
	One or more		405	859
Major Number of Left Turn Lanes Only	None		170	468
	One or more		626	1376
Major Median Type	Curb		264	565
	Flat & Others		235	463
	Line		297	816
Major Median Raised Median Indicator	Absent		366	982
	Present		430	862
Major Median Width in feet	Five or more		492	992
	Less than five		304	852
Major Speed Limit	35mph or lower		399	1012
	Over 35mph		397	832
Major Sidewalk Indicator	Absent		234	535
	Present		562	1309
Major Crosswalk Indicator	Absent		407	971
	Present		389	873
Major Street Parking Indicator	Absent		777	1738
	Present		19	106
Minor Function Class	Principal Arterial		105	176
	Minor Arterial		174	334
	Major Collector, Local, and others		517	1334
Minor Traffic Control	Not Signal		150	412
	Signal		646	1432
Minor Number of Through Lanes	One or less		176	418
	Two or more		620	1426
Minor Number of Right Turn Lanes	None	Categorical	313	751
	One or more		483	1093
Minor Number of Left Turn Lanes Only	None		110	287
	One or more		686	1557
Minor Median Type	Line		436	1098
	Others		360	746
Minor Median Raised Median Indicator	Absent		515	1324
	Present		281	520
Minor Median Width in feet	Five or more		296	559
	Zero		500	1285
Minor Speed Limit	25mph or lower		298	782
	NA		95	280
	Over 25mph		403	782
Minor Sidewalk Indicator	Absent		257	647
	Present		539	1197
Minor Crosswalk Indicator	Absent		403	984
	Present		393	860
Minor Street Parking Indicator	Absent		777	1738
	Present		19	106
Log of Annual Daily Traffic	NA	Continuous	NA	NA
NA – Not applicable				

Specification Development

In order to develop light level guidelines for intersections, a two-step approach was used. In the first step, a negative binomial regression analysis was conducted to identify which of the lighting variables were significantly associated with decreasing ND crash ratios. Night crashes were collected for a 5-year period, from 2014 to 2018. In the second step, a curve fitting analysis was undertaken between the significant lighting variables and night crash frequency. Specifications were developed only for significant lighting variables.

Prior to performing the curve fitting analysis, the lighting variables were binned by rounding them to the nearest whole number. Then the intersections were separated by their means of traffic control, and major and minor function class (see Table 4). A curve fitting analysis was only conducted if a certain major-minor function class combination had at least 10 intersections and at least five illuminance bins. For example, in Table 4, in the unsignalized category, only the following two combinations of major and minor classifications were used for curve fitting: principal arterial – local & others, and minor arterial & local & others.

Table 4. Number of Intersections and Illuminance Bins for Each of the Traffic Control and Major and Minor Function Classes

Traffic Control	Major Function Class	Minor Function Class	Number of Intersections	Number of Illuminance Bins
Unsignalized	Principal Arterial	Local & Others	23	5
	Minor Arterial	Minor Arterial	1	1
	Minor Arterial	Local & Others	30	8
	Local & Others	Local & Others	16	3
Signal	Principal Arterial	Principal Arterial	8	4
	Principal Arterial	Minor Arterial	14	5
	Principal Arterial	Major Collector & Others	39	8
	Minor Arterial	Principal Arterial	5	14
	Minor Arterial	Minor Arterial	15	4
	Minor Arterial	Major Collector & Others	48	10
	Major Collector & Others	Major Collector & Others	12	4

A three parameter exponential function was chosen as the appropriate curve fitting function. A three parameter exponential function is bounded at the lower asymptote (see Figure 7), indicating that increasing the light variable beyond a certain level while lowering the number of night crashes will not completely eliminate them. Such an assumption is realistic in nighttime roadway crashes, as increasing the light level will reduce the number of night crashes, but beyond a certain level they will not be reduced any further due to other factors like driver fatigue and distraction, weather etc. A three parameter exponential function will have the following form:

$$y = a + b * e^{(c*x)}$$

where, a is the asymptote, b is the scale, and c is the growth rate.

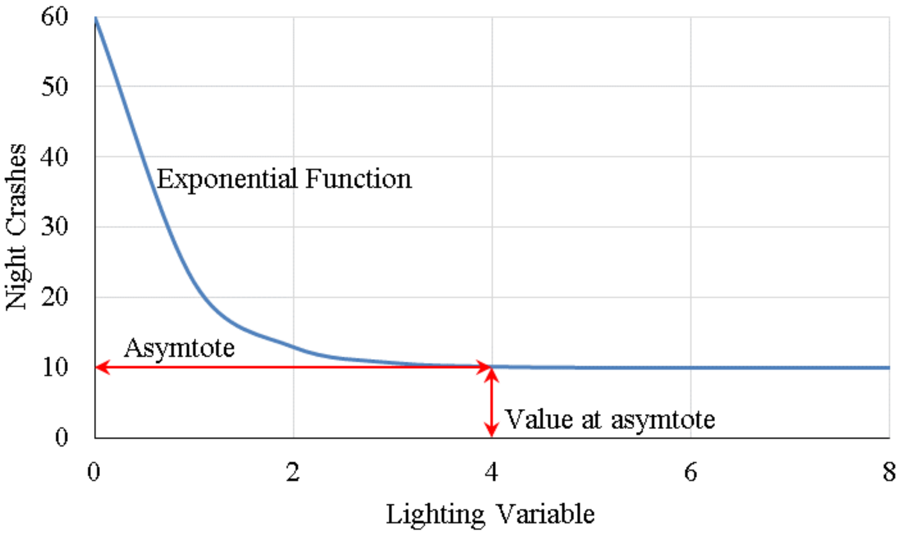


Figure 7. A Sample Three Parameter Exponential Function

The exponential curve fitting helped in determining the levels of the lighting variables where the asymptote was reached. An increase in light variables beyond where the asymptote was attained will not result in a decrease in the number of night crashes. The value of the lighting variable at the asymptote could be used as a specification to minimize the number of night crashes at intersections (see Figure 7). The minimum number of night crashes was established at one night crash per year, since the crash data from a 5-year period was considered for the current analyses.

Develop Crash Modification Factors

This project used negative binomial regression to identify and quantify the correlations between lighting variables and ND crash ratios. The project team, therefore, utilized the negative binomial regression results to develop CMFs:

$$CMF = Exp[\beta(x_2 - x_1)]$$

where:

- β = Coefficient in negative binomial regression function for the significant lighting variable;
- x_1 = Base value for the significant lighting variable; and
- x_2 = After value for the significant lighting variable.

To develop CMFs for with and without lighting conditions, the project team compared the average value of the significant lighting variable for locations with lighting and that for locations without lighting.

Conduct Safety Benefit-Cost Ratio Analysis

Overview of Benefit-Cost Analysis Methodology

During this project, the project team calculated lifetime safety BCRs for intersection lighting using the following method:

$$BCR = \frac{PVB}{PVC}$$

where:
BCR = Lifetime safety BCR;
PVB = Present value lifetime benefit; and
PVC = Present value lifetime cost.

To calculate present value lifetime benefit:

$$PVB = \sum_{t=0}^{LC} \sum_{j} PC_{j,t}, j \in \{K, A, B, C, O\}$$

where:
$PC_{j,t}$ = the total potential costs of severity j crashes prevented in year t in 2019 dollars by the infrastructure category;
LC = life cycle of the infrastructure category.

$$PC_{j,t} = (\frac{1}{(1+r)^t})PC_{j,0}$$

where:
r = discount rate. The Office of Management and Budget currently recommends a discount rate of 7% for long life projects in cost benefit analyses relevant to public investment and regulatory decisions.[10,11] Other publications typically recommend a rate between 3% and 7%.[12-15] Following the Office of Management and Budget recommendation, this study used a discount rate of 7%.
$PC_{j,0}$ = potential costs of severity j crashes prevented by lighting during year 0 (i.e., 2019) in 2019 dollars.

To calculate the lifetime present value cost:

$$PVC = IC + \sum_{t} AMC_t$$

where:
IC = installation cost for the infrastructure category in 2019 dollars.
AMC_t = the present value (in 2019 dollars) of the annual maintenance costs for lighting at year t, which is determined by applying the discount rate r to the original annual maintenance cost at year t, or AMC_0:

$$AMC_t = (\frac{1}{(1+r)^t})AMC_0$$

The type of intersections and safety benefits were determined based on the crash data analysis results. BCRs were only developed for the intersection types where the safety benefits of lights were found to be significant.

Intersection Lighting and Related Costs

Intersection lighting installation and operation involves a number of costs, including infrastructure and luminaire costs, power consumption costs, luminaire maintenance costs, costs related to installation traffic control and delay, costs due to changed pollution levels (caused by congestion due to lighting installation and maintenance, and crashes prevented/caused by intersection lighting systems), costs due to impacted wildlife, and costs due to light pollution. This project focused on the direct costs relevant to the lighting installation and maintenance. It did not consider costs due to delays during lighting installation and maintenance and environmental costs due to the use of lighting.

Initial Infrastructure, Luminaire, and Installation Costs

These costs include items such as lighting poles, arms, luminaires, and power supply items, which might include conduit, conductor cables, junction boxes and separate meter bases for lighting. During this project, VDOT's Traffic Engineering Division provided the following lighting cost estimates for a typical intersection between a minor arterial and a major collector for two scenarios:

- Installing luminaires with luminaire-signal combination poles (a total cost of $17,000):
    - The total infrastructure and luminaire cost is approximately $10,000, with variables such as existing power supply, right of way characteristics, and intersection geometry.
    - The lighting design cost is approximately $7,000.

- Installing luminaires with separate luminaire poles (a total cost of $43,200):
    - In addition to the $10,000 total infrastructure and luminaire cost, an additional $22,000 is estimated for four new light poles, including the required foundation materials and construction.
    - The lighting design costs with consultants are estimated at $11,200 for 80 hours of work.

VDOT policy requires traffic signals that have pedestrian accommodations to be built with Accessible Pedestrian Signals (APS) to make the intersection accessible to blind/visually impaired pedestrians. This often in turn requires supports placed very close to the curb cut to support the APS equipment and pedestrian signal indications. If it is not feasible to use combination signal/lighting poles at an intersection, it may be feasible to still illuminate the intersection by using lighting poles placed near the curb cuts that double as supports for the APS equipment and pedestrian signal indications.

Note that these costs assume available electricity at the site. If electricity is not available the engineering and installation of an electrical supply is significant and a separate benefit cost analysis should be performed. The cost estimates also do not include costs for VDOT construction engineering inspection (CEI) services. Due to limited data availability, the project team was not able to obtain direct estimates on the CEI costs for lighting projects. However, the VDOT approved CEI inspection hourly rates for consultants are provided in Table 5 and a standard mileage reimbursement rate for vehicles used on CEI contracts is \$0.58/mile or is a reduced rate of \$0.32/mile.[16] This analysis assumed that the CEI services for a typical lighting project would require:

- 8 hours for one Construction Inspector,
- 8 hours for one Construction Inspector Trainee,
- 8 hours for one Senior Construction Inspector,
- 4 hours for one Construction Inspection Coordinator, and
- 200 vehicle miles of travel in total.

The total CEI cost for a typical intersection lighting project based on the approved VDOT statewide rates would therefore be:

$$\$22.44 \times 8 + 28.6 \times 8 + 32.66 \times 8 + 34.29 \times 4 + \$0.58 \times 200 = \$922.76$$

Table 5. VDOT-Approved CEI Hourly Rate Pay Limits[17]

Inspection Classification	Maximum Statewide Hourly Rate	Maximum Northern VA Hourly Rate
Construction Inspector Trainee	\$22.40	\$23.44
Construction Inspector	\$28.60	\$30.98
Senior Construction Inspector	\$32.66	\$41.51
Construction Inspection Coordinator	\$34.29	\$42.24

Electricity Costs

Electricity costs for intersection lighting depend on a number of factors, including luminaire wattage, luminaire operational duration, and current and future electricity rates. Following is a discussion of the assumptions used for determining these costs:

- Luminaire wattage for intersection lighting. Traditionally, VDOT uses two types of high pressure sodium luminaires at intersections: 250 W and 400 W. Modern light emitting diode (LED) luminaires have different light distribution types and varying luminaire efficacies (based on factors such as manufacturers and color temperature). In the process of implementing LEDs, VDOT may use a variety of LED luminaires in terms of wattage. However, conversations with VDOT suggested that 100 W–140 W LED luminaires were frequently used for relatively small intersections while 200 W–250 W luminaires were used for large intersections, with material prices ranging between \$650 and \$900 per luminaire (not counting other costs such as installation/labor, maintenance of traffic, and electrical distribution infrastructure costs). For large intersections, VDOT uses four or more luminaires. However, for some smaller intersections, it is not rare to use two luminaires diagonally. Combining all factors, this analysis assumed, for simplicity, that four 200 W LED luminaires were used for all intersection lighting systems.

- Analysis life cycle for lighting systems. VDOT officials suggested that lighting poles at intersections were frequently used for more than 25 years and some might possibly even be used for more than 50 years if the intersection would not require major reconstruction/reconfiguration. The wirings associated with the lighting systems, however, would need to be replaced/repaired every 10–20 years depending on a number of factors. Although VDOT requires that LED luminaires have a warranty period of 10 years,[18] VDOT officials are expecting modern and newer LED luminaires to last significantly longer. Considering the different factors, this project used an analysis lifecycle of 20 years, with an annual number of operational hours of 4,380 operational hours, assuming 12 hours of operations per day on average. For an intersection with four luminaires, the total lifetime operational hours are 4,380 x 4 = 17,520 luminaire hours.

- Current electricity cost ($/kWh) for VDOT. Conversations with VDOT officials suggested that it would be difficult to obtain an accurate estimate of a unit electricity cost for roadway lighting at VDOT for a number of reasons. VDOT uses several different billing mechanisms depending on the agreements with power companies, location, and the service provider. However, lighting fixtures installed recently tend to use power meters. A previous study estimated that VDOT paid a power cost of $0.043 per kWh based on 2015 data.[19] This estimate is lower than the rates suggested by the Energy Information Administration (EIA) (see Table 6). For this analysis, the project team used the EIA average electricity price for 2019 (i.e., $0.0921/kWh for the entire operational life of luminaires installed in 2019. Note that the average electricity yearly increase rate was calculated as -0.51% based on the industrial sector data between 2010 and 2019, as shown in Table 6.

Table 6. Average Price of Electricity by Sector for Virginia[20]

Year	Residential	Commercial	Industrial	Transportation	All Sectors	Industrial Increase
Sep 2019	12.01	7.98	6.28	8.19	9.21	-8.19%
Sep 2018	11.90	8.32	6.84	8.14	9.48	-1.01%
Sep 2017	12.28	8.33	6.91	8.08	9.51	8.31%
Sep 2016	11.64	7.77	6.38	7.31	9.08	-7.27%
Sep 2015	11.85	8.13	6.88	7.81	9.34	-2.27%
Sep 2014	11.97	8.40	7.04	8.26	9.51	3.99%
Sep 2013	11.62	8.21	6.77	7.97	9.27	-0.73%
Sep 2012	11.15	7.96	6.82	8.07	9.00	-3.40%
Sep 2011	11.46	8.28	7.06	8.38	9.51	6.01%
Sep 2010	10.87	7.70	6.66	7.53	8.94	-
Average	**11.68**	**8.11**	**6.76**	**7.97**	**9.29**	**-0.51%**

- Annual power consumption by intersection lighting. Based on the relevant cost items discussed above, the annual power consumption at a typical intersection lighting scenario can be determined as:

  200W × 17,520 luminaire hours ÷ 1000 × $0.0921 = $322.72 per intersection.

This estimate was developed based on the assumption for a typical intersection with four 200 W luminaires and a 20-year operational life.

Maintenance Costs

VDOT currently does not conduct routine roadway luminaire cleaning and inspection. When functioning properly, therefore, LED luminaires themselves are considered “maintenance free” in this project assuming the luminaires do not require lamp replacement within their warranty period. However, interviews with VDOT suggested that lighting related infrastructure required periodic maintenance, although it was difficult to obtain an accurate estimate on the maintenance costs due to the lack of data tracking the time, travel, and salary costs allocated to intersection lighting maintenance work by VDOT personnel and the maintenance costs of contractors and utility companies specifically attributed to intersection lighting.

A previous VDOT project[19] estimated a $1.30/W (2015 dollars) annual maintenance cost for the infrastructure supporting LED lighting systems. Note that this maintenance cost was estimated for all LED luminaires instead of intersection lighting systems. Due to the lack of alternate data, however, this maintenance cost estimate was adopted for the current cost-benefit analysis.

To convert the maintenance cost to the current dollar value (i.e., 2019 dollars), the project team used the National Highway Construction Cost Index (NHCCI). FHWA publishes the NHCCI to measure the average changes in the prices of highway construction costs over time (Table 7). Based on the NHCCI, the lighting maintenance cost was adjusted to $1.40/W in 2019 dollars.

Table 7. 2015–2019 NHCCI[21]

Year	NHCCI* Index	Percent Increase
2015	1.72	-
2016	1.63	-5.23%
2017	1.62	-0.61%
2018	1.68	3.70%
2019	1.85	10.12%
Average	-	**1.99%**

NHCCI = National Highway Construction Cost Index.

For a typical intersection assuming four 200 W luminaires, the total annual maintenance cost is estimated as:

$$200\text{W} \times 4 \times \$1.40/\text{W} = \$1{,}120 \text{ per intersection}$$

Crash Costs

Available Crash Cost Estimates

Crashes prevented by adding or improving lighting at intersections are considered safety benefits. Table 8 lists the average crash unit cost estimates both for Virginia and nationwide. The project team was able to identify two versions of Virginia crash cost estimates from different sources and both estimates were broken down by cost units. The national estimates included estimates for both economic costs of the crashes and quality-adjusted life year (QALY) costs. Note that the crash unit cost estimates were for all crashes regardless of crash type, time, and location. The project team was not able to obtain crash unit cost estimates for nighttime intersection crashes for either Virginia or the entire nation.

Table 8. Average Crash Unit Cost by Severity - Virginia and National Data

Type		**K - Fatal**	**A – Severe Injury**	**B – Minor Injury**	**C – Possible Injury**	**O – Property Damage Only**	**Year**
Virginia[22]	-	$4,008,885	$216,059	$56,272	$56,272	$7,428	2001
Virginia[23]	-	$5,241,924	$280,664	$102,604	$58,132	$9,512	2012
National[22]	Economic	$1,722,991	$130,068	$53,700	$42,536	$11,906	2016
	QALY*	$9,572,411	$524,899	$144,792	$83,026	$0	
	Total	**$11,295,402**	**$654,967**	**$198,492**	**$125,562**	**$11,906**	

*QALY = quality-adjusted life year.

Converting Past Crash Cost Estimates to 2019 Values

During this study, the project team converted the Virginia crash unit costs to 2019 values based on the procedures recommended by the *Highway Safety Manual*.[24] The procedure recommends that crash costs of a certain year be adjusted to a target year by adjusting the direct economic costs and the QALY costs based on the corresponding Consumer Price Indices (CPIs) and Employment Cost Indices (ECIs), respectively:

$$CUC_{target} = ECUC_{data} \times \frac{CPI_{target}}{CPI_{data}} + QCUC_{data} \times \frac{ECI_{target}}{ECI_{data}}$$

Where:

CUC_{target} = target year total crash unit cost by severity
$ECUC_{data}$ = data year economic crash unit cost by severity
$QCUC_{data}$ = data year QALY crash unity cost by severity
CPI_{target} = target year CPI
CPI_{data} = data year CPI
ECI_{target} = target year ECI
ECI_{data} = data year ECI

During this project, the team was not able to find separate economic and QALY crash unit cost data for Virginia. The project team therefore obtained the economic and QALY portions of the Virginia crash unit cost estimates by applying the corresponding percentages based on the national estimates, as shown in Table 9.

Table 9. Determination of Economic and Quality-Adjusted Life Year Crash Costs for Virginia

Type		K - Fatal	A – Severe Injury	B – Minor Injury	C – Possible Injury	O – Property Damage Only
National	Economic	$1,722,991	$130,068	$53,700	$42,536	$11,906
	Economic %	15.25%	19.86%	27.05%	33.88%	100.00%
	QALY*	$9,572,411	$524,899	$144,792	$83,026	$0
	QALY %	84.75%	80.14%	72.95%	66.12%	0.00%
	Total	$11,295,402	$654,967	$198,492	$125,562	$11,906
Virginia 2001	Total	$4,008,885	$216,059	$56,272	$56,272	$7,428
	Economic	$611,512	$42,907	$15,224	$19,063	$7,428
	QALY	$3,397,373	$173,152	$41,048	$37,209	$0
Virginia 2012	Total	$5,241,924	$280,664	$102,604	$58,132	$9,512
	Economic	$799,599	$55,736	$27,758	$19,693	$9,512
	QALY	$4,442,325	$224,928	$74,846	$38,439	$0

*QALY = quality-adjusted life year.

Using the historical ECI and CPI data shown in Table 10, the project team estimated the Virginia crash unit costs by severity as shown in Table 11.

Table 10. Historical Employment Cost Index and Consumer Price Index Values

Year	Employment Cost Index*[25]	Consumer Price Index**[26]
2001	85.5	171.1
2012	116.8	223.2
2016	126.7	232.7
2019	137	246.3

* June values for all civilian workers.

**Annual average values for all items in census south region, all urban consumers, not seasonally adjusted.

Table 11. 2019 Virginia Crash Unit Costs by Severity based on 2001 and 2012 Estimates

Type		K	A	B	C	O
2019 Estimates based on 2001 Data	Economic	$880,277	$61,764	$21,915	$27,441	$10,693
	QALY*	$5,443,744	$277,449	$65,773	$59,621	$0
	Total	$6,324,021	$339,213	$87,688	$87,063	$10,693
2019 Estimates based on 2012 Data	Economic	$882,353	$61,505	$30,631	$21,731	$10,496
	QALY	$5,210,604	$263,828	$87,790	$45,087	$0
	Total	$6,092,957	$325,333	$118,421	$66,818	$10,496
Average 2019 Estimates		**$6,208,489**	**$332,273**	**$103,054**	**$76,940**	**$10,595**

*QALY = quality-adjusted life year.

Estimate Overall Crash Unit Costs Regardless of Crash Severity

Considering that the crash data analysis did identify severity-specific crash correlations with intersection lighting variables, the cost benefit analysis was performed for all crashes regardless of severity outcomes. The project team therefore had to convert the severity-specific unit crash cost estimates to unit costs for crashes of all severity levels. For this purpose, the project team obtained the average crash unit cost weighted by the crash proportions of individual severity levels as follows:

$$CUC_{all} = CUC_K \times P_K + CUC_A \times P_A + CUC_B \times P_B + CUC_C \times P_C + CUC_O \times P_O$$

Where:
CUC_{all} = Overall crash unit cost regardless of crash severity
CUC_i = Crash unit cost for severity i (e.g., CUC_K is the unit cost of fatal crashes)
P_i = Proportion of crashes of severity i (e.g., P_O is the proportion of property damage only crashes in the overall crash population) in the overall crash population

To estimate the proportions of crashes by severity, the project team used the 5-year (2014–2018) nighttime crashes that occurred at or that were related to an intersection, as based on the VDOT crash data. Table 12 contains the nighttime intersection crash proportions by severity level. Based on these proportions, the project team estimated the overall crash unit cost regardless of severity as:

$6,208,489 × 1.03% + $332,273 × 6.52% + $103,054 × 18.20% + $76,940 × 8.64% + $10,595 × 65.61% = $118,148.23/crash

The overall unit cost for fatal and injury crashes was estimated as:

$6,208,489 × 3.00% + $332,273 × 18.96% + $103,054 × 52.92% + $76,940 × 25.12% = $322,812.10/crash

Table 12. Proportions of Nighttime Intersection Crashes by Severity (VDOT 2013–2018)

Severity	Count	Percent among Total	Percent among KABC
K - Fatal Injury	1,294	1.03%	3.00%
A - Severe Injury	8,171	6.52%	18.96%
B - Visible Injury	22,795	18.20%	52.92%
C - Non-visible Injury	10,823	8.64%	25.12%
KABC – Fatal and Injury	43,083	34.39%	100%
O - Property Damage Only	82,196	65.61%	-
Total	**125,279**	**100.00%**	**-**

Summary of Cost Items and Estimates

Table 13 lists the cost estimates by cost item used for this study's safety benefit-cost analysis.

Table 13. Summary of Cost Estimates by Cost Items in 2019 Dollars

Cost Item	Cost in 2019 Dollars	Note
Initial lighting installation (including luminaires)	$17,000 per intersection	Installing luminaires by extending existing signal poles; typical intersection between a minor arterial and a major collector
	$43,200 per intersection	Installing luminaires with new poles; typical intersection between a minor arterial and a major collector
Construction engineering inspection	$922.76 per intersection	On average for all intersections
Annual electricity consumption	$322.72 per intersection	Typical intersection with four 200 W luminaires
Annual lighting maintenance cost	$1,120 per intersection	Typical intersection with four 200 W luminaires
Crash cost	$118,148.23 per crash	Regardless of crash type and severity

RESULTS

Literature Review Findings

The following are major findings based on the comprehensive literature review conducted as part of this project (see Appendix A):

- Previous research has mostly focused on the effects of lighting by comparing highways with and without lighting. While the results of those studies varied, many pointed to a positive safety impact due to the presence of lighting.

- A number of national guidelines are currently available, including particularly the ANSI/IES RP-8-18 *Recommended Practice for Roadway Lighting* developed by IES, *FHWA Roadway Lighting Handbook*, the TAC *Guide for the Design of Roadway Lighting*, and the *Roadway Lighting Design Guide* by American Association of State Highway Transportation Officials (AASHTO).

- Pedestrians and other vulnerable roadway users are frequently considered a major consideration factor for intersection lighting needs. For example, the presence of pedestrians and bicyclists is a warranting condition recommended by the AASHTO *Roadway Lighting Design Guide* as well.

- Studies identified a number of factors that could contribute to fixed-object crashes during the night but may be addressed with properly designed lighting:
    - Unconventional intersection layout features such as Y intersection and off-set left-turn lanes;
    - Channelization devices at intersections that are not well lit, such as raised/depressed medians and post-mounted delineators; and
    - Intersections on horizontal or vertical curves where sight distance to the intersection is reduced.

These factors have been taken into consideration in the AASHTO, FHWA, and TAC guidelines previously mentioned.

- The literature review has shown that the following areas need to be addressed in order to develop comprehensive guidelines for intersections:
    - CMFs for intersection lighting should be calculated based on measured lighting data from intersections.
    - There is a need to develop a lighting level for intersections that results in optimal visibility and reduces nighttime crashes without over-lighting the intersection.
    - Specifications of light levels and luminaire pole placements for intersections should be available for all intersection types and uniform so that departments of transportation can easily adopt them.

Virginia Lighting Practices and Practices in Other States/Canada

The following are lighting practices across Virginia as well as based on practices in other selected states and a Canadian province. The practices summarized below are based on state, district, and municipality interviews.

Intersection and Midblock Crosswalk Lighting Practices at Virginia

VDOT Lighting Responsibilities

Table 14 lists the roadway maintenance responsibilities in Virginia by roadway and locality type. Note that lighting maintenance responsibilities do not necessarily align with roadway maintenance responsibilities. At intersections and midblock crosswalks on the VDOT-maintained road network, lighting maintenance responsibility is as follows:

- Interchange lighting is typically owned and maintained by VDOT.

- Corridor street lighting and decorative post-top lighting is typically owned and maintained by the locality or power company, not VDOT. In such cases, street lighting decisions are made by the locality based on considerations such as locality lighting policies, safety needs, citizen requests, and/or aesthetic considerations. VDOT requires the locality to obtain a Land Use Permit before installing such lighting.

- “Node” lighting that is limited to individual intersections or midblock crosswalks, but not the segments between those nodes, is often owned/maintained by VDOT. VDOT almost always maintains the lighting if the luminaires are attached to combination signal pole/luminaire structures that also support VDOT-maintained traffic signal indications.

Table 14. Roadway Maintenance Responsibilities by Roadway and Locality Type

Locality Type	Interstates	**Primaries** (Route number < 600)	**Secondaries** (Route numbers ≥ 600)
Cities and Large Towns	VDOT maintains the entire Interstate system	Locality	Locality
Arlington & Henrico Counties	Signals at the interchange off-ramps may be maintained by VDOT or the locality	VDOT	Locality
All other Counties (including small Towns)	VDOT	VDOT	VDOT

Over the years, different districts have developed very different practices in intersection and midblock crosswalk lighting based on their needs and understanding of VDOT lighting policy. Due to the involvement of municipalities, power companies, and VDOT, the lighting process frequently requires a level of cooperation among the involved entities. Because they do not have jurisdiction over municipalities and power companies, VDOT officials may provide recommendations relevant to the lighting systems used at intersections within municipalities or managed by power companies but cannot require these entities to follow VDOT standards, except that VDOT can require the locality/power company to conform with VDOT lighting policy in order to receive a Land Use Permit. Localities and power companies must also install full-cutoff fixtures as required by §2.2-1111 of the Code of Virginia.

Lighting Needs Determination

The current VDOT *Traffic Engineering Design Manual* (TEDM)[27] contains some guidelines and policies (Chapter 2 – Roadway Lighting) on roadway lighting at the Department. However, the practices to determine lighting needs at different districts vary considerably. The following is a summary of the different practices at VDOT:

- **Traditional intersections**. When determining lighting needs at intersections, many districts do not have a systematic approach and therefore lighting needs are often determined on a case-by-case basis and, in some cases, are based on individual preferences and experience, although the current VDOT lighting policy has imposed some new requirements for when intersection lighting must be at least considered. Such districts generally consider one or multiple factors for lighting needs, such as nighttime crash history, pedestrian and bicyclist volume, traffic volume, intersection layout, and lighting presence along the corridor where the intersection is located. The Central Office and some districts use a Lighting Evaluation Worksheet for Existing Intersection to screen the needs for lighting at intersections. Two other worksheets are also used for identifying lighting needs for other types of facilities: Lighting Evaluation Worksheet for Existing Interchanges and Lighting Evaluation Work Sheet for Access Controlled Roadways. The worksheets are based on the 1978 *Roadway Lighting Handbook* published by FHWA.[28]

  The warranting worksheet for intersections considers several groups of factors:

  - Geometric factors, including number of legs, approach lane widths, turning lane configuration, approach sight distance, grades on approach, curvature on any approach, and street parking.

  - Operational factors including operating speed on approach legs, type of control, turn lane configuration (considered again but values in reverse order), level of service, and pedestrian volume.
  - ND crash ratio.

- **Roundabouts**. The interviewed districts had very different practices in determining lighting needs at roundabouts. Some districts add lighting to all roundabouts on state roadways partly due to the vague lighting recommendations at roundabouts for safety and navigation benefits in the 2005 AASHTO Roadway Lighting Design Guide, the VDOT TEDM, and the VDOT Roundabout Design Guidance.[29] Other districts treat roundabouts similarly to other intersections and primarily base their decisions on nighttime crash history and pedestrian volumes.

  Some interviewed VDOT officials noted that most roundabouts across the state were constructed recently and there was not a sufficient crash history to support such analyses. In addition, some officials believed that a primary reason for previously lit roundabouts was that users were not familiar with roundabouts when they were first implemented in the state. With an increasing number of roundabouts being used statewide, users are becoming more familiarized with the concept and that particular reasoning may no longer be applicable now. The current VDOT lighting policy states that "lighting is not automatically required at all roundabouts; it should be considered on a case-by-case basis."[30]

- **Midblock crosswalks**. Midblock crosswalks are not common on state highways according to many of the interviewed VDOT districts. Lighting decisions at midblock crosswalks across the state are generally made on a case-by-case basis based on municipality requests or crash history. Upon request, the Central Office may use the intersection lighting worksheet for midblock crosswalk lighting warranting analysis as well. VDOT's 2016 crosswalk policy states that "marked crosswalks across uncontrolled approaches should be avoided at locations that are unlit (roadway lighting not present) and have a higher speed (40 mph or greater) unless a high visibility crosswalk marking style and appropriate advance warning devices are utilized."[31]

Lighting decisions can be made by various district personnel, such as district traffic engineers, designers, and/or project managers, frequently with support from the Central Office. Both the AASHTO *Roadway Lighting Design Guide* and the FHWA *Roadway Lighting Handbook* are used in some cases to aid in the decision process.

Lighting Design and Maintenance

At VDOT, most large lighting projects are designed by consultants. Most in-house lighting projects are designed by the lighting group in the VDOT Central Office. Districts with lighting expertise may also handle some small lighting projects independently and/or review lighting designs submitted by municipalities. VDOT follows the IES RP-8 standard as much as possible for all lighting projects, including lighting at intersections and midblock crosswalks.

After lighting installations, VDOT occasionally takes lighting readings in the field and compares them with the initial lighting design values. Lighting systems for which readings are within a reasonable range from the design values are generally considered acceptable.

Maintenance and repairs of lighting systems at intersections and midblock crosswalks owned by VDOT are mostly done by district traffic signal/asset management crews and on-call maintenance contractors. Such work is generally performed when a lighting issue is reported to VDOT. Some districts occasionally prefer to use power companies for lighting maintenance due to their resources and staff availability.

Challenges and Limitations

An issue discussed during the interviews was the feasibility and associated challenges of collocating luminaires with traffic signals. At intersections where the right of way is limited or where overhead power lines conflict with luminaire poles, it may be desirable to collocate luminaires on top of signal poles. Despite the evident cost savings, however, some district officials indicated potential issues associated with the different maintenance responsibilities at intersections where lighting systems are maintained by municipalities and/or power companies. Shared signal poles would require shared conduits containing both signal cables maintained by VDOT and power cables for street lights maintained by other parties.

At intersections where existing lighting systems are replaced or upgraded, the height of previous lighting poles may be too low for newer lighting systems.

Intersection Lighting Practices at Municipalities

Lighting practices at municipalities across the state vary significantly due to size, availability of resources, and governing officials'/municipality engineers' preferences. Intersection lighting needs at many municipalities are largely determined based on citizen requests and types of facilities that officials/engineers choose to light. Municipalities typically do not light intersections and crosswalks at residential areas due to frequent complaints by nearby residents. The interviews showed that most, if not all, municipalities in the state did not have any formal warranting analysis processes when determining lighting needs. The municipalities and power companies that the research team talked to suggested the following:

- **Design**. Municipalities that go through a formal design process for intersection and midblock lighting mostly follow the IES RP-8-14 standard. Some municipalities may request that the minimal lighting levels be designed to exceed the minimal requirements in the standard. In addition, consultants and power company designers typically do not design lighting levels that are lower than the minimal requirements of the standard, mainly due to liability concerns. Some municipalities do not have formal design processes and use standard luminaires when adding lighting to intersections.

  When designing lighting, many municipalities only control average horizontal illuminance/luminance levels, without adequately considering uniformity levels. Many municipalities recognize the importance of vertical lighting levels for pedestrian safety and security, and for the benefit of older drivers.

- **Issues/challenges**. Interviewees noted the following issues and challenges:
    - Different resident opinions on lighting. Different residents have different opinions on the safety benefits of lighting. Municipalities frequently receive mixed feedback on lighting systems and therefore may not consider lighting as a high-priority investment.
    - Difficulty meeting vertical lighting levels. Many municipalities and power companies consider pedestrians to be the primary users benefitting from lighting and therefore recognize the importance of vertical lighting levels when creating lighting designs. However, it is frequently difficult to meet the required vertical levels, particularly at intersections or crosswalks on wide roadways. At downtown areas, the use of decorative lighting systems (e.g., pole-top systems) can make it hard to meet the minimum vertical levels required by the IES lighting standard.
    - Lack of resources at small municipalities. Many small municipalities do not have the resources or expertise for lighting. Some municipalities also discourage the use of lighting, citing reasons such as environmental or health effects.

Intersection and Midblock Crosswalk Lighting Practices in Other States/Canada

Across the country and internationally, lighting practices at intersections and midblock crosswalks vary significantly. The following summarizes the findings by state/province based on the state/province interviews.

Overview of Lighting Policies

The lighting policies in the states and province that were interviewed represented a wide range of practices and attitudes toward intersection and midblock crosswalk lighting at transportation agencies across the country and internationally:

- **Arizona**. Arizona’s lighting responsibilities are generally limited to roadways outside of municipalities. The agency typically prefers lighting at signalized intersections and lights rural intersections on a case-by-case basis, mostly based on crash history. Many midblock crosswalks in Arizona are located on continuously lit roadways within municipalities and therefore are lit as well. The state frequently uses Pedestrian Hybrid Beacons at major midblock crosswalks to improve pedestrian safety regardless if the crosswalks are lit.

- **Florida**. As cost-effective LED systems become increasingly available, Florida’s lighting policy encourages the use of lighting at all crosswalks on state maintained roadways. In accordance with this policy, the department lights most crosswalks at signalized intersections automatically without performing any warranting analyses. The state also lights most midblock crosswalks in accordance with the same policy. The Department currently has a major program adding lighting to existing intersections with crosswalks as well as midblock crosswalks that were not previously lighted.

- **Illinois**. Illinois' lighting policy[32] states that municipalities are responsible for intersections and midblock crosswalks within municipality boundaries. For isolated intersections and rural intersections, the Department typically determines lighting needs on a case-by-case basis based on factors such as crash history, intersection layout, pedestrian presence, and traffic pattern. Their lighting policy recommends lighting all roundabouts on state maintained roadways.

- **North Carolina and New York**. Neither state lights intersections or midblock crosswalks outside of municipalities, in general. When lighting is identified as a promising safety countermeasure at certain locations, the states typically work with the municipalities and/or power companies involved and let them take the lead. Lighting practices for roundabouts at both states vary across different districts. Some districts prefer lighting at most roundabouts while others do not light them.

- **Ontario, Canada**. The Ministry of Transportation (MTO) is responsible for lighting on provincial roadways, including those that run through municipalities. Lighting needs at traditional intersections are determined based on the methods outlined by the TAC roadway lighting design guide.[2] For local intersections and intersections not meeting the lighting warrants that municipalities would like to light, MTO requires that the lighting design meet MTO-approved standards. The MTO's lighting policy requires that all roundabouts on provincial roadways be lit.

Needs Determination

Among states that use lighting at intersections and/or midblock crosswalks, the lighting needs determination procedures vary considerably, ranging from simple control factors (e.g., pedestrian presence or high ND crash ratio based on engineering judgement) to systematic warranting analysis methods (e.g., AASHTO *Roadway Lighting Design Guide*, TAC method, and/or *FHWA Lighting Handbook*). For example, the TAC warranting analysis method bases lighting needs on ND crash ratios in conjunction with a number of roadway and traffic factors, resulting in recommendations for no lighting, delineation lighting, partial lighting, or full lighting. In general, most states consider the following factors at a varying level of importance:

- ND crash ratio. In the TAC screening method, for example, intersections with a ND crash ratio of 2.0 or higher automatically warrant lighting.
- Pedestrian and bicyclist traffic. For example, Florida's lighting policy recommends lighting for all intersections with crosswalks.
- Intersection layout. Intersections with unconventional layouts are frequently considered for lighting by some states. In addition, some states recommend that all roundabouts be lit. Some states also routinely add lighting at rural/isolated T/Y intersections to alert users.
- Channelization devices. The presence of channelization devices (e.g., raised islands) is a factor considered in the TAC warranting method and the aforementioned FHWA lighting screening tool.

- Other factors. Both the TAC and FHWA methods also consider a number of other factors, such as ambient lighting, nearby development, parking, sight distance, and speed limit.

Design Process and Standards

All states interviewed have adopted the IES RP-8-14 standard for lighting designs and all interviewees suggested that the minimum lighting levels specified in the standard seemed to be sufficient. Depending on project types and state practices, lighting at intersections and midblock crosswalks may be subject to the following levels of design:

- Strictly design to the required levels for horizontal illuminance/luminance levels, uniformity levels, and vertical levels.
- Design lighting to meet horizontal levels and in some cases uniformity levels as well, but allow vertical levels to be within a reasonable range of the minimal levels required.
- Install standard luminaires and installation layout at intersections and midblock crosswalks without performing formal designs. An example for this case is to install a standard luminaire on top of each signal pole at a typical intersection. Another example is that some states routinely install single luminaires at isolated T intersections to alert approaching drivers.

Most states interviewed do not inspect lighting levels after installation. However, some states recognized that lighting designs were performed based on the assumption that the designing area was flat, which is typically not the case in the field and therefore the actual lighting levels after installation could change. Some officials interviewed noted cases when the installed lighting systems at intersections had inconsistent characteristics compared to the designs.

Note that MTO does not allow manufacturer-specific lighting design software to be used for provincial lighting projects.

Lighting Installation

Many states routinely install luminaire fixtures on top of signal poles unless the lighting systems conflict with overhead power lines. Others avoid collocating lighting systems with signal poles, particularly on corridors where lighting systems are maintained by power companies, to prevent potential interruptions of signals due to lighting maintenance.

LEDs

All states interviewed during this project were in various stages of implementing LEDs. States typically use LED systems with a correlated color temperature of 4,000 K or 3,000 K (mostly in or near residential areas). The officials that VTTI talked to made the following observations relevant to the implementation of LEDs:

- LED systems allow better photometric performance (e.g., improved contrast and uniformity) compared to traditional high pressure sodium systems. In some cases, replacing existing lighting systems with LEDs allowed states to eliminate lighting poles that cause particular risks for fixed-object crashes or to meet right of way restraints.

- Some state officials noted that it would be beneficial to develop an LED-specific lighting design guide due to LEDs different photometric performance. Currently, all states that VTTI interviewed during this project are designing LED systems that follow the same standards to the same lighting levels.
- The availability of increasingly cost-effective LED systems are less power demanding, which reduces their reliance on fixed power supplies while also reducing material costs. Accordingly, some states are increasingly considering lighting at intersections and midblock crosswalks, particularly rural and isolated intersections.

Examples and Lessons

The state interviews provided the following observations and lessons:

- State transportation agency and user opinions regarding the safety benefits of lighting are frequently divided, which is clearly illustrated by the varying practices among different states and among districts of the same states. Some practitioners and users recognize and highly prioritize the benefits of lighting on safety and security, particularly for pedestrian/bicycle traffic and older drivers. Others fail to see tangible safety benefits and therefore frequently consider lighting a low-priority safety treatment.

- The warranting analysis and design methods at state transportation agencies and municipalities vary significantly, resulting in inconsistent lighting usage and performance at intersections and crosswalks.

- Although many practitioners recognize the importance of vertical lighting levels, they also noted that these minimum vertical levels are frequently not met, particularly at large intersections or crosswalks on wide roadways.

- Locations of luminaires at intersections or midblock crosswalks are important for the safety of pedestrians and bicyclists. Due to the practice of locating luminaires on top of signal poles in some states, they are frequently located upstream of crosswalks, resulting in limited benefits or in some cases adverse safety effects for pedestrians. Lighting at midblock crosswalks on roadways that are continuously lit are generally not designed separately. Such locations frequently have luminaires installed behind the crosswalk from the approaching traffic, which limits the lighting benefits as well.

- Some states indicated that the TAC and FHWA warranting analysis method requires a large amount of data, which may not be available, particularly for new projects. If a cost-benefit analysis is required, it is also extremely difficult to obtain accurate cost data for intersection lighting systems. Note that none of the states, municipalities, or power companies that VTTI spoke to tracked lighting-related material, maintenance, and/or electricity costs separately.

- Use of lighting as a safety measure in states with “no-lighting” policies can be challenging. In states that do not maintain lighting systems on non-access controlled facilities, the installation of lighting as a safety countermeasure on selected intersections can become a challenging collaborative effort between the state and the involved municipality and power companies. The required collaboration sometimes further discourages safety engineers from considering lighting as a safety countermeasure at intersections. Due to limited needs for lighting-related expertise, such states generally retain very few lighting experts, thereby further reducing advocacy for lighting.

- Lighting practices for roundabouts are significantly inconsistent across each state and among different states. Many states’ lighting policies recommend lighting all roundabouts, considering them to be unconventional intersections. Many practitioners, however, feel it is unnecessary to light all roundabouts, particularly in areas where they are common.

Crash Data Analysis Results

Summary of Illuminance and Uniformity Levels

The light levels are summarized for all the lighting variables at the intersection box (see Figure 8), major approach (see Figure 9) and minor approach (see Figure 10) in the following box plots. It is noteworthy that the unlighted intersections do not all have a lighting level of zero. Light in these intersections includes stray light from surrounding areas.

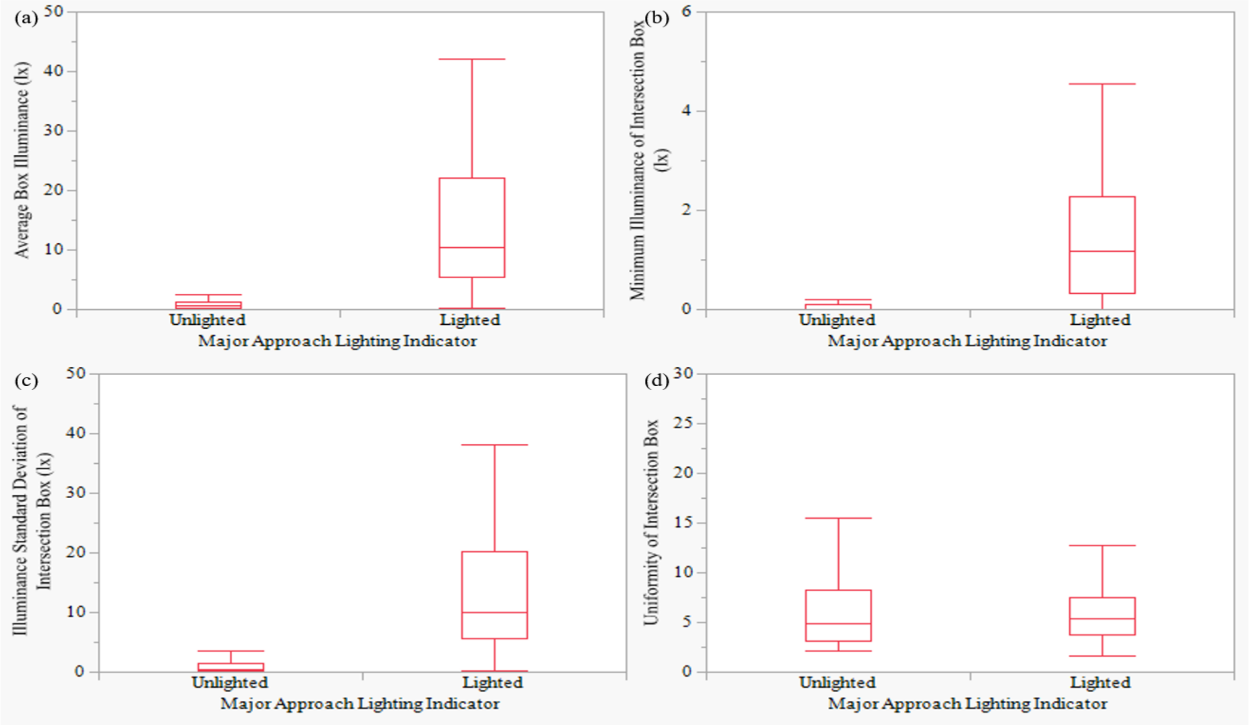


Figure 8. Box Plots of the Distribution of the Lighting Variables at the Intersection Box – (a) Average Illuminance, (b) Minimum Illuminance, (c) Illuminance Standard Deviation, and (d) Uniformity.

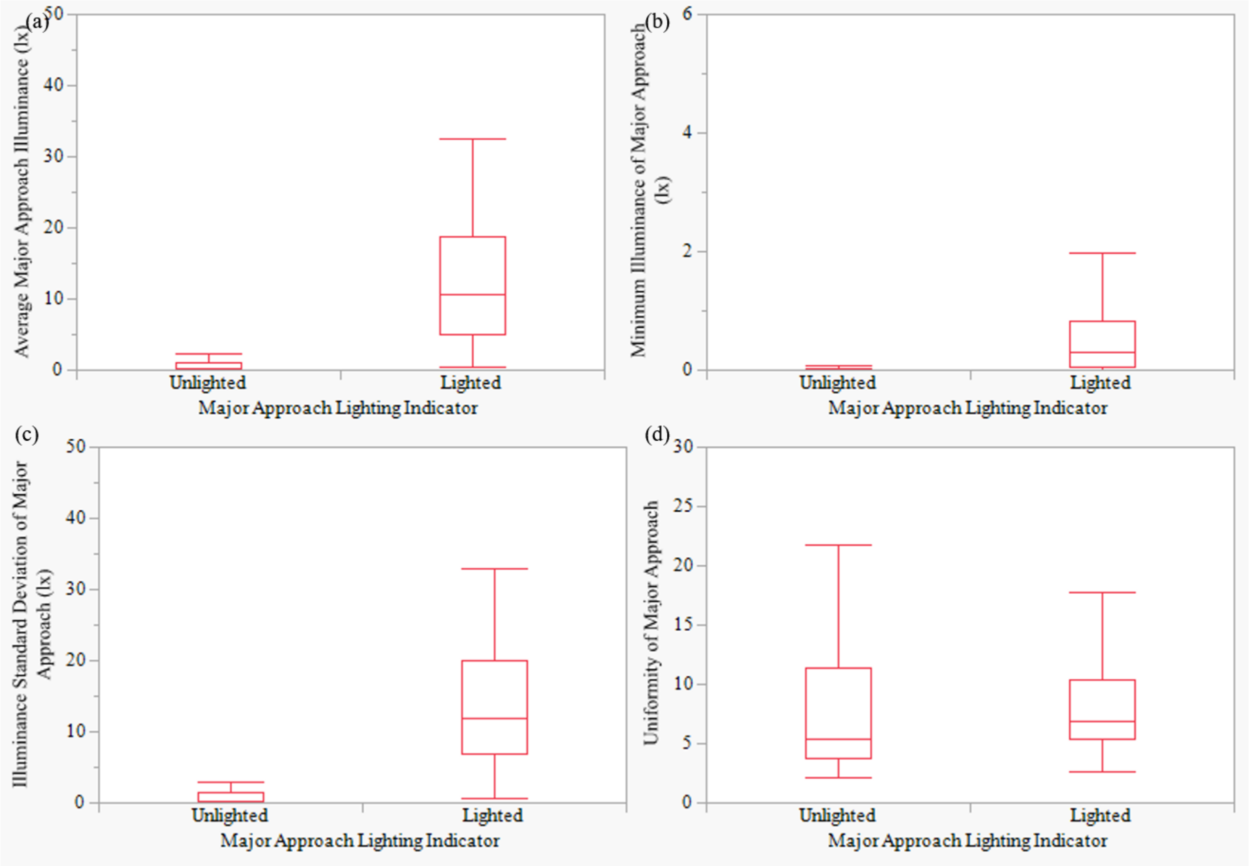


Figure 9. Box Plots of the Distribution of the Lighting Variables at the Major Approach of the Intersections – (a) Average Illuminance, (b) Minimum Illuminance, (c) Illuminance Standard Deviation, and (d) Uniformity.

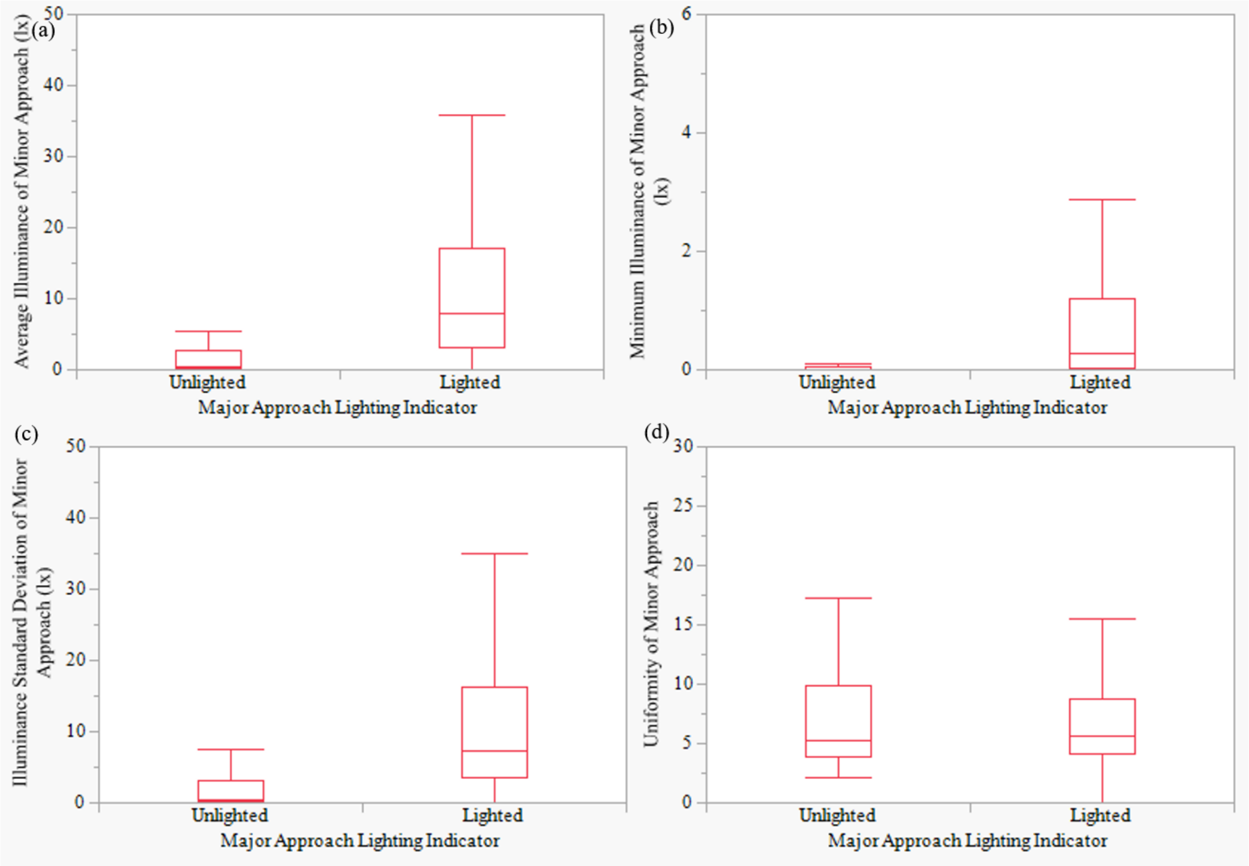


Figure 10. Box Plots of the Distribution of the Lighting Variables at the Minor Approach of the Intersections – (a) Average Illuminance, (b) Minimum Illuminance, (c) Illuminance Standard Deviation, and (d) Uniformity.

Summary of Night to Day Crash Ratios

Preliminary crash statistics showed that lighted intersections had lower ND crash ratios than unlighted intersections in the current data set (Figure 11). The difference of ND crash ratios between the lighted and unlighted intersections was higher for signalized intersections (69%) than for unsignalized intersections (27%).

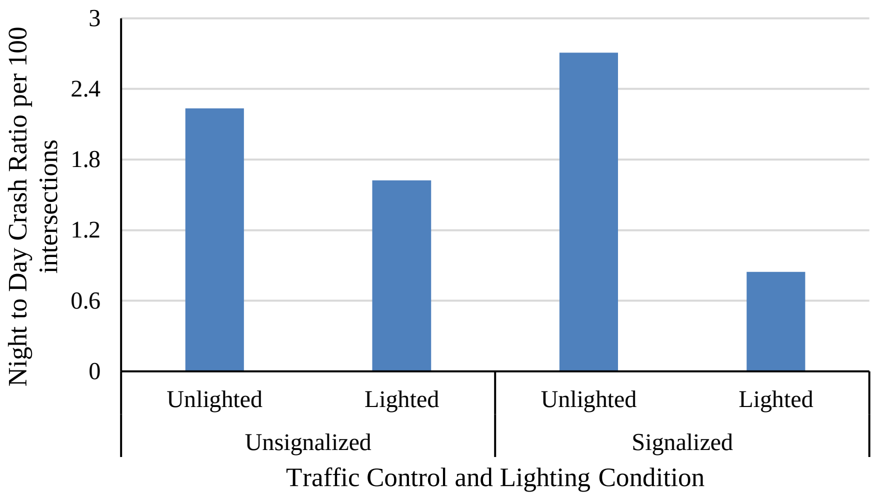


Figure 11. Night to Day (ND) Crash Ratios of Lighted and Unlighted Intersections at Unsignalized and Signalized Intersections

Effects of Average and Minimum Illuminance

In this model, the effects of average and minimum illuminances of the intersection box, major approach, and minor approach were evaluated. The results of the negative binomial regression along with the parameter estimates and risk ratios are show in Table 15. The only significant lighting factor is the minimum illuminance of the intersection box, where a 1-lux increase in illuminance is associated with a 2.9% reduction in the ND crash ratio. It is important to understand that this relationship is only valid within the range of the illuminance values (0 to 27 lux) recorded at the intersections used in the study. In addition, major roadways with function classes 3 (principal arterial) and 4 (minor arterial) had higher ND crash ratios than other function classes (major collector and others), by 32.5% and 29.2%, respectively.

Table 15. Significant Factors' Parameter Estimates and Risk Ratios for the Average and Minimum Illuminance Model

Explanatory Variables	Level Comparisons	Estimate	P Value	Risk Ratio
Major Approach Function Class	Principal Arterial vs. Major Collector & Others	-0.3924	0.0116	32.5%
	Minor Arterial vs. Major Collector & Others	-0.3455	0.0255	29.2%
Major Approach Median Type	Curb vs. Line	-0.6753	0.026	49.1%
Major Approach Median Width	Five or more vs. Zero	0.8839	0.0056	142.0%
Minimum Box Illuminance		-0.0297	0.0345	2.9%

Unsignalized intersections had higher ND crash ratios than signalized intersections for both the major (55.1%) and minor (47.1%) approaches. Intersections whose major approach had a curb type median had approximately 48% lower ND crash ratios than those with a line median. Median width of the major approach also had a significant impact on the ND crash ratios. ND crash ratios were higher when the median width was greater than 5 feet when compared to intersections with a major approach and no median. Increase in ADT is also associated with an increase in the ND crash ratio.

Fitting the Minimum Illuminance of the Intersection Box to the Night Crash Frequency

The fits showed that an increase in the minimum illuminance of the intersection box is associated with a decrease in the number of night crashes (5-year period; 2014–2018), as shown in Table 16 and Figure 12. All the parameter estimates were significant at $p < 0.05$, except for the asymptote for the signalized minor arterial-major collector and other intersections (see Table 16). The light levels associated with maintaining asymptote-level night crashes over 5 years are indicated in Table 17. The specified number of night crashes for each of the combination of traffic control and function classes are higher than the asymptote (shown in Table 16); this was deliberately done to ensure that the confidence interval of the predicted minimum illuminance level did not have an unrealistic illuminance (e.g., negative illuminance numbers). As the number of night crashes approaches the asymptote, the confidence interval widens exponentially. Thus, by establishing the specified number of night crashes as a number slightly higher than the asymptote, a realistic and a narrow confidence interval can be attained.

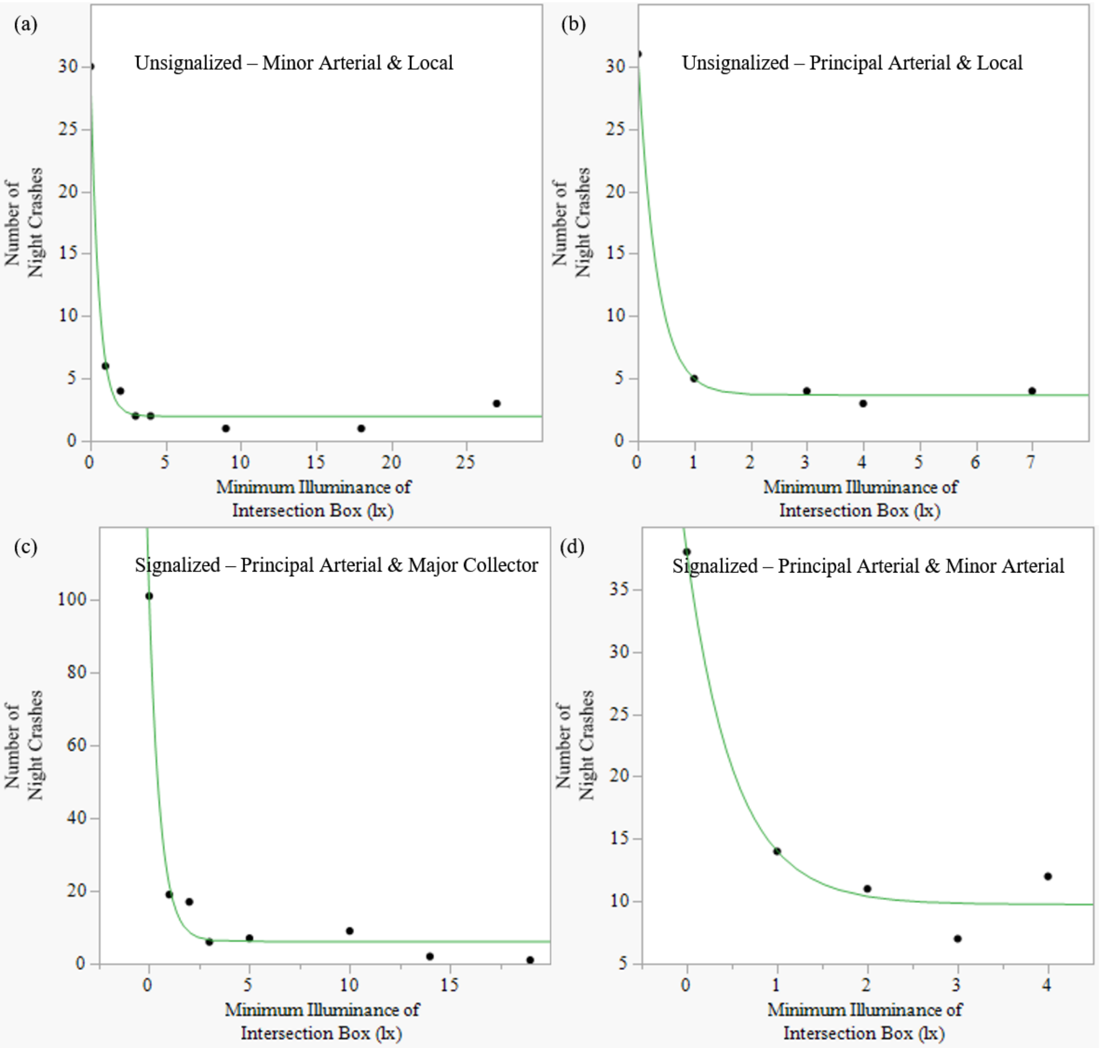


Figure 12. A Three Parameter Exponential Fit Between Night Crash Frequency and Minimum Illuminance of the Intersection Box at the Unsignalized Minor Arterial – Local (A), Unsignalized Principal Arterial- Local (B), Signalized Principal Arterial-Major Collector (C), and Signalized Principal Arterial-Minor Arterial

Table 16. Parameter Estimates of the Five 3-Parameter Exponential Models for Traffic Control and Major and Minor Function Class Combination

	Unsignalized		**Signalized**		
Parameter	**Minor Arterial - Local & Others**	**Principal Arterial-Local**	**Minor Arterial-Major Collector & Others**	**Principal Arterial - Major Collector & Others**	**Principal Arterial-Minor Arterial**
Asymptote (a)	1.96	3.66	-0.36*	6.08	9.74
Scale (b)	28.00	27.34	65.27	94.70	28.26
Growth Rate (c)	-1.84	-3.02	-0.50	-1.80	-1.89
R-Square	0.99	0.99	0.87	0.98	0.97

*Not significant at $p < 0.05$

Table 17. Predicted Minimum Illuminance of the Box and the 95% Confidence Intervals for the Intersections Based on Traffic Control and Function Class

Traffic Control	Function Class	Specified Number of Night Crashes in a 5 year period	Predicted Minimum Illuminance of Intersection Box (lx)	Lower 95%	Upper 95%
Unsignalized	**Minor Arterial -Major Collector & Others**	3	1.8	1.3	2.3
	Principal Arterial-Local	4	1.5	0.9	2.0
Signalized	**Principal Arterial -Major Collector & Others**	7	2.6	0.2	4.9
	Principal Arterial-Minor Arterial	11	1.6	0.5	2.8

Effect of Illuminance Uniformity

In this model, the effects of illuminance uniformity of the intersection box, major approach and minor approach were evaluated. The results of the negative binomial regression, along with the parameter estimates and risk ratios, are show in Table 18. Uniformity of the intersection box was found significant. A 1-unit increase in the illuminance uniformity of the intersection box was associated with a 1.9% increase in the ND crash ratio. It is important to understand that this relationship is only valid within the range of the uniformity values (i.e., 2 to 44) recorded at the intersections used in the study. In addition, major roadways with function classes 3 (principal arterial) and 4 (minor arterial) had lower ND crash ratios than other function classes (major collector and others), by 31.9% and 28.8%, respectively. Increase in the number of through lanes was also associated with an increase in the ND crash ratio. Intersections whose major approach had median types curb or flat and other types had approximately 50.4% lower ND crash ratios than those with a line type median. Median width of the major approach also had a significant impact on the ND crash ratios. ND crash ratios were higher when the median width was greater than 5 feet when compared to intersections with a major approach that had no median.

Table 18. Significant Factors' Parameter Estimates and Risk Ratios for the Illuminance Uniformity Model

Explanatory Variables	Level Comparisons	Estimate	P Value	Risk Ratio
Intersection Geometry	Right angle vs. Skewed	-0.201	0.028	18.2%
Major Approach Function Class	Principal Arterial vs. Major Collector & Others	-0.3839	0.0073	31.9%
	Minor Arterial vs. Major Collector & Others	-0.3394	0.0237	28.8%
Major Approach Median Type	Curb vs. Line	-0.7013	0.0193	50.4%
Major Approach Median Width	Five or more vs. Zero	0.9531	0.0023	159.4%
Minor Sidewalk Indicator	Absent vs. Present	-0.2803	0.0388	24.4%
Illuminance Uniformity of Intersection Box		0.0189	0.0345	1.9%

Standard Deviation of Illuminance Effects

In this model, the standard deviation of illuminance effects of the intersection box, major approach, and minor approach were evaluated. The results of the negative binomial regression along with the parameter estimates and risk ratios are shown in Table 19. The effect of the standard deviation of illuminance of the intersection box was significant but the risk ratio was negligible. Increase in the standard deviation of intersection box illuminance by 1-lux was associated with a 0.1% reduction in the ND crash ratio. All other significant factors were similar to the previous models. Intersection geometry was the only intersection factor that was significant in the current model (see Table 19). Right-angled intersections had a lower ND crash ratio than skewed intersections by 19.2%.

Table 19. Significant Factors' Parameter Estimates and Risk Ratios for the Standard Deviation of Illuminance Model

Explanatory Variables	Level Comparisons	Estimate	P Value	Risk Ratio
Intersection Geometry	Right angle vs. Skewed	-0.2144	0.0248	19.3%
Major Approach Function Class	Principal Arterial vs. Others	-0.3846	0.0108	31.9%
	Minor Arterial vs. Others	-0.3529	0.0219	29.7%
Major Approach Median Type	Curb vs. Line	-0.7249	0.019	51.6%
Major Approach Median Width	Five or more vs. Zero	0.9619	0.0038	161.7%
Minor Approach Sidewalk Indicator	Absent vs. Present	-0.3234	0.0228	27.6%
Illuminance Standard Deviation of Intersection Box	-	0.0011	0.0397	0.1%

Illuminance Uniformity Effects of the Box and Major Approach, and the Illuminance Standard Deviation of the Intersection Box on Night Crash Frequency

The model fits showed that an increase in the illuminance uniformity of the intersection box and major approach, and the illuminance standard deviation of the intersection box, were not strongly associated with a decrease in the number of night crashes (lower R-squares and non-significant parameter estimates). This shows that the relationship between illuminance uniformity, standard deviation of illuminance, and night crash frequency does not follow an exponential relationship (see Figure 13). As uniformity increases, the number of crashes increases, then decreases, and then rapidly increases again. Uniformity ratios of less than three and between six and seven seem to have a lower number of associated night crashes (see Figure 13).

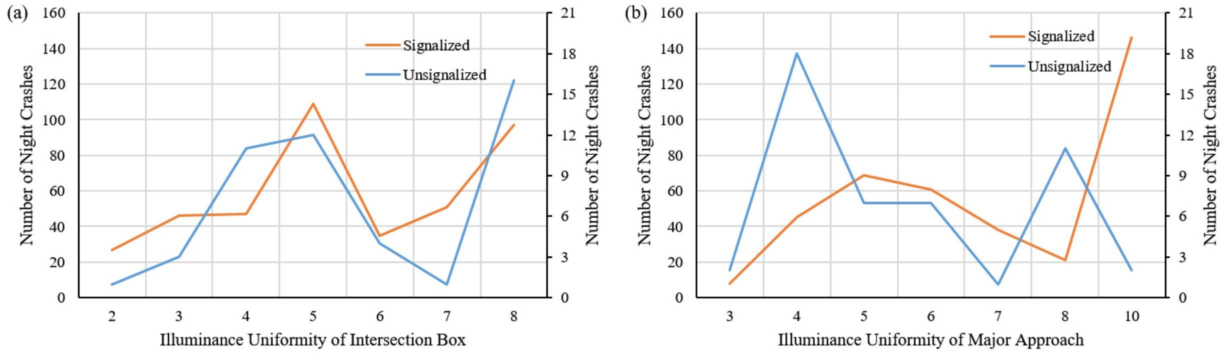


Figure 13. Relationship Between Uniformity and Night Crash Frequency

CMFs for Intersection Lighting

The negative binomial regression analysis showed that minimum illuminance and lighting uniformity at intersection boxes were significantly correlated with nighttime crashes. Based on these results, the project team developed CMFs for both minimum intersection box illuminance and intersection box lighting uniformity.

Minimum Illuminance at Intersections

When analyzing all intersections together, the results showed a -0.0297 coefficient for the minimum illuminance within the intersection box. Based on this result, a CMF can be determined as:

CMF for increase of each lux in minimum intersection illuminance = *Exp(-0.0297) = 0.97*.

Notes:

- This CMF is based on a total number of 243 intersections in Virginia with a minimum intersection illuminance ranging between 0 and 27 lux.
- The number of total crashes at the intersections used for developing this CMF ranged from 4 to 142 with an average of 30 crashes. The number of nighttime crashes ranged from 0 to 32 with an average of 6 crashes.
- This CMF applies to all nighttime intersection crashes regardless of severity and manner of collision. The project team did not develop separate models by crash severity or type during this project
- This CMF applies to all intersections regardless of intersection type. Separate models developed by intersection type did not result in significant findings relevant to lighting variables likely due to limited sample sizes.
- The minimum illuminance is for the intersection box defined as the intersection area bounded by the stop bar on each intersection approach.

Lighting Uniformity at Intersections

The negative binomial analysis also indicated a significant coefficient of 0.0189 for illuminance uniformity at intersection box. Based on this result, the following CMF was developed for intersection illuminance uniformity:

CMF for each unit decrease in illuminance uniformity at intersection box = *Exp(0.0189) = 0.98*.

Notes:

- This CMF is based on a total number of 243 intersections in Virginia with the illuminance uniformity at intersection box ranging between 2 and 25. Illuminance uniformity is defined as the difference between maximum illuminance and minimum illuminance divided by average illuminance.

- The number of total crashes at the intersections used for developing this CMF ranged from 4 to 142 with an average of 30 crashes. The number of nighttime crashes ranged from 0 to 32 with an average of 6 crashes.
- This CMF applies to all nighttime intersection crashes regardless of severity and manner of collision. The project team did not develop separate models by crash severity or type during this project
- This CMF applies to all intersections regardless of intersection type. Separate models developed by intersection type did not result in significant findings relevant to lighting variables likely due to limited sample sizes.

Safety Benefit-Cost Analysis Results

To conduct a safety benefit-cost analysis, the project team needed to identify the potential crashes prevented due to the use of lighting at intersections. Since this project did not conduct a comparison analysis for crashes between lit and unlit intersections, the project team used the optimal minimum illuminance values identified previously in Table 17 to calculate hypothetical CMFs for adding lighting (i.e., increasing minimum intersection box illuminance from 0 to the optimal values). In addition, the project team calculated CBRs for two scenarios: intersections with one nighttime crash per year regardless of crash severity, and intersections with one nighttime injury or fatal crash per year regardless of injury levels. Table 20 lists the hypothetical numbers of nighttime crashes prevented for intersections with one crash annually on average. Using the estimated number of crashes prevented by lighting, the project team developed the BCRs for the four types of intersections, as shown in Table 21 - Table 24.

Table 20. Annual Average Number of Nighttime Crashes Prevented by Lighting for Intersections with One Nighttime Crash

Intersection Type	Optimal Minimum Illuminance of Intersection Box (lx)	CMF for Optimal Illuminance Level	Nighttime Crashes Prevented per Year
Minor Arterial @ Major Collector, Minor Collector, or Local - Unsignalized	1.8	0.948	0.05
Other Principal Arterial @ Local - Unsignalized	1.5	0.956	0.04
Other Principal Arterial @ Major Collector, Minor Collector, or Local - Signalized	2.6	0.926	0.07
Other Principal Arterial @ Minor Arterial - Signalized	1.6	0.954	0.05

Table 21. BCRs for Adding New Poles at Intersections with One Nighttime Crash Annually (Regardless of Severity)

Parameter and Results	Unsignalized Intersections		Signalized Intersections	
	Minor Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Local	Other Principal Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Minor Arterial
Discount rate	0.07	0.07	0.07	0.07
Life Cycle (Years)	20	20	20	20
Initial Installation Cost	$43,200.00	$43,200.00	$43,200.00	$43,200.00
Construction Engineering Inspection	$922.76	$922.76	$922.76	$922.76
Annual Maintenance and Energy Consumption	$1,442.72	$1,442.72	$1,442.72	$1,442.72
Unit Crash Cost	$118,148.23	$118,148.23	$118,148.23	$118,148.23
Present Value Benefit	$69,717.78	$58,355.43	$99,527.05	$62,154.13
Present Value Cost	$60,476.85	$60,476.85	$60,476.85	$60,476.85
Benefit-Cost Ratio	**1.15**	**0.96**	**1.65**	**1.03**

Table 22. BCRs for Luminaire-Signal Combination or Existing Poles at Intersections with One Nighttime Crash Annually (Regardless of Severity)

Parameter and Results	Unsignalized Intersections		Signalized Intersections	
	Minor Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Local	Other Principal Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Minor Arterial
Discount rate	0.07	0.07	0.07	0.07
Life Cycle (Years)	20	20	20	20
Initial Installation Cost	$17,000.00	$17,000.00	$17,000.00	$17,000.00
Construction Engineering Inspection	$922.76	$922.76	$922.76	$922.76
Annual Maintenance and Energy Consumption	$1,442.72	$1,442.72	$1,442.72	$1,442.72
Unit Crash Cost	$118,148.23	$118,148.23	$118,148.23	$118,148.23
Present Value Benefit	$69,717.78	$58,355.43	$99,527.05	$62,154.13
Present Value Cost	$34,276.85	$34,276.85	$34,276.85	$34,276.85
Benefit-Cost Ratio	**2.03**	**1.70**	**2.90**	**1.81**

Table 23. BCRs for Adding New Poles at Intersections with One Nighttime Fatal or Injury Crash Annually

Parameter and Results	Unsignalized Intersections		Signalized Intersections	
	Minor Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Local	Other Principal Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Minor Arterial
Discount rate	0.07	0.07	0.07	0.07
Life Cycle (Years)	20	20	20	20
Initial Installation Cost	$43,200.00	$43,200.00	$43,200.00	$43,200.00
Construction Engineering Inspection	$922.76	$922.76	$922.76	$922.76
Annual Maintenance and Energy Consumption	$1,442.72	$1,442.72	$1,442.72	$1,442.72
Unit Crash Cost	$322,812.10	$322,812.10	$322,812.10	$322,812.10
Present Value Benefit	$190,487.34	$159,442.41	$271,934.13	$169,821.47
Present Value Cost	$60,476.85	$60,476.85	$60,476.85	$60,476.85
Benefit-Cost Ratio	**3.15**	**2.64**	**4.50**	**2.81**

Table 24. BCRs for Luminaire-Signal Combination or Existing Poles at Intersections with One Nighttime Fatal or Injury Crash Annually

Parameter and Results	Unsignalized Intersections		Signalized Intersections	
	Minor Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Local	Other Principal Arterial @ Major Collector, Minor Collector, or Local	Other Principal Arterial @ Minor Arterial
Discount rate	0.07	0.07	0.07	0.07
Life Cycle (Years)	20	20	20	20
Initial Installation Cost	$17,000.00	$17,000.00	$17,000.00	$17,000.00
Construction Engineering Inspection	$922.76	$922.76	$922.76	$922.76
Annual Maintenance and Energy Consumption	$1,442.72	$1,442.72	$1,442.72	$1,442.72
Unit Crash Cost	$322,812.10	$322,812.10	$322,812.10	$322,812.10
Present Value Benefit	$190,487.34	$159,442.41	$271,934.13	$169,821.47
Present Value Cost	$34,276.85	$34,276.85	$34,276.85	$34,276.85
Benefit-Cost Ratio	**5.56**	**4.65**	**7.93**	**4.95**

The benefit-cost analysis suggested that:

- When adding new poles, the BCRs for smaller, unsignalized intersections of minor arterials with collectors or local roads and other principal arterials with local roads were estimated to be around 1 assuming one nighttime crash on average annually regardless of severity at such locations. For the scenario of one fatal or injury nighttime crash per year at such intersections, adding lighting would result in a safety BCR of approximately 3. This suggests that adding lighting at unsignalized intersections with at least 1 nighttime crash would in general result in a safety BCR of 1 or higher.

- When adding new poles, the BCRs for the two types of signalized intersections on other principal arterials (i.e., other principal arterial with major collector, minor collector, or local; and other principal arterial with minor arterial) were estimated at 1.7 and 1.0, respectively, for intersections with one nighttime crash on average regardless of severity or 4.5 and 2.8 for intersections with a fatal or injury nighttime crash annually on average. Such results also suggest that the return in safety benefit would be higher than the cost of lighting at most major signalized intersections with only one nighttime crash.

- If using existing poles, adding lighting at the two types of unsignalized intersections (i.e., minor arterials with collectors or local roads and other principal arterials with local roads) would yield a BCR of 2.0 and 1.7 for just one annual crash at each intersection regardless of crash severity, or a BCR of 5.6 and 4.7 for locations with one fatal or injury nighttime crash each year. These results also suggest that the safety benefits considerably outweigh the lighting-related investments at the studied unsignalized intersections with at least one nighttime crash.

- When using luminaire-signal combination poles, the analysis showed a BCR of 2.9 and 1.8 for the two types of signalized intersections assuming one nighttime crash each year at such locations; and a BCR of 7.9 and 5.0 for the studied signalized intersections assuming one fatal or injury nighttime crash annually at such locations.

DISCUSSION

Intersection and Midblock Crosswalk Lighting Practices

VDOT Practices

The following is a discussion of the findings as they pertain to VDOT lighting practices:

- General VDOT lighting practices. The lighting process at VDOT generally involve a number of stakeholders, including the Central Office, districts, municipalities, and utility companies. In many cases, districts do not have a standard process for lighting-related decision making. Lighting-related expertise at districts varies significantly, although the Central Office can frequently serve as a central resource for lighting related decision making and design.

- Lighting needs identification. VDOT currently does not have a detailed intersection lighting guideline for districts' use. Lighting decisions can be made simply based on crash data or using a fairly data-demanding worksheet. The results of this study seem to point to the usefulness of a standardized, straightforward, and less data-demanding procedure for lighting needs identification.

- Midblock crosswalk lighting needs. Midblock crosswalks were not common on state highways in many of the VDOT districts that were interviewed. Based on district feedback, midblock crosswalk lighting needs have a lower priority compared to intersection lighting.

- Intersection lighting practices at municipalities in Virginia. Lighting practices at municipalities across the state vary significantly due to size, availability of resources, and governing officials'/municipality engineers' preferences.

- Lighting at roundabouts. Many districts believe that lighting should be provided at all roundabouts. While this was a requirement necessary when roundabouts were first introduced to the state, most citizens in the Commonwealth are now becoming increasingly familiar with roundabouts. Therefore, VDOT may consider requirements for lighting only for new roundabouts at counties/districts where roundabouts are not common.

Lighting Practices in Other States

The lighting policies in the states that were interviewed represented a wide range of practices and attitudes toward intersection and midblock crosswalk lighting at transportation agencies across the country and internationally. Some states do not light intersections on state highways while some other states attempt to add lighting at all crosswalks. Other states' lighting needs determination methods vary significant as well, but most methods consider factors such as crash history and intersection layout. Some states go through formal lighting design procedures at intersections, while it is not uncommon for certain states to simply use a predetermined number of standard luminaires at each intersection without any design process. Some states indicated that the TAC and FHWA warranting analysis method required a large amount of data, which may not be available, particularly for new projects. If a cost-benefit analysis is required, it is also extremely difficult to obtain accurate cost data for intersection lighting systems.

Based on the feedback from the states, it was important to at least maintain a lighting policy, a certain level of lighting expertise, and sustained support at the administrative level in order to most effectively use lighting at intersections as a safety tool. In addition to urban intersections, the interviews also seemed to suggest that lighting could be important for rural intersection safety.

Crash Data Analysis Results

The following are discussions pertaining to the crash analysis results:

- Among the different lighting variables tested, the minimum illuminance for intersection box and lighting uniformity for intersection box were found to be significantly associated with nighttime crashes. The negative binomial modeling results simplified the lighting-safety correlation to a linear relationship, overlooking the potentially non-linear relationships at certain lighting ranges. The three-parameter exponential curve that was developed for the intersection types with significant results, however, fully illustrates the non-linear nature of the lighting-safety correlation. Both analyses, however, were based on the lighting measurements obtained at lit and unlit intersections. The issue with lighting levels is then that they are frequently not continuous. Designed lighting systems tend to fall into ranges based on the design methods and standards used, leaving certain lighting ranges overrepresented, while others with very few data points are underrepresented. This is a limitation that almost all studies using field lighting data have to face.

- Based on the crash analysis results, the project team found optimal values between 1.5 lux to 2.6 lux for the minimum illuminance at intersection boxes for four types of intersections. These values confirm the findings of many previous studies that just a little light on roadways and streets would yield a significant safety benefit, while further lighting beyond a certain threshold becomes less cost-beneficial. These minimum illuminance levels were converted to average illuminance values based on uniformity measures and are provided in the Recommendations section. The values recommended are generally lower than those recommended by current IES standards, which indicates that there is room for lower lighting levels at intersections and therefore improved energy savings and environmental benefits.

- Within the roadway and traffic variables, the models suggested that functional classification, major approach median conditions, minor approach traffic control, intersection geometry, and ADT were significantly correlated with nighttime crashes. These are variables that would mostly likely affect nighttime crashes and therefore would indicate the factors that should be taken into consideration when making lighting decisions.

Note that VTTI is currently conducting the project “Roadway Lighting's Effect on Pedestrian Safety at Intersection and Midblock Crosswalks” (Project Number R27-202) with the Illinois Center for Transportation (ICT) on behalf of the Illinois Department of Transportation. The lighting levels developed based on the crash data analysis as part of this VDOT research will be further evaluated on the Smart Road as part of the ICT project. VTTI will update VDOT on the evaluation results of the ICT project and update the recommended lighting levels and the lighting needs identification guidelines accordingly.

Development of Crash Modification Factors

This project took a different approach for developing intersection lighting CMFs. The most common approach for CMF development is to compare crash data between site groups with and without the subject treatment. This approach was not suitable for this research due to the following:

- Lack of suitable unlit intersections for comparison. Both VDOT and major municipalities have a tradition of using lighting at intersections where there are perceived or proved (via warranting analyses) nighttime crash risks. Due to this practice, it was extremely difficult to identify a well-controlled sample of intersections, particularly in urban areas, where lighting was warranted but not used. The lack of a well-controlled sample of unlit intersections in Virginia was a major reason the project team chose not to use the traditional comparison methods (e.g., naïve comparison or empirical Bayes-based comparison analysis).

- The primary purpose of this project was to identify the optimal lighting levels for Virginia intersections in order to maximize safety benefits, based on which data-driven guidelines could be developed to improve intersection lighting design. For this purpose, the project team measured the lighting variables at more than 200 intersections in the field and correlated the variables with historical crash data. Based on the project goal, the project team did not conduct a separate analysis attempting to compare lit vs. unlit intersections.

- Intersection lighting levels measured in the field were not continuous. As previously noted, intersection lighting design practices at VDOT and different municipalities varied significantly. The lighting systems at some intersections were designed following applicable standards, while others were not the result of lighting designs (e.g., simply installing two or four luminaires of a specific type at an intersection without any design). Designed lighting systems were typically designed to a minimum level specified by the applicable standard. These factors, in combination, led to intersection lighting levels tending to fall into a number of discrete ranges instead of being evenly distributed across the entire range. Due to this, it was difficult to develop CMFs for per-lux lighting increases using an approach based on two-sample comparison analyses.

Nevertheless, this project developed CMFs for minimum intersection box illuminance levels and intersection box lighting uniformity. The CMFs were developed for unit changes in the two significant lighting variables. The project team however, did not develop CMFs for lighting as a binary variable (i.e., with versus without lighting) due to the factors discussed above.

Safety Benefit Analysis Results

This study showed that, on average, the safety BCRs for the four types of studied intersections in Virginia were greater than 1. When using these results, readers should note the following:

- The lighting-related cost data at VDOT is relatively limited. Due to this limitation, the project team had to develop estimates of the related cost items based on anecdotal information obtained from VDOT. In particular, the luminaire and initial installation costs were only based on sample lighting projects for one type of intersection. These costs would be considered for mid-sized intersections, although they are used for all four types of studied intersections for which BCRs were developed. At larger intersections, VDOT may need to install more than four lighting poles and more/higher wattage luminaires. The BCRs at such intersections therefore would be somewhat lower than estimated in this study.

- This benefit-cost analysis did not analyze crashes separately by severity or type. The study used combined cost estimates for all nighttime crashes or all fatal and injury crashes on average weighted by proportions of crashes of different severities. This method was used primarily because the crash data analysis did not find significant results for separate models by severity or by type. Due to this, the project team could not develop separate CMFs by severity or for different types of crashes. With regard to the BCRs, users should be aware that for intersections that had solely property damage only crashes, the lighting BCRs will be lower due to the lower costs associated with such crashes. Nighttime crashes mostly involve single vehicles and roadway/fixed objects. Their costs may be different from the general crash cost estimates used in this study.

- This benefit-cost analysis only considered safety benefits based on crashes potentially prevented by lighting systems. The analysis was not able to consider lighting impacts on environment, wildlife, and human health. In addition, the initial installation and maintenance cost estimates did not include potential costs due to travel time losses resulting from lighting-related installation and maintenance.

GUIDELINES ON LIGHTING DESIGN LEVELS AND NEEDS IDENTIFICATION AT INTERSECTIONS

Intersection Lighting Design Considerations

Lighting Design Levels at Intersections

Based on the crash data analysis, the project team was able to identify the illuminance levels for different types of intersections. Table 25 lists the recommended illuminance levels for VDOT intersections. Since data were not available to calculate the predicted minimum illuminance of the intersection box for all combinations, the lighting guidelines for the combinations that could not be estimated were determined based on the ratios of the light levels that could be estimated. Further, the guidelines for uniformity ratios will refer to the existing guidelines in IES-RP-8-18, as these are similar to the trends observed in the existing data.

Table 25. Illuminance Guidelines for Intersections

Traffic Control	Functional Classification	Minimum Illuminance of Intersection Box (lx)	Average Illuminance of Intersection Box (lx)	Uniformity Ratio (Avg./Min)
Unsignalized	Principal Arterial - Minor Arterial	1	3.0	3.0
	Principal Arterial - Local	1.5	4.5	3.0
	Minor Arterial - Minor Arterial	1.1	3.3	3.0
	Minor Arterial - Local	1.8	5.4	3.0
	Local - Local	2.8	8.4	3.0
Signalized	Principal Arterial - Principal Arterial	1.3	3.9	3.0
	Principal Arterial - Minor Arterial	1.6	4.8	3.0
	Principal Arterial - Major Collector	2.6	7.8	3.0
	Minor Arterial - Minor Arterial	1.9	5.7	3.0
	Minor Arterial - Major Collector and Local	3.1	9.3	3.0
	Major Collector and Local - Major Collector and Local	5	15.0	3.0

Note that, due to data availability, the intersection lighting analyses in this project were not able to consider vertical illuminance or presence of pedestrians.

Lighting Needs Determination

Based on the findings of this project, the research team recommends that the lighting decisions for existing intersections should be primarily based on historical crash data. With one injury nighttime crash per year on average for most intersection types, the installation of lighting over the luminaire lifetime would yield a BCR considerably higher than one for most intersection types. As such, the project team recommends that, for existing intersections with historical crash data, lighting should be considered where one or more nighttime fatal or injury crash occurs each year, on average, over a 3-year period.

At newly-constructed intersections or intersections without historical crash data, the following factors/conditions should be considered when determining whether lighting should be used based on the data analysis results:

- ADT and functional classification. The study showed that ADT and functional classification are highly correlated. For this reason, the project team recommends that functional classification be used instead of ADT data, since the former is more readily available than the latter. In addition, the use of functional classification would eliminate the need for defining ambiguous ADT ranges.

- Complex alignment and intersection layout. Lighting may be considered at intersections on horizontal and/or vertical curves. Some curve alignments may further complicate certain turning movements, resulting in impaired sightlines for drivers or challenges for headlights to reach the travel paths. Certain intersection layouts, such as T intersections, Y-shaped intersections, intersections with offset approaches, and intersections with more than four approaches, can be challenging for drivers to safely navigate through. Providing lighting at such intersections to illuminate critical travel paths can be beneficial to safety.

Note that, in addition to the crash data analysis results, this report also documents in detail the lighting practice interview results and findings based on a detailed literature review (Appendix A). The following factors, although not directly resulting from the crash data analysis, have been identified as major risks for crashes at intersections by previous studies, incorporated in national/state lighting guidelines in the U.S. and Canada, and/or considered to be risks that can potentially be mitigated with lighting. These factors were considered when developing the lighting needs identification guidelines as well.

- Presence of pedestrians and bicyclists. Presence of pedestrians and bicyclists at intersections during the night creates crash risks, particularly for turning vehicles. Vehicles turning at unlighted intersections may not be able to identify crossing pedestrians and bicyclists due to the deviation between the headlight direction and the driving path.

- Intersections with complex features. Some features, such as on-road delineators, raised channelization islands or median separations, multiple left turn lanes, and exits with wide medians, can cause crash risks for turning vehicles during the night if not correctly identified. These features should be sufficiently illuminated at intersections.

- Retroreflective pavement markings. The existence of well-maintained retroreflective pavement markings to outline paths for turning vehicles and to delineate hazardous features (e.g., raised medians or channelization devices) at intersections may reduce the need for intersection lighting.

Combining all factors, the project team recommends the following guidelines for newly constructed intersections without sufficient historical crash data:

- VDOT should consider installing lighting systems for all signalized urban intersections on other principal arterials that have one or more following features:
    - Intersections with crosswalks that are located next to commercial developments or within areas likely generating/attracting significant pedestrian volumes at night (e.g., restaurants, bars, campuses, and medical facilities).
    - Intersections located on a horizontal curve, or a vertical curve that significantly reduces driver sight distances at the intersection.
    - Wide (6 ft or wider) median separations where the median is depressed (e.g., a ditch) or raised but not clearly delineated by retroreflective markings.
    - Y intersections, intersections with skewed approaches, or intersections with more than four approaches.
    - Intersections with multiple left-turning lanes or multiple right-turning lanes on any approach.
    - Intersections with raised channelization devices or flexible delineators within the intersection boxes.
    - Other intersections with features considered hazardous for night travelers that were not previously stated.

- VDOT should consider installing lighting systems for all signalized urban intersections on minor arterials/major collectors with a speed limit ≥ 35 mph, or on minor arterials/major collectors in areas with a speeding-related (i.e., by ≥ 10 mph) crash history, that have one or more following features:
    - Intersections with crosswalks that are located next to commercial developments or within areas likely generating/attracting significant night pedestrian volumes (e.g., restaurants, bars, campuses, and medical facilities).
    - Intersections located on a horizontal curve, or a vertical curve that significantly reduces driver sight distances at the intersection.
    - Wide (6 ft or wider) median separations where the median is depressed (slope higher than 1V:3H) or raised but not clearly delineated by retroreflective markings.

    - Y intersections, intersections with skewed approaches, or intersections with more than four approaches.
    - Intersections with multiple left-turning lanes or multiple right-turning lanes on any approach.
    - Intersections with raised channelization devices or flexible delineators within the intersection boxes.
    - Other intersections with features considered hazardous for night travelers that were not previously stated.

- For other urban intersections, VDOT should consider lighting on a case by case basis, with emphasis given to the previously stated features that have a high likelihood of causing crashes during night.

- For rural signalized intersections on other principal arterials and minor arterials with speed limits ≥ 35 mph, VDOT should consider lighting if the intersections have one or more of the following features:

    - Likely high pedestrian volume during the night based on land use type and data/observations of nearby roadways/intersections.
    - Located on a horizontal curve, or a vertical curve that significantly reduces driver sight distances at the intersection.
    - Wide (≥ 6 ft) median separations where the median is depressed (slope higher than 1V:3H) or raised (≥ 6 inches or 150 mms) but not clearly delineated by retroreflective markings.
    - Y intersections, intersections with skewed approaches, or intersections with more than four approaches.

- For rural unsignalized intersections where other principal arterials or major arterials with speed limits ≥ 35 mph meet major collectors and minor collectors, VDOT should consider lighting if the intersections have one or more of the following features:

    - Located on a horizontal curve, or a vertical curve that significantly reduces driver sight distances at the intersection.
    - Y intersections, intersections with skewed approaches, or intersections with more than four approaches.
    - Wide ((≥ 6 ft) median separations where the median is depressed (slope higher than 1V:3H) or raised (≥ 6 inches or 150 mms) but not clearly delineated by retroreflective markings.

If lighting is considered, the lighting infrastructure should be installed at locations such that the likelihood of causing fixed-object crashes is minimized. Alternative, low-cost power sources (e.g., solar power) may be considered at locations where power sources are not readily accessible. Note: the benefit-cost analysis included in this report assumed existing power sources. For locations without existing power supplies, VDOT should perform separate benefit-cost analysis with consideration of additional costs required for supplying power to such locations.

During the VDOT interviews, several district officials suggested that lighting needs at roundabouts needed to be reexamined. This project did not include roundabouts in data analysis. However, based on VDOT inputs and the team's relevant research experience, VTTI recommends that lighting be considered for multilane roundabouts, where pedestrian crosswalks cross a slip lane or two or more lanes exiting the roundabout, or at roundabouts with a crash history.

Additional Lighting Design Consideration

Based on the site visits associated with lighting data collection and the researchers' previous experience, crashes frequently take place at lighted intersections due to drivers failing to identify on-road objects or pedestrians. The objects or pedestrians in such cases may be located outside the focal areas of the intersection luminaires, and the lighting environment in some cases can be complex due to multiple luminaires used, glare from oncoming vehicles, and/or lighting encroachment from nearby commercial developments. When exposed to such a lighting environment and while making complex decisions required for turning movements at intersections, drivers' eye-glance directions need to change rapidly in order to visually scan the surroundings within a short period of time. During this process, drivers may not identify objects that are not illuminated at a relatively higher illuminance level compared to other lighted areas within the intersection.

This observation suggests that merely meeting the minimum required lighting levels at intersections with high-risk object locations (e.g., channelization devices) or areas (e.g., crosswalks) may not effectively ensure safety at night. The research team recommends that a lighting level equal to, or no more than, 10% lower than the highest lighting levels within the same lighted intersection be provided at locations with high-risk objects and crosswalks.

CONCLUSIONS

- *There were significant correlations between ND crash rates and two lighting variables: minimum illuminance at intersection box and lighting uniformity at intersection box*. These metrics were used as the primary basis for the development of recommended lighting levels at intersections.

- *Based on the crash data analysis, the project team developed lighting guidelines, including warranting factors and optimal lighting levels*.

- *CMFs were developed for two lighting variables: minimum illuminance at intersection box and lighting uniformity at intersection box.* The CMFs were developed for each unit increase of the lighting variables. Due to data limitations, the project team did not develop CMFs for the presence of lighting (as compared to unlit intersections).

- *The results showed that for most intersections with one crash on average annually, the safety benefits of lighting systems would outweigh the associated costs*.

RECOMMENDATIONS

1. *The VDOT Traffic Engineering Division (TED) should consider adopting the lighting needs determination guidelines developed during this project*. The set of guidelines including optimal design values lighting needs determination factors are included in this report. A revised and expanded draft Instructional and Informational Memorandum (I&IM) IIM-TE-390 (separate document) with the proposed guidelines has also been provided to TED for review and adoption.

2. *VDOT TED and Location &Design Division should adopt the intersection lighting design guidelines for illuminance and uniformity ratio developed during this project*.

3. *The VDOT TED and the Districts should work together to implement a standardized lighting process across districts to facilitate lighting-related decision-making, including needs identification and processes for working with the involved municipalities and utility companies.* Based on feedback from the district interviews, a standard lighting process would be beneficial. This would include developing processes to prioritize requests to retrofit lighting at existing intersections, and processes for determining when land use developments should or shall be required to install intersection lighting.

4. *For improved safety and a more standard lighting process, VDOT TED should provide training sessions or outreach to municipalities to improve the awareness of the safety benefits of well-defined lighting systems and the lighting process at VDOT.*

IMPLEMENTATION AND BENEFITS

Implementation

With regards to Recommendations 1 and 2, VDOT TED will review the revised and expanded draft Instructional and Informational Memorandum developed by the researchers. The I&IM will be revised if needed, and adopted within 1 year of the publication of this report. With regards to Recommendation 3, standard lighting processes will be developed within 1 year of the adoption of the I&IM. Upon the development of standardized processes, training and outreach for municipalities (Recommendation 4) will be developed as funding is available.

Benefits

The benefits of adopting the report’s recommendations will be improved intersection lighting design and consistency in application of intersection lighting across Virginia. This should help reduce nighttime crashes through better and more consistent application of intersection lighting. During this project, the team conducted a detailed benefit-cost analysis. The results are listed in Table 21 - Table 24. In general, the project team found a BCR between 2.6 and 5.6 for unsignalized intersections and between 2.8 and 7.9 for signalized intersections, assuming one injury nighttime crash per year at such locations and depending on whether existing poles can be used. In other words, for signalized intersections with one nighttime fatal or injury crash each year, the benefit of adding lighting were estimated to range between approximately $150,00 and $190,000 in 2019 dollars at each intersection.

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APPENDIX A: REVIEW OF LIGHTING PRACTICES AT INTERSECTIONS AND MIDBLOCK PEDESTRIAN CROSSINGS

Introduction

For about the past 20 years, the motor vehicle death rate in the U.S. has been on a downward trend. Although the population has increased steadily since 1975, the rate of crash deaths per 100,000 people is about half of what it was 40 years ago.[1] Unfortunately, the same cannot be said for the pedestrian death rate. Multiple studies have confirmed that, although the motor vehicle death rate has been declining, U.S. streets are not getting any safer for pedestrians. According to a Governors Highway Safety Association (GHSA) 2017 report, the number of pedestrian fatalities since 2007 increased by 27% while all other traffic deaths decreased by 14%.[2]

One of the factors contributing to the pedestrian fatality rate is lack of light. The International Commission on Illumination (CIE) states that the reason fatal road accident rates during darkness are so high is mainly due to reduced visibility.[3] Since approximately 90% of the information drivers use to navigate the roads is visual, avoiding pedestrians becomes more challenging with less light.[4] In fact, fatal road accident rates during darkness are approximately three times greater than those during daylight.[3]

Nationally, on average about 75% of pedestrian fatalities occur after dark; in some states the estimate is as high as 84%.[1] However, this statistic is even more severe when considering the fact that only about 25% of all traffic volume occurs after dark.[3] This means that during the time of day when the least number of vehicles are on the road, the greatest number of pedestrians are killed in crashes. Furthermore, as mentioned earlier, pedestrian deaths are the only category of traffic deaths that are increasing. This shows a heightened need to add or improve safety measures to protect areas of roadway traffic with high pedestrian volume, especially after dark. Adding lighting to roadways has been shown to be an effective countermeasure against crashes at night. In the following sections, research that evaluated the safety benefits of lighting on intersections and midblock crosswalks is discussed.

Safety Effects of Intersection Lighting

Roadway lighting increases visibility, augments vehicle headlamps, and provides more information about the surrounding area, and consequently can lead to fewer crashes.[5] Wortman concluded that lighting could significantly help to reduce the number of nighttime crashes at intersections.[6] An analysis of rural intersections in Illinois found that illumination reduced nighttime crashes by about 30%.[7]

A meta-analysis of 37 published studies from 1948 to 1989 in 11 different countries indicated a reduction of 65% in nighttime fatal crashes, a 30% reduction in injury crashes, and a 15% reduction in crashes involving property damage when lighting was installed on both intersections and road segments (rural, urban, and freeway).[8] A study conducted by the Minnesota Local Road Research Board (LRRB) indicated that lighting at rural intersections not only reduces nighttime crashes but also is a cost-effective countermeasure against crashes.[9] A before-and-after study conducted in Kentucky concluded that installation of lighting reduced nighttime crashes by 45%.[10] A study of 48 intersections in Minnesota to determine the effectiveness of lighting on nighttime crashes found a 37% reduction in the nighttime crash rate after lighting was installed.[11] Donnell reported that the presence of lighting at intersections reduces the night crash frequency by 7.6% and the ND crash ratio by 12%, respectively.[12] Similarly, Sasidharan also reported that the presence of lighting at intersections reduces nighttime crash frequency by approximately 6%.[13]

Crash reduction is a common way to compare countermeasures and their effectiveness. The crash modification factor (CMF) is an estimate of the proportion of crashes expected to result after implementing a given countermeasure. A CMF for intersection lighting was established at 0.881 in the CMF Clearinghouse.[12] However, this CMF assumes that the lighting was installed at a previously unlighted intersection and treats lighting like a categorical variable (present vs. absent), whereas light levels in real life occur on a continuum.

A study measuring lighting levels (illuminance and luminance) at rural intersections in Iowa concluded that it was difficult to quantify the effect of lighting on intersection safety.[14] However, the authors noted that the presence of fixed overhead lighting made intersections safer than unlighted ones. More recently, lighting data collected from 100 rural intersections in Virginia showed that for a 1-unit increase in the illuminance, the number of night crashes decreased by 7%.[15] For the lighted intersections, the same increase in average horizontal illuminance decreased the number of night crashes by 9%. The largest decrease in the number of night crashes was for unlighted intersections, where for a 1-unit increase in the average horizontal illuminance the night crashes decreased by 21%. These relationships between illuminance and night crashes may only be valid, however, for the tested illuminance ranges (0.28 to 31.6 lux). A previous study[16] collected illuminance data from 63 intersections in Minnesota and reported that an increase in 1-lux of average intersection illuminance resulted in a 9% reduction in nighttime crash rates. The study also reported that an increase in 1-lux in average illuminance at lighted intersections was associated with a reduction in nighttime crashes by 20%.

While these studies show that an increase in the light levels is associated with a decrease in the night crash frequency or the ND crash ratio, research on determining the light level beyond which any increase will not result in a decrease of the night crash frequency or ND crash ratio or rate has yet to be reported. Determining this light level can help to illuminate intersections at the appropriate level without over-lighting, which results in energy wastage and glare.

In order to determine the appropriate light level at intersections, a new systems-level approach to intersection lighting design was introduced by VTTI.[17] In this study, three intersection lighting designs were evaluated (Lighted Approach, Lighted Box, and Lighted Approach and Box). This evaluation was done on the basis of drivers' nighttime visual performance, using the objective measure of detection distance for targets located at the entrances, exits, and middle of pedestrian crosswalks at intersections. The results indicate that the design illuminating the intersection box offered better visual performance and had fewer missed target detections, with visual performance plateauing between 7 and 10 lux average intersection illuminance. A subjective ratings analysis[18] was also conducted, which revealed that the lighting design illuminating the intersection box had the highest levels of perceived target and intersection visibility and the lowest ratings of glare. In this configuration, perceived visibility plateaued between 7 and 10 lux of average intersection illuminance.

Another study also examined the effect of intersection lighting design on subjective ratings of visibility.[19] Subjective ratings of visibility were obtained from drivers who were exposed to three different intersection lighting layouts (or configurations), each with three levels of illumination (5, 10, and 15 lux). The three intersection layouts were based on the part of the intersection that was illuminated, and used the following three configurations: approach, corner (or box), and both approach and corner. Drivers rated five statements—"visibility," "danger to pedestrian," "ease of driving," "brightness," and "safety"—on Likert-type scales (1 to 5). A mean rating higher than 3 (or the "neutral" anchor) was used as a measure of effectiveness of an intersection's lighting design. In this study, increases in illuminance levels resulted in higher subjective ratings of visibility. With illuminance levels higher than 10 lux, mean ratings of pedestrian visibility were higher than 3 on the Likert-type scale in all three layouts. The study also found that ratings (all statements including pedestrian visibility) depended on the illuminance level. At the 15-lux illuminance level, the lighting configuration illuminating the approach and corner was rated highest. At the 10-lux and 5-lux illuminance levels, the configuration illuminating the approach was rated the highest. The authors concluded that the approach lighting layout should be used to maintain a mean roadway surface luminance of 10 lux, but if a higher level of average roadway illuminance is needed, then both approach and corner illumination should be used. This study also analyzed the optical properties of intersections where accidents occurred frequently. The results indicate that a uniformity ratio of illuminance of 0.4 makes intersections safer.

One purpose of intersection lighting is to reduce or prevent fixed-object crashes and secondary crashes they cause. Based on naturalistic driving events, previous studies[20,21] found a number of factors could contribute to fixed-object crashes during nighttime, including:

- Unconventional intersection layout features such as Y intersection and off-set left-turn lanes;
- Channelization devices at intersections that are not well lit, such as raised/depressed medians and post-mounted delineators; and
- Intersections on horizontal or vertical curves where sight distance to the intersection is reduced.

Properly designed lighting at such locations may help drivers to identify the potential hazards during the night and therefore reduce fixed-object crashes and potential secondary crashes they cause.

Safety Effects of Lighting at Midblock Crosswalks

Very few studies have been conducted in the area of crosswalk lighting and pedestrian visibility. One of the earliest studies conducted on pedestrian visibility at intersection crosswalks reported that increasing the intensity of light resulted in an increased in the time available for drivers to respond and recommended at average horizontal illuminance of 75 lux for crosswalks.[22] A before-and-after study conducted in Israel reported that lighted crosswalks had significantly lower nighttime pedestrian crashes.[23]

Pedestrian visibility studies conducted in Switzerland showed that rendering pedestrian in positive contrast (i.e. pedestrians are illuminated from the approach side rendering them brighter than the background) reduced the pedestrian-vehicle crashes by two-thirds.[24] Pedestrians can be rendered in positive contrast by increasing the vertical illuminance on them. The lighting design that rendered the pedestrians in positive contrast was compared to existing design in a field test, which showed that the crosswalk lighting design that rendered the pedestrians in positive contrast provided significant benefits over the conventional one.[25] The benefits of positive contrast on pedestrians was also reported in research conducted in realistic nighttime environments. Edwards measured detection distances of pedestrians under different levels of vertical illuminance reported that increasing the vertical illuminance on pedestrians increases the distance at which drivers can detect them.[26]

All the above-mentioned research used fixed overhead lighting to illuminated pedestrian crosswalks, some of the recent research in pedestrian visibility used to bollard type lights to illuminate pedestrian crosswalks. A recent study exploring different ways to illuminate crosswalks for potential improvements in pedestrian visibility and safety.[27] The study consisted of photometric simulations various crosswalk lighting and surveying individuals with expertise in fields of transportation, transit operations and public safety specifically to analyze the visual performance, glare and economic impacts of each lighting system. The responses concluded that the bollard-based lighting for crosswalks increased pedestrian lighting and reduced costs. In a field test where four pedestrian crosswalk lighting configurations were evaluated along with a bollard lighting system, Bullough et al reported that the bollard-based system resulted in the shortest identification times of targets (adult- and child-sized black silhouettes).[28] A later study also reported demonstrations conducted at two crosswalks in Aspen, Colorado and Schenectady, New York over a two night period.[29] In the demonstrations, LED, bollard-level lighting was installed to illuminate the studied crosswalks. The findings showed the subjective judgements to be consistently generally positive concluding that the light levels needed for visibility can be achieved without excessive glare or other negative consequences through bollard-level lighting.

There are some differences in the light levels required for optimum pedestrian visibility in crosswalks, and these depend on the approach used for lighting of pedestrians in crosswalks. For example, a study used conventional overhead lighting for illuminating crosswalks reported that a vertical illuminance level of 20 lux at a height of 1.5 meters (5 feet) from the road surface resulted in good driver visual performance at midblock crosswalks.[26] Another study using bollard lighting system to illuminate a crosswalk reported that a vertical illuminance of at least 10 lux on the pedestrian at a height of 0.9 meters (3 feet) is required to increase contrast and thereby visibility.[30]

It is important to note that pedestrian visibility in bollard based lighting has never been directly compared to overhead lighting in realistic roadway conditions where the drivers approached the crosswalk at speed. Further, bollard-based lighting might increase transient glare for drivers approaching the crosswalk, however, glare control could be improved through use of louvers or baffles. Another disadvantage of the bollard-based lighting is that in involves placing additional fixed objects adjacent to the roadway that will increase the risk of drivers crashing into the bollard-based lights.

Lighting Standards and Informational Sources

The safety effects of lighting at intersections have been given special consideration by both the Illumination Engineering Society (IES) and the CIE. These organizations have recommended minimum lighting levels for intersections, with specific levels depending on a number of factors such as roadway classification, speed, traffic volume, and traffic composition. The light levels recommended for intersections, though, differ substantially from those recommended for roadways. In addition to IES and CIE, several information sources are available for lighting roadways from the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The intersection lighting guidance and warrants described by these agencies do not obligate state or local governments to provide lighting but do give important insight on when to investigate lighting and how to improve safety at an intersection. Lighting standards, guidelines, and warrants from each agency are discussed in the following sections.

Illuminating Engineering Society

The ANSI/IES RP-8-18[31] is the most current report IES published on roadway lighting and guidelines. It states that typically about 50% of accidents in urban areas, excluding freeways, occur at intersections. To help reduce this crash rate, IES defines the recommended minimum lighting values for intersections, depending on determining factors such as speed, traffic volume, and traffic composition. Specifically, IES warrants that the lighting level at an intersection should be equal to the sum of the lighting levels of each road at the intersection. The warranted lighting levels by IESRP-8-18 are illustrated in the table below.[31]

Table A1. IES Recommended Illuminance Levels at Intersections

Functional Classification	Average illumination by pedestrian volume (lux)	Uniformity Ratio
Major/Major	18 - 34	3
Major/Collector	15 - 29	3
Major/Local	13 - 26	3
Collector/Collector	12 - 24	4
Collector/Local	10 - 21	4
Local/Local	8 - 18	6

In Table A1, the functional classification refers to the classification of the two streets involved in the intersection. The classification of major, collector, or local is dependent on the streets’ average daily traffic (ADT) measured as vehicles per day. Major streets have an ADT of over 3,500; local streets have an ADT of less than 1,500; and collector streets fall in between these values. From the functional classification of an intersection, IES warrants the recommended illuminance values at intersections of continuously lighted streets. For other traffic conflict areas, such as midblock pedestrian crossings, the report recommends a 50% higher illuminance than that recommended for the street.

IES's guidelines on lighting design recommend horizontal and vertical illuminance for pedestrian areas, such as midblock crossings, and specify horizontal illuminance for intersections. For midblock crosswalks, the IES RP-8-18 recommends a vertical illuminance of 20 lux measured at a height of 1.5 meters (5 feet) with the light meter orientated towards the approaching vehicle. This specification is based on the research conducted during the development of the FHWA's *Informational Report on Lighting Design for Midblock Crosswalks*.[32] This report also recommends that pedestrians be rendered in positive contrast in order to aid detection by approaching drivers and that light poles be placed in front of the crosswalk in the direction of a vehicle's approach (see Figure A1).

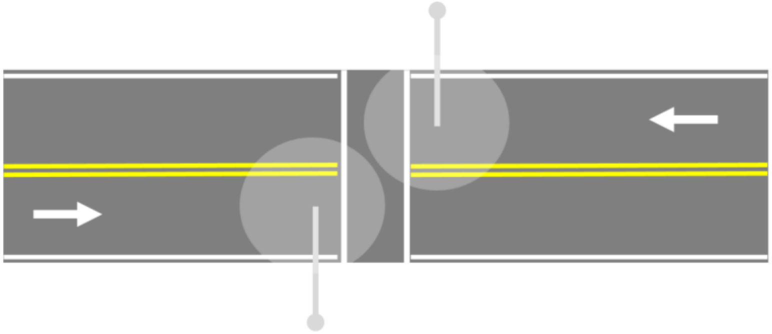


Figure A1. Recommended Midblock Crosswalk Lighting Layout from FHWA's Informational Report on Lighting Design for Midblock Crosswalks

International Commission on Illumination

The CIE is an independent, international organization devoted to the exchange of information on all scientific topics related to light, lighting, vision, etc. A CIE report discusses roadway lighting for motorists and pedestrian traffic.[33] In the report, the CIE recommends that lighting in conflict areas (intersections) should reveal the entirety of the conflict area, including curb positions, roadway markings and directions, pedestrians, other road users, and any obstructions. The CIE categorizes intersection lighting levels into six classes, from class C5; providing the lowest level of illuminance, to class C0; providing the highest level of illuminance.

For this warrant, an intersection's lighting classification is determined by applying the appropriate weight to each scored parameter. The parameters considered in the warrant included:

- Speed with a weight of 0 – 3 where 0 is assigned to the low speed and 3 is assigned to the "very high" speed category.
- Traffic volume with a weight ranging between -1 for very low and 1 for very high.
- Traffic composition with a weight between 0 and 2 where 2 is assigned for traffic with a high mix of non-motorized users.
- Separation of carriageways with a weight score of 1 for no separation and 0 for separation.

- Ambient luminance with a weight between -1 and 1 where 1 indicates high ambient luminance.
- Visual guidance/traffic control with a weight score of 0 or 0.5 where 0.5 indicates poor visual guidance.

The sum of these weighted values is subtracted from the value 6 to determine the C lighting class:[33]

$$C = 6 - V_{ws}$$

Table A2 summarizes the recommended intersection lighting levels given an intersection's lighting class.[33]

Table A2. CIE Recommended Lighting Classes and levels for Intersections Based on Illuminance

Lighting Class	Average Illuminance in Lux
C0	50
C1	30
C2	20
C3	15
C4	10
C5	7.5

An important point to make is that CIE does not cover lighting design guidelines for midblock pedestrian crossings except for stating that they may require special consideration in design.

Federal Highway Administration

The *FHWA Lighting Handbook*[34] and FHWA *Design Criteria for Adaptive Roadway Lighting*[35] supplement the guidance provided by the IES and CIE. The *FHWA Lighting Handbook* gives guidance on intersection lighting justification by including various warranting methods. The lighting warrants described assist in evaluating intersections where the addition of lighting will maximize benefit based on FHWAs' defined intersection conditions and rating system. The handbook also states that the warrants should not be interpreted as an absolute indication of whether or not lighting is required and emphasizes that the need for lighting should be determined by sound engineering judgement.

FHWA's warrant system is a point system based on geometric, operational, environmental, and crash factors. A certain number of points is allotted based on how the intersection is categorized in each defined criterion. Each criterion is then assigned a weight due to its relative importance. The critical factors that determine the need for illumination and, therefore, hold the greatest weight are traffic volume, the presence of crosswalks, the extent of raised medians, and nighttime crashes. The point score indicates what level of lighting is recommended by the FHWA for each intersection: full intersection lighting, partial intersection lighting, or delineation lighting. The handbook describes full intersection lighting as illumination covering the intersection in a uniform manner over the traveled portion of the roadway. Partial intersection lighting is defined as the illumination of key decision areas, potential conflicts, and/or hazards within the intersection. Partial lighting can also guide motorists from one key point to the next. Delineation lighting is defined as lighting that marks an intersection’s location for approaching traffic, lights vehicles on a cross street, or lights a median crossing.

In summary, the more points an intersection is scored results in a greater illumination warrant. Regardless of the points allotted, the FHWA warrants full lighting to signalized intersections. The FHWA also approves some other warranting methods in determining lighting priority, such as using the point system in conjunction with a benefit/cost analysis or a simpler method developed by Preston and Schoenecker[36] for rural areas with functional classifications based on the traffic volume of the major street.

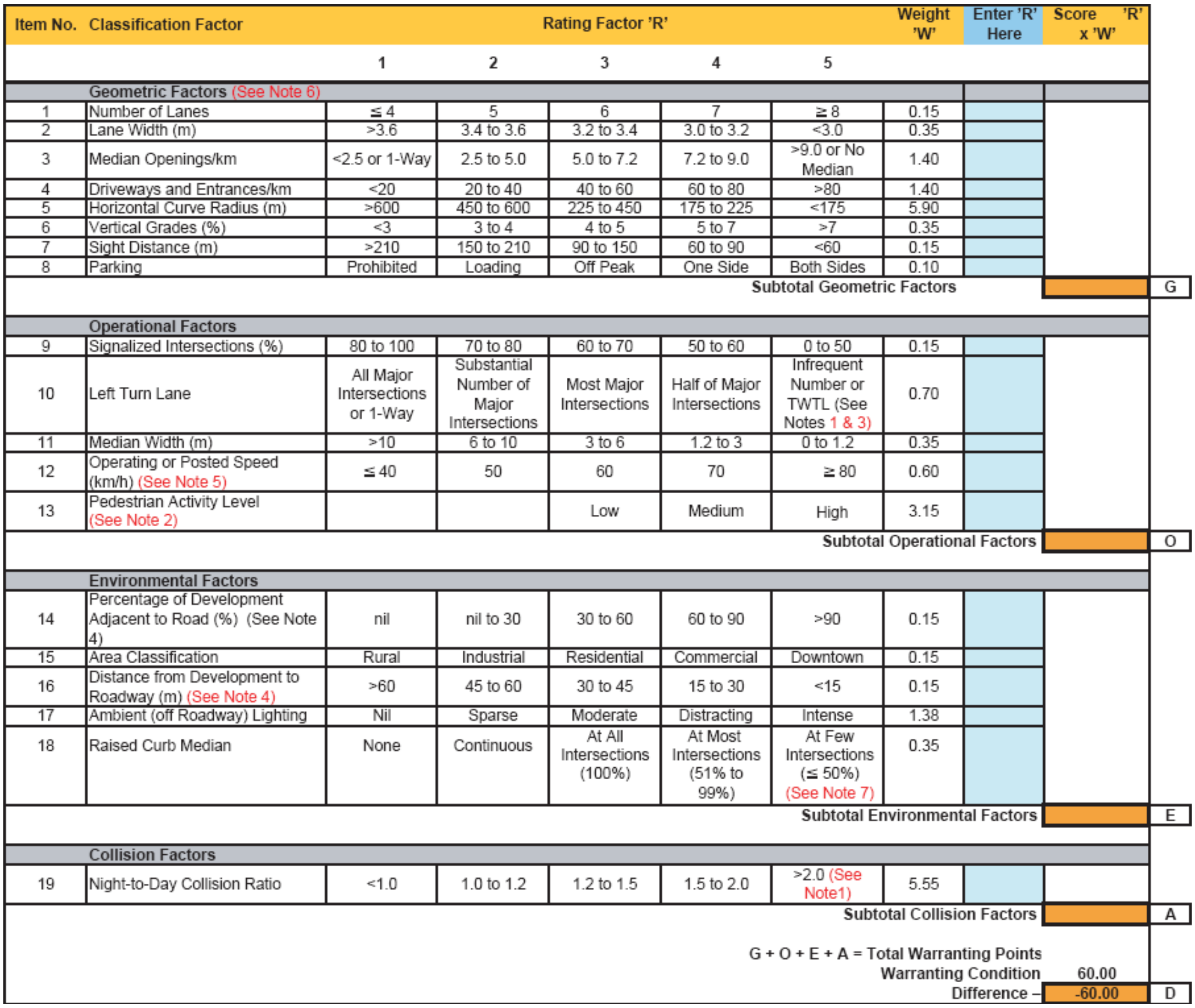
Another FHWA report, *Guidelines for the Implementation of Reduced Lighting on Roadways*[35], details methods for classifying highways and provides dimming specifications based on factors such as traffic volume, speed, and ambient light levels. However, adaptive lighting guidelines are not currently available for intersections or midblock crosswalks.

American Association of State Highway and Transportation Officials

AASHTO is an American standards agency that publishes specifications and guidelines and tests protocols that are used in highway design and construction throughout the country. The current AASHTO *Roadway Lighting Design Guide*[37] provides a general overview of U.S. lighting systems to guide state transportation departments and recommends minimum design parameters. Based on quantitative predictions using Crash Modification Factors (CMFs), AASHTO has concluded that when lighting is installed at intersections, nighttime injury crashes are predicted to be reduced by 38%, and nighttime pedestrian injury crashes reduced by 42%. From these results, along with other studies with similar data, AASHTO strongly recommends luminance or illuminance design methods. The range of recommended illuminances is from 2 lux to 17 lux, and luminances range from 0.2 cd/m^2 to 1.2 cd/m^2 depending on the roadway classification, land use, and pavement reflectance. For intersections, AASHTO recommends that key decision points and conflict points be illuminated. The AASHTO *Roadway Lighting Design Guide* also urges lighting designers to consider rendering the pedestrians at intersection crosswalks in positive contrast by placing lighting poles before the crosswalks or lighting the approach side of the crosswalk.

Transport Association of Canada (TAC) Guide for the Design of Roadway Lighting

The TAC *Guide for the Design of Roadway Lighting*[38] specifies warrants and lighting guidelines for roadways in Canada. TAC has a warranting system for intersection lighting that also forms the basis for the warranting method for intersections in the *FHWA Lighting Handbook*. This warranting system considers several factors in its approach, like geometric, operational, environmental, and collision factors (see Figure A). The light levels recommended for intersections in the TAC *Guide for Design of Roadway Lighting* are based on ANSI/IES RP-8. In addition, the TAC *Guide for the Design of Roadway Lighting* also specifies photometric calculation grids (Figure A2) and luminaire pole placement locations for lighted intersections. The vertical illuminance specifications for midblock crosswalks are also similar to the ANSI/IES RP-8 specification (20 lux at 1.5 meters).



Item No.	Classification Factor	Rating Factor 'R'					Weight 'W'	Enter 'R' Here	Score 'R' x 'W'	
		1	2	3	4	5				
	Geometric Factors (See Note 6)									
1	Number of Lanes	≤ 4	5	6	7	≥ 8	0.15			
2	Lane Width (m)	>3.6	3.4 to 3.6	3.2 to 3.4	3.0 to 3.2	<3.0	0.35			
3	Median Openings/km	<2.5 or 1-Way	2.5 to 5.0	5.0 to 7.2	7.2 to 9.0	>9.0 or No Median	1.40			
4	Driveways and Entrances/km	<20	20 to 40	40 to 60	60 to 80	>80	1.40			
5	Horizontal Curve Radius (m)	>600	450 to 600	225 to 450	175 to 225	<175	5.90			
6	Vertical Grades (%)	<3	3 to 4	4 to 5	5 to 7	>7	0.35			
7	Sight Distance (m)	>210	150 to 210	90 to 150	60 to 90	<60	0.15			
8	Parking	Prohibited	Loading	Off Peak	One Side	Both Sides	0.10			
						Subtotal Geometric Factors				G
	Operational Factors									
9	Signalized Intersections (%)	80 to 100	70 to 80	60 to 70	50 to 60	0 to 50	0.15			
10	Left Turn Lane	All Major Intersections or 1-Way	Substantial Number of Major Intersections	Most Major Intersections	Half of Major Intersections	Infrequent Number or TWTL (See Notes 1 & 3)	0.70			
11	Median Width (m)	>10	6 to 10	3 to 6	1.2 to 3	0 to 1.2	0.35			
12	Operating or Posted Speed (km/h) (See Note 5)	≤ 40	50	60	70	≥ 80	0.60			
13	Pedestrian Activity Level (See Note 2)			Low	Medium	High	3.15			
						Subtotal Operational Factors				O
	Environmental Factors									
14	Percentage of Development Adjacent to Road (%) (See Note 4)	nil	nil to 30	30 to 60	60 to 90	>90	0.15			
15	Area Classification	Rural	Industrial	Residential	Commercial	Downtown	0.15			
16	Distance from Development to Roadway (m) (See Note 4)	>60	45 to 60	30 to 45	15 to 30	<15	0.15			
17	Ambient (off Roadway) Lighting	Nil	Sparse	Moderate	Distracting	Intense	1.38			
18	Raised Curb Median	None	Continuous	At All Intersections (100%)	At Most Intersections (51% to 99%)	At Few Intersections (≤ 50%) (See Note 7)	0.35			
						Subtotal Environmental Factors				E
	Collision Factors									
19	Night-to-Day Collision Ratio	<1.0	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	>2.0 (See Note1)	5.55			
						Subtotal Collision Factors				A
						G + O + E + A = Total Warranting Points				
						Warranting Condition			60.00	
						Difference –			-60.00	D

Figure A2. Screenshot of intersection lighting warrants in TAC *Guide for the Design of Roadway Lighting*

Lighting Practices in the United States

To understand intersection lighting design practices in the United States, the research team conducted a thorough search and review of guidelines for the lighting of intersections in all 50 states and Washington, D.C. The search and review included investigating whether states have specific intersection lighting design guidelines and specific guidelines for rural versus urban intersections. The review also covered whether the guidelines included specific luminaire placement locations or light levels (illuminance or luminance) for intersections. Finally, the review also focused on whether the guidelines referred to specific standards documents (e.g., IES RP-8) or informational sources such as the *FHWA Lighting Handbook* or AASHTO *Roadway Lighting Design Guide*. This information is summarized in the following section.

In the U.S., 32 states have roadway lighting design guides with specific sections for intersection lighting. The remaining states do not have intersection-specific guidelines for lighting. Of the 32 states that have specific intersection-related lighting guidelines, 18 have different guidelines for urban versus rural intersections, whereas the other 14 do not differentiate between urban and rural locations for intersection lighting. Of the states that have specific intersection lighting guidelines, once again 18 had prescribed luminaire pole placement locations or lighting layouts for intersections. Twenty-two of the states that had intersection lighting guidelines also had specific lighting levels that were recommended.

There is wide variation in the way the states refer to specific standards or informational sources (see Figure A3). Four states (Colorado, Kansas, New Jersey, and New Mexico) refer to all three roadway lighting standards originating in the United States: IES RP-8, the *FHWA Lighting Handbook*, and the AASHTO *Roadway Lighting Design Guide*. Six states do not refer to any standards documents or informational sources. The most commonly used informational source is the AASHTO *Roadway Lighting Design Guide*, which is used by about 39% of states (or 20 states). Some states like Arizona and Maryland have their own specific lighting guideline documents. Maryland's lighting guidelines also refer to IES RP-8. Some states use a combination of two documents. The most common combination is the AASHTO *Roadway Lighting Design Guide* and IES RP-8, which is used by 10% of the states. Approximately 8% of the states just use either IES RP-8 or the *FHWA Lighting Handbook*.

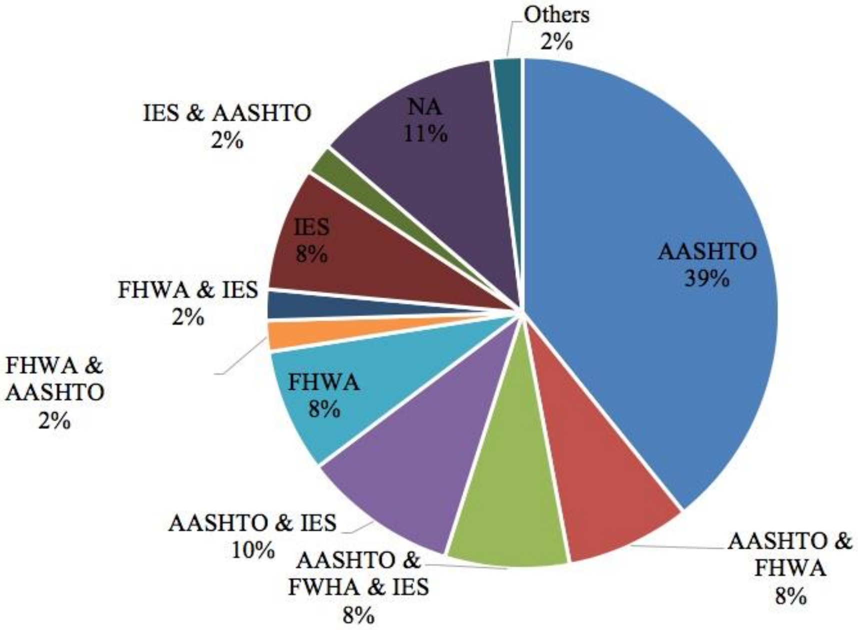


Figure A3. Pie Chart of Lighting Standards and Informational Source Usage in the United States

Gaps in Research

The literature review has shown that the following areas need to be addressed in order to develop comprehensive guidelines for intersections:

- CMFs for intersection lighting should be calculated based on measured lighting data from intersections.

- There is a need to develop a lighting level for intersections that results in optimal visibility and reduces nighttime crashes without over-lighting the intersection.
- Specifications of light levels and luminaire pole placements for intersections should be available for all intersection types and uniform so that departments of transportation can easily adopt them.

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