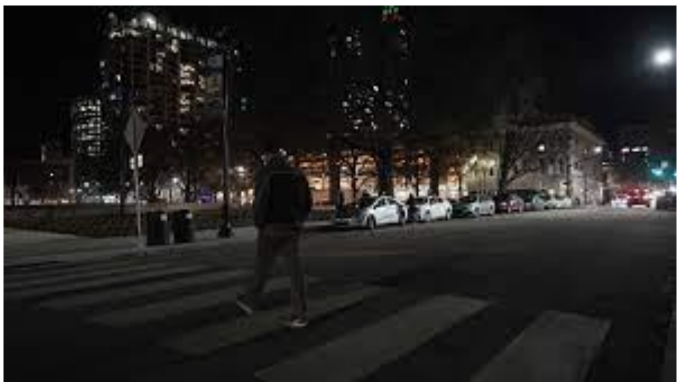
City of Alexandria Pedestrian Lighting Improvements Study

Final Report

(Task 4, August 23, 2024)



Submitted to:

City of Alexandria, VA

Funded by:

National Capitol Region

Transportation Planning Board

Submitted by:

KLS Engineering, LLC

and

WSP

City Project Manager:

Bryan Hayes

Consultant Team:

Leverson Boodlal, P.E., PMP, P.M. (KLS)

Paul Lutkevich, P.E., FIES (WSP)

Jeff Parker, P.E., PTOE (WSP)

Regis Stinson (WSP)

Kevin Chiang, P.E., (KLS)

Table of Contents

1. Background 4
2. Crash Data Analysis 4
3. Recent Lighting Upgrades 5
4. Priority Areas 6
4.1 Priority Locations (5) 7
4.1.1 North Patrick Street at Madison Street 7
4.1.2 West Glebe Road at Elbert Avenue 8
4.1.3 North Van Dorn Street at West Braddock Road 9
4.1.4 North Van Dorn Street at Maris Avenue 10
4.1.5 South Pitt Street at Duke Street 11
5. Field Investigations and Analysis 12
5.1 Currently Available Lighting Criteria 12
5.2 North Patrick Street at Madison Street 15
5.3 West Glebe Road and Elbert Avenue 16
5.4 North Van Dorn Street at West Braddock Road 17
5.5 North Van Dorn Street at Maris Avenue 18
5.6 South Pitt Street at Duke Street 19
5.7 Example of Lighting Improvement 20
5.8 General Recommendations for Lighting 22
Appendix A. Literature Review Submitted under Task 2 (Separate Deliverable) 24

List of Tables

Table 1. List of All Sites with Possible Visibility-related Pedestrian or Bicyclist Crashes. 5
Table 2. Excerpt of Table 12-1 from RP-8-22 Intersection Lighting (2022). 13
Table 3. Recommended Vertical Illuminance Light Levels (lux/fc) 13

List of Figures

Figure 1. Map of Priority Lighting Evaluation Sites. 6
Figure 2. Diagram of North Patrick Street at Madison Street. 7
Figure 3. Diagram of West Glebe Road at Elbert Avenue. 8
Figure 4. Diagram of North Van Dorn Street at West Braddock Road. 9
Figure 5. Diagram of North Van Dorn Street at Maris Avenue. 10
Figure 6. Diagram of South Pitt Street and Duke Street. 11
Figure 7. Vertical and Horizontal Illuminance 12
Figure 8. Vertical Illuminance Readings (lux) in Crosswalks at Patrick and Madison Streets (A: Aerial view; B: Street / Approach View) - (Red arrow shows direction of travel and white arrows show light-meter orientation). 15
Figure 9. Vertical Illuminance Readings (lux) in Crosswalks at West Glebe Road and Elbert Avenue (A: Aerial View; B: Street / Approach View). 16
Figure 10. Vertical Illuminance Readings (lux) in Crosswalks at North Van Dorn Street and West Braddock Road (A: Aerial View; B: Street / Approach View). 17
Figure 11. Vertical Illuminance Readings (lux) in Crosswalks at North Van Dorn Road and Maris Avenue (A: Aerial View; B: Street / Approach View). 18
Figure 12. Vertical Illuminance Readings (lux) in Crosswalks at South Pitt and Duke Streets (A: Aerial View; B: Street / Approach View). 19
Figure 13. Example of Crosswalk Area with Insufficient Lighting (Measured vs. Visually Observed). 21

Table of Acronyms

ANSI	American National Standards Institute
E_{avg}	Average Illuminance
E_{min}	Minimum Illuminance
fc	foot candle
FHWA	Federal Highway Administration
GIS	Geographic Information System
IES	Institute of Education Sciences
LED	Light-Emitting Diode
NCHRP	National Cooperative Highway Research Program
PHB	Pedestrian Hybrid Beacon
RP	Recommended Practice
SR	Surround Ratio
VRU	Vulnerable Road Users

City of Alexandria Pedestrian Lighting Improvements Study Final Report

1. Background

This Final Report is designed to inform the City of Alexandria about recently developed lighting strategies to improve pedestrian and cyclist safety and how these strategies can be applied and implemented in areas considered higher safety risks. The overall project supports the City's Vision Zero efforts to eliminate traffic fatalities and severe injuries. The City conducted a roadway crash study in 2022 and found that more than 25 percent of fatal and severe crashes involved people walking, and 25 percent of these pedestrian crashes occurred at night and resulted in death or severe injury. The City anticipates using the lighting recommendations produced under this project to improve lighting and increase safety in future projects.

The report describes the methodology developed by the KLS Team to prioritize locations in the City and conduct field investigations and analysis to determine current lighting conditions with regard to pedestrian safety. The Team identified these locations by examining recent crash data, geographical distribution across the City, Geographic Information System (GIS) data regarding when Light-emitting Diode (LED) lighting upgrades occurred, and a desktop review of current site conditions. The priority areas may be candidates for upgrading current lighting or installing additional lighting.

2. Crash Data Analysis

The Team obtained crash data at the time of the study for the most recent five (5) years (January 2018 through June 2023) and studied it to identify crash locations on which to focus. During that same 5-year timeframe, the City of Alexandria reported 287 pedestrian crashes. Based on available data, 45 percent (128) of the 287 pedestrian crashes were categorized as nighttime crashes and 41 of those nighttime crashes occurred between 2021 and June 2023 (post-pandemic).

The City of Alexandria also reported 75 bicycle crashes from 2019 to June 2023. Based on the data, 30 percent (23) of the 75 bicycle crashes were categorized as nighttime crashes, and 10 of those crashes occurred between 2021 and 2023 (post-pandemic).

To select the study sites, the KLS Team reviewed nighttime pedestrian crash data and police report narratives. Locations were shortlisted based on whether the narrative mentioned visibility as a potential factor. Several of these locations were then eliminated because there appeared to be other site characteristics that could have contributed to the crash, including:

- Skewed intersection alignment,
- Unusual traffic control device configuration, or
- Obstructed sight lines.

3. Recent Lighting Upgrades

The City also provided GIS data identifying the approximate dates when the City updated streetlights to LED lighting. To further refine the list, other locations were eliminated because crashes occurred *before* the LED lighting updates. This presumes the LED lighting updates solved the previous visibility-related crash problem, as no visibility-related crashes were reported at these locations *after* the lighting upgrades. However, the City should continue to monitor locations removed from the initial list of crash sites, verify that LED lighting upgrades successfully prevented these types of crashes, and perform lighting safety-improvement studies at any of those locations where visibility-related pedestrian or bicyclist crashes occur in the future.

Table 1 shows all locations where possible visibility-related crashes were reported (based on the crash-report narratives), crash dates, dates when LED lighting upgrades were completed, and whether crash(es) occurred prior to LED lighting upgrades. Intersections in **bold type** indicate intersections located in the five (5) Priority Areas across the City.

Table 1. List of All Sites with Possible Visibility-related Pedestrian or Bicyclist Crashes.

Study Intersection (Map Link)	Crash Date(s)	Did the crash occur before the LED lighting upgrade? (Y/N)
Oronoco Street and North Street, Asaph Street	2/17/2018	Y (7/14/2022)
Duke Street and North Paxton Street	3/1/2018	Y (5/11/2020)
North Beauregard Street and North Morgan Street	12/19/2018	Y (8/7/2020–7/11/2022)
North Fairfax Street and Pendleton Street	3/21/2019	Y (10/11/2022–12/29/2022)
North Patrick Street and Madison Street	1/7/2019, **4/13/2022**	N (6/15/2021–1/12/2023)
Madison Street and North Henry Street	12/2/2019	Y (7/13/2020–1/12/2023)
Winston Court and Rayburn Avenue	2/6/2020	Y (2/9/2021)
Osage Street and Kenwood Avenue	3/12/2020	Y (9/29/2022)
Bellefonte Avenue and Dewitt Avenue	11/17/2021	Y (4/1/2022–11/15/2022)
North Van Dorn Street and West Braddock Road	2/3/2021	N (6/30/2020–8/29/2022)
North Van Dorn Street and Maris Avenue	4/13/2022	N (7/22/2020)
North Fayette Street and Braddock Place	6/21/2022	Y (6/16/2022–11/20/2023)
South Fayette Street and Prince Street	11/17/2022	Y (2/28/2023)
North Patrick Street and First Street	12/3/2022	Y (9/27/2022–1/12/2023)
Elbert Avenue and West Glebe Road	12/15/2022	N (5/10/2022)
West Glebe Road and Valley Drive	1/24/2018	Y (11/16/2021)
Stevenson Avenue and South Walker Street	7/12/2020	Y (11/17/2020)
Seminary Road and Library Lane	2/1/2017, 8/11/2016	Y (6/9/2020)
South Pitt Street and Duke Street	**8/30/2023**, 3/9/2020	N (11/29/2022)
Edsall Road and South Whiting Street	5/14/2019, 10/14/2018	Y (7/24/2020–11/17/2020)
Sanger Avenue and Knole / Essex Courts	11/22/2019	Y (10/4/2019–3/8/2021)

4. Priority Areas

Figure 1 identifies the five (5) Priority Areas — intersections where visibility-related pedestrian or bicyclist crash(es) occurred after completing LED lighting upgrades. As noted above, **Table 1** shows these locations in boldface type:

1. North Patrick Street and Madison Street,
2. West Glebe Road and Elbert Avenue,
3. North Van Dorn Street and West Braddock Road,
4. North Van Dorn Street and Maris Avenue, and
5. South Pitt Street at Duke Street.

Because visibility-related crashes occurred at these intersections after LED lighting upgrades, it is assumed that upgraded lighting at these locations did not resolve visibility issues. Therefore, the intersections should be reevaluated in detail to determine whether existing lighting meets standards and best practices and whether upgrades or additional lights are needed.

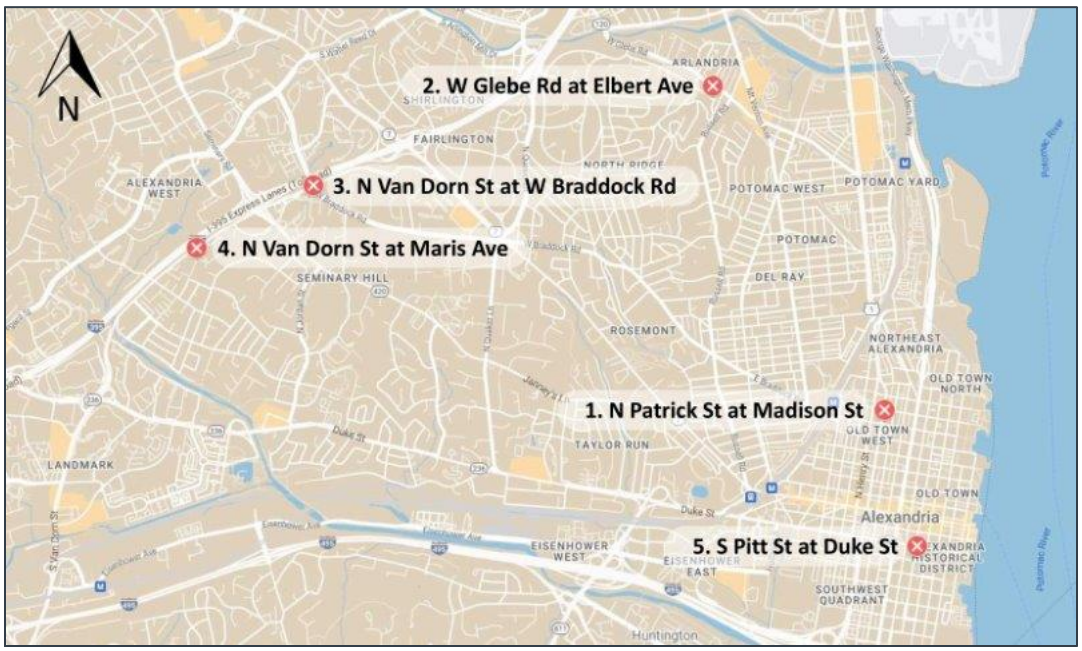


Figure 1. Map of Priority Lighting Evaluation Sites.

Figure 1 shows a map of the geographic spread of the five (5) Priority Areas across the City. Two (2) sites are located in the City's Old Town section, one (1) in the Arlandria neighborhood, and two (2) in Alexandria's West End. The following sections summarize the site characteristics of each Priority Area, including current lighting locations, nearby bus stop locations (if any), crosswalk locations, the position of the pedestrian or bicyclist within the intersection when struck by a vehicle (if known), and the striking vehicle direction of travel (if known).

Section 4.1 discusses the attributes and other unique characteristics of each priority location.

4.1 Priority Locations (5)

4.1.1 North Patrick Street at Madison Street

North Patrick Street and Madison Street is a four-leg signalized intersection; North Patrick Street is a one-way northbound principal arterial with two through lanes and one shared through-right lane.

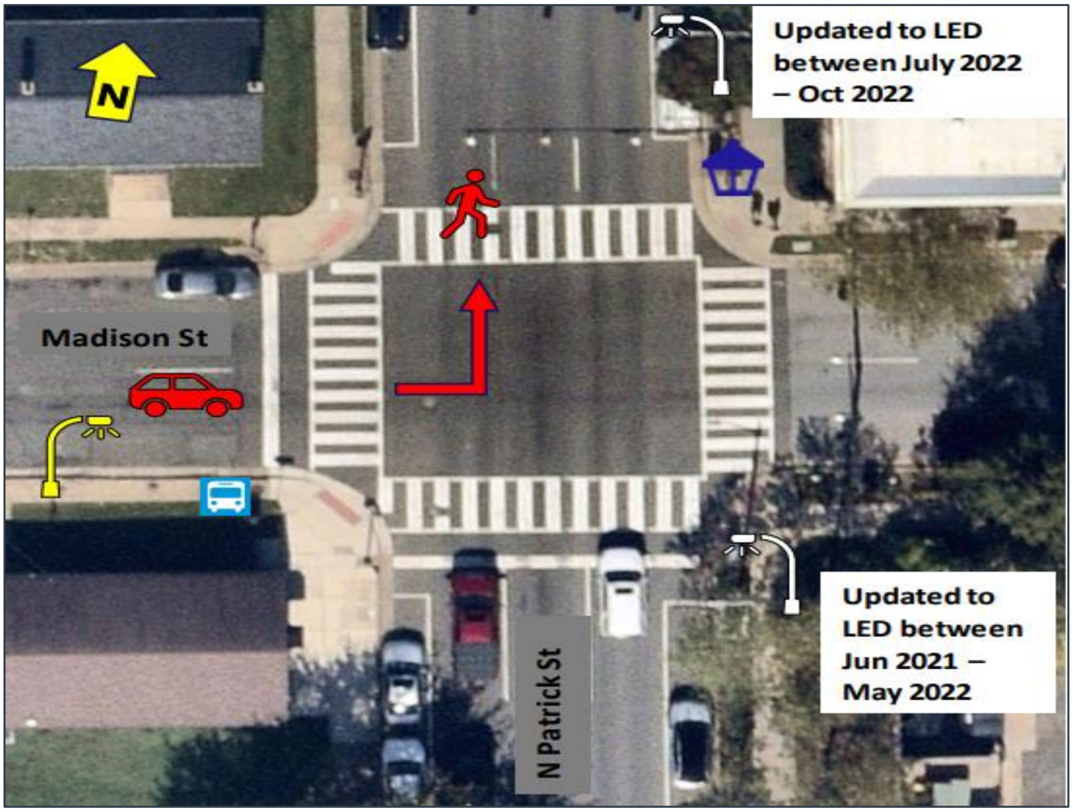


Figure 2. Diagram of North Patrick Street at Madison Street.

Madison Street is a one-way eastbound local road with one shared though left lane and one through lane. The traffic signal has no protected left-turn phases. A bus stop is located on Madison Street in the southwest quadrant of the intersection. There are high-visibility ladder crosswalks with pedestrian signals across all four legs of this intersection; however, the desktop review of this location (using historical Google Street View imagery) shows that these high-visibility crosswalks were installed after the date of the noted pedestrian crash at this location. There are three existing light poles near the intersection: Two along the east side of North Patrick Street and one on the south side of Madison Street. Both lights along North Patrick Street have been updated to LED. See **Figure 2** for schematic of the referenced reported crash and intersection attributes.

4.1.2 West Glebe Road at Elbert Avenue

The intersection of West Glebe Road and Elbert Avenue is a three-leg unsignalized intersection with free movements along West Glebe Road and a STOP sign on Elbert Avenue. West Glebe Road is an east-west minor arterial with two travel lanes each direction: Westbound has a through lane plus a shared through/right-turn lane; eastbound includes a through lane and a shared through/left-turn lane. Elbert Avenue is a two-way local road, north of West Glebe Road. The curb-to-curb width on Elbert Avenue is approximately 26 ft, with no centerline markings, and parallel parking is allowed along both sides of the street.

Figure 3. Diagram of West Glebe Road at Elbert Avenue.

The nearest bus stops are along westbound West Glebe Road, approximately 175 ft east of the intersection and along eastbound West Glebe Road, approximately 315 ft west of the intersection. There is a marked high-visibility ladder crosswalk across Elbert Avenue on the north side of the intersection (which was present on the date of the noted crash); however, the nearest marked crosswalk across West Glebe Road is located about 400 ft west of the intersection at the signalized intersection of Old Dominion Drive. There is one existing pedestal light pole along West Glebe Road on the south side of the intersection, opposite Elbert Avenue. This light was updated to LED in May 2022. See **Figure 3** for a schematic of the referenced reported crash and intersection attributes.

4.1.3 North Van Dorn Street at West Braddock Road

The intersection of North Van Dorn Street and West Braddock Road is a four-leg signalized intersection. Both streets are classified as minor arterials. The traffic signal has protected/permissive left-turn phasing in all directions. Each approach has a separate left-turn lane, and the eastbound and westbound approaches each have a through lane plus a shared through/right-turn lane. The northbound approach has a through lane plus a yield-controlled channelized right-turn lane; the southbound approach has a shared through/right-turn lane.

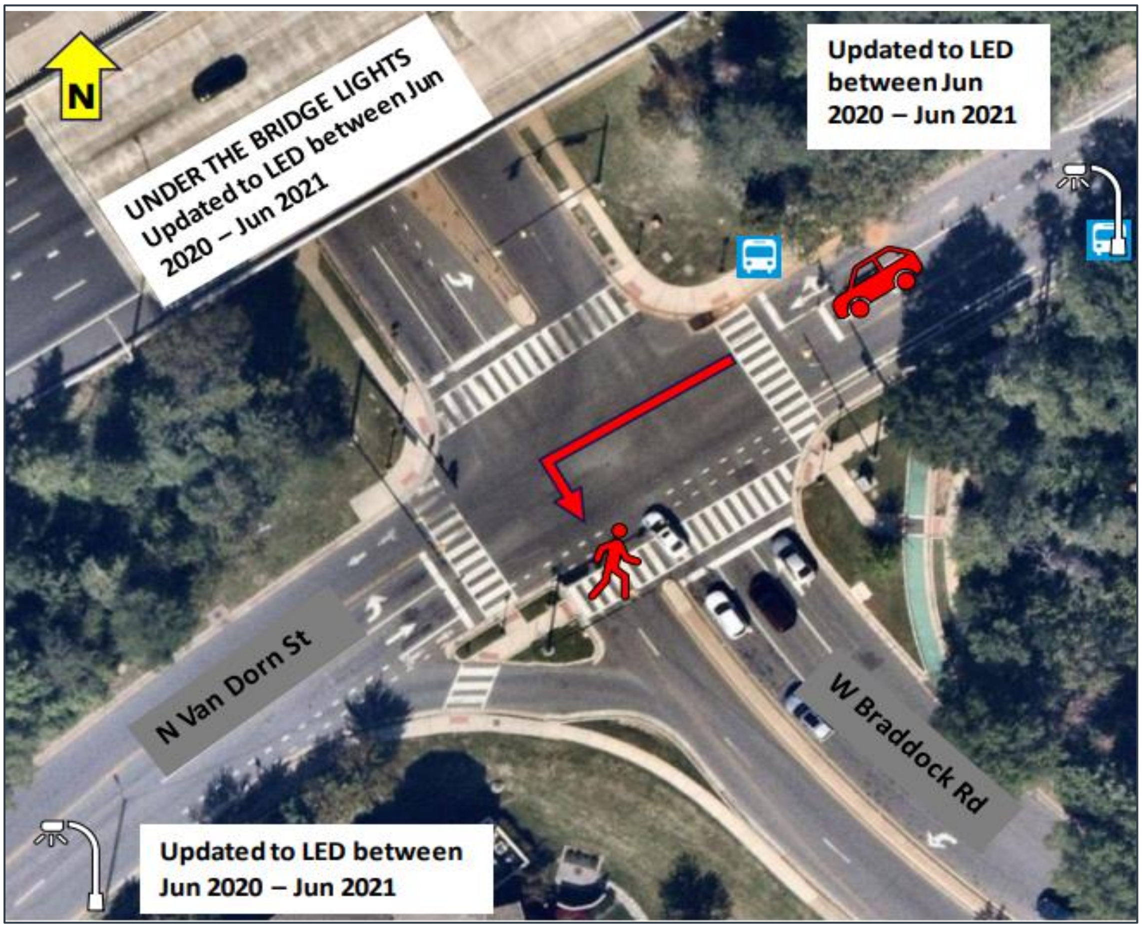


Figure 4. Diagram of North Van Dorn Street at West Braddock Road.

A bus stop is located along southbound North Van Dorn Street in the northwest quadrant of the intersection, and along northbound North Van Dorn Street about 170 ft north of the intersection. High-visibility ladder crosswalks across all four legs of the intersection have been in place since at least 2014, according to historical Google Street View imagery. There is no street lighting at this intersection. The nearest lights along North Van Dorn Street are about 140 ft north and south of the intersection. There are two lights along West Braddock Road — approximately 170 ft east of the intersection and pole-mounted underpass lighting beneath I-395 beginning at about 80 ft west of the intersection. See **Figure 4** for schematic of the referenced reported crash and intersection attributes.

4.1.4 North Van Dorn Street at Maris Avenue

The intersection of North Van Dorn Street and Maris Avenue is a three-leg intersection with a STOP sign on Maris Avenue and a Pedestrian Hybrid Beacon (PHB) along North Van Dorn Street. Traffic along North Van Dorn Street is free-flowing when the PHB is dark. The PHB remains dark until activated by a pedestrian needing to cross North Van Dorn Street. The activated PHB displays flashing yellow, then steady yellow, then steady red, then a flashing red signal. Approaching vehicles must stop and remain stopped during steady red; they may proceed only during the flashing-red interval. Pedestrians receive a walk signal during the steady-red interval for vehicles. It is important that pedestrians watch for vehicles turning from Maris Avenue — turns are permitted after stopping at the STOP sign and if traffic is stopped along North Van Dorn Street. Vehicles must still yield to any pedestrians crossing North Van Dorn Street.

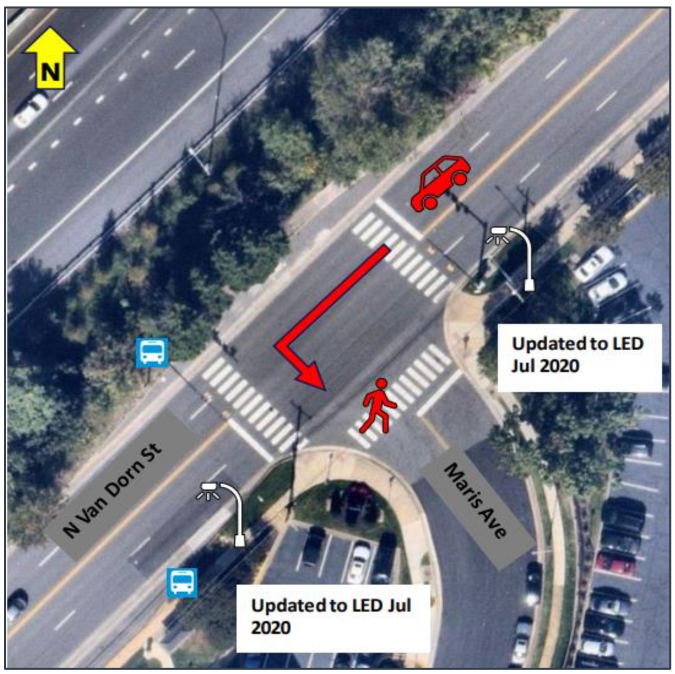


Figure 5. Diagram of North Van Dorn Street at Maris Avenue.

There are two travel lanes in each direction along North Van Dorn Street. Southbound is a through lane plus a shared through/left-turn lane; northbound is a through lane plus a shared through/right-turn lane. Maris Avenue is 44 ft wide from curb-to-curb with a double yellow centerline. No parking is allowed along Maris Avenue within the 70 ft of the nearest intersection. This allows for two unmarked approach lanes at the STOP sign. Bus stops are located along southbound North Van Dorn Street on the south side of the intersection opposite Maris Avenue and along northbound North Van Dorn Street just south of the intersection. There are high-visibility longitudinal-bar crosswalks across all three legs of the intersection, which have been in place since at least 2019, according to historical Google Street View imagery. Streetlights at this intersection are located on the southeast and northeast corners, but there are no lights on the west side of North Van Dorn Street. See **Figure 5** for schematic of the referenced reported crash and intersection attributes.

4.1.5 South Pitt Street at Duke Street

The intersection of South Pitt Street and Duke Street is a four-leg unsignalized all-way STOP-controlled intersection. Duke Street is a two-way minor arterial with a double-yellow centerline, one travel lane per direction, and parallel parking on both sides of the street. South Pitt Street is a two-way local road with no yellow centerline and there is parallel parking on both sides of the street. There are no bus stops near this intersection. Currently, transverse crosswalks are across all four legs of this intersection. There are two existing light poles near the intersection — one on the southwest corner and one on the northeast corner. Both lights have been updated to LED. See **Figure 6** for schematic of the referenced reported crash and intersection attributes.

Figure 6. Diagram of South Pitt Street and Duke Street.

5. Field Investigations and Analysis

The KLS Team evaluated current lighting recommendations for the five test locations and conducted nighttime visits to each Priority Area to measure current lighting levels and observe traffic operations.

5.1 Currently Available Lighting Criteria

Industry standards for roadway lighting have recently increased focus on lighting systems to benefit the visibility of Vulnerable Road Users (VRU). Horizontal roadway illuminance is the amount of light falling on the roadway surface; vertical illuminance is the amount of light falling on a vertical surface, such as a pedestrian (**Figure 7**). The major areas of new criteria include adding vertical illuminance recommendations for crosswalks and sidewalks, and a criteria for the area adjacent to the roadway travel lanes defined as Surround Ratio (SR). The vertical illuminance criteria for pedestrians in the crosswalks is the most applicable for the identified priority test sites.

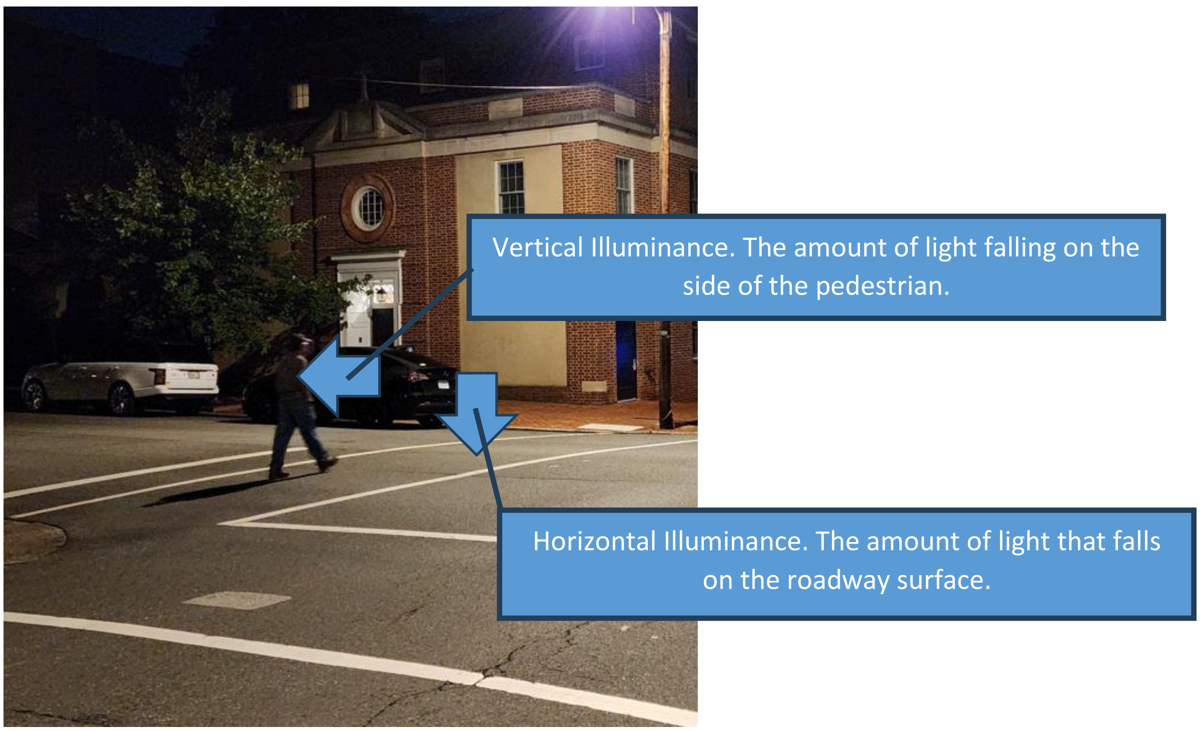


Figure 7. Vertical and Horizontal Illuminance

The Institute of Education Sciences (IES) RP-8-22, *Recommended Practice: Lighting Roadways and Parking Facilities,* recommends the vertical illuminance value be equal to the horizontal illuminance values for crosswalk lighting at intersections. These values are included in the **Table 2** excerpt from RP-8-22 shown below. In this Table, the functional classification column shows the classifications for the first intersecting street/second intersecting street. Illuminance criteria are shown as lux/foot candle (fc) based on functional classification and pedestrian activity level. Uniformity is shown as the ratio of average illuminance to minimum illuminance (E_{avg}/E_{min})

Functional Classification	Pedestrian Activity Level Classification			E_{avg}/E_{min}
	High	Medium	Low	
Major/Major	34/3.2	26/2.4	18/1.7	3.0
Major/Collector	29/2.7	22/2.0	15/1.4	3.0
Major/Local	26/2.4	20/1.9	13/1.2	3.0
Collector/Collector	24/2.2	18/1.7	12/1.1	4.0
Collector/Local	21/2.0	16/1.5	10/0.9	4.0
Local/Local	18/1.7	14/1.3	8/0.7	6.0

Table 2. Excerpt of Table 12-1 from RP-8-22 Intersection Lighting (2022) — Pavement Illuminance Criteria (Both Horizontal and Vertical) for Full Intersection Lighting (lux/fc, 1 fc = 10.764 lux))[1]**.**

Selecting the appropriate lighting level is based on the roadway classification of the intersecting streets. From a lighting standpoint, this can sometimes be subjective and even RP-8-22 has conflicting definitions for classifying roadways depending on the section of the document used. Also, RP-8 only uses three classification types for roadways — Major, Collector, and Local, so the selected roadway classification needs to relate to one of these classifications. **Table 3** below presents the recommended light levels for the five sites being studied based on the classification definitions (which uses traffic volumes) included in RP-8 Chapter 12 and assuming medium pedestrian activity.

Site	RP-8, Chapter 12 Definition	Lux/fc Value
North Patrick Street and Madison Street	Major / Local	20/1.9
Elbert Avenue and West Glebe Road	Local / Major	20/1.9
North Van Dorn Street and West Braddock Road	Major / Major	26/2.4
North Van Dorn Street and Maris Avenue	Major / Local	20/1.9
South Pitt Street and Duke Street	Collector / Major	22/2.0

Table 3. Recommended Vertical Illuminance Light Levels (lux/fc) for Selected Sites.

These recommended values can be compared against the lighting levels measured during the field investigations. The Team used an illuminance meter to measure light levels at a height of approximately 1.5 meters, and aimed in the direction of the approaching vehicle. This measurement essentially

[1] This study does not address Midblock crosswalks.

indicates how much light is being placed on the pedestrian in the crosswalk from the viewing direction of the driver.

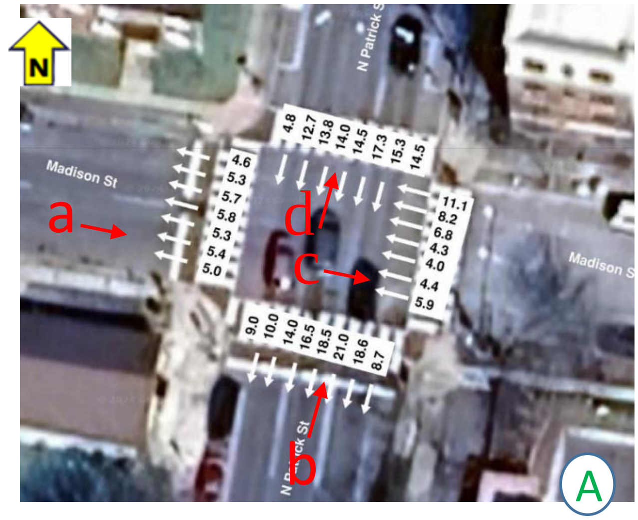
Note: Lighting recommendations for intersections and crosswalks are under review by the IES standards committees, as well as ongoing FHWA research. Current consensus is the values that have historically been included in the standards are likely higher than they need to be. The lighting levels discussed in this report are appropriate in the 10 lux to 20 lux range.

5.2 North Patrick Street at Madison Street

Based on RP-8-22, the recommendation for this intersection would be 20 vertical lux.

The crosswalk at the reported crash location is lit to approximately 13.4 lux.

Observationally, the intersection seems adequately lit. One reason for this is that high vertical illuminance on adjacent buildings helps increase contrast and visibility. Because of the likelihood of future adjustments in current recommendations to between 10 and 20 lux, additional lighting may not affect safety as the current lighting levels fall within this range.



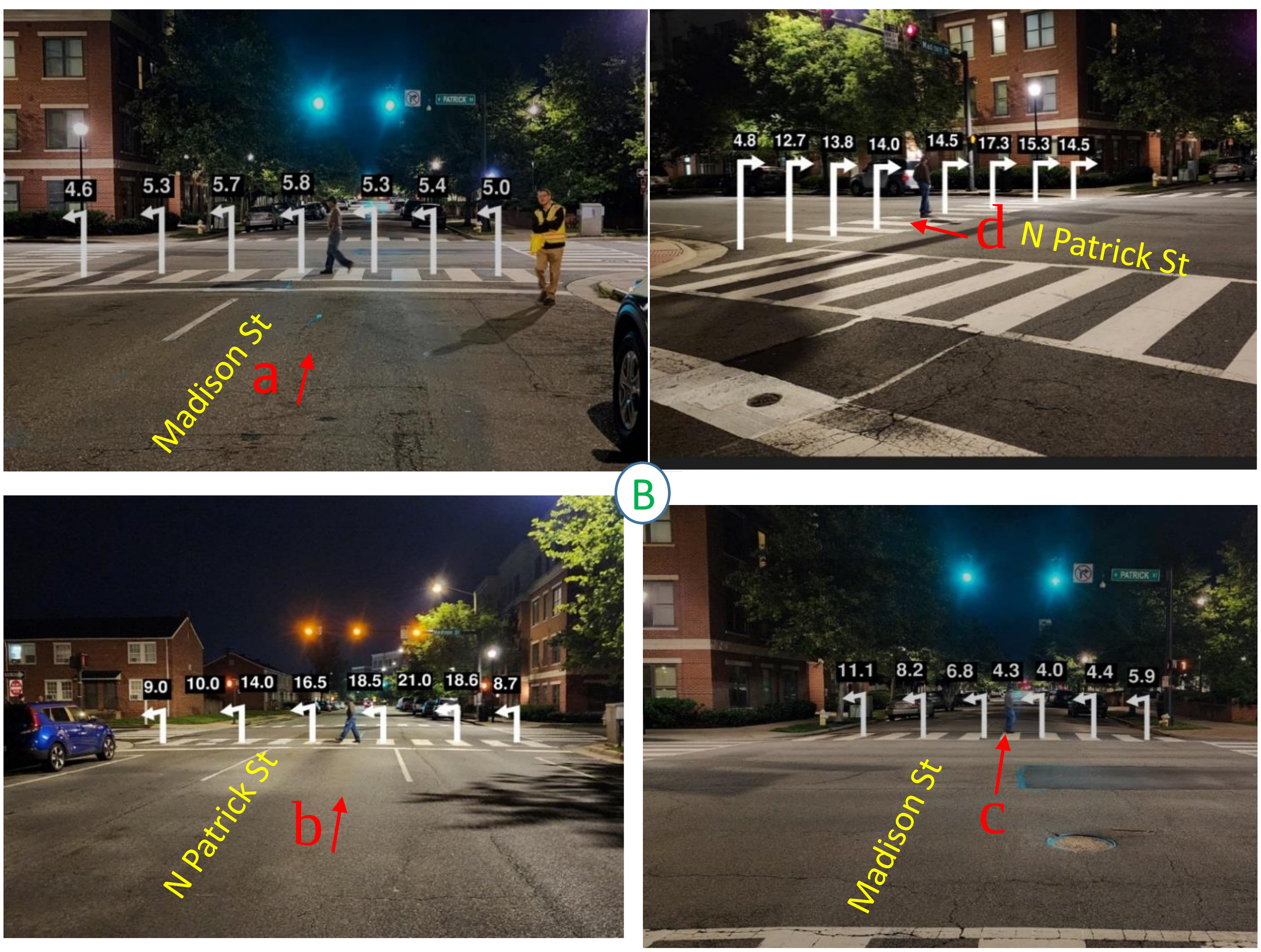


Figure 8. Vertical Illuminance Readings (lux) in Crosswalks at Patrick and Madison Streets (A: Aerial view; B: Street / Approach View) - (Red arrow shows direction of travel and white arrows show light-meter orientation).

5.3 West Glebe Road and Elbert Avenue

Based on RP-8-22, the recommended lighting level for this intersection would be 20 lux.

The crosswalk at the reported crash location is lit to approximately 7.7 lux.

Pedestrians in the crosswalk on Elbert Avenue are framed by a relatively dark background. There are also bus stops nearby that could generate higher pedestrian volumes. An additional complication for vehicles turning left onto Elbert is having to cross two travel lanes. Because of the lower lighting levels in the crosswalk and the items previously discussed, additional lighting may be an element to enhance pedestrian visibility at this location. One option could be doubling the output of the current lighting. However, the risk in this solution would create a light trespass issue so would not be recommended. Another possible solution is a change in the type and distribution of the lighting on the utility pole located at the intersection to direct most of its light toward the crosswalk. *The most straightforward solution, however, would be to add lights at each corner on the approach side of the crosswalk. Design installation should meet IES RP-8 standards*.

Figure 9. Vertical Illuminance Readings (lux) in Crosswalks at West Glebe Road and Elbert Avenue (A: Aerial View; B: Street / Approach View).

5.4 North Van Dorn Street at West Braddock Road

Based on RP-8-22, the recommended lighting level for this intersection would be 26 lux. The crosswalk at the reported crash location is lit to approximately 1.4 lux.

This intersection is essentially unlit with illuminated areas around it creating further visibility issues at the intersection. Considering the bike route along the road and nearby bus stops, intersection lighting with appropriate crosswalk lighting should be a consideration. *Lighting the intersection would include the approach roads and can add 8 to 12 luminaires to the existing infrastructure.*

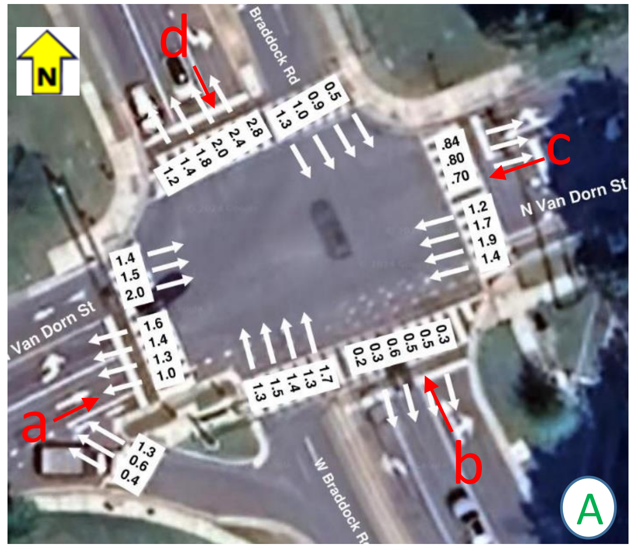


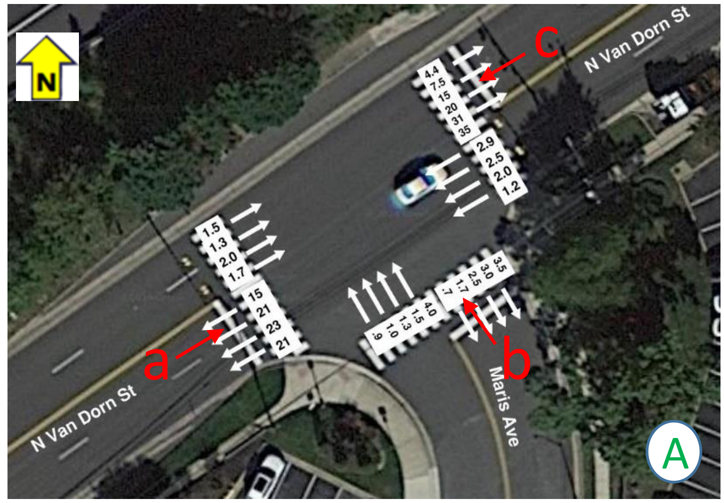
Figure 10. Vertical Illuminance Readings (lux) in Crosswalks at North Van Dorn Street and West Braddock Road (A: Aerial View; B: Street / Approach View).

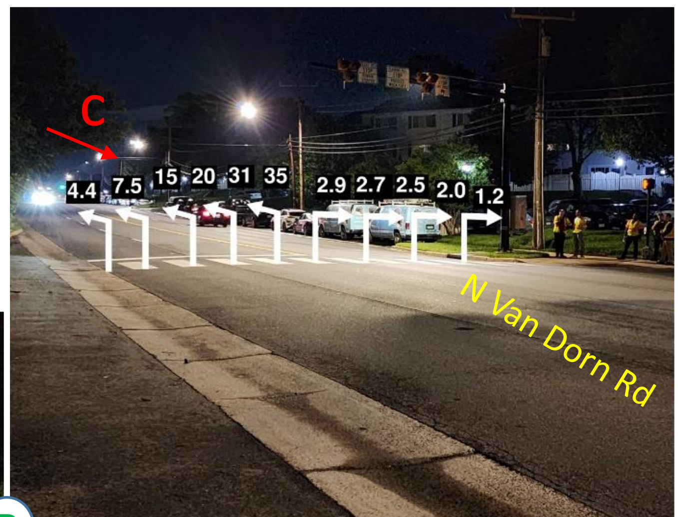
5.5 North Van Dorn Street at Maris Avenue

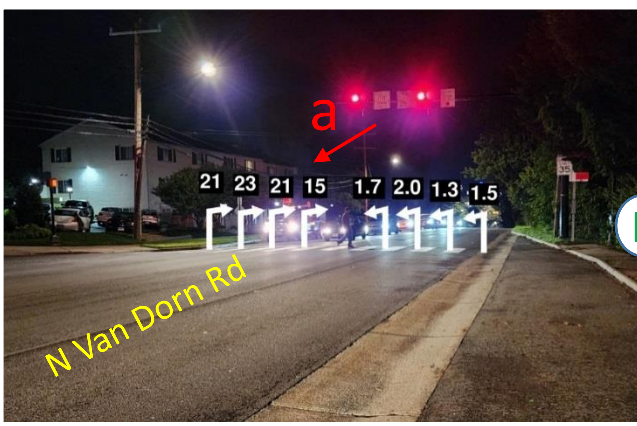
Based on RP-8-22, the recommended lighting level for this intersection would be 20 lux.

The crosswalk at the reported crash location is lit to approximately 1.7 lux.

This intersection has bus stops at and near the intersection. There are also PHBs located at the crosswalks on Van Dorn Street. The lighting levels along Van Dorn Street appear adequate. The lighting at the crosswalk on Maris Avenue appears low. Given the possibility of higher pedestrian activity in this area and pedestrians exposed to vehicles making turns from Van Dorn, adding lighting may be a consideration. An option would be an additional light, as **Section 5.7** discusses.







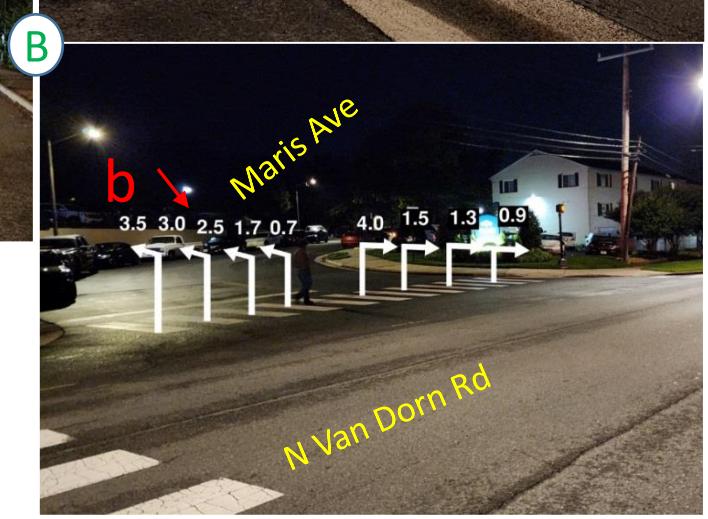


Figure 11. Vertical Illuminance Readings (lux) in Crosswalks at North Van Dorn Road and Maris Avenue (A: Aerial View; B: Street / Approach View).

5.6 South Pitt Street at Duke Street

Based on RP-8-22, the recommended lighting level for this intersection would be 22 lux. The crosswalk at the reported crash location is lit to approximately 3.5 lux.

This intersection is four-way STOP controlled. There is also relatively high vertical illuminance on surrounding buildings, which helps visibility in this area. Because of the STOP control, the vertical brightness and the additive effect of headlights stopped at a relatively short distance from the crosswalks, this intersection could be considered a lower priority for additional lighting.

Figure 12. Vertical Illuminance Readings (lux) in Crosswalks at South Pitt and Duke Streets (A: Aerial View; B: Street / Approach View).

5.7 Example of Lighting Improvement

This section includes an example of how to improve lighting and bring lighting levels closer to the recently introduced levels (RP-8-22). Implementation would need to include a complete design and analysis (not included in this project).

The Team selected the North Van Dorn Street and Maris Avenue for this example because the lighting levels for one section of the crosswalk on Maris Avenue were relatively low from the viewing position of turning vehicles. Also, as the location is adjacent to a bus stop with a pull-off lane, greater pedestrian volumes are expected.

There are several types of light distribution patterns — the way the fixture directs light onto the roadway. Because the specific type of fixture and distribution of the existing lights at this example location is unknown, the analysis assumes a commonly used LED cobra head roadway light. Current roadway lights are mounted on utility poles on either side of the intersection (See **Figure 5**). In **Figure 12** below, solid isolines (the blue isoline represents 20 horizontal lux and the black isoline represents 10 horizontal lux) show the existing light; the dashed isolines show a proposed new light with its distribution. Recall from the field visit described in Section 5.5 that the measured lighting level of the Maris Avenue crosswalk at the reported crash location (as indicated by the red box on Figure 12) is 1.7 lux.

Adding one light at the noted location would increase the vertical illuminance levels in this part of the crosswalk to 20 lux, which meets the 20 lux recommendation included in RP-8-22. This added fixture could be utility pole mounted (depending on the pole class and utility requirements) or placed on a separate pole.

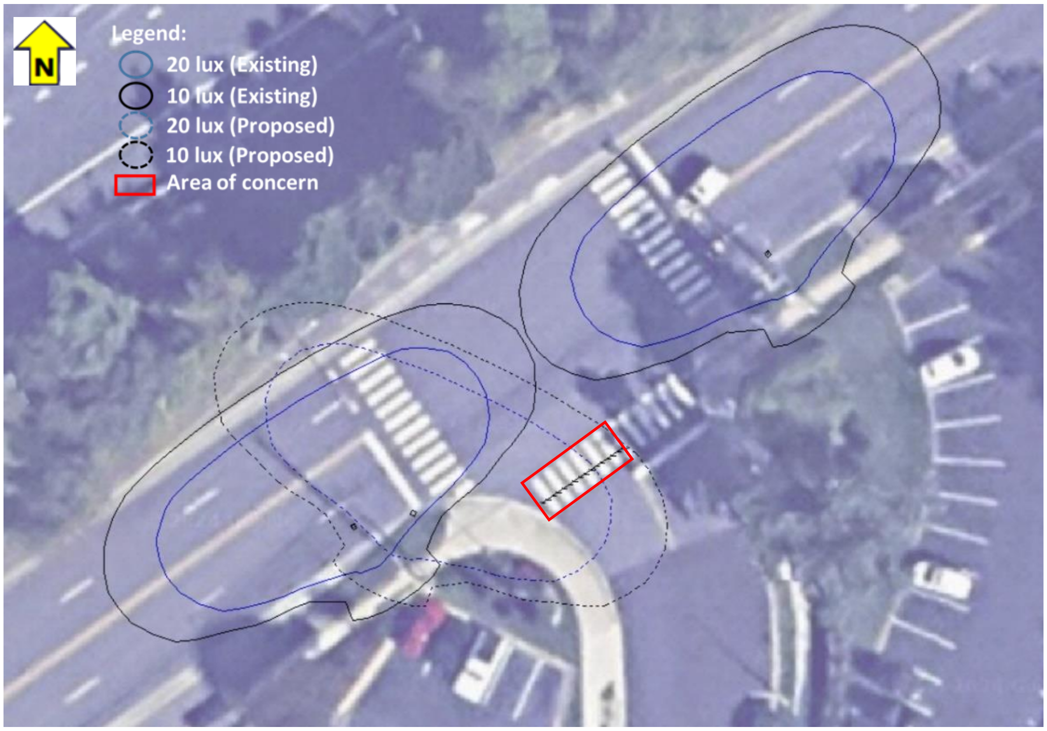


Figure 13. Example of Crosswalk Area with Insufficient Lighting (Measured vs. Visually Observed).

5.8 General Recommendations for Lighting

Recommendations for the City of Alexandria going forward should include the following:

- Any new construction involving lighting in the City should consider using IES RP-8-22 (2022) (or latest edition) as the criteria for the lighting system. For utility-provided lighting systems, layouts for meeting this criteria would need to be provided to the utility for guidance. The City's Complete Street document should be updated to reference the latest edition of ANSI/IES RP-8.
- Evaluating existing areas that need improvements is a more complex process. Based on the example locations in this study (Section 5), it is evident that simply checking for IES RP-8-22 compliance does not consider the context of the surrounding area and its functional use. Other studies are currently being conducted regarding contextual modifiers (e.g., NCHRP 05-25), but these will not be completed in the near future. Currently, the most reasonable approach includes the following elements:

    1) Use after-dark severe injury and fatal crash history to determine areas of concern.

        a. Assess potential risks from higher, after-dark pedestrian or cyclist volumes combined with higher vehicular traffic volumes, as well as the complexity of the intersection configuration, sight line obstructions that interfere with crosswalk visibility, type of traffic control, and proximity to bus stops and schools, etc.

        b. Consider mitigating contextual factors that reduce risk, such as all-way STOP control, posted speed limits of 25 mph or less, or exceptionally high pedestrian or cyclist volumes (based on the assumption that VRUs are more visible when crossing in groups and that drivers focus more on pedestrians and cyclists when there are more of them present).

        c. Compare the mitigating contextual factors to the potential risks and the magnitude of the safety concerns raised by the historical after-dark severe injury and fatal crash data.

    2) Measure lighting levels and perform subjective visibility observations at those areas for comparison to the measurement; focus on marked crosswalks and unmarked areas where pedestrians are known to cross. Determine the following:

        a. Identify potential locations for new lights based on the measured lighting levels, crash data and observations and suitability for installation. Avoid conflicting features such as trees or other existing infrastructure.

        b. Select type of fixture based on the desired lighting distribution pattern and take care to avoid having light illuminate adjacent residences. Dominion Electric has a reasonable palette of lighting fixture types to meet most of the City's lighting needs.

        c. Ensure new lighting installations comply with IES RP-8-22.

3) Evaluate treatment/implementation location to determine if improvement resolved the issues or further changes are required. (Preliminary evaluation at 12th month, additional evaluation at 36th month.)

- Future initiatives the City may want consider:

1) Future evaluation of the sites is listed in **Table 1** but not included in this study for reasons such as crashes occurring before the LED conversion can be evaluated in the same way as performed as part of this study. This would require the purchase of a suitable illuminance meter. The one used in this study was a Minolta T-10A meter.

2) In the short-term Traffic and/or Safety staff can take advantage of available FHWA resources at:

   https://highways.dot.gov/safety/other/visibility/web-based-training-fhwa-roadway-lighting-workshop

3) Longer-term, hire or train a dedicated staff member in aspects of lighting design and inspection. Many times, staff with this expertise also has expertise in traffic signals and smart city systems, which allows them to consider many related systems. (Option - Review the agreement with Dominion Electric regarding street lighting with the intent to provide additional technical support as needed.)

4) Revisit the street-lighting approach in 24-36 months and compare its overall success and compliance with new lighting and safety approaches currently in the study phase.

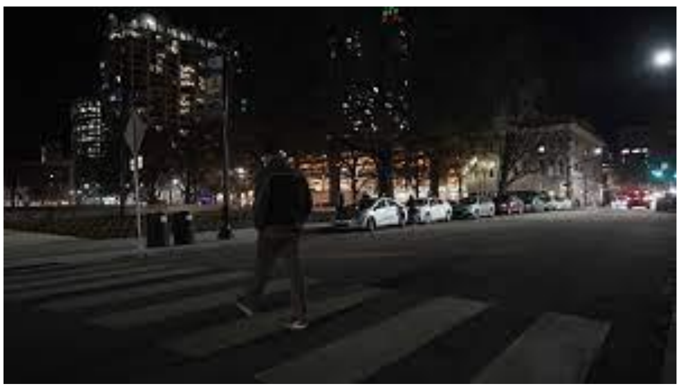
5) Monitor Federal safety grants and other funding opportunities. Grants (# 6 below) are available for not only improving safety on roadways but also for demonstration projects, (e.g., assess intersections and/or corridors for lighting improvements - design, implement, and evaluate safety outcomes). Consider showcasing successful/innovative approach/s for other States and municipalities to follow.

6) The Bipartisan Infrastructure Law (BIL) established the Safe Streets and Roads for All (SS4A) discretionary program with $5 billion in appropriated funds over 5 years, 2022-2026. The SS4A program funds regional, local, and Tribal initiatives through grants to prevent roadway deaths and serious injuries. Over $3 billion is still available (2024) for future funding rounds. https://www.transportation.gov/grants/SS4A

Appendix A. Literature Review (Submitted under Task 2)

City of Alexandria Pedestrian Lighting Improvements Study
Literature Review (Task 2)

Final Report, April 18, 2024



Submitted to:

City of Alexandria, VA

Funded by:

National Capitol Region

Transportation Planning Board

Submitted by:

KLS Engineering, LLC

and

WSP

National Capital Region
Transportation Planning Board

City Project Manager:

Bryan Hayes

Consultant Team:

Leverson Boodlal, PE, PMP (KLS - P.M)

Paul Lutkevich, PE, FIES (WSP)

Jeff Parker, P.E., PTOE (WSP)

Table of Contents

1. CURRENT STANDARDS ... 2
1. 1 ANSI / IES RP-8-22: Lighting Roadway and Parking Facilities ... 2
1. 2 AASHTO GL-7 Roadway Lighting Design Guide ... 4
1. 3 FHWA Lighting Handbook 2023 ... 4
2. RECENT RESEARCH ... 5
2. 1 Visibility Variables and Considerations ... 5
2. 1. 1 Off-Roadway Lighting ... 5
2. 1. 2 Spectral Content of Light ... 7
2. 2 Disability and Discomfort Glare ... 10
2. 3 Considerations for Pedestrians, Cyclists, and Motorists ... 11
3. IMPACTS OF WEATHER AND CLIMATE ON LIGHTING EFFECTIVENESS ... 15
3. 1 Potential Environmental and Health Risks ... 16
4. METRICS FOR LIGHTING ... 20
4. 1 Intersection Lighting ... 20
4. 2 Partial Intersection Lighting ... 21
4. 3 Areas of High Pedestrian Risk ... 22
5. SUMMARY OF LITERATURE REVIEW FINDINGS ... 25

List of Figures

Figure 1. Roadway Lighting Levels, IES RP-8-22. ... 2
Figure 2. Pedestrian Area Lighting Levels from RP 8-22 ... 3
Figure 3. Intersection Lighting Levels from IES RP-8-22. ... 3
Figure 4. Lighting Levels from AASHTO GL-7. ... 4
Figure 5. Excerpt from CIE 115, Table 2. ... 6
Figure 6. Example Diagram for Applying Surround Ratio from NCHRP 940. ... 7
Figure 7. Location and Type of Pedestrians and Targets Used in Test. ... 9
Figure 8. Effect of Light Type on Driver Detection of Pedestrians. ... 10
Figure 9. Effect of Light Type on Driver Detection of Objects. ... 10
Figure 10. Night-to-Day Crash Rate Ratio to Lighting Level. ... 12
Figure 11. Night-to-Day Crash Rate Ratio to Lighting Level for Various Road Classes. ... 13
Figure 12. Overhead-Lighting Level Experiment — SNK Groupings — for Pedestrian Detection Distance with Headlights On by Overhead-Lighting Level. ... 14
Figure 13. Detection Distance by Weather Condition and Light Source. ... 15
Figure 14 (a). Plan View for Conflict Points; (b) Positive Contrast for Pedestrians. ... 20

Figure 15. Lighting Levels from FHWA-ICT-21-023 21
Figure 16. Lighting Levels from VCRT 20-R31 22
Figure 17: Existing an Emerging Metrics 23
Figure 18. Light Levels from FHWA-SA-20-062. 23
Figure 19. Grid Placement Included in FHWA-SA-20-062. 24

Executive Summary

The literature review conducted for this study examines the current state of lighting design for roadways and pedestrians, recent research on lighting, and focuses on ways to improve lighting and increase safety. Because of this, recommended practices for lighting systems now include:

- Increased emphasis to focus lighting more acutely on vulnerable road users.
- Awareness of the amount of light adjacent to the travel lanes (Surround Ratio).
- Better lighting on crosswalks to improve pedestrian and bicyclist visibility.
- Incorporate elements such as the spectral content of light (color) to determine how it affects drivers' detection of distance.

Many of the recommendations and results of this safety research task were not available when the City of Alexandria installed its current lighting systems, but will be helpful in areas of concern the City may identify.

The Summary of Literature Review Findings in **Section 5** includes key items of the findings of this review and items warranting consideration.

City of Alexandria Pedestrian Lighting Improvements Study
Literature Review

This Literature Review identifies, summarizes, and references the most current pedestrian-lighting best practices, including prioritizing and analyzing methods and identifies appropriate lighting levels, types of lighting, and placing roadway lighting.

1. CURRENT STANDARDS

The three resources most widely used to determine lighting criteria for roadways, adjacent pedestrian facilities, and intersections include ANSI / IES RP-8-22 *Lighting Roadway and Parking Facilities*, AASHTO GL-7 *Roadway Lighting Design Guide*, and the 2023 FHWA *Lighting Handbook*. While the sources generally agree, they may also be in various stages of development.

1. 1 ANSI / IES RP-8-22: LIGHTING ROADWAY AND PARKING FACILITIES

RP-8-22, Chapter 11, offers the most direction for pedestrian safety adjacent to streets. Street lighting levels vary by both street classification and pedestrian volumes. **Figure 1** shows how criteria values include luminance levels for the street, uniformity ratios, and glare limits (Maximum Veiling Luminance Ratio).

Street Classification	Pedestrian Activity Classification*	Average Luminance L_{avg} (cd/m^2)	Average Uniformity Ratio L_{avg}/L_{min}	Maximum Uniformity Ratio L_{max}/L_{min}	Maximum Veiling Luminance Ratio $L_{V,max}/L_{avg}$
Major	High	1. 2	3. 0	5. 0	0. 3
	Medium	0. 9	3. 0	5. 0	0. 3
	Low	0. 6	3. 5	6. 0	0. 3
Collector	High	0. 8	3. 0	5. 0	0. 4
	Medium	0. 6	3. 5	6. 0	0. 4
	Low	0. 4	4. 0	8. 0	0. 4
Local	High	0. 6	6. 0	10. 0	0. 4
	Medium	0. 5	6. 0	10. 0	0. 4
	Low	0. 3	6. 0	10. 0	0. 4

Table Notes:

* **Section 11. 3. 3** defines Pedestrian Activity Classifications.

L_{avg}:Maintained average pavement luminance.

L_{min}:Minimum pavement luminance.

$L_{V,max}$:Maximum veiling luminance.

Figure 1. Roadway Lighting Levels, IES RP-8-22.

Recommendations for walkways within the right-of-way, which include not only sidewalks, but also include horizontal illuminance, horizontal uniformity, and vertical illuminance values based on the level of pedestrian activity, as **Figure 2** shows.

Condition	E_{avg}, lux (fc)	$E_{v,avg}$ lux (fc)	E_{avg}/E_{min}*
High pedestrian activity	10 (0.9)	5 (0.5)	5.0
Medium pedestrian activity	5 (0.5)	2 (0.2)	5.0
Low pedestrian activity	2 (0.2)	1 (0.1)	10.0

Table Notes:

E_{avg}: Minimum maintained average horizontal illuminance at pavement

E_{min}: Minimum horizontal illuminance at pavement

$E_{V,avg}$: Average vertical illuminance at 1.5m above the pavement in both directions and parallel to the main pedestrian flow

* Horizontal only

Figure 2. Pedestrian Area Lighting Levels from RP 8-22.

Chapter 12 (RP 8-22) addresses intersection, roundabout, and crosswalk lighting levels. **Figure 3** shows how roundabouts and intersections essentially use street classification and pedestrian volumes to develop the recommended criteria.

Functional Classification	Pedestrian Activity Level Classification			E_{avg}/E_{min}
	High	Medium	Low	
Major / Major	34/3. 2	26/2. 4	18/1. 7	3. 0
Major / Collector	29/2. 7	22/2. 0	15/1. 4	3. 0
Major / Local	26/2. 4	20/1. 9	13/1. 2	3. 0
Collector / Collector	24/2. 2	18/1. 7	12/1. 1	4. 0
Collector / Local	21/2. 0	16/1. 5	10/0. 9	4. 0
Local / Local	18/1. 7	14/1. 3	8/0. 7	6. 0

Figure 3. Intersection Lighting Levels from IES RP-8-22.

Vertical illuminance values are given for the crosswalks associated with intersections and roundabouts equal to the horizontal recommendations given for the roadway.

For midblock crosswalks, recommended lighting levels are 20 vertical lux for low pedestrian conflict, 30 vertical lux for medium pedestrian conflict, and 40 vertical lux for high pedestrian conflict areas.

1. 2 AASHTO GL-7 ROADWAY LIGHTING DESIGN GUIDE

The AASHTO *Roadway Lighting Design Guide* includes lighting levels for both illuminance and luminance, uniformity ratios, and glare limits by roadway and area classifications. Sidewalks and Pedestrian ways are also included with horizontal illuminance, uniformity ratios and vertical illuminance in sidewalk options that meet horizontal recommendations.

Roadway and Walkway Classification[a]	Area Classifications	Illuminance Method						Luminance Method			Additional Values (both Methods)
		Average Maintained Illuminance (E_{avg})				Minimum Illuminance E_{min}	Illuminance Uniformity Ratio E_{avg}/E_{min}	Average Maintained Luminance			Veiling Luminance Ratio
		R1	R2	R3	R4			L_{avg}	Uniformity		
	General Land Use	(foot-candles) (min)	(foot-candles) (min)	(foo-t-candles) (min)	(foot-candles) (min)	(foot-candles)	Avg/min (max)[b]	cd/m^2 (min)	L_{avg}/L_{min} (min)	L_{max}/L_{min} (max)	$L_{v(max)}/L_{avg}$ (max)[c]
Principal Arterials:											
Interstate and other freeways	All	0. 4	0. 6	0. 6	0. 5	0. 2	4:1	0. 4[d]	3. 5:1	6:1	0. 3:1
Other Principal Arterials (partial or no control of access)	Commercial	1. 1	1. 6	1. 6	1. 4	As uniformity ratio allows	4:1	1. 2	3:1	5:1	0. 3:1
	Intermediate	0. 8	1. 2	1. 2	1. 0		4:1	0. 9	3:1	5:1	0. 3:1
	Residential	0. 6	0. 8	0. 8	0. 8		4:1	0. 6	3. 5:1	6:1	0. 3:1
Minor Arterials	Commercial	0. 9	1. 4	1. 4	1. 0		4:1	1. 2	3:1	5:1	0. 3:1
	Intermediate	0. 8	1. 0	1. 0	0. 9		4:1	0. 9	3:1	5:1	0. 3:1
	Residential	0. 5	0. 7	0. 7	0. 7		4:1	0. 6	3. 5:1	6:1	0. 3:1
Collectors	Commercial	0. 8	1. 1	1. 1	0. 9		4:1	0. 8	3:1	5:1	0. 4:1
	Intermediate	0. 6	0. 8	0. 8	0. 8		4:1	0. 6	3. 5:1	6:1	0. 4:1
	Residential	0. 4	0. 6	0. 6	0. 5		4:1	0. 4	4:1	8:1	0. 4:1
Local	Commercial	0. 6	0. 8	0. 8	0. 8		6:1	0. 6	6:1	10:1	0. 4:1
	Intermediate	0. 5	0. 7	0. 7	0. 6		6:1	0. 5	6:1	10. 1	0. 4:1
	Residential	0. 3	0. 4	0. 4	0. 4		6:1	0. 3	6:1	10:1	0. 4:1
Alleys	Commercial	0. 4	0. 6	0. 6	0. 5		6:1	0. 4	6:1	10. 1	0. 4:1
	Intermediate	0. 3	0. 4	0. 4	0. 4		6:1	0. 3	6:1	10:1	0. 4:1
	Residential	0. 2	0. 3	0. 3	0. 3		6:1	0. 2	6:1	10:1	0. 4:1
Sidewalks	Commercial	0. 9	1. 3	1. 3	1. 2		3:1	Use illuminance requirements			
	Intermediate	0. 6	0. 8	0. 8	0. 8		4:1				
	Residential	0. 3	0. 4	0. 4	0. 4		6:1				
Pedestrian Ways and Bicycle Ways[e]	All	1. 4	2. 0	2. 0	1. 8		3:1				

Figure 4. Lighting Levels from AASHTO GL-7.

1. 3 FHWA LIGHTING HANDBOOK 2023

The FHWA *Lighting Handbook* was developed to fill information gaps in IES and AASHTO guidance. The FHWA strongly promotes safety initiatives, including lighting to improve safety of vulnerable road users as part of the FHWA *Every Day Counts* initiative. Part 1 of the handbook reviews approaches to these types of facilities and new research in the area, which is discussed later; Part 2 includes design examples for a wide selection of roads and pedestrian areas to help walkway designers and owners through the complex process of selecting criteria and identifying critical safety.

2. RECENT RESEARCH

The following section includes recent research regarding lighting effects on visibility and pedestrian safety. Portions of the literature review (**noted with ***) were generated as part of the NCHRP 05-22 research project and resulted in NCHRP Report 940 *Solid State Lighting Design Guide* (Lutkevich, Gibbons, Bhagavathula, McLean, 2020).

Lighting Definitions

Foot-candle. (fc, lm/f2) unit of illuminance or light intensity, defined as one lumen per square foot.

CCT (Correlated Color Temperature). Gauge of how yellow or blue the color of light emitted from a bulb appears.

Lumens. Unit that represents the visible light output of a light source.

Illuminance. Measures amount of light that falls on a surface.

Luminance. Apparent brightness of an object appearing to the human eye.

Mesopic. Vision under low-light conditions of i illumination (between photopic and scotopic) produces greater stimulation of eye rods.

Photopic. Vision in bright light with light-adapted eyes mediated by cones of the retina.

Scotopic. Vision under dim light and involves only retinal rods as light sensors.

Spectral Power Distribution (SPD). Serves as the starting point for quantitative analyses of color.

2. 1 VISIBILITY VARIABLES AND CONSIDERATIONS

2. 1. 1 Off-Roadway Lighting*

In *scotopic* conditions, where adaptation luminance is 0. 001 candela per square meter (cd/m^2) or lower, the choice of a light source based on color is not important because the use of retinal rods in the periphery of the eye is more prevalent. Cones in the eye are not active at that low level of light and rods, which are active, do not see color. In a *mesopic* scenario, spectral effects are slight. However, in scotopic conditions where adaptation luminance is very low (0. 001 cd/m^2 or lower), peripheral vision and off-axis spectral effects become primary (Gibbons et al., 2015a). Research suggests that for lighted roadways, drivers should focus on the lighted portion of the road (Mortimer & Jorgenson, 1974) and the adaptation luminance of the eye remains somewhat steady. On rural roads, which may not be straight or conventional, drivers tend to vary their gaze direction, which causes multiple spatial and temporal levels of eye adaptation. In these conditions, lighting off-axis may benefit rod photoreceptors, which are active in the periphery and operate mainly in low-light conditions (Boyce, 2009).

Off-road lighting (the area adjacent to the travel lanes) has been standard in Europe for several years. In CIE 115, *Lighting of Roads for Motor and Pedestrian Traffic*, the metric of *Surround Ratio* (*SR*) is used to "ensure that light directed on the surrounds is sufficient for objects to be revealed" (CIE, 2010a), as **Figure 5** shows. Essentially, this standard is used for illuminated roadways in darker surroundings to help increase visibility of pedestrians, cyclists, and hazards. Evidence suggests that increased lighting in areas immediately adjacent to the roadway may help increase visibility and associated safety. This lighting would not be extended to areas beyond the right-of-way, which needs to be limited, but addresses the area between the edge of the right-of-way and the edge of the travel lane.

Lighting class	Road surface luminance				Threshold increment	Surround ratio
	Dry			Wet *		
	L_{av} in cd/m^2	U_o	U_l	U_o	*TI* in%	*SR*
M1	2. 0	0. 40	0. 70	0. 15	10	0. 5
M2	1. 5	0. 40	0. 70	0. 15	10	0. 5
M3	1. 0	0. 40	0. 60	0. 15	15	0. 5
M4	0. 75	0. 40	0. 60	0. 15	15	0. 5
M5	0. 50	0. 35	0. 40	0. 15	15	0. 5
M6	0. 30	0. 35	0. 40	0. 15	20	0. 5

Figure 5. Excerpt from CIE 115, Table 2.

The approach for determining the visibility of off-road or off-axis objects stems from a paper (Gibbons, 1993) that shows Visibility Levels (*VL*) at different angles from the driver. A distance of 197 ft (60 m) at a 7 degree angle requires a VL of 3. The wider the angle of view, the higher the VL needed. The higher the calculated VL of a target, the more visible it is. The VL model is generally used in static observations to determine the ability of a light source to provide sufficient visibility. In general, VL values are only comparable to other VLs calculated in the same scenario. No scales display VL benchmarks for visibility; therefore, VL has generalizable limitations.

Surface Luminance includes the amount of light hitting the surface, the surface reflectance, and the color under artificial illumination. Adrian and Gibbons (1993) also suggest a procedure for designing a roadway illumination system that considers off-roadway reflectance. This investigation shows the complexity of visibility-based lighting.

To benefit safety, agencies should consider areas adjacent to the roadway. These include sidewalk areas next to urban and suburban streets as well as areas adjacent to the travel lanes, streets without sidewalks, and limited-access highways. This lighting benefits pedestrians and cyclists in these areas and research conducted in NCHRP 940 also showed improved detection distances for hazards on the roadway travel lanes.

The research indicates that for streets with sidewalks, IES or AASHTO recommendations are preferred. For other roadways, research performed as part of NCHRP 940 showed that detection distances increase when lighting is used in areas adjacent to the roadway; therefore, agencies should consider Surround Ratio (*SR)* as a criterion of 0. 8. This is the ratio of the average illuminance of an area adjacent to the travel way of 12 ft (3. 6 m) and average illuminance of the lane of the travel way adjacent to it. For example, using the configuration shown in **Figure 6**, the average illumination of the area shown as shoulder (*which can be any area, paved or unpaved, parking, etc.)* divided by the average illumination of the adjacent lane should be 0. 8 or greater.

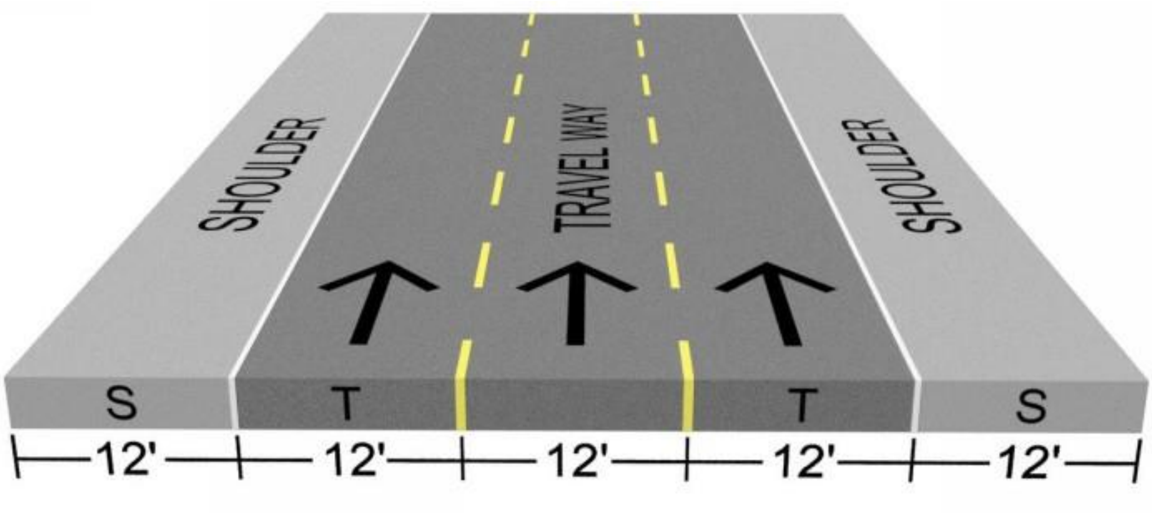


Figure 6. Example Diagram for Applying Surround Ratio from NCHRP 940.

SR = Average Illumination on Shoulder Area / Average Illumination in Travel Lane

Applying SR has shown improved ability to detect the distances of objects on and adjacent to the roadway. There are situations, however, where agencies need to consider the balance and need of these visibility improvements against any potential negative impacts, for example:

- Residential local roads where pedestrian volumes are low, and lower speeds, and objects within the useful range of headlights can be detected.
- Rural roundabouts with low pedestrian and cyclist volumes.
- Identified environmentally sensitive areas where the lighting of areas immediately adjacent to the travel lane can have damaging effects.
- Bridges or structures that lack shoulder or sidewalk areas.
- Streets where sidewalk lighting is provided will likely produce the same visibility improvements.

2. 1. 2 Spectral Content of Light*

A number of important metrics define the performance of a light source. *Lumens* measure the luminous flux of light or the quantity of visible light emitted by a source. The *Special Power Distribution* (*SPD*) renders the color, or more specifically, the characteristics of the wavelengths that contribute to the color of a light source. Luminance and illuminance are measures of light incident on a surface or from a source, respectively, and are the most prominent and often the easiest characteristics to measure aspects of light. Depending on the amount of light in a given scenario, three different modes of human vision come into play — *photopic*, *mesopic* and s*cotopic*.

Lighting design guidelines often attempt to account for these basic metrics (CIE, 2010a; Federal Highway Administration, 2009; IES, 2014); however, other elements, such as eccentricity, contrast polarity, speed, and individual differences, make it difficult to apply universal models for visibility.

Luminous Flux (lumens) describes the quantity of visible light emitted by a source. To determine how the human eye evaluates lumens, a response curve V(λ) was adopted to define the spectral response that a typical person would experience under photopic conditions. The *Spectral Power Distribution* (SPD) is weighted by V(λ) at each wavelength, then all values are integrated to determine lumen output. This output is regarded as accurate until there is a change in the viewing condition, which results in a change in the effectiveness of a lamp's output.

A light's color depends on the SPD of the light's source and spectral metrics or measures of colors produced by a light source are important for differentiating a light source's abilities. A *High-Pressure Sodium* (HPS) lamp, for example, emits wavelengths that spike between 560 nanometers (nm) and 625 nm. The colors associated with this range are yellow and orange, which unsurprisingly result in the hue perceived of an HPS lamp. A *Low-Sodium Pressure* (LPS) lamp has a minimal spectral output, except for a doublet-emission line at 589 nm and 589. 6 nm, which gives the light output a deep orange appearance. White light sources are more evenly balanced across the electromagnetic spectrum and are composed of more blue light, or shorter wavelengths, than HPS or LPS (Gibbons et al. , 2015a; Lewin, Box, & Stark, 2003).

Basic measures of luminance, such as average, minimum, and average-to-minimum ratios, drive design criteria and recommended practices. For example, in IES RP-8-22, a recommended practice guide for roadway lighting has specifications for average luminance and average uniformity ratios for certain road classes. A street classified as major, with a high pedestrian conflict, should have an average luminance of 1.2 cd/m^2 and an average uniformity ratio of 3. 0 L_{avg}/L_{min}. A roadway classified as local, with high pedestrian conflict, is required to have an average luminance of 0. 6 cd/m^2 and an average uniformity ratio of 6. 0 L_{avg}/L_{min}.

The difference in the two scenarios is the road class, which often involves differences in speed, lane width, and identifiable markings. Luminance metrics for road classes and pedestrian zones do not differ based on the type of lighting system or the color temperature produced (IES, 2014). The AASHTO *Roadway Lighting Design Guide* uses luminance design values similar to IES RP-8-22, but also includes illuminance design values that can be used instead of luminance values. However, the illuminance recommendations include using Veiling Luminance Ratio limits on glare, which requires calculating roadway luminance as well as the illuminance. Neither of these methods include spectral modifiers.

Similarly, illuminance specifications do not differ depending on the light source. A vehicle and pedestrian conflict zone, such as a walkway or crosswalk, requires an average vertical illuminance of 1.9 footcandle (fc) (20 lux) at 5 ft (1 5 m) from the ground; this is true regardless of spectral content.

Part of NCHRP 940 includes using various spectral content sources with a Correlated Color Temperature (CCT) of 3000K, 4000K, and 5000K as a variable test to detect distances of targets and pedestrians on and adjacent to the roadway (refer to **Figure 7**). The intent was to see how the spectral content of light could affect visibility.

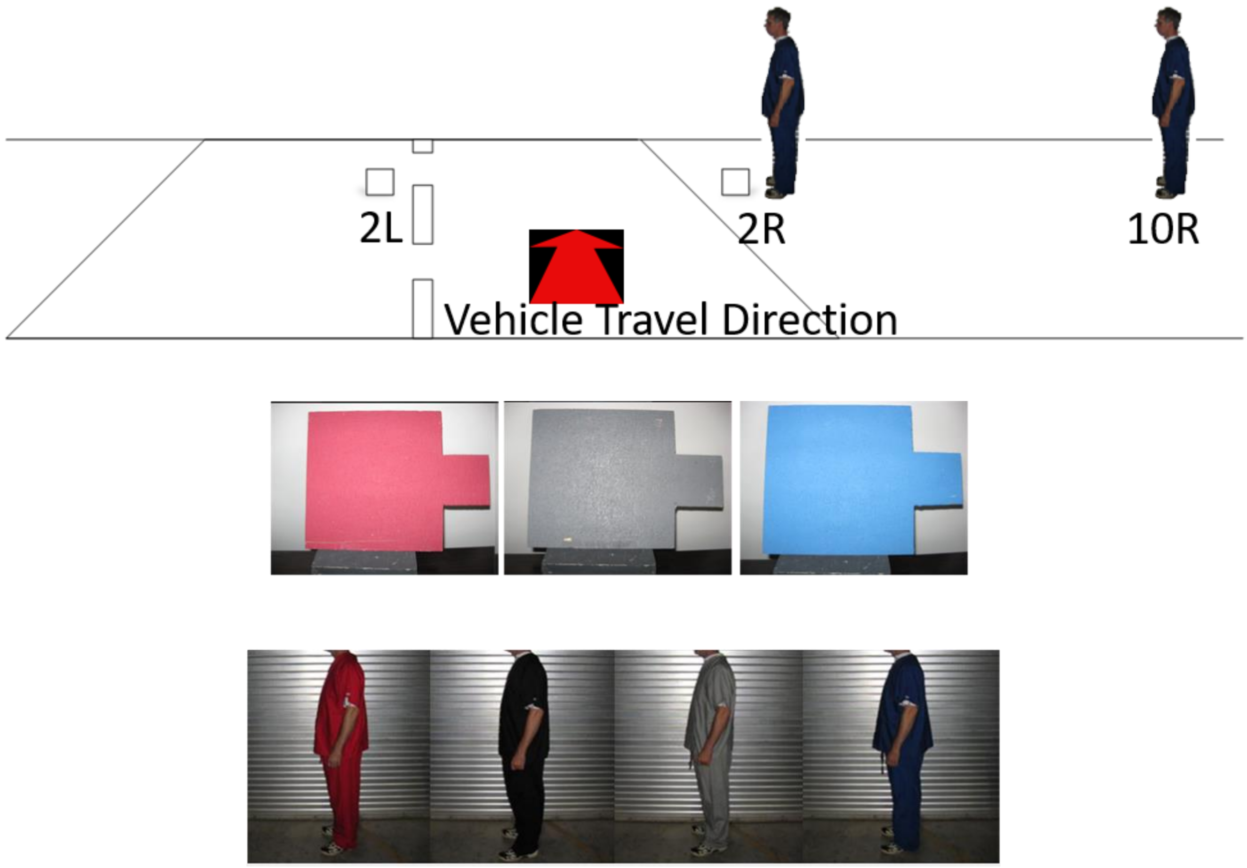


Figure 7. Location and Type of Pedestrians and Targets Used in Test.

For the test, objects were placed on the roadway and pedestrians located outside the roadway; subjects were asked when they could see objects under different CCT sources, roadway uniformity, light levels, and surround ratio. The results of the tests indicated longer detection distances with 4000K sources when associated with recommended surround ratio values.

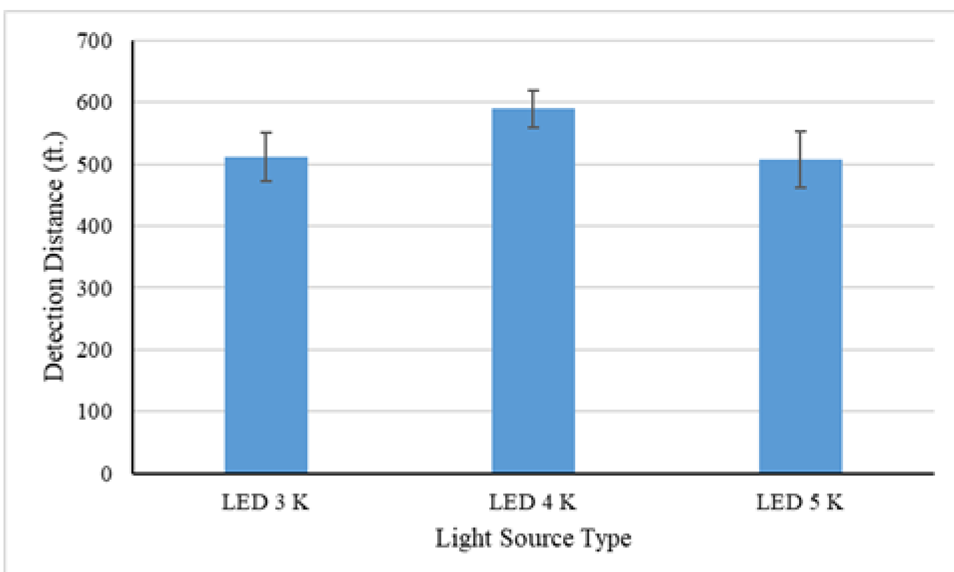


Figure 8. Effect of Light Type on Driver Detection of Pedestrians.

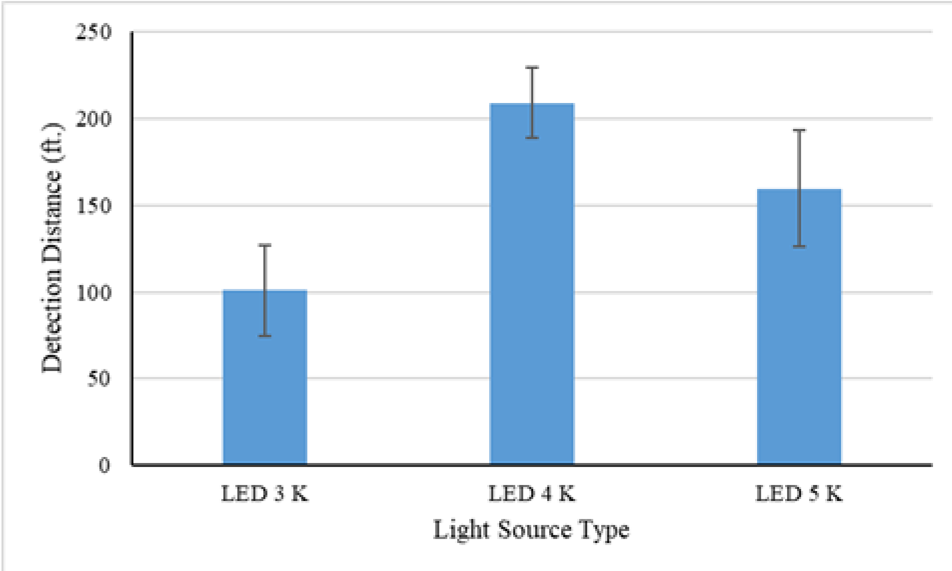


Figure 9. Effect of Light Type on Driver Detection of Objects.

Figures 8 and **9** show the differences in detecting distances. An assumption regarding the results of this research is that detection is assisted by color contrast and the way the spectral content of a light source affects it.

2. 2 DISABILITY AND DISCOMFORT GLARE*

Nonconformities in the visual field, particularly those caused by bright sources, affect the adaptation level of the eye because

- Sources tend to fluctuate as the driver proceeds, and
- Adaptation levels constantly change (transient adaptation).

Roadway lighting thus aids the eyes in adapting to an increased level of luminance — more than headlights alone. Bright sources create other effects, collectively termed *glare*, which is best avoided is practical.

Disability Glare occurs when light rays passing through the eye are slightly scattered, primarily because of diffusion in the lens and the vitreous humor that fills the anterior chamber of the eye. When a high-intensity light source is present in the field of view, this scattering tends to:

- Superimpose a luminous haze over the retina; effect is similar to looking at the scene through a luminous veil.
- This *veil* is added to both the task and background luminance, thereby reducing contrast.
- Effect is termed *disability glare* or *veiling luminance*, and can be numerically evaluated by expressing the luminance of the equivalent luminous veil.

A well-known example of this is a driver trying to see beyond oncoming headlamps at night. Because of contrast reduction by disability glare, visibility decreases. Increasing luminance will counteract this effect by reducing the eye's contrast sensitivity. Research shows that disability glare is not significantly influenced by the spectral power distribution of the glare source (Davoudian, Raynham, & Barrett, 2014; Woten & Geri, 1987). Thus, roadway lighting from LED sources will have the same effect on disability as other conventional roadway lighting sources.

Discomfort glare is a further result of overly bright light sources in the field of view and causes a sense of pain or annoyance. While its exact cause is not known, it may result from pain in the muscles that cause the pupil to close.

Spectral Power Distribution (SPD) of the light source could affect discomfort glare perception from vehicle headlamps that have a higher blue content, which causes more discomfort glare (Bullough, Van Derlofske, Fay, & Dee, 2003). Moreover, recent research into perception of discomfort glare from LED luminaires shows that higher discomfort glare ratings result from luminaire design rather than from SPD (van Bommel, 2014).

LED roadway luminaires are composed of arrays of small LEDs, which have a non-uniform luminance LED distribution when compared to a conventional luminaire. Research shows that this non-uniform luminance distribution results in a higher discomfort glare rating (Tashiro, Kawanobe, Kimura-Minoda, Kohko, Ishikawa, & Ayama, 2015). Therefore, discomfort glare is the result of the optical design of the luminaires, not the SPD from LED sources.

Disability glare and *discomfort glare* normally accompany one another, and beneficial luminaire light control that reduces one form of glare is likely to reduce the other. Discomfort glare, which can cause effects from an increased blink rate to tears and pain, does not reduce visibility. It is also generally accepted that reducing disability glare will reduce discomfort glare; however, it is possible to reduce discomfort glare and increase disability glare. North American roadway lighting standards do not specify numerical limits for discomfort glare. Methods exist to quantify discomfort glare for roadway lighting but are mostly subjective. In addition, there are currently no instruments to measure discomfort glare.

The presence of extraneous light in the field of view may cause nuisance or distraction to the driver, independent of the effects of disability and discomfort. Bright-light sources tend to cause distraction, and draw the eye may to them. Lighting used for advertising, for example, may cause visual clutter and add complexity to the scene, which makes driving more challenging. Beyond this definition, there is no measure or method to assess nuisance glare.

2. 3 CONSIDERATIONS FOR PEDESTRIANS, CYCLISTS, AND MOTORISTS*

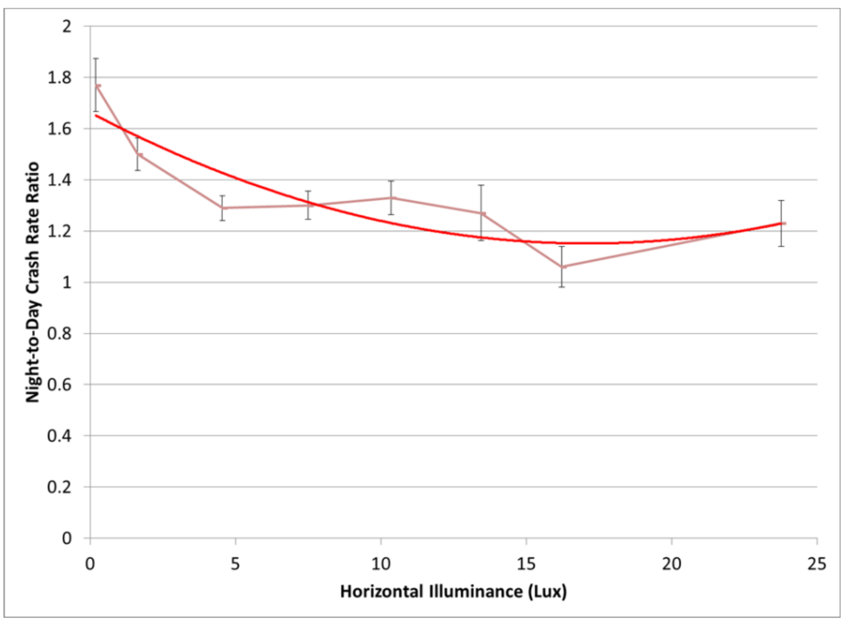
There are fewer road users at night, far fewer than during the day; even so, the areas where traffic volumes and rates of conflict between drivers and pedestrians are higher and typically lighted with artificial lighting intended to improve safety. In addition, locations where pedestrians and cyclists are common are typically lighted to specifications regarding their visibility and safety (IES, 2014). There were 32,166 fatal crashes in the United States in 2015, — 28 percent occurred at night on unlit roadways. Considering the significant decrease in nighttime traffic exposure, 28 percent represents a significant number of crashes (National Highway Traffic Safety Administration, 2017). These statistics indicate a significant need for research to improve lighting and motorist, pedestrian, and cyclist safety. While exposure is not directly accounted for in this data, lighted areas are known to have a higher volume of traffic and more frequent conflicts with pedestrians and cyclists. These fatality statistics show a benefit in lighting, although not all crashes can be attributed to an absence of lighting.

Roadway lighting increases the visibility of the roadway and road environment and increases visual awareness of potential conflicts. While there is no direct link between visibility and safety, studies show that roadway lighting improves safety (Donnell, Shankar, Porter, & Larson, 2009; Rea, Bullough, Fay, Brons, Van Derlofske, & Donnell, 2009). Roadway lighting also augments the amount of lighting provided by motor vehicle headlamps and provides context by illuminating roadway surroundings.

Improving visibility and roadway lighting can reduce accidents and increase safety and the feeling of safety. Elvik (1995) conducted meta-analysis that aggregated results from 37 studies and determined that introducing roadway lighting should reduce fatal nighttime crashes by up to 65 percent. There were some issues with the study because the research analysis involved a wide variety of approaches and measures. Further studies have been undertaken to build the link between safety and roadway lighting (Bruneau, Morin, & Pouliot, 2001; Gransberg, Gilman, Senadheera, Culvalci, & Green, 1997; Oya, Ando, & Kanoshima, 2003).

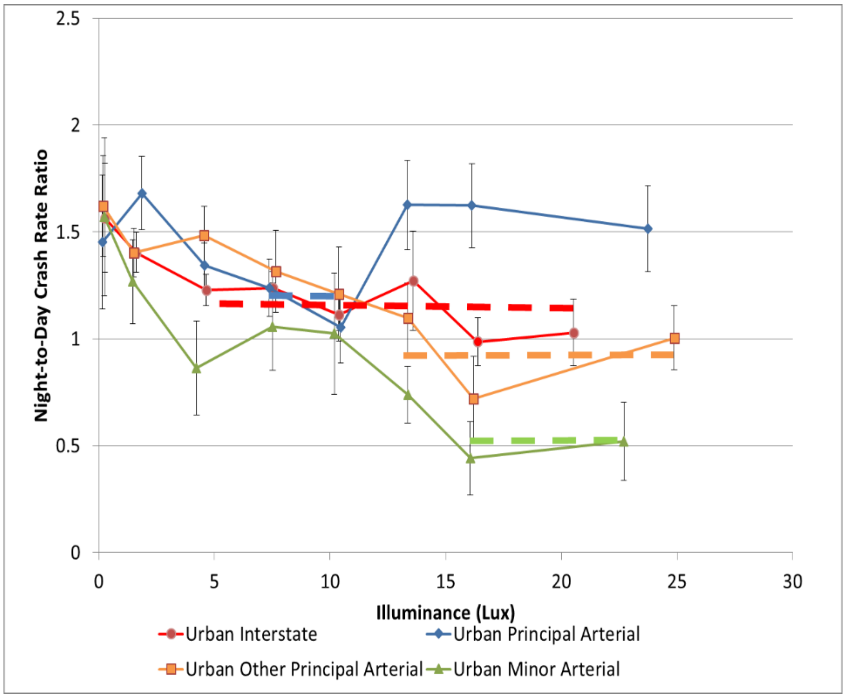
One such study (Gibbons, Guo, Median, Terry, Du, Lukevich, Corkum, & Vetere, 2014) investigated the link between lighting level and the night-to-day crash rate ratio. This is the largest study of lighting and crash reduction ever undertaken, measuring 1,000 center-lane miles of lighting and considering more than 88,000 crashes. The study examined lighting measured in-situ and was not based on estimates from design approaches or typical luminaire layouts from State DOT specifications. Rather, it investigated lighting effect and found a limit to safety improvements — while additional lighting on a roadway provides benefits, it also exhibits diminishing returns.

The *x*-axis in **Figure 10** shows increasing light levels decrease the night-to-day crash rate ratio. **Figure 11** shows how the effect of the decrease differs based on road class. The dashed lines indicate where additional lighting does not improve road safety for those roadway types.



Source: (Gibbons et al. , 2014)

Figure 10. Night-to-Day Crash Rate Ratio to Lighting Level.

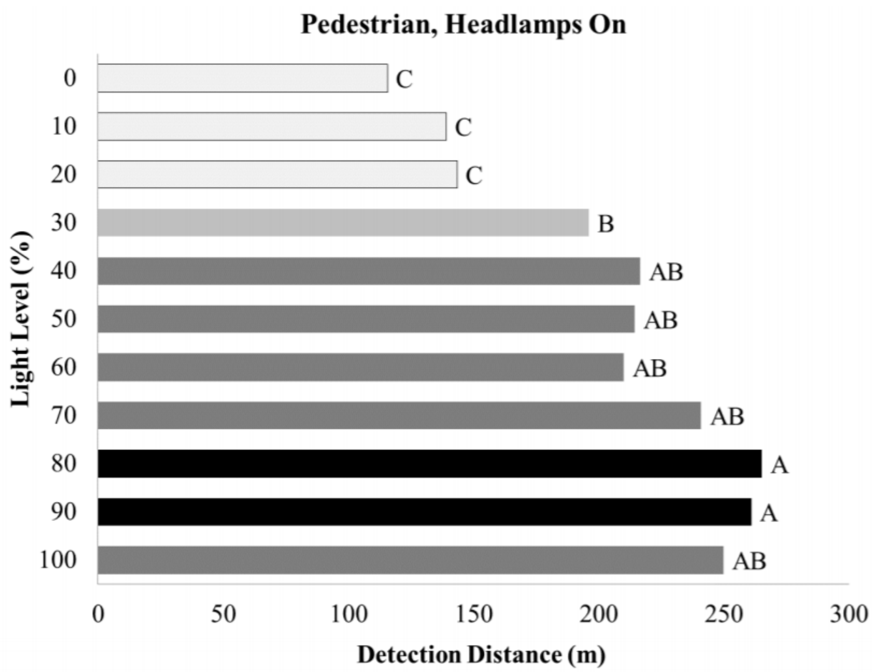


Source: (Gibbons et al. , 2014)

Figure 11. Night-to-Day Crash Rate Ratio to Lighting Level for Various Road Classes.

Several metrics were investigated to better understand the link between lighting, visibility, and safety, including small target visibility, relative visual performance, and cumulative detection probability (Adrian, 1989a; Bhagavathula & Gibbons, 2015; Bullough, Donnell, & Rea, 2013); however, none of these metrics fully describe the relationship. Many experiments have measured time-to-collision at the moment a participant detects a conflict. Time-to-collision is a standard safety surrogate (Gettman & Head, 2003) but is often not explicitly calculated from the separation distance at detection (detection distance) because experiments are performed on a test track at fixed speeds; therefore, *detection distance* is often used as a safety surrogate.

These test track studies have shown that increasing lighting also increased detection distances for pedestrians and cyclists (Gibbons et al. , 2012). When compared to headlamps alone, roadway lighting doubles the distance at which a pedestrian is visible (Gibbons et al. , 2015a). This is true even when the lighting system is at 40 percent of its full power (Gibbons et al., 2015a) (**Figure 12**), which likely results from the effect of increased surface luminance that reduced crash rates by 35 percent when augmented by an average of 1 cd/m^2 (Scott 1980). The Scott study shows that an increase in road surface luminance and a smaller increase in the headlight power or the vertical illuminance on an object in the roadway increases the contrast (negatively). An increase of negative contrast makes an object more visible through its silhouette and therefore increases its visibility.



Note: Same letters indicate no significant differences.

Figure 12. Overhead-Lighting Level Experiment — SNK Groupings — for Pedestrian Detection Distance with Headlights On by Overhead-Lighting Level.

Aside from its visibility aspects, lighting can also modify driver behavior. A study conducted by Li et al. (2017) related the naturalistic time series driver-behavior data from the second Strategic Highway Research Program (SHRP2) to field-lighting measurements conducted by the Virginia Tech Transportation Institute (VTTI) to explore correlations between roadway lighting parameters (average illuminance and uniformity). The study also involved several safety surrogate variables related to driver behavior (e. g., speed, acceleration, time to collision) at entrances and exits of highway ramps. Effects of lighting were more significant for entrance than for exit ramps. Results indicated that higher right-lane illuminance are correlated with lower speeds and lower, more gradual, lane changes. Overall, illuminance seemed to correlate more with driver behavior than uniformity.

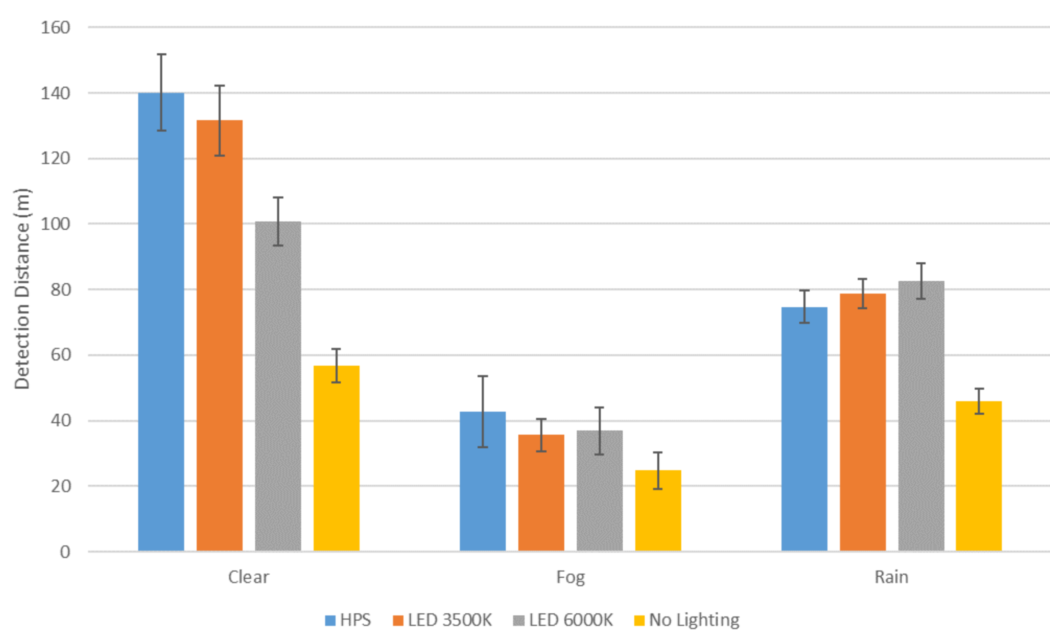
Recommendations and guidelines for lighting implementations can be found in publications from IES, CIE, the Transportation Association of Canada, and AASHTO. The organizations recommend that minimum lighting levels, placements, luminaire types, and lighting trajectory guides aid implementation. While adding lighting proves to have a net positive effect on safety, the guides also address important special considerations in terms of economy, glare, and distribution. As an example, the IES RP-8 -22 recommends basing lighting levels on luminance at the roadway surface for several road classifications to maximize uniformity and provides details of best methods for measuring lighting distribution over a given area (IES, 2022).

3. EFFECTS OF WEATHER AND CLIMATE ON LIGHTING EFFECTIVENESS*

Weather can dramatically change the way light behaves and affects the human perception of brightness, glare, and depth. Roadway lighting is also occasionally an even greater hindrance during certain inclement weather such as dense fog, rain, or heavy snow. The United Kingdom has roadway lighting recommendations for wet versus dry roadways. More accustomed to rainfall than most parts of the United States, the UK developed specific guidelines regarding wet pavement. In general, these guidelines specify that the *ratio of uniformity* be lower for wet pavement versus dry — lighting on wet pavement should also be more uniform (IES, 2022).

It is difficult to design lighting for areas of dense fog because fog is dynamic and consists of pockets of varying thickness. Research discourages more intense or brighter light during times of heavy fog because fog particles scatter and reflect light, resulting in a greater difficulty to see (Boyce, 2009). While the effect is most pronounced with headlights, it also occurs with roadway lighting. This scattering of light results in veiling luminance, or glare, that restricts motorist visibility (Boyce, 2009). This is the reason that using high beams in fog is not recommended. Conventional roadway lighting is not *smart* enough to dim during periods of fog, which can result in light scatter. In this case, driving situations are more difficult because visibility is diminished in the presence of light.

A recent study investigated detection of pedestrians in clear, rain, and fog situations; researchers found that the spectral effect of the light source diminishes in rain and fog conditions, but the more critical effect is that of light-source intensity (Gibbons, 2016). **Figure 13** shows the mean detection distance of objects in the various weather conditions. Note: Weather also affects vehicle speed and object contrast, so these results require significant analysis and caution.



Source: (Gibbons, 2016)

Figure 13. Detection Distance by Weather Condition and Light Source.

Conventional roadway lighting is mounted between 26 ft and 29.5 ft (8 and 9 m) from the ground, pointing downward. Computer simulations by Girasole (1998) found that a lower mounting height of about 3.2 ft (1 m) illuminated the forward roadway, and he postulated that, at this height, the light did not have to permeate as much fog, thus resulting in less light scatter and therefore less glare to the driver.

Snow presents unique issues to visibility. Snowfall obstructs visibility and can obscure the roadway, depending on the size of falling snowflakes and rate of snowfall. In general, lighting cannot improve visual conditions caused by heavy snowfall. Standing snow on the roadway and on the edges of the roadway is highly reflective and can cover important lane markings.

In general, the reflective nature of standing snow is more likely to be beneficial for visibility (Boyce, 2009) because reflective ambient light illuminates the environment.

With the advent of adaptive lighting technologies, it may soon be possible for lighting to change and conform to weather conditions. In cases of severe inclement weather, such as heavy rain or fog, it may be best to dim lighting or increase spacing (Boyce, 2009). More research is needed on the properties different lighting systems provide for visibility because of the difficulty in replicating fog-like or heavy rain-like conditions in a road setting.

3. 1 POTENTIAL ENVIRONMENTAL AND HEALTH RISKS*

Using LED sources and their spectral content has raised environmental and health concerns. Research in human-circadian rhythms show that exposure to blue light from LEDs in light sources and devices in the evening could disturb circadian rhythms and cause sleep loss by suppressing melatonin production (Cajochen, Frey, Spati, Bues, Pross, Mager, Wirz-Justice, & Stefani, 2011; Chang, Aeschbach, Duffy, & Czeisler, 2015; West, Jablonksi, B, Cecil, M, Ayers, Maida, Bowen, Sliney, Rollag, Hanifin, & Brainard, 2011). The shorter LED wavelengths can also cause higher discomfort glare when compared to other light sources for the same photopic illuminance measured at the eye of the observer (Rea, 2017).

Another drawback of LED roadway lighting pertains to maintaining dark skies and limiting light trespass related to astronomical and ecological considerations. With added blue content from the SPD of the LEDs, Rayleigh scattering of light in the atmosphere increases sky glow (Luginbuhl, Duriscoe, Moore, Richman, Lockwood, & Davis, 2009). LED light sources can also result in sky glow because they emit more energy in the shorter wavelengths, which scatter more than longer wavelengths and can affect the visibility of stars from the earth (Kinzey, Perrin, Miller, Kocifaj, Aube, & Lamphar, 2017). Sky glow is also affected by from the light source total output and distribution of light from the luminaire (up light, in particular) (Kinzey et al., 2017). In addition to the SPD, recent research shows that sky glow is also affected by aerosol content and the operating characteristics of the detector used to assess sky glow (Rea & Bierman, 2014). Using adaptive lighting technology could minimize the total amount of flux generated from the source and mitigate the effects of sky glow.

Because of the above-mentioned concerns, a recent report by the American Medical Association, *Human and Environmental Effects of Light Emitting Diode Community Lighting*, recommends using lower CCTs (possibly because of lower SPD blue content) to minimize potential ill effects on health and the environment (Kraus, 2016).

Using CCT as a defining metric for determining harmful health effects from LED lighting is inaccurate because:

- CCT is not the only factor involved in defining light exposure (Rea & Figueiro, 2016).
- The spectral content of the LED light source determines the amount of blue light emitted by the source. There is no metric to determine the blue content in an LED light source other than measuring the energies of each of the wavelengths that compose the spectrum.
- Lack of an easy metric to determine the blue content of LED light sources has led to adopting CCT in the lighting industry, but CCT is not a metric of the SPD; rather, CCT gives information on the color appearance of the light source.

Dosage, which is the duration and intensity (or level) of light exposure, also plays an important role in disrupting circadian rhythms. A majority of research examining the effect of light on circadian rhythms was conducted on shift workers or animals in controlled environments who were exposed to very high light levels (Borugain, Gallagher, Friessen, Switzer, & Aronson, 2005; Cisse, Peng, & Nelson, 2016, 2017; Dauchy, Xiang, Mao, Brimer, Wren, Yuan, Anbalagan, Hauch, Frasch, Rowan, Blask, & Hill, 2014; Fonken, Aubrecht, Melendez-Fernandez, Weil, & Nelson, 2013; Lewy, Wehr, Goodwin, Newsome, & Markey, 1980; Schernhammer, Lade, Speizer, Willet, Hunter, Kawachi, Fucjs, & Colditz, 2003).

Relationship to street lighting:

- Duration of exposure to light is much lower than the duration of exposure for shift workers.
- Light levels from street and outdoor lighting are also much lower than those in a lighted nighttime work environment (McLean, 2016).
- Exposure to light levels from inside a person's home could be much higher than exposure to light levels from street lighting (Kinzey, 2016).

Another study (Lerhl, Schindler, Eichhorn, F., & Erren, 2009) assessed the effect of melatonin suppression induced by indirect blue light from inside a stationary automobile and reported no melatonin suppression when exposed to light level of up to 1.25 lux (lx).

Some epidemiological studies that examined the effect of artificial light at night on the incidence of breast cancers found that higher levels of outdoor artificial light at night were correlated with higher incidences of breast cancer (Hurley, Goldberg, Nelson, Hertz, P.L., Bernstein, & Reynolds, 2014; Kloog, Haim, Stevens, Barchana, & Portnov, 2008; Kloog, Stevens, Haim, & Portnov, 2010; Portnov, Stevens, Samociuk, Wakefield, & Gregorio, 2016). All of these studies used satellite imagery from the U.S. Defense Meteorological Satellite Program and light levels to estimate outdoor nighttime light exposure — but not measured at an individual level. Research also showed no relationship between light levels estimated from satellite imagery and light levels experienced by individuals (Rea, Brons, & Figueiro, 2011). However, no existing research shows that LED roadway lighting (of any SPD) at light-trespass levels and exposure durations in realistic road conditions disrupts human circadian rhythms.

Research also shows that using LED roadway lighting enables longer detection distances. A human factors study (Clanton & Associates Inc., 2014) compared various types of LED and HPS sources in an urban roadway environment and concluded that the CCT of an LED source could play an important role in detecting distance and relative safety.

Because CCT was the only metric available during the testing, it was used as the metric of interest. The study also incorporated a variety of colored targets located on the roadway under matched LEDs with different CCTs dimmed to match the road surface luminance. The targets were located in the roadway at points of equivalent vertical illuminance to control the object contrast. As a *foveal* task:

- Participants were asked to search for and indicate when they could perceive the target in the roadway.
- Targets were of different colors; therefore, the benefit of the lighting is believed to be from color contrast.

As noted, CCT was the only metric available during the time period of this testing; therefore, it is the metric used to describe the results. Research results found that objects lighted with a 4100K CCT had as much as a 20 percent higher detection distance over other color temperatures. Detection distances of color targets were also the highest for the 4100K CCT LED. The study results also indicated:

- To achieve the same level of visibility with a 3000K light source, higher levels of light are required than with a 4000K light source.
- The higher light levels needed for the 3000K LEDs could result in increased power consumption by about 8 percent to 10 percent compared to the 4000K LED (McLean, 2016).
- Therefore, reducing the blue spectral component in the light source may increase energy consumption.

Researchers argue that to correctly understand the effect of light on the disruption of circadian rhythms, light stimulus must be measured in terms of circadian response rather than in terms of the conventional visual response (Figueiro, 2017). One proposed mathematical model (Rea, Figueiro, Bullough, & Bierman, 2005) allows the response of acute melatonin suppression to be predicted after 1-hour exposure to a specific light level and light spectrum. The circadian light (*CLA*) is comparable to photopic lux measured at the eye (but takes into account the circadian response of the eye) and can then be used to determine circadian stimulus (*CS*). The CS is the effectiveness of the incident light at suppressing melatonin and ranges from 0 to 0. 7, where 0. 1 is the threshold CS and 0. 7 is the saturation CS. Comparing CLA values for 4000K and 3000K LEDs showed that the 4000K LED was less effective at melatonin suppression than the 3000K LED (Rea, 2017).

The biological effects of light on humans can also be measured in terms of the response of the five potential *photoreceptors (short-wavelength cones, medium wavelength cones, long-wavelength cones, the intrinsically photosensitive retinal ganglion cells [ipRGCs], and rods*) in the eye, which can affect circadian responses (Lucas, Peirson, Berson, Brown, Cooper, Czeizler, Figueiro, Gamlin, Lockley, O'Hagan, Price, Provencio, Skene, & Brainard, 2014).

The five sensitivity functions (one for reach receptor) can be used to calculate the activation of each of the receptors, which can help compare the light sources of different SPDs. Research evaluating the effect of time of exposure and light level from 3000K and 4000K LEDs on melatonin suppression (Lighting Research Center, 2016) showed that time of exposure and the light level significantly affected melatonin suppression. CCT (or the light source spectrum) did not significantly affect melatonin suppression. These results show no discernable differences between the CCTs of the 3000K and 4000K LEDs in terms of health effects; however, a higher light level is required for the 3000K LED to maintain a level of visibility similar to the 4000K LED, which causes higher energy consumption.

In 2021, The National Academies of Science issued the study *LED Roadway Lighting: Impact on Driver Sleep Health and Alertness*. One purpose of this study was to determine if roadway lighting, at currently recommended light levels, affected human health. Testing was to determine melatonin levels in saliva in various test conditions and gauge any change caused by roadway lighting. The results of this study determined that, based on salivary melatonin suppression, there was no effect to sleep health for LED roadway lighting.

Other environmental impacts include the effect of roadway lighting significantly delaying the maturity of plants like soybeans that need a night cycle to mature. Research that evaluated the effect of HPS road lighting on the maturity of the soybean plants in Illinois showed that soybeans exposed to light trespass were delayed from two to seven weeks (Palmer, Gibbons, & Bhagavathula, 2017). The effect of LED roadway lighting on the maturity of soybean plants is yet to be reported. However, a study conducted in a lab examined the effect of the LEDs with increasing amounts of blue content on the growth and development of soybeans and reported that higher blue content LEDs resulted in shorter stems (Cope & Bugbee, 2013). Overall, lower blue content LEDs resulted in stem elongation and leaf expansion, and higher blue content LEDs resulted in plants that are more compact. These results show that blue content on the LED spectrum of roadway lighting could potentially influence the maturity of soybeans, and that proper precautions must be taken to limit light trespass into fields adjacent to lighted roadways.

The presence of artificial light also affects the activities of wildlife. For example, the regular movements of hatchling marine turtles toward the sea occur primarily at night, but the presence of artificial light disrupts their photic cues and can cause them to move away from the sea, which often leads to mortal consequences (Peters & Verhoeven, 1994). Artificial light also adversely affects specific breeds of bats (Rydell, 1991) and mice (Bird, Branch, & Miller, 2004) that forage predominantly in areas of darkness. Because roadway lighting can affect the health, growth, behavior, and maturity of some plants and wildlife, it is important to engage in research that leads to favorable outcomes for both ecology and highway safety.

4. METRICS FOR LIGHTING

4. 1 INTERSECTION LIGHTING

According to AASHTO GI-7, intersection lighting should illuminate key decision points and conflict points (**Figure 14a**). Crosswalks are a crucial part of the intersection, thus, the lighting designer should always consider positive contrast for pedestrians. Poles positioned in advance of the crosswalk provide this positive contrast, as **Figure 14b** shows. The advantage to providing positive contrast (lighting the approach side of the pedestrian in the crosswalk) is that vehicle headlights help increase that contrast and improve the visibility of the pedestrian in the crosswalk.

(a)

(b)

Figure 14 (a). Plan View for Conflict Points; (b) Positive Contrast for Pedestrians.

Roadway designers should use vertical illumination calculations in pedestrian conflict areas and in areas of higher pedestrian use to increase detection of pedestrians. These calculations are taken along the crosswalk centerline at a 5-ft (1.5-m) height, with the vertical calculation point orientated toward the approaching vehicle. Some lighting guides recommend that vertical lighting levels in the crosswalk be equal to the average horizontal illuminance provided within the intersection.

Negative contrast (or silhouette) designs have also been used for crosswalks at intersections where intersection lights are on the opposite side of the intersection. Negative contrast of objects has been found to increase visibility; however, when headlights are accounted for, this advantage can be minimized.

Both intersection lighting methods have differing visibility benefits costs and should be considered in context with the intersection arrangements and goals.

Intersection Lighting for Continuously Lighted Roadways

Historically, the approach to intersection lighting was to increase the lighting level in the area of the conflict points within the intersection to 1.5 to 2 times the approach roads or by simply summing the recommended levels for each road to determine the intersection value. This methodology was based more on consensus than research. The Illinois Center for Transportation, in conjunction with FHWA and VTTI, prepared Research Report FHWA-ICT-21-023 *Roadway Lighting's Effect on Pedestrian Safety at Intersection and Midblock Crosswalks*. The study evaluated safety countermeasures, including visual performance of drivers at several intersections and midblock crosswalks. The study recommended that intersections be illuminated to a minimum of 14 lux and up to 24 lux when visual complexities are considered, e. g., the likelihood of opposing vehicle headlights or ambient lighting in the area around the intersection.

Intersection Lighting Design (location of luminaires)	Average Horizontal Illuminance lx (fc)
Approaches	14 (1.3)
Exits	24 (2.2)
Luminaires located on the signal mast arm directly over the crosswalk (IDOT lighting design)	14 (1.3)

Figure 15. Lighting Levels from FHWA-ICT-21-023.

4. 2 PARTIAL INTERSECTION LIGHTING

The Virginia Transportation Research Council conducted research with VTTI and issued report VTRC 20-R31 *Safety Benefits and Best Practices for Intersection Lighting*. Based on study results and crash analysis, agencies can develop minimum lighting levels for un-signalized and signalized intersections. **Figure 16** below includes light levels for the area of the intersection box, which is defined by the intersection itself extending to the STOP bars of the intersecting streets. Based on the variables and methodology used in this and other research on this topic, these levels are considered appropriate for intersections of unlit approach streets. The values include the minimum illuminance level for any point within the intersection, as well as average illuminance and minimum uniformity.

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

Figure 16. Lighting Levels from VCRT 20-R31.

4. 3 AREAS OF HIGH PEDESTRIAN RISK

Some areas have a high risk for pedestrians because of the volumes and demographics of the users. An example of this children traveling to school. The 2023 FHWA *Lighting Handbook* (Gibbons, Lutkevich, and McLean) states:

> These children may travel at twilight, in both the morning when going to school and in the early evening when coming from school, which creates unique issues. Children are especially vulnerable to traffic. In addition to being small and easily distracted, children:
>
> - Have difficulty judging the direction of sounds, estimating the speed and distance of oncoming vehicles, and anticipating driver behaviors.
> - In a recent virtual reality simulation performed at the University of Iowa, 6-year-old children were struck 8 percent of the time when crossing busy one-lane streets, while the crash rates for 8-, 10-, and 12-year-old children were 6 percent, 5 percent, and 2 percent, respectively.
> - Children's difficulty in crossing streets involves limited ability to judge the available gap in traffic at a young age.
> - Younger children also need more time to take the first step to cross the street, which shortens the available gap.
> - Children's crossing speeds do not differ from those of adults (O'Neal et al., 2018).

One safety improvement to consider is higher light levels for pedestrians in these areas. FHWA / VTTI produced Research Report FHWA-SA-20-062 *Street Lighting for Pedestrian Safety*, which was also the basis for FHWA-SA-21-087 *Pedestrian Lighting Primer*. As part of that study, researchers conducted driver experiments to determine visibility in terms of detection distance for child-sized mannequins along the side of the road. Research variables included light levels as well as source color. The design metrics evaluated included roadway luminance and vertical illuminance of pedestrian areas, in addition to semi-cylindrical illuminance of pedestrian areas, as **Figure 17** shows. Semicylindrical illuminance is a realtively new concept in the U.S., but it has been used in other standards for decades. To better understand the method, refer to CIE 140 *Road Lighting Calculations*. It is available in commonly used roadway lighting software as part of the CIE 140 standard calculation metrics.

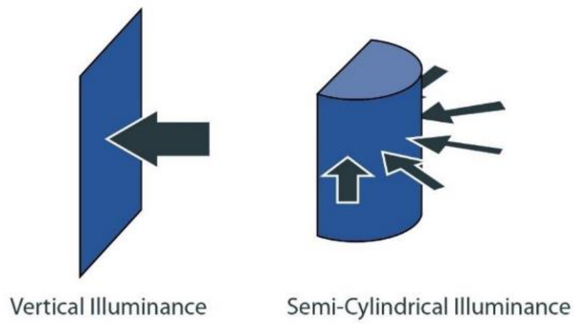


Figure 17: Existing an Emerging Metrics

The results of the experiment of FHWA-SA-20-062 were used to develop design criteria for these types of areas. The values included are in either vertical illuminance or semicylindrical illuminance for pedestrain areas and values for the luminance of the roadway. The categories of average luminance shown with asterisks in **Figure 18** are the values recommended in AASHTO and IES. This research also showed better performance using 4000K sources; however, if there are other considerations for CCT by the surrounding areas, then consider a minimum of 3000K sources.

Pedestrian facility characteristics		Light Source Characteristics			
		Average Illuminance	Average Luminance		CCT (LED only)
			Rural	Urban	
Intersection crosswalk		30 lux vertical	*	*	3000 K to 4000 K
Midblock crosswalk		20 lux vertical	*	*	3000 K to 4000 K
Facility adjacent to roadway	Low[2] to Medium[3] Pedestrian Activity	2 lux vertical	*	1 cd/m^2	3000 K to 4000 K
	High[4] Pedestrian Activity and/or School Zones	10 lux SC	1 cd/m^2	2 cd/m^2	3000 K to 4000 K

Figure 18. Light Levels from FHWA-SA-20-062.

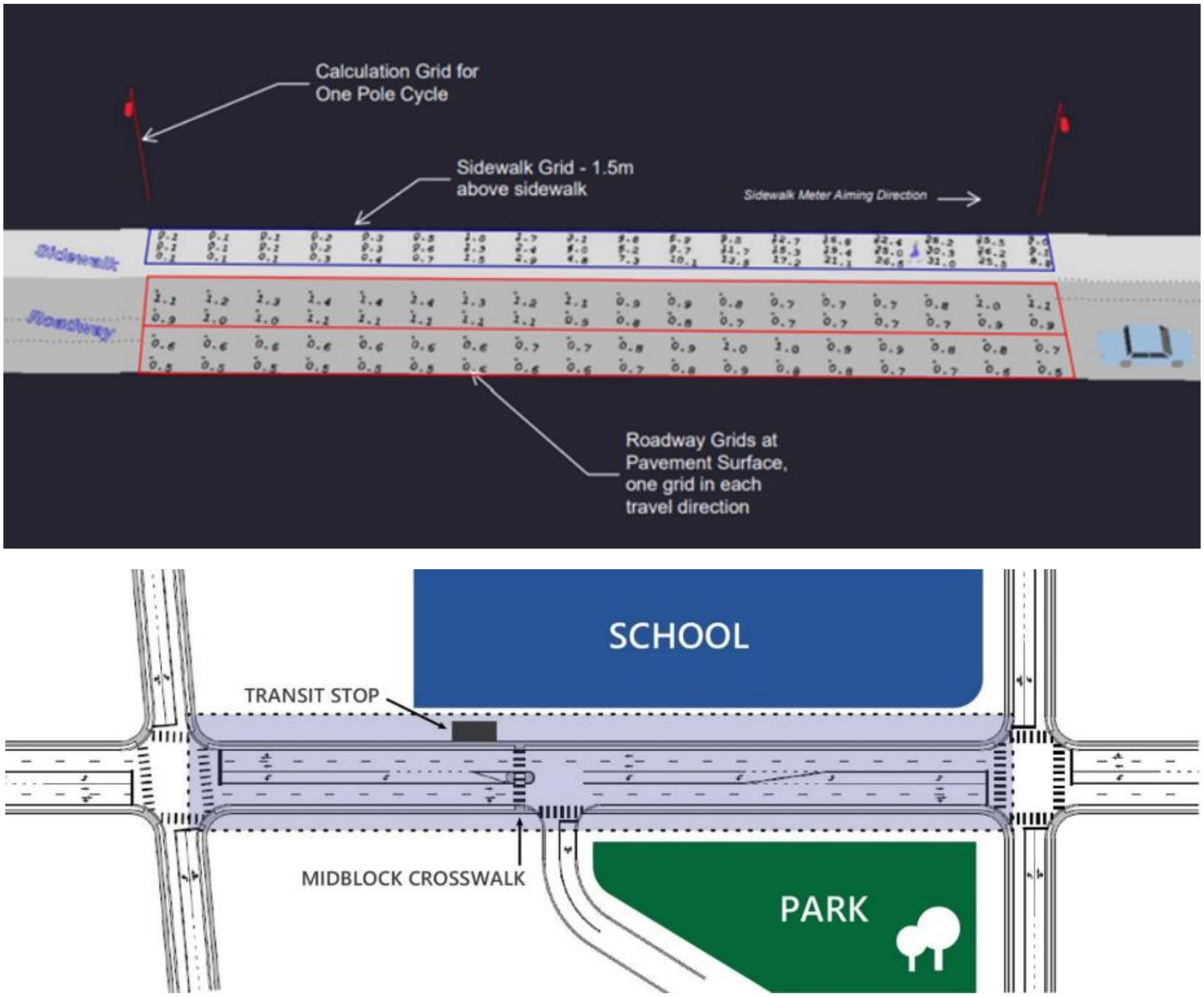


Figure 19. Grid Placement Included in FHWA-SA-20-062.

Figure 19 shows grid placement for roadway and sidewalk grids.

5. SUMMARY OF LITERATURE REVIEW FINDINGS

The following conclusions are derived from reviewing available research related to roadway lighting for pedestrian safety. These include:

- Lighting is a contributing element to pedestrian safety.
- Currently available design standards consider pedestrian safety as part of their recommendations. Most relevant is ANSI / IES RP-8-22, which includes recommendations for surround ratio to help with visibility, as well as horizontal and vertical illuminance for intersections and midblock crosswalks. The standards also provides disability glare criteria to limit visibility reductions.
- The City's *Complete Street Guideline* references Alexandria's requirements to meet the recommended values in ANSI / IES RP-8-00. Always consider any updates that reference the current versions, which include the updates previously mentioned.
- The spectral content of the lighting system used can affect the ability to detect distances of pedestrians. Current research shows 4000K sources generally provide greater detection distances. These findings do not restrict lighting CCT to 4000K because there are other factors to consider that may also warrant slight increases in lighting levels when using other CCT light sources.
- Based on recent studies, roadway lighting — when used in the ranges recommended by IES and AASHTO — do not present a health risk to humans. There are however other effects of light at night on flora and fauna, which should be considered when lighting is provided for safety.
- Lighting recommendations for intersections and crosswalks are available but, based on recent research, may be modified in the future. The change based on the research would likely slightly reduce the current recommended values.
- Lighting for high-risk pedestrian areas like schools requires higher lighting levels based on recent research and will likely work their way into national standards.

In addition to the findings of this literature review, the Research Team also had a discussion about existing lighting, available streetlights, and process(es) with Dominion Energy, should a special request be made for a streetlight not currently included in its inventory. The results of that discussion include the following:

- Streetlights were converted to LED in the 2020 to 2022 timeframe.
- Dominion Energy does not design the street lighting; rather, it installs what is requested and assumes the design was by others. It is unclear if any design was performed for the LED conversions.
- Dominion has an inventory of standard light fixtures, which includes LED.
- When there is a request for a different light fixture from what is in its inventory, Dominion has established a rate structure and requires that the requestor store all spare light fixtures to be used for maintenance.