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Lighting Handbook

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Cover Photo, Ronald Gibbons, VTTI

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16. Abstract This handbook has been prepared to provide recommendations to lighting designers and State, city, and town officials concerning the design and application of roadway lighting. It is not intended to be a detailed design guide. It is primarily a resource for policy makers and the design and construction community to evaluate potential needs, benefits, and applicable references when considering a roadway or street lighting system. This handbook is an update of the document published in 2012 by the Federal Highway Administration (FHWA).		
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acronyms

Abbreviations	Definition
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AMA	American Medical Association
BIPOC	Black, Indigenous, and People of Color
CCT	Correlated Color Temperature
CFL	Continuous Freeway Lighting
CIE	Commission Internationale de l'Eclairage
CIL	Complete Interchange Lighting
CMF	Crash Modification Factor
CMS	Central Management System
CPTED	Crime Prevention Through Environmental Design
CSAPH	Council on Science and Public Health
C-V2X	Cellular Vehicle-To-Everything
DGONE	Discomfort Glare in Outdoor Environments
FARS	Fatality Analysis Reporting System
FCC	Federal Communication Commission
FHWA	Federal Highway Administration
GHSA	Governors Highway Safety Association
HID	High-Intensity Discharge
HPS	High-Pressure Sodium
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America

ipRGC	intrinsically photosensitive Retinal Ganglion Cells
ITS	Intelligent Transportation Systems
LCS	Luminaire Classification System
LDD	Luminaire Dirt Depreciation
LED	Light-Emitting Diode
LLD	Lamp Lumen Depreciation
LLFs	Light Loss Factors
LOS	Level Of Service
LZs	Lighting Zones
MTBF	Mean Time Between Failure
NCHRP	National Cooperative Highway Research Program
NEC	National Electric Code
PIL	Partial Interchange Lighting
PPFD	Photosynthetic Photon Flux Density
SPD	Spectral Power Distribution
SR	Surround Ratio
SRTS	Safe Routes to School
SSSD	Safe Stopping Sight Distance
STV	Small Target Visibility
TAC	Transportation Association of Canada
U.S.	United States
UPD	Unit Power Density
USDOT	U.S. Department of Transportation
VPH	Vehicles Per Hour
VTTI	Virginia Tech Transportation Institute

2023 FHWA Lighting Handbook

Purpose of Handbook

This handbook has been prepared to provide recommendations to lighting designers and State, city, and town officials concerning the design and application of roadway lighting. It is not intended to be a detailed design guide. It is primarily a resource for policy makers and the design and construction community to evaluate potential needs, benefits, and applicable references when considering a roadway or street lighting system. This handbook is an update of the document published in 2012 by the Federal Highway Administration (FHWA).

The primary goal of this handbook is improving safety for common roadway lighting applications with a focus on how best to apply roadway lighting in various applications.

Documents available from organizations such as the American Association of State Highway and Transportation Officials (AASHTO), the Illuminating Engineering Society (IES), the Transportation Association of Canada (TAC), and the Commission Internationale de l'Eclairage (CIE) offer recommendations on lighting levels, lighting configurations, and other considerations. This handbook directs users to that information where applicable and provides supplemental information on topics not addressed in those documents.

The primary goal of this handbook is to improve safety for common roadway lighting applications. It focuses on how best to apply roadway lighting in various applications and is therefore educational in nature. The handbook is also intended to further clarify and enhance elements discussed in the above-mentioned publications. However, this document does not provide the lighting level recommendations found in other publications. Any lighting level recommendation tables are cited but not included.

This handbook uses metric units, such as lux, which are defined in IES RP-8-21, CIE publications, and much of the research cited herein. The metric unit lux can be converted into footcandles (imperial) as follows: 1 footcandle = 10.76 lux.

This document is divided into two parts: Part I provides technical discussion and recommendations, while Part II provides lighting design examples to help illustrate the lighting design process.

Part I consists of six areas of discussion:

- Vision Principles and Lighting Metrics, including significant terms and concepts used in roadway and street lighting projects
- Lighting Considerations
- Warranting, including various warranting methods available when considering lighting
- Lighting Planning and Design Process
- Environmental Impacts and Mitigation
- Lighting Controls

Part II includes a section on general topics such as light source color and light trespass as well as examples that cover roadway lighting, tunnel lighting, and other roadway facilities as follows:

- Roadway Lighting
  - Urban Street Lighting
  - Rural Road Lighting
  - Expressway Lighting
  - Urban Freeway Lighting
  - Suburban Freeway Lighting
  - Rural Freeway Lighting
- Other Facilities
  - Roundabout Lighting
  - Walkway & Bikeway Lighting
  - At-grade Railway Crossing Lighting
- Tunnel and Underpasses
  - Short Tunnel Lighting
  - Long Tunnel Lighting
  - Underpass Lighting

Key documents that provide recommendations for roadway lighting design and associated applications further referenced in this document are listed below. The latest versions of these documents should be used as references for design projects.

- AASHTO GL-7 Roadway Lighting Design Guide (www.transportation.org)
- NCHRP Solid State Roadway Lighting Design Guide (www.trb.org)
- ANSI/IES RP-8-21-Standard Practice for Roadway Lighting (www.ies.org)
- ANSI/IES LP-2-20 Lighting Practice: Designing Quality Lighting for People in Outdoor Environments
- ANSI/IES LP-12-21 Lighting Practice: IOT Connected Lighting
- ANSI/IES TM-37-21 Description, Measurement and Estimation of Skyglow
- ANSI/IES RP-45-21 Horticultural Lighting
- FHWA-SA-14-015 Handbook for Designing Roadways for the Aging Population (www.fhwa.dot.gov)
- FHWA-SA-18-040/FRA-RRS-18-001 Highway-Rail Crossing Handbook, 3rd Edition (www.fhwa.dot.gov)
- FHWA-HRT-14-050 Guidelines for The Implementation of Reduced Lighting on Roadways (www.fhwa.dot.gov) Design Criteria for Adaptive Roadway Lighting
- FHWA-HRT-14-051 - Design Criteria for Adaptive Roadway Lighting (www.fhwa.dot.gov)
- FHWA-SA-20-062- Research Report: Street Lighting for Pedestrian Safety (www.fhwa.dot.gov)

- NCHRP 672 Roundabouts: An Informational Guide, 2nd Edition– Second Edition (www.trb.org)
- TAC Guide for the Design of Roadway Lighting (www.tac-atc.ca)

Additional useful non-lighting related documents include:

- AASHTO RSDG-4 Roadside Design Guide 4th Edition (www.transportation.org)
- AASHTO Highway Safety Manual (www.highwaysafetymanual.org)
- AASHTO – A Policy on Geometric Design of Highways and Streets 7th Edition (www.transportation.org)

Purpose and Benefits of Roadway and Street Lighting

In general, the purpose of roadway lighting is generally defined as follows:

- Provide a visual environment for road users to safely use the road system during hours of darkness.
- Reduce the impacts of disability glare from approaching headlights and off-roadway lighting, thereby improving visibility.
- Reveal objects on the roadway beyond the range of vehicle headlamps.

From a safety perspective, the main benefits of roadway lighting include:

- Increased visibility that could reduce fatal nighttime crashes up to 65% (Box, 1989). Roadway lighting allows for increased visibility of pedestrians in crosswalks, sidewalks, and pathways (FHWA, 2021) and increased visibility and detection distance of other potential road hazards, such as cyclists, wildlife, and other unexpected objects (Edwards & Gibbons, 2008; R. Gibbons, B. et al., 2015).
- Mitigation of headlamp glare.
- Increased visibility both in the roadway and along the sides of the roadway and greater visibility for older drivers (Gibbons, Edwards, Williams, & Andersen, 2008).

Other benefits of roadway lighting include:

- **Enhanced personnel security**. Lighting can enhance personal security by improving visibility of objects and other individuals in the roadway environment, including being able to discern intent.
- **Enhanced wayfinding.** Lighting provides wayfinding for road users and pedestrians on sidewalks.
- **Enhanced pedestrian safety.** Lighting improves the visibility of pedestrian trip hazards on sidewalks. An example is shown in Figure 1 where a well-lighted street highlights the sidewalk and any potential curbs or trip hazards.

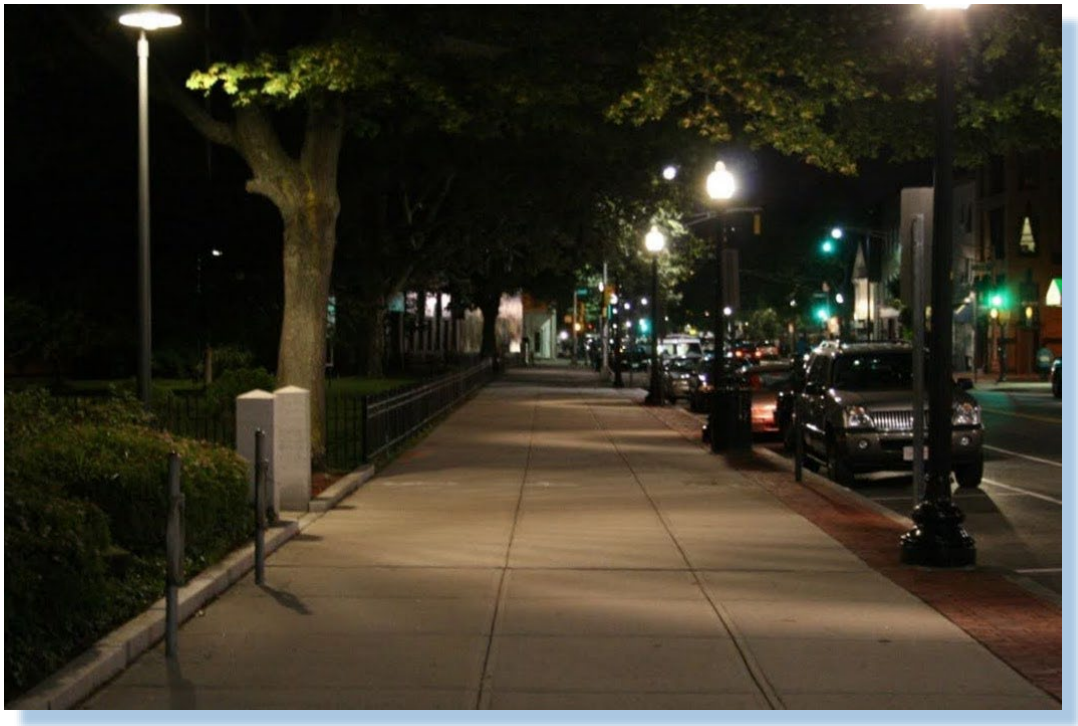


Figure 1. Photo. Pedestrian-scale lighting of a sidewalk (Image Credit: WSP).

- **Economic benefits.** Lighting may draw people into commercial areas by providing well-designed lighting for walkways and appropriate lighting design for the commercial area, which may increase business visibility and a sense of personal security, thereby increasing commerce. Decorative lighting can be used for economic revitalization by contributing to a "sense of place" or supporting a community architectural/urban design theme (Figure 1).
- **Improved aesthetics.** Lighting may draw attention to architecture and other aesthetic features on structures such as bridges and monuments. Figure 2 shows an example of aesthetic lighting on a bridge tower and cables. Aesthetic lighting cases that involve changing colors and light shows are becoming more commonplace. Such lighting should be reviewed carefully, as light show effects such as light chasing, flashing, and flickering may be distracting to drivers and, in some cases (3 Hz to 20 Hz), induce epileptic seizure (Wilkins, Veitch, & Lehman, 2010). Notably, aesthetic lighting, particularly on bridges, can also impact wildlife and fisheries (these issues are discussed later in the document).

Figure 2. Photo. Bridge structure lighting (Image Credit: WSP).

PART I – Technical Background

1 VISION AND PHYSIOLOGY PRINCIPALS & LIGHTING METRICS

1.1 Light and Vision

Many factors influence a road user's ability to see an object, including both the luminance and color contrast of the object (i.e., the difference between the object and its background); the person's adaptation level (which is affected by the brightness of the road and its surroundings, how much glare is present from approaching vehicles' headlamps and luminaires, etc.); and how long the person has to view other road users or a hazard. Understanding these factors is vitally important to developing an effective design for roadway and street lighting.

The eye adapts to different luminance levels, providing the capability to see under very low light levels. In practical terms, however, the nighttime driving scene does not consist solely of the road surface and potential hazards to be detected; it also includes extraneous light from bright sources such as opposing vehicle headlights, off-roadway light sources, and street lighting luminaires.

To understand the basic principles of vision, it is important to understand how the eye works. The basic components of the eye are shown in Figure 3. The human eye is complex; a more complete description can be found in Wyszecki and Stiles (1982).

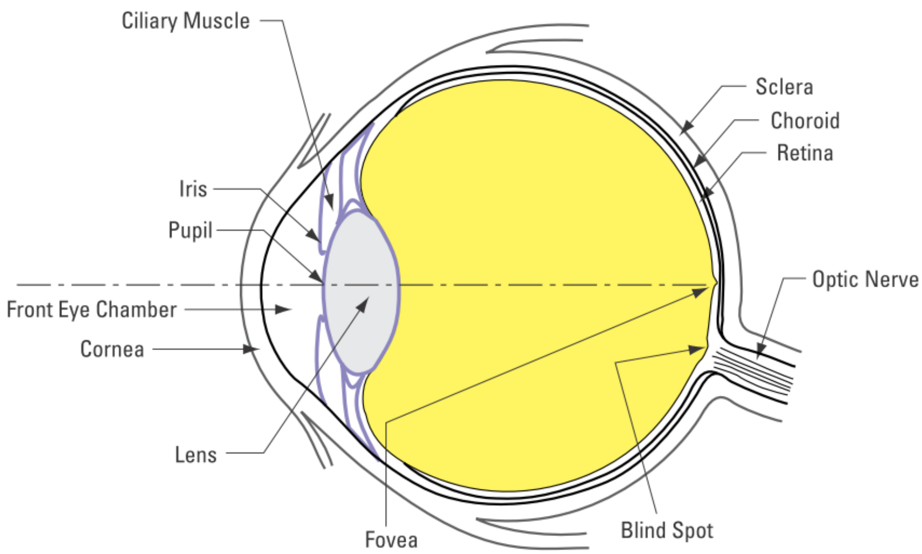


Figure 3. Diagram. Fundamental structure of the human eye (Transportation Association of Canada, 2006).

While the retina contains several photoreceptors, the only image-forming receptors are rods and cones. Rods, which are most numerous in the retina, are more sensitive, function at lower light levels, and are not color sensitive. Cones are sensitive to color and are divided into red (64%), green (32%), and blue (2%) cones (Williamson & Cummins, 1983). The cones are concentrated in the center of the retina with the most being in the fovea, which contains only cones. Cones provide the sensitivity and high-acuity vision needed for daytime tasks.

In the 1990s, a type of photoreceptor was discovered and named “intrinsically photosensitive Retinal Ganglion Cells” (ipRGCs). These ipRGCs are linked in the pineal gland in the brain, which is responsible for the production of melatonin, a hormone that drives the human sleep cycle and circadian rhythms. Ongoing research is exploring the links of these photoreceptors to human health and well-being.

The range of luminance (physical brightness) to which the retina can satisfactorily respond is much smaller than the range of luminance that occurs in nature and that the eye must view. The eye is equipped with two control mechanisms to overcome this problem:

- Alteration of pupil diameter. Pupil size is governed by the iris of the eye. Closing the iris reduces the pupil diameter, which decreases the amount of light entering the eye and falling on the retina. The iris is modified by a feedback system from the brain. If a bright object is viewed, the retina gives a signal to the brain, which then signals the iris to close. Thus, an unconscious control is continually exercised as the luminance of the field of view changes.
- Adaptation. The adaptation of the eye occurs in the retina as the eye adjusts to the varying brightness of a scene resulting from such things as the overhead lighting system, approaching vehicle headlights, and ambient lighting conditions. States of adaptation include:
  - Scotopic vision – vision by the normal human eye when only the rods of the retina are being used and the adaptation luminance at the eye is 0.034 cd/m^2 or lower. At this state of adaptation, there is no sensation of color.
  - Mesopic vision – when both the rods and cones are active at varying percentages based on the conditions and the adaptation luminance at the eye is between 0.034 and 3.4 cd/m^2. At this state of adaptation, the eye is sensitive to color (“bluer” at the lower end of the adaptation range and “redder” at the higher end).
  - Photopic vision – when predominantly cones are active and normal color vision is possible. The adaptation luminance at the eye is 3.4 cd/m^2 or greater.

  The various states of eye adaption as they relate to roadway lighting levels are defined in Figure 4. The eye does not shift suddenly from photopic to scotopic vision; rather, it undergoes a gradual change as light levels are reduced through the mesopic “twilight” range. The eye's mesopic response is a combination of the photopic and scotopic responses.

  For the purpose of roadway lighting, photopic adaption is used for lighting photometry. Mesopic factors (as discussed in the 2012 Lighting Handbook) have minimal impact on the lighting levels and are typically not applied (refer to Section 1.2.4, Spectral Effects).

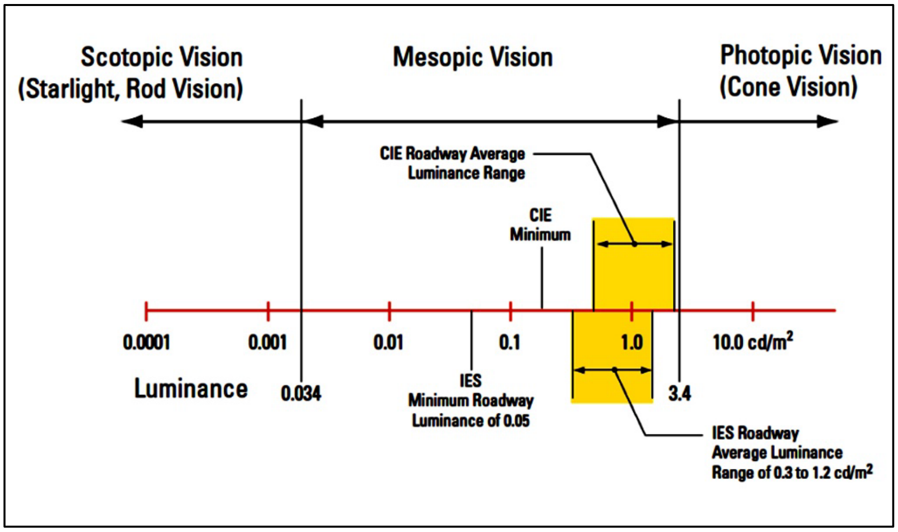


Figure 4. Diagram. States of eye adaptation as related to roadway lighting levels (Transportation Association of Canada, 2006).

1.1.1 Spectral Properties

Visible light represents a limited wavelength range of all electromagnetic radiation. Within this range, different wavelengths are seen as different colors. As Figure 5 demonstrates, radiation with a shorter wavelength on the visible spectrum is perceived as bluer in color, while radiation with a longer wavelength is perceived as redder in color.

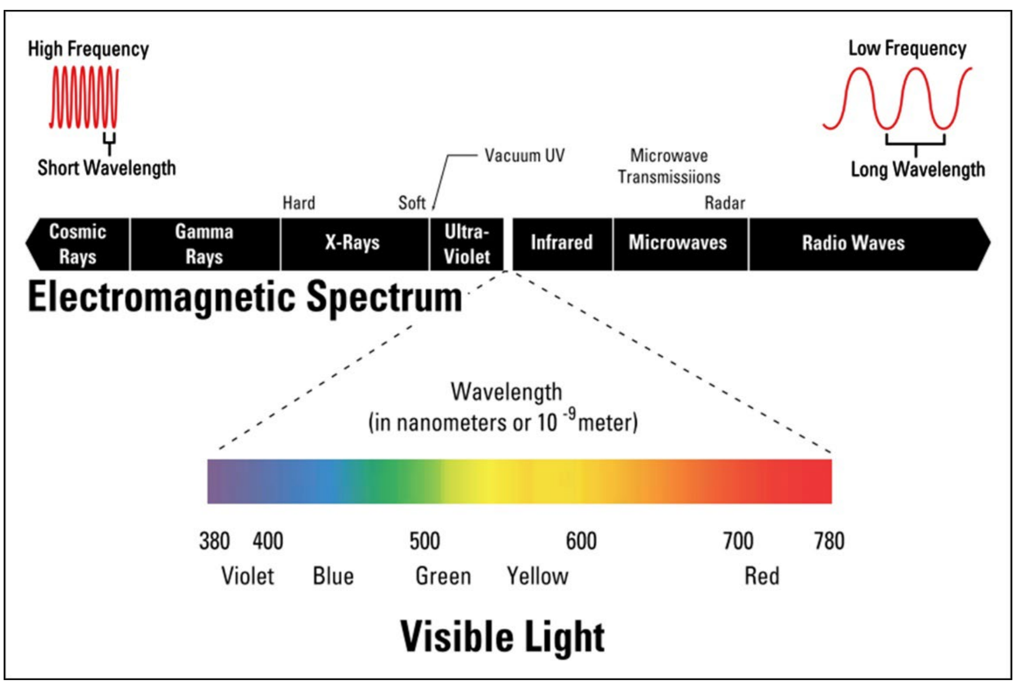


Figure 5. Diagram. Electromagnetic spectrum and visible spectrum (Transportation Association of Canada, 2006).

The eye has varying sensitivity to different wavelengths within the visible spectrum depending on the state of adaptation. Figure 6 shows the curves of relative spectral luminous efficiency at different wavelengths for day (photopic) vision (blue line with squares, known as the V Lambda [V(**l**)] curve) and night (scotopic) vision (orange line with dots). For photopic vision, light sources with wavelengths in the more "yellow" range, such as amber high-pressure sodium (HPS) sources, are rated at a higher power value (lumen), than sources with the same amount of "bluer" content, such as correlated color temperature (CCT) light-emitting diode (LED) sources. The scotopic curve, V'(λ), (orange line with dots) represents the eye response when using scotopic vision and shows that at low light levels, sources with more blue content are perceived to be brighter for the same lumen value, as a result of higher visual sensitivity.

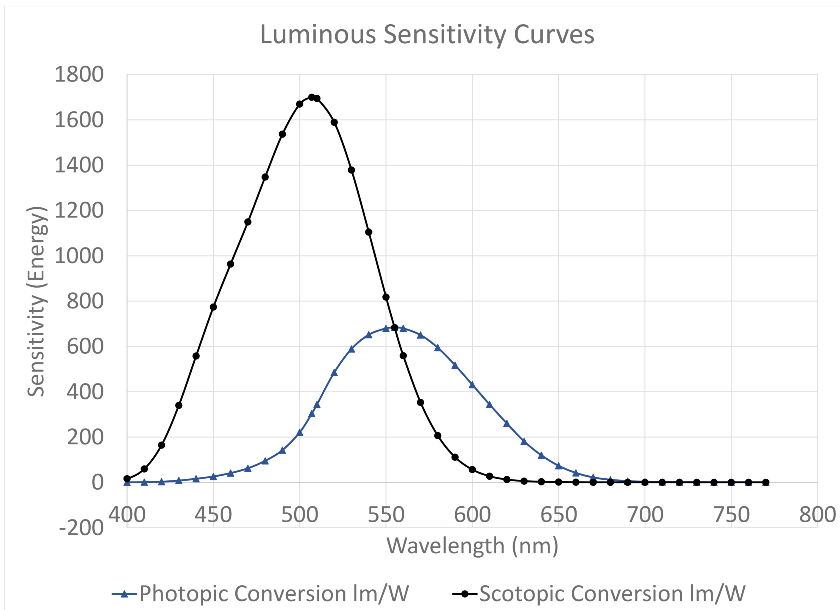


Figure 6. Line graph. Eye sensitivity curves. (Image Credit: VTTI)

> *While commonly used, CCT is not a good measure of the spectral properties of a light source. The spectral power distribution (wavelength in nm) should be used when assessing lighting sources for environmental impacts.*

CCT is defined as the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source (Illuminating Engineering Society, 2010). More simply put, CCT is a measure of the color appearance of a light source in degrees Kelvin. CCT is often used as a proxy for the color quality of a light source due to its ease of use. Two light sources with identical CCTs can be perceived differently, however; these differences are not reflected by CCT due to the loss of information caused by reducing the spectral power distribution of a light source into a one-dimensional metric (Durmus, 2021). Therefore, while commonly used, CCT is not a good measure of the spectral properties of a light source. The spectral power distribution (wavelength in nm) should be used when assessing lighting sources for environmental impacts (see Section 1.2.4, Spectral Effects).

1.2 Fundamentals of Visibility and Physiology

1.2.1 Contrast

Objects are seen by “contrast,” which is essentially the visible difference between an object and its background. There are two forms of contrast: the first is luminance contrast and the second is color contrast. Each contributes to visibility in a different way.

1.2.1.1 Luminance Contrast

For luminance contrast, an object that is darker than its background will be seen by “negative” contrast, while an object that is sufficiently brighter than its background will be seen by “positive” contrast. In Figure 7, the upright object shown in the upper frames is in negative contrast (a darker object silhouetted against a brighter background), and in the lower frames it is in positive contrast (brighter object against darker background). It is also worth noting that contrast may vary within the object itself. The upper right frame shows the bottom portion of the object in negative contrast, and the upper portion in positive contrast. The value of contrast can also change along an object’s length.

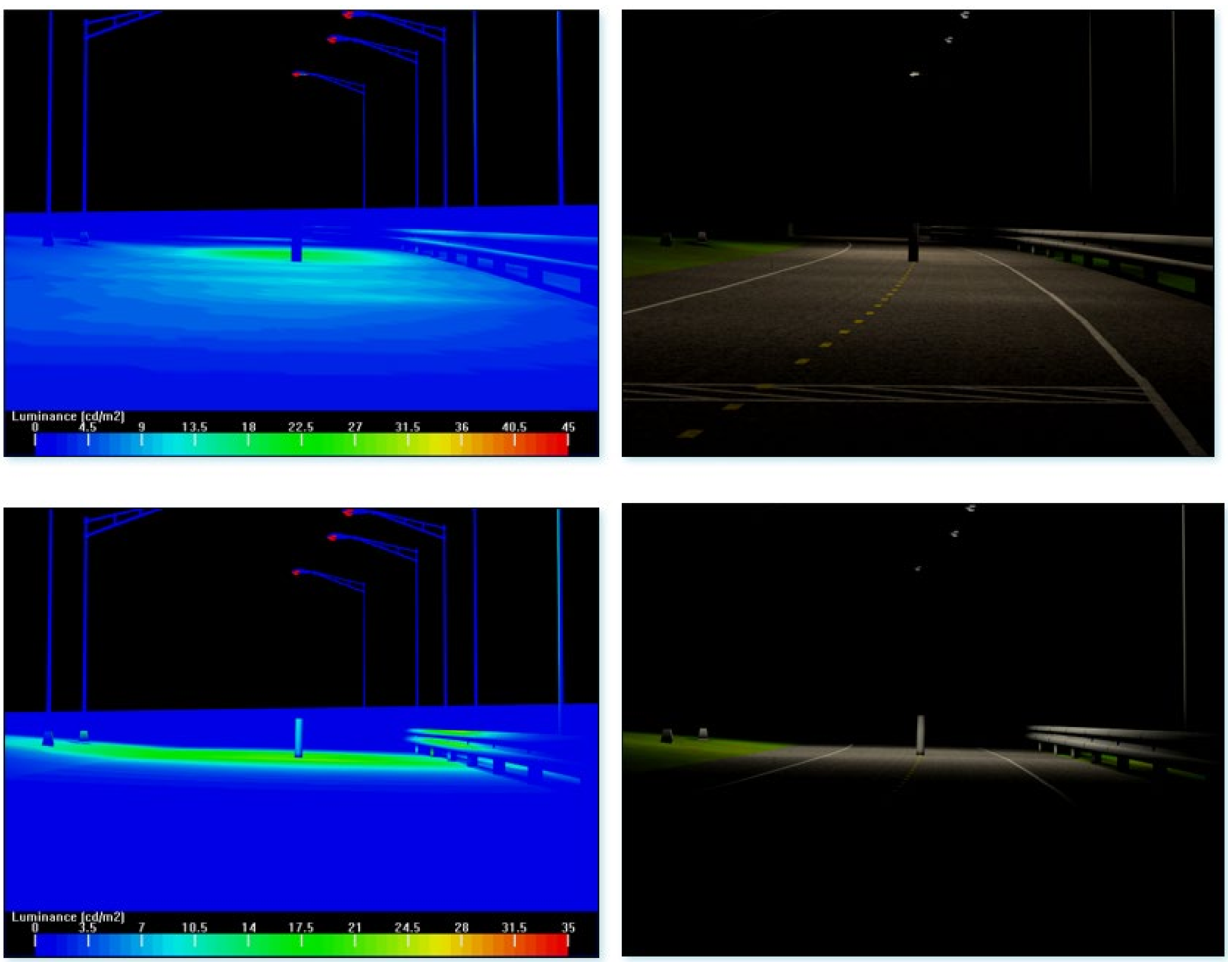


Figure 7. Luminance images and photos. Positive (lower) and negative (upper) contrast levels in pseudo-color (left) and visible (right) models (Image Credit: WSP).

The formula for calculating luminance contrast (Weber contrast) is shown in Equation 1.

Equation 1: Weber Contrast

$$\text{Contrast} = \frac{L_{\text{Object}} - L_{\text{Background}}}{L_{\text{Background}}}$$

L_{Object} = Luminance of the object

$L_{\text{Background}}$ = Luminance of the background

To assess contrast, a pseudo-color luminance calculation model can be undertaken (example shown in the left side of Figure 7). This modelling would not typically be undertaken as part of a usual lighting design and would be undertaken to prove concepts and methods.

As an example of a negative contrast calculation, the luminance values shown in the upper left panel of Figure 7 have been calculated as follows:

- Background luminance (blue area 1 cd/m^2),
- Lower portion of the cylinder, where the roadway is the background (green area = 22 cd/m^2)

Negative Contrast Equation: (1 cd/m^2 − 22 cd/m^2) / 22 cd/m^2 = −0.95 cd/m^2, with the negative value denoting negative contrast.

Similarly, for the object with positive contrast (lower left panel in Figure 7) the calculation is as follows:

- Luminance of the cylinder is 10.5 cd/m^2,
- Background is a dark sky with a luminance of 0.5 cd/m^2

Positive Calculation Equation: (10.5 cd/m^2 − 0.5 cd/m^2) / 0.5 cd/m^2 = 20 cd/m^2, where the positive value indicates positive contrast.

These two calculations are included only as examples and highlight an issue with the contrast metric: negative contrast is bound within the range of 0 to −1, whereas positive contrast is unbounded.

A roadway lighting system ensures that the actual contrast of an object on the road exceeds the threshold contrast required by the driver to detect the object. Obtaining this level of contrast is primarily a function of the lighting placement and optical characteristics.

How much contrast a person needs to see an object (i.e., the threshold contrast) depends on several factors, including the size of the object, how long a person looks at it, their age, and their adaptation luminance (determined by the luminance of the road, glare from lights, approaching headlights, and ambient lighting levels). Threshold contrast is defined as the probability of detecting an object 99.9% of the time (Adrian, 1989). The purpose of a roadway lighting system is to ensure that the actual contrast of an object on the road exceeds the threshold contrast required by the driver to detect the object. Blackwell and Blackwell (1971) suggested that good object visibility can be achieved if the actual contrast is three to four times the threshold contrast. Obtaining this level of contrast is primarily a function of the lighting placement and optical characteristics.

Small target visibility (STV) is a contrast-based metric for roadway lighting that can be used to design roadway lighting installations based on object visibility in the roadway. While no longer used as the primary metric for roadway lighting, STV provided insights for the placement of luminaires along the roadway with respect to crosswalks and intersections as well as the effect of uniformity in the roadway installation. Ultimately, the variability of the roadway scene and the nature of the potential objects that appear in the roadway limited the applicability of STV. However, STV can be used in roadway lighting design to compare various lighting layouts that all meet luminance and other design requirements.

Color contrast is important in the detection of objects in the roadway and can add as much as 20% to detection distance.

Thus, while there is no design metric for contrast, there are specific applications for which contrast can be used to determine design layout. Luminance contrast for an object in the roadway is typically a result of luminance driven by the vertical illuminance on the object, with horizontal illuminance providing the background luminance. This means that luminaires can be placed in a way that provides vertical illuminance on an object of concern. As an example, vertical illuminance on a crosswalk can increase the visibility of pedestrians within the crosswalk. In this case, contrast drives the visibility and is controlled by luminaire position (Gibbons et al., 2008).

1.2.1.2 Color Contrast

Color also provides additive contrast benefits. As shown in Figure 8, color contrast can improve the visibility of objects and pedestrians. This effect depends upon the color of the object or clothing and the color rendering ability of the source used for roadway lighting. For example, in the left frame of Figure 8, the pedestrian's red shirt and the red color of the approaching vehicle provide additional visibility via color contrast. However, this effect varies based on the environment. Both the light source spectrum and the spectral reflectivity affect the detection of objects in the roadway, which makes color contrast quite situational and variable. As such, the impact is not easily quantified and is generally not currently built into lighting design standards.

Figure 8. Photos. Effect of color contrast. (Image Credit: WSP)

As mentioned, the color of the light source affects the ability to generate color contrast. Light sources such as HPS do not provide a complete spectrum, meaning certain colors are not fully visible. However, LED sources allow for a more complete spectral output, and color becomes more significant. Research has shown that the selection of a 4000K light source provides an additional benefit over traditional ones through contrast and the balance of the spectrum in terms of red and blue content in the spectral power distribution (SPD).

The impact of contrast design to roadway lighting can be considered first as the position and layout of the luminaires, to provide luminance contrast, and the light source selection, to provide color contrast.

1.2.2 Glare

Non-uniformities in the visual field, particularly those caused by bright sources, affect the adaptation level of the eye. Because these sources tend to fluctuate as the road user proceeds, the adaptation level is constantly changing ("transient adaptation"). By stabilizing the lighting level on the roadway, roadway lighting thus aids the eye in adapting to an increased level of luminance compared to that provided by headlights alone. Bright sources create other effects, collectively termed "glare," which should be avoided as much as is practical.

Glare can be a significant problem that seriously impairs both safety and quality of life. Glare can be a serious safety hazard for both drivers and pedestrians because it demands attention (since one's eyes are naturally attracted to bright light) and causes an issue called transient adaptation when the eye's dark adaptation is destroyed and there is a loss of sensitivity to lower light levels while the eye adaptation recovers.

When cast into surrounding residential neighborhoods, glare not only detracts from quality of life, but it can also make it difficult for pedestrians and homeowners to see their surroundings. Glare is experienced when the light-producing source (such as a bulb or lamp) is directly visible, although it also depends on the luminance (brightness) of the light source and the contrast between the source and the surrounding background. For example, a very bright light source viewed against a daytime sky does not seem particularly glaring or objectionable; however, the same source viewed against a fully dark night sky would seem so bright as to be almost painful.

Glare or excessive brightness is a complex and difficult-to-measure phenomenon. Often the impact of glare is confounded with several other issues, including mood, predisposition to brightness, and past experiences. This makes the assessment of glare in the roadway difficult and often requires consideration of several competing issues.

1.2.2.1 Disability Glare

Disability glare is one of the most important elements to control in a lighting system. It affects the ability to adequately see, particularly for older drivers.

Light rays passing through the eye are slightly scattered, primarily due to 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. The effect is similar to looking at the scene through a luminous veil. The luminance of this veil is added to both the luminance of the objects in the roadway and background luminance, thereby reducing contrast (Equation 1). This effect is termed "disability glare" or "veiling luminance," and it can be numerically evaluated by expressing the luminance of the equivalent luminous veil. Consider the example of trying to see beyond oncoming headlights at night. In this case, contrast is reduced by disability glare, leading to decreased visibility. Increasing luminance can counteract this effect by reducing the eye's contrast sensitivity. A well-designed roadway lighting system will minimize glare by employing luminaires with proper optical design. Disability glare on the roadway should be limited to veiling luminance ratios recommended by AASHTO and IES.

1.2.2.2 Discomfort Glare

Discomfort glare results from overly bright light sources in the field of view and causes a sense of pain or annoyance. While its exact cause is not known, discomfort glare may result from pain in the muscles that close the pupil. 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. While discomfort glare can cause effects ranging from increased blink rate to tears and pain, it does not automatically reduce visibility, and roadway lighting standards do not specify numerical limits for discomfort glare.

LED and HPS light sources are not a significant source of discomfort glare for drivers on the roadway. The severity of discomfort glare is mainly affected by the light level, and even the highest roadway lighting level was not found to produce "noticeable" discomfort glare (Engineering & Medicine, 2020). Therefore, the sources of discomfort glare are typically off the roadway and do not include street and roadway lights (especially high-mast lighting) and illuminated signs.

CIE 243:2021, *Discomfort Glare in Road Lighting & Vehicle Lighting* (Commission Internationale de l'Eclairage, 2021) discusses discomfort glare in the context of road and vehicle lighting. This report provides an overview of the research methods, mathematical models, and variables considered to influence discomfort glare. CIE 243:2021 also describes the difficulties associated with evaluating and measuring discomfort glare and the variance in the models. The goal of the IES committee, Discomfort Glare in Outdoor Environments (DGONE), is to define a metric to measure and calculate discomfort glare.

Discomfort glare can be a source of complaint from residents located off the roadway. CIE 150, *Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations* provides information for assessing the source intensity of light sources set against a dark background. This document defines the maximum allowable intensity in candela from a light source based on physical and design criteria such as the size of the light source, the environmental zone, whether pre- or post-curfew, and the distance from the lighting source. Some lighting software can calculate the intensity at given locations.

> *Discomfort glare can be greatly reduced by adjusting the mounting height and shielding of the optical system.*

Several strategies can be applied to reduce or eliminate discomfort glare. For example, adding a diffusing lens over the optical system of pedestrian-scale luminaries can minimize discomfort glare caused by those mounted at 10 to 15 feet above the walkway. Eliminating the direct view of the optical system, which can appear very bright in the case of LED lighting, can also mitigate discomfort glare off the roadway. Discomfort glare can be greatly reduced by adjusting the mounting height and shielding of the optical system.

1.2.3 Perception-Reaction Time

Perception-reaction time, often referred to simply as reaction time, involves several components. To stop or avoid a hazard or person on a roadway, a motorist must first detect the object's presence, recognize or otherwise assess the object, and then react to that assessment. The mechanical operation of the braking/steering mechanisms and the road/tire/vehicle performance conditions also factor into perception-reaction time.

> *In many cases, a roadway lighting system is required to provide the visibility needed for a driver to detect a pedestrian or road hazard in time to stop at high speed.*

The key elements involved in reaction time include whether a situation is expected, cognitive load and distraction, personal physical response attributes, and age. In terms of whether a situation is expected, the AASHTO Green Book (American Association of State Highway and Transportation Officials, 2018a) classifies reaction times as follows:

- Expected: The driver is alert and aware of the possibility that braking will be necessary, providing the best reaction time possible. The best estimate is 0.7 seconds, which includes 0.5 seconds for perception and 0.2 seconds for movement (the time required to release the accelerator and depress the brake pedal).
- Unexpected: The driver detects a common road signal (e.g., braking by the car ahead or a traffic signal). The reaction time in this case is approximately 1.25 seconds (the AASHTO Green Book states that the reaction time is approximately 35% longer than in the expected condition) due to the increased perception time (> 1 second). The movement time remains around 0.2 seconds.
- Surprise: The driver encounters an unusual circumstance such as a pedestrian or another car crossing the road in the near distance. In this case, extra time is needed to interpret the event and decide on a response. The reaction time depends to some extent on the distance to the obstacle and whether it is approaching from the side and first viewed in the driver's peripheral vision. The best estimate for reaction time in this case is 1.5 seconds for side incursions and a few tenths of a second faster for straight-ahead obstacles. In surprise scenarios, the perception time is around 1.2 seconds, and the movement time lengthens to approximately 0.3 seconds.

The perception-reaction time affects the distance required for a driver to stop when encountering an object in the roadway. For example, a person traveling at 55 mph is moving at approximately 80 ft/sec. The distance traveled during the reaction time alone can be anywhere from 40 to 120 ft. When this is added to the distance covered during actual stopping, the total distance traveled can be significant. The AASHTO *Policy on Geometric Design of Streets and Highways* ((American Association of State Highway and Transportation Officials, 2018a) includes a method for determining stopping distance based on a number of factors, including reaction time. Table 1 and Table 2 show examples of estimated safe stopping sight distance (SSSD) based on the AASHTO method with modifiers showing the impact of roadway grades. Note that the SSSD calculations are typically for wet pavement.

Table 1. Metric AASHTO safe stopping sight distances on wet surfaces with variation due to grade (from American Association of State Highway and Transportation Officials (2018a)).

Metric						
Design Speed (km/h)	Stopping Sight Distance (m)					
	Downgrades			Upgrades		
	3%	6%	9%	3%	6%	9%
20	20	20	20	19	18	18
30	32	35	35	31	30	29
40	50	50	53	45	44	43
50	66	70	74	61	59	58
60	87	92	97	80	77	75
70	110	116	124	100	97	93
80	136	144	154	123	118	114
90	164	174	187	148	141	136
100	194	207	223	174	167	160
110	227	243	262	203	194	186
120	263	281	304	234	223	214
130	302	323	350	267	254	243

Table 2. U.S Customary AASHTO safe stopping sight distances on wet surfaces with variation due to grade (from American Association of State Highway and Transportation Officials (2018a)).

U.S. Customary						
Design Speed (mph)	Stopping Sight Distance (ft)					
	Downgrades			Upgrades		
	3%	6%	9%	3%	6%	9%
15	80	82	85	75	74	73
20	116	120	126	109	107	104
25	158	165	173	147	143	140
30	205	215	227	200	184	179
35	257	271	287	237	229	222
40	315	333	354	289	278	269
45	378	400	427	344	331	320
50	446	474	507	405	338	375
55	520	553	593	469	450	433
60	598	638	686	538	515	495
65	682	728	785	612	584	561
70	771	825	891	690	658	631
75	866	927	1003	772	736	704
80	965	1035	1121	859	817	782

Although stopping distances are not generally applied to roadway lighting, with the exception of tunnel lighting systems, the distances shown in Table 1 and Table 2 demonstrate one benefit of roadway lighting. Assuming that most low-beam vehicle headlights are effective approximately 300 ft in front of the vehicle (American Association of State Highway and Transportation Officials, 2018a), the stopping distance exceeds 300 ft when the vehicle speed is 40 mph or greater. For a driver to detect a pedestrian or road hazard in time to stop at high speed, the roadway lighting system therefore needs to provide the necessary visibility.

1.2.4 Spectral Effects

The color of light (wavelength) affects the response in the eye, which also depends on the eye's state of adaptation. While response curves for adaptation have been established for the photopic and scotopic states (as discussed above, the increase in blue sensitivity in the scotopic rod-driven vision), none have been established for the mesopic state, where the eye spectral sensitivity changes depending on the adaptation luminance based on the balance of rod and cone usage. Scotopic levels are too low to be applied to roadway lighting. IES TM-12-12 and *The Lighting Handbook, 10th Edition* (Illuminating Engineering Society, 2010) suggested that mesopic adjustment factors may be relevant to street and highway lighting calculations. However, an FHWA project demonstrated that these factors had no significant impact in a live roadway application (Gibbons et al., 2015). Since the driver is primarily photopically adapted, mesopic adjustment factors are not appropriate for street and highway lighting calculations at posted speeds of 25 mph and higher. Therefore, calculations for street and highway luminance and illuminance should be based on the photopic luminous efficiency function without mesopic adjustment factors.

The spectral contents of street and highway lighting products vary and are controllable to a limited extent. Luminaires are available with many different spectral contents from nearly monochromatic yellows and reds to combinations of red, blue, and green that appear as white light to many observers. Designers may select the spectral content of luminaires to achieve the effects of color in the environment of their projects (Illuminating Engineering Society, 2018). The color spectra of various light sources are shown in Figure 9. The spike around 450 nm in the spectra of the LED sources in Figure 9 is referred to as the "blue pump." The LED sources also have a much broader range of color compared to the HPS source.

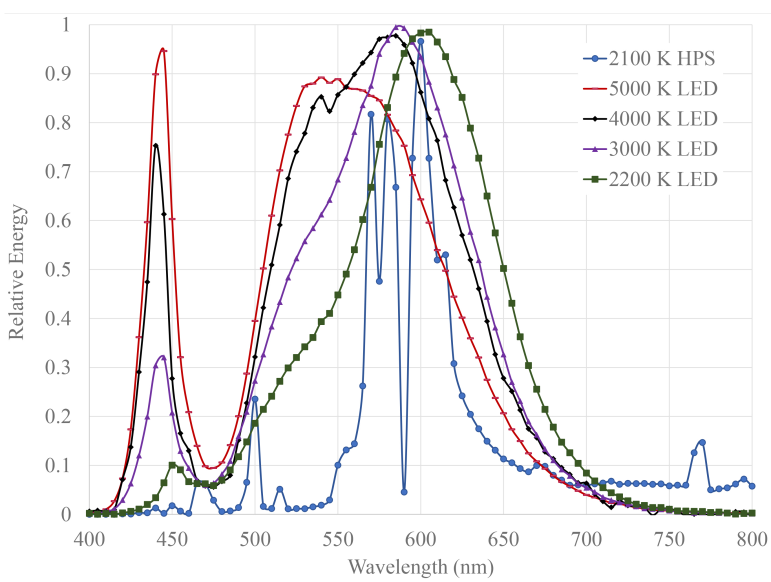


Figure 9. Line graph. Color spectra for various light sources. (Image Credit: VTTI)

Under some conditions, the color temperature of an LED or HPS light source does not affect the visual performance of drivers. However, as mentioned above, color contrast can be improved by the selection of the light source. National Cooperative Highway Research Program (NCHRP) research evaluated driver visual performance by measuring the detection distance of pedestrians at two different offset distances (2 and 10 ft on the right shoulder) and under two speeds (35 and 55 mi/h), three light sources (3000K, 4000K, and 5000K LEDs), and two surround ratios (high and low). Visual performance was maximized under the 4000K LED at both offset distances (Figure 10) and speeds (Figure 11), especially at the higher surround ratio. This result indicates that at higher speeds, 4000K LED lighting might be beneficial for increasing driver visibility (Engineering & Medicine, 2020). Similarly, other research has shown that the use of 4000K light sources generally improves object detection distance (Clanton & Associates & Virginia Tech Transportation Institute, 2014; Mutmansky et al., 2010)

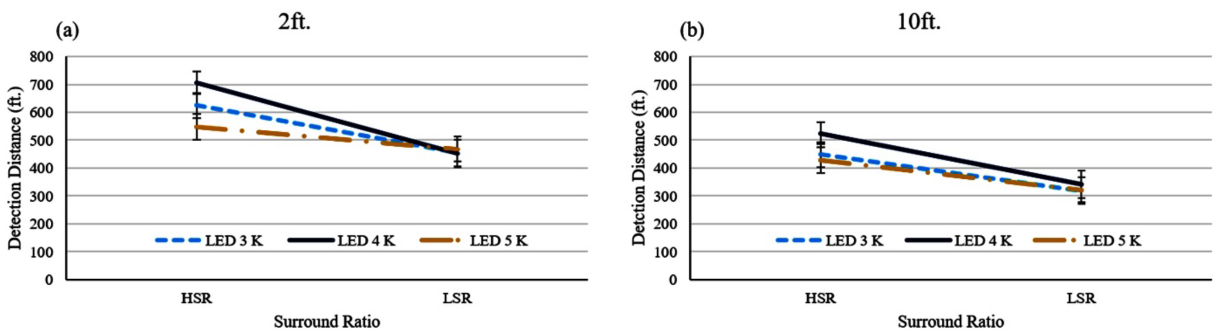


Figure 10. Line graphs. Effect of light source, surround ratio, and offset on the detection distance of pedestrians (Engineering & Medicine, 2020).

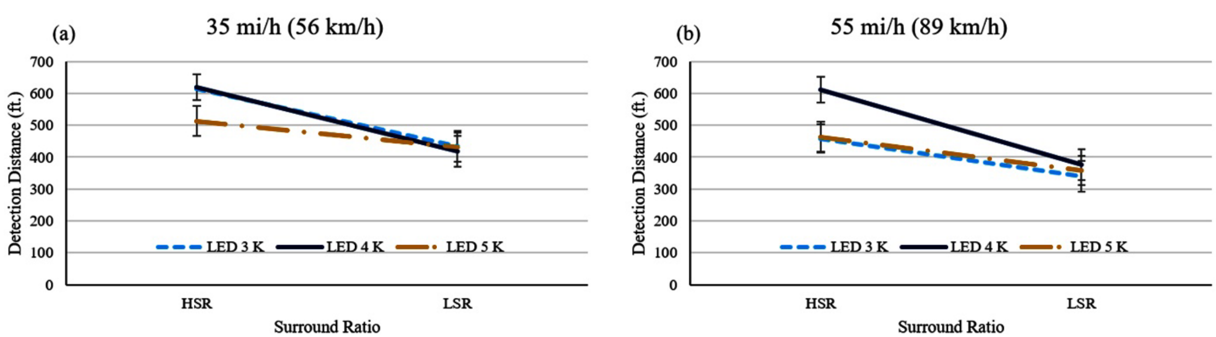


Figure 11. Line graphs. Effect of light source type, surround ratio, and speed on the detection distance of pedestrians (Engineering & Medicine, 2020).

The CIE S 026/E:2018 international standard (Commission Internationale de l'Eclairage, 2018) defines spectral sensitivity functions, quantities, and metrics to describe the ability of optical radiation to stimulate each of the five photoreceptor types that can contribute to retina-mediated non-visual effects of light in humans via the melanopsin-containing ipRGCs. CIE S 026/E:2018 is applicable to visible optical radiation in the wavelength range of 380 to 780 nm. It also includes information on the effects of age and field of view when quantifying retinal photoreceptor stimulation for ipRGC-influenced responses to light. An α-optic calculation toolbox and user guide were developed and are available through CIE.

Spectral effects as they relate to health and environment are discussed further in Section 6, ENVIROMENTAL IMPACTS AND MITIGATION.

1.3 Lighting Metrics

This section provides a brief overview of key lighting metrics used in lighting design. For a more complete explanation and definitions, refer to IES RP-8-21(Illuminating Engineering Society, 2021e).

1.3.1 Illuminance

Illuminance is a measure of the lumens incident on the pavement divided by the area. Illuminance follows the inverse square law; that is, the illuminance on a surface varies by the square of the distance from the light source. Illuminance is not impacted by the pavement's surface type or the angle of observation. Illuminance is measured as the number of lumens per unit area, either in footcandles (fc) (lumens/ft^2) or in lux (lumens/m^2). The conversion from fc to lux is 10.76, therefore 1 fc = 10.76 lux.

The drawback to illuminance as a metric is that the amount of luminous flux reaching a surface is often not indicative of how bright a surface is or how well a person can see.

As a lighting metric, illuminance is simple to calculate and measure. The determination of illuminance does not require consideration of the reflective properties of the roadway surface, and only an inexpensive illuminance meter is needed for field verification. The drawback to this metric is that the amount of luminous flux reaching a surface is often not indicative of how bright a surface is or how well a person can see.

Illuminance has two components (horizontal and vertical) and a third metric, semi-cylindrical illuminance, by which the light striking a semi-cylinder is measured (Figure 12).

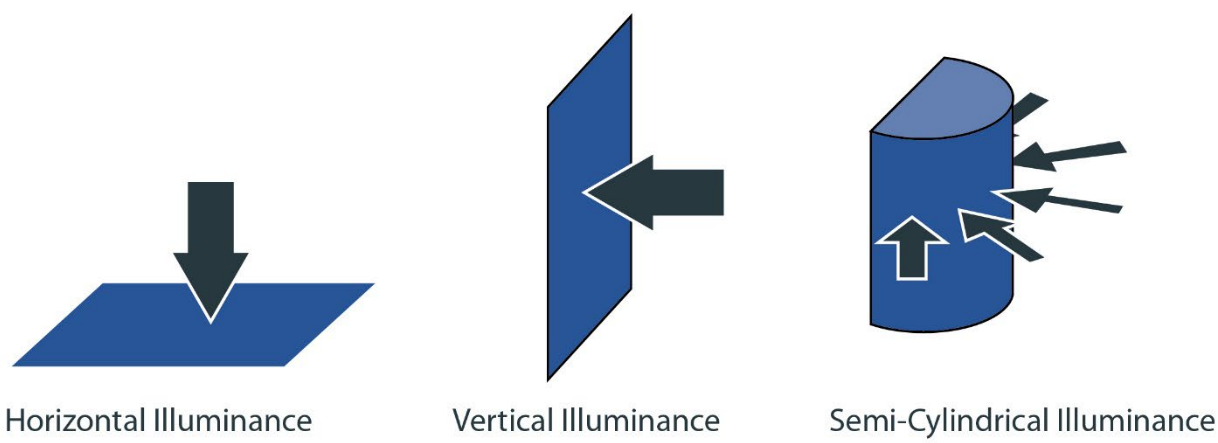
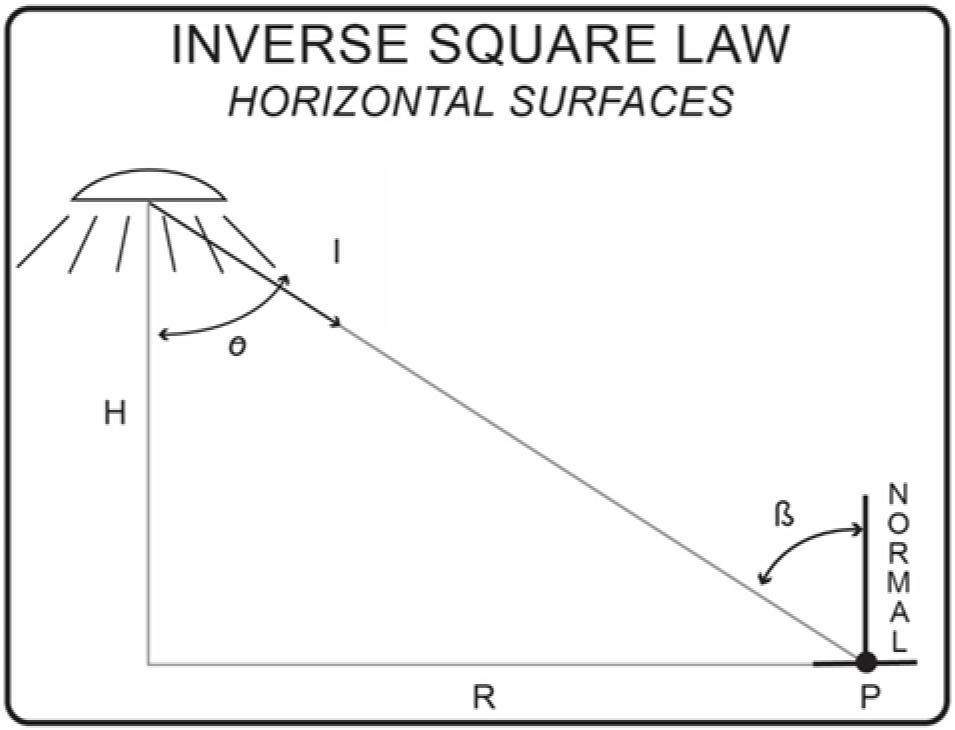


Figure 12. Diagram. Schematic showing the three aspects of illuminance.(Image Credit: VTTI)

1.3.1.1 Horizontal Illuminance

Horizontal illuminance (E) is the illuminance component falling on a horizontal surface, defined using the cosine of the angle of incidence. Figure 13 highlights the calculation method and the impact of the inverse square law. Here, the illuminance (E) is equal to the intensity from the luminaire (I) divided by the distance from the luminaire (D) multiplied by the cosine of the angle between the light ray from the luminaire and the normal to the surface being measured (β).



$$Illuminance = \frac{Intensity}{(Distance)^2} \times \cos\beta \qquad E = \frac{I}{D^2} \times \cos\beta$$

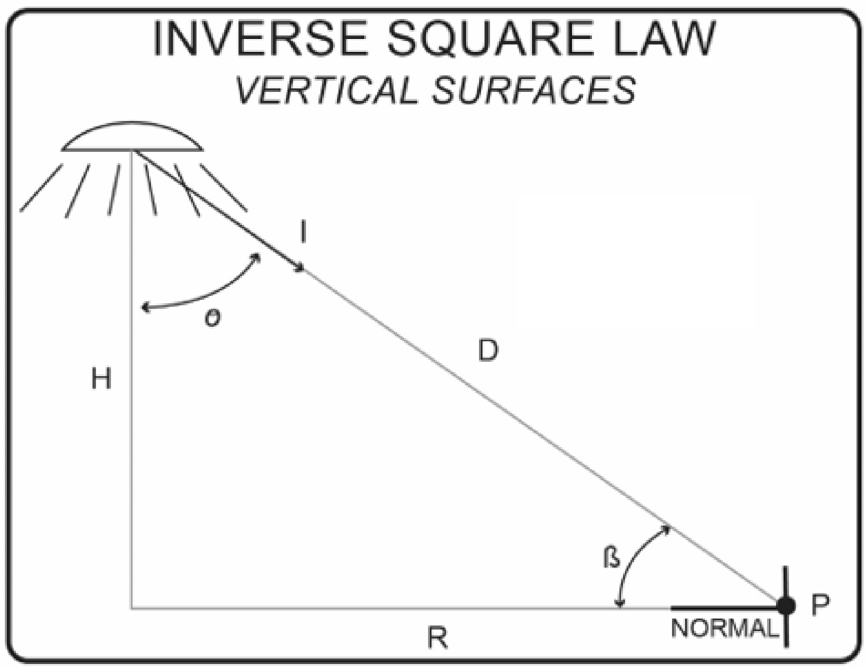
Figure 13. Diagram. Inverse square law calculation of illuminance at a point (Image Credit: IES).

Typically, illuminance is a poor measure of visibility. As an example, imagine a half-white/half-black surface. Due to the better reflectance of light on a white surface than on a black surface, the appearance of the white surface would be totally different from that of the black surface, even though each may be receiving identical illuminance. Our eyes do not see illuminance or the light incident on a surface; they only perceive the proportion of light reflected toward them.

Illuminance is the primary metric calculated for intersections and roundabouts, curved roadways (curve radius < 2000’), sidewalks, and railway crossings. Rather than using luminance as is used in tangent roadway sections, illuminance is used due to the geometry of the view of the roadway. As discussed later in this document (Section 1.3.2), pavement surfaces are evaluated at a 1-degree down angle assuming a person is looking 83 m in front of them. This is not the case for intersections and curves, as the driver’s glance point is different (Gibbons, Edwards, Bhagavathula, Carlson, & Owens, 2012), nor for pedestrians on sidewalks. As such, illuminance is used because the required geometry for the luminance calculation does not apply.

1.3.1.2 Vertical Illuminance

Vertical illuminance is the amount of illuminance that lands on a vertical surface. The units and properties are the same as horizontal illuminance. In roadway lighting, vertical illuminance is generally a reasonable criterion for determining the amount of light landing on pedestrians. It is also used as a criterion for determining adequate illumination for facial recognition from a security perspective. For roadway applications, vertical illuminance is most often used at a height of 5 ft above the roadway or sidewalk (the approximate height of a pedestrian's face). Figure 14 highlights the calculation method for vertical illuminance (note the position of the angle β is normal to a vertical surface rather than a horizontal surface as in Figure 13).



$$E_V = \frac{I \times \cos\beta}{D^2}$$

Figure 14. Diagram. Calculation of vertical illuminance.(Image Credit: IES)

Because vertical illuminance can represent the amount of light falling on pedestrians, vertical illuminance is important in terms of the visibility and detection of pedestrians from a safety perspective, especially those in or approaching crosswalks. This is discussed further in the examples in Part II.

1.3.1.3 Semi-cylindrical Illuminance

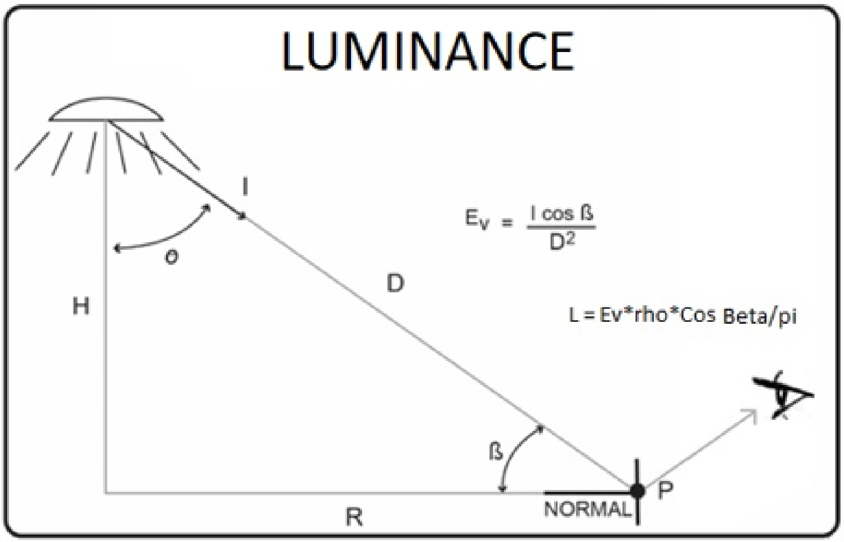
> *Semi-cylindrical illuminance is similar to vertical illuminance but shows all of the pedestrian profile.*

Semi-cylindrical illuminance is similar in principle and application to vertical illumination but is calculated differently. Semi-cylindrical illuminance is the average vertical illuminance on the curved surface of an upright semi-cylinder. It is calculated at 4.75 ft (1.5 m) above the road surface on a half-cylinder whose front is parallel to the main direction of pedestrian movement (for a road, the main direction of pedestrian movement is usually longitudinal). The calculation grid points are the same points as the roadway grid. Specific lighting calculation software is required to calculate semi-cylindrical illuminance. According to research (van Bommel, 2014), semi-cylindrical illuminance at face height is a better metric than vertical illuminance for recognition because the human face is three-dimensional and not flat. Therefore, semi-cylindrical illuminance is a better parameter to estimate visibility than a measure of illuminance incident on a flat surface (vertical/horizontal illuminance). It is important to note that semi-cylindrical illuminance has almost always been studied from the point of view of one pedestrian identifying another pedestrian on the street (Rombauts, Vandewyngaerde, & Maggetto, 1989). The effect of semi-cylindrical illuminance on the detection of a pedestrian by an approaching driver was investigated as part of a research effort for FHWA; the results suggest that semi-cylindrical illuminance is a similar metric to vertical illuminance but is more forgiving as it shows all of the pedestrian profile (Terry et al., 2020). As part of a cross-walk study, Gibbons et al. (2008) used a semi-cylinder as a surrogate for a pedestrian in human factors testing and found it to most closely models the detection of an actual pedestrian in the roadway.

1.3.2 Luminance

Luminance is a much better visibility metric than illuminance because it considers not only the amount of light that reaches a surface, but also how much of that light is reflected toward the driver.

Luminance is the amount of light that reflects from a surface in the direction of the observer. Luminance is often referred to as the “brightness” of the surface, although apparent brightness takes a number of other factors into consideration. Luminance is a much better visibility metric than illuminance because it considers not only the amount of light that reaches a surface, but also how much of that light is reflected toward the driver. Luminance is calculated using a fixed group of conditions. The observer is 83 meters back from the calculation point, the eye height of the observer is 1.45 meters, and the assumed viewing angle is down 1 degree (Figure 15). These conditions are fixed because of the limits of the R-tables (reflection tables) used to calculate luminance. Because of these fixed conditions, designers sometimes use illuminance-based calculations for areas like intersections and curved roadways where the assumptions of 83 meters back from the calculation point and a 1-degree downward viewing angle are not applicable.



$$E_V = \frac{I \times \cos\beta}{D^2} \qquad L = \frac{E_V \times P \times \cos\beta}{\pi}$$

Figure 15. Diagram. Calculation of luminance. (Image Credit: IES)

Luminance on the pavement is based on the quantity and direction of light, observer location, and the pavement reflectance characteristics. The overall average luminance of the road surface as observed from a specific point in cd/m^2 is used for roadway lighting calculations. Metric units for luminance are used regardless of the units used in the calculation specification. To calculate luminance, the observer position is 4.5 ft (1.45 m) above the pavement surface and 272.5 ft (83.0 m) back from the computation point along a longitudinal line parallel to the direction of travel. The observer line of sight is 1 degree below horizontal. Observer position changes relative to the curb line to align with each row of calculation points. A roadway luminance grid represents the calculation points for a single directional flow of traffic. To consider the entire roadway, a calculation grid should be created for each direction of traffic flow (Illuminating Engineering Society, 2018).

IES RP-8-21 defines luminance as the primary metric to be calculated for lighting on roadways, whereas AASHTO G-7 indicates that luminance or illuminance calculations can be used. Where possible, luminance is recommended to be used as it is a better measure of visibility. It is also important to note that defining the veiling luminance ratio (see Section 1.3.3) requires a luminance calculation.

1.3.3 Veiling Luminance (Lv)

Veiling luminance (also referred to as disability glare) can be numerically evaluated for street and roadways. Because veiling luminance reduces contrast, it also decreases visibility. Increasing the luminance level can counteract this effect by reducing the eye's contrast sensitivity. As glare limits visibility, veiling luminance is an important consideration.

The reduction of glare is one of the most important design factors related to visibility on the roadway. The calculation of veiling luminance is critical to quantifying that glare. Defining the veiling luminance ratio also requires the calculation of luminance.

Both IES RP-8-21 and AASHTO G-7 define Lv as a lighting requirement; however, it is sometimes omitted in calculations of illuminance. Given the significant impact of glare on visibility, Lv should not be omitted from the calculation.

As glare is a function of adaptation luminance, the road is used as the assumed scene from which the luminance reaches the eye. From this, the design metric (the veiling luminance ratio) is used as the metric of disability glare. Here, the ratio is calculated as the maximum value of calculated veiling luminance (Lv,max) divided by the average pavement luminance (Lavg).

Equation 2: Veiling Luminance

$$L_v = \frac{L_{\text{v,max}}}{L_{\text{Avg}}}$$

For this calculation, the Lv from every luminaire is calculated at the same calculation points as pavement luminance with the observer 272.5 ft (83.0 m) back from each point under consideration. The observer height is 4.5 ft (1.45 m) above the road surface, and the line of sight is 1 degree below horizontal.

The calculation of veiling luminance includes the contribution from poles before and after the calculation grid. For a proper calculation, the observer needs to be within the calculated array of luminaires. For further information refer to IES-RP-8-21, Chapter 3.

1.3.4 Weighted-average Visibility Level or Small-target Visibility (STV)

STV is a measure of the visibility level of small targets as seen against the pavement background. The following factors are considered in STV: target luminance, background luminance, adaptation level, and disability glare. When considering the visibility level and STV, designs are created that produce negative and positive contrast, all positive contrast, and all negative contrast. The weighted average of the calculated visibility levels is the STV. The visibility levels are computed at the same points as the pavement luminance. As with all luminance calculations, the observer position is 272.5 ft (83.0 m) back from each point.

Although STV is not used as the primary metric, it can be used to compare lighting designs.

Although STV is not used as the primary calculated metric, it can be used as a method to compare lighting designs. If multiple designs meet the luminance or illuminance, uniformity, and Lv criteria, the optimal design could be determined as the one with the higher STV value. STV may be considered by those with the experience and knowledge to understand the concept and theory.

1.3.5 Uniformity Ratio

Uniformity is the evenness of light over a given area. Uniform lighting throughout an area would have a uniformity ratio of 1:1. A high degree of uniformity of street lighting is generally accepted as desirable. As discussed, lighting calculations involve a series of grid points at which the luminance or illuminance levels are calculated. The uniformity is assessed based on two ratios: (1) the ratio of the average luminance or illuminance from all points to the minimum calculated level at all points (the average-to-minimum ratio); and (2) the ratio of the maximum calculated value to the minimum calculated value (the maximum-to-minimum ratio). Uniformity ratios should be used for all lighting scenarios.

Newer technologies such as LEDs offer improved uniformity through efficient optical systems, making even uniformity (1:1 ratio) possible. However, completely even uniformity can actually limit visibility. As shown in Figure 16, an object on a roadway with a completely uniform lighting level fades into the background. Thus, a level of non-uniformity is required to improve visibility and reduce crashes. The non-uniformity in the roadway increases the contrast and thus increases visibility.

> *Completely even uniformity can actually limit visibility. Some non-uniformity in the roadway increases the contrast and thus increases visibility.*

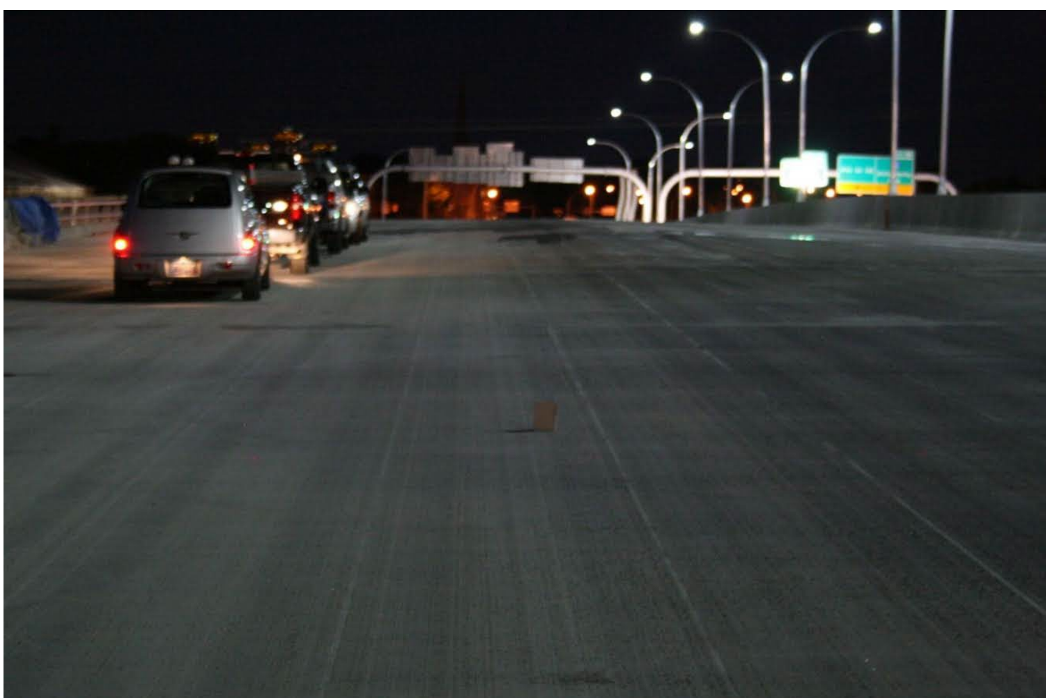


Figure 16. Photo. Completely uniform roadway lighting results in poor contrast (Image credit: Paul Lutkevich, WSP).

1.3.6 Surround Ratio

Providing lighting outside the limits of the travel lanes has been shown to have significant benefits in terms of object detection. Accordingly, it is necessary to define the surround ratio.

Roads and streets typically have lighting requirements for travel lanes and sidewalk areas. Providing additional lighting outside of the limits of the travel lanes has been shown to have significant benefits in terms of object detection (Engineering & Medicine, 2020). Accordingly, a surround ratio should be defined. The surround ratio is calculated as the ratio of the average horizontal illuminance on the outermost lane to that on a similar area off the roadway adjacent to the outermost lane (the surround illuminance; see Figure 17). For example, if the average horizontal illuminance on the outermost lane is 10 lux, to obtain a surround ratio of 0.8:1, the area off the roadway would require a maintained average horizontal illuminance of at least 8 lux. Figure 18 compares a high surround ratio (left) and a low surround ratio (right).

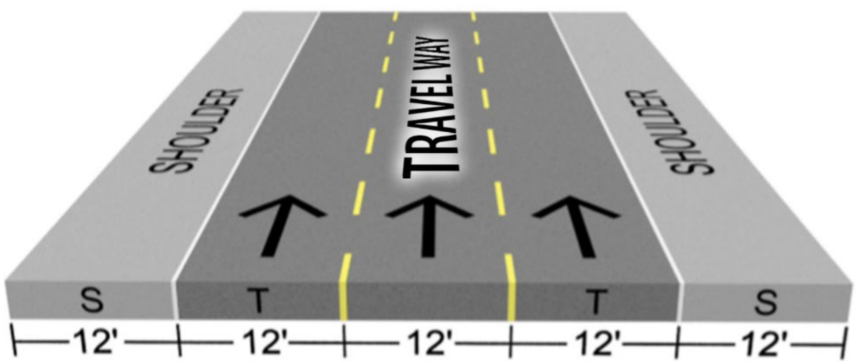


Figure 17. Diagram. Surround ratio calculation layout from NCHRP 940.

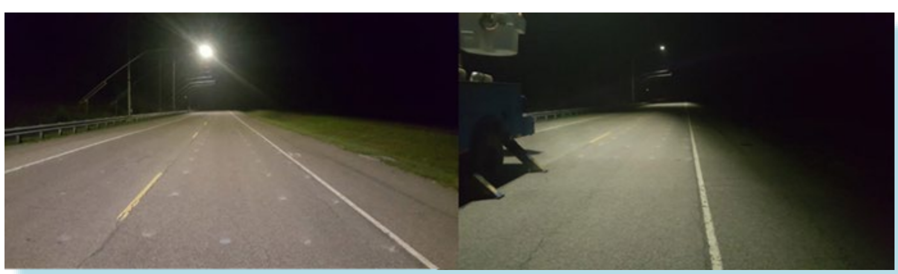


Figure 18. Photos. Images showing high (left) and low (right) surround ratios (Image credit: VTTI).

As a result of the desire to reduce light trespass out of the roadway, LED luminaire manufacturers have focused on tight optical controls to reduce light spill and maximize the light on the roadway. This creates a dark surround (low surround ratio) and a "light tunnel" effect. Previous high-intensity discharge lighting technologies had far less optical control and therefore provided a reasonable amount of surround lighting. Figure 19 shows a comparison of an HPS lighting system, which creates significant lighting off the roadway, with an LED lighting system, which provides tight optical control.

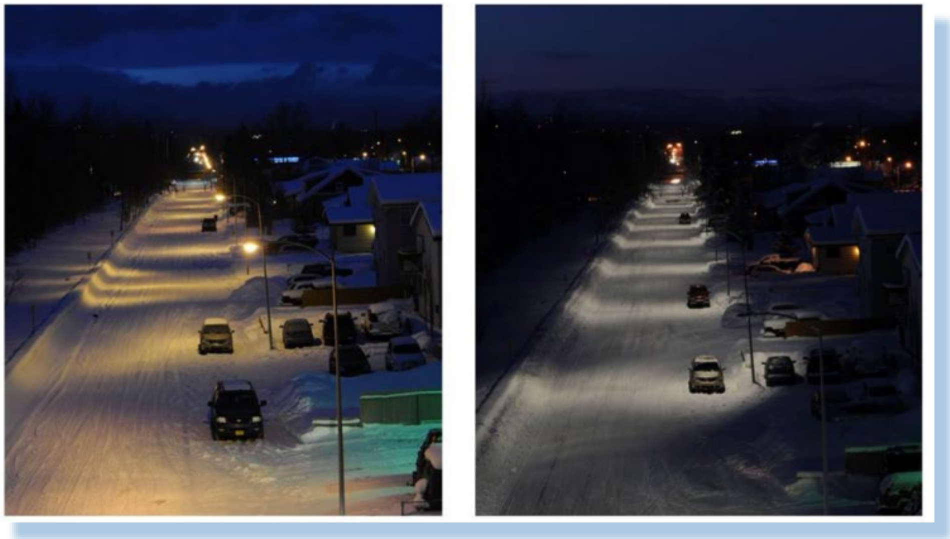


Figure 19. Photos. Images showing surround ratios from LED lighting (right) and traditional lighting sources (left) (Image Credit: DMD).

2 LIGHTING CONSIDERATIONS

This section defines key lighting considerations, with the most significant being safety. Other considerations include the value of lighting design, security and livability, equity, complete streets, aging population, cost, and alternatives to lighting. Many of these impacts can be enhanced (the positive impacts) or mitigated (the negative impacts) through good lighting design.

2.1 Safety

FHWA's goal is to reduce transportation-related fatalities and serious injuries across the transportation system. Designs should follow the FHWA Safe System approach to eliminate fatal & serious injuries for all road users.

Safety is the top priority of the U.S. DOT. For FHWA, this means that road systems should be designed to protect their users through life-saving programs and infrastructure safety solutions. FHWA's goal is eliminate all transportation-related fatalities and serious injuries across the transportation system.

In reaching the vision of zero deaths and serious injuries, there are several considerations, including the approach to safety, the type of roadway user, and the roadway environment.

2.1.1 Safe Systems Approach

Design should follow the FHWA Safe System approach, which aims to eliminate fatal and serious injuries for all road users. It does so through a holistic view of the road system that (1) anticipates human mistakes and (2) keeps impact energy on the human body at tolerable levels. In a safe system, neither a human mistake nor force on the human body should lead to death, which means that the infrastructure should be designed in such a way as to manage the potential risk to any driver.

Figure 20 defines the safe systems through six principles that form the basis of a Safe System: deaths and serious injuries are unacceptable, humans make mistakes, humans are vulnerable, responsibility is shared, safety is proactive, and redundancy is crucial. These six principles define the approach used in each of the five Safe System Elements (Safe Roads, Safe Road Users, Safe Vehicles, Post-Crash Care, and Safe Speeds), which together create the required layers of protection for the driver. One of the keys to the Safe System approach is the safety culture that an agency has that places safety first and foremost in their decision making.

Lighting falls into the Safe Roads element in a Safe System approach. As part of the roadway infrastructure, a well-designed roadway lighting system will improve visibility and make for safer roads and safer road users. Investment in lighting for a roadway is a critical decision for an agency to consider.

For more information on the FHWA's Safe System Approach, refer to https://safety.fhwa.dot.gov/zerodeaths/zero_deaths_vision.cfm

Figure 20. Infographic. The FHWA Safe System. (Image Credit: (Image Credit: FHWA)

2.1.2 Road User Safety

Pedestrians are 3 to 6.8 times more vulnerable at night. Lighting can improve visibility where pedestrians and cyclists are present. Lighting of roads with these users should be a priority.

Over the last 50 years and more, many studies have indicated significant benefits of roadway lighting with respect to crash reduction.

One of the more recent studies (Gibbons et al., 2014) examined over 2,000 miles of roadway lighting and 83,000 crashes to build a link between the lighting level and the night-to-day crash rate ratio. Figure 21 shows the developed relationship. The drop in the night-to-day crash rate ratio is evident with increasing illuminance level. It is noteworthy that the benefit of the lighting decreases with increasing lighting level. This research also showed the impact of lighting on safety in a variety of road classifications. Figure 22 shows the drop in the night-to-day crash rate ratio for a lighting level by roadway classification. The horizontal dashed lines in this figure show where additional lighting does not improve the roadway safety aspects.

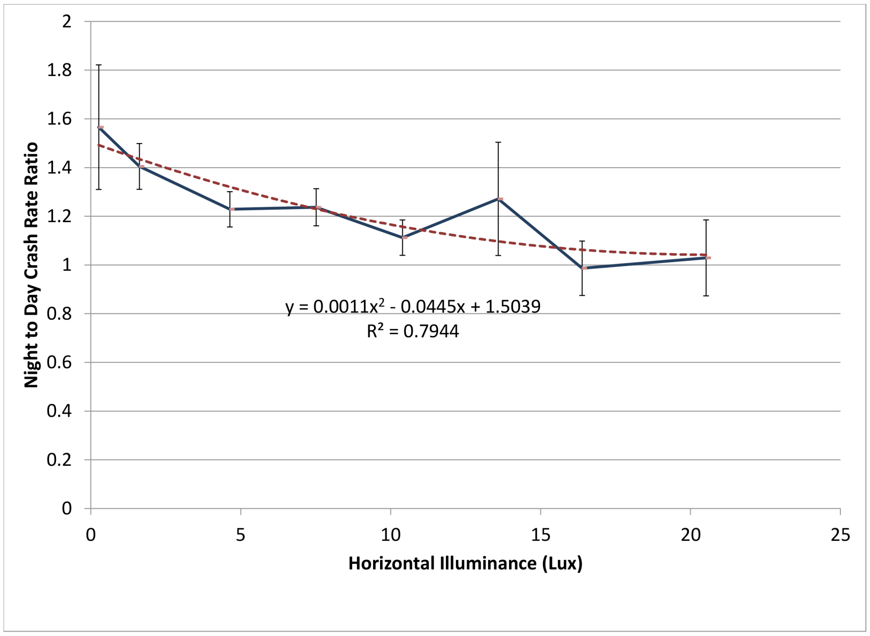


Figure 21. Line graph. Night-to-day crash rate ratio at different horizontal illuminance (Gibbons, Guo, Medina, Terry, Du, Lutkevich, & Li, 2014).

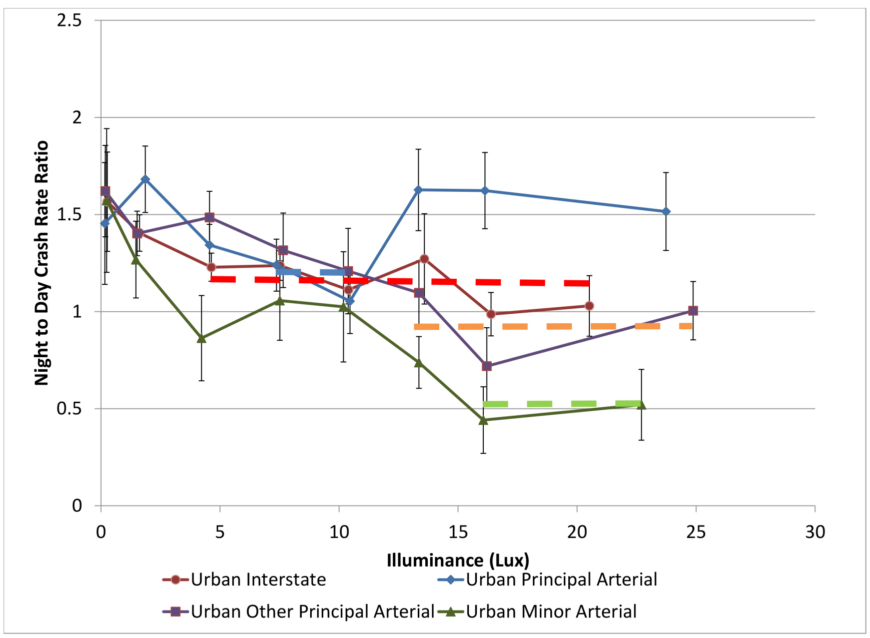


Figure 22. Line graph. Night-to-day crash rate ratio at different horizontal illuminance (Gibbons, Guo, Medina, Terry, Du, Lutkevich, & Li, 2014).

This study and others indicate that road users such as pedestrians and bicyclists are affected by darkness far more than motorists. According to a National Center for Statistics and Analysis (2020) fact sheet, three fourths of all pedestrian-related fatalities occurred during periods of darkness (76%). These data show that not only pedestrian crossing areas but all areas of the roadway where pedestrians might interact with the roadway should be included in lighting decisions. One of the primary factors differentiating other road users and the motorist is the active lighting on the vehicle itself. Headlamps, side markers, and taillamps define the presence and motion of a vehicle at night. As there is no similar active lighting system consistently carried by pedestrians, roadway lighting roadway lighting becomes very important in providing visibility for these roadway users.

Based on crash analyses from 2009 to 2018, Benson, Tefft, Arnold, and Horrey (2021) showed that most pedestrian fatalities occurred in darkness, accounting for 87% of the overall increase in pedestrian fatalities during this period. A University of Michigan Transportation Research Institution study showed that pedestrians are 3 to 6.8 times more vulnerable at night, and that lighting can improve visibility where pedestrians are present (Sullivan & Flannagan, 2002). In 2017, the National Highway Traffic Safety Administration (NHTSA) reported that 74% of all pedestrian fatalities occurred at night, and pedestrian and cyclist nighttime fatalities increased substantially from 2017 to 2018, as shown in Figure 23) (National Center for Statistics and Analysis, 2020). Thus, proper lighting is needed to enhance pedestrian visibility to drivers. This figure indicates a trend that seems to continue even throughout 2020, with pedestrian fatalities remaining consistent with time but cyclist fatalities increasing by 5% in 2020 over 2019 levels (National Center for Statistics and Analysis, 2022).

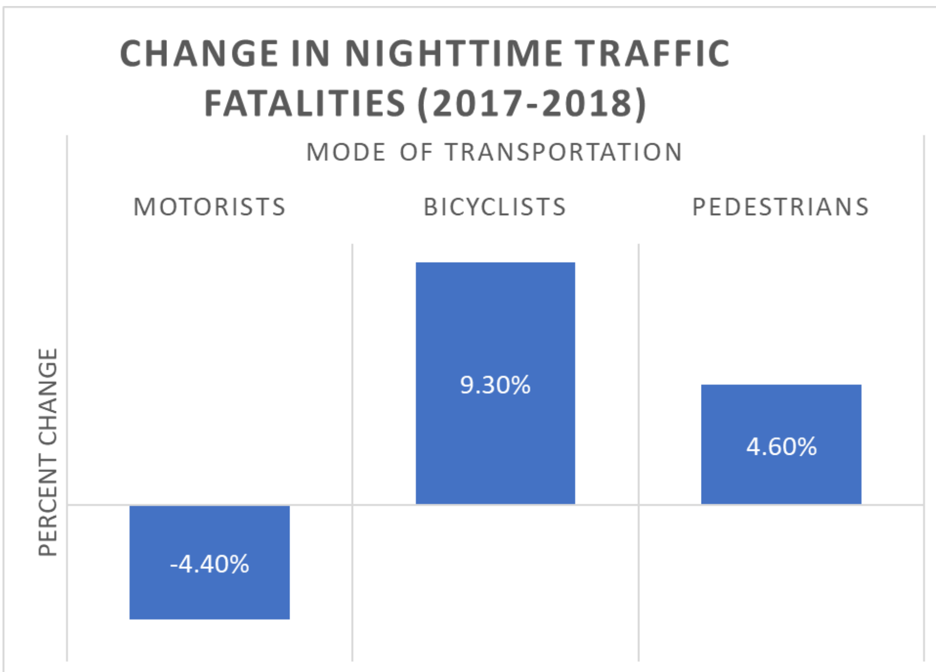


Figure 23. Bar graph. Change in nighttime fatalities from 2017–2018. (Image Credit: DMD)

Given increases in fatalities among vulnerable road users such as pedestrians and bicyclists, the lighting of roads with these users in mind should be a priority. As shown in Figure 24, speed is a significant factor in determining survivability when a pedestrian is hit by a motor vehicle, with higher-speed crashes resulting in a lower chance of survival. Therefore, the greatest need for lighting is on higher-speed roads (30 mph and greater). The needs for lighting should be defined using the policies and practices of the jurisdiction that owns the roadway along with sound engineering judgment.

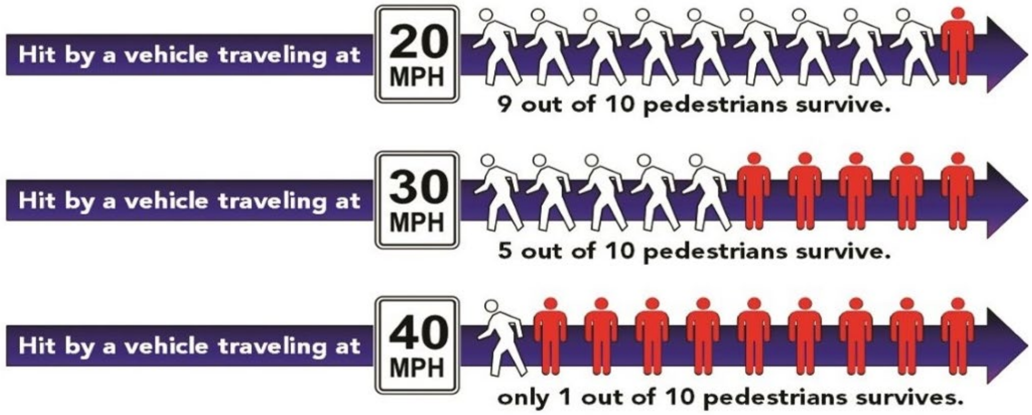


Figure 24. Infographic. Relation between vehicle speed and chance of pedestrian survival (Fesler, 2014).

2.1.3 Intersections and Roadside Areas

While there is a need to consider safety on all areas of the roadway, particular consideration should be placed on intersections and roadside facilities. These are the primary areas of the roadway for potential interaction of vulnerable road users and vehicles.

Intersections are challenging locations for all road users but can be especially dangerous for pedestrians and bicyclists. Based on Fatality Analysis Reporting System (FARS) data, approximately 27% of pedestrians and 38% of bicyclists killed from 2014 to 2016 were struck at intersections (National Center for Statistics and Analysis, 2020). In urban areas, these numbers were even higher: 32% of pedestrian fatalities and 44% of bicyclist fatalities occurred at intersections or were intersection related. Often, these fatalities occurred while crossing two-way, undivided streets with no traffic control. Other factors such as a lack of roadway lighting, large number of lanes, and high vehicle speeds compound safety problems for non-motorized road users at intersections (Medicine, 2020).

Ensuring safety in roadside facilities such as sidewalks and bike lanes is equally critical. According to a National Center for Statistics and Analysis (2020) fact sheet, in 2018, 74% of all pedestrian fatalities occurred at non-intersections (opposite of the statistic listed above) and 10% occurred on roadsides, shoulders, parking lanes, bicycle lanes, sidewalks, and midblock crosswalks, among other sites. This suggests the need to provide careful consideration of lighting for pedestrian facilities not only at intersections but along the roadway in areas such as sidewalks and bikeways as well.

An important design factor for street crossings is providing sufficient sight distance for pedestrians, bicyclists, other road users, and motorists to view each other clearly on the approaches to any conflict points. All parties should be able to perceive and react to a potential conflict, and motorists should be able to come to a full stop before conflicting with a pedestrian, bicyclist, or other road users.

The final aspect of lighting for a roadway is that other road users not only need to be seen but also need to see, meaning that they should be able to see their surroundings, which provides them with the ability to detect trip-and-fall hazards and provides perceptions of safety and security.

2.1.4 Safe Routes to School

Photo. emin kuliyev, shutterstock

Of particular concern are school-age children traveling to school. These children may travel at twilight in both the morning when going to school and in the early evening when coming from school, creating 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% of the time when crossing busy one-lane streets, while the crash rates for 8-, 10-, and 12-year-old children were 6%, 5%, and 2%, respectively. Children's limited ability to judge the available gap in traffic at a young age primarily attributes to this difficulty in crossing streets. Younger children also take more time to take the first step in crossing the street, shortening the available gap. However, children's crossing speeds do not differ from those of adults (O'Neal et al., 2018).

Safe Routes to School (SRTS) is an international approach using engineering, enforcement, safety education, and incentives to encourage children to walk and bike to school (https://www.fhwa.dot.gov/environment/safe_routes_to_school/). Engineering approaches broadly incorporate design, implementation, operation, and maintenance of infrastructure improvements like traffic control devices or physical devices such as barriers and roadway islands. Enforcement approaches encompass strategies to stop unsafe behaviors in drivers, pedestrians, and bicyclists. Enforcement strategies also encourage all road users to obey all traffic safety rules and share the road with other road users. Education approaches involve teaching road users the benefits of SRTS and creating awareness about them. Encouragement approaches closely follow education approaches and aim to promote walking and bicycling by getting road users interested in those means of transportation. The Federal-Aid SRTS Program provides funding to enable and encourage children to walk and bike to school; to make bicycling and walking to school a safer and more appealing transportation alternative; and to facilitate the planning, development, and implementation of projects and activities that will improve safety and reduce traffic, fuel consumption, and air pollution in the vicinity of schools (23 U.S.C. 208(c)). Funds can be spent on the Federal-Aid SRTS Program under the Surface Transportation Block Grant program (23 U.S.C. 133(b)(7)), the Transportation Alternatives Set-Aside (23 U.S.C. 133(h)(3)(B)), and the Highway Safety Improvement Program as a specified safety project (23 U.S.C. 148(a)(11)(B)(v)). SRTS funds can be used by States to provide financial assistance to State, local, Tribal, and regional agencies (23 U.S.C. 208(f)). Other programs that promote safety for schoolchildren can be implemented by a state department of transportation, metropolitan planning organization, local government, school district, or even a school.

Roadway and pathway lighting focusing on the visibility of children at night can serve as an SRTS intervention as current lighting guidelines focus primarily on the visibility of adult pedestrians. Recent research on the needs for pedestrian lighting provides recommendations for lighting in areas common to children who walk to school, in both rural and urban areas (Terry et al., 2020). Careful consideration to the characteristics of urban and rural environments should be given as contrast, visual clutter, and multiple light sources impact a pedestrian's visibility. The scope of this research not only includes the visibility of children as pedestrians from the point of view of the driver but also the ability of pedestrians, children, and adults to detect hazards in their walking path under the same lighting conditions. This method ensures that any recommendation for lighting that benefits the visual performance of a driver also considers the visual performance of pedestrians of all ages.

2.1.5 Warrants for Pedestrian Lighting

No lighting warranting system has been developed that gives suitable weight to pedestrian crossings and bike lanes, which should be highly prioritized, especially where motor vehicles and pedestrians/bicyclists conflict.

Despite the high-risk pedestrians and bicyclists face, no lighting warranting system has been developed that gives suitable weight to pedestrian crossings and bike lanes. These areas should be highly prioritized, especially where motor vehicles and vulnerable road users conflict. More light is not always the best solution; the appropriate amount of light is critical to increasing contrast and making vulnerable road users more visible, especially at nighttime. Warrants are considered in much more detail in Chapter 4 of this document.

2.1.6 Roadway Environmental Factors

Weather can dramatically change the way light behaves and affects the human perception of brightness, glare, and depth. Weather conditions significantly impact the reflection properties of the pavement surface and can make the road surface reflect light specularly rather than diffusely, particularly in the rain. This leads to high contrast levels and poor visibility, as shown in Figure 25.

Figure 25. Photo. Lighting performance in different weather conditions (Dry [Left], Rain [Center], Fog [Right]), (Image Credit: Paul Lutkevich, WSP).

Gibbons and Williams (in review) studied the detection of pedestrians in clear, rainy, and foggy conditions and found that the spectral impacts of the light source are diminished in rainy and foggy conditions and that the effect of light source intensity is more important. The study also revealed significant impacts of weather conditions on vehicle speed and object contrast; thus, the results require careful interpretation.

Wanvik (2009) performed a meta-analysis of crash data in three different countries and considered the impact of weather and road surface condition on crashes. Table 3 shows the effective reduction in collisions provided by street lighting under various conditions, demonstrating the significant impacts of weather and road surface conditions on the ability of street lighting to reduce collisions (Note that Wanvik also included crash type and road user type with similar results to those from U.S. data sources.)

Table 3. Effects of lighting on collisions under various road and weather conditions on Dutch Roads (Wanvik, 2009).

Conditions		Effect	95 % conf.
All		-54%	-56 %, -52 %
Weather conditions	Fine weather	-54%	-56 %, -52 %
	Rainy weather	-45%	-53 %, -37 %
	Foggy conditions	0%	-15 %, +18 %
	Snowy weather	-26%	-40 %, +8 %
Road surface conditions	Dry road surface	-56%	-59 %, -54 %
	Wet road	-46%	-50 %, -43 %
	Snow / ice covered	-22%	-31 %, -11 %
Road user	Pedestrian	-70%	-77 %, -61 %
	Bicycle	-60%	-65 %, -54 %
	Moped	-61%	-64 %, -56 %
	Motorcycle	-26%	-42 %, -5 %
	Automobile	-50%	-52 %, -47 %
Accident type	Hit fixed object	-54%	-58 %, -49 %
	Frontal collisions	-50%	-55 %, -43 %
	Flank collisions	-46%	-51 %, -41 %
	Hit animal	-57%	-63 %, -50 %
	Rear end collisions	-51%	-54 %, -46 %

2.2 The Value of Lighting Design

For a quality outcome for roadway users, a proper lighting design is an important aspect of the lighting development process. While the purpose of street and road lighting is to improve the driver's visual performance, not all street lighting produces the same benefits. Some jurisdictions look at lighting in terms of standardized cookie-cutter layouts without requiring lighting calculations. This can significantly limit the value and benefits of lighting. Unlike HPS luminaires, which provided similar performance from product to product, allowing for one-to-one replacement regardless of the manufacturer, LED luminaires vary greatly in optical efficiency and light distribution from product to product. LEDs have opened the door to new manufacturers, optical systems, and light distributions; as such, many more specific optical systems are available. This means that simply defining a luminaire wattage, lumen output, and optical distribution (IES Type II, III, IV) and assuming all products meeting those specifications will produce equal results can reduce the overall effectiveness of the lighting system. The differences in current technologies and products are further discussed in Section 5.1.1.

The benefits of increasing the lighting level reach a plateau beyond which there are diminishing returns. It is therefore recommended that lighting not exceed the required maintained level by more than 50%.

Given the vast differences in LED product performance, it is worth properly evaluating the performance of lighting designs. Lighting calculation software and the power of computing systems have evolved, resulting in quick and easy lighting calculations that provide methods to optimize a lighting design.

One area IES RP-8-21 and AASHTO G-7 have not specified is the maximum average maintained illuminance or luminance level. This has led to an impression that increasing the illuminance or luminance level will always improve visibility and safety. However, the benefits of increasing the lighting level reach a plateau beyond which there are diminishing returns. Figure 21 and Figure 26 demonstrate the diminishing returns observed in detection distance and night-to-day crash rate ratio when the lighting level exceeds 12 lux (Bhagavathula & Gibbons, 2019; Gibbons, Guo, Medina, Terry, Du, Lutkevich, & Li, 2014). This threshold level will vary with speed and road class; however, these figures show that over-lighting does not inevitably produce additional benefits, and lighting beyond the level defined in IES RP-8-21 and AASHTO G-7 may not have any real value. Therefore, it is recommended that lighting not exceed the maintained lighting level specified for the roadway by more than 50%. The 50% is a maximum target to allow for variability in the designs and is not absolute. Designers are encouraged to get as close as possible to the required maintained level while not going below that level.

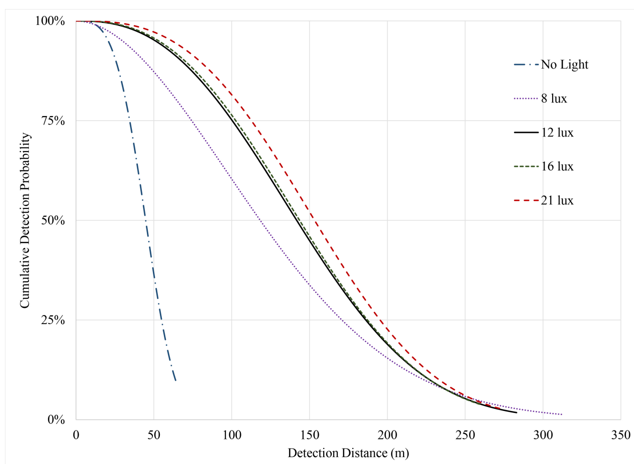


Figure 26. Line graph. Detection distances at various lighting levels (Bhagavathula & Gibbons, 2019).

Typically, when lighting is mounted on utility poles, the necessary lighting levels are difficult to achieve since the pole spacing is defined by the power line design as opposed to the lighting design. In some cases, the poles are two to three times further apart than the distance required for achieving the minimum recommended uniformity ratios (this is often referred to as “half code” lighting). The rationale for half code is that some lighting is better than no lighting, even if well below the requirements (i.e., install half the lighting and get half the benefit). However, reductions in the required lighting

Selecting the most appropriate lighting system is best done through lighting design and calculation on a per-project basis as opposed to using a one-size-fits-all approach.

criteria and specifically uniformity may be more detrimental to visibility than the absence of lighting. Rather than providing lighting that does not meet the requirements, it may have a greater benefit to add lighting at critical conflict points such as intersections.

From the perspective of under- versus over-lighting, there is clearly a sweet spot where the lighting system provides maximum benefits in terms of visibility, environmental impact, and energy efficiency. Selecting the most appropriate lighting system is best done through lighting design and calculation on a per-project basis as opposed to using a one-size-fits-all approach.

When designing lighting for sidewalks, the lighting levels can be misleading as the reflective properties of sidewalks and buildings can affect the overall surround brightness and visibility.

All designs should consider light blockage from landscaping and street trees as shown in Figure 27. Where trees are proposed, lights may have to be installed on arms that extend out over the roadway beyond the ultimate tree canopy. With the lighting extended over the roadway, additional pedestrian-scale lighting will often be required to properly light the sidewalks. The proposed locations, spacing, pole height, arm length, and frequency of the trees may also need to be adjusted in conjunction with the lighting pole spacing. A pole spacing shorter than the calculated value may be required to compensate for anticipated light blockage, resulting in additional poles and luminaires. When a roadway or pedestrian lighting project includes new or existing trees near the lighting, an additional light loss factor should be included in the design for light loss due to shading. At this time, no research has quantified this factor; however, an additional 10% to 20% of light loss should be considered. In addition, it is recommended that the required pole spacing be adjusted so that luminaires are located outside of tree canopies.

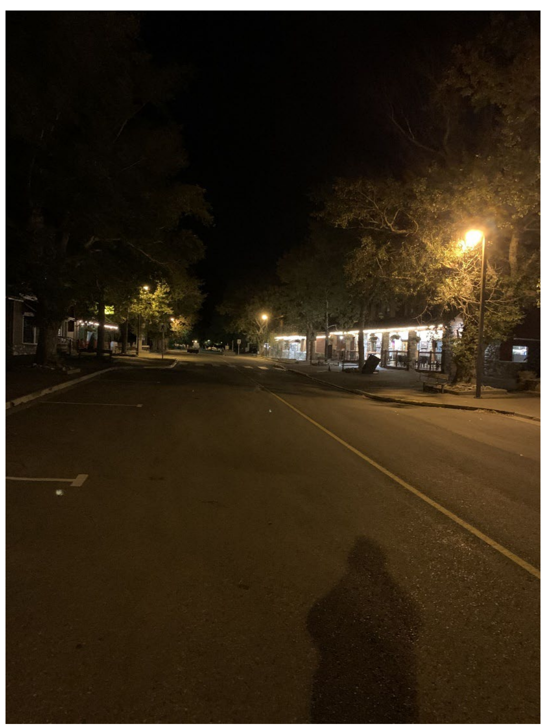


Figure 27. Photo. Example of trees blocking lighting and creating shadows (Image Credit: DMD).

In streetscape applications with trees and sidewalks separated from the roadway, it is recommended that the roadway lighting and sidewalk lighting be provided by separate luminaires, each of which is designed in consideration of the effects of the tree canopy. Refer to Figure 28 for an example of such lighting.

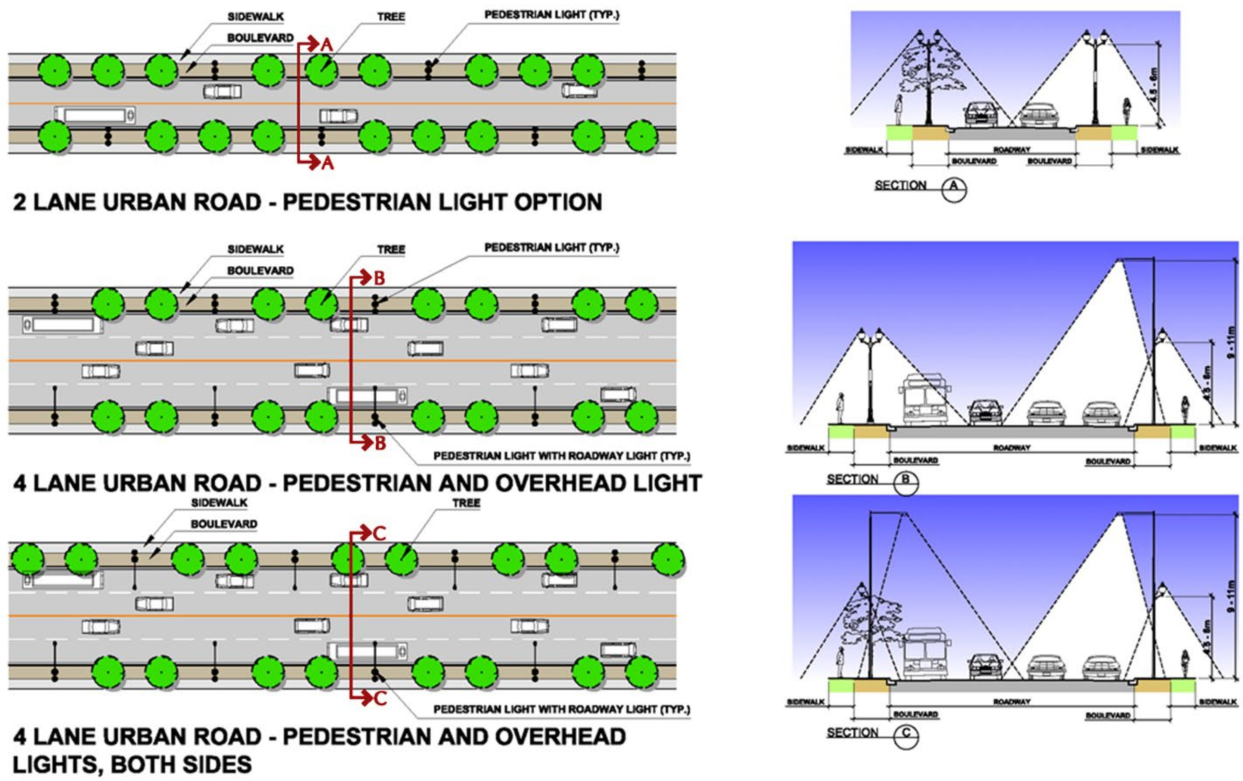


Figure 28. Illustration. Examples of streetscape lighting (Image Credit: DMD).

2.3 Security and Livability

A livable city promotes health and the happiness of its citizens. One primary concern is the security of the citizens as they use city facilities. Lighting is a key component in a livable city, as lighting has been shown to provide a sense of security to citizens (Painter, 1996). One of the considerations here is also uniformity of the lighting, as dark areas and lower lighting level can negatively affect the feeling of security for roadway users.

While street lighting and walkway (sidewalk) lighting have been shown to provide better visibility for pedestrians at night, the impact of lighting on crime is less clear. Research on the effects of street lighting on security and crime have been inconclusive. Some studies found that improved street lighting was effective in reducing crime (Atlanta Regional Commission, 1974; Lewis & Sullivan, 1979; Wright, Heilweil, Pelletier, & Dickinson, 1974), while other studies did not find any reductions in crime due to improvements in street lighting (Department, 1976; Inskeep & Goff, 1974; Quinet & Nunn, 1998; Sternhell, 1977). These differences may be a result of differing demographics and analysis approaches. In a more recent study, Chalfin, Hansen, Lerner, and Parker (2021) evaluated the effect of street lighting on crime in New York City and found that street lighting was associated with an approximately 36% reduction in outdoor nighttime crimes and an approximately 4% reduction in overall crimes.

Lighting can affect crime through two indirect mechanisms. The first is the obvious mechanism of facilitating surveillance by authorities and the community after dark. If law enforcement responds to a reported crime, improved lighting may enhance their ability to identify and apprehend a fleeing criminal. If criminals perceive the presence of surveillance as increasing effort and risk and this results in decreasing the risk/reward ratio for a criminal activity, the level of crime is likely to be reduced. The second mechanism by which lighting might affect the level of crime is by enhancing community confidence, leading to increased pedestrian activity and greater potential for crime detection. If community improvements (including lighting) give residents a sense of ownership and pride in an area, the probability of a detected crime being reported and/or impeded can also be increased. More significantly, the perceived likelihood of detection, reporting, and apprehension is likely to deter crime.

Research on the effects of street lighting on security and crime have produced mixed results. Crime Prevention Through Environmental Design (CPTED) is an industry accepted way to integrate security elements into lighting design.

Instead of providing lighting everywhere or indiscriminately, Crime Prevention Through Environmental Design (CPTED) is a common practice for integrating security elements into lighting design by adopting certain strategies. CPTED is a proactive crime prevention strategy utilized by planners, engineers, police services, security professionals, and everyday users of space. Effective implementation of CPTED principles leads to environments that provide adequate visibility, encourage a sense of ownership, and facilitate desirable activities and traffic (e.g., an environmental design that gives pedestrians sufficient visibility to avoid hazards ahead). In CPTED terms, visibility allows the person to choose flight rather than fight. When a crime is in progress, those same visibility features along with the sense of ownership and pride among nearby motorists, business owners, residents, etc. improve the potential for intervention and reporting.

From a livability and security standpoint, lighting sidewalks improves pedestrian visibility, provides guidance, and can create a feeling of comfort. Unlike motor vehicles, which have headlamps to improve visibility, pedestrians typically do not have their own lighting unless they carry flashlights. Outdoor lighting is the most practical aid to pedestrian visibility and guidance. Therefore, outdoor lighting is critical to prevent personal injuries due to tripping and falling, which in turn improves livability. Increasing light levels by 1 lux horizontally (between 0 and 18.6 lux) was found to promote pedestrian activity, as indicated by increased pedestrian and bicycle counts at night (Bhagavathula, Gibbons, & Hankey, 2018). Increasing light levels to 2 lux of average horizontal illuminance can also help pedestrians detect tripping and falling hazards as well as enhance perceptions of safety, comfort, and visibility (Bhagavathula & Gibbons, 2020). No statistically significant improvements in visual performance or perceptions of safety, comfort, and visibility were observed by enhancing average horizontal illuminance by more than 2 lux.

2.4 Equity

Equity in the application of roadway lighting is an important consideration in the lighting planning process. The impact of the lighting system in terms of equity should include all aspects of race, gender, income, mobility, age, and living location. These considerations form the basis for the decision making on where, what level, and what type of lighting is implemented in an area.

This section has been written to create awareness of equity considerations. As the understanding of equity issues and lighting are an evolving body of knowledge, the latest information should be sought in the ideal application of the lighting.

Black, Indigenous, and Hispanic people are disproportionately represented in nighttime traffic fatalities, according to a Governors Highway Safety Association (GHSA(Governors Highway Safety Association, 2021) report that analyzed 2015–2019 FARS data. Figure 29 and Figure 30 show the comparison of daytime fatalities by ethnicity and nighttime fatalities by ethnicity, respectively. Of note is the change in rank order of the ethnicities between day and nighttime crashes. Even more demonstrative are the data indicating pedestrian deaths by race and ethnicity; here again, the rank order shows that the ethnicity of the pedestrian plays an important role in traffic deaths (Figure 31).

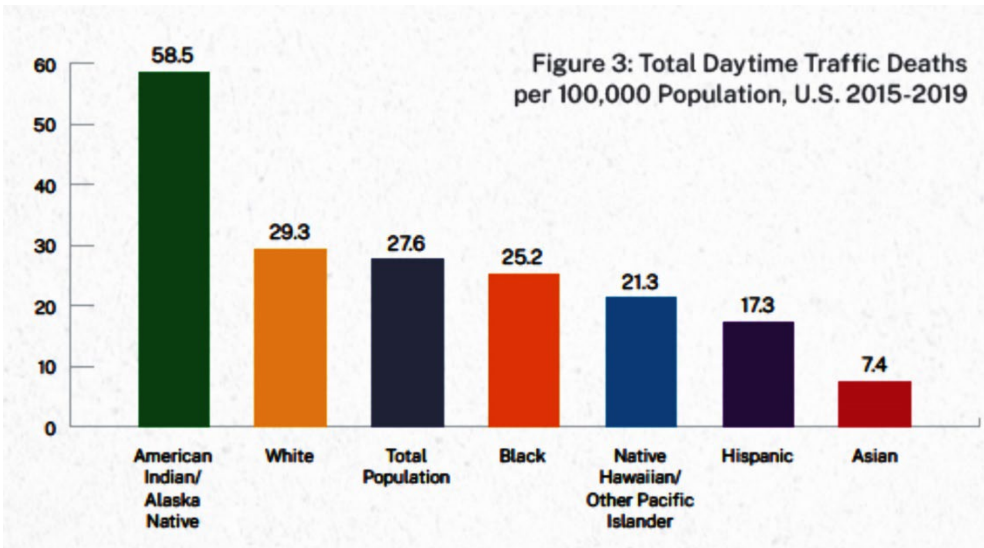


Figure 29. Bar chart. Daytime fatalities per 100,000 population by race and ethnicity (GHRS, 2021).

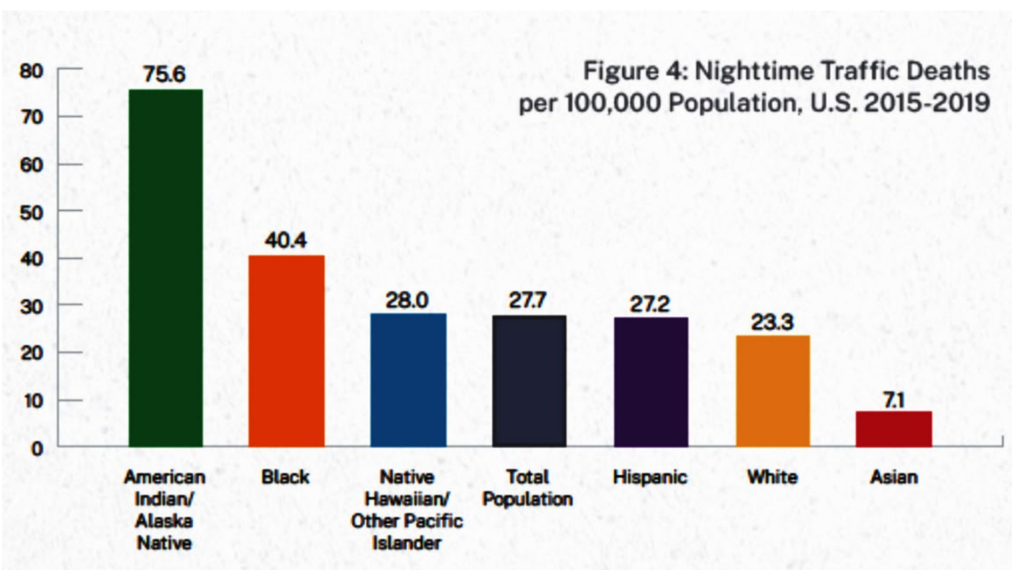


Figure 30. Bar chart. Nighttime fatalities per 100,000 population by race and ethnicity (GHRS, 2021).

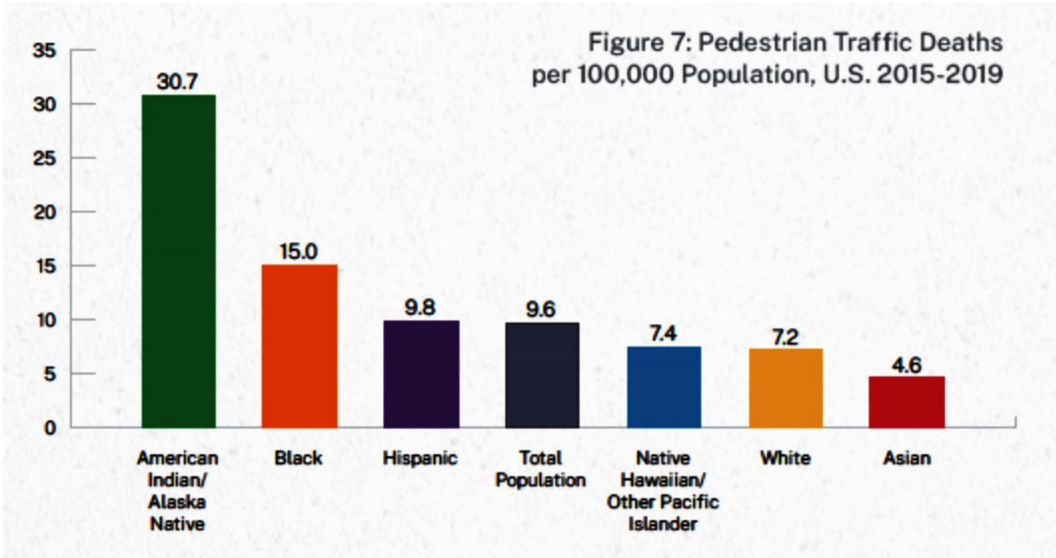


Figure 31. Bar chart. Pedestrian deaths per 100,000 population by race and ethnicity (GHRS, 2021).

Disparities between the amount of streetlight illumination provided in underserved communities may factor into the higher presence of Black, Indigenous, and People of Color (BIPOC) in fatal crashes. There are two primary issues:

- Underserved communities may not have adequate roadway lighting infrastructure because of a history of disinvestment, complaints-based lighting repair processes, and underrepresentation in transportation decision making.
- Underserved communities may have greater demand for well-lit pedestrian facilities as these areas also tend to have higher pedestrian volume.

These issues highlight the need for comprehensive efforts to address longstanding inequities that have led to the overrepresentation of BIPOC in crash statistics.

As mentioned, lighting is an important treatment for roadways in terms of safety and interpersonal violence reduction, so design considerations with respect to lighting should be carefully made. The following are recommendations for dealing with lighting inequalities:

- The social equity of all roadway users and stakeholders should be considered in the design, and decisions should be based on data regarding the makeup of the people using the space and how they want to use it. This will require public involvement, particularly from the underserved communities, in the lighting design process.

- The area to be lit should be considered holistically, where the impact of the lighting encompasses not only safety and security but how the lighted space provides social meaning, aesthetics, and accessibility.

- Lighting design that uses mockups and elicits stakeholder involvement is critical to maximizing the positive impact of the lighting implementation. This allows the designers and technical experts to understand and act on the decisions made by the public.

- The lighting system should be adaptable and user responsive to the changing nature of the lighted area to achieve the full potential of the lighting system (adaptive lighting is considered later in this document).

- The value of the lighting system should be assessed both pre- and post-installation and be supported by the roadway authority and the local agency. These evaluations include both the lighting level assessment and the evaluation of the social impact of the lighting system after installation.

- The agency should also prioritize post-installation maintenance of installed lighting systems. The impact of the installation of a lighting system to address inequities is lost if the system is not maintained properly. Lack of maintenance propagates the underservice of a community.

An approach to equity of lighting application has been undertaken by many cities. These efforts included the implementation of the Equity Impact Analysis into the decision-making process (Koonce, 2017). As an example of this, the City of Portland, Oregon, created a system of weights to consider a variety of analysis factors. These analysis factors include demographics, safety, and access. Each of these factors include subfactors and within each subfactor, like race, crashes and transit are considered when assessing lighting need. This evaluation was performed for a variety of communities to allow for prioritization of lighting need. Example tables from the Portland process are shown in Table 4 and Table 5.

Table 4. Example of City of Portland Equity Analysis (Illuminating Engineering Society, 2018).

Criteria	Category	Measures	Score	Possible Score
Equity	Race	% people of color	3	3
Equity	Income	% below poverty	3	3
Safety	Crime	Annual crimes per sq mi.	2	2
Safety	Crashes	Bike/Ped crashes	0	2
Safety	Sidewalks	Lack of sidewalks	0	2
Access	Pedestrian	Ped District or City Walkway	1	2
Access	Bicycle	Bike Network	2	2
Access	Transit	Transit Network	0	2
Total			11	18

Table 5. Example of City of Portland Equity Analysis by Community (Illuminating Engineering Society, 2018).

Location	# of LEDs	Equity Score	Safety Score	Access Score	Total Score
Lents	52	5	4	6	15
Cully	20	6	2	3	11
Powell Butte	68	3	1	2	6
Eastridge	127	3	1	0	4
Clatsop Butte	139	3	0	0	3
Jenne Butte	53	0	1	0	1

For more information on this process, please refer to: https://nationalequityatlas.org/ and https://equityatlas.org/.

2.5 Complete Streets

FHWA is working with State, Tribal and local transportation agencies across the United States to increase the proportion of transportation projects that Federal-aid highway funding recipients routinely plan, design, build, and operate that are safe and accessible for all users. Lighting is a critical element of this approach to safety. FHWA is encouraging the use of a Complete Streets design model (https://www.transportation.gov/mission/health/complete-streets). A Complete Streets design model prioritizes safety, comfort, and connectivity for all users of the roadway, including but not limited to pedestrians, bicyclists, motorists, and transit riders across a broad spectrum of ages and abilities. In general, this design model includes careful consideration of measures to set and design for appropriate speeds; separation of various users in time and space; improvement of connectivity and access for pedestrians, bicyclists and transit riders; consideration of pedestrian access routes for people with disabilities; and addressing safety issues through implementation of safety countermeasures.

One hallmark of a Complete Streets approach is the application of a variety of safety treatments, of which lighting can be an important treatment in the assessment. Typically, the lighting impact is assessed by the application of the crash modification factor (CMF) to the roadway to determine the safety impact. Other considerations such as those above can also be used to assess the whole roadway and the equity of the lighting application.

An important aspect of transitioning to a Complete Streets design model is to make it easier to routinely use these safety countermeasures. In the case of lighting, this may entail close coordination with the Public Works Department or another agency that has primarily responsibility for roadway lighting. Routine procedures, planning, and budgeting processes may need to be updated to ensure that lighting improvements for safety are given priority.

2.6 Aging Population

According to the IIHS, the number of drivers over seventy increased 75% from 1997 to 2020. As these older drivers have reduced visual capabilities, there is a potential for visibility issues at night (Insurance Institute of Highway Safety, 2022). A daytime vision of 20/20 can be reduced to 20/40 at night regardless of age. Age has a significant impact on nighttime visibility due to the reduction in visual capability and the reduction in general physical ability that comes with aging. These factors combine to affect the safety of the older population. Such effects are particularly important as our population ages and life expectancy continues to increase.

> *Locations expecting increased roadway use by older drivers should consider reducing glare.*

As we age, visibility is reduced as the lens of our eye discolors, decreasing the amount of light that can penetrate the eye. This leads to a reduction in visual acuity and contrast sensitivity. The decline generally begins slowly after age 40 followed by an accelerated decline after age 60 (Richards, 1966)). Age also results in increased lens opacity and decreased pupil diameter (Commission Internationale de l'Eclairage, 1987). The maximum area of the iris in eyes of people at age 60 is approximately half that of those at age 20 (Mortimer, 1989). These changes result in less light reaching the retina. Weale (1961) reported a 50% reduction in retinal illumination at age 50 compared to at age 20, with this reduction increasing to 66% at age 60. Figure 32 demonstrates the significant reduction in visibility level for a small target on the roadway (STV) that occurs with age. Further information can be found in IES RP-8-21 and CIE 1995.

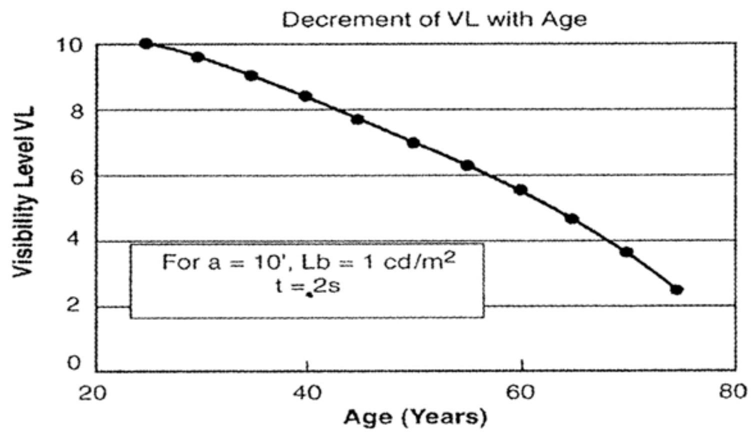


Figure 32. Line graph. Decrease in visibility level with age (Illuminating Engineering Society, 2018).

In addition to the reduction in light through the lens and the reduced visibility, the light is also scattered more significantly, which leads to additional veiling luminance in the eye and therefore additional impacts of glare (Adrian & Bhanji, 1991).

For all road users, a vital factor is the ability to see the movement of potentially hazardous objects out of the corner of the eye. The ability to see movement 40 and 80 degrees away from the line of sight is reduced by as much as 60% for those over 60 years old. While a younger person can typically see in the presence of very little light, this ability is reduced by approximately one half at 80 or more years old. It can take up to 30 minutes for an 85-year-old person to adapt to low outdoor nighttime brightness after having been adapted to high interior brightness (Illuminating Engineering Society, 1999). This long eye adaptation time can be greatly reduced with roadway lighting.

Another aging-related issue is the limited agility and movement of older adults. Older drivers typically do not move their heads as much, resulting in a limited scan pattern (Antin, Wotring, & Foley, 2011). This reduced mobility further adds to the vision and visibility issues for older drivers by limiting their effective field of view. These limitations often cause older drivers to stop driving; thus, overcoming some of these limitations with roadway lighting may increase the mobility and level of comfort for aging drivers (Bjørnskau & Fosser, 1996).

The visibility factors noted above also apply to older pedestrians as reduced visibility reduces a pedestrian's ability to see motor vehicles and avoid collisions. Reaction times for both the driver and pedestrian also decrease with age (Mortimer & Fell, 1989). As shown in Figure 33, while pedestrians ages 20 to 24 are at the highest risk of injury among all age groups, the proportion of fatalities also spikes for pedestrians over 70 years old.

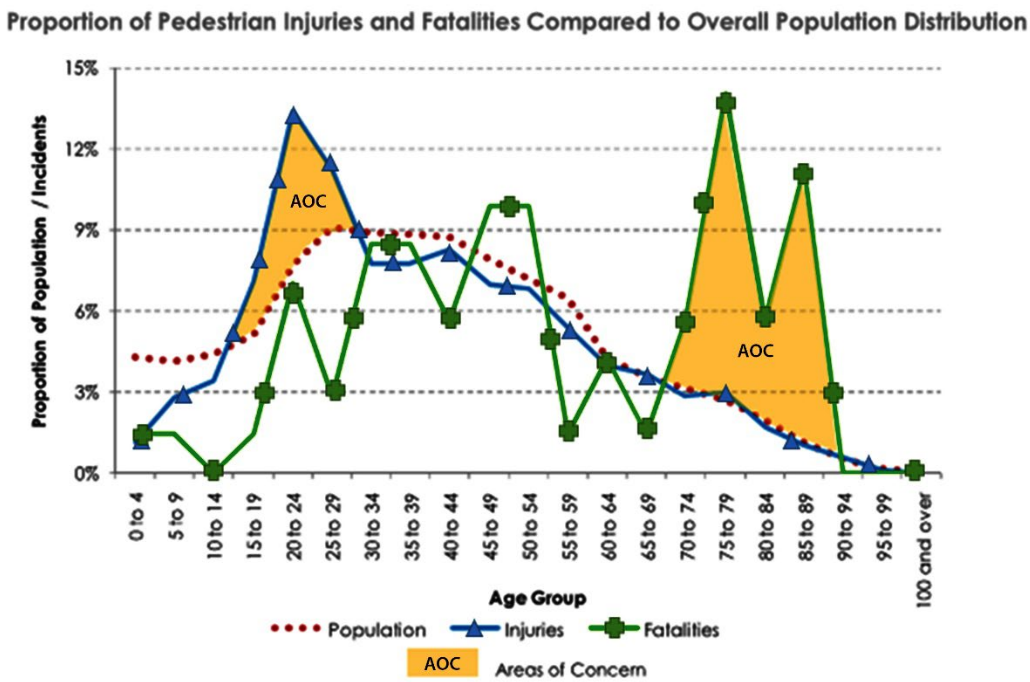


Figure 33. Line graph. Pedestrian fatalities by age (City of Vancouver, 2012).

Hills and Burg (1977) indicated no significant correlation between vision measures and crash data for participants under the age of 54. However, for drivers ages 54 and older, acuity showed significant correlations with crash data. In an NCHRP study, increasing the lighting level improved detection distance for both the older and younger driver (Figure 34; (Engineering & Medicine, 2020). However, the detection distance for older drivers was significantly lower than that of younger drivers, even with the higher lighting level. These results highlight the effects of reduced driver visual capabilities and the need for adequate lighting.

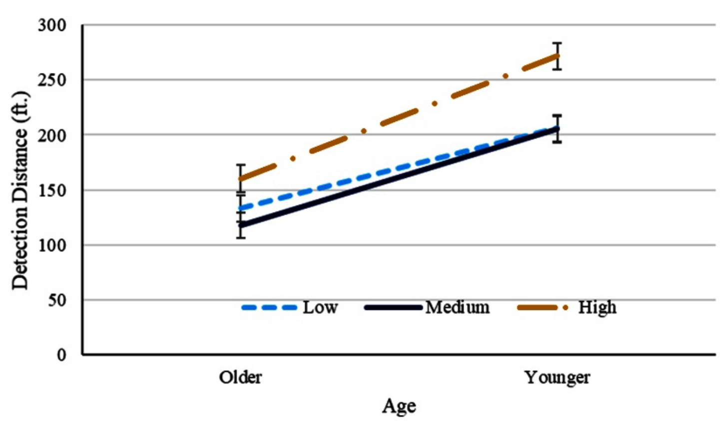


Figure 34. Line graph. Detection distance by light level and age (Engineering & Medicine, 2020).

In terms of lighting design, reducing the veiling luminance ratio is an effective way to improve visibility for older drivers. Simply increasing the luminance levels can also be considered; however, this should only be done to improve the veiling luminance ratio. The best way to reduce the veiling luminance ratio is by assessing various luminaire optical systems and photometric files using lighting design calculation software. The veiling luminance ratios defined in IES RP-8-21 are based on a 25-year-old driver. IES RP-8-18 Table 3.6 (refer to Table 6) defines age factors by which the calculated veiling luminance can be multiplied to account for normal physiological changes in the eye with aging. Incorporating this age factor reduces the calculated veiling luminance ratio.

Table 6. Veiling luminance age factors (Illuminating Engineering Society, 2018).

Age	Age Factor
25	1.0
35	1.1
45	1.2
55	1.4
65	1.7
75	2.3
85	3.2

The Handbook for Designing Roadways for the Aging Population (Brewer, Murillo, & Pate, 2014; Staplin, Lococo, Byington, & Harkey, 2001) provides information linking the declining functional capabilities of older road users to the need for design, operational, and traffic engineering enhancements keyed to specific roadway features. As noted in the handbook, although nighttime driving is associated with a higher crash risk for drivers of all ages, the effects of aging on the visual system are further compounded by the effects of darkness. Particularly difficult is the ability to notice and recognize objects at night and in low-light conditions such as dawn and dusk, rain, fog, haze, and snow. Between age 20 and age 70, aging directly reduces contrast sensitivity by a factor of about 3.0 (Blackwell & Blackwell, 1971); thus, aging drivers are at a greater relative disadvantage at low luminance levels than younger drivers. With a significant and increasing population over age 65, the quality of roadway lighting design is especially important. Today, the population of older individuals in the United States is increasing (the population of people ages 65 or older is up to 13.3% in 2011 from 12.4% in 2002 [Brewer, 2014]) and lighting design should be considered with them in mind. Roadway lighting has significant benefits for this population, and the value and benefits of roadway lighting will increase over time as the population both increases and ages. However, it is also important to consider that older drivers are far less likely to drive late at night compared to younger drivers. For those over 65 years old, it is important to maintain proper lighting levels, uniformity, and veiling luminance ratios on the roadways as well as proper sidewalk lighting levels.

2.7 Cost

To define life cycle costs, both capital cost and maintenance and operating costs should be considered.

FHWA requires that federally funded lighting systems be adequately maintained. Under 23 U.S.C. 116(b), it is the duty of the State transportation department or other direct recipient to maintain, or cause to be maintained, any project constructed under the provisions of chapter 1 of title 23, U.S.C. The Federal Regulations (23 CFR 1.27) further state, “The responsibility imposed upon the State highway department, pursuant to 23 U.S.C. 116, for the maintenance of projects shall be carried out in accordance with policies and procedures issued by the Administrator. The State highway department may provide for such maintenance by formal agreement with any adequately equipped county, municipality or other governmental instrumentality, but such an agreement shall not relieve the State highway department of its responsibility for such maintenance."

As such, recipients of FHWA financial assistance should consider the cost of a system over its usable life, known as its life cycle cost. Life cycle cost analysis includes:

- Capital cost (also known as construction cost). Capital cost varies widely by area and depends on the state of the economy and materials used. Because labor and material costs typically vary by location, it is difficult to establish standard costs for lighting installations. For budgeting purposes, however, it is appropriate to establish a per-mile cost or a unit pole cost, including wiring, boxes, and conduits between each set of typical poles.
- Maintenance and operating costs. These costs, which include power, corrective, and preventative maintenance costs, are typically calculated annually and are used by a jurisdiction to establish operating budgets. When calculating power cost, the method of payment used by the local electrical utility should be confirmed. Some utilities establish a monthly flat rate for various luminaire wattages. Others use a set kilowatt-hour rate for roadway lighting. Cleaning the luminaire optical system is a corrective maintenance cost that should be based on the luminaire dirt depreciation factor used in the design.

A lighting system is made of various components, some of which will last longer than others. The luminaire itself is a key component that may require repair or replacement during its life cycle. Manufacturer data often define an expected life of 100,000 hours (approximately 22 years), although this can be misleading as it does not define the product failure rate during that time.

Luminaire products have different levels of reliability depending on their design and manufacturing. These differences can be considered in the prediction of luminaire failure rate. Generally, mean time between failure (MTBF) data from the luminaire supplier can be used to define the predicted failure rate of the luminaire over a defined period, and the cost of replacement and repair can be considered when defining operating costs. MTBF can be calculated as follows (Transportation Association of Canada, 2013):

Equation 3. Reliability as a Function of Time and Mean Time Between Failures

$$\textbf{Reliability} = e^{-(\textbf{time}/\textbf{MTBF})}$$

The recommended minimum MTBF should be as high as possible to minimize product failure; however, this should be determined by defining the number of product failures that can be tolerated. MTBF values provided by manufacturers typically range from 1,000,000 to over 2,000,000 hours. For example, a reliability prediction of failures for an MTBF of 2,000,000 hours for 10,000 luminaires operating for 20 years (87,600 hours) would be:

Equation 4. Example Reliability Calculations using MTBF

$$\begin{aligned}\textbf{Reliability} &= e^{-(87{,}600/2{,}000{,}000)} = \mathbf{0.957} \\ \textbf{Failures} &= \mathbf{100\%} - \textbf{reliability x 100\%} \\ &= \mathbf{100\%} - \mathbf{95.7\%} \\ &= \mathbf{4.3\%}\ \textbf{failures over 20 years.}\end{aligned}$$

The failure rate typically varies by manufacturer. However, accurate MTBF data from the manufacturer can be hard to come by.

Defining usable life involves the consideration of other factors such as corrosion resistance, damage via motor vehicle crashes, lightning strikes, power quality, and rodent damage. All these factors should be discussed with maintenance personnel.

2.8 Alternatives to Lighting

Although roadway lighting typically has high value for each dollar spent (Wald, 1998), it can be expensive to install and operate. Lighting generally has the highest value where pedestrians and cyclists are present. However, vehicle headlamps may provide adequate vertical illumination on straight roads with speeds below 30 mph (IES RP-8-18 Section 3.1). The AASHTO Green Book suggests that for the assumed 24-inch height of headlamps, an object 16 inches above the roadway will be within the line of the headlamps at a distance equal to the stopping sight distance. Therefore, lighting is of less value on low-speed roads (< 30 mph).

> *Vehicle headlights are the primary system intended to assist drivers with detecting objects on and along the road. The contributions of vehicle headlamps are not considered in roadway lighting design.*

As noted by the FHWA Focus on Reducing Rural Roadway Departures (Federal Highway Administration, 2020), roadway departures (i.e., lane departures) on the rural road network account for one third of all traffic fatalities. FHWA prescribes proven roadway departure countermeasures such as rumble strips, friction treatments, and clear zones to help keep vehicles in their travel lanes, reduce the potential for crashes, and reduce the severity of crashes that do occur. While lighting would provide benefits on rural roads, it may be impractical from a cost perspective, and lighting poles can themselves be a hazard when placed in the clear zone.

Vehicle headlights are the primary system intended to assist drivers with detecting objects on and along the road. Traditionally, the contributions of vehicle headlamps are not considered in roadway lighting design. Figure 35 shows an example of vehicle headlights creating disability glare for the oncoming driver.

Figure 35. Photo. Example of glare from oncoming vehicle headlamps. (Image Credit: Ronald Gibbons, VTTI)

A key benefit of lighting is mitigating glare from oncoming vehicle headlamps by improving the contrast ratio. An effective alternative to lighting is glare screens (Figure 36), which can effectively block car headlamps to mitigate the issue.

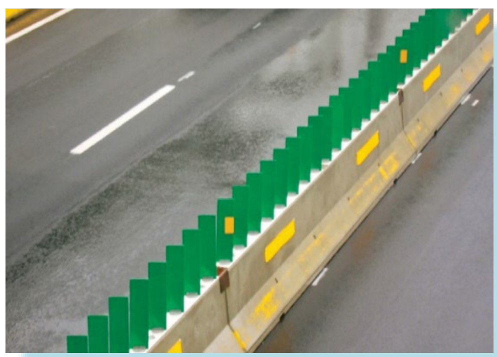


Figure 36. Photo. Median-mounted glare screens (Traffic Safety Supply Company, 2022).

In terms of driver guidance, retroreflective pavement markings and roadside delineators can be a cost-effective option compared to roadway lighting. When roadway lighting is not present, nighttime navigation generally depends upon a road user's visibility of the roadway and pavement markings via vehicle headlamps. Treatments such as retroreflective pavement markings and roadside delineators can be considered as alternatives to lighting in rural applications; however, (Carlson & Miles, 2011) reported that continuous roadway lighting provided better visibility of pavement markings at longer distances than unlit highways. Significantly, the use of retroreflective pavement markings and roadside delineators may aid in keeping a vehicle in their lane but does not address pedestrian/cyclist needs.

Unlike motor vehicles (which have headlamps to make the retroreflective pavement markings visible), pedestrians do not typically supply their own lighting unless they opt to carry flashlights. Therefore, fixed outdoor lighting is the most practical aid to visibility and guidance for pedestrians. Sidewalks and marked bike lanes are a good indication that pedestrians are likely present. In these applications, retroreflective pavement markings would not be a good alternative to lighting because the markers do not help with visibility of the pedestrians as lighting would.

Notably, no research has been reported on the trade-off between lighting and marking systems. However, delineators have been shown to reduce crashes (Crash Modification Factor Clearning House, 2022; Elvik, Vaa, Hoye, & Sorensen, 2009), and it has also been found that lighting systems improve the detection of markers and markings (Gibbons & Hankey, 2007). To assess the cost and benefits of retroreflective pavement markings and post-mounted delineators versus roadway lighting, a life cycle cost analysis that considers the capital and operational costs of both alternatives should be undertaken.

3 WARRANTING

This section discusses methods for determining lighting warrant for roadway lighting systems. AASHTO provides warranting methods for continuous freeway lighting, complete interchange lighting, and partial interchange lighting. Other methods for collector/arterial/local roads and intersections from the TAC are also included in this section.

It is important to note that warrants do not represent a requirement to provide lighting. Satisfaction of a lighting warrant does not in itself require the installation of a lighting system. Beyond the warrants, lighting is of a high value and should be considered where vulnerable road users such as pedestrians and cyclists are present. Given the distance limitations of car headlamps, lighting is also of higher value on higher-speed roadways, as defined in Section 1.2.3 Perception – Reaction Time of this document. Similarly, this treatment of the warranting process is only a summary, and the warranting method used should be followed in the source documents referenced below.

FHWA administers funding for State roadway lighting projects under certain programs with specific requirements. These projects may qualify as highway safety improvement projects and may be eligible under Section 148 of Title 23, United States Code (Highway Safety Improvement Program) if the requirements of that program are met. In addition, these projects are eligible for the increased Federal share under 23 U.S.C. 120(c). When Federal aid is used for a lighting project, the applicant can support the need for a roadway lighting system by including the following items:

- A warrant analysis showing that lighting is a warranted safety feature.
- A project criteria document showing that the design criteria established by AASHTO or IES will be used and met as part of the design.

3.1 Warrants

Warrants are not a requirement to light but an indication of situations where lighting should be investigated. Lighting should be considered where vulnerable road users such as pedestrians and cyclists are present.

Warranting is used by many State and local DOTs and safety practitioners to define the need for lighting. Currently, there are two main warranting systems for roadway lighting: one is found in the AASHTO Roadway Lighting Design Guide (American Association of State Highway and Transportation Officials, 2018b), which defines lighting warrants for freeways and highways; the second is found in the TAC Guide for the Design of Roadway Lighting (Transportation Association of Canada, 2006), which defines warranting for streets and intersections. Most warranting in the TAC guide is based on a weighted point score system developed in the 1970s and derived from an early 1970s NCHRP Report along with the 1978 FHWA Federal Highways Lighting Handbook. The AASHTO warranting system was developed in the early 1980s and has not changed significantly since then.

Existing warrants for lighting were developed before active safety systems in vehicles, solid-state lighting, and the implementation of CMFs in roadway safety analysis. With the development of LED lighting systems, it is necessary to obtain new data to define modern lighting needs. In addition, warrants do not address safety-based alternatives to roadway lighting, which include retroreflective pavement marking and roadside delineators. The FHWA safety initiative to enhance visibility for pedestrians includes various alternatives, with roadway lighting being one of the several solutions for consideration (https://highways.dot.gov/safety/pedestrian-bicyclist/step/). Recent research findings indicated there is a need to reduce the potential environmental impacts of roadway lighting, and jurisdictions often must balance the safety benefits of roadway lighting with the environmental impacts.

Roadway lighting can also be expensive to install and operate. Over-lighting and unwarranted lighting can result in excessive glare and lighting trespass in adjoining neighborhoods. Additionally, current warranting systems do not address the costs and benefits of roadway lighting as a safety countermeasure when compared to other safety alternatives. As a result, inconsistencies exist in terms of where and when roadway lighting is applied.

Lighting warrants help evaluate locations where lighting will have the maximum benefit based on defined conditions or rating systems. Meeting these warrants does not obligate the State or any agency to provide lighting. In other words, warrants indicate where lighting may be beneficial but should not be interpreted as an absolute indication of whether lighting is required. The need for lighting should be determined by sound engineering judgment, and the decision should be made by the agency with jurisdiction over the roadway. From a consistency standpoint, a jurisdiction should develop a master plan (refer to Section 4.1 of this document) rather than allowing third parties to use warrants to decide whether to light or not.

3.2 AASHTO Warranting System

Warrants for highways, freeways, interchanges, and bridges may be undertaken using the AASHTO Roadway Lighting Design Guide Warranting System. AASHTO defines warrants for continuous freeway lighting, complete interchange lighting, and partial interchange lighting based on warrant conditions including:

- Traffic volumes
- Spacing of freeway interchanges
- Lighting in adjacent areas
- Night-to-day crash ratio

AASHTO recommends providing lighting on long bridges in urban and suburban areas, even if the approaches are not lit. On bridges without full shoulders, lighting can enhance both bridge safety and utility and is therefore recommended by AASHTO. Where bridges are provided with sidewalks for pedestrian movements, lighting is recommended by AASHTO for pedestrian safety and guidance.

3.3 Warranting Method for Collector/Major/Local Streets

The AASHTO warranting method does not cover collector, major, and local roads. For these types of roads, the TAC Guide for the Design of Roadway Lighting (Transportation Association of Canada, 2006), which was based on the 1974 National Cooperative Highway Research Program Report 152 (National Academies of Sciences Engineering and Medicine, 1974), Warrants for Highway Lighting, can be used. The warrant system is based on geometric, operational, environmental, and crash factors. For each factor, a numeric rating from 1 to 5 is defined, and each factor is assigned a weight to indicate its relative importance. The rating is then multiplied by the weight to obtain a point score for each factor that indicates the factor's relative significance. The overall point score for all items indicates the need for lighting as well as the relative risk on that road compared with other roadways. Lighting under this method is warranted where a total point score of 60 or more is achieved. If the night-to-day crash ratio is 2:1 or greater, lighting is automatically warranted using this method regardless of the overall point score. Lighting may be prioritized solely based on the point scores, or in conjunction with a benefit/cost analysis. Benefits are typically based on the potential reduction in crash frequency and severity. Depending on road authority practice, costs typically include the initial cost of the lighting system, its ongoing (electricity) costs, and its maintenance costs. Initial costs may be substantial if a power source is not present.

When undertaking a warrant analysis, the length of the roadway segment being analyzed should be as long as possible where the variables remain constant (i.e., geometric, operational, environmental, and crash factors), and future development should be considered. When the roadway classification or roadway land use classification changes, a separate warrant analysis should be considered for each roadway section. Where classifications are relatively constant along the segment of roadway under consideration, a single warrant analysis may be undertaken.

The example warranting analysis sheet from the TAC Guide for the Design of Roadway Lighting (Transportation Association of Canada, 2006) is shown in Figure 37. The classification factors listed on the warrant sheets are defined as follows.

3.3.1 Geometric Factors

The warranting analysis considers the key geometric factors of the length of roadway to which the warrant is being applied. These factors include:

- Number of lanes
- Lane width
- Number of median openings per kilometer
- Driveways and entrances per kilometer
- Horizontal curve radius (small curve radii have a much higher impact on the warrant than large curve radii)
- Vertical grade
- Sight distance
- Parking

The applicable rating factors are used for the entire length of road being considered. If the rating changes over the length of the road being considered, then the worst-case rating value is used.

3.3.2 Operational Factors

The warranting analysis considers the operational factors for the entire length of roadway to which the warrant is being applied. These factors include:

- Signalized intersections
- Left turn lanes

- Median width
- Operating or posted speed
- Pedestrian activity (conflict) levels (refer to IESNA RP-8-21 for the definition of high, medium, and low activity)

The applicable rating factors are applied for the entire length of road being considered. If the rating changes over the length of the road being considered, then the worst-case rating value is used.

3.3.3 Environmental Factors

The warranting analysis considers the environmental factors for the entire length of road to which the warrant is being applied. These factors include:

- Percentage of development adjacent to the roadway. Adjacent development should be a reasonable distance from the roadway and should tie into the roadway for which the warrant is being undertaken via a driveway or intersection that generates a reasonable amount of traffic. Determining the amount of ambient lighting present in an area depends on the judgment of the individual performing the warrant analysis. The following ambient lighting definitions may be helpful to consider:
    - Sparse: rural freeways and highways with little or no development outside of city boundaries.
    - Moderate: rural or urban roads with some building lighting and development outside of commercial areas. Areas with residential and industrial development will typically have moderate ambient lighting.
    - Distracting: downtown commercial areas with well-lighted building exteriors adjacent to the roadway. Distracting lighting can also include lighting from fuel stations, automotive sales lots, and other commercial development where lighting is used to attract attention to businesses.
    - Intense: areas with large advertising signs, sports lighting, and other intense light sources adjacent to the roadway. Intense sources can be found in both rural and urban areas.
- Area classification
- Distance from development to roadway
- Presence of raised median curb

The applicable rating factors are used for the entire length of road being considered. If the rating changes over the length of the road being considered, then the worst-case rating value is used.

Warrants for Lighting Arterial, Collector and Local Roads

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

Notes:

1 Lighting Warranted
2 Pedestrian Activity Level (Refer to 9.1.3 - Pedestrian Definitions)
3 Two-way Left Turn Lane
4 Development Defined as Commercial, Industrial or Residential Buildings
5 85th Percentile Night Speed Should Be Used if Available, Otherwise Posted Speed Shall Be Used
6 Worst Case Geometric Factors for a Segment of Roadway Shall Apply
7 Also Includes Isolated Medians (Non-Continuous) Between Intersections

v1.0

Figure 37. Image. Example warranting analysis sheet for warrant for arterial, collector, and local roadways (TAC, 2006).

3.3.4 Crash Factors (Night and Day)

Crash factors are included in the warranting forms based on the night-to-day crash rate ratio for the given length of road to which the warrant is being applied. As the warrant point score for this category is heavily based on the night-to-day crash ratio, it is important that detailed and well-defined crash data be applied. Where crash ratios are not known, engineering judgment should be applied using crash statistics from similar roads for which data are available.

Where a low number of crashes have been recorded, while lighting may meet the warrant crash ratio, it may be of less benefit than for other areas with similar ratios and higher numbers.

3.4 Crash Modification Factors (CMFs)

A safety analysis and study showing that a lighting system is a cost-effective safety alternative for the project may be considered. There are various ways of executing a study of this type. One is to use the AASHTO Highway Safety Manual (HSM; https://www.highwaysafetymanual.org/). The HSM assembles currently available information on crash frequency and severity so that various improvements to roadways can be quantified and evaluated in terms of their effectiveness. The effects of various treatments such as geometric improvements and operational changes on roadways are quantified as CMFs. CMFs represent the change expected in crash frequency due to a specific change in conditions.

CMFs represent the change expected in crash frequency due to a specific change in conditions.

For example, when looking at the impact of highway lighting on all roadway types that previously had no lighting, the HSM method indicates a CMF of 0.72 for nighttime injury crashes (indicating a 28% reduction in nighttime injury crash types). Thus, if the expected average crash frequency is 10 injury crashes/year for a no-lighting condition, after the implementation of a highway lighting system, one would expect 10 × 0.72 = 7.2 injury crashes/year resulting in a reduction of 2.8 crashes per year (1-.72 = 2.8 crashes per year).

3.4.1 CMF Clearinghouse

The amount of information for crash analysis and evaluation is actively growing and can be found in the CMF Clearinghouse at www.cmfclearinghouse.org. In this clearinghouse, the viewer can sort through data by type of countermeasure, crash type, crash severity, and roadway type. The viewer can also see a measure of accuracy and precision of the data as well as applicability, as judged by a panel of reviewers and rated on a 1- to 5-star scale.

It is important to note that most CMFs provided in the clearinghouse for lighting use lighting as a binary “On/Off” metric only. There is very little information regarding the lighting level. Work in this area is still ongoing.

3.5 Warranting Method for Intersections

The AASHTO Warranting method does not cover intersections. The TAC Guide for the Design of Roadway Lighting includes a warranting system for intersection lighting that can be used to define the need for intersection lighting. The warranting system is based on geometric, operational, environmental, and crash factors. The critical factors this warranting method uses to determine the need for illumination are traffic volumes and nighttime crashes. The warrant point score indicates whether full intersection lighting, partial lighting, or delineation lighting is needed.

The critical factors used by this warranting method to determine the need for illumination are:

- Traffic volumes (particularly on the cross street).
- The presence of crosswalks.

- Nighttime crashes that may be attributed to the lack of illumination.
- The extent of raised medians.

Several secondary factors are also considered in the warrant but are given less weight in the overall point score. In the warrant, traffic volumes and nighttime crashes are given greater weight than raised medians, which can be designed, marked, or modified to reduce the risk associated with their presence in the roadway.

The following terminology is used with respect to the amount of lighting, as determined by the warrant system:

- Full Lighting – Denotes lighting covering an intersection in a uniform manner over the traveled portion of the roadway.
- Partial Lighting – Denotes lighting of key decision areas, potential conflict points, and/or hazards in and on the approach to an intersection. Partial lighting may also guide a driver from one key point to the next, and (if sufficient luminaires are used) place the road user on a safe heading after leaving the lighted area.
- Delineation Lighting – Denotes lighting that marks an intersection location for approaching traffic, lights vehicles on a cross street, or lights a median crossing.

An example analysis sheet for an intersection warranting analysis is shown in Figure 38.

Warrants for Intersection Lighting (See Note 2)

Item No.	Classification Factor	Rating Factor 'R' 0	1	2	3	4	Weight Subcategory (If Applicable)	Weight 'W'	Enter 'R' Here	Score 'R'x'W'	
	Geometric Factors										
1	Channelization	None	Right and/or Left Turn Lanes on Minor Approach Only	Right Turn Lane(s) Only on Major Leg(s)	Left Turn Lane(s) on Major Leg(s)	Left and Right Turn Lanes on all Legs	Raised and Operating Speed Less than 70 km/h on at Least One Channelized Approach or:	15		0	Only ONE 'R' Value is to be Entered for these Three Rows
							Raised and Operating Speed More than 70 km/h on at Least One Channelized Approach or:	20		0	
							Painted Only	5		0	
2	Approach Sight Distance on the Most Constrained Aproach (Relative to Recommended Minimum Intersection Sight Distances)	100% or More	75% to 99%	50% to 74%	25% to 49%	<25%		10		0	
3	Horizontal Curvature (Radius) at or Immediately Before Intersection on Any Leg — 110 km/hr:	Tangent	>1800 m	1150 to 1800 m	750 to 1150 m	<750 m		5		20	
	90 or 100 km/hr:	Tangent	>1400 m	950 to 1400 m	600 to 950 m	<600 m					
	70 or 80 km/hr:	Tangent	>950 m	550 to 950 m	340 to 550 m	<340 m					
	60 km/hr:	Tangent	>575 m	320 to 575 m	190 to 320 m	<190 m					
4	Angle of Intersection or Offset Intersection	90 Degree Angle	80 or 100 Degree Angle	-	70 or 110 Degree Angle	<70 or >110 Degree or Offset Intersection		5		0	
5	Downhill Approach Grades at or Immediately Before Intersection on Any Leg	<3.0%	3.1 to 3.9% and Meets Design Guidelines for Type and Speed of Road	4.1 to 4.9% and Meets Design Guidelines for Type and Speed of Road	5.0 to 7.0% and Meets Design Guidelines for Type and Speed of Road	>7.0% OR Exceeds Gradiant for Type and Speed of Road		3		0	
6	Number of Legs	-	3	4	5	6 or More		3		0	
								Subtotal Geometric Factors		20	G
	Operational Factors										
	If the Intersection is Signalized, Illumination is Warranted. If the Intersection is NOT Signalized, Points should be Calculated on the Basis of EITHER the AADT Factor or, the Signalization Warrant Factor.										
7	Either AADT (2 Way) (See Note 1): On Major Road	<1000	1000 to 2000	2000 to 3000	3000 to 5000	>5000		10		0	ONE 'R' Value is to be Entered for EACH of these Two Rows
	and On Minor Road	<500	500 to 1000	1000 to 1500	1500 to 2000	>2000		20		0	
	Or										OR
	Signalization Warrant (See Note 1)	Intersection Not Signalized and Volume-Based Signal Warrant is Less Than 20% Satisfied	Intersection Not Signalized and Volume-Based Signal Warrant 20% to 40% Satisfied	Intersection Not Signalized and Volume-Based Signal Warrant 40% to 60% Satisfied	Intersection Not Signalized and Volume-Based Signal Warrant 60% to 80% Satisfied	Intersection Not Signalized and Volume-Based Signal Warrant is Over 80% Satisfied		30		0	Only ONE 'R' Value is to be Entered for this ONE Row
8	Regular Nighttime Hourly Pedestrian Volume (See Note 2)	No Pedestrians	Up to 10	10 to 30	30 to 50	Over 50		10		0	
9	Intersecting Roadway Classification	No Primary Road Involved	Primary/Rural Major, Primary Rural Minor or Primary/Designated Community Access	Primary/Secondary	Primary/Primary	Intersection Includes Divided Highway		5		30	
10	Operating Speed or Posted Speed Limit on Major Road (see Note 3)	50 km/h or Less	60 KM/h	70 KM/h	80 KM/h	90 KM/h or Over		5		0	
11	Operating Speed or Posted Speed Limit on Minor Road (See Note 3)	50 km/h or Less	60 KM/h	70 KM/h	80 KM/h	91 KM/h or Over		5		0	
								Subtotal Operational Factors		30	O
	Environmental Factors										
12	Lighting Development Within 150 m Radius of Intersection	-	In One Quadrant	In Two Quadrants	In Three Quadrants	In Four Quadrants		5		0	
								Subtotal Environmental Factors		0	E
	Collision Factors										
13	Average Annual Nighttime Collision Frequency (See Note 4) or Rate over Last Three Years (Only Collisions Potentially Attributable to Inadequate Lighting)	0 Collisions per Year	1 Collision per Year	2 Collision per Year	3 or More Collisions Per Year OR At Least 1.5 Collisions per Million Entering Vehicle per Year and an Average Ratio of All Night to Day Collisions of at Least 1.5		1 or 2 Collisions per Year	15		0	Only ONE 'R' Value is to be Entered for these Two Rows
							3 or More Collisions per Year OR Rate ≥ 1.5 Collisions/MEV	30		30	
								Subtotal Collision Factors		30	A
								G + O + E + A = Total Warranting Points		80	
								Warranting Condition (80, 120-Partial, 240-Full)			
								Difference ±		80	D

Notes:

1 If the Intersection is not Signalized, the user should choose EITHER the AADT factor OR the signalization factor. The points from either factor, but not both factors, may be used for the warrant point calculations

2 The number of certain types of vulnerable pedestrians should be factored to reflect their increased need for visibility:
The number of child pedestrians (ages 12 and under) should be multiplied by two, and the number of senior pedestians (age 65 and over) should be multiplied by 1.5

3 85th Percentile Night Speed Should Be Used if Available, Otherwise Posted Speed may Be Used

4 Reported Collisions, rounded to the nearest whole number

Figure 38. Image. Intersection warranting analysis sheet (Transportation Association of Canada, 2006).

Based on the warrant analysis, the following conditions define the need for full, partial, or delineation lighting:

- If the intersection is signalized, full lighting is warranted.
- If the intersection is not signalized, the need for and the amount of lighting is determined by comparing the point score obtained from the warrant form categories to the following criteria:
  1) Full lighting is warranted where the total point score is 240 points or greater.
  2) Partial lightning is warranted where the point score is between 151 and 239 points.

3) Delineation lighting is warranted where the point score is between 120 and 150 points.

Generally, a point score under 120 indicates that lighting is not warranted. This score suggests that neither the critical operational warranting factor (substantial traffic volumes) nor the critical crash warranting factor (repeated nighttime crashes) is present.

Lighting may be prioritized solely based on the point score or in conjunction with a benefit/cost analysis. Benefits would typically be based on the potential reduction in crash frequency and severity at the intersection. Depending on the practice of the road authority, costs would typically include the initial cost of the lighting system, its ongoing (electricity) costs, and its maintenance costs. Initial costs may be substantial if a power source is not present at the intersection.

3.6 Pedestrian/Bicycle Facilities

There is no defined warranting system for pedestrians, but these road users are a critical aspect of the roadway environment. Typically, decisions about roadway lighting have considered crosswalks only as the location where there is an interaction between vehicles and people.

In terms of warranting, a defined point score and weighting for pedestrians is included in the warranting point score system for roadways and intersections. Lighting of sidewalks and pathways provides the pedestrian both guidance and a feeling of security. Where the sidewalk is adjacent to roadway, the lighting can also make the pedestrian more visible to drivers. Bike lanes are not included in the current warrant point score system. Bike lanes come in a variety of configurations, but from a lighting perspective the main consideration is the bike lane defined via pavement markings or by a barrier, fence, or curb separation from roadway traffic. Lighting is of the greatest benefit where the bike lane is defined by pavement markings as there is no barrier to protect the cyclist from the motor vehicle. Further information on types of bike lanes can be found in the AASHTO Guide for the Development of Bicycle Facilities, 4th Edition, 2012 (American Association of State Highway and Transportation Officials, 2012). The highest potential for conflict with a motor vehicle is at intersections and defined cross-over areas (e.g., dashed lines shown in Figure 39) where the motor vehicle and bicyclist are in potential conflict.

Although not specifically defined in current warrants, bicycle lane lighting is of high value. NCHRP Report 926, Guidance to Improve Pedestrian and Bicyclist Safety at Intersections, noted: “Illumination at crosswalks and along the roadway can help increase visibility for pedestrians and bicyclists, particularly at approaches to crossings” (Medicine, 2020). (Harkey, 2008) reported that increasing or adding lighting to crosswalks, road segments, and intersections improves pedestrian and bicyclist safety by reducing crashes, increasing yielding and compliance with traffic control devices, and improving visibility, with a CMF of 0.73 for injury crashes.

Although not specifically defined in current warrants, bicycle lane lighting is of high value.

Figure 39. Photo. Bike lane example (Warehouse, 2020).

Figure 39 shows an example of a bike lane adjacent to a roadway. The example includes dashed pavement markings where vehicles and cyclists interact. It is the generally accepted practice that unprotected bicycle lanes adjacent to a roadway should be lighted.

4 LIGHTING PLANNING AND DESIGN PROCESS

4.1 Lighting Master Plans

Lighting master plans are formal documents created through a study and planning process. They can be based on input from staff, public officials, lighting professionals, citizens, business owners, and others. Lighting master plans define the purpose of lighting and contain area maps with road types, classifications, land use, pedestrian and cyclist routes, parks, and other infrastructure information. They can also contain information regarding luminaires and poles, light sources, lighting levels, design criteria, design and construction specifications, historical considerations, and recommendations. This information is combined in a single, organized package that becomes the basis for lighting projects.

Lighting master plans consider anticipated economic and cultural changes, a community's public image and economic development goals, and technological advancements. Public engagement is recommended, but jurisdictions can define how that takes place. The benefits of such plans include coordination of various municipal lighting functions and the proactive planning of lighting for different areas of a community by recognizing their unique character and needs. The plans also allow for the scheduling of capital expenditures as well as implementation and maintenance strategies. Lighting master plans are based on the core concept that public facilities should enhance safety, encourage economic development, contribute to beautification, and provide a secure environment for people and property. Transportation-related lighting is generally a key component of community management. Lighting master plans should include equity considerations.

Lighting master plans should include considerations for equity.

Lighting master plans are typically adopted by a jurisdiction through bylaw, resolution, or similar measure. As such, lighting master plans may dictate specific design requirements for roadway lighting. The purpose of a lighting master plan is to ensure adequate lighting is provided for future development and that public lighting will be installed in a consistent manner that considers the needs and desires of citizens. If an area is designated for historic preservation, the lighting master plan may define luminaires and light sources that are compatible with, preserve, and/or improve the area's existing historical character.

Lighting master plans typically address the following major subject areas:

- Improved safety provided by lighting
- Improved sense of security provided by lighting
- Costs of lighting (capital and operating)
- Aesthetics of lighting (daytime and nighttime)
- Lighting design criteria
- Lighting-associated environmental issues and constraints, including the control of spill light, glare, and skyglow
- Energy used by lighting (through the definition of unit power density)
- Potential for economic development and the enhancement of nighttime activities through lighting

- Considerations of equity and Complete Streets
- Preservation of areas of darkness (e.g., areas around observatories)
- Maintenance requirements

A lighting master plan should define where to light from a corridor strategy, which will create consistency. Leaving decisions as to where to light to pure engineering judgment may lead to inconsistency.

4.2 Design process

The lighting design process is highlighted in Figure 40.

4.2.1 Pre-Design

Prior to starting any design, the roadway lighting designer should address the following typical pre-design considerations:

- Identify applicable standards and requirements.
- Review roadway geometrics and utilities.
- Define the clear zone (refer to the AASHTO Roadside Design Guide).
- Using warrants, determine the requirement for full or partial lighting for the type of installation under consideration.
- Investigate site conditions for the following:
    1) Availability of power (the lack of available power may affect the cost/benefit of a lighting installation).
    2) Proximity to aircraft landing facilities and railways, which may dictate specific lighting requirements.
    3) Presence of distribution and transmission power lines that require specific clearances, as defined by the local utility, Occupational Health and Safety Administration, and the National Electric Code (NEC).
    4) Environmental issues, including lighting impacts on humans, plants, and wildlife.
    5) Maintenance and operations considerations (e.g., access to light poles and luminaires for servicing).

4.2.2 Lighting Design Criteria

Prior to undertaking lighting design, the designer should identify basic lighting criteria for the project. The criteria selected are generally based on the recommendations of the IES or the ASSHTO. A State may modify the recommended values based on their own experience and needs. The criteria include the following:

- Pavement type (R1 to R4; refer to IES RP-8 -21 or the AASHTO Lighting Design Guide)
- Roadway type and pedestrian activity level (refer to IES RP-8-21 or the AASHTO Lighting Design Guide)

- Recommended lighting level and uniformity (refer to IES RP-8-21 or the AASHTO Lighting Design Guide)
- Roadway geometry, including the number and width of traffic lanes, median width, and sidewalks
- Light trespass (i.e., define lighting limitations outside of the right-of-way in reference to IES RP-8-21 and RP-33)

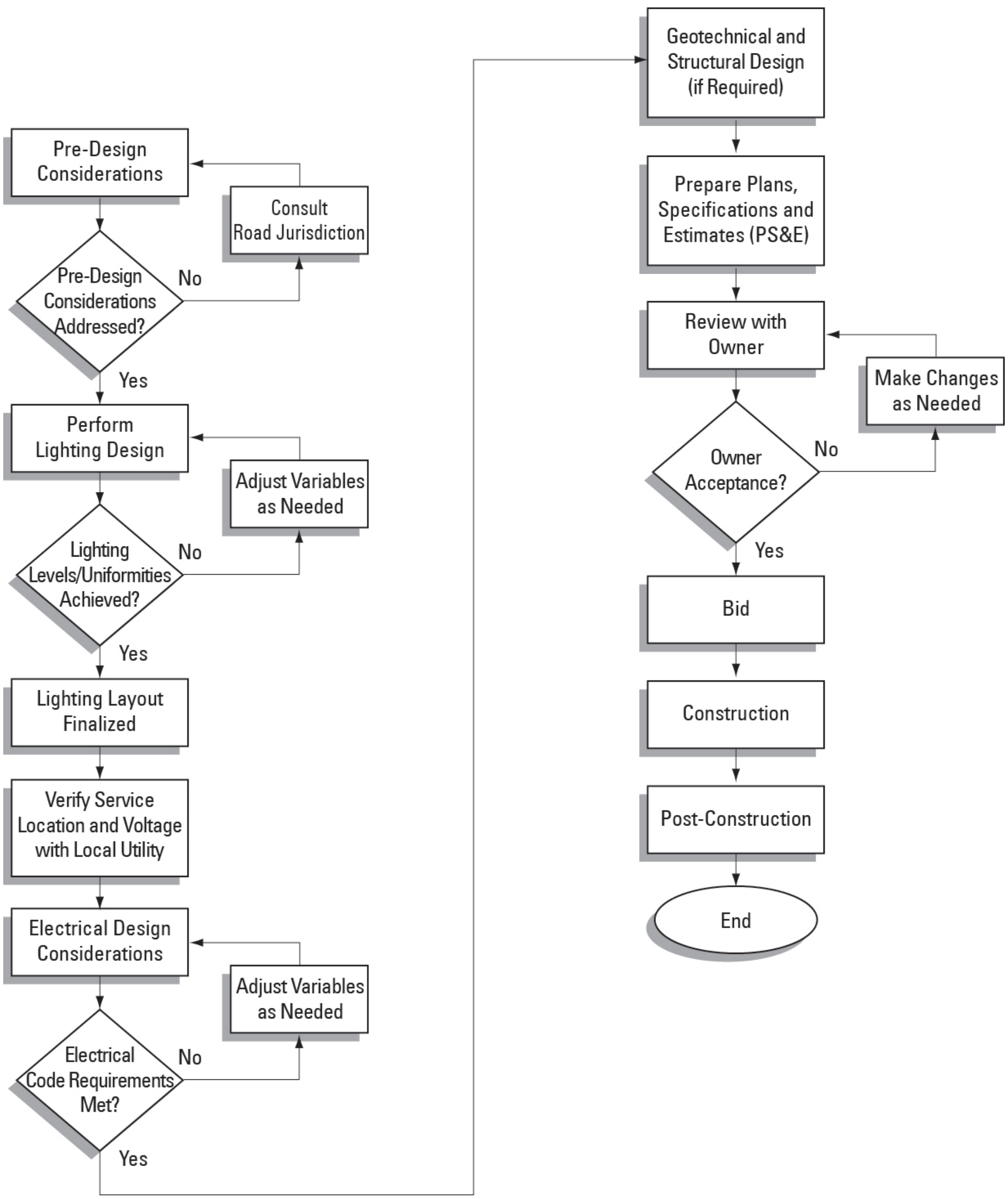


Figure 40. Flow chart. Lighting project design process (Transportation Association of Canada, 2006).

4.2.3 Perform Lighting Design

Selecting a suitable luminaire, obtaining IES-formatted photometric files, and undertaking lighting design using computer lighting design software are typical steps in performing lighting design. A “trial and adjustment” process using computer design software to achieve the optimal design is generally performed based on the following variables:

- Light source specification (type, wattage, CCT, CRI, fidelity, gamut)
- Light loss factor (LLF; refer to IES RP-8-21 and TM-21)
- Pole type, height, and luminaire arm length
- Pole offset (the pole location relative to the edge of the edge of pavement or curb and gutter)
- Luminaire type (e.g., cobra head, decorative, tunnel, wall pack)
- Pole spacing (e.g., one sided, staggered, or opposite)

Typically, the more experienced the designer, the shorter the trial and adjustment period. As photometrics of fixtures will vary from supplier to supplier for similar products, it may be appropriate to review photometrics from multiple suppliers.

Lighting design is typically undertaken using a “trial and adjustment” process using computer design software to achieve the optimal design.

The design of intersections, crosswalks, roundabouts, parking lots, and interchanges will follow a similar process but without the benefit of optimization. The steps will be similar to those described above with the spacings pre-set and refined by trial and adjustment. The specific method of calculation to be undertaken will vary depending on the application.

Lighting design requires the use of computer lighting design software and the photometric files from lighting suppliers in IES format. For LED lighting, the photometric files should be “absolute,” meaning that the photometric file will be for the exact luminaire tested. The designer then selects photometric files for luminaires that light the roadway and sidewalks while minimizing light pollution.

Light levels are based on the end-of-lamp life. However, in the past, a standard LLF was applied based on a given re-lamping cycle. Unlike other lighting technologies, LEDs typically do not fail catastrophically during use and will gradually depreciate over time, resulting in lower-than-required light levels over time. While LEDs can last beyond 100,000 hours, it is typically recommended that 88,000 (20 years) be applied as the useful life.

For LEDs, the LLF is a combination of several factors representing the deterioration of the lamp and luminaire over their life span. Several individual factors combine to form the overall LLF, which is applied to a lighting design. The main factors in the LLF are lamp lumen depreciation (LLD) and luminaire dirt depreciation (LDD). LLF is calculated as LLF = LLD × LDD. Once defined, the LLF is incorporated into the design calculations. The calculation of LLF is discussed in detail in IES RP-8-21.

The LLD is based on data measured by the manufacturer, as per IES LM80, and presented in the TM-21 format, which defines LLD based on the end-of-lamp life. The LDD tables in RP-8-21 only define up to 8 years and are dated. To better define LDD, the IES published IES RES-1-16, Measure and Report Luminaire Dirt Depreciation (LDD) in LED Luminaires for Street and Roadway Lighting Applications. This document is available from the IES at: http://media.ies.org/docs/research/IES-RES-1-16.pdf. This document defines LDD values based upon field examination and measurements of actual LED roadway luminaires. The report recommends different levels of LDD for different optical systems based on a fairly limited sampling of luminaires. As the actual factors are difficult to predict, good practice is to use a deprecation factor of 1% per year. The factor applied to the design depends on the cleaning cycle (i.e., 0.9 for a 10-year cleaning cycle or 0.8 for a 20-year cycle). Lighting in tunnels is an exception because these lighting systems accumulate significantly more dirt than roadway lighting.

To accommodate the LLF, a lighting system is overly bright when first installed and then depreciates over its life. LDD is recoverable with cleaning, whereas LLD deprecates over time. Adaptive lighting systems (see Section 7) can be of benefit as lighting can be dimmed and then ramped up over time to accommodate the LLF, which will save power and cost over the life cycle. This is sometimes referred to as “constant light output.”

4.2.4 Other Considerations

Other considerations involved in the lighting design process include:

- Electrical design considerations in accordance with NEC and any local requirements
- Structural and geotechnical considerations for poles and foundations in accordance with AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals
- Plans specification and estimates in accordance with local jurisdiction documentation and requirements
- Bid estimates in accordance with local jurisdiction documentation and requirements
- Construction (monitor and review construction)
- Post construction (record drawings and operation & maintenance documentation along with field measurements of lighting)

Examples of design elements typically considered when performing lighting design for freeway and urban roadways are shown in Figure 41 and Figure 42. Each of these elements in the roadway design should be considered in the lighting analysis. These elements are further defined in NCHRP Report 940, Solid-State Roadway Lighting Design Volume 1: Guidance (National Academies of Sciences Engineering Medicine, 2020), and AASHTO GL-7, Roadway Lighting Design Guide (American Association of State Highway and Transportation Officials, 2018b).

Part II of this Handbook includes examples for various roadway types and applications in addition to those described above.

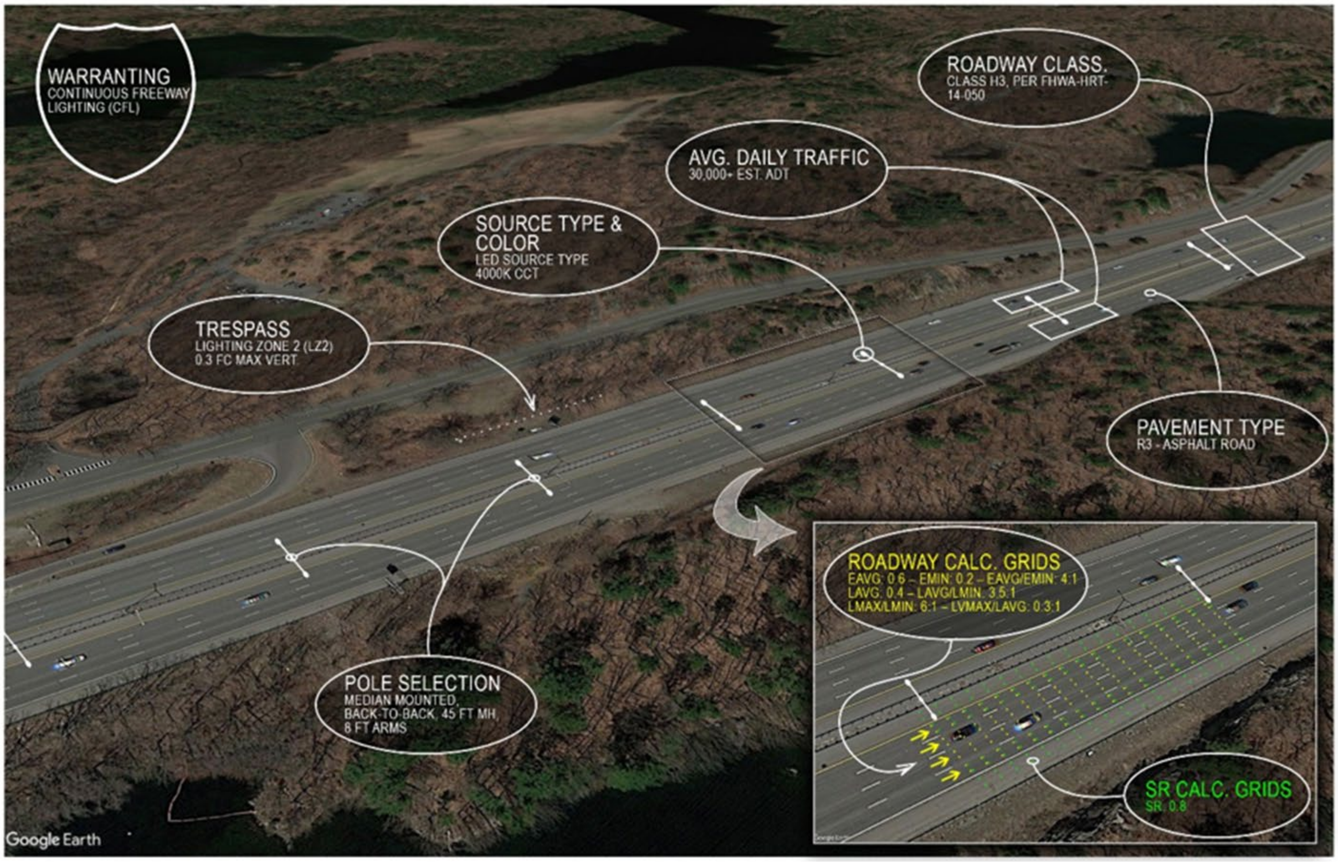


Figure 41. Photo. Freeway lighting design elements (National Academies of Sciences Engineering Medicine, 2020).

Figure 42. Photo. Urban roadway lighting design elements (National Academies of Sciences Engineering Medicine, 2020).

4.3 Design Applications

4.3.1 Roadway

As previously stated, the lighting design criteria for roadways are typically drawn from the IES RP-8-21 or the AASHTO Roadway Lighting Design Guide and are not repeated in this document. Examples of the application of these criteria are highlighted for several common lighting applications in Part II of this document:

- Urban Street Lighting
- Rural Road Lighting
- Expressway Lighting
- Urban Freeway Lighting
- Suburban Freeway Lighting
- Rural Freeway Lighting
- Roundabout Lighting
- Walkway & Bikeway Lighting

4.3.2 Tunnels

Lighting tunnels is generally more complex than lighting a typical roadway. The lighting in a tunnel requires considering both daytime and nighttime conditions, the dark adaptation process of the eye, geographical orientation of the tunnel, and the portal design, to name just a few of the specific tunnel criteria. To add to the complexity of the tunnel lighting design, long tunnels are also divided into zones, each of which requires a different design and system specification. Considerations and design examples for short, long, and underpass tunnel applications are defined in Part II, Design Examples. These are provided to aid in the design process and to clarify the requirements defined in IES RP-8-21.

4.3.3 Pedestrian Facilities

Lighting for pedestrians is discussed in the IES- RP-8-21 guidelines that provide recommendations for the lighting of pedestrian facilities. Studies considering high pedestrian volumes and facilities for children such as school zones have been undertaken.

A recent research effort (Terry et al., 2020) primarily considered the visibility needs of children but included adults for comparison through a group of experiments that examined lighting needs from the perspectives of both the driver and pedestrian. The experiments included an effort in which drivers were asked to detect child-size mannequins at the side of a roadway, an effort in which both adult and child pedestrians detected trip-and-fall hazards, and a final effort in which pedestrians judged acceptable gaps to cross the roadway in front of a moving vehicle. The project allowed for the development of criteria for pedestrian lighting in areas where children are present such as school zones or event venues.

The research results show a correlation between the lighting level on the roadway and visibility of pedestrians. The research indicates that at a level of 9 lux semi-cylindrical or 3 lux vertical illuminance, additional light does not increase visibility. A higher lighting level is needed for high visual clutter on a roadway; however, this seems to indicate that a luminance level of 2 cd/m^2 is required for visibility in urban settings. As there is a stronger link between the roadway luminance and the semi-cylindrical illuminance, it has been determined that the more stringent criteria for pedestrian lighting shall be used in areas with high pedestrian volumes and potential uncertainty in pedestrian behavior. These areas might include school zones or roadways with pedestrian levels of 100 pedestrians per hour, which is drawn from existing lighting design standards (Illuminating Engineering Society, 2021e).

A grid of calculation and measurement points aligned along the side of the roadway for adjacent sidewalks or along the pedestrian walkway for separated pedestrian paths should be illuminated to a minimum level based on a line of calculation points along the path and spaced at no more than 2 m (6.6 ft).

4.3.3.1 Crosswalk Lighting

Current research shows that crosswalk light levels should be at 10 lux vertical illuminance or higher (Bhagavathula, Gibbons, & Kassing, 2021). Recognizing that this level is significantly higher than the levels recommended along the side of the roadway, these facilities are in the roadway and the path of the vehicle, and as such a higher lighting level is recommended. Further research is being developed for these criteria.

In terms of lighting for pedestrians at crosswalks, results of this research indicated that neither light level nor light scale impacted the responses of children and adults in regard to the point at which they would no longer attempt to cross a roadway; however, it was determined that the presence of roadway lighting may inform an adult's perception of depth more accurately. Most crosswalks are lit for the primary purpose of making pedestrians visible to drivers. The results of this study also indicate a benefit to the pedestrian in being able to make a more confident decision regarding the vehicle's distance from the crosswalk. The decision-making abilities of children, however, are not improved with the addition of lighting, nor are they impacted by the lane positioning or speed of approaching vehicles (Terry et al., 2020).

4.3.3.2 Luminaire Height

On roadways, pedestrian lighting is typically provided by the roadway lighting system itself. However, pedestrian-scale lighting is used for some roadways and pathways. Typically, pedestrian scale lighting is mounted at a lower height and provides high levels of vertical illumination. Roadway lighting is mounted at a higher elevation and provides a higher level of horizontal illuminance. The issue with a lower mounting height is that luminaires that direct vertical illuminance towards the pedestrian also typically have higher glare rating for both the pedestrian and vehicle driver. As a result, the roadway luminance may need to increase to overcome the potential for disability glare. The glare should be confirmed via a veiling luminance calculation as per IES RP-8-21.

4.3.3.3 Recommendations

Based on the research results on pedestrian lighting performed for the FHWA and documented in report FHWA-SA-20-02 Research Report: Street Lighting for Pedestrian Safety (Terry et al., 2020), the criteria in Table 7 are extracted from the research report for pedestrian areas. Table 8 notes that while these recommendations can be applied to any light source, the color temperature recommendation typically applies to LED light sources only.

Table 7. Recommended criteria for pedestrian facilities including school areas. (Terry et al., 2020)

Pedestrian facility characteristics	Pedestrian lighting minimum	Rural (Average Luminance)	Urban (Average Luminance)
Low/medium pedestrian volumes	2 lux vertical	N/A	1 cd/m^2
High pedestrian volume/ school zones	10 lux SC	1 cd/m^2	2cd/m^2
Light source spectral characteristics	3000 K to 4000K	N/A	N/A
Pedestrian crosswalk	20 lux vertical	N/A	N/A

Table 8. Pedestrian volume criteria (IESNA RP-8-21, 2018).

Pedestrian volume levels	Pedestrians per hour
Low	0–10
Medium	11—100
High	>100

4.3.3.4 Design and Verification Approach

For the calculation and the verification of the lighting in the pedestrian sidewalks and areas, the calculation grid should be spaced between the luminaires and centered in the design area with a maximum spacing of 1.5 meters (5 ft) between grid points in each direction.

Verification of lighting levels should be made at the same location as in the calculation grid. Please refer to IES RP-8-21 for more information (Illuminating Engineering Society, 2021e).

4.3.4 Railway Crossings

Unsignalized rail crossings pose high risk to both the train and road users in terms of collisions. The risk increases in hours of darkness when visibility is reduced. Road users at risk include motor vehicles, pedestrians, and cyclists.

Lighting railway crossings (specifically those that are unsignalized) is very important given the increased risk to road users when trains are present. As trains do not have typical retroreflective markings and active lighting on the railcars, trains are essentially invisible at night at a rail crossing. Properly designed lighting will improve visibility of the train. Lighting for railway crossings was defined in the 2012 Handbook but not included in this document, as it is well covered in IES RP-8-21. Consult the FHWA Highway Rail Crossing Handbook (safety.fhwa.dot.gov) for further information on rail crossings. An example design is provided in Part II of this handbook.

For more information on the FHWA Railway Crossing programs, refer to:
https://safety.fhwa.dot.gov/hsip/xings/

4.3.5 Work Zones

Work zone safety is an important consideration for construction and maintenance activities on U.S. roadways. In the last 10 years, the number of injuries and fatalities in work zones has risen considerably (American Road & Transportation Builders Association, 2022), as shown in Figure 43. As traffic volumes increase and more construction activities occur at night, the safety issues grow more complex. Although traffic volumes are lower at night, travel speeds are generally higher and visibility is lower, leading to potentially higher risks for motorists and workers.

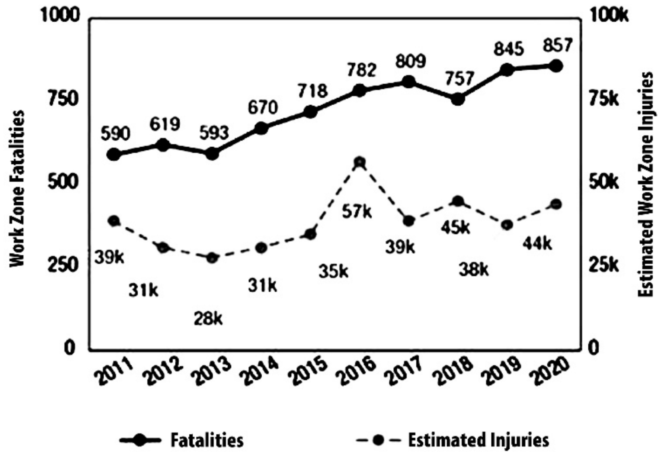


Figure 43. Graph. Fatalities and estimated injuries occurring in work zones from 2011 to 2020 (American Road & Transportation Builders Association, 2022).

Work zone lighting increases the visibility for workers and their visibility to motorists entering the work zones, thus ensuring safety for workers as well as motorists. Work zone lighting typically involves the use of portable, high-intensity floodlights or balloon lights with portable generators to direct a high level of light onto the work area. These portable light towers can be a significant source of glare to motorists entering the work zone, if aimed incorrectly. Glare in the eyes of the drivers entering the work zone could reduce visibility and potentially increase the risk of a crash. Great care should be taken when prescribing lighting for work zones so that workers have adequate light levels to complete their tasks effectively and safely without introducing glare for drivers entering the work zone. Orientation of the portable light tower and their mounting height can significantly affect drivers' perception of glare and visibility (Bhagavathula & Gibbons, 2017, 2018). For portable light towers that can be aimed, the angle between the light beam axis and the driver's line of sight should always be greater than 90 degrees, and the angle between the light beam axis and vertical should be less than or equal to 30 degrees. For the portable light towers that can be aimed, a mounting height of at least 6 meters (~20 ft) is recommended. Light towers that cannot be aimed, like the balloon type portable light towers, should be located in the shoulder of the roadway and be mounted at a height of at least 8 meters (~25 ft). The features of different kinds of portable light towers commonly used in work zones is shown in Table 9 and Figure 44. Lighting for work zones was defined in the 2012 Handbook but is not included in this document, as it is well covered in IES RP-8-21. Several common work zone lighting applications are defined in Part II, Design Examples. These are provided to aid in the design process.

Table 9. Pros and cons of different types of portable light towers used in work zones (Bhagavathula, Gibbons, Medina, & Terry, 2017).

Type of Portable Light Tower	Pros	Cons
Metal Halide	Widely available Can be aimed Offers excellent visibility	Could cause glare if aimed poorly
Light Emitting Diode	Newer and energy efficient technology Can be aimed Can be dimmed Could illuminate without light trespass	Visibility lower than metal halide and balloon portable light tower types
Balloon	Newer technology and could be energy efficient Aiming not required Potential for lower glare Offers excellent visibility	Susceptible to wind

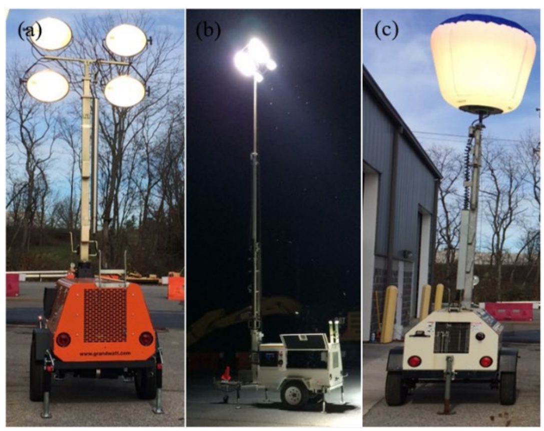


Figure 44. Image. Common portable light towers used in work zone lighting (a) Metal Halide, (b) LED, and (c) Balloon portable light towers. (Image Credit: Rajaram Bhagavathula, VTTI)

5 LIGHTING SYSTEM SELECTION

5.1 Lighting Selection

A key task for the roadway lighting designer is the selection and specification of products and equipment. Many manufacturers produce outdoor lighting equipment that is marketed and available throughout North America. Variables that affect the pole layout and spacing include the pole style, pole height, arm length, luminaire wattage, optical distribution, and luminaire type (cobra head, decorative, etc.).

5.1.1 Luminaires

An important key task for the roadway lighting designer is the selection and specification of products and equipment.

The use of high-quality products is critical to prolonging the overall operating life of roadway lighting systems. Quality relates to the features and characteristics of a product that impact its ability to satisfy stated or implied needs. While quality could be overlooked if low price is the primary criterion for product selection, it is an important consideration in product selection. There can be vast differences in product performance and quality of optical distribution and output that affect the light level and durability. In general, focusing on price alone will not deliver best-value installations. Simply put, you get what you pay for.

In addition to quality, other considerations when specifying a product include:

- Certification. Electrical products should bear an Underwriters' Laboratories label.
- Photometric performance (for luminaires). A photometric comparison of luminaires is critical to selecting the best product for a given application, as shown in Figure 45. Comparisons should be based on photometric data provided by the supplier from an independent testing laboratory. As mentioned earlier, LED luminaires are typically not swappable from one manufacturer to another. The optical design is particular to one product. Thus, an individual design is needed for each product used and maintenance and inventory levels may increase if multiple product types are used by one agency.

Figure 45. Photo. Photo displaying luminaires of different correlated color temperatures (Image Credit: Rajaram, Bhagavathula, VTTI)

- Optical system and shielding. Luminaires have varying optical systems and shielding options that can produce differing effects such as disability glare (veiling luminance) impacts on drivers; therefore, it is critical to select luminaires that meet the veiling luminance requirements on the roadway. Luminaires can also produce varying light trespass impacts off the roadway. When using pedestrian scale luminaires (typically 20 ft or lower luminaire mounting height), consider a diffusing lens (also referred to by some manufactures as comfort optics) to reduce the direct brightness of the LEDs and reduce impacts. Shielding of optical systems, defined further in Section 6.3, will also help mitigate light trespass impacts off the roadway.
- Durability. Durability is the capability of a product to resist deterioration, damage, and corrosion over time. Designers should consider the potential for vandalism and the corrosive nature of the project's environment when choosing specific products.

> *Lighting systems should be selected to optimize the life-cycle cost of the system.*

- Aesthetics. The products selected should be aesthetically compatible with their surroundings. Manufacturers offer a wide range of equipment shapes, configurations, colors, and styles. Similar or identical-looking products should be used, if possible, when the new installation will be integrated with existing installations. The height of lighting structures should be visually compatible with the height of other structures in the area.
- Availability. Custom and/or decorative products or products manufactured in small quantities often have long lead times for replacement. Designers should verify that the products selected will be available to avoid construction schedule impacts. Designers should also confirm that parts or complete replacement units will be available following installation. If products or parts will not be readily available, the designer should advise the owner to consider purchasing replacement units or parts to stock for maintenance purposes.
- Maintenance requirements. Maintenance considerations include ease of access for servicing, maintenance frequency, and level of service required over the product's anticipated useful life.
- Operations cost. Similar products can have different costs of operation. This is particularly true of products that consume energy. The designer should review operational costs when specifying products and choose those products that are both economical to operate and provide the required performance.

Based on the recommendations in NCHRP 940 and other state specifications, specific minimum luminaire typical recommendations are as follows:

- Optical system ingress protection rating of IP66 or better
- Min 3G vibration rating
- Salt spray rating of 6 or better as per ASTM D1654
- Surge suppression rating of 20kV/10kA
- Ten-year warranty
- Power factor of 0.9 or better
- Total harmonic distortion < 20%
- FCC 47 CFR Part 15 Inference Requirements for Class B (residential areas)
- Glare shielding

In addition, all luminaires should have a 7-pin photocell receptacle (as recommended per ANSI C136.41) and be enabled for adaptive controls via a 0-10 V dimming driver. A photocell would then operate each luminaire or a shorting cap would be provided if a single photocell would operate groups of luminaires.

It is important to note that, typically, the higher the drive current, the greater the light output, and with that comes a higher product failure rate. However, a lower drive current corresponds to a greater MTBF and thus a higher reliability (fewer failures over time). Obtaining accurate MTBF data from suppliers is challenging as the market is focused on maximum optical efficiency at the lowest cost; reliability and product failure rates are not typically considered.

Another option offered by many suppliers is an adjustable driver current setting in the luminaire. In effect, this setting varies the luminaire wattage by providing 5 to 10 different wattages from the same luminaire. The number of wattages depends on the product. Typically, the design is based on the middle setting so that the wattage can be increased or decreased if required.

5.1.2 Energy Efficiency

To ensure the selection of energy-efficient luminaires, a unit power density (UPD) analysis is a good method for defining optimal luminaire performance and energy efficiency.

To meet demand, energy-efficient roadway lighting technologies and adaptive controls have been developed and show significant potential for energy reduction, reduced maintenance, and cost savings. While LED lighting has scaled well into the market, adaptive lighting controls have lagged given the lower return on investment and longer payback based on power savings as compared to LED lighting (See Section 7 of this Handbook). The conversion to LEDs has resulted in good payback and return on investment, whereas lighting controls have not had the same levels of benefits.

Efficacy is a simple measure of the light output of the light source. It is measured in lumens per watt. Efficacy does not deal with how efficiently the light source delivers the light to the surface and is therefore limited as a measure of performance. In the past, all streetlights used high-intensity discharge lamps with similar inefficiencies with respect to how the light is distributed from the luminaire. Although LEDs have similar efficacies (lumens per watt) as some of the better high-intensity discharge sources, LEDs offer a far more effective optical distribution of light from the source, making them highly optically efficient.

To ensure the selection of energy-efficient luminaires, a unit power density (UPD) analysis is a good method for defining optimal luminaire performance and energy efficiency. UPD is the ratio of the rated luminaire watts to the amount of lighting delivered for a given area; thus, a lower UPD indicates better lighting. It is an excellent way to assess the efficiency of luminaires for various roadway lighting applications. The determination of UPD does not mitigate the need to meet lighting criteria, however. UPD allows the consideration of multiple lighting criteria, road widths, and pole heights and spacings to select the optimal product. The defined UPD value can be used as a benchmark to pre-approve products based on their performance.

The UPD calculation is mathematically expressed in Equation 5 and shown schematically in Figure 46 (UPD is measured in Watts per meter squared [Watts/meters^2]).

Equation 5. UPD Calculation (source TAC)

$$\text{UPD}\ (\frac{W}{m^2}) = \frac{\text{Rated Luminaire Wattage}}{\text{Roadway Width } \times \text{X Luminaire Spacing}}$$

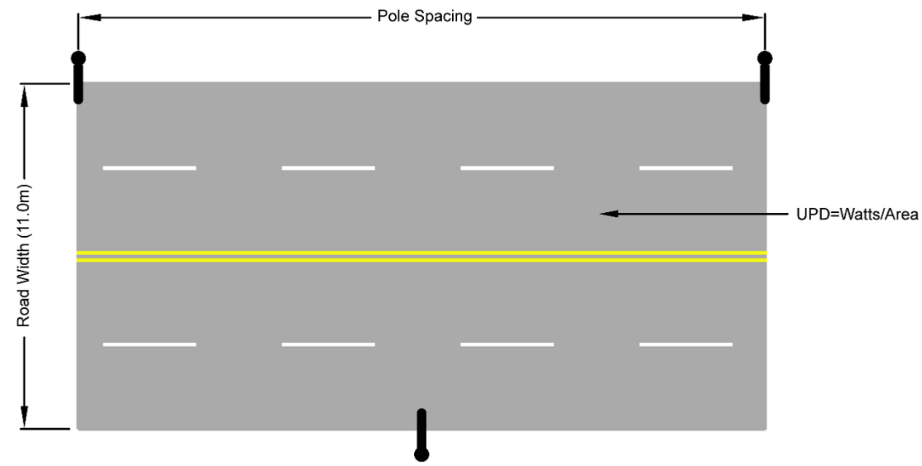


Figure 46. Diagram. Geometry for the UPD calculation. (Image Credit: WSP)

5.2 Other Design Considerations

In some cases, site conditions may dictate certain constraints on the design. Therefore, the following site conditions should be investigated:

- Availability of power. The availability of power is a major factor in determining if roadway lighting can be provided. If power is not available, the local utility should be consulted and cost estimates for power supply should be determined.
- Proximity to aircraft landing facilities. Prospective installations close to airports and helicopter landing pads may pose problems with defined glide paths and air traffic control operations. Typically, an airport authority or their governing authority will have specific pole height limitations and/or optical requirements for the luminaires. Where a lighting installation is proposed close to an aircraft landing facility, the facility should be contacted so requirements specific to that facility can be met.
- Proximity to railroads. Lighting systems near railroad tracks will have specific clearance requirements from the tracks.
- Presence of overhead distribution and transmission lines. Distribution and transmission lines often conflict with lighting poles. Where transmission or distribution lines exist or are proposed and lighting is required, the designer should consult the local utility provider and investigate applicable codes and standards to determine clearance requirements. Typically, the higher the voltage of the overhead lines, the greater the clearance distance required. In the case of overhead transmission lines, the local electrical utility may define additional clearance requirements due to the potential sag of the transmission lines. Line sag will vary with the change in ambient temperature and power demand.
- Environmental issues. Local lighting ordinances may also dictate the type of lighting that may be installed along with light trespass and skyglow limits.
- Maintenance and operations considerations. Maintenance should be considered as part of the roadway lighting design. Where possible, maintenance personnel should be consulted by those undertaking the roadway lighting design. It is critical that the luminaires be safely accessible via

available service vehicles (used by those undertaking the maintenance) with minimal disruption to traffic. The height limits of maintenance equipment may impact pole height and location.

- Roadside safety considerations. Poles can be a potential hazard to errant motor vehicles. Clear zones and pole placement issues should be known and addressed. Additional information can be found in the AASHTO Roadside Design Guide (https://highways.dot.gov/safety/pedestrian-bicyclist/safety-tools/51-52-roadside-design-guide-4th-edition.

5.3 Luminaire Classification

A system exists to define optical distribution for roadway lighting (refer to IES RP-8-21). The system shows different light distribution patterns used to define the distribution (Figure 47). Prior to LEDs, this system worked fairly well to define the required luminaire wattage and optical system (e.g., 100-W HPS with type II full cut-off distribution).

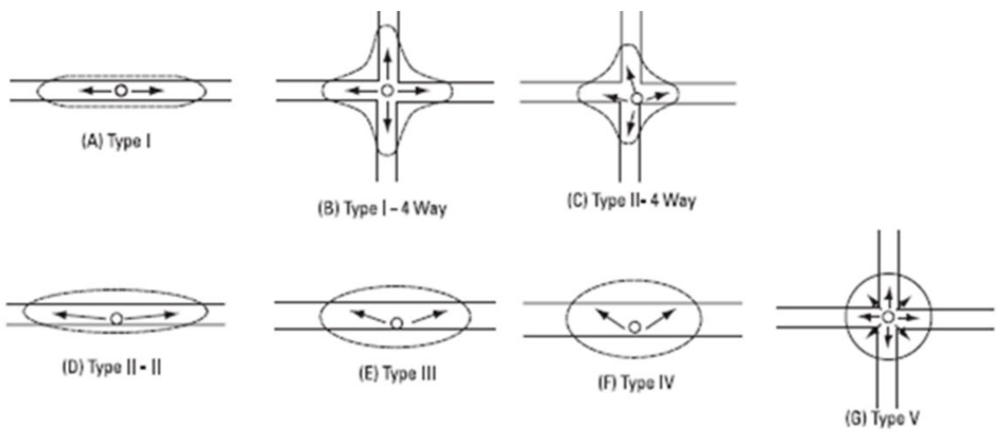


Figure 47. Image. IES roadway luminaire classifications (Illuminating Engineering Society, 2018).

The advent of LEDs with arrays of optical systems has rendered the existing classification system defined in IES RP-8-21 ineffective. Figure 48 compares four type II luminaires which produce quite different light distributions. Thus, this classification system should not be used generally to specify luminaires.

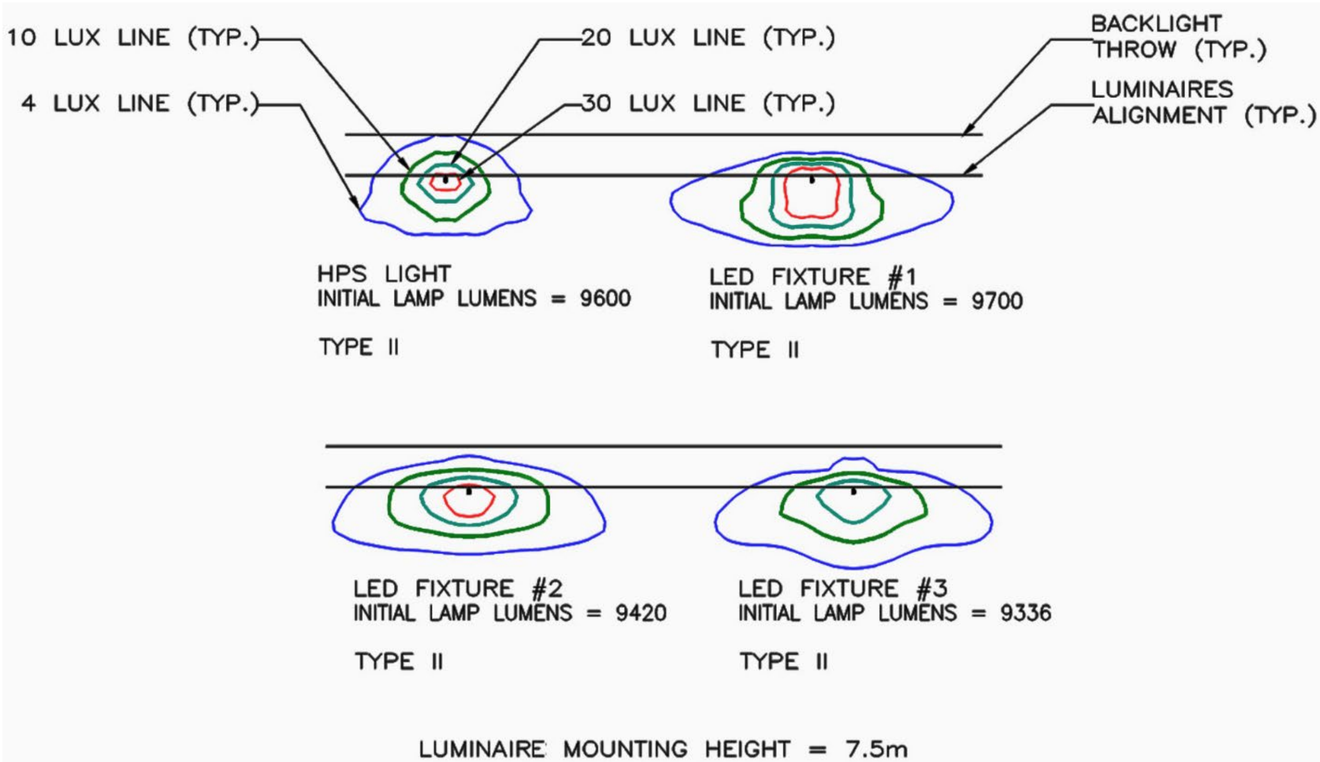


Figure 48. Image. Comparison of light distributions for four type II luminaires (Image Credit: DMD).

Various luminaires of similar wattages in terms of their ability to meet various light levels based on IES RP-8-21 road classifications and pedestrian activity levels were compared. Luminaire photometric data were provided by eight different manufacturers based on common road geometrics. The photometric files were then applied in common lighting calculation models, and the spacing was optimized to meet the lighting criteria. The results showed vastly different pole spacings in each scenerio, indicating that performance varies greatly from supplier to supplier. Thus, standized pole spacings cannot be transferred from product to product.

A luminaire classification system (LCS) was developed to define luminaire distribution and assess and mitigate light trespass, glare, and skyglow (see IES TM-15, Luminaire Classification System for Outdoor Luminaires (Illuminating Engineering Society, 2020b)). This LCS was intended to replace the luminaire cutoff classification system, which uses designations like cutoff, non-cutoff, semi-cutoff, and full cutoff. The LCS defines a method for evaluating and comparing outdoor luminaires. It provides a basic model that defines maximum lumens within defined angles of primary areas: back light, up-light, and glare (BUG). The sum of percentages of lamp lumens within these three primary areas is equal to the photometric luminaire efficiency. The BUG ratings are further defined in IES TM-15 (Illuminating Engineering Society, 2020a).

Standardized pole spacings cannot be transferred from product to product.

The intent of the BUG metric is to allow a designer to select the optimal optics for a given application while also reducing light trespass and skyglow. For a luminaire selection, the optimal up-light rating would be U0, which indicates reduced potential skyglow. The glare rating should not be used, as it can conflict with the veiling luminance ratio, which is a better measure of glare. Using the lowest back light rating possible will achieve sidewalk lighting levels and surround levels, which should take priority in the design.

6 ENVIROMENTAL IMPACTS AND MITIGATION

This section discusses the impacts of lighting beyond its effects on safety. These impacts can be both positive and negative. Though safety should generally be the priority, these other impacts may warrant consideration during lighting design.

6.1 Wildlife Impacts

Light is a major factor in controlling physiological and behavioral processes in organisms and thus plays a central role in the lives of many plants and animals. Over the past century, artificial lighting has transformed the nighttime environment for wildlife over large areas, influencing the movement, reproduction, and migration of various species. The large-scale conversion of traditional streetlighting to LED roadway lighting is beginning to occur in cities around the world. As such, scientific studies investigating how urban and suburban wildlife are affected by this conversion are lacking.

> *Lighting in environmentally sensitive areas with animal activity should minimize the duration of lighting, direct the light only where needed, and reduce intensity as much as possible.*

According to World Atlas, there are approximately 8.7 million species on Earth, with studies suggesting that 86% of all land species and 91% of all sea species are yet to be discovered or noted (Mora, Tittensor, Adl, Simpson, & Worm, 2011). The animal kingdom comprises only approximately 0.4% of the total living organisms on Earth; plants comprise the most at 82%, and microscopic bacteria comes next at 13%. Existing literature (discussed below) highlights the variability in wildlife responses to different lighting levels and spectral distributions. These variations stem from the large range of activity patterns (e.g., diurnal vs. nocturnal) and spectral perception and sensitives found among wildlife species. The wide variety of species and varying sensitivity to light make defining impacts difficult.

6.1.1 Lighting Impacts on Animals

Much animal activity takes place at night; almost all small rodents and carnivores, 80% of marsupials, and 20% of primates are nocturnal. Lighting in environmentally sensitive areas with animal activity should minimize the duration of lighting, direct the light only where needed, and reduce intensity as much as possible. As an example of the impact of lighting on wildlife, (Witherington & Martin, 1996) found that lighting caused significant issues for turtle hatching and shore bird nesting on the coast of Florida.

Roadway lighting can negatively affect animals by disrupting their habitats, disorientating them, or disturbing their circadian rhythms (van Bommel, 2014). An estimated 40% of the world has not experienced darkness at levels below moonlight (Swaddle et al., 2015). All animals with visual systems, including mammals, fish, and insects, are impacted by artificial light at night (Brüning, FranzHölker, Franke, Kleine, & Kloas 2016). Extensive literature is available on this topic: refer to (Rich & Longcore, 2006). Typically, the issues associated with lighting are related to attraction and disorientation (Allen, 1880), although lighting may also impact breeding, feeding, and behavior. For example, the timing of morning song in robins is significantly affected by the robin’s proximity to roadway lighting installations; however, lighting also increased the probability of siring offspring.

One of the early examples of the impact of light at night was on sea turtles. Sea turtle hatchlings are genetically programmed to use starlight and moonlight reflections off the water to guide them from their nest to the water. However, man-made light sources can confuse the hatchlings and lead them inland, away from the ocean and onto lighted roadways. Beach areas where both street lighting and turtle populations are present can discourage females from nesting. If a female fails to nest after multiple false crawls, she will resort to less-than-optimal nesting spots or deposit her eggs in the ocean. In either case, the survival outlook for hatchlings is slim (Silva et al., 2017). Lighting near the shore also can cause hatchlings to become disoriented and wander inland, where they often die of dehydration or predation. Scientists believe that hatchlings have an innate instinct that leads them in the brightest direction, which is normally moonlight reflecting off the ocean. Excess lighting from the nearshore buildings and streets draws hatchlings toward land, where they may be eaten or run over. Although further investigation is required to fully understand the safety impacts, custom "sea turtle-friendly" lighting appears warranted. Luminaires with amber or red LEDs with a spectral power distribution range of 580 to 640 nm are defined as turtle friendly and approved by sea turtle conservation groups (Witherington & Bjorndal, 1991),(Figure 49).

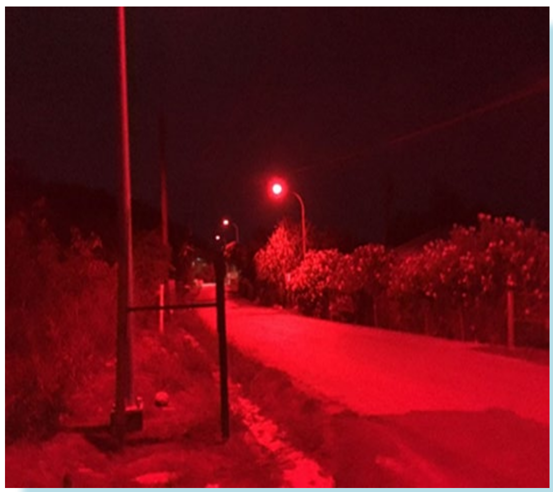


Figure 49. Red LED (610 nm) green turtle-friendly lighting (Image Credit: DMD).

Insects such as rain flies can be attracted to light sources. In this case, the flies are attracted to the light source, causing them to mate and die on the luminaire (Figure 50).

Figure 50. Photo. Rain flies on a luminaire (Image Credit: DMD).

A method to assess the impact of lighting, particularly the lighting spectrum, on wildlife is provided in the research paper "Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night" (Longcore et al., 2018a). This method considers the actinic (activating) spectrum for a variety of animals and effects (Figure 51). Notably, the example actinic curves represent only a small number of species and their relative sensitivities. Ongoing work is cataloging the spectral sensitivities of animals based on their biological taxonomy. To calculate the impact on the species, the curves shown in Figure 51 are convolved with the spectrum of the light source to estimate the effect of lighting.

In the work by Longcore et al. (2018b), sample calculations with example spectrum were made to consider the light source color in CCT versus the impact on the species. In most but not all cases, lower CCT values corresponded to a lower impact on the metric of interest (Longcore et al., 2018b). The information in Figure 51 shows that, in the case of green turtles, the adults have different sensitivity to light than the hatchlings, which makes the selection of the light sources even more challenging.

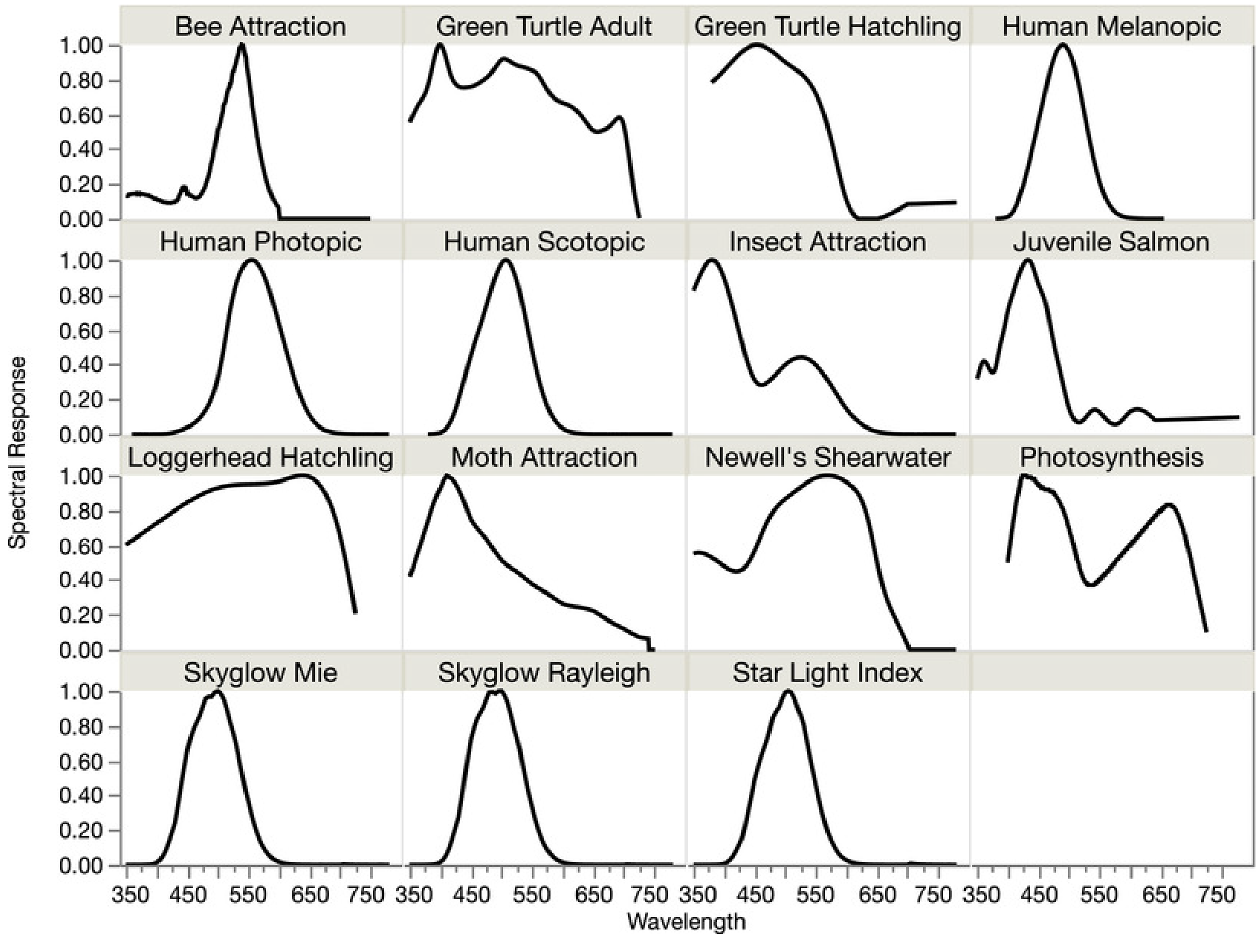


Figure 51. Line graphs. Actinic curves for a variety of lighting effects (Longcore et al., 2018a).

6.1.2 Lighting Impacts on Plants

Similar to the effects on wildlife, roadway lighting tends to affect plants that require a dark cycle to reach maturity (e.g., soybeans). Roadway lighting has been shown to affect the growth and maturity of soybeans (Briggs, 2006; Palmer, Gibbons, Bhagavathula, Holshouser, & Davidson, 2017; Zong-Ming, 2007) and maize (Sinnadurai, 1981). The effects of LED roadway lighting on plant growth and maturity have not yet been reported; however, laboratory studies have shown that LEDs with high blue contents make soybean plants more compact (Cope & Bugbee, 2013). Limiting the light that is emitted outside of the right-of-way can mitigate the impact of the lighting. The recommended limits for vertical and horizontal illuminance at the property line to reduce lighting impacts on soybean are shown in Table 10.

Table 10. Lighting limits at the property line to reduce impacts on soybeans (Palmer, Gibbons, Bhagavathula, & Holshouser, 2018).

Illuminance	Maximum value, lux
Horizontal	2.2
Vertical	1.8

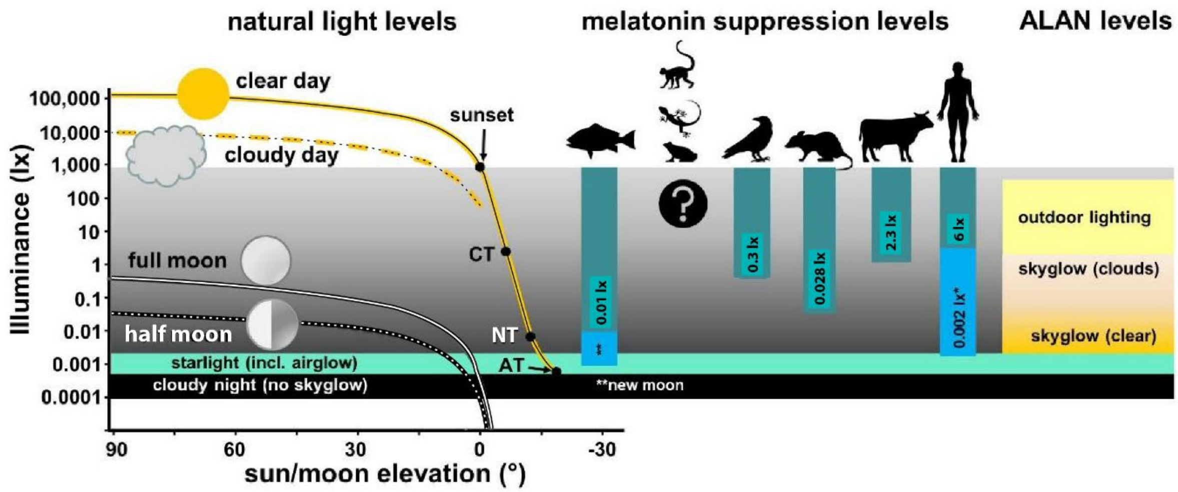
The method for evaluating the impact of lighting on plants is like evaluating lighting impacts on animals. In the case of plants, the actinic curve for photosynthesis (see Figure 51) is used to characterize the light source. The result is a factor known as the photosynthetic photon flux density (PPFD), which represents the effective photon strength required for photosynthesis. A conversion factor for lighting for humans versus lighting for plants can be applied for a given light source. Given a similar lighting level, lower CCT values correspond to higher PPFD conversion factors and thus stronger impacts on the plant being considered. Refer to IES RP-45 Horticultural Lighting (Illuminating Engineering Society, 2021b) for further information.

6.1.3 Mitigating the Impacts of Lighting on Plants and Animals

While the impacts of lighting on wildlife have been studied, these assessments are much more difficult than studies on humans due to the sheer number of species to consider and the difficulty in monitoring animal behaviors. As a result, the effects on most species are not well understood in terms of the specific effects along with the associated lighting dosage and duration. *Ecological Consequences of Artificial Nighttime Lighting* (Rich & Longcore, 2013) provides a comprehensive assessment of the wildlife effects of lighting; however, little information is provided about mitigation, and no recommendations are provided on lighting dosage and duration, which are key factors when designing a roadway lighting system.

Managing animal exposure to light relies on the selection of luminaire optics to reduce light trespass and skyglow along with dimming or even turning off the lighting system in times of critical animal behavior such as mating, migration, and birth.

The two primary concerns in terms of wildlife effects are the lighting spectrum and dosage. The selection of the spectrum can be made considering the animal sensitivity and the spectral output of the luminaires. However, the selection of dosage is more complicated. Identifying the lighting threshold that will not impact animals is difficult because nocturnal wildlife species are sensitive to levels of light ranging from the full moon (~0.1 lux) to a clear starry sky (~0.001 lux). Figure 52 graphically depicts these levels in comparison to moonlight and starlight. The lighting threshold for impact on melatonin in the species is listed in the figure and compared to the lighting levels in civil, nautical, and astronomical twilight as well as full darkness. Since the levels of natural light shown in Figure 52 indicate that all the magnitude of light levels are lower than that for roadway lighting, it is unlikely that any roadway lighting will fall below a threshold value for impacts at the roadway. Even melatonin suppression, which generally has a higher threshold value than behavioral responses, occurs in non-human vertebrates at full moon and lower levels (Grubisic et al., 2019). Thus, unlike for plant species, a minimum lighting level that would be below the threshold of impact on the species is likely not easily determined.



ALAN – Artificial Light at Night / CT – Civil Twilight / NT – Nautical Twilight / AT – Astronomical Twilight

Figure 52. Illustration. Melatonin suppression for vertebrates relative to moonlight and starlight (reprinted from Grubisic et al., 2019).

Managing animal exposure to light relies on the selection of luminaire optics to reduce light trespass and skyglow as much as possible along with the application of dimming and even turning off the lighting system in times of critical animal behavior such as mating, migration, and birth.

6.2 Human Health Impacts

On June 14, 2016, the American Medical Association (AMA) announced its adoption of recommendations contained in CSAPH Report 2-A-16, Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting. One of the key recommendations was, "That our AMA encourage the use of 3000K or lower lighting for outdoor installations such as roadways. All LED lighting should be properly shielded to minimize glare and detrimental human and environmental effects, and consideration should be given to utilize the ability of LED lighting to be dimmed for off-peak time periods." While shielding the luminaire light sources from view off the roadway and dimming in off-periods are well-supported benefits, the recommendation that CCT not exceed 3000K has caused concern with the IES. The IES believes that CCT is inadequate for evaluating potential health outcomes and that the AMA recommendations target only one component of light exposure (spectral composition) out of multiple established inputs that affect sleep disruption, including the quantity of light at the retina of the eye and the duration of exposure to that light (IES, 2017).

There are no differences between 4000K LED roadway lighting, 2100K HPS roadway lighting, and no roadway lighting in terms of salivary melatonin suppression.

NCHRP Research Report 968 (Bhagavathula, Gibbons, Hanifin, & Brainard, 2021) evaluated the impact of LED roadway lighting on driver sleep health and alertness in naturalistic conditions. LED lighting has a higher blue spectral content than traditional high-intensity discharge (HID) light sources. Exposure to light with higher blue spectral content such as those in LEDs in the evening has been shown to disturb circadian rhythms, resulting in sleep loss (Cajochen et al., 2011; Chang, Aeschbach, Duffy, & Czeisler, 2015). In contrast, there is evidence that light with a high blue content can increase alertness and enhance cognitive performance in humans (Chellappa et al., 2011; Lehrl et al., 2007). LED roadway lighting with higher blue content could potentially make road users more alert and enhance nighttime traffic safety. To design effective roadway lighting, there is a growing need to understand the relationships between roadway light level, melatonin suppression, and driver alertness and health. This was one of the first empirical studies to quantify melatonin and alertness responses to the intensity and spectrum of roadway lighting in healthy drivers. The results indicated that there were no differences between 4000K LED roadway lighting, 2100K HPS roadway lighting, and no roadway lighting in terms of salivary melatonin suppression as well as subjective and objective measures of alertness. There were also no differences in salivary melatonin suppression between LED and HPS roadway lighting when measured at the same light level (roadway luminance of 1.5 cd/m^2 or a corneal illuminance of 1.9 lux). These results suggest that the SPD (or CCT) of roadway lighting at the light level recommended by IES RP-8-21 is not a major factor affecting human salivary melatonin or alertness. The results from this research also indicated that the potential for melatonin suppression from exposure to consumer electronic devices such as televisions, monitors, smartphones, and tablets is considerably higher than from 4000 K LED roadway lighting.

6.3 Light Pollution Impacts

The main elements of lighting pollution are (Figure 53) (Illuminating Engineering Society, 2021d):

- Light trespass: The encroachment of light, typically across property boundaries, causing annoyance, loss of privacy, or nuisance.
- Spill light: The light emitted by a floodlight that is outside the floodlight distribution as defined by the field angle classification. Although the definitions vary in practice, the terms spill light and light trespass are used interchangeably.
- Glare: The sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted, resulting in annoyance, discomfort, or loss in visual performance or visibility. Note that the magnitude of the sensation of glare depends on factors such as the size, position, and luminance of a source, the number of sources, and the luminance to which the eyes are adapted.

As a rule of thumb, if the view of the light source is blocked, the glare impact off the roadway will be eliminated.

- Skyglow: The brightening of the night sky that results from the scattering and reflection of light from the constituents of the atmosphere (gaseous molecules and aerosols) in the direction of the observer. Skyglow has two separate components: natural skyglow and artificial skyglow.

It is important to note that the reduction or elimination of light trespass should never take precedence over the provision of adequate roadway lighting. Lighting the area adjacent to roadway travel lanes (surround) can benefit a driver’s peripheral vision as well as improve the visibility of crossroads, driveways, and sidewalks. Lighting the area adjacent to the road can also help in the detection of large animals that pose a safety hazard. While balancing the needs of the road user with any potential impacts of the lighting system can be difficult for many roadway types, this issue should be approached holistically.

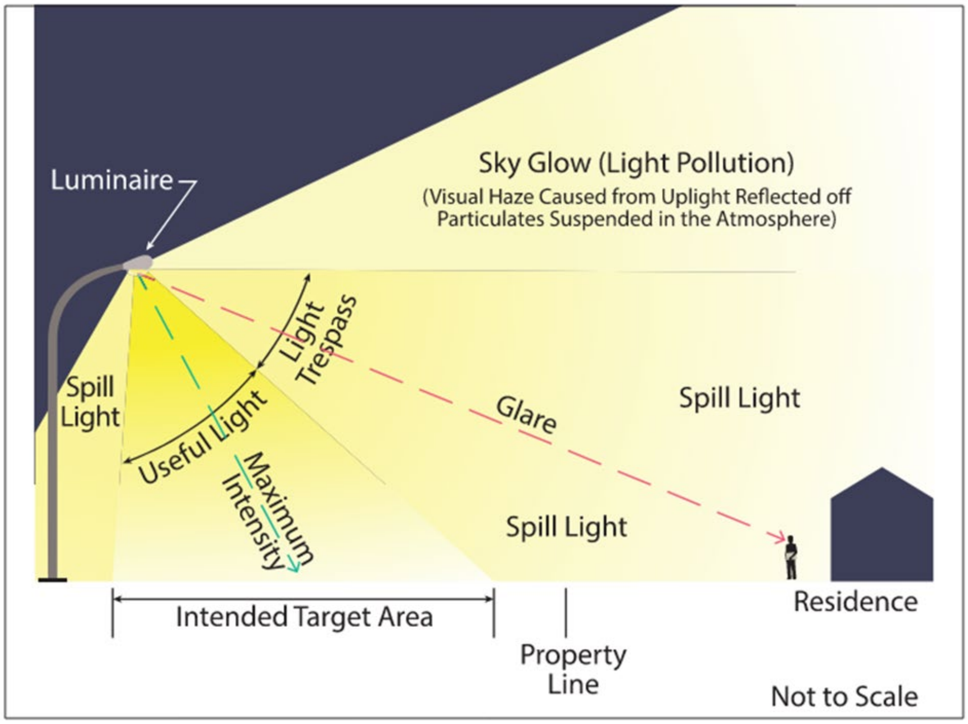


Figure 53. Illustration. Spill lighting, glare, and skyglow (Image Credit: DMD).

As a general rule, if the view of the light source is blocked, the glare impacts off the roadway will be eliminated. Luminaire shielding can be effective at reducing light trespass impacts such as spill light and glare. Examples of shielding are shown in Figure 54 and Figure 55. While shielding can effectively reduce the brightness of LEDs behind the pole, most shields are not effective when viewing from across the road, with the exception of the custom shield in the image on the lower right side of Figure 55. These shields can also significantly reduce the lighting on the roadway; therefore, lighting calculation using photometric data provided by the manufacturer with the shielding installed should be undertaken to confirm the provision of the necessary light levels on the roadway and sidewalks. It is important to note that these shields can reduce light level and uniformity on the roadway (especially the eyelid shields). Photometric files with shields should be obtained from the manufacturers, and photometrics with the shield should be included in the light calculations. As there is no industry standard for shielding, what is offered by each supplier should be considered when selecting a product.

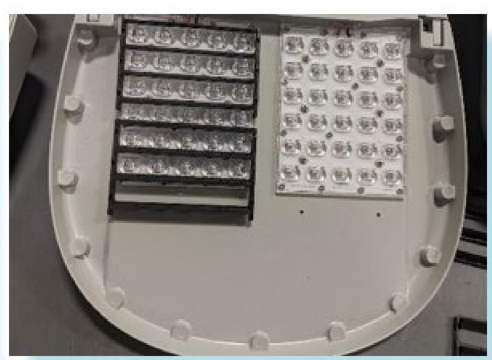


Figure 54. Photos. Eyelid shielding (Image Credit: DMD).

Figure 55. Photos. External back lighting and forward light shields (Image Credit: DMD).

Typically, following an LED installation, the most common residential complaint is glare from the direct view of the light source. This glare is magnified when residents are looking up slope in the bright part of the optical system. Here, a back shield could be utilized given the steep angle between the resident's view of the light source versus the flatter angle across the road. The key is to shield the view of the light source.

Some manufacturers also offer optical systems with diffusing lenses that effectively diffuse the brightness of the LED over a larger area. In effect, the lens acts as a diffuser as shown in Figure 56. These optical systems are typically less optically efficient from a UPD standpoint; however, they can be effective in reducing the overall glare and pixelization of the luminaire. Some supplies refer to this as "comfort optics."

Figure 56. Photo. Luminaire optics with a diffusing lens (Image Credit: DMD).

Because of its shorter wavelength, LED light tends to scatter more than HPS light, which increases the potential for skyglow. This effect may be offset by the improved optics of LED luminaires, which reduce up-light.

Spill light levels are defined in IES RP-8-21 to assess and mitigate light trespass off the roadway. Maximum allowed vertical illuminance levels are based on the level of ambient lighting in the area defined as the lighting zone. The lighting zones vary from LZ0 to LZ4. The maximum vertical illuminance levels are typically calculated and measured at the residence or property line. Reducing spill light can be effective for reducing light trespass.

Glare from luminaires very distant from the roadway can be a source of complaint from residents, particularly for high-wattage luminaires at mounting heights of 50 ft or greater. Even when the light source is located well away from the residence and the spill light level is well below the defined limit, glare complaints can result where there are bright light sources set against a dark background such as the night sky. Blocking the light source from view via shielding or optical systems is an effective solution. Refer to Table 3 in CIE 150, Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations (Commission Internationale de l'Eclairage, 2017), for assistance for assessing the intensity of light sources set against a dark sky. Based on the size of the light source, environmental zone, time of night, and distance from the lighting source, the maximum allowable intensity (brightness) can be defined in candela. Some lighting software can be used to calculate the candela values when viewed from given locations.

With respect to skyglow, increasing the short-wavelength content of the exterior lighting source increases the potential for skyglow. These effects can be reduced or completely offset by other features of LED street lighting luminaires. The three main characteristics of luminaires that influence skyglow are SPD, total lumen output, and luminaire light distribution (most importantly, the amount of that distribution emitted as up-light). Each of these characteristics can be specified through the selection of luminaires and should therefore be carefully evaluated as part of the system design.

Except for installations made in the early years of LED street lighting, most conversions utilized 4000K CCT products up to 2016. Following the shift to 3000K LEDs in 2016 based on the AMA report (CSAPH Report 2-A-16), the majority of LED conversions involved 3000K LEDs. Although this cannot be confirmed without analyzing the specific SPDs for the new LED systems, a study suggests that for residents near the city, the visible contribution to skyglow from a typical LED street light conversion (i.e., half the output, 0% up-light) should be no worse than before conversion and may be reduced. (Kinzey et al., 2017). Thus, when the conditions in the model calculations are achieved, skyglow from the streetlights should be considerably reduced (by roughly one third to one half) for any observatories near the city (Kinzey et al., 2017).

As skyglow increases, it obscures fainter stars until only a handful of the brightest stars are visible at night from urban areas. This is disastrous for both professional and amateur astronomers as well as an aesthetic and cultural concern for the public. The problem becomes much worse under cloudy skies; clouds are effective at backscattering upward light, making the nocturnal environment considerably brighter in overcast weather conditions. The key points with respect to skyglow include the following:

- Skyglow is a complex phenomenon that is difficult to control in urban areas, where roadway lighting is a relatively minor contributor; satellite-based measurements of emission (Kyba et al., 2021) and ground-based measurements of broadband night sky radiance (Barentine et al., 2020) indicated that roadway lighting contributed only 18% of total irradiance and 14% of light emittance, respectively.

- The atmosphere and viewing point have a huge impact on skyglow.
- Because of its shorter wavelength, LED light tends to scatter more than HPS light, which increases the potential for skyglow. However, this effect may be offset by the improved optics of LED luminaires, which reduce up-light.
- To reduce skyglow, lighting designers should use luminaires with cutoff optical systems and avoid over-lighting.

Luminaires with a low rating in each of the BUG rating categories will minimize skyglow, light trespass, and veiling luminance (glare) from the luminaire on and off the roadway, thereby improving overall visibility. BUG is a luminaire rating system developed by the IES to categorize a luminaire in terms of back light, up-light, and glare. BUG is typically not used in roadway lighting (See IES TM-15-15).

Refer to IES TM-37 Technical Memorandum: Description, Measurement, and Estimation of Sky Glow (Illuminating Engineering Society, 2021a) for further information.

6.4 Five Principals in Reducing Environmental Impacts

The International Dark-Sky Association and IES have jointly published Five Principles for Responsible Outdoor Lighting (Figure 57), (Liebel & Hartley, 2020). These organizations have the shared goal of reducing light pollution via the proper application of quality outdoor electric lighting. By applying these principles, properly designed lighting at night can be functional and enhance the nighttime environment. Projects that incorporate these principles will save energy and money, reduce light pollution, and minimize wildlife disruption. Thus, designers and jurisdictions are encouraged to follow these five principals when designing roadway lighting. It should be made clear that these factors potentially influence safety and roadway usability. A balance between safety and the potential impact on the surrounding area should be considered.

LIGHT TO PROTECT THE NIGHT Five Principles for Responsible Outdoor Lighting		
USEFUL		**ALL LIGHT SHOULD HAVE A CLEAR PURPOSE** Before installing or replacing a light, determine if light is needed. Consider how the use of light will impact the area, including wildlife and the environment. Consider using reflective paints or self-luminous markers for signs, curbs, and steps to reduce the need for permanently installed outdoor lighting.
TARGETED		**LIGHT SHOULD BE DIRECTED ONLY TO WHERE NEEDED.** Use shielding and careful aiming to target the direction of the light beam so that it points downward and does not spill beyond where it is needed.
LOW LIGHT LEVELS		**LIGHT SHOULD BE NO BRIGHTER THAN NECESSARY.** Use the lowest light level required. Be mindful of surface conditions as some surfaces may reflect more light into the night sky than intended.
CONTROLLED		**LIGHT SHOULD BE USED ONLY WHEN IT IS USEFUL.** Use controls such as timers or motion detectors to ensure that light is available when it is needed, dimmed when possible, and turned off when not needed.
COLOR		**USE WARMER COLOR LIGHTS WHERE POSSIBLE.** Limit the amount of shorter wavelength (blue-violet) light to the least amount needed. Light where you need it, when you need it, in the amount needed, and no more.

Figure 57. Infographic. Five principals in reducing environmental impacts (Liebel & Hartley, 2020).

7 ADAPTIVE LIGHTING

Adaptive lighting refers to the dimming of roadway lighting during periods of low vehicular and pedestrian activity. The concept of dimming streetlights was developed and evaluated via pilot installations in Canada and Europe in the early 2000s. The technology for dimming street lighting gained popularity around 2010 with the use of LEDs, which allow for more effective dimming and control compared to previous high-intensity discharge sources. Other than energy efficiency, the ability to easily control and dim LED luminaires is one of their biggest advantages over other roadway lighting sources.

Adaptive lighting refers to the dimming of roadway lighting during periods of low vehicular and pedestrian activity.

Adaptive lighting is the most effective way to minimize the potential negative aspects of roadway lighting as it can be applied to reduce the impacts of exterior lighting systems on skyglow, glare, and light trespass while also saving energy and reducing maintenance costs. Although it is considered an emerging technology, adaptive lighting has already been effectively applied. The benefits of adaptive control can be quite different when used for highway lighting compared to street lighting; thus, the benefits are quantified based on roadway type.

The application of adaptive lighting is discussed in the Urban Street Lighting Example in Part II of this handbook. In this example the method considered for the adaptation of lighting levels is based on the existing IES RP-8-21 lighting recommendations. In this method, the pedestrian volume is used to discern the lighting level within a road category. As the pedestrian volume changes, the lighting level can change.

A new method has been developed through research for the FHWA and is currently in the IES RP-8-21 as an alternative method for lighting selection. This method is defined below.

While the application of adaptive lighting practices have many benefits, the use of adaptive lighting is not required under Federal law or regulations

7.1 Luminance Selection

Selecting the appropriate lighting level for the given roadway is the key component to implementing the adaptive lighting. The approach specified here has been developed from the results of an analysis of crashes and lighting levels on the roadway (Gibbons, Guo, Medina, Terry, Du, Lutkevich, & Li, 2014; Gibbons, Guo, Medina, Terry, Du, Lutkevich, Corkum, et al., 2014). The lighting data were measured *in situ* on a variety of roadways in seven different states, and crash data were then used to determine the relationship of the lighting data to the crash rate. A variety of criteria were determined to be significant to the lighting-safety relationship, including traffic volume and roadway type. Other criteria were added to the selection process based on the design approaches and relevant literature. An accompanying document, Design Criteria for Adaptive Roadway Lighting, provides more detail on the criteria listed here.

For the proposed methodology, three different selection criteria based on the IESNA approach are used to determine the lighting level. IESNA separates design criteria by the following facilities: roadways, streets, and residential/pedestrian:

- ***Roadway lighting*** is provided for freeways; expressways; limited-access roadways; and roads on which pedestrians, cyclists, and parked vehicles are generally not present. The primary purpose of roadway lighting is to help the motorist remain on the roadway and aid in the detection of obstacles within and beyond the range of the vehicle headlamps (Figure 58).

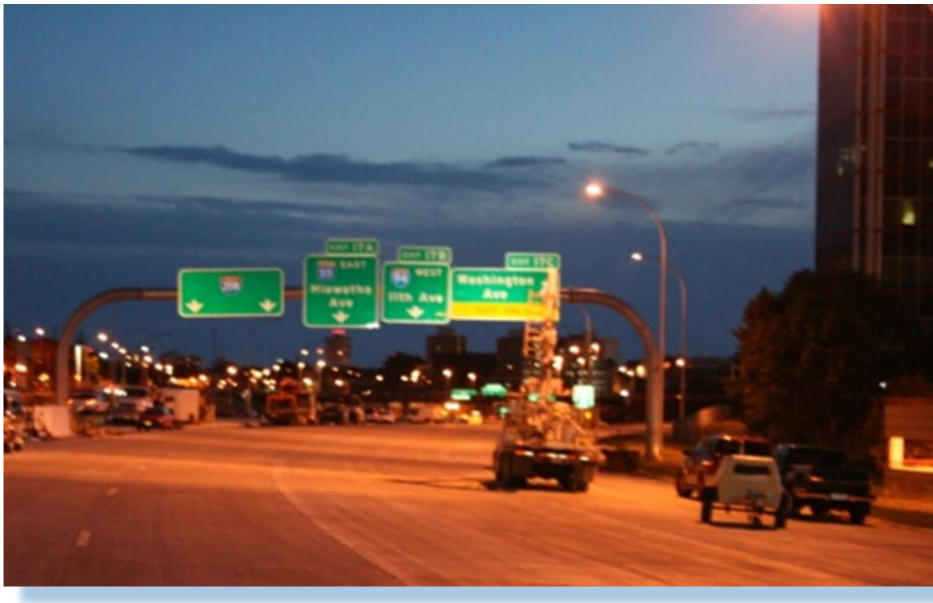


Figure 58. Photo. Roadway lighting. (Image Credit: WSP)

- ***Street lighting*** is provided for major, collector, and local roads on which pedestrians and cyclists are generally present. The primary purpose of street lighting is to help motorists identify obstacles, provide adequate visibility of pedestrians and cyclists, and assist road users in visual search tasks both on and adjacent to the roadway (Figure 59).

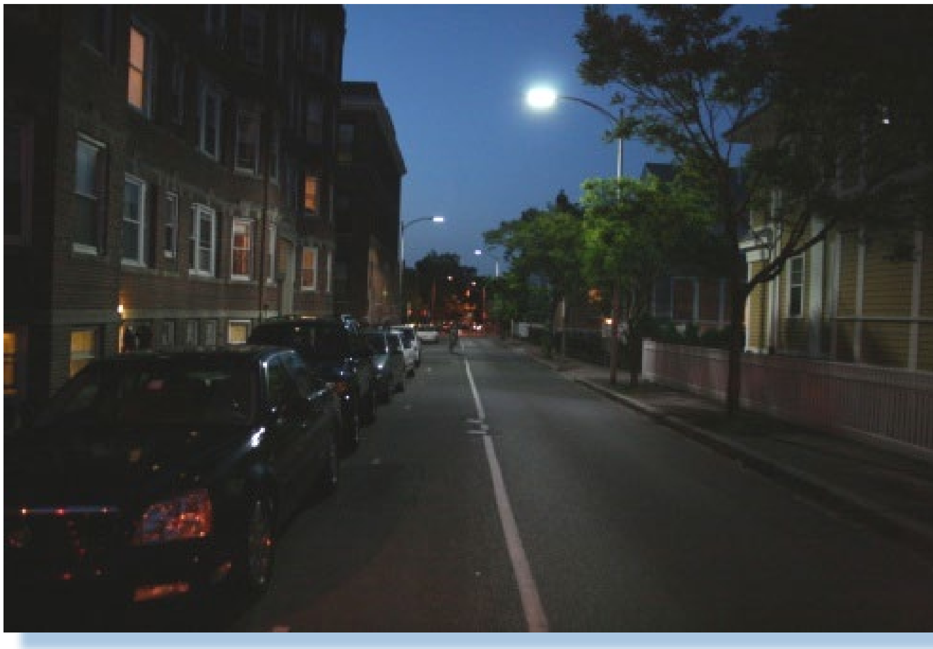


Figure 59. Photo. Street lighting (Image Credit: WSP).

- ***Residential/pedestrian area lighting*** is provided primarily for the safety and security of pedestrians (not specifically for drivers). These facilities typically have driving speeds slower than 25 mi/hr (40 km/hr), where vehicle headlights provide adequate lighting for drivers (Figure 60).

Figure 60. Photo. Residential/pedestrian area lighting (Image Credit: WSP).

These three facility types that form the basis for lighting requirement selection are characterized as H (Roadway), S (Street), or P (Residential/Pedestrian) class. Each of these classes has a specific set of criteria for the selection of lighting requirements.

Once the facility type has been selected and the class identified, the characteristics of the facility are used as weighting factors to determine the requirements of the lighting system. The Equation 6 for the lighting design class is shown below:

Equation 6. Lighting Class Calculation

$$Lighting\ Class = Base\ Value - \sum Weighting\ Values$$

The base value changes depending on the facility type as it is based on the number of lighting classes for each road class. For highways there are four classes, five classes for roadways, and five for pedestrian areas. Hence the base value for these facilities types Roadway, Street and Residential/Pedestrian are 5, 6, and 6, respectively.

To determine the lighting level, the sum of the weighting values is then subtracted from this base value, which then determines the lighting class. If the result is not a whole number, the next lowest positive whole number should be used (e.g., an H3.5 would use the H3 value). Negative numbers call for the highest lighting level class (i.e., H1, S1, and P1 are the highest classes and have the highest lighting requirements). Similarly, numbers resulting in a class lower than the lowest class would default to the lowest class (e.g., a lighting class of H6 would use the H4 value).

For an adaptive lighting system, the lighting level requirements change based on the roadway conditions. In response, the current approach calls for changes in the corresponding weighting factors as the roadway conditions change, resulting in a different lighting class and, therefore, a different required design level.

7.1.1 Parameters

The parameters for each of the weighting factors are defined below. Each of these parameters has been determined to be an important aspect of the driving environment based on its relationship to vehicular crashes.

7.1.1.1 Speed

The speed parameter is the posted speed of the roadway (as opposed to the design speed of the roadway). For an active adaptive system, the 85th percentile speed or other measured vehicle speed can be used instead.

7.1.1.2 Traffic Volume

The traffic volume parameter typically used in the selection of a roadway lighting level is average daily traffic (ADT). While ADT is an effective parameter for the selection of a basic lighting level, it is not practical for the application of adaptive lighting. Actual traffic volumes vary by day of the week and hour of the day, limiting the applicability of ADT to driver needs at any particular time.

The hourly traffic volume of a roadway is a recommended parameter for the application of adaptive lighting because it is indicative of current roadway conditions. For hourly traffic volume parameters, the level of service (LOS), as defined by the Highway Capacity Manual, can be used to determine the traffic flow level criteria for the adaptive lighting level. These levels are selected as they represent when the road reaches maximum free flow (LOS B to C) and when crash rates begin to increase (LOS C to D). Note that the traffic volume values listed in Table 11, Table 12, and Table 13 are for single-direction travel. Thus, the values would have to be doubled when applied to undivided roads.

Table 11. Hourly traffic flow criteria for roadways. (FHWA)

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	> 2,000 Vehicles Hourly per lane	1
	Moderate	1,000 – 2,000 Vehicles Hourly per lane	0
	Low	< 1,000 Vehicles Hourly per lane	-1

Table 12. Hourly traffic flow criteria for streets.

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	> 1,500 Vehicles Hourly per lane	1
	Moderate	750 – 1,500 Vehicles Hourly per lane	0
	Low	< 750 Vehicles Hourly per lane	-1

Table 13. Hourly traffic flow criteria for residential/pedestrian roads.

Parameter	Options	Criteria	Weighting Value
Traffic Volume	High	> 750 Vehicles Hourly per lane	0.5
	Moderate	300 – 750 Vehicles Hourly per lane	0
	Low	< 300 Vehicles Hourly per lane	-0.5

An agency may choose to recalculate these limits for their specific roadway conditions.

7.1.1.3 Median

The median parameter defines the presence of a median barrier. Typically, a median is present on large roadways to separate the two directions of travel. The median should have a barrier or be designed such that the light from opposing headlamps is limited and not visible by drivers approaching each other. The AASHTO Roadway Design Guide defines a median width of 15 meters where a barrier is not required in a roadway; this median width is suitable to limit glare between vehicles. Median widths between 10 and 15 meters require a design review with engineering judgment.

7.1.1.4 Intersection/Interchange Density

The intersection/interchange density parameter refers to the number of intersections and entrances into the roadway per mile or kilometer. This parameter represents the possibility of vehicles interacting in the roadway. In addition to other roadways, this parameter includes driveways and other entrance areas.

7.1.1.5 Ambient Luminance

The brightness and amount of light in the surrounding area impacts the lighting requirements for the roadway and is accounted for in the lighting level selection. To differentiate lighting and ambient zones, the IESNA has developed Lighting Zones (LZs) describing different ambient lighting conditions.

7.1.1.6 LZ0: No Ambient Lighting

LZ0 represents areas where the natural environment will be seriously and adversely affected by lighting (e.g., by disturbing the biological cycles of flora and fauna or detracting from human enjoyment and appreciation of the natural environment, although human activity is considered less important than nature in this zone). The vision of human residents and users is adapted to total darkness, and they expect to see little or no lighting. When not needed, lighting should be extinguished, although lighting is not typically applied in LZ0 conditions.

7.1.1.7 LZ1: Low Ambient Lighting

LZ1 represents areas where lighting might adversely affect flora and fauna or disturb the character of the area. The vision of human residents and users is adapted to low light levels. Lighting may be used for safety and convenience, but it is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.

7.1.1.8 LZ2: Moderate Ambient Lighting

LZ2 represents areas of human activity where the vision of human residents and users is adapted to moderate light levels. Lighting may typically be used for safety and convenience, but it is not necessarily uniform or continuous. After curfew, lighting may be reduced as activity levels decline.

7.1.1.9 LZ3: Moderately High Ambient Lighting

LZ3 represents areas of human activity where the vision of human residents and users is adapted to moderately high light levels. Lighting is generally desired for safety, security, or convenience, and it is often uniform and/or continuous. After curfew, lighting may be reduced as activity levels decline.

7.1.1.10 LZ4: High Ambient Lighting

LZ4 represents areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security, or convenience, and it is mostly uniform and/or continuous. After curfew, lighting may be reduced in some areas as activity levels decline.

7.1.1.11 Pavement Marking Quality

The Pavement Marking Quality parameter refers to the presence and quality of the other non-lighting-related visibility and guidance tools on the roadway. In particular, the quality of the pavement markings has been shown to interact with the lighting in terms of driver performance. The criterion presented here for guidance is the retroreflectivity of the pavement markings in $mcd/m^2 \cdot lx$.

7.1.1.12 Pedestrian/Bicycle Interaction

The pedestrian/bicycle interaction parameter refers to the number of pedestrians and bicycles present in the roadway, either crossing or walking parallel to the roadway.

7.1.1.13 Parked Vehicles

The parked vehicles parameter refers to the presence of parked vehicles along the side of the roadway.

7.1.1.14 Facial Recognition

The facial recognition parameter refers to the requirement of a driver or pedestrian to recognize the facial characteristics of a person walking in the roadway or on the sidewalk (Figure 61 and Figure 62). This parameter is related to the feeling of safety and security of the roadway users. Typically, facial recognition can be expected to be an important aspect of the roadway environment.

Figure 61. Photo. Facial recognition under low lighting. (Image Credit: Paul Lutkevich, WSP)

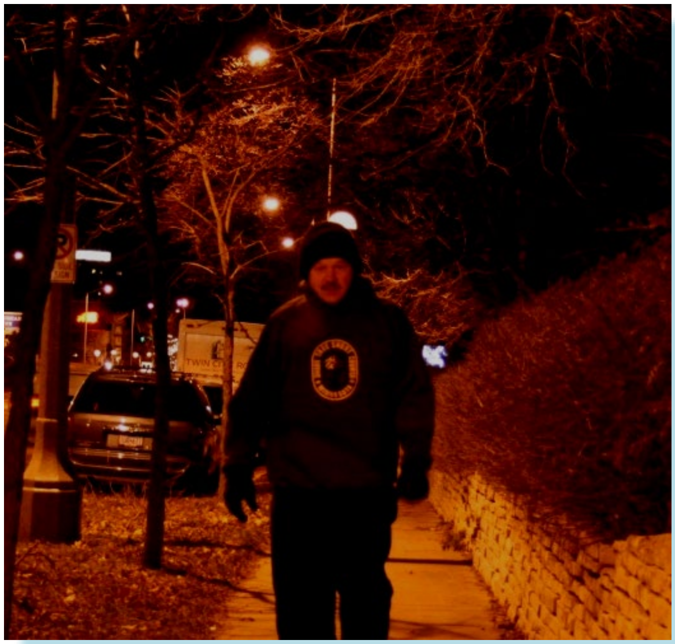


Figure 62. Photo. Facial recognition under high lighting. (Image Credit: Paul Lutkevich, WSP)

7.1.1.15 Conflict Areas

Although not a specific criterion for the selection of the luminance level, conflict areas are a consideration in the design process and may be affected by the adaptive lighting design. Lighting in conflict areas, such as intersections and crosswalks, can also be adjusted in relation to the lighting levels of nearby roadways, streets, and residential/pedestrian areas. For example, the IESNA RP-8-21 recommended lighting level for intersections is the sum of the lighting levels of the intersecting roads. In an adaptive lighting design, if a change in use of the intersecting roads allows a reduction in lighting levels, the lighting level of the intersection will also be reduced.

7.1.2 Design Recommendation and luminance Selection

The parameters above are used to determine the lighting level. Table 14, Table 16, and Table 18 show the weighting parameters, while Table 15, Table 17, and Table 19 show the recommended lighting design levels (based on the lighting class) for roadway, street, and residential/pedestrian facilities, respectively. The base values for each facility type are also provided for each classification. It is important to note that the lighting design recommendations for the residential/pedestrian areas are horizontal and vertical illuminance, not luminance. Road luminance is the criterion for both roadway and street facilities.

It is also important to note that as the weighting values change, the lighting level can change. For example, the traffic volume or the number of pedestrians can change, which affects the weighting value of that parameter. This, in turn, may change the roadway lighting class; therefore, the lighting level requirements may change as well. This is particularly critical with respect to the traffic volume and pedestrian levels.

7.1.2.1 Design Criteria for Roadways (H-Class)

Base value for class: 5 (This value is used in the calculation of the road class)

Table 14. Roadway design level selection criteria (FHWA).

Parameter	Options	Criteria	Weighting Value
Speed	Very High	> 60 mi/h (100 km/h)	1
	High	45–60 mi/h (75 –100 km/h)	0.5
	Moderate	< 45 mi/h (75 km/h)	0
Traffic Volume	High	> 30,000 ADT*	1
	Moderate	10,000 – 30,000 ADT	0
	Low	< 10,000 ADT	-1
Median	No		1
	Yes	Should be glare blocking	0
Intersection/ Interchange Density	High	< 1.5 miles between intersections (2.5 km)	1
	Moderate	1.5–4 miles (2.5 km – 6.5 km) between intersections	0
	Low	> 4 miles (6.5 km) between intersections	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Pavement Marking Quality	Good	> 100 mcd/m^2 lx**	0
	Poor	< 100 mcd/m^2 lx	0.5

*ADT = Average Daily Traffic

**mcd/m^2 lx = millicandela/meter squared lux

Table 15. H-Class lighting design levels (FHWA).

Class	Average Luminance (cd/m^2)	Max Uniformity Ratio (avg/min)	Max Uniformity Ratio (max/min)	Veiling Luminance Ratio
H1	1	3	5	0.3
H2	0.8	3.5	6	0.3
H3	0.6	3.5	6	0.3
H4	0.4	3.5	6	0.3

7.1.2.2 Design Criteria for Streets (S-Class)

Base value for class: 6

Table 16. Street design level selection criteria (FHWA).

Parameter	Options	Criteria	Weighting Value
Speed	High	> 45 mi/h (70 km/h)	1
	Moderate	35–45 mi/h (55–70 km/h)	0.5
	Low	< 35 mi/h (55 km/h)	0
Traffic Volume	High	> 15,000 ADT*	1
	Moderate	5,000–15,000 ADT*	0
	Low	< 5,000 ADT*	-1
Median	No		1
	Yes (or one-way)	Should be glare blocking	0
Intersection/ Interchange Density	High	> 5 per mile (1.6 km)	1
	Moderate	1–5 per mile (1.6 km)	0
	Low	< 1 per mile (1.6 km)	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Guidance	Good	> 100 mcd/m^2 lx	0
	Poor	< 100 mcd/m^2 lx	0.5
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per hour	2
	Moderate	10–100 pedestrians per hour	1
	Low	< 10 pedestrians per hour	0
Parked Vehicles	Yes		1
	No		0

*ADT = **average daily traffic for a single direction on the roadway**

Table 17. S-Class lighting design levels (FHWA).

Class	Average Luminance (cd/m^2)	Max Uniformity Ratio (avg/min)	Max Uniformity Ratio (max/min)	Veiling Luminance Ratio
S1	1.2	3	5	0.3
S2	0.9	3.5	6	0.4
S3	0.6	4	6	0.4
S4	0.4	6	8	0.4
S5	0.3	6	10	0.4

7.1.2.3 Design Criteria for Residential/Pedestrian Areas (P-Class)

Base value for class: 6

Table 18. Residential/pedestrian design level selection criteria (FHWA).

Parameter	Options	Criteria	Weighting Value
Speed	High	> 45 mi/h (70 km/h)	1
	Moderate	35–45 mi/h (55–70 km/h)	0.5
	Low	< 35 mi/h (55 km/h)	0
Traffic Volume	High	> 7,500 ADT*	0.5
	Moderate	3,000–7,500 ADT*	0
	Low	< 3,000 ADT*	-0.5
Intersection/ Interchange Density	High	> 5 per mile (1.6 km)	1
	Moderate	1–5 per mile (1.6 km)	0
	Low	< 1 per mile (1.6 km)	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per hour	1
	Moderate	10-100 pedestrians per hour	.5
	Low	< 10 pedestrians per hour	0
Parked Vehicles	Yes		.5
	No		0
Facial Recognition	Required		1
	Not Required		0

*ADT = average daily traffic for a single direction on the roadway

Table 19. P-Class lighting design levels (E = Illuminance) (FHWA).

Class	E Average Lux	E Vertical (minimum point)	Ratio E_{avg}/E_{min}
P1	10	5	4
P2	5	2	4
P3	4	1	4
P4	3	0.8	6
P5	2	0.6	10

7.1.3 Example of Lighting Design Criteria Selection

The following example illustrates how to select a roadway lighting class:

- Speed limit of 70 mph.
- Equivalent of 35,000 ADT.
- 12 m median between opposing directions with no barrier.
- An average of 2 mi between interchanges.
- Zoned as an LZ3 lighting area.
- Has brand-new pavement markings measuring at 425 mcd/m^2 lx.

The resulting weighting functions are shown in Table 20.

Table 20. Example lighting level selection process for a roadway facility.

Parameter	Options	Criteria	Weighting Value
Speed	Very High	> 60 mph	1
Traffic Volume	High	> 30,000 ADT	1
Median	No		1
Intersection/Interchange Density	Moderate	1.5–4 miles between intersections	0
Ambient Luminance	High	LZ3 and LZ4	1
Guidance	Good	> 100 mcd/m^2 lx	0
		Sum of Weights	**4**

The resulting road class is H1 (weighting value total of 4 subtracted from base value of 5), and the lighting design level has an average luminance of 1, maximum-to-average uniformity ratio of 3, a maximum-to-minimum uniformity ratio of 5, and a veiling luminance ratio of 0.3.

If this design was for an active adaptive system, the lighting design level would be changed based on the roadway conditions. For example, if the traffic volume of the roadway decreased from 35,000 ADT to 15,000 ADT, the weighting value of traffic volume would decrease from 1 to 0, and the road class would change from H1 to H2, allowing for a decrease in the lighting level from 1.0 to 0.8 cd/m^2 (shown in Table 14 and Table 15).

An alternative method for defining the traffic volume is to use hourly traffic volume. For example, if the hourly traffic volume was 4,100 vehicles per hour (vph), the weighting value would be 1 (Table 11). This would still result in an H1 class, assuming the same variables listed in Table 20 are used. If the hourly traffic volume dropped to 1,000 vph, the weighting value would be −1, and the roadway classification would drop to H3.

A similar example is provided for a street facility. The design level criteria are shown in Table 21. Here, a change in the number of pedestrians per hour could result in a change in the recommended lighting level.

Table 21. Example lighting level selection process for a street facility. (FHWA)

Parameter	Options	Criteria	Weighting Value
Speed	Moderate	> 35 mph (55 kph)	0.5
Traffic Volume	High	> 15,000 ADT	1
Median	Yes	Should be glare blocking	0
Intersection/Interchange Density	High	> 5 per mile (1.6 km)	1
Ambient Luminance	Moderate	LZ2	0
Guidance	Poor	< 100 mcd/m^2 lx	0.5
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per hour	2
Parked Vehicles	Yes		1
		Sum of Weights	**6**

The sum of the weighting values is 6 in this example, which would be subtracted from the base value of 6, resulting in a value of 0. This value would then imply the use of the lighting class S1 (Table 17). If the traffic volume changed to less than 5,000 vehicles per day, and the pedestrian volume changed from more than 100 pedestrians per hour to less than 10 per hour, the sum would change from 6 to 4, allowing for a reduction in light levels at the S2 class.

7.2 Adaptive Lighting Application

The approach taken for adaptive lighting affects where and when the lighting system should be controlled. This section applies specifically to active adaptive systems.

7.2.1 Where to Adapt Lighting

Adaptive lighting can be used in most roadway scenarios. However, there are certain areas where it is not advisable to implement active adaptive lighting systems, such as in critical visibility areas where it is vital to see objects and vehicles in the roadway. Designers of adaptive lighting should evaluate areas of critical visibility such as roadways that have a significant number of curves with short visibility distances or locations where traffic and pedestrian volume are at consistent levels throughout the night (e.g., a hospital or other service facility). It is also important that adaptive policies not replace other responsible lighting activities such as luminaire maintenance and tree trimming (i.e., increasing light level to overcome regrowth).

Another consideration when implementing adaptive lighting is the size of the area covered by the lighting system. Depending upon nighttime use and driver needs, dimming a roadway lighting system can occur broadly over all the roadways in the area or section by section on each of the roadways being dimmed.

In general, dimming a large area will maintain a constant lighting level such that drivers do not experience a high lighting condition on one roadway and then turn onto a dark roadway, requiring significant adaptation between the lighting levels. Depending on the range of light level changes, the abruptness of the change, and the age of the driver, this transition can be uncomfortable and dangerous. However, dimming a large area without consideration of differences in road usage at night may cause some sections to be too dark.

To control for varying lighting levels, the following recommendations are made for each of the road facility types:

For roadway facilities, each roadway should be assessed individually, but drivers should not experience greater than one lighting class change per mile (1.6 km) of travel.

For streets, each street should be evaluated in terms of the lighting needs. However, the difference in lighting classes for streets in a given vicinity should be no greater than two.

Residential/pedestrian areas should be adapted to a single lighting level. This means that a neighborhood would be considered as one lighting class and individual low volume residential streets would not be adapted to different lighting levels.

7.2.2 When to Adapt Lighting

The optimal approach to selecting the timing of adaptive lighting is to continually monitor the roadway and the environment. As an example, ITS systems can provide traffic and pedestrian counts as inputs to an algorithm that establishes the lighting level in real time.

When ITS systems are not available (e.g., on smaller streets and residential/pedestrian areas), curfews are typically established to determine when the lighting system can be dimmed. The following criteria can be used to establish a curfew:

- Changes in vehicular traffic level sampled over a period of time.
- Typical closing hours of surrounding businesses.
- Changes in the transportation schedule.
- Changes in parking regulations.
- Sampled pedestrian activity level.

It is important that exceptions to the curfew (e.g., for sporting or entertainment events) be considered, and agencies should have the ability to override the adaptive lighting program on demand.

It is not advisable to adapt the lighting system during periods of adverse weather. The impact of dimming lighting during fog, snow, and rain is not clear. Some research has shown that visibility on a wet roadway is negatively impacted by dimming of luminaires. Further investigations are underway.

7.3 Lighting Controls

Streetlights are generally controlled (turned off during the day) to reduce power consumption and cost. Photocontrols are typically used to control the lighting. A photocontrol is a solid-state or thermal device that is connected to the luminaire(s) and includes an internal photo-sensor. This photo-sensor detects a defined level of ambient light and switches the connected load on and off using an internal relay.

New technologies and wireless controls provide connectivity of street lighting and allow the data to be transmitted and received via wireless nodes, either internal or connected to the luminaires. A typical adaptive control system is shown in Figure 63.

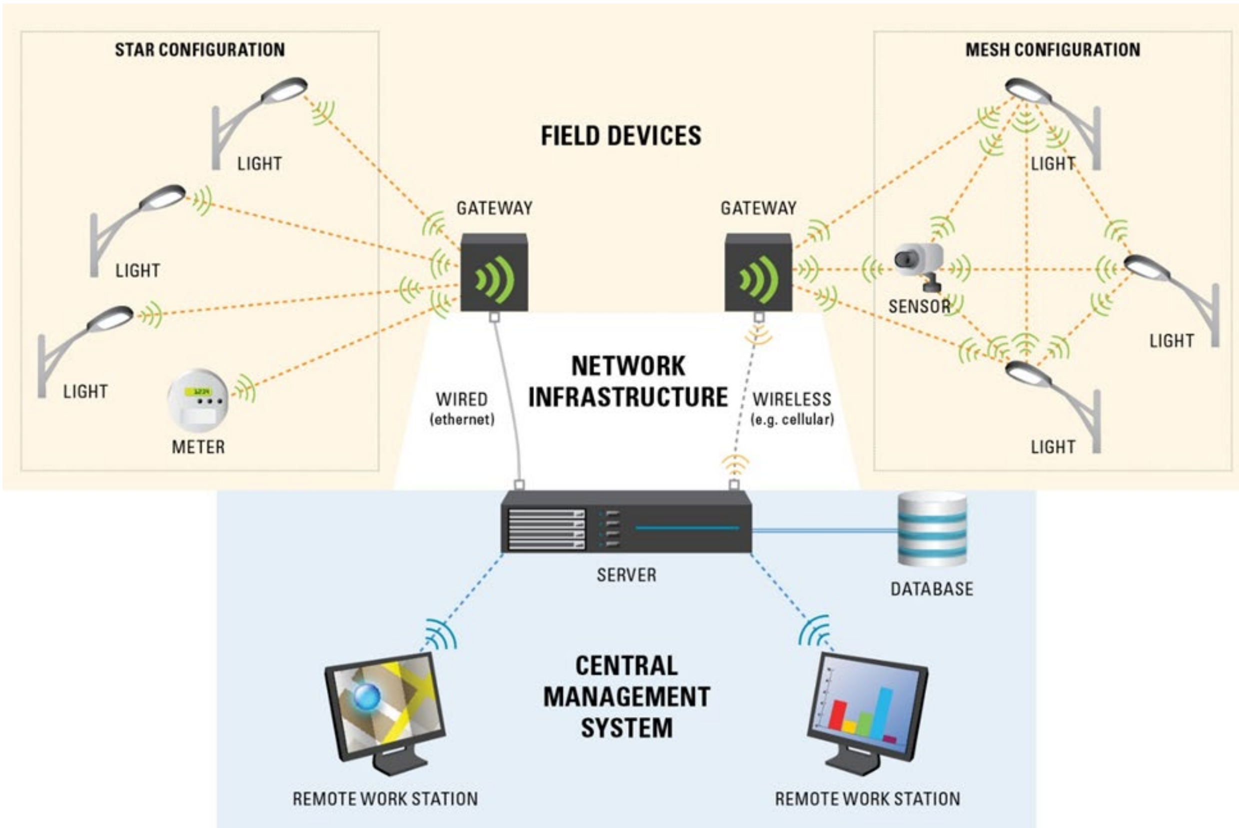


Figure 63. Diagram. Major components of a wireless outdoor lighting control (Image Credit: California Lighting Technology Center, UC Davis).

In today's world of smart technology and smart cities, sensors can be included with lighting to provide important data to determine what type of lighting is needed to enhance visibility, improve safety, and maintain the lighting infrastructure over the long term. These data can be used to highlight what is happening at an intersection, fine-tune problems, and ensure that the investment in connected lighting pays off. Further, similar to traffic lights, the lighting can be controlled remotely. In addition to sensors, cameras can also be added to lighting controls to gather data. Combined with analytics, cameras can be used to evaluate pedestrians and their movement patterns over time.

Developing streetlighting as digital infrastructure also has the unique value of future-proofing the built environment by providing a platform for the integration of new technologies as they come online. The data provided by connected lighting and smart infrastructure can support many services within a municipality, including law enforcement, environmental improvement, transportation, and natural disaster preparedness. The benefits of intelligent streetlights with sensors can be summarized in terms of the seven categories shown in Figure 64.

Figure 64. Image. Benefits of street light sensors. (Image Credit: California Lighting Technology Center, UC Davis)

Intelligent streetlighting applications provide opportunities for additional revenue generation for municipalities and/or their partners. Two currently available applications are Wi-Fi access points and electric vehicle charging stations. Wi-Fi hotspots installed on poles can generate revenue through data access leases, advertising, and usage fees. These hotspots can also improve internet availability in public spaces such as libraries and community centers and promote digital inclusion by providing free access in low-income areas. Demand for electric vehicles is growing faster than the availability of charging stations in many major municipalities.

The successful implementation of intelligent outdoor lighting networks requires the engagement of key stakeholders to support the project champion, develop a robust business case, foster utility partnerships, advocate for good public procurement, and effectively monitor and report.

The successful implementation of outdoor lighting networks with intelligent applications requires the engagement of key stakeholders to support the project champion, develop a robust business case, foster utility partnerships, advocate for good public procurement, and effectively monitor and report. Moreover, the setup, commissioning, testing, and operation of lighting controls system requires expertise and manpower. For more information on commissioning, refer to ANSI/IES LP-8-20, Lighting Practice: The Commissioning Process Applied to Lighting and Control Systems.

For adaptive roadway lighting, these control systems are information sharing systems that allow for both the production and consumption of data. Data can be used for energy analysis, maintenance planning, and the identification of environmental conditions and system status. Data consumption activities include dimming, time-of-day control, and remote control of the lighting system. These data-related activities can then be divided into three functional categories: monitoring, control, and sensing.

7.3.1 Communication Protocols

Communication protocols are a set of rules governing how messages and data elements are encoded and transmitted between electronic devices. The equipment at each end of a data transmission must use the same protocol to successfully communicate. The protocol is very much like a human language with an alphabet, vocabulary, and grammar rules used by everyone speaking that language.

With a proprietary standard, the manufacturer owns the protocol, and the owner is committed to a single manufacturer. Another downside of a proprietary protocol is that operational issues may arise if the product is discontinued or updated and is not supported by the manufacturer. Questions as to how the product will be supported if it is discontinued should be addressed along with the longevity of the manufacturer because systems are not yet interoperable.

Open standard protocols allow owner control and the potential for interoperability between systems. Open protocols are updated and developed on an ongoing basis (National Transportation Communications for Intelligent Transportation Systems, 2011).

7.3.2 Monitoring Center

For networked controls, data from the luminaires are collected and analyzed in a communications or monitoring center. Systems may be supplied where the data are stored and managed by the supplier via cloud networking and accessed via a web browser or perhaps stored and managed on the owner's network system. The cloud is where all computing resources (hardware and software) are delivered as a service over a network (typically the internet). In this case, the owner should decide if it will manage the system or use a cloud system that, once installed, would require no further internal resources to manage.

Centrally hosted systems are typically web-based systems with a secure login (user ID and password). Data from the control network are processed by a service provider at a central location. The cost of hosting is often scaled to suit the overall size of the system. IT infrastructure, upgrades, and support resources are often provided as part of the service. Ongoing service fees (often charged) should be considered.

Customer-hosted systems are typically located on the customer's network. Servers, databases, and networks are usually owned and maintained by the customer's IT resources. Upgrades and support are generally provided on a version-specific basis, thus minimizing security concerns and ongoing service fees. When considering a customer-hosted system, firewall requirements and system integration should be discussed early on with the customer's IT group.

7.3.3 Networks

Networked control systems conceptually consist of three interacting component sets: field devices, network infrastructure, and a central management system (CMS). Although the component sets contain different types of physical devices, information is shared across the entire system. Lighting control networks can be either wireless or hard wired.

Currently, field devices always include controllers, which necessarily consume data to implement some control function according to internal programming. Field devices may also include sensors that produce data. Multiple controllers are often used to route data through gateways that act as communication bridges to outside networks and may also communicate (via cellular) directly to the CMS. Field devices may be accessed and managed remotely by a CMS that consolidates and stores retrieved data, facilitates user interaction through graphical user interfaces, and consolidates and stores retrieved data. The CMS communicates to field devices through network infrastructure consisting of one or more backhaul communication networks that may take various forms (e.g., wired, wireless, powerline communications).

7.3.4 Network Infrastructure

Wireless roadway lighting controls make use of three network topologies: mesh, star, and point to point. All topologies rely in some way on a point-to-point configuration as an example, creating a bridge between network gateways or routers. Limiting factors are distance, line of sight, and information density (capacity), which are resolved through frequency and network communication protocols. The frequencies used by wireless networks to communicate between the gateways and nodes are specific to the system. Communication between the gateways and a CMS are either hard-wired into the communications infrastructure or based on cellular communications. In all situations, the control system should maintain robust and redundant security along with continuity.

7.3.5 Measuring Power Usage

The power savings provided by dimming lights using adaptive controls can help offset system costs. Many roadway lighting systems in North America are supplied power on an unmetered (flat-rate) basis. For unmetered roadway lights, adaptive systems can provide accurate measurements of power consumption. Monitoring the power consumption of these adaptive systems should not, however, be confused with a “utility grade meter,” which may have specific regulatory requirements and recalibration requirements that go beyond the capability of an adaptive system.

If accepted by power utilities as an accurate means to measure power consumption, owners could be billed for power used, taking full advantage of energy savings. Including power consumption measurements as part of adaptive controls could resolve the shortcomings of the flat-rate system and make the full financial benefits of dimming available to owners. A typical power measurement system may require re-calibration and validation via utility grade check meters. Even if not acceptable to the local utility, power consumption monitoring can be used to track power costs for comparison to utility flat-rate billing.

7.4 Smart City Applications

In recent years, the rapid rise of urbanization has coincided with a massive growth in connected devices (or things that talk to the internet). Cisco predicts that 50 billion connected devices will exist as of 2021. To be competitive in the emerging economy, there is significant benefit in employing connectivity to support smarter, healthier, and more sustainable communities. However, the increasing array of technology choices may be difficult for municipalities to navigate, preventing the full potential of connected devices from being realized. Digital master planning has recently emerged as a process for developing coherent strategies to develop intelligent communities. Digital master planning can be applied to produce roadmaps for the effective and beneficial integration of technologies.

The term “intelligent community” is generally used to refer to applying digital information technology throughout the built environment to improve the overall quality of life for people at home, work, and play. The technology is used to provide opportunities for economic development and enhance urban services, resource conservation, and cost effectiveness.

When implementing a Smart City network, it is critical that all stakeholders be engaged in a needs assessment.

The Smart City “digital twin” approach is one strategy (Petrova-Antonova & Ilieva, 2019) for adaptive lighting in which sensors and controls in the physical world are linked to data in a digital world (Figure 65). The result is that the status of the real world is reflected in the digital world, and decisions can be made based on these data to control applications in the real world. Traffic volume, pedestrian volume, or weather conditions, for example, can be used to control intersections or an adaptive lighting system.

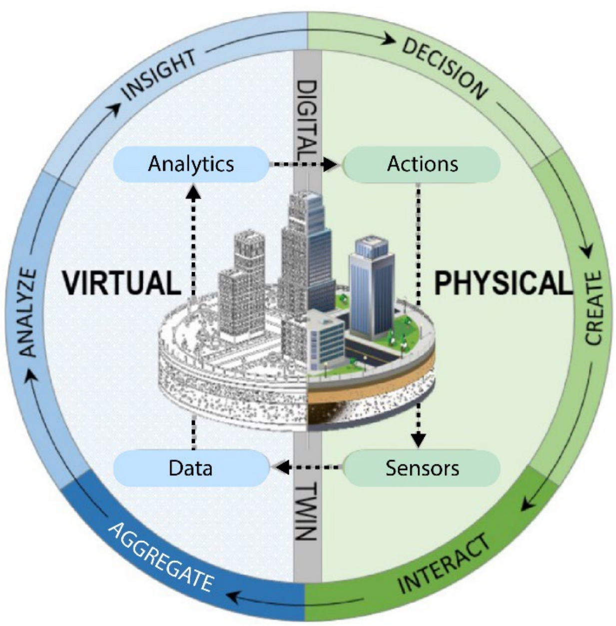


Figure 65. Image. Smart City digital twin concept (Petrova-Antonova & Ilieva, 2019).

Adaptive lighting is a critical application that can be enabled through a Smart City application allowing for high levels of control and an increased level of adaptability. Level 4 adaptability can be achieved through a Smart City application where lighting on demand is a possibility.

For network considerations, Smart City technologies should integrate into the Autonomous and Connected Vehicle framework that those systems use. Some authorities are considering communications/data backhaul networks to incorporate various systems into a single network. Others are looking for available bandwidth on adaptive control networks for connecting Internet of Things devices that do not have large bandwidth requirements. When implementing a Smart City network, all stakeholders should be engaged in a needs assessment. For further information on Smart Cities, please refer to ANSI/IES LP12-21 Lighting Practice: IOT Connected Lighting (Illuminating Engineering Society, 2021c).

7.5 Vehicle-to-Infrastructure/Infrastructure-to-Vehicle Communication

Connected vehicle technology allows vehicles to communicate with each other and with infrastructure to transmit important safety information and other related information. Connected vehicle technology can also be used to communicate information from a vehicle to a lighting system to tell lighting when to dim or turn on and to detect pedestrians who are outside the line of sight of vehicle sensors. A pilot test of an on-demand and just-in-time lighting developed by the Virginia Tech Transportation Institute (Gibbons, Palmer, and Jahangiri (2016)) demonstrated a connected vehicle/infrastructure system that detected a vehicle approaching a lighted roadway section and turned on the roadway lighting on demand. The system did not distract the driver and provided a safe driving environment.

A recent decision by the Federal Communication Commission (FCC) repurposed the spectrum currently allocated for dedicated short-range communications (Stone, 2020). In its place, the FCC offers a smaller but exclusive spectrum for a newer technology called cellular vehicle-to-everything (C-V2X; (Federal Communications Commission, 2020). Given that C-V2X is still in its infancy, more research and development is required for the consideration for vehicle-to-infrastructure, infrastructure-to-vehicle, and vehicle-to-everything systems that include direct communication with roadway lighting systems.

7.6 Cybersecurity

Cybersecurity is the practice of protecting systems, networks, and programs from digital attacks. Cyberattacks are usually aimed at accessing, changing, or destroying sensitive information; extorting money from users; and interrupting normal business processes. As new digital infrastructure and smart technologies are adopted, the benefits of increased infrastructure connectivity should be balanced against the new security, safety, and performance risks. A connected network can be vulnerable to cybersecurity attacks at varying threat levels.

Governments across the globe have responded to the rising cyber threat with guidance to help organizations implement effective cybersecurity practices. For example, the National Institute of Standards and Technology has created a cybersecurity framework that recommends continuous, real-time monitoring of all electronic resources to combat the proliferation of malicious code and aid in early detection of cyber threats.

Security programs continue to evolve new defenses as cybersecurity professionals identify new threats and new ways to combat them. To make the most of end-user security software, employees need to be educated on how to use it. Crucially, keeping such software running and frequently updating it helps ensure that it can protect users against the latest cyber threats.

8 SUMMARY

A properly designed lighting system can enhance safety while balancing the need to minimize the impacts on roadway users, the surrounding environment, wildlife and the night sky. Other elements that should be considered include equity and diversity and the societal impact of lighting. The handbook focuses on how best to apply roadway lighting in various applications and is therefore educational in nature. The handbook is also intended to further clarify and enhance elements discussed in the mentioned publications. However, this document does not reproduce the lighting level recommendations found in other publications. Any lighting level recommendation tables are cited but not included.

The purpose of this handbook is to provide recommendations to lighting designers and State, city, and town officials to improve the design and application of roadway lighting. It is not intended to be a detailed design guide. It is a resource for policy makers and the design and construction community to evaluate potential needs, benefits, and applicable references when considering a roadway or street lighting system.

It is important to note that lighting is an evolving science. Research is continually enhancing our knowledge and understanding of lighting applications, and technological advancements continue to evolve our lighting capabilities. This handbook is a snapshot in time of the current best practices for roadway lighting application. It is important that the designer continues to be involved in the ever-evolving science to ensure that their projects fully utilize the latest available technologies.

As defined in this handbook and other documents referenced, roadway lighting has significant safety benefit to road users. However, simply providing lighting without following the most current design practices will often lead to reduced benefit. The way lighting is designed can have significant impact on the level of visibility it provides, thus impacting the safety benefits. In considering this, it is important to note lighting technologies have evolved since the previous 2012 Handbook. This has led to research and enhanced design considerations, which are included in this handbook. The technical information provided in this part of the handbook has been laid out to provide the lighting designer and policy makers with information and methods to enhance their designs and provide a lighted environment that enhances safety while also considering all other benefits and impacts of the lighting system. The proper application of roadway lighting can improve safety and mobility. The principles discussed in this document can help designers achieve these benefits while considering and where possible reducing any the negative impacts of lighting.

Documents available from organizations such as the American Association of State Highway and Transportation Officials (AASHTO), the Illuminating Engineering Society (IES), the Transportation Association of Canada (TAC), and the Commission Internationale de l’Eclairage (CIE) offer recommendations on lighting levels, lighting configurations, and other considerations and are therefore not repeated. This handbook directs users to that information where applicable and provides supplemental information on topics not addressed in those documents.

The use of these design criteria from the above organizations, such as AASHTO, IES, TAC and CIE, is not required under Federal Law or regulation.

The examples in Part II of this document are an important aspect of the handbook because they demonstrate the application of the technical knowledge provided in Part I to real-life design efforts.

9 REFERENCES

Adrian, W. (1989). Visibility of targets: Model for calculation. *Lighting Research & Technology, 21*(4), 181-188. doi: 10.1177/096032718902100404

Adrian, W., & Bhanji, A. (1991). *Fundamentals of disability glare. A formula to describe stray light in the eye as a function of the glare angle and age.* Paper presented at the Proceedings of the First International Symposium on Glare, Orlando, Florida.

Allen, J. A. (1880). Destruction of Birds by Lighthouses. *Bulletin of the Nuttail Ornithological Club, 5*, 131-138.

American Association of State Highway and Transportation Officials. (2012). Guide for the Development of Bicycle Facilities (Fourth Edition ed.). Washington, DC: American Association of State Highway and Transportation Officials.

American Association of State Highway and Transportation Officials. (2018a). *A Policy on Geometric Design of Highways and Streets* (Vol. 7th Edition). Washington, DC: American Association of State Highway and Transportation Officials.

American Association of State Highway and Transportation Officials. (2018b). *Roadway Lighting Design Guide* (Seventh ed.): American Association of State Highway and Transportation Officials.

American Road & Transportation Builders Association. (2022). National Workzone Safety Information Clearing House - Work Zone Data. 2022, from https://workzonesafety.org/work-zone-data/

Antin, J., Wotring, B., & Foley, J. (2011). *Exploring older driver lateral head rotations at intersections using naturalistic driving data.* Paper presented at the proceedings of the sixth Internationl driving symposium on human factors in driving assessment.

Atlanta Regional Commission. (1974). Street light project: final evaluation report. *Atlanta, GA: Author*.

Barentine, J. C., Kundracik, F., Kocifaj, M., Sanders, J. C., Esquerdo, G. A., Dalton, A. M., . . . Kyba, C. C. (2020). Recovering the city street lighting fraction from skyglow measurements in a large-scale municipal dimming experiment. *Journal of Quantitative Spectroscopy and Radiative Transfer, 253*, 107120.

Benson, A. J., Tefft, B. C., Arnold, L. S., & Horrey, W. J. (2021). Fatal hit-and-run crashes: Factors associated with leaving the scene. *Journal of Safety Research, 79*, 76-82. doi: https://doi.org/10.1016/j.jsr.2021.08.007

Bhagavathula, R., Gibbons, R., Hanifin, J., & Brainard, G. (2021). LED Roadway Lighting: Impact on Driver Sleep Health and Alertness. *NCHRP Research Report*(968).

Bhagavathula, R., Gibbons, R., & Kassing, A. (2021). Roadway Lighting's Effect on Pedestrian Safety at Intersection and Midblock Crosswalks (pp. 49). Springfield, IL: Illinois Center for Transportation.

Bhagavathula, R., & Gibbons, R. B. (2017). Effect of Work Zone Lighting on Drivers' Visual Performance and Perceptions of Glare. *Transportation Research Record, 2617*(1), 44-51. doi: 10.3141/2617-06

Bhagavathula, R., & Gibbons, R. B. (2018). Effects of Mounting Height, Offset Distance, and Number of Light Towers on Drivers' Visual Performance and Discomfort Glare in Work Zones. *Transportation Research Record, 2672*(16), 105-112. doi: 10.1177/0361198118782762

Bhagavathula, R., & Gibbons, R. B. (2019). *Understanding Driver Visual Performance By Examining Distributions of Detection Distances*. Paper presented at the CIE 2019, Washington, DC.

Bhagavathula, R., & Gibbons, R. B. (2020). Light Levels for Parking Facilities Based on Empirical Evaluation of Visual Performance and User Perceptions. *LEUKOS, 16*(2), 115-136. doi: 10.1080/15502724.2018.1551724

Bhagavathula, R., Gibbons, R. B., & Hankey, S. (2018). *Exploring the relationship between street lighting levels and physical activity after dark: Results of a pilot study* Paper presented at the Active Living Research Conference 2018, Banff, Alberta.

Bhagavathula, R., Gibbons, R. B., Medina, A., & Terry, T. N. (2017). Examination of the current practice of lighting in Virginia: nighttime work zones and improving safety through the development of nighttime lighting specifications: Virginia Transportation Research Council.

Bjørnskau , T., & Fosser, S. (1996). Car drivers' behavioral adaptation to the installation of road lighting. Before - and - after study on Route E-18 in Norway. Norway: Institute of Transport Economics.

Blackwell, O. M., & Blackwell, H. R. (1971). IERI: Visual performance data for 156 normal observers of various ages. *Journal of the Illuminating Engineering Society, 1*(1), 3-13.

Box, P. C. (1989). Major road accident reduction by illumination. *Transportation Research Record, 1247*(32-38).

Brewer, M., Murillo, D., & Pate, A. (2014). Handbook for designing roadways for the aging population.

Briggs, W. R. (2006). Physiology of plant responses to artificial lighting. *Ecological consequences of artificial night lighting (C. Rich and T. Longcore, eds.). Island Press, Washington, DC*, 389-411.

Brüning, A., FranzHölker, F., Franke, S., Kleine, W., & Kloas , W. (2016). Impact of different colours of artificial light at night on melatonin rhythm and gene expression of gonadotropins in European perch. *Science of the Total Environment, 543*, 214-222.

Cajochen, C., Frey, S., Anders, D., Späti, J., Bues, M., Pross, A., . . . Stefani, O. (2011). Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. *Journal of Applied Physiology, 110*(5), 1432-1438.

Carlson, P., & Miles, J. (2011). Nighttime visibility of in-service pavement markings, pavement markers, and guardrail delineation in Alaska (with and without continuous lighting): Alaska. Dept. of Transportation and Public Facilities. Research, Development ….

Chalfin, A., Hansen, B., Lerner, J., & Parker, L. (2021). Reducing crime through environmental design: Evidence from a randomized experiment of street lighting in New York City. *Journal of Quantitative Criminology*, 1-31.

Chang, A.-M., Aeschbach, D., Duffy, J. F., & Czeisler, C. A. (2015). Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness. *Proceedings of the National Academy of Sciences, 112*(4), 1232-1237.

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? *PloS one, 6*(1), e16429.

City of Vancouver. (2012). PEDESTRIAN SAFETY STUDY (pp. 182). Vancouver, BC: City of Vancouver.

Clanton & Associates, I., & Virginia Tech Transportation Institute. (2014). Seattle LED Adaptive Lighting Study (pp. 197): Northwest Energy Efficiency Alliance.

Commission Internationale de l'Eclairage. (1987). Road Lighting as an Accident Countermeasure. Vienna: Commission Internationale de l'Eclairage.

Commission Internationale de l'Eclairage. (2017). Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition (Vol. CIE 150:2017). Vienna: Commission Internationale de l'Eclairage.

Commission Internationale de l'Eclairage. (2018). CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light (Vol. CIE S 026/E:2018): Commission Internationale de l'Eclairage.

Commission Internationale de l'Eclairage. (2021). CIE 243:2021 Discomfort Glare in Road Lighting and Vehicle Lighting (Vol. CIE 243:2021): Commission Internationale de l'Eclairage.

Cope, K. R., & Bugbee, B. (2013). Spectral effects of three types of white light-emitting diodes on plant growth and development: absolute versus relative amounts of blue light. *HortScience, 48*(4), 504-509.

Crash Modification Factor Clearning House. (2022). 2022, from https://www.cmfclearinghouse.org/about_cmf.cfm

Department, H. P. (1976). Final Evaluation Report of the 'High Intensity Street Lighting Program': Planning and Research Section, Staff and Technical Services Division ….

Durmus, D. (2021). Correlated color temperature: Use and limitations. *Lighting Research & Technology*, 14771535211034330.

Elvik, R., Vaa, T., Hoye, A., & Sorensen, M. (2009). *The handbook of road safety measures*: Emerald Group Publishing.

Engineering, N. A. o. S., & Medicine. (2020). Solid-State Roadway Lighting Design Guide: Volume 2: Research Overview: National Academies of Sciences, Engineering,

Medicine.

Federal Communications Commission. (2020). *FCC Modernizes 5.9 GHz Band to Improve Wi-Fi and Automotive Safety*. Washington, DC: Retrieved from https://www.fcc.gov/document/fcc-modernizes-59-ghz-band-improve-wi-fi-and-automotive-safety-0.

Federal Highway Administration. (2020). Focus on Reducing Rural Roadway Departures. Retrieved April 15, 2022, from https://safety.fhwa.dot.gov/FoRRRwD/

Fesler, S. (2014). ICYMI: New York City Implements 'Vision Zero'. Retrieved April 15, 2022, from https://www.theurbanist.org/2014/11/11/icymi-new-york-city-implements-vision-zero/

Gibbons, R., B., Meyer, J. E., Terry, T., Bhagavathula, R., Lewis, A. L., Flannagan, M., & Connell, C. (2015). Evaluation of the Impact of Spectral Power Distribution on Driver Performance: Virginia Tech Transportation Institute.

Gibbons, R., Guo, F., Medina, A., Terry, T., Du, J., Lutkevich, P., & Li, Q. (2014). Design criteria for adaptive roadway lighting.

Gibbons, R., Guo, F., Medina, A., Terry, T. N., Du, J., Lutkevich, P. J., . . . Vetere, P. (2014). Guidelines for the implementation of reduced lighting on roadways: United States. Federal Highway Administration.

Gibbons, R. B., Edwards, C. J., Bhagavathula, R., Carlson, P., & Owens, D. A. (2012). Development of Visual Model for Exploring Relationship between Nighttime Driving Behavior and Roadway Visibility Features. *Transportation Research Record, 2298*(1), 96-103. doi: 10.3141/2298-11

Gibbons, R. B., Edwards, C. J., Williams, B., & Andersen, C. K. (2008). Informational report on lighting design for midblock crosswalks.

Gibbons, R. B., & Hankey, J. (2007). Wet night visibility of pavement markings: dynamic experiment. *Transportation Research Record, 2015*(1), 73-80.

Gibbons, R. B., Palmer, M., & Jahangiri, A. (2016). Connected vehicle applications for adaptive overhead lighting (on-demand lighting) : final research report.

Gibbons, R. B., & Williams, B. (in review). Light Sources in Fog & Performance of New Roadway Lighting in Rain and Wet Conditions Blacksburg, VA: Virginia Tech Transportation Institute.

Governors Highway Safety Association. (2021). An Analysis of Traffic Fatalities by Race and Ethnicity (pp. 24): Governors Highway Safety Association.

Grubisic, M., Haim, A., Bhusal, P., Dominoni, D. M., Gabriel, K., Jechow, A., . . . Riley, W. (2019). Light pollution, circadian photoreception, and melatonin in vertebrates. *Sustainability, 11*(22), 6400.

Harkey, D. L. (2008). *Accident modification factors for traffic engineering and ITS improvements* (Vol. 617): Transportation Research Board.

Hills, B., & Burg, A. (1977). *A reanalysis of California driver vision data : general findings*. Crowthorne.

Illuminating Engineering Society. (1999). IES CP-31 Value of Public Roadway Lighting. *Journal of the Illuminating Engineering Society, 28*(2), 137-157. doi: 10.1080/00994480.1999.10748285

Illuminating Engineering Society. (2010). *The Lighting Handbook* (Vol. 10th Edition). New York, NY: Illuminating Engineering Society,.

Illuminating Engineering Society. (2018). American National Standard Practice for Design and Maintenance of Roadway and Parking Facility Lighting (Vol. IES RP-8-18). New York, NY: Iluminating Engineering Society.
Illuminating Engineering Society. (2020a). Luminaire Classification System for Outdoor Luminaires (pp. 10). New York, NY: Illuminating Engineering Society.
Illuminating Engineering Society. (2020b). Luminaire Classification System for Outdoor Luminaires (Vol. ANSI/IES TM-15-20, pp. 10). New York, NY: Illuminating Engineering Society.
Illuminating Engineering Society. (2021a). Description, Measurement, and Estimation of Sky Glow (Vol. ANSI/IES TM-37-21, pp. 44). New York, NY: Illuminating Engineering Society,.
Illuminating Engineering Society. (2021b). Horticulture Lighting (Vol. ANSI/IES RP-45-21, pp. 55). New York, NY: Illuminating Engineering Society.
Illuminating Engineering Society. (2021c). Lighting Practice: IOT Connected Lighting for further information Smart Cities (Vol. LP-12-21, pp. 43). New York: Illuminating Engineering Society.
Illuminating Engineering Society. (2021d). Lighting Science: Nomenclature and Definitions for Illuminating Engineering (Vol. ANSI/IES LS-1-21). New York, NY: Illuminating Engineering Society.
Illuminating Engineering Society. (2021e). Recommended Practice: Lighting Roadway and Parking Facilities (Vol. ANSI/IS RP-8-21, pp. 546). New York, NY: Illuminating Engineering Society.
Inskeep, N., & Goff, C. (1974). PRELIMINARY EVALUATION OF THE PORTLAND (OR) LIGHTING PROJECT.
Insurance Institute of Highway Safety. (2022). Older Drivers. 2022, from https://www.iihs.org/topics/older-drivers
Kinzey, B. R., Perrin, T. E., Miller, N. J., Kocifaj, M., Aube, M., & Lamphar, H. A. (2017). An investigation of LED street lighting's impact on sky glow: Pacific Northwest National Lab.(PNNL), Richland, WA (United States).
Koonce, P. (2017). Inclusion of Equity in an LED Citywide Street Lighting Replacement Program. *ITE Journal,* 5.
Kyba, C., Ruby, A., Kuechly, H. U., Kinzey, B., Miller, N., Sanders, J., . . . Espey, B. (2021). Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. *Lighting Research & Technology, 53*(3), 189-211.
Lehrl, S., Gerstmeyer, K., Jacob, J., Frieling, H., Henkel, A., Meyrer, R., . . . Bleich, S. (2007). Blue light improves cognitive performance. *Journal of neural transmission, 114*(4), 457-460.
Lewis, E. B., & Sullivan, T. T. (1979). Combating crime and citizen attitudes: A study of the corresponding reality. *Journal of Criminal Justice, 7*(1), 71-79.
Liebel, B., & Hartley, R. (2020). Joining Forces to Protect the Night from Light Pollution. Retrieved April 15, 2022, from https://www.darksky.org/joining-forces-to-protect-the-night-from-light-pollution/
Longcore, T., Rodriguez, A., Witherington, B., Penniman, J., Herf, L., & Herf, M. (2018a). Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, 1-11.
Longcore, T., Rodriguez, A., Witherington, B., Penniman, J., Herf, L., & Herf, M. (2018b). Software for the Rapid Assessment of Lamp Spectrum to Quantify Ecological Effects of Light at Night. Retrieved November 11, 2018, 2018, from https://fluxometer.com/ecological/?mode=d65&group=all
Medicine, N. A. o. S. E. a. (2020). Guidance to Improve Pedestrian and Bicyclist Safety at

Intersections Washington, DC: National Academies of Sciences, Engineering, and Medicine.
Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G., & Worm, B. (2011). How many species are there on Earth and in the ocean? *PLoS biology, 9*(8), e1001127.
Mortimer, R. G. (1989). *Older drivers' visibility and comfort in night driving: Vehicle design factors.* Paper presented at the Proceedings of the Human Factors Society Annual Meeting.

Mortimer, R. G., & Fell, J. C. (1989). Older drivers: Their night fatal crash involvement and risk. *Accident Analysis & Prevention, 21*(3), 273-282.

Mutmansky, M., Givler, T., Garcia, J., Clanton, N., Gibbons, R. B., & Edwards, C. J. (2010). Advanced Street Lighting Technologies Assessment Project - City of San Jose (pp. 134). San Jose, CA: City of San Jose.

National Academies of Sciences Engineering and Medicine. (1974). NCHRP Report 152: Warrants For Highway Lighting (pp. 130). Washington, DC: National Academies of Sciences Engineering and Medicine,.

National Academies of Sciences Engineering and Medicine. (2020). Solid-State Roadway Lighting Design Guide: Volume 2: Research Overview. Washington, DC: The National Academies Press.

National Academies of Sciences Engineering Medicine. (2020). Solid-State Roadway Lighting Design Guide: Volume 1: Guidance: National Academies of Sciences, Engineering, Medicine.

National Center for Statistics and Analysis. (2020). Pedestrians: 2018 data (Traffic Safety Facts. Report No. DOT HS 812 850). (pp. 13): National Highwat Traffic Safety Administration.

National Center for Statistics and Analysis. (2022). Bicyclists and other cyclists: 2020 data (Traffic Safety Facts. Report No. DOT HS 813 322). Washington, DC: National Highway Traffic Safety Administration.

National Transportation Communications for Intelligent Transportation Systems. (2011). National Transportation Communications for ITS Protocol: Object Definitions for Electrical and Lighting Management Systems (ELMS) (Vol. NTCIP 1213 version v02, pp. 178): AASHTO, ITE, NEMA.

O'Neal, E. E., Jiang, Y., Franzen, L. J., Rahimian, P., Yon, J. P., Kearney, J. K., & Plumert, J. M. (2018). Changes in perception–action tuning over long time scales: How children and adults perceive and act on dynamic affordances when crossing roads. *Journal of Experimental Psychology: Human Perception and Performance, 44*, 18-26. doi: 10.1037/xhp0000378

Painter, K. (1996). The influence of street lighting improvements on crime, fear and pedestrian street use, after dark. *Landscape and Urban Planning, 35*(2), 193-201. doi: https://doi.org/10.1016/0169-2046(96)00311-8

Palmer, M., Gibbons, R., Bhagavathula, R., & Holshouser, D. (2018). Roadway Lighting's Impact on Altering Soybean Growth – Volume 2: LED versus HPS Color Spectral Impact: Illinois Center for Transportation.

Palmer, M., Gibbons, R., Bhagavathula, R., Holshouser, D., & Davidson, D. (2017). Roadway Lighting's Impact on Altering Soybean Growth.

Petrova-Antonova, D., & Ilieva, S. (2019). *Methodological framework for digital transition and performance assessment of smart cities.* Paper presented at the 2019 4th International Conference on Smart and Sustainable Technologies (SpliTech).

Quinet, K. D., & Nunn, S. (1998). Illuminating crime: The impact of street lighting on calls for police service. *Evaluation Review, 22*(6), 751-779.

Rich, C., & Longcore, T. (2006). *Ecological Consequences of Artificial Night Lighting*. Washington: Island Press.

Rich, C., & Longcore, T. (2013). *Ecological consequences of artificial night lighting*: Island Press.

Richards, O. W. (1966). Vision at levels of night road illumination. XII. Changes of acuity and contrast sensitivity with age. *Am J Optom Arch Am Acad Optom, 43*(5), 313-319. doi: 10.1097/00006324-196605000-00004

Rombauts, P., Vandewyngaerde, H., & Maggetto, G. (1989). Minimum semicylindrical illuminance and modelling in residential area lighting. *Lighting Research and Technology, 21*(2), 49-55.

Silva, E., Marco, A., da Graça, J., Pérez, H., Abella, E., Patino-Martinez, J., . . . Almeida, C. (2017). Light pollution affects nesting behavior of loggerhead turtles and predation risk of nests and hatchlings. *Journal of Photochemistry and Photobiology B: Biology, 173*, 240-249. doi: https://doi.org/10.1016/j.jphotobiol.2017.06.006

Sinnadurai, S. (1981). High pressure sodium street lights affect crops in Ghana. *World crops*.

Staplin, L., Lococo, K., Byington, S., & Harkey, D. L. (2001). Highway design handbook for older drivers and pedestrians: Turner-Fairbank Highway Research Center.

Sternhell, R. (1977). The limits of lighting: The New Orleans experiment in crime reduction. *Final Impact Evaluation Report. New Orleans, LA: Mayor's Criminal Justice Coordinating Council*.

Stone, T. (2020). FCC chairman signals an end to DSRC as he prepares to carve up 5.9GHz spectrum – but ITS America hits back. Retrieved October 4, 2021, from https://www.traffictechnologytoday.com/news/connected-vehicles-infrastructure/fcc-chairman-signals-an-end-to-dsrc-as-he-prepares-to-carve-up-5-9ghz-spectrum-but-its-america-hits-back.html

Sullivan, J. M., & Flannagan, M. J. (2002). The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis & Prevention, 34*(4), 487-498. doi: https://doi.org/10.1016/S0001-4575(01)00046-X

Swaddle, J. P., Francis, C. D., Barber, J. R., Cooper, C. B., Kyba, C. C. M., Dominoni, D. M., . . . Longcore, T. (2015). A framework to assess evolutionary responses to anthropogenic light and sound. *Trends in Ecology and Evolution, 30*(9), 550-560.

Terry, T., Gibbons, R., Kassing, A., Bhagavathula, R., Lowdermilk, C., & Lutkevich, P. (2020). Research Report: Street Lighting for Pedestrian Safety (pp. 88). Washington, DC: Federal Highway Administration.

Traffic Safety Supply Company. (2022). Median-mounted Glare Screens

Transportation Association of Canada. (2006). *Guide for the design of roadway lighting*: Transportation Association of Canada.

Transportation Association of Canada. (2013). Roadway Lighting Efficiency and Power Reduction Guide (Vol. PTM-LIGHTING06): Transportation Association of Canada.

van Bommel, W. (2014). *Road Lighting: Fundamentals, Technology and Application*: Springer.

Wald, M. (1998). Balancing Costs and Benefits of Highway Improvements. *New York Times*. Retrieved from https://www.nytimes.com/1998/03/27/automobiles/autos-on-friday-safety-balancing-costs-and-benefits-of-highway-improvements.html

Wanvik, P. O. (2009). Road lighting and traffic safety: Do we need road lighting?

Warehouse. (2020). Colored Pavement Material Guidance Retrieved April 15, 2022, from https://nacto.org/publication/urban-bikeway-design-guide/bikeway-signing-marking/

Weale, R. A. (1961). Retinal Illumination and Age. *Transactions of the Illuminating Engineering Society, 26*(2_IEStrans), 95-100. doi: 10.1177/147715356102600204

Wilkins, A., Veitch, J., & Lehman, B. (2010). *LED lighting flicker and potential health concerns: IEEE standard PAR1789 update.* Paper presented at the 2010 IEEE Energy Conversion Congress and Exposition.

Williamson, S. J., & Cummins, H. Z. (1983). *Light and color in nature and art*: Wiley-VCH

Witherington, B., & Martin, R. (1996). Understanding, Assessing, and Resolving Light-Pollution Problems on Sea Turtle Nesting Beaches: Florida Marine Research Institute.

Witherington, B. E., & Bjorndal, K. A. (1991). Influences of wavelength and intensity on hatchling sea turtle phototaxis: implications for sea-finding behavior. *Copeia*, 1060-1069.

Wright, R., Heilweil, M., Pelletier, P., & Dickinson, K. (1974). *The impact of street lighting on street crime*: University of Michigan.

Wyszecki, G., & Stiles, W. S. (1982). *Color science* (Vol. 8): Wiley New York.

Zong-Ming, Z. (2007). Influence of Street light illumination on soybean growth and Yield [J]. *Anhui Agricultural Science Bulletin, 20*, 028.

PART II – Design Examples

Part II of this document includes design examples to highlight key focus areas on various street and roadway types. These examples have been selected to highlight the more common areas of the roadway and are not meant to be a comprehensive list. It is expected that the information applied in these examples will be applied to other areas as needed. The examples illustrate the different design recommendations applicable to the areas being studied and highlight the key safety elements that should be considered. The examples also include new and emerging research and approaches that the designer may want to consider.

The two most applicable design recommendations used in these examples are AASHTO GL-7, Roadway Lighting Design Guide, and IES RP-8-21, Recommended Practice Lighting Roadway and Parking Facilities. These documents generally agree but do contain some differences. The examples here include elements and topics that pertain to typical situations, while the reference documents contain significant information on specifics and details. The reference documents should be referenced when performing lighting design, and the authority responsible for the design can choose which document should take precedence. The use of these design criteria is not required under Federal Law or regulation.

The lighting design elements discussed address four broad groups: surface types; conflict zones; surroundings; and strategic aspects. Roadways, bike lanes, and walkways are the surfaces being traveled and are lighted to provide visibility of that surface to the traveler. Crosswalks, intersections, interchanges, driveways, and work zones are conflict areas, where two streams of traffic might use the same space. Surroundings describe the walls in tunnels and the surround ratio for suitable roadways, providing guidance to travelers. Strategic aspects discussed in these examples are partial (beacon) lighting, light trespass, adaptive lighting, and color of light. These examples are almost all for continuous lighting, but situations occur where partial (beacon) lighting may be appropriate instead, such as an at-grade railway crossing. Similarly, adaptive lighting is a strategic option that may be appropriate for some projects.

In every lighting project, the topics of color of light and light trespass are important. Color of light is a significant issue in some situations such as high-speed roadways or environmentally sensitive areas. Light trespass is also a consideration in every project, influenced by the unique features of the situation. These universal design elements are discussed below as general topics. A range of aspects of lighting design that are relevant to particular projects are discussed in these various examples, but not all combinations of situations are covered. Table 22 shows the breakdown of topics covered in each of the examples.

Table 22. Examples listed by topics covered.

	Topic	1 General Considerations	2 Urban Street	3 Rural Road	4 Expressway	5 Freeway, Urban	6 Freeway, Suburban	7 Freeway, Rural	8 Roundabout	9 Walkway / Bikeway	10 Short Tunnel	11 Tunnel	12 Underpass	13 At-grade Railway Crossing
	Roadways		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Crosswalks		Y		Y				Y					
	Sidewalks		Y		Y				Y				Y	
	Bike Lanes		Y											
	Intersections		Y			Y	Y	Y						
	Interchanges				Y									
	Driveways				Y									
	Work Zones				Y		Y	Y						
	Surround Ratio			Y		Y	Y	Y						
	Partial Beacon			Y				Y						
	Walls										Y	Y	Y	
	Adaptive Lighting		Y											
	At Grade Rail Crossings													Y
	Color of Light	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y
	Light Trespass	Y	Y	Y	Y	Y	Y	Y	Y	Y				Y

Each of the relevant topics are identified by an icon chart.

Table of Contents

1 General Considerations

Two topics, color of light and light trespass, have applications in multiple categories and are considered here due to the importance of their design considerations.

1.1 Color of Light

Credit: Don McLean

General Considerations	
	Color of Light
	Light Trespass

1.1.1 Currently Available Design Recommendations

The spectral content of a light source affects visibility. Basic object detection is often discussed in terms of luminance contrast (essentially, how bright the object is compared to how bright the background is). In addition to luminance contrast, there is also color contrast to consider. For example, a red object against a gray background will be more easily detected than a gray object against a gray background. Based on the spectral content of the light source, lighting can either enhance or detract from the color contrast of an object. With LED lighting systems, the ability to change the spectral content is less daunting than with older technologies.

Although the spectral content indicated by the SPD of a source is a more precise metric, CCT can be used as an approximate metric to compare similar technologies (e.g., a white LED comprised of a base blue LED with a phosphor coating to achieve a white source).

1.1.2 Emerging Research

Several aspects of the implementation of roadway lighting and spectrum are being researched, and several reports are being published to include these changes. The following highlights the current state of the research:

- NCHRP 940 evaluated the detection distances of pedestrians and targets on roadways under various conditions and various lighting sources and found that 4000K light sources resulted in longer detection distances than 3000K or 5000K sources (National Academies of Sciences Engineering and Medicine, 2020) .
- The spectrum of the light source is connected to human health and melatonin levels. However, emerging research suggests that roadway lighting has no health impacts regardless of the CCT because the lighting levels (dosage) from roadway lighting are too low.

- Although subjective preferences have been reported for lower CCT sources, this preference has not been validated by research, and subjective questioning performed under NCHRP 940 showed no preference difference.

The relative impacts of light scatter and the effects of spectral content on flora and fauna are also being studied. The variety of responses among flora and fauna complicates general recommendations on mitigating impacts. The suitability of a specific color of light depends on the situation and priorities involved, and designers should be aware of the implications.

SAFETY HIGHLIGHTS

For the best detection distance, a CCT of 4000K light source should be used. If specific conditions exist related to impacts on wildlife or light scatter, they should be evaluated in terms of visibility, perhaps by changing CCT but increasing light levels.

1.2 Light Trespass

Credit: Paul Lutkevich

General Considerations	
	Color of Light
	Light Trespass

1.2.1 Currently Available Design Recommendations

Light trespass should be considered for all designs (See Section 6.3 of Part I). The boundaries of light trespass will depend on the lighting installation and corresponding location(s) of visual receptors. For example, for a roadway lighting system installed on a road with few abutters, the light trespass evaluation might best be made at the edge of the right-of-way of the roadway. For an urban setting with properties and homes located on the back edge of the sidewalk, the border for light trespass might be the property line, building edge, or windows facing the roadway. Because the conditions vary greatly between roadway types and abutters, engineering judgment should be applied to determine the best places to gauge and mitigate impacts.

Mitigation of light trespass involves diminishing the visibility of light sources and the spread of illumination. When lighting is warranted, source location and aiming should keep illumination within the property. Luminaire output and mounting height should each be as low as is suitable, and shielding should be applied as appropriate. Management of these system characteristics can help reduce light trespass.

Light trespass does have various considerations depending on the roadway surroundings. For urban streets, the height of poles should be managed to reduce light trespass into upper floors. For urban freeways and expressways, the issue of light trespass arises when providing lighting in areas adjacent to residential properties. Multi-story buildings, freeway ramps, and frontage roads can be close to right-of-way boundaries, and high-mast lighting can be challenging to constrain. Lighting with lower mounting heights and appropriate shielding can help reduce light trespass.

For rural roads, the issue of light trespass arises when providing lighting in areas that have otherwise limited exterior illumination. In rural areas that are intrinsically dark, even limited lighting can be obtrusive and disturb adaptation, and it may be visible for a significant distance. Reducing lighting and using shielding can constrain light trespass.

For roundabouts, walkways and bikeways, and at-grade railway crossings, the issue of light trespass may arise when providing lighting in areas that have otherwise limited exterior illumination. Lighting of vertical surfaces can be challenging with lower mounting heights without increasing trespass. Pole location recommendations for roundabouts illustrate preferred layouts. For at-grade railway crossings, this is particularly true for isolated crossings that may be near residential areas.

For all situations, local topography can be a factor in light trespass. Lighting installed upslope from observers will generally be more conspicuous than lighting installed below observers.

Chapter 4 of IES RP-8-21 and Chapter 11 of AASHTO GL-7 include recommendations for minimizing light trespass by using lighting zones to classify areas based on their level of ambient lighting (none, low, moderate, or high, LZ0–LZ4). Based on the classification, light trespass limits ranging from 0.5 to 15 lux are established for the lighting design. AASHTO uses a vertical plane located at the property line as the analysis area for light trespass. ANSI/IES RP-8-21 uses the same light trespass values and analysis method and includes additional information about the classification method used to determine the lighting zones.

While light trespass usually addresses the impact of lighting onto areas adjacent to the project being designed, the reverse may also occur, and lighting from adjacent areas may impact the proposed project. In general, lighting design does not account for any contributions or effects from specific lighting installations outside of the project because that illumination is unpredictable and unreliable. While accommodation to high levels of ambient illumination is appropriate, lighting design that relies on lighting from outside the project is not.

1.2.2 Emerging Research

Research is currently being conducted on the impacts of roadway light trespass on human health along with flora and fauna. Soybeans, for example, are limited in yield and bean production when the light level in the field exceeds 2.4 lux. There is also a push to use lower CCTs where areas adjacent to the roadway have a high potential for light trespass; this is an ongoing topic of research.

Adaptive lighting can mitigate light trespass by reducing illumination levels at appropriate times.

SAFETY HIGHLIGHTS

Safety is an important design consideration. In most cases, however, light trespass beyond the area included for the surround ratio can be controlled easily by correctly selecting the pole height and fixture optics and eliminating luminaire tilt.

2 Urban Street Lighting Example

This example consists of an urban street with bike lanes, parking, crosswalks, interections, and sidewalks. For this example, the key elements are discussed along with the potential criteria that can be used. The example also includes possible adjustments to current criteria or approaches expected from emerging research. These sections address the different traveled paths found in a typical urban setting and their intersections, along with discussions about lighting issues that arise in urban environments.

Urban Street	
	Roadways
	Crosswalks
	Sidewalks
	Bike Lanes
	Intersections
	Adaptive Lighting

Credit: Google Maps. google.com/maps

2.1 The Roadway

Credit: Google Maps. google.com/maps

	Urban Street
	Roadways
	Crosswalks
	Sidewalks
	Bike Lanes
	Intersections
	Adaptive Lighting

2.1.1 Currently Available Design Recommendations

The design for the roadway portion of this example is meant to achieve visibility for the drivers as they travel the roadway, allowing them to see hazards, pedestrians, and cyclists. The criteria for the roadway include the following:

- Average luminance (or illuminance, which is an option in AASHTO GL-7) of the roadway
- Uniformity ratio for the roadway
- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 11-1 are for the travel lanes. For this example, the criteria do not include the median with pavers, the bike lane (which is addressed separately), parking area, or other areas outside the travel lanes. Light for pedestrians in the median at crosswalk locations is included as part of the crosswalk design and analysis.

This example road has the following characteristics:

Street or Roadway Classification:	Collector
Pedestrian Classification:	Medium
Land Use Classification:	Intermediate
Pavement Type:	R3 Asphalt

The selection of the street or roadway classification can vary with respect to lighting. The roadway classifications defined by FHWA[1] do not always align with the non-regulatory definitions found in IES RP-

[1] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

8-21 and ASSHTO GL-7. For example, land use (e.g., urban vs. rural) is not defined in the GL-7 or RP-8-21 lighting criteria selection tables; therefore, engineering judgment is required when selecting the street classification. Factors such as traffic volume, speed limit, and number of lanes can impact the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town. IES RP-8-21 uses pedestrian activity level, which is based on pedestrian volumes derived from judgment rather than sample counts. AASHTO uses land use classifications (commercial, intermediate, and residential) that are also somewhat subjective because the land use can vary on any given street and is subject to change over time.

2.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a design metric. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (National Academies of Sciences Engineering and Medicine, 2020). Surround ratio, which is the ratio of the lighting value on the area adjacent to the travel lane (3.6-m strip) to the lighting value for the roadway, should be at least 0.8. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

In this example, the specific situation with lighted sidewalks (and parked cars) means that the application of surround ratio is not appropriate. There is additional discussion about surround ratio in some of the other examples and in RP-8-21 section 10.5.2.3.

2.2 Crosswalks

Credit: Google Maps. google.com/maps

Urban Street	
	Roadways
	Crosswalks
	Sidewalks
	Bike Lanes
	Intersections
	Adaptive Lighting

2.2.1 Currently Available Design Recommendations

Lighting should be provided for both midblock and intersection crosswalks. The addition of lighting in crosswalks increases the visibility of pedestrians using the crosswalk, allowing motorists to safely stop for the pedestrian.

This example of crosswalks for an urban street has the following characteristics:

Street or Roadway Classification:	Collector
Cross-street Classification:	Local
Pedestrian Classification:	Medium
Land Use Classification:	Intermediate
Pavement Type:	R3 Asphalt
Crosswalk Location:	Intersection

AASHTO GL-7 discusses crosswalk lighting at intersections and roundabouts, including the placement of lighting to optimize pedestrian detection. Other lighting guides suggest that the vertical lighting level in the crosswalk should be equal to the horizontal lighting level recommended for the intersection or roundabout. IES RP-8-21 includes recommendations for crosswalk lighting at intersections, roundabouts, and midblock crosswalks.

For intersections, both AASHTO GL-7 and IES RP-8-21 recommend that the average vertical lighting value in the crosswalk be equal to the average horizontal illuminance in the intersection. Similarly, for the lighting of crosswalks at roundabouts, the average vertical lighting level should also be equal to the average horizontal lighting level in the roundabout. The one difference in this case is that the vertical lighting level is in the direction of the approaching vehicle as opposed to perpendicular to the centerline of the crosswalk. For the lighting of midblock crosswalks, IES RP-8-21 recommends an average of vertical illuminance of 20, 30, and 40 lux for areas with low, medium, and high levels of pedestrian conflict, respectively.

2.2.2 Emerging Research

The current recommendations for high lighting levels in crosswalks are being discussed by technical committees and investigated through ongoing research. The current investigations seem to show that vertical lighting levels (oriented toward the vehicle) equal to horizontal lighting levels on the roadway do perform well from a pedestrian detection perspective. On unlit roads, however, crosswalk lighting does have safety benefits, and current recommendations may be higher than necessary. Lighting levels of 10 lux on medium to high pedestrian areas and 8 lux for isolated intersections and low pedestrian areas appear to provide adequate lighting for visibility.

SAFETY HIGHLIGHTS

Lighting crosswalks is a critical safety issue in areas with moderate to high pedestrian volumes.

Average vertical illuminance values of at least 10 lux should be maintained in the crosswalk in the direction of the approaching driver.

2.3 Sidewalks

Credit: Google Maps. google.com/maps

Urban Street
Roadways
Crosswalks
Sidewalks
Bike Lanes
Intersections
Adaptive Lighting

2.3.1 Currently Available Design Recommendations

Sidewalk (walkway) lighting within the right-of-way serves two purposes: (1) providing pedestrians with sufficient light on the sidewalk to avoid trip hazards, allow facial recognition, and impart a sense of security; and (2) assisting drivers in detecting pedestrians approaching the roadway.

This example of sidewalks for an urban street has the following characteristics:

Street or Roadway Classification:	Collector
Pedestrian Classification:	Medium
Land Use Classification:	Intermediate
Pavement Type:	Concrete (assumed 30% reflective)

AASHTO GL-7 recommends maintaining horizontal illuminance levels for sidewalk areas at 3 to 14 lux depending on the sidewalk material and whether it is in a commercial, intermediate, or residential land use type. AASHTO GL-7 also provides uniformity criteria for sidewalks. IES RP-8-21 recommends sidewalk lighting levels based on pedestrian volumes. Lighting levels are given in terms of average horizontal illuminance, average vertical illuminance, and uniformity across the pavement. Average horizontal levels can range from 2 to10 lux and up to 20 lux for rare roadway conditions where pedestrians and vehicles use the roadway as a common space without curbed sidewalk areas.

In general, the roadway lighting system provides lighting for the sidewalk area. There are, however, design issues when considering these systems. Pedestrian-scale lighting is often used to better define the sidewalk area and relate better in scale and feel to the pedestrians using the area. Pedestrian-scale lighting is often an attractive aesthetic for lighting in areas pedestrians frequent. There are, however, issues that can arise when trying to use pedestrian-scale lighting for lighting a street. The lumen output often generally needs to be significantly increased to light the roadway, which increases the amount of disability glare produced by the lighting system. It is also difficult to achieve high lighting levels in areas such as intersections and crosswalks. In areas where sidewalks use pedestrian-scale lighting, it is often recommended that a mix of higher roadway lighting poles be used in combination with lower pedestrian-scale poles to achieve the desired result.

2.3.2 Emerging Research

The recommended sidewalk lighting levels are currently undergoing review. In addition, semi-cylindrical illuminance is being investigated as a predictive metric to replace vertical illuminance because it may represent a complex form like a person better than a single vertical plane.

SAFETY HIGHLIGHTS

Proper sidewalk lighting is focused on pedestrians both seeing and being seen, so lighting levels on the pedestrian are critical.

Limits on light trespass need to be carefully balanced with needs for sidewalk lighting.

2.4 Bike Lanes

Credit: Google Maps. google.com/maps

	Urban Street
	Roadways
	Crosswalks
	Sidewalks
	Bike Lanes
	Intersections
	Adaptive Lighting

2.4.1 Currently Available Design Recommendations

Given the high risk cyclists face, lighting bike lanes should receive high priority, specifically where motor vehicles and pedestrians/cyclists conflict. This is discussed further in Section 3.6 of Part I. Lighting benefits cyclists by making them more visible to drivers and allowing the cyclists to see hazards in the roadway.

This example of bike lanes for an urban street has the following characteristics:

Street or Roadway Classification:	Collector
Pedestrian Classification:	Medium

Land Use Classification:	Intermediate
Pavement Type:	R3 Asphalt
Bile Lane Location:	Adjacent to roadway

In terms of lighting, AASHTO G-7 defines the bike lane as part of the roadway. Therefore, the roadway lighting criteria would extend onto the bike lane. The criteria in IES RP-8-21 are based solely on where the bikeway is located. When the bikeway is not adjacent to the roadway, the lighting levels should match those for walkways. When the bikeway is adjacent to the roadway, it should be lighted based on the roadway illuminance, with 80% of the lighting provided for the street applied to the bike lane. This can be evaluated by simply defining the bike lane width and calculating the horizontal illuminance within the marked bike lane. The calculation grid spacing within the bike lane should be the same longitudinal spacing used for a street with lateral spacing of two rows to suit the lane width. Since bike lanes typically terminate at intersections, the intersection lighting requirements should be applied.

2.4.2 Emerging Research

Although many studies have defined the value of lighting bike lanes, more information and research are needed to inform lighting requirements beyond what is noted above.

SAFETY HIGHLIGHTS

Cyclists are vulnerable road users who face a very high risk.

Lighting bike lanes improves visibility and thus enhances safety.

2.5 Intersections

Credit: Google Maps. google.com/maps

Urban Street
Roadways
Crosswalks
Sidewalks
Bike Lanes
Intersections
Adaptive Lighting

2.5.1 Currently Available Design Recommendations

Intersections create a complex environment for navigation and pose challenges for lighting. Intersections include multiple conflict points for vehicles as well as pedestrians and cyclists. During some left- and right-hand movements of vehicles in intersections, vehicle headlamps are ineffective, and driver attention is divided into multiple tasks. The complexity of the environment makes it difficult to define key tasks and lighting criteria to improve safety and visibility.

For this urban street example, the intersection has the following characteristics:

Street or Roadway Classification:	Collector
Cross-street Classification:	Local
Pedestrian Classification:	Medium
Land Use Classification:	Intermediate
Pavement Type:	R3 Asphalt

AASHTO GL-7 states that “intersections with high pedestrian volumes, curbs, or divisional islands may require somewhat higher light levels.” It also states: “Intersections of two continuously lit streets are typically lit to a value equal to the sum of the individual lighting level values.” IES RP-8-21 classifies intersections based on the categories of the intersecting streets along with the pedestrian volume (low, medium, or high). Intersection lighting levels range from 8 to 34 lux depending on the characteristics of the streets and pedestrian volumes. These lighting levels were first developed by summing the design illuminance values for the intersecting streets, as recommended by AASHTO.

SAFETY HIGHLIGHTS

An important focus for intersection lighting is pedestrians and cyclists, who are at the greatest risk during vehicle movements in intersections.

Meeting vertical lighting level requirements in the crosswalks will aid in pedestrian detection.

2.5.2 Emerging Research

Historically, lighting values for intersections have been developed from consensus rather than research into safety or visibility. As more research on this topic becomes available, the approach to lighting intersections is changing. For example, vehicle-to-vehicle conflict points are becoming less prioritized, while vehicle-to-pedestrian conflict points in crosswalks are becoming more important (refer to Section 11.2 on Crosswalks). Lighting levels and where the lighting should be applied are also being fine-tuned. One critical aspect of intersection lighting is the lighting of crosswalks, particularly those located at the left- or right-turn directions where both pedestrians in the crosswalk and the left-turning vehicles have signals that allow for potential conflict (both are permissible signals).

2.6 Adaptive Lighting

Credit: Google Maps. google.com/maps

	Urban Street
	Roadways
	Crosswalks
	Sidewalks
	Bike Lanes
	Intersections
	Adaptive Lighting

2.6.1 Currently Available Design Recommendations

Driven by the development of new lighting technologies and a nationwide push to reduce energy use and environmental impacts, adaptive lighting is gaining popularity. In adaptive lighting, the light output of a system is adjusted as traffic conditions change. More specifically, the level of lighting can be reduced or dimmed as follows:

- Reduce initial light output to maintained levels. Light output from a light source depreciates over time; therefore, roads are typically over-lit when the lighting is first installed. To maintain the minimum required lighting levels on the roads and sidewalks, lighting designs are based on the end-of-lamp life. Accordingly, the design incorporates a maintenance factor that accounts for this depreciation. Applying adaptive lighting technology can control the light output over time so the luminaires operate at a maintained level for the entire maintenance cycle, thereby reducing power input and saving energy.
- Match light output to pedestrian activity levels. The amount of light required for a roadway or sidewalk is based on two key criteria: the classification of the roadway itself and the level of pedestrian activity. The classification of the roadway is based on the road designation, which is fixed. Pedestrian activity levels do not remain constant throughout the day; in most instances, the number of pedestrians present in each area will be dramatically lower in the late-night and early-morning hours, thus requiring lower light levels.

2.6.2 Emerging Research

The FHWA report *Design Criteria for Adaptive Roadway Lighting* (Gibbons, Guo, Medina, Terry, Du, Lutkevich, & Li, 2014) includes an in-depth assessment of the effect of adaptive lighting on the overall safety performance of roadways. The report defines optimal times, conditions, and suitable approaches for reducing lighting; appropriate lighting levels for various roads and features; energy savings and reductions in greenhouse gases resulting from adaptive lighting; and potential legal issues. The resulting design methodology can be used by transportation agencies to determine whether adaptive lighting is appropriate for a given roadway. The methodology includes a set of criteria to help jurisdictions make sound, safety-based decisions when considering adaptive lighting approaches. In addition, the evaluation of real-world lighting data in this report provides a foundation for future analyses related to roadway lighting.

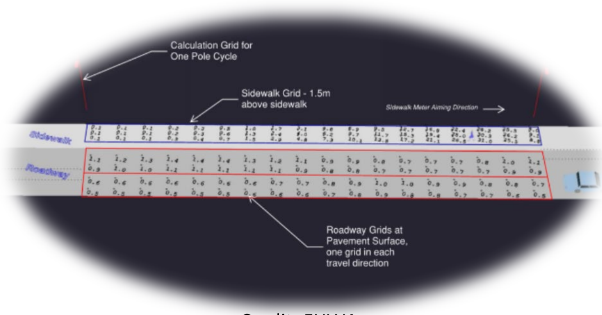
Notably, adaptive lighting requires a control system and "controls-ready" luminaires. Thus, to allow for future implementation of adaptive lighting, luminaire selection should consider controls-ready luminaires, even if adaptive lighting is not planned at the time of installation.

In RP-8-21, Annex K *Alternative Lighting Criteria Selection Methodology* includes a discussion and suggested process for establishing adaptive lighting levels.

SAFETY HIGHLIGHTS

The use of an adaptive lighting system should be considered in all aspects of exterior lighting.

2.7 Criteria Values Applicable to this Example



Credit: FHWA

The characteristics of this roadway are as follows:

Street Classification:	Collector
Cross-street Classification:	Local
Pedestrian Classification:	Medium
Land Use Classification:	Intermediate
Pavement Type:	R3 Asphalt
Sidewalk Material:	Concrete (assumed 30% reflective)
Crosswalk Location:	Intersection
Bike Lane Location:	Adjacent to roadway

The criteria for the lighting design could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 11-1)

Average Luminance:	>= 0.6 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.4

Intersection Lighting Level (RP-8-21, Table 12-1)

Average Illuminance:	>= 16 lux
Average/minimum Uniformity Ratio:	<= 4.0

Crosswalk Lighting Level (RP-8-21, Table 12-1)

Average Illuminance:	>= 16 lux
Average Vertical Illuminance:	>= 16 lux

Sidewalk Lighting Level (RP-8-21, Table 11-2)

Average Illuminance:	>= 5 lux
Average/minimum Uniformity Ratio:	<= 5.0
Average Vertical Illuminance:	>= 2 lux

Bike Lane Lighting Level (RP-8-21)

Average Illuminance:	>= 80% of roadway illuminance provided

AASHTO GL-7

Roadway Lighting Level (Table 3-5b)

Average Luminance:	>= 0.6 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.4

Intersection Lighting Level (Section 3.4.4 and Table 3-5b)

Average Illuminance:	>= 16 lux

Crosswalk Lighting Level (Section 3.5.6 and Table 3-5b)

Average Illuminance:	>= 16 lux

Sidewalk Lighting Level (Table 3-5b)

Average Illuminance:	>= 6 lux
Average/minimum Uniformity Ratio:	<= 4.0

Bicycle Way Lighting Level (Table 3-5b)

Average Illuminance:	>= roadway lighting level
Average/minimum Uniformity Ratio:	<= 3.0

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The light loss factors (LLFs) are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

3 Rural Road Lighting Example

	Rural Road
	Roadways
	Surround Ratio
	Partial Beacon

Most rural roadways are unlikely to have continuous lighting systems. More commonly, rural roads will be unlit or mostly unlit with partial or beacon lighting at higher-volume intersections. There are times, however, when the road usage and pedestrian volume may warrant continuous lighting. An example of such a case is a rural road with frequent pedestrian or cyclist use due to the presence of recreational areas or trailheads.

The example discussed in this section is for a road with parking and hiking trail access, resulting in substantial pedestrian volumes and frequent use by cyclists. This example includes the following key elements:

- The Roadway
- Surround Ratio
- Partial or Beacon Lighting

Discussions about these elements cover the basics for lighting on rural roads, with additional sections addressing light trespass and color, which may be especially important in sensitive rural areas.

For the lighting of rural roads, mounting lights to wood utility poles is the most common solution, and the pole locations and spacing between poles are often not ideal for lighting placement. However, given the variety of distributions that can be obtained from solid-state lighting components, design values can be met with proper equipment selection.

Credit: Google Maps. google.com/maps

3.1 The Roadway

Credit: Google Maps. google.com/maps

	Rural Road
	Roadway
	Surround Ratio
	Partial Beacon

3.1.1 Currently Available Design Recommendations

The lighting design for the roadway in this example is meant to provide visibility for drivers to guide them as they travel along the roadway and allow them to identify hazards, pedestrians, and cyclists. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 11-1 provide recommendations for the lighting of roadways. The criteria for roadways include:

- Average luminance (or Illuminance in AASHTO GL-7) for the roadway
- Uniformity ratios of the roadway
- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in these documents are for the travel lanes and the adjoining areas. This example road is one lane each way with the following characteristics:

Street or Roadway Classification:	Local
Pedestrian Classification:	Low (although expected volumes should be used)
Land Use Classification:	Residential (Rural is not a term used in the AASHTO area classification)
Pavement Type:	R3 Asphalt

SAFETY HIGHLIGHTS

The limit on disability glare is one of the most critical design elements.

The addition of surround ratio (SR) or sidewalk lighting is helpful to increase detection distance.

The presence of pedestrians and cyclists along the roadway edge increases the safety risk. This is the most critical consideration when determining design requirements.

3.2 Surround Ratio

Credit: Google Maps. google.com/maps

Rural Road
Roadways
Surround Ratio
Partial Beacon

3.2.1 Currently Available Design Recommendations

Recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (also referred to as edge illuminance ratio by CIE, although with a somewhat different definition) as a design metric. Research has shown that the addition of lighting in areas adjacent to the travel lane of the roadway increases the driver's detection distance of objects and people both on the roadway and adjacent to the roadway. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (National Academies of Sciences Engineering and Medicine, 2020). Surround ratio is considered in both AASHTO GL-7 and ANSI/IES RP-8-21. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

The surround ratio (SR) is defined in RP-8-21 as the ratio of the average illuminance value on the area adjacent to the travel lane (3.6-m strip) to the average value for the edge lane of the roadway. The criterion for surround ratio in AASHTO GL-7 and ANSI/IES RP-8-21 is 0.8 minimum.

This value is higher than that used by CIE. For example, an average illumination on the outermost lane of the roadway of 0.4 fc would result in a minimum lighting level on the surround of 0.4 fc × 0.8 = 0.32 fc.

Surround ratio might not be appropriate in some situations, such as: where there is no area adjacent to the roadway, as on some bridges; where sidewalks are lighted; environmentally sensitive areas; and where additional poles might be required to meet the 0.8 minimum, thereby increasing the risk of collisions. More discussions about surround ratio are in Section 1.3.6 of Part I and in RP-8-21 Section 10.5.2.3.

3.3 Partial or Beacon Lighting

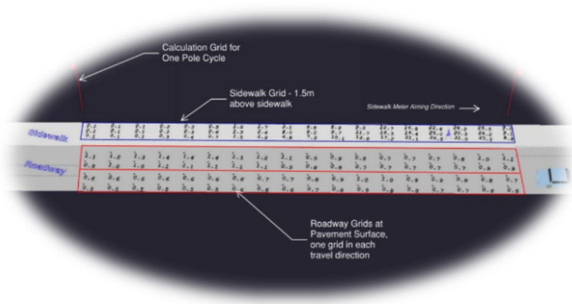
Credit: Google Maps. google.com/maps

Rural Road	
	Roadways
	Surround Ratio
	Partial Beacon

As mentioned, in most rural road applications, continuous lighting may not be warranted. In those cases, partial or beacon intersection lighting is used primarily to alert the approaching driver to an upcoming intersection. Partial lighting lights the entire intersection area to make pedestrians or cyclists crossing the street more visible. Beacon lighting is more of an identifier than a visibility enhancement.

AASHTO GL-7 describes this type of lighting and includes installation diagrams with pole locations but does not specify light levels. IES RP-8-21, Table 12-2 includes light levels for partial intersection lighting based on the road classification of the roadway with the most traffic volume.

3.4 Criteria Values Applicable to this Example



Credit: FHWA

The classifications for the elements of this roadway would be:

Street or Roadway Classification:	Local
Pedestrian Classification:	Low (although expected volumes should be used)
Land Use Classification:	Residential (Rural is not a term used in the AASHTO area classification)
Pavement Type:	R3 Asphalt

The criteria for the design of this installation could use either AASHTO GL-7 or IES RP-8-21. In general, the recommendations of AASHTO and IES are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from AASHTO GL-7 or IES RP-8-21 for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 11-1)	
Average Luminance:	>= 0.3 cd/m^2
Average/minimum Uniformity Ratio:	<= 6.0
Maximum/minimum Uniformity Ratio:	<= 10.0
Veiling Luminance Ratio:	<= 0.4

Surround Ratio Lighting (Section 10.5.2.3)	
Average Illuminance:	>= 80% of illuminance provided on roadway

Partial Intersection Lighting (RP-8-21, Table 12.2)	
Average Illuminance:	>= 4 lux
Average/minimum Uniformity Ratio:	<= 6.0

AASHTO GL-7

Roadway Lighting Level (Table 3-5b)	
Average Luminance:	>= 0.3 cd/m^2
Average/minimum Uniformity Ratio:	<= 6.0
Maximum/minimum Uniformity Ratio:	<= 10.0
Veiling Luminance Ratio:	<= 0.4
Surround Illuminance:	>= 3.4 lux

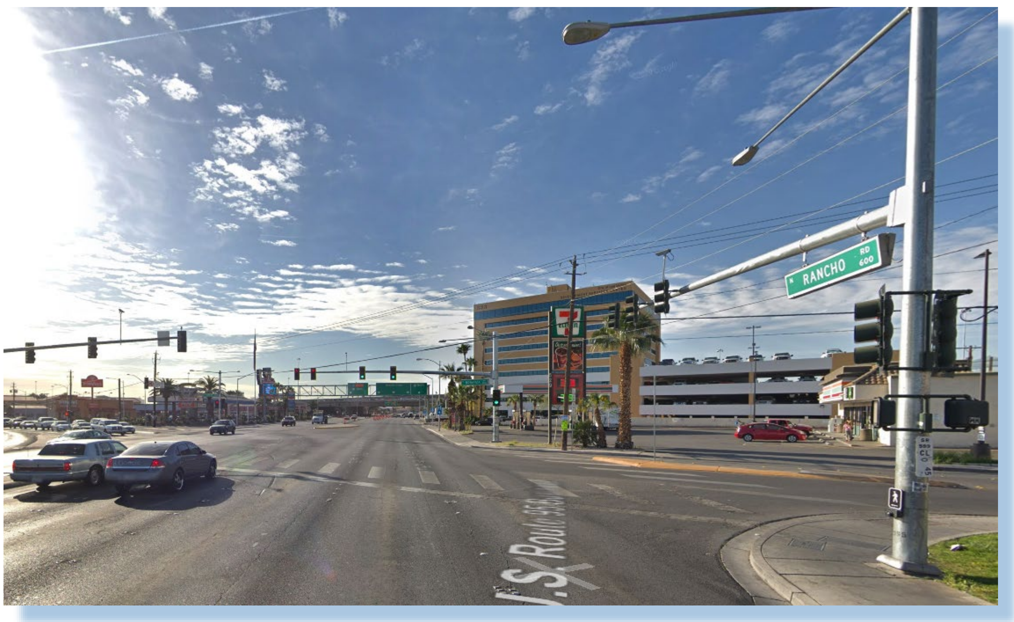
The surround ratio value is included in this example assuming that speeds are over 30 mph, so headlights are likely not sufficient, and would only apply in areas with continuous lighting. The value shown assumes that the travel lane has illuminance matching the design criterion and is a minimum average value for the surround area. If the average illuminance on the roadway were designed to be higher than the criterion, the average illuminance value of the surround area would need to increase proportionally to meet the SR criterion.

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

4 Expressway Lighting Example

Expressways are highways that have divided traffic like freeways, but where access is only partially controlled and includes at-grade intersections. This example includes roadway elements associated with expressways in urban areas, illustrating the complexity of the situation for drivers. Suitable nighttime illumination helps drivers navigate safely through these challenging environments.

Expressway	
	Roadways
	Crosswalks
	Sidewalks
	Driveways
	Work Zones



Credit: Google Maps. google.com/maps

This example discusses the following key elements of expressways:

- The Roadway
- Crosswalks
- Sidewalks
- Driveways
- Work Zones

These elements are typical components of expressways, with regularly feature complex traffic patterns and unexpected features and hazards. Expressways have “a lot going on,” and they also may include construction projects with work zones, too.

4.1 The Roadway

Credit: Google Maps. google.com/maps

Expressway	
	Roadway
	Crosswalks
	Sidewalks
	Driveways
	Work Zones

4.1.1 Currently Available Design Recommendations

The roadway lighting in this example is designed to promote visibility for drivers as they travel the roadway. Visual tasks for the driver in these areas include navigating the vehicle while simultaneously recognizing features and hazards such as medians, lane markings, signs, construction zones, and other vehicles. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 10-1 provide recommendations for the lighting of roadways. The criteria for the roadway include:

- Average luminance (or illuminance in AASHTO GL-7) for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in AASHTO GL-7 and ANSI/IES RP-8-21 apply to the travel lanes. In this example, the roadway does not include medians, islands, or any other areas outside of the travel lanes.

For this expressway example, the roadway has the following characteristics:

Street or Roadway Classification:	Major (IES) or Principal Arterial (AASHTO)
Pedestrian Classification:	Medium
Land Use Classification:	Commercial
Pavement Type:	R3 Asphalt

The selection of the street or roadway classification varies with respect to lighting. The roadway classifications defined by FHWA[2] do not always align with those defined in IES RP-8-21 and AASHTO GL-7. Land use (e.g., urban vs. rural) is not defined in the AASHTO GL-7 and IES RP-8-21 lighting criteria selection tables. Thus, engineering judgment is required when selecting the street classification. Factors such as traffic volume, speed limit, and number of lanes can affect the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town.

[2] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

IES RP-8-21 uses a pedestrian classification based on pedestrian volumes determined by judgment rather than sample counts. AASHTO uses land use classifications (commercial, intermediate, and residential) that are somewhat subjective because the land uses can vary on any given street and are subject to change over time.

4.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a design metric, as discussed in Section 1.3.6 in Part I. Since this example includes lighted sidewalks, surround ratio does not apply here. (Engineering & Medicine, 2020)

SAFETY HIGHLIGHTS

The limit on disability glare is one of the most critical design elements.

The addition of surround ratio (SR) or sidewalk lighting is helpful to increase detection distance.

The presence of pedestrians and cyclists along the roadway edge increases the safety risk. This is the most critical consideration when determining design requirements.

The limit on disability glare is one of the most critical design elements.

4.2 Crosswalks

Credit: Google Maps. google.com/maps

	Expressway
	Roadways
	Crosswalks
	Sidewalks
	Driveways
	Work Zones

4.2.1 Currently Available Design Recommendations

Lighting should be provided for both midblock and intersection crosswalks. The addition of lighting in crosswalks improves the visibility of pedestrians using the crosswalk, allowing motorists to safely stop for pedestrians.

For this expressway example, the intersection has the following characteristics:

Street or Roadway Classification:	Major (IES) or Principal Arterial (AASHTO)
Cross-street Classification:	Collector
Pedestrian Classification:	Medium
Land Use Classification:	Commercial
Pavement Type:	R3 Asphalt
Crosswalk Location:	Intersection

AASHTO GL-7 discusses crosswalk lighting at intersections and roundabouts, including the placement of lighting to optimize pedestrian detection. Other lighting guides suggest that the vertical lighting level in the crosswalk should be equal to the horizontal lighting level recommended for the intersection or roundabout. IES RP-8-21 includes recommendations for crosswalk lighting at intersections, roundabouts, and midblock crosswalks.

For the lighting of intersections, both AASHTO GL-7 and IES RP-8-21 recommend that the average vertical lighting value in the crosswalk be equal to the average horizontal illuminance in the intersection. Similarly, for the lighting of crosswalks at roundabouts, the average vertical lighting level should also be equal to the average horizontal lighting level in the roundabout. The one difference in this case is that the vertical lighting level is in the direction of the approaching vehicle as opposed to perpendicular to the centerline of the crosswalk. For the lighting of midblock crosswalks, ANSI/IES RP-8-21 recommends average vertical illuminance levels of 20, 30, and 40 lux for areas with low, medium, and high levels of pedestrian conflict, respectively.

4.2.2 Emerging Research

The current recommendations for high lighting levels in crosswalks are being discussed by technical committees dealing with the topic and investigated through ongoing research. The current findings suggest that vertical lighting levels (oriented toward the vehicle) equal to horizontal lighting levels on the roadway perform well from the perspective of pedestrian detection. However, crosswalk lighting also has safety benefits on unlit roads, and current recommendations may be higher than necessary. Lighting levels of 10 lux on areas with medium to high pedestrian volumes and 8 lux for isolated intersections with low pedestrian volumes appear to provide adequate lighting for visibility. Crosswalks in areas with medium to high pedestrian volumes along with high levels of activity and ambient illumination may warrant higher levels of illumination. For example, in areas near bus stops, public facilities, or corner-commercial locations with bright facility lighting, lighting levels of 20 lux may be appropriate for crosswalks.

SAFETY HIGHLIGHTS

Lighting crosswalks is a critical safety issue in areas with moderate to high pedestrian volumes.

Average vertical illuminance values of at least 10 lux should be used, with higher values in suitable locations. The vertical values in the crosswalk should always be in the direction of the approaching driver.

4.3 Sidewalks

Credit: Google Maps. google.com/maps

Expressway
Roadways
Crosswalks
Sidewalks
Driveways
Work Zones

4.3.1 Currently Available Design Recommendations

Sidewalk (walkway) lighting within the right-of-way serves two purposes: (1) providing pedestrians with sufficient light on the sidewalk to avoid trip hazards, allow facial recognition, and impart a sense of security; and (2) assisting the driver in detecting pedestrians approaching the roadway.

This example of sidewalks for an expressway has the following characteristics:

Street or Roadway Classification:	Major (IES) or Principal Arterial (AASHTO)
Pedestrian Classification:	Medium
Land Use Classification:	Commercial
Pavement Type:	Concrete (assumed 30% reflective)

AASHTO GL-7 recommends maintained horizontal illuminance levels for sidewalk areas from 3 to 14 lux depending on the sidewalk material and the land use type (commercial, intermediate, or residential). AASHTO GL-7 also provides uniformity criteria for sidewalks. IES RP-8-21 recommends sidewalk lighting levels based on pedestrian volumes; areas with low pedestrian volume are further categorized into medium-density, low-density, and rural locations. IES RP-8-21 provides lighting levels in terms of average horizontal illuminance, average vertical illuminance, and uniformity over the paved surface. The average horizontal lighting levels can range from 2 to 10 lux and up to 20 lux for rare roadway conditions where pedestrians and vehicles use the roadway as a common space without curbed sidewalk areas.

In general, the roadway lighting system provides the lighting for the sidewalk area. However, design considerations should be taken into account when developing these systems. Pedestrian-scale lighting is often used to better define the sidewalk area and relate better in scale and feel to the pedestrians using the area. It is often an attractive aesthetic for lighting these areas. However, issues can arise when trying to use pedestrian-scale lighting to light a street. The lumen output often must be significantly increased to light the roadway, which increases the amount of disability glare produced by the lighting system. It is also difficult to achieve high lighting levels in areas like intersections and crosswalks. In areas where sidewalks use pedestrian-scale lighting, a mixture of higher roadway lighting poles in coordination with lower pedestrian-scale poles is often recommended to achieve the desired result.

4.3.2 Emerging Research

Recommendations for sidewalk lighting levels are currently undergoing review. Semi-cylindrical illuminance is also being investigated as a metric to replace vertical illuminance because it models a complex form like a person better than a single vertical plane does.

SAFETY HIGHLIGHTS

Proper sidewalk lighting is focused on both the pedestrian's ability to see and the driver's ability to see pedestrians; thus, lighting levels on the pedestrian are critical.

Limits on light trespass should be carefully balanced with needs for sidewalk lighting.

4.4 Driveways

Credit: Google Maps. google.com/maps

	Expressway
	Roadways
	Crosswalks
	Sidewalks
	Driveways
	Work Zones

4.4.1 Currently Available Design Recommendations

Driveways connect the travel lanes with adjacent facilities and typically cross sidewalks within the right-of-way. Lighting for pedestrians should provide sufficient illumination for them to navigate the driveway and provide drivers with adequate light to detect pedestrians and cyclists proceeding along the sidewalk at the driveway.

Driveways also allow for vehicle access on and off the roadway, thereby increasing the potential for unexpected events. For example, drivers may encounter oncoming headlights from outside of the roadway as vehicles approach a driveway.

Some driveways may be highly developed, including divided roadways with medians, signage, landscaping, or crosswalks. When feasible, driveways should be coordinated with the lighting design.

4.4.2 Emerging Research

The density of driveways in a section of roadway can indicate the overall level of risk along that section. Consideration of driveway presence may be part of warranting or evaluations of roadways for adaptive lighting levels.

SAFETY HIGHLIGHTS

As driveways allow vehicles to enter and exit the roadway by crossing the sidewalk, lighting is focused on both pedestrians seeing and being seen, with lighting levels measured at the potential locations of pedestrians.

4.5 Work Zones

Credit: Google Maps. google.com/maps

	Expressway
	Roadways
	Crosswalks
	Sidewalks
	Driveways
	Work Zones

4.5.1 Currently Available Design Recommendations

Work zones are elements in streets and highways associated with construction, maintenance, or other work that impinges on the normal ability of pedestrians, cyclists, and/or vehicles to travel. Work zones are inherently temporary and are described as mobile or having short, intermediate, or long duration. Work zones may have active work areas along with associated activities and lighting at night; alternatively, they may only have temporary traffic control equipment. All work zones should have lighting that is, at a minimum, consistent with the illumination of the adjacent roadway, sidewalks, etc. In some situations, additional illumination is appropriate, such as in areas with abrupt shifts in lanes, surface unevenness, high pedestrian activity, or high traffic volume. When operations in the work area occur at night, the associated illumination from equipment and task lighting may generate requirements for additional lighting in the work zone and perhaps beyond.

AASHTO GL-7 recommends that the maintained horizontal illuminance levels for work zones meet or exceed the criteria shown in Table 3-5 in that document and discussed above. Considering practical constraints around work zones and construction, these criteria may be reasonably relaxed.

In recognition of the increase in nighttime construction activity, *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work* provides information on lighting for workers and inspectors in work zones as well as lighting for roadways in the work zone. Particular attention is given to providing temporary lighting in work zones and considering the potential for increased glare experienced by motorists, which may necessitate accommodation using temporary roadway lighting. In IES RP-8-21, glare from work zone lighting is discussed with recommendations for mitigating glare through luminaire aiming and shielding and increased illumination levels on the roadway. The effect of transient adaptation, which can prolong the visibility reductions due to glare, is also discussed, including the greater impact on drivers with older eyes or impaired vision. In work zones where illumination is significantly higher compared to adjacent areas of the roadway or sidewalk, transition lighting may be appropriate on the approach and departure to reduce the effect of transient adaptation.

Table 19-1 in IES RP-8-21 provides information for the lighting of long-duration work zones (those in place for more than three days). This table indicates which work zone roadways and activities should have illumination for rural highways, urban streets, and urban highways. The table indicates that the work zone should meet the lighting criteria for the roadway, either by maintaining existing lighting or providing temporary lighting. IES RP-8-21 also discusses the illumination of flagger stations from above and in front so that flaggers are in positive contrast against their background.

4.5.2 Emerging Research

Lighting for work zones has been the subject of much discussion in recent years, and new products have expanded options. For example, luminous equipment has been developed for flaggers. Luminous paddles, signs, and attire can increase the visibility of flaggers to motorists. Additional approaches outside of typical illumination are being considered, and recent work has stressed glare control and proposed corresponding metrics.

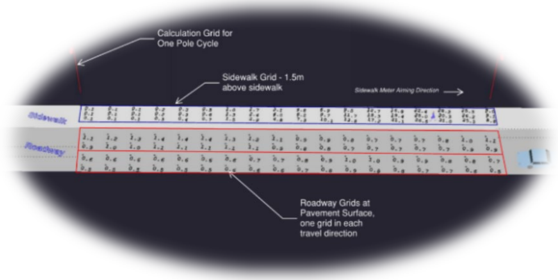
SAFETY HIGHLIGHTS

Lighting for work zones should meet or exceed lighting levels for adjacent areas and be provided by existing equipment and temporary lighting when necessary.

For work areas with nighttime operations; pedestrians, cyclists, and drivers may face additional challenges with visibility while navigating atypical conditions.

Limits on glare from work area lighting should be consistently applied, and when glare is excessive, roadway lighting should be supplemented.

4.6 Criteria Values Applicable to this Example



Credit: FHWA

The classifications for the elements of this roadway would be:

Roadway Classification:	Major (IES) or Principal Arterial (AASHTO)
Cross-street Classification:	Collector
Pedestrian Classification:	Medium
Land Use Classification:	Commercial
Pavement Type:	R3 Asphalt
Sidewalk Material:	Concrete (assumed 30% reflective)
Crosswalk Location:	Intersection

The criteria for the design of the installation could be based on AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 10-1)

Average Luminance:	>= 1.0 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.0
Maximum/minimum Uniformity Ratio:	<= 5.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 80% of roadway illuminance provided

Intersection Lighting (RP-8-21, Table 12-1)

Average Illuminance (Major / Collector):	>= 22 lux
Average/minimum Uniformity Ratio:	<= 3.0

Crosswalk Lighting Level (RP-8-21, Table 12-1)

Average Illuminance:	>= 22 lux

Average Vertical Illuminance:	>= 22 lux

Sidewalk Lighting Level (RP-8-21, Table 11-2)

Average Illuminance:	>= 5.0 lux
Average/minimum Uniformity Ratio:	<= 5.0
Average Vertical Illuminance:	>= 2.0 lux

AASHTO GL-7

Roadway Lighting Level (Table 3-5b)

Average Luminance:	>= 1.2 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.0
Maximum/minimum Uniformity Ratio:	<= 5.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 14 lux

Intersection Lighting Level (Section 3.4.4 and Table 3-5b)

Average Illuminance:	>= 29 lux

Crosswalk Lighting Level (Section 3.5.6 and Table 3-5b)

Average Illuminance:	>= 29 lux

Sidewalk Lighting Level (Table 3-5b)

Average Illuminance:	>= 10 lux
Average/minimum Uniformity Ratio:	<= 3.0

The surround ratio criterion is 0.8, for the average illuminance value of the road-adjacent surround area divided by the value for the outside lane. If the average for the outside lane were the design criterion for the roadway in this example, the minimum value for the average illuminance over the surround area would be 1.3 footcandles. Where an expressway has a sufficiently wide median and continuous lighting, there are separate surround areas on each side of each direction of travel.

Lighting criteria for work zones are not specified by AASHTO or IES based on roadway type; instead, the recommendation is often to maintain the existing or intended lighting levels. Some situations may deserve greater illumination due to sudden changes. For more information, see section 4.3.1.4 in Part 1 and *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work.*

The values given above are considered maintained values; that is, they represent the level recommended on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in IES RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

5 Urban Freeway Lighting Example

Freeways are highways that have divided traffic with controlled access. The freeway surroundings can vary tremendouly and thus influence the lighting design. This example includes the key roadway elements involved in lighting freeways in urban areas. Suitable nighttime illumination helps drivers navigate safely through these challenging environments.

	Freeway, Urban
	Roadways
	Interchanges
	Surround Ratio

This example discusses three key elements of urban freeways:

- The Roadway
- Interchanges
- Surround Ratio

The universal issues of light trespass and color of light are also design considerations, due to the importance of these aspects in suitable lighting design for the complex visual environments like urban freeways.

5.1 The Roadway

Credit: Google Maps. google.com/maps

	Freeway, Urban
	Roadway
	Interchanges
	Surround Ratio

5.1.1 Currently Available Design Recommendations

The design of the roadway in this example is intended to provide visibility for drivers as they travel the roadway. Visual tasks for the driver include vehicle guidance and location as well as recognizing features and hazards such as medians, lane markings, signs, construction zones, and other vehicles. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 10-1 provide recommendations for the lighting of roadways. The criteria for the roadway include:

- Average luminance (or Illuminance in AASHTO GL-7) for the roadway
- Uniformity ratios for the roadway

- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in AASHTO GL-7 and ANSI/IES RP-8-21 apply to the travel lanes. This example does not consider the lighting of medians, islands, or any other areas outside of the travel lanes.

This example road has the following characteristics:

Street or Roadway Classification:	Freeway A
Pavement Type:	R3 Asphalt

The selection of the street or roadway classification does vary with respect to lighting. The roadway classifications defined by FHWA[3] do not always align with those defined in IES RP-8-21 and AASHTO GL-7. Land use (e.g., urban or rural) is not defined in the lighting criteria selection tables in AASHTO GL-7 or ANSI/IES RP-8-21. Thus, engineering judgment is required when selecting the street classification.

Factors such as traffic volume, speed limit, and number of lanes can affect the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town. IES RP-8-21 uses a pedestrian classification based on pedestrian volumes determined by judgment rather than sample counts. The land use classifications used in AASHTO GL-7 (commercial, intermediate, and residential) are also somewhat subjective because areas can vary on any given street and are subject to change over time.

5.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a design metric as discussed below (Engineering & Medicine, 2020).

5.2 Interchanges

Credit: Google Maps. google.com/maps

Freeway, Urban	
	Roadways
	Interchanges
	Surround Ratio

[3] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

5.2.1 Currently Available Design Recommendations

Interchanges provide connections between freeways and local roads through exits from and entrances to the freeway linking ramps and intersections. These sections where roadways connect include conflict areas that deserve special design consideration. AASHTO GL-7 and ANSI/IES RP-8-21 provide recommendations for lighting interchanges. AASHTO GL-7, Section 3.2 includes warranting conditions for freeways that assist in establishing the lighting strategy for specific interchanges.

Some situations may have no lighting requirements. Where lighting is applied, there are generally three different approaches: continuous freeway lighting, complete interchange lighting, and partial interchange lighting. As indicated in the names, these three approaches provide lighting on different portions of the freeway and associated interchanges:

- Continuous freeway lighting (CFL) applies lighting to the entire freeway from the interchange to the intersection at the ramp terminal.
- Complete interchange lighting (CIL) applies lighting to the complete ramp and the terminal intersection but not the freeway outside the interchange.
- Partial interchange lighting (PIL) applies lighting to the ramp conflict areas at the diverge or merge areas and perhaps terminal intersections but not the ramps themselves or the freeway beyond the merge or diverge areas.

The criteria for the warranting conditions in AASHTO GL-7 differ for the three levels of lighting and include the following:

- AADT (Annual Average Daily Traffic) of the freeway and surround conditions: urban / suburban / rural
- AADT of the ramp traffic and surround conditions: urban / suburban / rural
- AADT of the cross road and surround conditions: urban / suburban / rural
- Lighting extends along the cross roadway or in adjacent commercial or industrial areas
- Ratio of nighttime to daytime crash rates sufficiently exceeds the Statewide average for unlighted similar sections along with a supporting study

This example road has the following characteristics:

Surrounding conditions:	Urban
ADT of the freeway:	Over 50,000
Surrounding lighting:	Urban commercial-industrial
Interchange separation:	Under 1.5 miles

After the extent of the lighting is established, typical equipment layouts can be applied and suitable transitions considered. For lighting entire interchanges, low-mast and high-mast lighting may be merged. For ramps, poles should be on the insides of curves. For PIL, “four in the gore” (meaning four luminaires located around the exit gore point) is a typical pattern at ramp exits and entrances to cover the conflict areas, with local modifications able to be made as necessary.

The selected lighting strategy indicates the extent of the lighting but does not define the level of lighting to be provided. The selected lighting strategy does not modify the criteria defined in IES RP-8-21 and AASHTO GL-7 for roadway lighting in terms of average maintained values, uniformity ratios, or veiling luminance ratios when proper evaluations can be made. However, proper luminance calculations are not feasible in some situations, and illuminance criteria should be applied. When “four in the gore” is not long enough to determine the proper luminance and veiling luminance values, these values would not be part of the criteria; however, the illuminance average and uniformity criteria would apply over the lighted area.

5.2.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design approach indicate that human visual performance and aging should be considered. The application of lighting can cause glare that reduces visual performance after exposure to the lighting. These transient adaptation effects are enhanced with age. For intermittent lighting, transition sections may be appropriate to reduce the effects of glare.

5.3 Surround Ratio

5.3.1 Currently Available Design Recommendations

Freeway, Urban	
	Roadways
	Interchanges
	Surround Ratio

Research has shown that the addition of lighting in areas adjacent to the travel lane of the roadway increases the driver’s detection distance of objects and people both on the roadway and adjacent to the roadway. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (National Academies of Sciences Engineering and Medicine, 2020). Surround ratio (also referred to as edge illuminance ratio by CIE, although with a somewhat different definition) is considered in both AASHTO GL-7 and ANSI/IES RP-8-21. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

The surround ratio (SR) is defined as the ratio of the illuminance value on the area adjacent to the travel lane (3.6-m strip) to the value for the edge lane of the roadway. The criterion for surround ratio in AASHTO GL-7 and ANSI/IES RP-8-21 is 0.8.

This value is higher than that used by CIE. For example, an average illumination on the outside lane of the roadway of 0.4 fc would result in a minimum lighting level on the surround of 0.4 fc × 0.8 = 0.32 fc.

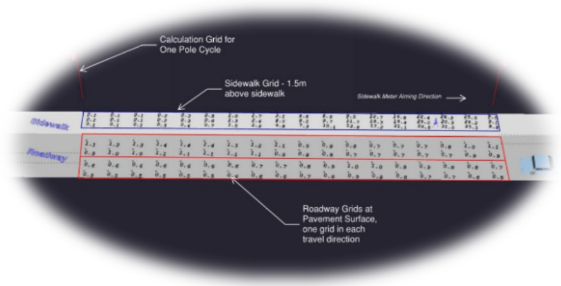
Surround ratio might not be appropriate in some situations, such as: where there is no area adjacent to the roadway, as on some bridges; areas where speeds are low and pedestrian volumes are low, so headlights provide adequate detection distance; where sidewalks are lighted; environmentally sensitive areas; and where additional poles might be required, increasing the risk of collisions. These considerations are discussed further in RP-8-21 section 10.5.2.3.

SAFETY HIGHLIGHTS

Limits on disability glare are one of the most critical design elements.

Increasing the surround ratio is helpful to increasing detection distance.

5.4 Criteria Values Applicable to this Example



Credit: FHWA

The classification for the elements of this roadway is:

Roadway Classification:	Freeway A

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 10-1)

Average Luminance:	>= 0.6 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0Veiling Luminance Ratio: <= 0.3
Surround Ratio:	>= 80% of illuminance provided on roadway

AASHTO GL-7

Roadway Lighting Level (Table 3-5)

Average Luminance:	>= 0.4 cd/m^2

Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 5.4 lux

The surround ratio criterion is 0.8, for the average illuminance value of the road-adjacent area divided by the value for the outside lane. If the average for the outside lane were the design criterion for the roadway in this example, the minimum value for the average illuminance over the surround area would be 0.5 footcandles. For divided highways where the median is sufficiently wide, there are separate surround areas on each side of each direction of travel.

The values given above are considered maintained values; that is, they represent the level recommended on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

6 Suburban Freeway Lighting Example

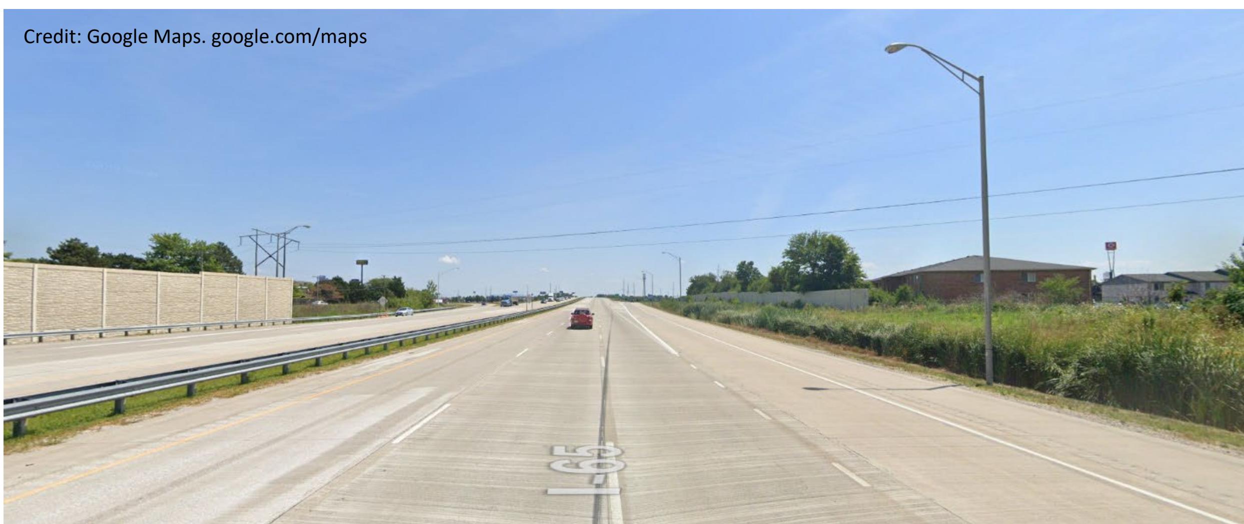
Freeways are highways that have divided traffic with controlled access. The freeway surroundings can vary tremendouly, thereby affecting the lighting design. This example includes the key roadway elements involved in lighting freeways in suburban areas. Suitable nighttime illumination helps drivers navigate safely while respecting those living adjacent to the freeway.

Freeway, Suburban	
	Roadway
	Interchanges
	Work Zones
	Surround Ratio

This example discusses the following key elements of rural freeways:

- The Roadway
- Interchanges
- Surround Ratio
- Work Zones

Suburban freeways are comprised of roadways and interchanges next to commercial and residential areas, often with the presence of construction and work zones. The following sections discuss lighting for these transportation heavyweights.



Credit: Google Maps. google.com/maps

6.1 The Roadway

Credit: Google Maps. google.com/maps

Freeway, Suburban	
	Roadway
	Interchanges
	Work Zones
	Surround Ratio

6.1.1 Currently Available Design Recommendations

The design of the roadway lighting system in this example is intended to provide visibility for drivers as they travel the highway. Visual tasks for the driver include vehicle guidance and current vehicle location along with the recognition of features and hazards such as medians, lane markings, signs, construction zones, and other vehicles. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 10-1 provide recommendations for the lighting of roadways, including the following criteria:

- Average luminance (or illuminance in AASHTO GL-7) for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in AASHTO GL-7 and ANSI/IES RP-8-21 apply to the travel lanes. This example does not include the lighting of any medians, islands, or other areas outside of the travel lanes.

This example road has the following characteristics:

Street or Roadway Classification:	Freeway B
Pavement Type:	R1 concrete

The selection of the street or roadway classification can vary with respect to lighting. The roadway classifications defined by FHWA[4] do not always align with those defined in IES RP-8-21 and AASHTO GL-7. For example, land use (e.g., urban vs. rural) is not defined in the GL-7 or RP-8-21 lighting criteria selection tables; therefore, engineering judgment is required when selecting the street classification.

Factors such as traffic volume, speed limit, and number of lanes can impact the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town. IES RP-8-21 uses pedestrian activity level, which is based on pedestrian volumes derived from judgment rather than sample counts. AASHTO uses land use classifications (commercial,

[4] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

intermediate, and residential) that are also somewhat subjective because the land use can vary on any given street and is subject to change over time.

6.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a possible design metric (Engineering & Medicine, 2020).

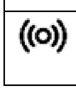
SAFETY HIGHLIGHTS

Limits on disability glare are one of the most critical design elements.

Increasing the surround ratio is helpful to increasing detection distance.

6.2 Interchanges

Credit: Google Maps. google.com/maps

Freeway, Suburban	
	Roadway
	**Interchanges**
	Work Zones
	Surround Ratio

6.2.1 Currently Available Design Recommendations

Interchanges provide connections between freeways and local roads through exits from and entrances to the freeway linking ramps and intersections. These sections where roadways connect include conflict areas that deserve special design consideration. AASHTO GL-7 and ANSI/IES RP-8-21 provide recommendations for lighting interchanges. The information contained in AASHTO GL-7, Section 3.2 includes warranting conditions for freeways that assist in establishing the lighting strategies for specific interchanges.

Some situations have no lighting requirements. Where lighting is applied, there are generally three different approaches: continuous freeway lighting, complete interchange lighting, and partial interchange lighting. As indicated in the names, these three approaches provide lighting on different portions of the freeway and associated interchanges:

- Continuous freeway lighting (CFL) applies lighting to the entire freeway from the interchange to the intersection at the ramp terminal.
- Complete interchange lighting (CIL) applies lighting to the complete ramp and the terminal intersection but not the freeway outside the interchange.

- Partial interchange lighting (PIL) applies lighting to the ramp conflict areas at the diverge or merge areas and perhaps terminal intersections but not the ramps themselves or the freeway beyond the merge or diverge areas.

The criteria for the warranting conditions in AASHTO GL-7 differ for the three levels of lighting and include the following:

- ADT of the freeway and surround conditions: urban / suburban / rural
- ADT of the ramp traffic and surround conditions: urban / suburban / rural
- ADT of the cross road and surround conditions: urban / suburban / rural
- Lighting extends along the cross roadway or in adjacent commercial or industrial areas
- Ratio of nighttime to daytime crash rates sufficiently exceeds the Statewide average for unlighted similar sections, along with a supporting study

This example road has the following characteristics:

Surrounding conditions:	Rural
ADT of the freeway:	Over 77,000
ADT of the ramps:	Under 1,000
ADT of the crossroad:	Under 4,000
Surrounding lighting:	None

After the extent of the lighting is established, typical equipment layouts can be applied and suitable transitions considered. For lighting entire interchanges, low-mast and high-mast lighting may be merged. For ramps, poles should be on the insides of curves. For PIL, “four in the gore” (meaning four luminaires aligned at the exit gore point) is a typical pattern at ramp exits and entrances to cover the conflict areas, with local modifications where applicable.

The selected lighting strategy indicates the extent of the lighting but does not define the level of lighting to be provided. The selected lighting strategy does not modify the criteria defined in IES RP-8-21 and AASHTO GL-7 for roadway lighting in terms of average maintained values, uniformity ratios, or veiling luminance ratios when proper evaluations can be made. However, proper luminance calculations are not feasible in some situations, and illuminance criteria should be applied. When “four in the gore” is not long enough to determine the proper luminance and veiling luminance values, these values would not be part of the criteria; however, the illuminance average and uniformity criteria would apply over the lighted area.

6.2.2 Emerging Research

Emerging recommendations on roadway lighting criteria and lighting design indicates that human visual performance and aging should be considered. The application of lighting can cause glare that reduces visual performance after exposure to the lighting. These transient adaptation effects are enhanced with age. When intermittent lighting is considered, transition sections may be appropriate to reduce the effects of glare.

SAFETY HIGHLIGHTS

When lighting is applied, it should cover all conflict areas where roads connect.

Increasing the surround ratio is helpful to increasing detection distance.

Limits on disability glare are one of the most critical design elements.

6.3 Surround Ratio

Credit: Google Maps. google.com/maps

	Freeway, Suburban
	Roadway
	Interchanges
	Work Zones
	Surround Ratio

6.3.1 Currently Available Design Recommendations

Research has shown that the addition of lighting in areas adjacent to the travel lane of the roadway increases the driver's detection distance of objects and people both on the roadway and adjacent to the roadway. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (National Academies of Sciences Engineering and Medicine, 2020). Surround ratio (also referred to as edge illuminance ratio by CIE, although with a somewhat different definition) is considered in both AASHTO GL-7 and ANSI/IES RP-8-21. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

The surround ratio (SR) is defined as the ratio of the illuminance value on the area adjacent to the travel lane (3.6-m strip) to the value for the outside lane of the roadway. The criterion for surround ratio in AASHTO GL-7 and ANSI/IES RP-8-21 is 0.8.

This value is higher than that used by CIE. For example, an average illumination on the outside lane of the roadway of 0.4 fc would result in a minimum lighting level on the surround of 0.4 fc × 0.8 = 0.32 fc.

For divided highways with sufficiently wide medians, there are separate surround areas on each side of each direction of the highway.

Surround ratio might not be appropriate in some situations, such as: where there is no area adjacent to the roadway, as on some bridges; areas where speeds are low and pedestrian volumes are low, so headlights provide adequate detection distance; where sidewalks are lighted; environmentally sensitive areas; and where additional poles might be required, increasing the risk of collisions. These considerations are discussed further in RP-8-21, section 10.5.2.3.

SAFETY HIGHLIGHTS

Safety is an important design requirement. In most cases, light trespass beyond the area included for the surround ratio can be easily controlled by the appropriate selection of pole height and fixture optics and the elimination of luminaire tilt.

6.4 Work Zones

Credit: Google Maps. google.com/maps

Freeway, Suburban	
	Roadway
	Interchanges
	Work Zones
	Surround Ratio

6.4.1 Currently Available Design Recommendations

Work zones are elements in streets and highways associated with construction, maintenance, or other work that impinges on the normal ability of pedestrians, cyclists, and/or vehicles to travel. Work zones are inherently temporary and are described as mobile or having short, intermediate, or long duration. Work zones may have active work areas along with associated activities and lighting at night; alternatively, they may only have temporary traffic control equipment. All work zones should have lighting that is, at a minimum, consistent with the illumination of the adjacent roadway, sidewalks, etc. In some situations, additional illumination is appropriate, such as in areas with abrupt shifts in lanes, surface unevenness, high pedestrian activity, or high traffic volume. When operations in the work area occur at night, the associated illumination from equipment and task lighting may generate requirements for additional lighting in the work zone and perhaps beyond.

AASHTO GL-7 recommends that the maintained horizontal illuminance levels for work zones meet or exceed the criteria shown in Table 3-5 in that document and discussed above. Considering practical constraints around work zones and construction, these criteria may be reasonably relaxed.

In recognition of the increase in nighttime construction activity, *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work* provides information on lighting for workers and inspectors in work zones as well as lighting for roadways in the work zone. Particular attention is given to providing temporary lighting in work zones and considering the potential for increased glare experienced by motorists, which may necessitate accommodation using temporary roadway lighting. In IES RP-8-21, glare from work zone lighting is discussed along with recommendations for mitigating glare through luminaire aiming and shielding as well as increased illumination levels on the roadway. IES RP-8-21 also discusses the effect of transient adaptation, which can prolong the visibility reductions caused by glare, including the greater impact on drivers with older eyes or impaired vision. In work zones where illumination is significantly higher compared to adjacent areas of the roadway or sidewalk, transition lighting may be appropriate on the approach and departure to reduce the effect of transient adaptation.

Table 19-1 in IES RP-8-21 provides recommendations for the lighting of long-duration work zones (those

SAFETY HIGHLIGHTS

Lighting for work zones should meet or exceed lighting levels for adjacent areas, provided by existing equipment and temporary lighting when necessary.

For work areas with nighttime operations, pedestrians, cyclists, and drivers may face additional challenges with visibility while navigating atypical conditions.

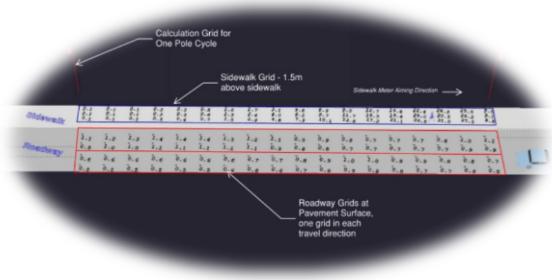
Limits on glare from work area lighting should be consistently applied, and excessive glare and excessive roadway lighting should be supplemented.

in place for more than three days). This table indicates where it would be useful for work zone roadways and activities to have illumination for rural highways, urban streets, and urban highways. The table indicates the importance for the work zone to meet the lighting criteria for the roadway, either by maintaining existing lighting or providing temporary lighting. IES RP-8-21 also discusses the illumination of flagger stations from above and in front so that flaggers are in positive contrast against their background.

6.4.2 Emerging Research

Lighting for work zones has been the subject of much discussion in recent years, and new products have expanded options. For example, luminous equipment has been developed for flaggers. Luminous paddles, signs, and attire can increase the visibility of flaggers to motorists. Additional approaches outside of typical illumination are being considered, and recent work has stressed glare control and proposed corresponding metrics.

6.5 Criteria Values Applicable to this Example



Credit: FHWA

The classification for the elements of this roadway is as follows:

Roadway Classification:	Freeway B

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 10-1)

Average Luminance:	>= 0.4 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 80% of illuminance provided on roadway

AASHTO GL-7

Roadway Lighting Level (Table 3-5b)

Average Luminance:	>= 0.4 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 5.4 lux

The surround ratio criterion is 0.8, for the average illuminance value of the road-adjacent surround area divided by the value for the edge lane. If the average illuminance for the outside lane were the design criterion for the roadway in this example, the minimum value for the average illuminance over the surround area would be 0.5 footcandles. For divided highways where the median is sufficiently wide, there are separate surround areas on each side of each direction of travel.

Lighting criteria for work zones are not specified by AASHTO or IES based on roadway type; instead, the requirement is often to maintain the existing or intended lighting levels. Some situations may deserve greater illumination due to sudden changes. For more information, see section 4.3.1.4 in Part 1 and *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work.*

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

7 Rural Freeway Lighting Example

Freeway, Rural	
	Roadways
	Interchanges
	Work Zones
	Surround Ratio
	Partial Beacon

Freeways are highways that have divided traffic with controlled access. The freeway surroundings can vary tremendouly and thus influence the lighting design. This example includes the key roadway elements involved in lighting freeways in rural areas. Suitable nighttime illumination helps drivers navigate safely while respecting the freeway's suroundings.

This example discusses the following key elements of rural freeways:

- The Roadway
- Interchanges
- Work Zones
- Surround Ratio
- Partial (Beacon) Lighting

Most freeway is rural, and lighting design should provide appropriate illumination with minimal impacts. The elements covered here include the basic elements and their connections along with the discussions above about light trespass and color of light, which can be particularly important in rural settings.

Credit: Google Maps. google.com/maps

7.1 The Roadway

Credit: Google Maps. google.com/maps

Freeway, Rural	
	Roadways
	Interchanges
	Work Zones
	Surround Ratio
	Partial Beacon

7.1.1 Currently Available Design Recommendations

The design of the roadway lighting system in this example is intended to provide visibility for drivers as they travel the highway. Visual tasks include vehicle guidance and current vehicle location as well as recognizing features and hazards such as medians, lane markings, signs, construction zones, and other vehicles. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 10-1 provide recommendations for the lighting of roadways, including the following criteria:

- Average luminance (or illuminance in AASHTO) for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (to limit disability glare)

The criteria given in these documents apply to the travel lanes. This example does not include the lighting of any medians, islands, or other areas outside of the travel lanes.

This example road has the following characteristics:

Street or Roadway Classification:	Freeway B
Pavement Type:	R3 Asphalt

The selection of the street or roadway classification can vary with respect to lighting. The roadway classifications defined by FHWA[5] do not always align with those defined in IES RP-8-21 and AASHTO GL-7. For example, land use (e.g., urban vs. rural) is not defined in the GL-7 or RP-8-21 lighting criteria selection tables; therefore, engineering judgment is required when selecting the street classification. Factors such as traffic volume, speed limit, and number of lanes can impact the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town. IES RP-8-21 uses pedestrian activity level, which is based on pedestrian volumes derived

[5] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

from judgment rather than sample counts. AASHTO uses land use classifications (commercial, intermediate, and residential) that are also somewhat subjective because the land use can vary on any given street and is subject to change over time.

7.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a design metric. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (Engineering & Medicine, 2020). Surround ratio, which is the ratio of the lighting value on the area adjacent to the travel lane (3.6-m strip) to the lighting value for the roadway, should be at least 0.8. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

SAFETY HIGHLIGHTS

Limits on disability glare are one of the most critical design elements.

Increasing the surround ratio of lighting is helpful for increased detection distance.

7.2 Interchanges

Freeway, Rural
Roadways
Interchanges
Work Zones
Surround Ratio
Partial Beacon

Credit: Google Maps. google.com/maps

7.2.1 Currently Available Design Recommendations

Interchanges provide connections between freeways and local roads through exits from and entrances to the freeway linking ramps and intersections. These sections where roadways connect include conflict areas that deserve special design consideration. AASHTO GL-7 and ANSI/IES RP-8-21 provide recommendations for lighting interchanges. The information contained in AASHTO GL-7, Section 3.2 includes warranting conditions for freeways that assist in establishing the lighting strategy for specific interchanges.

Some situations have no lighting requirements. Where lighting is applied, there are generally three different approaches: continuous freeway lighting, complete interchange lighting, and partial interchange lighting. As indicated in the names, these three approaches provide lighting on different portions of the freeway and associated interchanges:

- Continuous freeway lighting (CFL) applies lighting to the entire freeway from the interchange to the intersection at the ramp terminal.
- Complete interchange lighting (CIL) applies lighting to the complete ramp and the terminal intersection but not the freeway outside the interchange.
- Partial interchange lighting (PIL) applies lighting to the ramp conflict areas at the diverge or merge areas and perhaps terminal intersections but not the ramps themselves or the freeway beyond the merge or diverge areas.

The criteria in AASHTO GL-7 for the warranting conditions differ for the three levels of lighting and include the following:

- ADT of the freeway and surround conditions: urban / suburban / rural
- ADT of the ramp traffic and surround conditions: urban / suburban / rural
- ADT of the cross road and surround conditions: urban / suburban / rural
- Lighting extends along the cross roadway or in adjacent commercial or industrial areas
- Ratio of nighttime to daytime crash rates sufficiently exceeds the Statewide average for unlighted similar sections, along with a supporting study

This example road has the following characteristics:

Surrounding conditions:	Rural
ADT of the freeway:	Over 77,000
ADT of the ramps:	Under 1,000
ADT of the crossroad:	Under 4,000
Surrounding lighting:	None

After the extent of the lighting is established, typical equipment layouts can be applied and suitable transitions considered. For lighting entire interchanges, low-mast and high-mast lighting may be merged. For ramps, poles should be on the insides of curves. For PIL, “four in the gore” is a typical pattern at ramp exits and entrances to cover the conflict areas, with local modifications.

The selected lighting strategy indicates the extent of the lighting but does not define the level of lighting to be provided. The selected lighting strategy does not modify the criteria defined in IES RP-8-21 and AASHTO GL-7 for roadway lighting in terms of average maintained values, uniformity ratios, or veiling luminance ratios when proper evaluations can be made. However, proper luminance calculations are not feasible in some situations, and illuminance criteria should be applied. When “four in the gore” is not long enough to determine the proper luminance and veiling luminance values, these values would not be part of the criteria; however, the illuminance average and uniformity criteria would apply over the lighted area.

7.2.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design suggests that human visual performance and aging should be considered. The application of lighting can cause glare that reduces visual performance after exposure to the lighting. These transient adaptation effects are enhanced with age. When intermittent lighting is considered, transition sections may be appropriate to reduce the effects of glare.

7.3 Work Zones

Credit: Google Maps. google.com/maps

Freeway, Rural
Roadways
Interchanges
Work Zones
Surround Ratio
Partial Beacon

7.3.1 Currently Available Design Recommendations

Work zones are elements in streets and highways associated with construction, maintenance, or other work that impinges on the normal ability of pedestrians, cyclists, and/or vehicles to travel. Work zones are inherently temporary and are described as mobile or having short, intermediate, or long duration. Work zones may have active work areas along with associated activities and lighting at night; alternatively, they may only have temporary traffic control equipment. All work zones should have lighting that is, at a minimum, consistent with the illumination for the adjacent roadway, sidewalks, etc. In some situations, additional illumination is appropriate, such as in areas with abrupt shifts in lanes, surface unevenness, high pedestrian activity, or high traffic volume. When operations in the work area occur at night, the associated illumination from equipment and task lighting may generate requirements for additional lighting in the work zone and perhaps beyond.

SAFETY HIGHLIGHTS

When lighting is applied, it should cover all conflict areas where roads connect.

Increasing the surround ratio is important to increasing detection distance.

Limits on disability glare are one of the most critical design elements.

AASHTO GL-7 recommends that the maintained horizontal illuminance levels for work zones meet or exceed the criteria shown in Table 3-5 in that document and discussed above. Considering practical constraints around work zones and construction, these criteria may be reasonably relaxed.

In recognition of the increase in nighttime construction activity, *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work* provides guidance on lighting for workers and inspectors in work zones as well as lighting for roadways in the work zone. Particular attention is given to providing temporary lighting in work zones and considering the potential for increased glare experienced by motorists, which may necessitate accommodation using temporary roadway lighting. In IES RP-8-21, glare from work zone lighting is discussed along with recommendations for mitigating glare through luminaire aiming and shielding and increased illumination levels on the roadway. The effect of transient adaptation, which can prolong the visibility reductions due to glare, is also discussed, including the greater impact on drivers with older eyes or impaired vision. In work zones where illumination is significantly higher compared to adjacent areas of the roadway or sidewalk, transition lighting may be appropriate on the approach and departure to reduce the effect of transient adaptation.

Table 19-1 in IES RP-8-21 provides recommendations for the lighting of long-duration work zones (those in place for more than three days). This table indicates which work zone roadways and activities should have illumination for rural highways, urban streets, and urban highways. The table indicates the importance for the work zone to meet the lighting criteria for the roadway, either by maintaining existing lighting or providing temporary lighting. IES RP-8-21 also discusses the illumination of flagger stations from above and in front so that flaggers are in positive contrast against their background.

7.3.2 Emerging Research

Lighting for work zones has been the subject of much discussion in recent years, and new products have expanded options. For example, luminous equipment has been developed for flaggers. Luminous paddles, signs, and attire can increase the visibility of flaggers to motorists. Additional approaches outside of typical illumination are being considered, and recent work has stressed glare control and proposed corresponding metrics.

SAFETY HIGHLIGHTS

Lighting for work zones, including lighting provided by equipment and temporary lighting, should meet, or exceed lighting levels for adjacent areas.

For work areas with nighttime operations, pedestrians, cyclists, and drivers may face additional challenges with visibility while navigating atypical conditions.

Limits on glare from work area lighting should be consistently applied. Excessive glare may require roadway lighting to be supplemented.

7.4 Surround Ratio

Credit: Google Maps. google.com/maps

Freeway, Rural	
	Roadways
	Interchanges
	Work Zones
	Surround Ratio
	Partial Beacon

7.4.1 Currently Available Design Recommendations

Research has shown that the addition of lighting in areas adjacent to the travel lane of the roadway increases the driver's detection distance of objects and people both on the roadway and adjacent to the roadway. Surround ratio has been considered in international standards for some time and was recently shown to be a reliable indicator of detection distance for drivers (National Academies of Sciences Engineering and Medicine, 2020). Surround ratio (also referred to as edge illuminance ratio by CIE, although with a somewhat different definition) is considered in both AASHTO GL-7 and ANSI/IES RP-8-21. Since surround ratio applies to an area that may have variable surface type, surround ratio is determined based on illuminance.

The surround ratio (SR) is defined as the ratio of the illuminance value on the area adjacent to the travel lane (3.6-m strip) to the value for the outside lane of the roadway. The criterion for surround ratio in AASHTO GL-7 and ANSI/IES RP-8-21 is 0.8.

This value is higher than that used by CIE. For example, an average illumination on the outside lane of the roadway of 0.4 fc would result in a minimum lighting level on the surround of 0.4 fc × 0.8 = 0.32 fc.

For divided highways with sufficiently wide medians, there are separate surround areas on each side of each direction of the highway.

Surround ratio might not be appropriate in some situations, such as: where there is no area adjacent to the roadway, as on some bridges; areas where speeds are low and pedestrian volumes are low, so headlights provide adequate detection distance; where sidewalks are lighted; environmentally sensitive areas; and where additional poles might be required, increasing the risk of collisions. These considerations are discussed further in RP-8-21, section 10.5.2.3.

7.5 Partial or Beacon Lighting

Freeway, Rural
Roadways
Interchanges
Work Zones
Surround Ratio
Partial Beacon

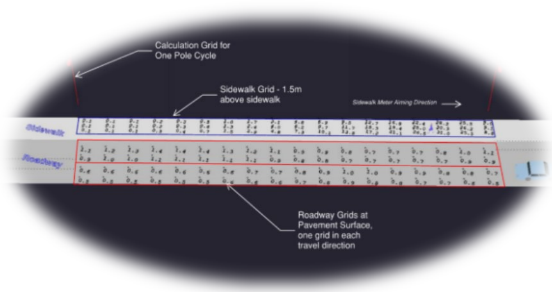
Rural freeways often have partial interchange lighting (PIL), covering the exit and entry conflict areas on the freeway. In those cases, the ends of the entrance and exit ramps may connect with rural roads in intersections that have either partial or beacon lighting. Beacon intersection lighting is used primarily to alert the approaching driver to an upcoming intersection. Partial lighting does light the entire intersection area to make pedestrians or cyclists crossing the street more visible. Beacon lighting is more of an identifier than a visibility enhancement.

AASHTO GL-7 describes this type of lighting and includes installation diagrams with pole locations but does not specify light levels. IES RP-8-21, Table 12-2 includes light levels for partial intersection lighting based on the road classification of the highest-volume roadway.

SAFETY HIGHLIGHTS

Safety is an important design requirement. In most cases, light trespass beyond the area included for the surround ratio can be easily controlled by the appropriate selection of pole height and fixture optics and the elimination of luminaire tilt.

7.6 Criteria Values Applicable to this Example



Credit: FHWA

The classification for the elements of this roadway is:

Roadway Classification:	Freeway B

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Level (RP-8-21, Table 10-1)

Average Luminance:	>= 0.4 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 80% of illuminance provided on roadway

AASHTO GL-7

Roadway Lighting Level (Table 3-5b)

Average Luminance:	>= 0.4 cd/m^2
Average/minimum Uniformity Ratio:	<= 3.5
Maximum/minimum Uniformity Ratio:	<= 6.0
Veiling Luminance Ratio:	<= 0.3
Surround Ratio:	>= 5.4 footcandles

The surround ratio criterion is 0.8, for the average illuminance value of the road-adjacent area divided by the value for the outside lane. If the average for the outside lane matched the design criterion for the roadway in this example, the minimum value for the average illuminance over the surround area would be 0.5 footcandles. For divided highways where the median is sufficiently wide, there are separate surround areas on each side of each direction of travel.

Lighting criteria for work zones are not specified by AASHTO or IES based on roadway type; instead, the requirement is often to maintain the existing or intended lighting levels. Some situations may deserve greater illumination due to sudden changes. For more information, see section 4.3.1.4 in Part 1 and *NCHRP Report 498: Illumination Guidelines for Nighttime Highway Work.*

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

8 Roundabout Lighting Example

This example consists of an urban roundabout connecting multiple streets with crosswalks, intersections, and sidewalks. These key elements provide the traveled ways for vehicles, pedestrians, and others moving through the roundabout at their own speeds and directions. Lighting to promote safety is discussed and the potential criteria that can be used are identified. The example also considers possible adjustmets to current criteria or approaches expected from emerging research.

	Roundabout
	Crosswalks
	Sidewalks
	Intersections

This example includes three key elements:

- The Roundabout Roadway
- Crosswalks
- Sidewalks

Credit: Google Maps. google.com/maps

8.1 Roundabout

Roundabout	
	Crosswalks
	Sidewalks
	Intersections

Credit: Google Maps. google.com/maps

8.1.1 Currently Available Design Recommendations

The lighting design for the roundabout in this example is meant to provide guidance and visibility for the drivers, pedestrians, and cyclists as they travel the roundabout, allowing them to see hazards including other drivers, pedestrians, and cyclists. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 12-4 provide recommendations for the lighting of roundabouts. In the AASHTO guide, the separate tables are for different categories of roundabouts as defined by FHWA. The criteria for roundabout illumination include:

- Average illuminance for the pavement
- Uniformity ratio for the pavement
- Minimum vertical illuminance at 1.5 m above the crosswalk facing approaching traffic

The criteria given in AASHTO GL-7 and ANSI/IES RP-8-21 are for the roundabout, crosswalks, and approaches. This example does not include the roundabout's center island, splitter islands, or other areas.

The example roundabout has the following characteristics:

Street or Roadway Classifications:	Major / Collector
Pavement Type:	R3 Asphalt
Pedestrian Classification:	Medium

The selection of the street or roadway classification can vary with respect to lighting. The roadway classifications defined by FHWA[6] do not always align with those defined in IES RP-8-21 and AASHTO GL-7. For example, land use (e.g., urban vs. rural) is not defined in the GL-7 or RP-8-21 lighting criteria selection tables; therefore, engineering judgment is required when selecting the street classification.

[6] https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section03.cfm

Factors such as traffic volume, speed limit, and number of lanes can impact the level of risk. For example, an urban collector in a major city will have a very different risk factor than a rural collector in a small town. IES RP-8-21 uses pedestrian activity level, which is based on pedestrian volumes derived from judgment rather than sample counts. AASHTO uses land use classifications (commercial, intermediate, and residential) that are also somewhat subjective because the land use can vary on any given street and is subject to change over time.

8.1.2 Emerging Research

Emerging recommendations on roadway lighting criteria and design approach is based on the results of safety and human factors research. One recent development is the inclusion of surround ratio (or edge illuminance ratio) as a design metric. Surround ratio is not applied when the area includes lighted sidewalks, like in this example. If there were no lighted sidewalks, surround ratio would be an additional design criterion.

SAFETY HIGHLIGHTS

Limits on disability glare are one of the most critical design elements.

The presence of pedestrians and cyclists increases safety risk. This is an important consideration when determining design requirements.

8.2 Crosswalks

Credit: Google Maps. google.com/maps

	Roundabout
	Crosswalks
	Sidewalks
	Intersections

8.2.1 Currently Available Design Recommendations

Lighting should be provided for both midblock and intersection crosswalks. The addition of lighting in crosswalks assists in the visibility of pedestrians using the crosswalk, allowing motorists to safely stop for pedestrians.

The crosswalks for this example roundabout have the following characteristics:

Street or Roadway Classification:	Major / Collector
Pedestrian Activity Level:	Medium
Pavement Type:	R3 Asphalt

AASHTO GL-7 discusses crosswalk lighting at intersections and roundabouts, including the placement of lighting to optimize pedestrian detection. Other lighting guides suggest that the vertical lighting level in the crosswalk should be equal to the horizontal lighting level recommended for the intersection or roundabout. IES RP-8-21 includes recommendations for crosswalk lighting at intersections, roundabouts, and midblock crosswalks.

For intersections, both AASHTO GL-7 and IES RP-8-21 recommend that the average vertical lighting value in the crosswalk be equal to the average horizontal illuminance in the intersection. Similarly, for the lighting of crosswalks at roundabouts, the average vertical lighting level should also be equal to the average horizontal lighting level in the roundabout. The one difference in this case is that the vertical lighting level is in the direction of the approaching vehicle as opposed to perpendicular to the centerline of the crosswalk. For the lighting of midblock crosswalks, IES RP-8-21 recommends an average vertical Illuminance level of 20, 30, and 40 lux for areas with low, medium, and high levels of pedestrian conflict, respectively.

8.2.2 Emerging Research

The current recommendations for high lighting levels in crosswalks are being discussed by technical committees dealing with the topic and investigated through ongoing research. The current findings suggest that vertical lighting levels (oriented toward the vehicle) equal to horizontal lighting levels on the roadway perform well from the perspective of pedestrian detection. However, crosswalk lighting also has safety benefits on unlit roads, and current recommendations may be higher than necessary. Lighting levels of 10 lux on areas with medium to high pedestrian volumes and 8 lux for isolated intersections with low pedestrian volumes appear to provide adequate lighting for visibility. Crosswalks in areas with medium to high pedestrian volumes along with high levels of activity and ambient illumination may warrant higher levels of illumination. For example, in areas near bus stops, public facilities, or corner-commercial locations with bright facility lighting, lighting levels of 20 lux may be appropriate for crosswalks.

SAFETY HIGHLIGHTS

Lighting crosswalks is a critical safety issue in areas with moderate to high pedestrian volumes.

Average vertical values of at least 10 lux maintained average vertical illuminance should be used, with higher values in suitable locations. Vertical values in the crosswalk should always be in the direction of the approaching driver.

8.3 Sidewalks

	Roundabout
	Crosswalks
	Sidewalks
	Intersections

Credit: Google Maps. google.com/maps

8.3.1 Currently Available Design Recommendations

Sidewalk (walkway) lighting within the right-of-way serves two purposes: (1) providing pedestrians with sufficient light on the sidewalk to avoid trip hazards, allow facial recognition, and impart a sense of security; and (2) assisting drivers in detecting pedestrians approaching the roadway.

The sidewalk for this example roundabout has the following characteristics:

Street or Roadway Classification:	Major / Collector
Pedestrian Activity Level:	Medium
Land Use Classification:	Intermediate
Pavement Type:	Concrete (assumed 30% reflective)

AASHTO GL-7 recommends maintaining horizontal illuminance levels for sidewalk areas at 3 to 14 lux depending on the sidewalk material and whether it is in a commercial, intermediate, or residential land use type. AASHTO GL-7 also provides uniformity criteria for sidewalks. IES RP-8-21 recommends sidewalk lighting levels based on pedestrian volumes. Lighting levels are given in terms of average horizontal illuminance, average vertical illuminance, and uniformity over the paved surface. Average horizontal levels can range from 2 to 10 lux and up to 20 lux for rare roadway conditions where pedestrians and vehicles use the roadway as a common space without curbed sidewalk areas.

In general, the roadway lighting system provides the lighting for the sidewalk area. There are, however, design considerations to consider when designing these systems. Pedestrian-scale lighting is often used to better define the sidewalk area and relate better in scale and feel to the pedestrians using the area. Pedestrian-scale lighting is often an attractive aesthetic for lighting in areas where pedestrians frequent. There are, however, issues that can arise when trying to use pedestrian-scale lighting for lighting a street. The lumen output often must be significantly increased to light the roadway, which increases the amount of disability glare produced by the lighting system. It is also difficult to achieve high lighting levels in areas like intersections and crosswalks. In areas where sidewalks utilize pedestrian-scale lighting, it is often recommended that a mix of higher roadway lighting poles be used in combination with lower pedestrian-scale poles to achieve the desired result.

8.3.2 Emerging Research

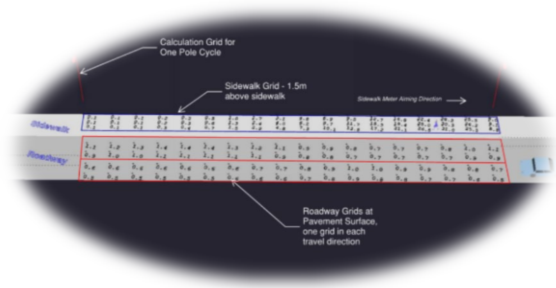
The recommended sidewalk lighting levels are currently undergoing some changes. IES is replacing the minimum vertical lighting level with an average vertical lighting level while maintaining the recommended light levels and eliminating the mixed pedestrian/vehicle recommendation. In addition, semi-cylindrical illuminance is being investigated as a predictive metric to replace vertical illuminance because it can analyze a complex form like a person instead of just a single vertical plane.

SAFETY HIGHLIGHTS

*Lighting for sidewalks includes providing visibility **of** the pedestrian and **for** the pedestrian.*

Facial recognition and detection of trip and fall hazards are critical. Providing both vertical and horizontal illuminance are important.

8.4 Criteria Values Applicable to this Example



Credit: FHWA

The classifications for the elements of this roadway are as follows:

Street Classification:	Roundabout
Functional Classification:	Major / Collector
Pedestrian Activity Level:	High
Land Use Classification:	Intermediate
Pavement Type:	R3 asphalt
Sidewalk Material:	Concrete (assumed 30% reflective)
Crosswalk Location:	Intersection

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roundabout Lighting Level (RP-8-21, Table 12-4)

Average Illuminance:	>= 29 lux
Average/minimum Uniformity Ratio:	<= 3.0

Crosswalk Lighting Level (RP-8-21, Table 12-4)

Average Illuminance:	>= 29 lux
Average Vertical illuminance:	>= 29 lux

Sidewalk Lighting Level (RP-8-21, Table 11-2)

Average Illuminance:	>= 10 lux
Average/minimum Uniformity Ratio:	<= 5.0
Average Vertical illuminance:	>= 5 lux

AASHTO GL-7

Roundabout Lighting Level (Table 3-5b per section 6.3)

Average Illuminance:	19 to 26 lux
Average/minimum Uniformity Ratio:	<= 3.0

Crosswalk Lighting Level (Section 3.5.6 and Table 3-5b)

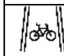
Average Illuminance:	19 to 26 lux
Average Vertical Illuminance:	19 to 26 lux

Sidewalk Lighting Level (Table 3-5b)

Average Illuminance:	>= 6 lux
Average/minimum Uniformity Ratio:	<= 4.0

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

9 Walkway & Bikeway Lighting Example

Walkway / Bikeway	
	Sidewalks
	Bike Lanes

This example consists of an urban walkway and bikeway connecting with crosswalks, intersections, and sidewalks (see Section 2 Urban Street Lighting Example for additional information). Walkways and bikeways may be together, adjacent, or separate; when overlapping, they combine movement at very different speeds. This section discusses the key aspects involved in an urban walkway/bikeway and identifies the potential criteria that can be used. The example also considers possible adjustments to current criteria or approaches expected from emerging research.


Credit: Google Maps. google.com/maps

9.1 Walkway / Bikeway

Credit: Google Maps. google.com/maps

Walkway / Bikeway	
	Sidewalks
	Bike Lanes

9.1.1 Currently Available Design Recommendations

The lighting design for the pavement portion of this example is meant to provide guidance and visibility for the pedestrians and cyclists as they travel the path, allowing them to see hazards, including other pedestrians and cyclists. AASHTO GL-7, Table 3-5 and ANSI/IES RP-8-21, Table 11-2 provide recommendations for the lighting of pathways. The separate tables in ANSI/IES RP-8-21 correspond to different pedestrian activity levels and underpasses. The criteria for walkway/bikeway illumination include:

- Average illuminance for the pavement
- Uniformity ratio for the pavement
- Minimum vertical illuminance at 1.5 m above the pathway facing along the direction of travel

The criteria given in these documents is for the pathway. For this example, it would not include any other areas outside of the pathway.

The example pathway has the following characteristics:

Street or Roadway Classification:	Pedestrian way / Bicycle way
Pavement Type:	R3 Asphalt
Pedestrian Activity Level:	High

Identification of pedestrian ways or bicycle ways has a set level of lighting. This classification of roadway (Pedestrian way / Bicycle way) as defined by FHWA may not align with those defined in the AASHTO GL-7 or IES RP-8-21. Land use (e.g., urban vs. rural) is not included in the lighting criteria tables of AASHTO GL-7 or IES RP-8-21; thus, engineering judgment is required when selecting the pedestrian activity level. Factors such as traffic volume, speed limit, and number of intersections can affect the level of risk. For example, an urban pathway in a major city will have a very different risk factor than a rural pathway in a small town. Since the lighting criteria are for a pathway that may have curves and variable surface types, illuminance is used as the metric.

9.1.2 Emerging Research

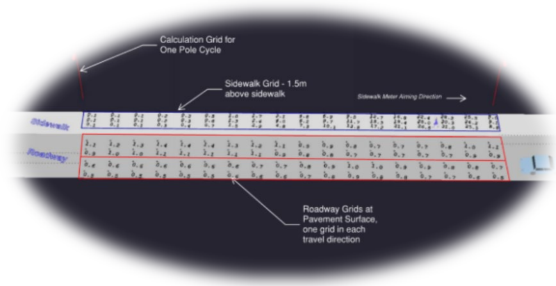
Emerging recommendations on pathway lighting criteria and approach is based on the results of safety and human factors research. One topic being investigated is an alternative metric for evaluating vertical surface illumination. Semi-cylindrical illuminance may provide a better representation of the visibility of other pedestrians and cyclists as compared to vertical illuminance.

SAFETY HIGHLIGHTS

Limits on disability glare are one of the most critical design elements.

The presence of pedestrians and cyclists increases the safety risk, which is an important consideration when determining design requirements.

9.2 Criteria Values Applicable to this Example



Credit: FHWA

The classifications for the elements of this roadway would be:

Street Classification:	Pedestrian way & Bicycle way (AASHTO) or Walkway / Bikeway (IES)
Pedestrian Activity Level:	High
Pedestrian Only:	Yes
Pavement Type:	R3 Asphalt

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Walkway / Bikeway Lighting Level (RP-8-21, Table 11-2)

Average Illuminance:	>= 10 lux
Average/minimum Uniformity Ratio:	<= 5.0
Average Vertical illuminance:	>= 5 lux

AASHTO GL-7

Pedestrian way and Bicycle way Lighting Level (Table 3-5b)

Average Illuminance:	>= 22 lux
Average/minimum Uniformity Ratio:	<= 3.0

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.8 is used.

10 Short Tunnels Lighting Example

Short Tunnel	
	Roadway
	Walls

Short tunnels are different from underpasses and long tunnels, although the distinctions can be subtle. An underpass (e.g., a road under a highway bridge) is a structure that has no effect on driver visibility. Short tunnels are usually defined by length (e.g., under 400 ft from portal to portal) and should be treated differently than long tunnels. The most significant factor in determining how a short tunnel should be lighted is how big the exit portal is in an approaching driver's view. This may even be the basis for describing a tunnel as short. Additional factors are the presence of pedestrians or cyclists, whether the tunnel is undivided with bi-directional traffic, and traffic speed and volume.

This example discusses the following two key elements of short tunnels:

- The Roadway
- Walls

10.1 The Roadway

Credit: Google Maps. google.com/maps

Short Tunnel	
	Roadway
	Walls

10.1.1 Currently Available Design Recommendations

Tunnel roadway lighting is provided in the daytime to allow drivers to see into the tunnel ahead, which is relatively dark compared to the daytime conditions in which drivers have been. Accordingly, some design metrics and aspects differ from those for the lighting of other roadways, although the objective is the same: to provide sufficiently bright roadway lighting.

For short tunnels, the lighting situation is complicated by the appearance of the bright exit portal at the same time as the darker tunnel interior. The brightness of the exit portal reduces or prevents the adaptation of a driver's visual system from the exterior conditions to the darker surroundings of the tunnel.

Tunnels that do not have the exit portal in view during the approach should be designed as long tunnels, with the provision of supplemental daytime lighting at the tunnel threshold to support driver adaptation when entering the tunnel.

When the exit portal is in the view of approaching drivers, the tunnel interior typically appears as a "black frame" around the brightness of the exit. While approaching the tunnel, the driver's visual adaptation level does not change significantly (it would decrease if the exit portal were not as much in view, as in a long tunnel). As a result, any object with reduced visual task size might be entirely "within the black frame" and would be much less visible. Smaller objects, such as a box on the side of the roadway, might not be detected. Larger objects with greater task size that extend out of the black frame are seen silhouetted against the exit portal brightness and so are more easily detected. Cyclists or small vehicles are typically large enough to be visible against the exit portal, but in some conditions this may not occur.

IES RP-8-21 discusses tunnels (as does the following example on long tunnels), providing recommendations on adjusting the tunnel threshold illumination based on various considerations shown in Table 14-2. Using this approach, the tunnel threshold luminance values determined by the Lseq method may be reduced because less illumination is necessary for some short tunnels.

The quantity of supplemental illumination can be determined using the Lseq method (RP-8-21, section 14.6.1.2), which evaluates the exterior view of the tunnel approach to establish an appropriate threshold luminance level. The traffic speed and threshold level are used to define lengths and luminance levels for sequential zones along the tunnel. These transitional zones have sequentially reduced roadway luminance requirements and extend until traffic reaches the interior zone or exit portal. The overall length for all transition zones together is roughly two to three times the SSSD. For short tunnels, the entire length is probably all transitional zones.

Typically, daytime supplemental lighting is not extended the full length of a tunnel since daylight is considered to provide adequate illumination for a distance of roughly 25 feet from the entry portal into the tunnel, and 50 feet from the exit portal. Any remaining length may merit illumination.

Most short tunnels are unlikely to have supplemental daytime lighting through the entire tunnel. More commonly, a short tunnel will be unlit or lit along a part of its length. Possible exceptions to this are short tunnels that have frequent pedestrian or cyclist presence, or those with curvature so the exit portal is not in the view of approaching drivers.

The criteria for the short tunnel roadway include the following items:

- Average luminance for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (limits disability glare)

The criteria given in these documents is for the travel lanes. For this example, it would not include any other areas outside of the travel lanes.

This example of short tunnel roadway has the following characteristics:

Tunnel length:	< 200 ft
Traffic flow:	undivided
Traffic volume (AADT):	< 2,500
Traffic speed:	35 mph
Safe stopping sight distance (SSSD):	250 ft on level
Pedestrians and/or cyclists:	Yes
Portal height:	20 ft
Daylight penetration:	Good
Pavement type:	R3 Asphalt

For this example, the SSSD exceeds the length of the short tunnel, so if supplemental lighting is provided, the entire tunnel would be in the threshold zone (excluding 25-foot insets from each portal).

10.1.2 Emerging Research

The current recommendations for high lighting levels in short tunnels are being discussed by technical committees dealing with the topic as well as being investigated with ongoing research. The current investigations indicate that there are three significant areas for consideration: task visibility; tunnel characteristics; and traffic.

Task visibility is the goal for all illumination. It is directly related to task size and corresponds with detection distance. As task size increases, from small targets (9-inch square) to pedestrians or cyclists (3 by 6 feet) to vehicles (9 by 6 feet), a driver’s ability to discern the task improves tremendously under all conditions.

Tunnel characteristics have several aspects. The primary aspect for short tunnels is the approaching driver's view of the exit portal. Another element is the proportion of tunnel enclosure, such as solid walls or piers or open sides, which has a significant effect on daytime illumination within the tunnel. For fully enclosed tunnels such as culverts, the lighting requirements may be significant, while tunnels with one or two open sides, such as under highway bridges, may not need any supplemental daytime lighting. Additional considerations include tunnel orientation, local weather conditions and surfaces' reflectance.

Traffic aspects include whether the tunnel is divided or undivided, along with speed, volume, and complexity of situation. The suitability of supplemental lighting increases as any one of these aspects increases, and even more when multiple aspects occur.

One of the most significant aspect of traffic is the presence of pedestrians or cyclists in the roadway, as demonstrated by the significance shown in RP-8-21, Table 14-2. In short tunnels, detecting pedestrians and cyclists who do not appear in silhouette against the exit portal may be challenging.

Accordingly, when visual task size is reduced—from vehicles to pedestrians or cyclists—the benefits from supplemental lighting increase.

For relatively flat straight short tunnels, one of the primary issues considers if the presence of supplemental daytime illumination is needed. A simplified evaluation can be based on daylight penetration extending from the portals into the tunnel. Using a "rule of thumb" that daylight sufficient to support driver visibility extends into the tunnel 1.5 times the average height of the opening in from the entrance portal, and 3 times "portal height" from the exit, this approach indicates that short tunnels with length under 5 times "the portal height" would not need lighting. For portals that are each 18 feet high on average, the corresponding length would be 90 feet.

When supplemental lighting is provided, partial lighting limited to the "second quarter" of the tunnel may be sufficient. For a 120-foot tunnel, the "second quarter" would cover the section from 30 to 60 feet in from the entrance portal. Supplemental daytime illumination provided in the "second quarter" provides partial illumination into the adjacent areas to enhance visibility for the entire tunnel length. For "longer short tunnels," the illuminated section may become a greater extent of the short tunnel while keeping consistent insets from the portals.

10.2 The Walls

Short Tunnel	
	Roadway
	Walls

Credit: Google Maps. google.com/maps

10.2.1 Currently Available Design Recommendations

Lighting design for tunnels includes a recommendation, in RP-8-21 section 14.4.4, that the wall illuminance be at least 40% of the adjacent roadway illuminance. This provides visibility of the surroundings for drivers entering and driving through the tunnel.

10.2.2 Emerging Research

A recommended approach for improving visibility in short tunnels is to raise the brightness of some of the tunnel walls, creating at least a partial silhouette for predominately-vertical objects that otherwise are entirely within the black frame. This can be achieved by instructing drivers to turn on headlights, as well as painting walls white or adding reflectors. More active approaches include installing horizontal bands or patterns of light sources. These bands do not need to be continuous, as long as an approaching driver would see pedestrians or cyclists in partial silhouette. The objective is to promote detection, without necessarily providing recognition.

Another technique to improve detection of pedestrians and cyclists is to inform drivers that pedestrians or cyclists are present using signage or beacon lighting.

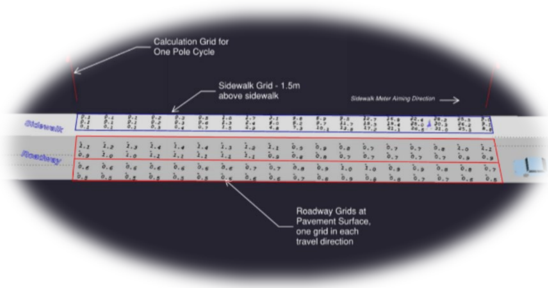
SAFETY HIGHLIGHTS

A driver's view of the exit portal is an important element for determining if and how to light short tunnels.

Wall and roadway brightness are key for increased detection distance.

More pedestrians and cyclists present a greater safety risk. This is a critical consideration when determining design requirements.

10.3 Criteria Values Applicable to this Example



Credit: FHWA

The criteria for the design of the installation could be based on either AASHTO GL-7 or IES RP-8-21. In general, the AASHTO and IES recommendations are similar but may vary depending on the classifications used. The choice of which recommendations to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria from each for this example are listed below:

IES RP-8-21

Roadway Lighting Requirement (RP-8-21, Table 14-2 and Lseq evaluations)

Tunnel length:	< 200 ft
Traffic flow:	undivided
Traffic volume (AADT):	< 2,500
Traffic speed:	35 mph
Safe stopping sight distance (SSSD):	250 ft on level
Pedestrians and/or cyclists:	Yes
Portal height:	20 feet
Daylight penetration:	Good
Pavement type:	R3 Asphalt

Roadway Lighting Level (RP-8-21 Chapter 14)

Threshold luminance (Lth) from Lseq evaluations of each portal	
Average Luminance:	varies by zones
Average/minimum Uniformity Ratio:	<= 2.0
Maximum/minimum Uniformity Ratio:	<= 3.5
Veiling Luminance Ratio:	<= 0.3

Wall Illuminance Level (RP-8-21, Section 14.4.4)

Avg Wall Illuminance / Avg Road Illuminance:	>= 0.40
Average/minimum Uniformity Ratio :	<= 3.0

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.5 is used.

11 Long Tunnel Lighting Example

Tunnel	
	Roadways
	Walls

Lighting long tunnels involves providing nighttime illumination as well as supplemental daytime lighting at high levels to support drivers' visual adaptation when entering a tunnel at speed.

Long tunnels are different from underpasses and short tunnels, although the distinctions can be subtle. An underpass is considered a structure that has minimal effect on driver visibility, such as roads under highway bridges. Short tunnels are regularly defined by length, e.g., under 400 ft from portal to portal, or by how visible the exit is during approach and have distinct design issues. When the exit portal is in view during the driver's approach to a tunnel and the length is under 400 ft, short tunnel design considerations can be applied. IES RP-6-21, Table 14-2 has recommendations for lighting required in short tunnels (i.e., 80'-410').

Tunnel roadway lighting should be provided at night and during the day. At night, tunnel lighting is provided to promote guidance within the structure. In the daytime, supplemental lighting is provided to enable drivers to see into the relatively dark tunnel ahead, despite the comparatively bright daytime conditions that drivers have been experiencing. Accordingly, tunnel lighting has some metrics and design aspects that differ from other roadway lighting, while the common objective is to make the roadway sufficiently bright during hours of darkness.

For nighttime tunnel lighting, the design criteria address roadway luminance quantity and roadway and wall uniformity, maximum veiling luminance, wall brightness, and flicker. These apply over the entire length of the tunnel at night. For daytime supplemental lighting, these same design criteria apply but with variations along the length of the tunnel to accommodate eye adaptation. For emergency lighting, the design criteria address illuminance on the tunnel floor (roadway and walkways) for average illuminance, minimum illuminance, and illuminance uniformity.

A significant factor in tunnel lighting for daytime is how bright the surroundings (scene) are in an approaching driver’s view. This provides the basis for lighting levels in the threshold and transition zones inside the portal. Additional significant factors are the presence of pedestrians or cyclists in the roadway, whether the tunnel is undivided, tunnel curvature where the exit is not visible from one SSSD, having traffic in both directions, and traffic complexity.

For tunnels that do not have existing portals, the design requires greater assumptions. Renderings of the approach can be used in place of photographic images and luminance values established from measurements in the area of the anticipated surroundings.

Evaluation of solar positions over the year for drivers approaching the tunnel is also recommended. An example is shown in Figure 66. In the example, the sun position relative to the tunnel can be defined based on the GPS location, and the sun position throughout the day can be tracked. The sun is typically at its highest point in the horizon at summer solstice and at its lowest point at winter solstice.

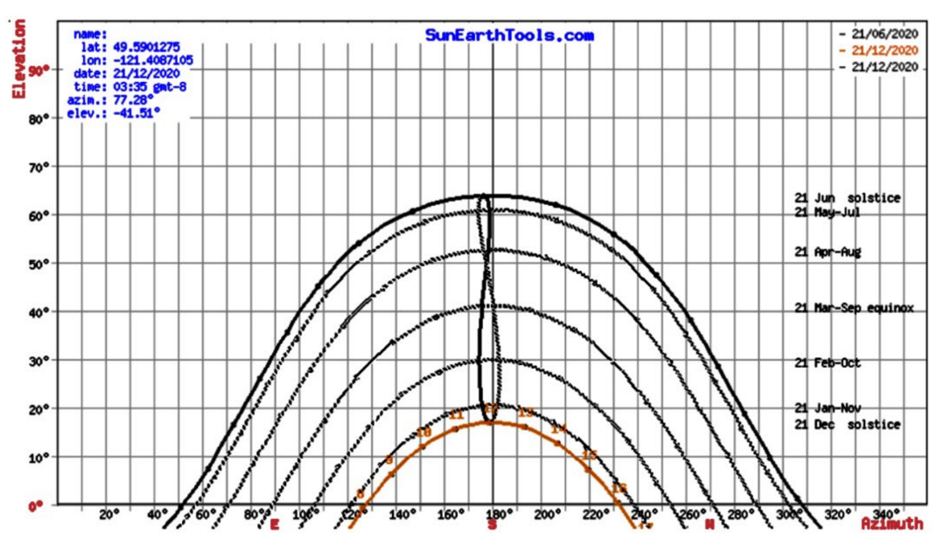


Figure 66. Line graph. Evaluation of solar positions visible to drivers relative to tunnel over one year.(Image Credit: Sunearthetools.com)

Where the sun is in direct view of drivers entering the tunnel, it is important to note no tunnel lighting system can allow a driver to adapt to the direct view of the sun. Therefore, seasonal tracking of the sun can indicate if higher threshold luminance or mitigation measures may be appropriate. Mitigation measures may include blocking of the sun from the drivers view. The direct view of the sun is most prevalent when the tunnel is oriented in the east–west direction and the sun is low in the horizon at sunrise or sunset and a significant amount of sky is prevalent.

ANSI/IES RP-8-21 divides a tunnel into four sequential adaptation zones and an exit zone as follows:

1 Approach zone
2 Threshold zone Transition zone
3 Interior zone
4 Exit zone

The approach zone is the area of open road immediately prior to the entry portal. The length of this zone is one SSSD. The phenomenon of pre-adaptation begins here. As the portal increasingly fills the driver's field of view, the eye begins to adapt from the luminance of the wider general view to the significantly lower luminance within the approaching threshold. The point where the portal structure completely fills the field of view is called the adaptation point and is considered the start of the threshold zone. The threshold zone extends one SSSD from the adaptation point into the tunnel and is followed by the transition zone(s) with decreasing luminance levels until the interior zone level—or the exit portal—is reached.

For each zone in the tunnel, the length and associated lighting recommendations vary with the vehicle speed and associated SSSD, exterior daylight conditions, and driver's current adapted state.

The pavement luminance produced by the lighting system in each zone also depends on the reflectance of the materials used for the road and structure.

The length of these threshold and transition zones and associated daytime lighting level are based on design criteria and the human eye's adaptation rate to darkness.

It is important to note that different luminance levels are used for the interior zone during daytime and nighttime operations unless the tunnel is bi-directional, where daytime levels can be used at night.

Because human adaptation to higher brightness is practically instantaneous and adaptation to lower levels is time dependent, standard practice does not require increases in luminance levels in the exit zone. However, transitional nighttime roadway lighting is typically recommended for the approach and exterior zones.

This example discusses the key elements for lighting tunnels, based on the design elements that form overlapping operational systems within the tunnel:

- Daytime supplemental lighting
    - approach
    - Lseq evaluation
    - luminance levels for various zones
- Emergency lighting
- Nighttime lighting
- Lighting control system

11.1 Tunnel Roadway, Daytime

Credit: Google Maps. google.com/maps

Tunnel
Roadways
Walls

11.1.1 Currently Available Design Recommendations

The lighting zones are defined in Figure 67 from RP-8-21. The lighting design for the threshold zone just inside the entry includes the potential to provide very high roadway luminance to support visibility as drivers adapt from daylight conditions. Sequential zones inside the tunnel provide decreasing levels of roadway luminance until the interior zone or the exit portal is reached. Lighting for the exit zone at the end of the tunnel may also be provided to prepare drivers who are adapted to the tunnel interior to enter daytime conditions.

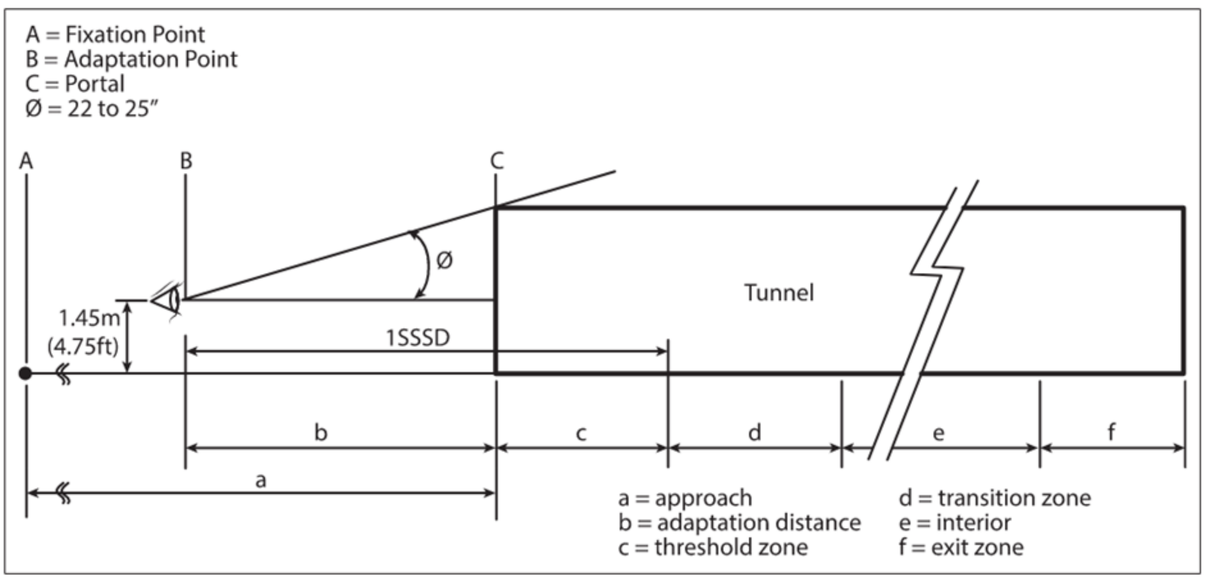


Figure 67. The primary external and internal areas associated with and affected by tunnel lighting design (RP-8-21).

The quantity of supplemental daytime illumination can be determined using the Lseq method (RP-8-21, section 14.6.1.2), which evaluates the exterior view of the tunnel approach to establish an appropriate threshold luminance level. This value is the design criterion for the threshold zone inside the entry portal and can be the starting point for determining the luminance levels for the remaining transition zones. The final design of tunnel lighting systems may be performed through an L_{seq} analysis. Key measures to perform an L_{seq} analysis include:

Luminance readings during the day of the approach conditions for the tunnel. These include sky luminance, roadway luminance, luminance of natural features around the portal such as vegetation or rocks, and luminance of the structural portal.

If the tunnel is a new tunnel, the same readings are taken at the proposed location of the tunnel for sky and natural features. Typical luminance readings are also taken on surfaces like roadways in the area with approximately the same orientation as the new roadway for the new tunnel.

The luminance readings gathered need to be adjusted for the time of year and conditions when they are made and when the highest brightness conditions are expected to occur. For example, if lighting levels are taken in January and peak brightness would be expected in July, then the readings should be factored to those peak condition. Methods of making those adjustments vary, but typical sky and surface brightness values from daylight analysis data and factors generally can be developed with those. It is also recommended that readings be done on clear sky days, at peak hour or throughout the day. Factors can be derived for clear versus overcast skies but are much more complex and variable.

The factored readings are then used to determine the L_{seq} value as outlined in IES RP-8-21, Chapter 14.

For transition zones, the traffic speed and threshold level can be used to define lengths and luminance levels for the transitional zones along the tunnel. These transitional zones typically have sequentially reduced roadway luminance requirements and extend until traffic reaches the interior zone or exit portal. The overall length for all transition zones together is roughly two to three times the SSSD. IES RP-8-21 offers two methods for determining transition zone levels and lengths. These include the step-down method or the curve method. Either can be used, but the curve method generally provides a better analysis of human eye adaptation because it uses the research formulas for determining the reductions.

The criteria for the tunnel roadway include the following items:

- Average luminance for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (limits disability glare)

The criteria given in these documents is for the travel lanes. For this example, it would not include any other areas outside the travel lanes except for marked bike lanes, which should be included as part of the roadway.

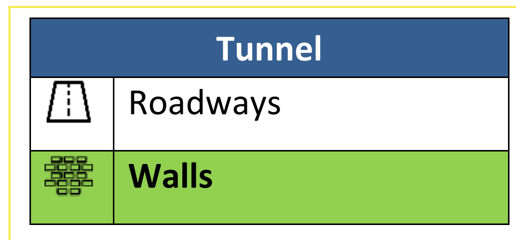
The recommendations for tunnel wall illumination apply during daytime to promote guidance within the structure. As discussed in RP-8-21, section 14.4.4, the lower area of the walls is evaluated, up to 6.6 ft above the roadway shoulder. The ratio of roadway-to-wall illuminances should be no more than 2.5. In other words, the average wall illuminance should be at least 40% of the average illuminance on the adjacent traveled lanes of the roadway.

This example tunnel roadway has the following characteristics:

Posted speed:	35 mph (56.4 km/h) = 51 ft/sec
Length:	873 feet (along Baseline)
Portal height:	23 ft
Orientation:	entry portal faces SSE

Longitude:	83deg31’6” West
Latitude:	35deg44’40” North
Traffic volume:	25,000 Average Annual Daily Traffic (AADT)
	30,000 Seasonally Adjusted Daily Traffic (SADT)
Safe-sight stopping distance (SSSD):	250 ft (not considering grade)
Structure surfaces:	Poured concrete (= 30%)
Roadway surface:	Portland cement, (R1), Qo=10%

11.2 Tunnel Walls



Credit: Google Maps. google.com/maps

11.2.1 Currently Available Design Recommendations

Lighting design for tunnels includes a recommendation, in RP-8-21, section 14.4.4, that the wall illuminance be at least 40 % of the adjacent roadway illuminance. This provides visibility of the surroundings for drivers entering and driving through the tunnel.

11.3 Emergency Lighting

Credit: Google Maps. google.com/maps

11.3.1 Currently Available Design Recommendations

Lighting design for tunnels includes a recommendation, in RP-8-21 section 14.4.10, that the emergency illumination be consistent with NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Generally, this system is to provide visibility of the tunnel during emergency situations to assist escape along the path of egress when power fails.

Following NFPA 502, the illuminance onto the roadway and walkway surfaces should have an average value of at least 10 lux maintained, with a minimum at any point of at least 1 lux maintained. The overall uniformity ratio of maximum-to-minimum should be no more than 40:1. This should be done from portal to portal.

Emergency lighting has power supplied through protected conduits and wiring, to be automatically switched on when regular power fails or lights otherwise go out. Note that, because emergency lighting needs to remain operational during conditions like fires within tunnels, the electrical system to support their operation should be 2-hour fire rated with specific testing and operational functions defined in NFPA 502.

Also to be considered in the design is egress lighting consisting of illuminated markers mounted to be seen in smoke conditions leading to exits that also have added lighting. Additional information can be found in NFPA 502.

11.3.2 Emerging Research

The emergency lighting in tunnels is intended to provide visibility of the structure and guidance along the egress path when the lighting has otherwise failed. In such conditions, visibility may be significantly reduced, e.g., smoke and people may be agitated, so the emergency illumination should be sufficiently robust to show how to proceed from any location toward an exit.

Additional fire safety measures may also be applied and should be coordinated with the emergency lighting, including cross-passage doors, Distance-to-Exit signage, and emergency communications equipment.

For designers, starting luminaire layouts using a regular pattern of emergency-capable equipment that supports the emergency requirements assures compliance after higher lighting levels from non-emergency luminaries are included.

11.4 Nighttime Lighting

Tunnel	
	Roadways
	Walls

Credit: Google Maps. google.com/maps

11.4.1 Currently Available Design Recommendations

Lighting design for tunnels includes a recommendation, in RP-8-21, section 14.4.3, that the nighttime luminance be at least 2.5 cd/m^2 for divided tunnels (this will vary depending on the posted speed). This level is more than recommended roadway luminance levels to provide visibility of the tunnel structure consistent with the adjacent roadway for drivers entering and driving through the tunnel at night.

When the tunnel is undivided, with bi-directional traffic, then the nighttime roadway luminance should be the same as the daytime interior level. This should assist drivers in such higher-conflict situations.

Following these recommendations, the tunnel at night probably has higher roadway luminance than the exterior roadway. For such situations, RP-8-21, section 14.4.3 includes recommendations that for a distance of at least one SSSD before and beyond the portals, the roadway luminance should be at least one third of the tunnel nighttime luminance. This applies even when the roadway is not otherwise lighted. For example, based on an anticipated nighttime interior lighting level of 2.5 cd/m^2, the approach zone and exterior exit zone roadways should be illuminated to a minimum average pavement luminance of 0.8 cd/m^2.

The recommendations for tunnel wall illumination apply at night to promote guidance within the structure. As discussed in RP-8-21, section 14.4.4, the lower area of the walls is evaluated up to 6.6 ft above the roadway shoulder. The ratio of roadway-to-wall illuminances should be no more than 2.5. In other words, the average wall illuminance should be at least 40% of the average illuminance on the adjacent traveled lanes of the roadway.

The recommendations concerning flicker from tunnel lighting apply at night, as discussed in RP-8-21, section 14.4.8. The effect is considered minimal for any duration under 20 seconds, or for frequencies under 2.5 Hz or over 15 Hz. Exposure for more than 20 seconds to frequencies between 4 Hz and 11 Hz should be avoided. For example, at 60 mph (88 fps) the spacings between 22 and 8 feet on center should be avoided for sections over 1,700 feet in extension.

Flicker is not usually an issue when linear luminaires are used or regular spacings do not extend beyond 20 seconds of exposure. At night, when a luminaire pattern could extend from portal to portal, a recurring spacing pattern should be evaluated for flicker. In addition, when lighting levels are increased by operating additional luminaires at the midpoint of longer spacings, the frequency will double, so luminaire layouts and control strategies may need to be adjusted accordingly.

11.4.2 Emerging Research

The nighttime lighting in tunnels is brighter than the general roadway to enhance visibility of the structure and guidance along the roadway. Driver challenges at night are not necessarily the same as during the day, and designers should be aware of the nighttime surroundings of the tunnel.

For existing tunnels, comparison of nighttime crash rates between "the combined approach and exit roadways" to "inside the tunnel" can provide information about how well the nighttime illumination meets drivers needs.

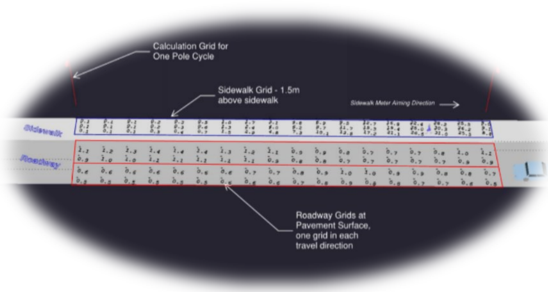
SAFETY HIGHLIGHTS

Brightness surrounding the driver's view of the portal is the most important element for determining how to light tunnels.

Wall and roadway brightness are key for increased detection distance.

More pedestrians and cyclists present a greater safety risk. This is a critical consideration when determining design requirements.

11.5 Criteria Values Applicable to this Example



Credit: FHWA

The criteria for the design of this installation would be found in IES RP-8-21 Chapter 14, *Tunnel Lighting*. The choice of whether to use these recommendations or which one to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria for this example are below:

IES RP-8-21

Roadway Lighting Requirement (RP-8-21, Table 14-2 and Lseq evaluations)

Tunnel length:	873 ft
Traffic flow:	divided
Traffic volume (AADT):	25,000
Traffic speed:	35 mph (51 fps)
Safe stopping sight distance (SSSD):	257 ft on 3% down grade
Portal height:	23 feet
Pavement type:	R3 Asphalt

Roadway Lighting Level (RP-8-21 Chapter 14)

Daytime

Threshold luminance (Lth) from Lseq evaluations of each portal

Average Luminance:	>= 121 cd/m^2
Average/minimum Uniformity Ratio:	<= 2.0
Maximum/minimum Uniformity Ratio:	<= 3.5
Veiling Luminance Ratio:	<= 0.3

Nighttime

Average Luminance:	>= 2.5 cd/m^2 for divided tunnel
Average/minimum Uniformity Ratio:	<= 2.0
Maximum/minimum Uniformity Ratio:	<= 3.5
Veiling Luminance Ratio:	<= 0.3

Wall Illuminance Level (RP-8-21, Section 14.4.4)

Avg Wall Illuminance / Avg Road Illuminance:	>= 0.40
Average/minimum Uniformity Ratio:	<= 3.0

Emergency Lighting (NFPA 502)

Average floor illuminance:	>= 1.0 fc
Minimum-at-any-point illuminance:	>= 0.1 fc
Maximum/minimum Uniformity Ratio:	>= 40

The values given above are considered maintained values. This means they represent the level required on the roadway and walls after depreciation of the system occurs due to reductions in the lumen output of the luminaires, dirt accumulating on the luminaire, and other factors. LLFs are further discussed in RP-8-21, Section 3.1.6 as well as AASHTO GL-7, Section 10.2.4. For this example, an LLF of 0.5 is often used. It is important to base the luminaire dirt deprecation that is part of the LLF on the tunnel cleaning and washing schedule. There is no exact formula for linking the dirt deprecation to the cleaning schedule, but it is recommended that cleaning be undertaken every 3 to 6 months. Sensors can be considered in the tunnel to measure light levels and access the degradation via the reduction in light output.

For emergency lighting, recommendations come from NFPA 502, for 1 fc average over the entire tunnel floor, including roadway and shoulders and walkways, with at least 0.1 fc at any point and uniformity over the tunnel as maximum-to-minimum limited to 40:1.

For nighttime lighting, the recommended luminance level extends from portal to portal, with uniformity limits of 2.0 for average-to-minimum and 3.5 for maximum-to-minimum. The pavement average depends on the tunnel traffic as divided or undivided, as discussed in RP-8-21, section 14.4.3. For this example, with one-way divided traffic, the average maintained luminance for nighttime is 2.5 cd/m^2, from portal to portal. Therefore, adjacent roadway lighting should be at least 0.8 cd/m^2 for at least one SSSD from each portal.

For daytime supplemental lighting, the design is intended to provide sufficient lighting during the transition from the exterior conditions through the threshold zone to the interior zone. The level for the threshold zone, Lth, is consistent with the driver's adaptation level approaching the portal, as determined using the Lseq method. The interior zone daytime level is established from RP-8-21, section 14.6.3. For a tunnel with 35 mph speed and over 24,000 AADT, the recommended nighttime pavement luminance is 5 cd/m^2 based on extrapolation in Table 14-7. The lighting is designed to transition from the driver's adaptation from Lth to the interior level, since this tunnel is that long.

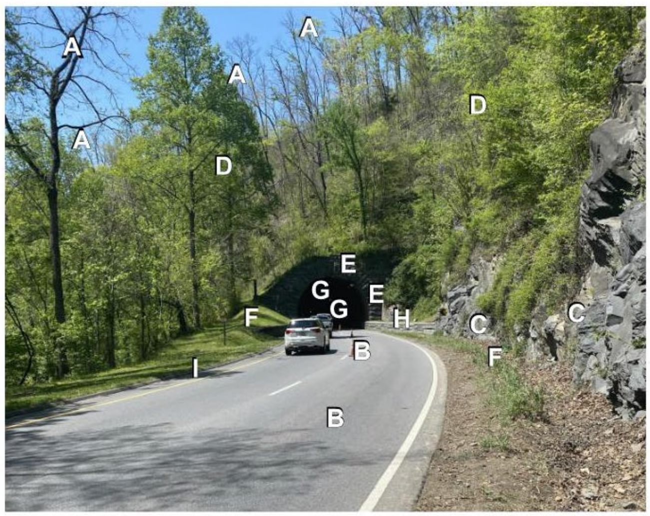
The length of the total threshold zone should be equal to one SSSD, which at 35 mph is approximately 250 feet, minus the pre-adaptation distance. When using the reduction curve, the first half—called Threshold Zone 1 (TH1)—should be illuminated to the full threshold pavement luminance (Lth), while the second half—Threshold Zone 2 (TH2)—should begin reducing to the calculated value of the first transition zone (TZ1). Based on the height of the portal, the adaptation distance for the tunnel is 43 feet, so the first section of the threshold zone should be 159 feet long and the second half should be 54 feet long.

Typically, daytime lighting is not provided for a distance into the tunnel from either portal corresponding to roughly 1.5 times the portal height due to daylight contribution. For portals approximately 16 feet high, this distance would be 25 feet in accordance with ANSI/IES RP-8-21. This inset only applies to daytime lighting, as nighttime lighting should be extending to the roadways outside the portals and emergency lighting is intended to cover the entire tunnel floor.

Figure 68. Tunnel entrance luminance evaluation polar diagram (Image Credit: WSP).

The required values for Lth in the threshold zone(s) depend on the design speed, structure orientation, ambient daylight conditions, and the visual environment immediately surrounding the structure portal. The current standard practice, RP-8-21, states that the threshold luminance is determined by using the Equivalent Veiling Luminance Method, also called the Lseq Method.

The Lseq value is determined using an image of the portal taken at one SSSD from the portal, with the Lseq polar graph overlayed (Figure 68). The Lseq figure is specified in RP-8-21, Table 14-4 and in CIE 88-2004, with concentric rings divided into 12 sectors so each 4-sided area has an equivalent spatial contribution to the driver's view. With this diagram, the sum of the luminance values from each area corresponds to the veiling luminance for drivers approaching the tunnel under such conditions.



EXTERIOR LUMINANCE SITE READINGS @ ENTRY PORTAL AREA									
	A	B	C	D	E	F	G	H	I
	SKY	ROAD	ROCK-DK	TREE	PORTAL	GRASS	WALL-INT	WALL-EXT	ROAD-SH
cd/m2	2750	3649	1840	1422	1902	3098	72	3200	437
cd/m2	1902	3200	392	1594	2838	2463	94		
cd/m2	2770								
cd/m2	4540								
avg kcd/m2	2.99	3.42	1.12	1.51	2.37	2.78	0.08	3.20	0.44
READINGS TAKEN AT 11:40AM ON APRIL 28, 2021 UNDER A CLEAR SKY									
APPROACH ROAD IS R3, TUNNEL ROAD FROM PORTAL TO PORTAL IS R1									

Figure 69. Tunnel entrance luminance evaluation example points (Image Credit: WSP).

The 12 sectors are numbered starting from zenith and increasing clockwise. Each sector has eight or nine rings outside the center circle. The diameter of the center circle corresponds to the 2-degree field of central vision and is determined by the length of the SSSD and 1 degree angle that represents the center circle's radius. The circle should be filled by an area of the tunnel to be illuminated to the level being determined by the Lseq method.

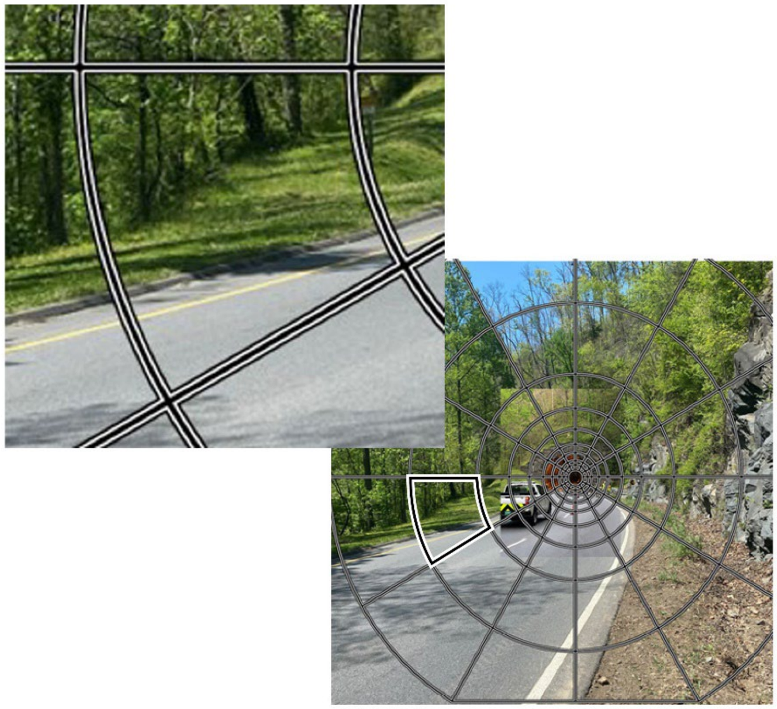


Figure 70. Tunnel entrance luminance example assignments polar diagram (Image Credit: WSP).

The luminous elements in the image are grouped together and assigned luminance values based on site evaluations. For example, roadway surface luminance values may be measured on site and averaged to establish the luminance used for roadway surface in the Lseq calculation. For this example, the defined elements are shown in Figure 69. The luminance readings collected for sky, portals, roads, and vegetation at the entrance of the tunnel are also dependent on the time of year and conditions at that time. There are daylighting factors that would need to be applied if readings are taken during a time of the year with reduced ambient light levels and what would be considered the peak ambient light levels. Information of daylighting of the sky and surfaces for different latitudes can be found in the IES Handbook and other daylighting references.

For each sector-ring area, the contribution from the surroundings is determined by area-weighting the luminance values in view in that area. For example, the detail in Figure 70 shows the area for sector 9 ring 8, which clearly includes different defined luminous elements. This area's area-weighted luminance has 20% road, 40% grass, and 40% trees, and the value is 2.4 kcd/m^2 with the defined luminance for these elements.

The calculated luminance values from the sector-ring areas are summed and multiplied by a factor to determine the value of Lseq. The Lseq is combined with the specified design factor, typically 4.7, that corresponds to a level of visual contrast that would be effective for detection if the Lth is produced in the center circle. For the design factor 4.7, that contrast level is 0.301, and the corresponding ratio for Lth/Lseq is 1.26.

This method accounts for the complete visual field around the portal. For this example, using all luminance within the visual field and for the contrast visibility recommended, the resultant design threshold luminance (Lth) is 121 cd/m^2.

An additional factor may be applied to the Lth value for adjustment of the luminance values from those measured during a site visit to values that represent the highest anticipated brightness for the situation. Because the calculation of Lseq is simple arithmetic, any multiplier to the set of luminance values used in the Lseq calculation can be applied at this stage of the calculation. In CIE 88-04 (6.2.b), the recommendation is to represent the 75 hours per year with the brightest conditions. For example, if site readings were taken in April under cloudy skies, it may be appropriate to adjust those luminance values to be consistent with a June day with partly cloudy skies, which typically corresponds to the brightest conditions. Orientation of the approach should determine which hours of the day are most significant.

The length of the threshold zone is one SSSD from the adaptation point, the location outside the portal where the tunnel fills the driver's view. The distance from the portal to the adaptation point is determined using a cutoff angle between 22 and 24 degrees for the driver's view. With the poral height at 23 feet and using a cutoff angle of 22 degrees, the adaptation point is 45 feet from the portal. When this distance is subtracted from the one SSSD length of the complete threshold zone, the length inside the tunnel is 212 feet. This distance is divided in two parts, with the part inside the portal at the threshold luminance Lth value for three quarters of the length (100%), and the remaining quarter of the threshold zone's length at 70% of Lth. At the end of the threshold zone, the luminance level drops to 41% and the transition zone begins. This portion of the luminance profile is shown at the upper left in Figure 71.

Tunnel (FT)	873.00
Tunnel (FT)	214.30
ft/s ec	51.33
Duration (sec)	17.01

Zone	Luminance	Distance (FT) Step Method	Distance (m) Step Method	Zone	Luminance ratio	Cumm. Dur.s (s) Reduc. Curve	Duration (s) Reduc. Curve
Lth1	121 cd/ M2	161	49	Lth1	n.a.	0.0	3.1
Lth2	85 cd/ M2	54	16	Lth2	1.4	3.1	1.0
Ltr1	49 cd/ M2	103	31	Ltr1	1.7	4.2	2.0
Ltr2	18 cd/ M2	154	47	Ltr2	2.7	6.2	3.0
Ltr3	8.1 cd/ M2	205	63	Ltr3	2.2	9.2	4.0
Ltr4	NA	0	0	Ltr4		13.2	
Ltr5	NA	0	0	Ltr5		-	
Int-Day	6.00 cd/ M2	197	60	Int-Day	1.3	17.0	3.8
Int-Night	2.5 cd/ M2	873	266		Total Duration:	17.0	

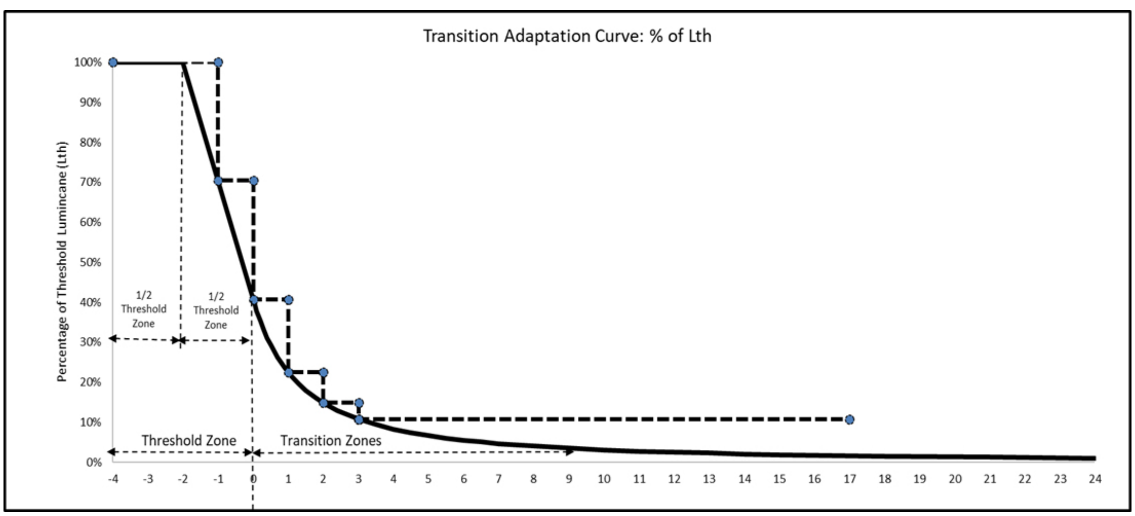


Figure 71. Line graph and tables. Example Zone and Recommended Luminance Calculations (Image Credit: WSP).

After the threshold zone luminance and length are determined, the remaining luminance profile can be established using the curve shown in RP-8-21 and CIE 88-04 and in red in Figure 71. This curve represents the minimum luminance level to be provided at that position inside the tunnel, and the intent of the design is to stay above that curve in every zone. This is typically achieved through steps in pavement luminance for each zone. The profile shown in the figure in blue uses transition zone durations of 2, 2, and 4 seconds for those steps.

Combined with the threshold zones' duration of 4.1 seconds, the time from portal to the interior zone is 12.1 seconds. This is adequate time for drivers' adaptation to decrease from the exterior daytime conditions and achieve suitable adaptation for the roadway luminance in the interior zone. Many other choices of zone durations can be used to achieve the same overall transition.

Exit portal lighting is not provided in this example since the driver's view out the portal will allow for suitable adaptation before leaving the tunnel.

The lighting calculations are performed with the luminance method with a grid located in each zone, typically in the first third of the zone, to capture the full effect of the lighting in that zone. Calculations represent maintained values, so an LLF is applied. Wall illuminance calculations should be coordinated with the roadway calculations to provide the averages for comparison to meet the 40% minimum level.

Flicker evaluations should be made for any section of the tunnel where the luminaire pattern remains the same for 20 seconds or more of travel. For example, with speed at 35 mph equal to 51 fps, luminaires spaced at 25 feet on center will produce a 2 Hz frequency, lower than the range of concern. Because this tunnel is 873 feet long, the anticipated duration of 17 seconds is lower than the 20-second threshold for flicker concern.

12 Underpass Lighting Example

Underpasses (including overpasses) are different from short tunnels and long tunnels, although the distinctions can be subtle. An underpass is considered a structure like roads under highway bridges, which typically have minimal impact on a driver's visibility. A significant factor in determining when and how an underpass should be lighted is how well daylight extends into the underpass, which involves the geometry and particularly the extent of enclosure. Additional significant factors are the presence of pedestrians or cyclists and whether the tunnel is undivided, having traffic in both directions, as well as traffic speed and volume.

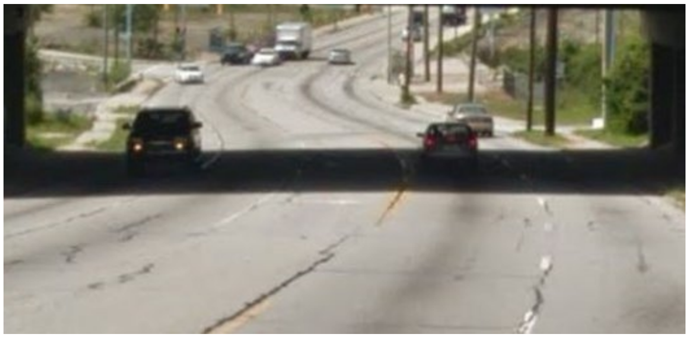
Underpass	
	Roadways
	Sidewalks
	Walls

This example discusses the key elements for underpasses:

- The Roadway
- Sidewalks
- Walls


Credit: Google Maps. google.com/maps

12.1 The Roadway



Credit: Google Maps. google.com/maps

Underpass	
	Roadways
	Sidewalks
	Walls

12.1.1 Currently Available Design Recommendations

Tunnel roadway lighting is provided in the daytime to enable drivers to see into the relatively dark road ahead, despite the comparatively bright daytime conditions in which drivers have been. Accordingly, it has some metrics and design aspects that differ from other roadway lighting, but the common objective is to make the roadway sufficiently bright.

RP-8-21 discusses underpasses and tunnels and provides recommendations on adjusting threshold illumination based on those considerations (RP-8-21 Table 14-2). This approach modifies the tunnel design criteria for threshold luminance values in recognition that reduced illumination is appropriate for some underpasses. With this approach, supplemental daytime illumination may be provided for part or all of the underpass. RP-8-21, Table 14-2 does define daytime lighting as not required for a tunnel 80 ft or less in length. This length should not be considered absolute, as the amount of daylight penetration will vary greatly depending on tunnel opening size. Investigations are being performed to determine if a four-lane and an open median underpass will have significantly more daylight penetration than a two-lane structure vertical wall. Determining the need for daytime lighting should therefore require a level analysis and engineering judgment.

The quantity of supplemental illumination can be determined using the Lseq method (RP-8-21 section 14.6.1.2), which evaluates the exterior view of the underpass approach to establish an appropriate threshold luminance level. The traffic speed and threshold level are used to define lengths and luminance levels for sequential zones along the underpass. These transitional zones have sequentially reduced roadway luminance requirements and extend until traffic reaches the interior zone or exit portal. The overall length for all threshold and transition zones together is roughly two to three times the SSSD. For underpasses, the entire length is typically all within the threshold zone.

Most underpasses are unlikely to have supplemental daytime lighting throughout. More commonly, underpasses will be unlit or lit with partial daytime lighting. Possible exceptions to this are underpasses that have frequent pedestrian or cyclist presence in the roadway itself.

The criteria for the underpass roadway include the following items:

- Average luminance for the roadway
- Uniformity ratios for the roadway
- Maximum veiling luminance ratio (limits disability glare)

The criteria given in these documents is for the travel lanes. For this example, it would not include any other areas outside of the travel lanes.

This example of underpass roadway has the following characteristics:

Underpass length:	< 120 ft
Traffic flow:	undivided
Traffic volume (AADT):	unknown
Traffic speed:	35 mph
Safe stopping sight distance (SSSD):	250 ft on level

Pedestrians and/or cyclists:	Yes, on sidewalk
Portal height:	16-18 ft
Daylight penetration:	Good
Pavement type:	R3 Asphalt

For this example, the SSSD exceeds the length of the underpass, so if supplemental lighting is provided, the entire tunnel would be in the threshold zone (excluding 25-foot sections inside the tunnel at each entry portal and 50-foot sections approaching the exit portal for single direction underpasses).

12.1.2 Emerging Research

The current recommendations for high lighting levels in underpasses are being discussed by technical committees (reference IES RLC) dealing with the topic as well as being investigated with ongoing research. The current investigations indicate that there are generally three significant areas for consideration: task visibility; tunnel characteristics; and traffic.

Task visibility is the goal for all illumination, and it is directly related to task size and corresponds with detection distance. As task size increases, from small targets (9 inches square) to pedestrians or cyclists (3 by 6 feet) to vehicles (9 by 6 feet), a driver’s ability to discern the task improves tremendously under all conditions.

Tunnel characteristics have several aspects. The primary aspect for underpasses is the approaching driver’s view of the exit portal. Another element is the proportion of tunnel enclosure, such as solid walls or piers or open sides, which has a significant effect on daytime illumination within the underpass. For fully enclosed roadways such as culverts, the lighting requirements may be significant, while underpasses with one or two open sides, such as under highway bridges, may not need any supplemental daytime lighting. Additional considerations include driver orientation, local weather conditions, and surfaces’ reflectance.

Traffic aspects include whether the underpass is divided or undivided, along with speed, volume, and the complexity of the situation. The suitability of supplemental lighting increases as any of these aspects increases individually, and more when multiple aspects combine.

A significant aspect of traffic is the presence of pedestrians or cyclists in the roadway, as demonstrated by its position in RP-8-21, Table 14-2. Pedestrians and cyclists on a sidewalk adjacent to the roadway are less significant. When task size is reduced from vehicles to pedestrians or cyclists, the benefits from supplemental lighting increase.

For relatively flat straight underpasses, an important issue is whether any supplemental daytime illumination is required. A simplified evaluation can be based on daylight penetration extending from the portals into the underpass. Using a rule of thumb that daylight sufficient to support driver visibility extends into the underpass 1.5 times the average height of the opening in from the entrance portal, and 3 times portal height from the exit, this approach indicates that underpasses with length under 5 times the portal height would not generally need lighting. For portals that are each 18 feet high on average, the corresponding length would be 90 feet.

When supplemental lighting is provided, partial lighting limited to the second quarter of the tunnel may be sufficient. For a 120-foot tunnel, the second quarter would cover the section from 30 to 60 feet in from the entrance portal. Supplemental daytime illumination provided in the second quarter provides partial illumination into the adjacent areas to enhance visibility for the entire tunnel length.

12.2 Sidewalks

Credit: Google Maps. google.com/maps

	Underpass
	Roadways
	Sidewalks
	Walls

12.2.1 Currently Available Design Recommendations

When sidewalks are present in tunnels, adequate illumination should be provided consistent with the lighting on the roadway and sidewalks outside the underpass. The objective in lighting the sidewalk surface is to provide safety, e.g., avoid tripping. There are also recommendations for vertical illumination, providing lighting for faces and hands of other pedestrians to promote personal security.

The sidewalk for this example underpass has the following characteristics:

Street or Roadway Classification:	Collector
Pedestrian Activity Level:	Medium
Land Use Classification:	Intermediate
Pavement Type:	Concrete (assumed 30% reflective)

AASHTO GL-7 recommends maintaining horizontal illuminance levels for sidewalk areas at 3 to 14 lux depending on the sidewalk material and whether it is in a commercial, intermediate, or residential land use type. AASHTO GL-7 also provides uniformity criteria for sidewalks. IES RP-8-21 recommends sidewalk lighting levels based on pedestrian volumes. Lighting levels are given in terms of average horizontal illuminance, average vertical illuminance, and uniformity over the paved surface. Average horizontal levels can range from 2 to 10 lux and up to 20 lux for rare roadway conditions where pedestrians and vehicles use the roadway as a common space without curbed sidewalk areas.

In general, the roadway lighting system provides the lighting for the sidewalk area. There are, however, separate design considerations for these systems. In particular, the scale of the illumination and equipment for pedestrians may be smaller than for roadways or tunnels, so using one system to light both areas may lead to undesirable consequences such as increases in disability glare (and corresponding challenges meeting the veiling luminance ratio limit).

IES provides recommended values (Table 11-2 in RP-8-21), for day or night, for maintained illuminance values for sidewalks and corresponding uniformity criteria. An average illuminance recommendation applies to the horizontal sidewalk surface, and a minimum illuminance recommendation for vertical illuminance at 1.5 m above grade, onto surfaces facing in each direction of pedestrian traffic. The uniformity criteria apply to the horizontal surface, limiting the average-to-minimum ratio value.

12.2.2 Emerging Research

Sidewalk lighting levels are currently under review and subject to research.

In particular, semi-cylindrical illuminance is being investigated as a better predictive metric compared to vertical illuminance because it represents a complex form such as a person better than a single vertical plane does.

Current IES recommendations for sidewalk areas are being reconsidered and may result in lower recommended values, closer to open area sidewalks.

12.3 Walls

Credit: Google Maps. google.com/maps

Underpass	
	Roadways
	Sidewalks
	Walls

12.3.1 Currently Available Design Recommendations

Lighting design for tunnels includes a recommendation, in RP-8-21, section 14.4.4, that the ratio of road-to-wall illuminance values be no more than 2.5. This is the same as saying that wall illuminance be at least 40% of the adjacent roadway illuminance. This provides visibility of the surroundings for drivers entering and driving through the tunnel.

For underpasses, there may not be walls to the tunnel, with piers or clear spans commonly applied.

12.3.2 Emerging Research

When the exit portal is in the view of approaching drivers, the tunnel interior typically appears as a “black frame” around the brightness of the exit. While approaching the tunnel, the driver’s visual adaptation level does not change significantly (it would decrease if the exit portal were not as much in view, as with long tunnels). A driver’s ability to distinguish details within the black frame is compromised due to visual adaptation to daylight surroundings. As a result, while objects with larger task size will appear in silhouette against the exit portal, different objects with smaller task size may be viewed entirely against the black frame and would be much less visible. Smaller objects, such as a box on the side of the roadway, might not be detected. Larger objects with greater task size that extend out of the black frame are seen silhouetted against the exit portal brightness and so are more easily detected.

Cyclists or small vehicles are typically large enough to be visible against the exit portal, but in some situations this may not occur.

The recommended approaches for improving visibility in short tunnels aim to raise the brightness of some of the tunnel walls, creating at least a partial silhouette for predominately vertical objects that otherwise are entirely within the black frame. Detection can be improved by instructing drivers to turn on headlights, combined with painting walls white or using tile or adding reflectors. More active approaches include installing horizontal bands or patterns of light sources on the roadway, thus reducing uniformity and improving object contrast. These bands do not need to be continuous as long as an approaching driver would see pedestrians or cyclists in partial silhouette. The objective is to promote detection without necessarily providing recognition.

Where feasible, introducing daylight into the underpass, through a gap in the cover near the middle of the underpass, can provide significant improvement in visibility for approaching drivers. For example, projects with median in-fills of freeways could retain some open space between parallel overpasses.

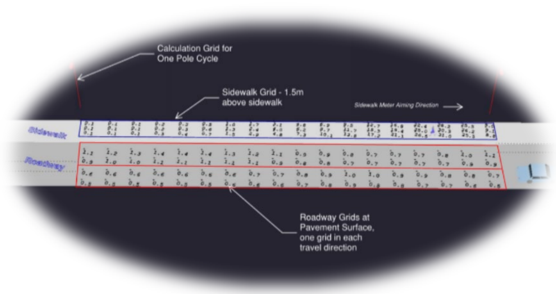
Another technique to improve detection of pedestrians and cyclists is to inform drivers that pedestrians or cyclists are present using signage or beacon lighting.

SAFETY HIGHLIGHTS

A driver's view of the exit portal is an important element for determining if and how to light short tunnels.

Wall and roadway brightness are key for increased detection distance.

More pedestrians and cyclists present a greater safety risk. This is a critical consideration when determining design requirements.



Credit: FHWA

12.4 Criteria Values Applicable to this Example

The criteria for the design of this installation would be found in IES RP-8-21, Chapter 14, *Tunnel Lighting*. The choice of whether to use these recommendations or which one to use is up to the owner and designer of the lighting system based on their requirements and applicability. The criteria for this example are below:

IES RP-8-21

Roadway Lighting Requirement (RP-8-21, Table 14-2 and Lseq evaluations)

Underpass length:	117 ft
Traffic flow:	undivided
Traffic volume (AADT):	unknown
Traffic speed:	35 mph
Safe stopping sight distance (SSSD):	250 ft on level
Pedestrians and/or cyclists:	Not on Roadway / Low
Portal height:	17 feet
Daylight penetration:	Good
Pavement type:	R3 Asphalt

Roadway Lighting Level (RP-8-21 Chapter 14)

Threshold luminance (Lth) from Lseq evaluations of each portal

Average Luminance:	100 cd/m^2
Average/minimum Uniformity Ratio:	<= 2.0
Maximum/minimum Uniformity Ratio:	<= 3.5
Veiling Luminance Ratio:	<= 0.3

Wall Illuminance Level (RP-8-21, Section 14.4.4)

Avg Wall Illuminance / Avg Road Illuminance:	>= 0.40
Average/minimum Uniformity Ratio:	<= 3.0

Sidewalk Lighting Level (RP-8-21, Table 11-2)

Average Illuminance:	>= 2 lux
Average/minimum Uniformity Ratio:	<= 10.0
Average Vertical illuminance:	>= 2 lux

The extent of illumination in the underpass is less than the overall length due to daylight, which is considered to extend roughly a distance of 1.5 times the height of the underpass into the underpass from each side. When the sides of the underpass are open and allow daylight penetration, these distances may be increased.

The values given above are considered maintained values; that is, they represent the level required on the roadway and walls after depreciation of the system occurs due to reductions in the lumen output of the luminaires, dirt accumulating on the luminaire, and other factors. LLFs are further discussed in RP-8-21, Section 3.1.6 as well as AASHTO GL-7, Section 10.2.4.

13 At-grade Railway Crossing Lighting Example

This example consists of a railway crossing at grade with isolated illumination of the roadway, a particular type of intersection that has unusual lighting considerations. The two sections include the key aspects involved in lighting such as a railroad crossing for drivers, pedestrians, cyclists, and neighbors and the criteria to be used.

At-grade Railway Crossing	
	At Grade Rail Crossings

The application of lighting at isolated interchanges, including at-grade railway crossings, is based on a safety concern that could arise from several aspects of the situation. For this example, these could include: nighttime train operation; limited visibility of the crossing or the trains; view under the train showing oncoming headlights; and crash history.

Chapter 13 of RP-8-21 discusses at-grade railway crossings, including considerations such as pole characteristics and location, and provides detailed figures and specific recommendations for lighting.

Credit: Google Maps. google.com/maps

13.1 At-grade Railway Crossing

Credit: Google Maps. google.com/maps

At-grade Railway Crossing

At Grade Rail Crossings

13.1.1 Currently Available Design Recommendations

The lighting design in this example is intended to provide guidance and visibility for drivers as they approach an at-grade railway crossing, allowing them to see hazards in general as well as other vehicles and trains. ANSI/IES RP-8-21 provides recommendations for the lighting of crossings in Chapter 13. The criteria for illumination for at-grade railway crossings address:

- Average illuminance onto the pavement
- Uniformity ratio for the pavement
- Average vertical illuminance above the outside of the tracks, facing toward approaching drivers

The criteria given here are for the approaches to the crossing, for 30 m in each direction away from the tracks, and for the vertical calculation grids above the edge of the tracks and facing toward drivers. These vertical grids are located on the outsides of the track(s) and extend along the tracks a bit beyond the outside edges of the roadway, shoulder, sidewalk, or pathway on each side of the traveled way.

The example roadway has the following characteristics:

Street or Roadway Classification:	Major
Pavement Type:	R3 Asphalt

In RP-8-21, Chapter 13, there are detailed figures and descriptions of the surfaces to be evaluated, both real and virtual, with relevant dimensions. The recommendations for roadway illumination are based on the road classification, while the criterion for the virtual vertical surfaces is the same for all situations.

For isolated interchanges, including railway crossings, the assignment of a road classification corresponds to a specific level of lighting. Such a classification as defined by FHWA may not align with those defined in the AASHTO GL-7 or IES RP-8-21. Land use (e.g., urban vs. rural) is not included in the lighting criteria tables of AASHTO GL-7 or IES RP-8-21; thus, engineering judgment is required when selecting the pedestrian activity level. Factors such as traffic volume, speed limit, and number of pedestrians and cyclists can affect the level of risk. For example, an urban crossing in a major city will have a very different risk factor than a rural crossing outside a small town. Since the lighting criteria are for crossings that typically have sloped sections and variable surface type, as well as a conceptual vertical surface, illuminance is the metric used.

SAFETY HIGHLIGHTS

Identifying both the presence of a crossing and the presence of a train is critical for safety at at-grade railway crossings.

The presence of pedestrians and cyclists increases the safety risk for crossing the embedded tracks.

13.2 Criteria Values Applicable to this Example

For this example of at-grade railway crossings, the classifications for the isolated interchange are:

Street or Roadway Classification:	Major
Pavement Type:	R3 Asphalt

The criteria for the design of the installation discussed here are from IES RP-8-21 and listed below:

IES RP-8-21	
Partial (Isolated) Intersection Lighting Level (RP-8-21, Table 12-2)	
Average Pavement Illuminance:	>= 9 lux
Average/minimum Uniformity Ratio:	<= 3.0

Railway Crossing Lighting Level (RP-8-21 Section 13.3)	
Average Vertical Illuminance:	>= 10 lux

The values given above are considered maintained values; that is, they represent the level required on the roadway and sidewalk after system depreciation due to reductions in the lumen output of the luminaire, dirt accumulating on the luminaire, and other factors. The LLFs are further discussed in RP-8-21, Section 3.1.6 and AASHTO GL-7, Section 10.2.4.

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For More Information:

https://safety.fhwa.dot.gov/

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