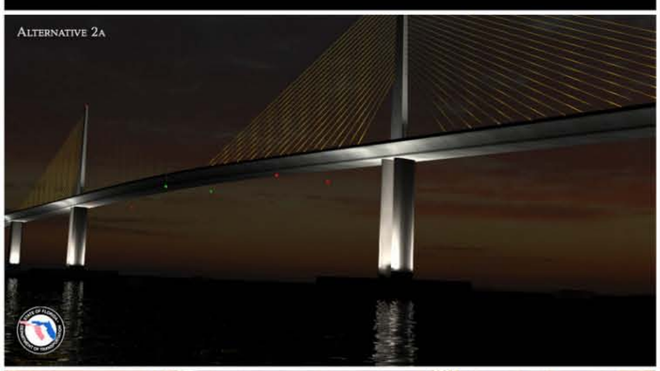
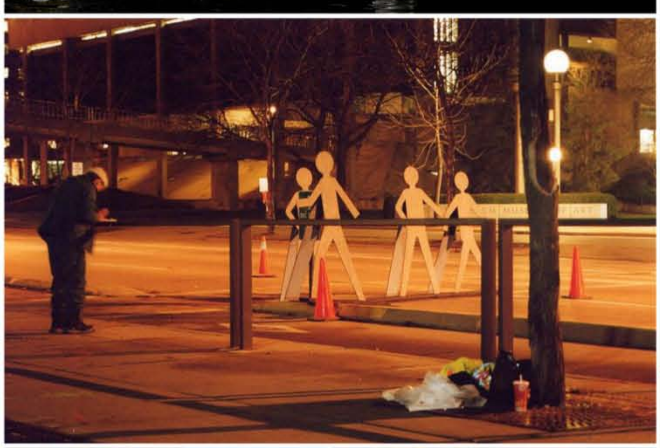
FHWA Lighting Handbook

August 2012





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This handbook is an update to the 1978 FHWA Lighting Handbook 78-15 as well as the 1983 addendum. It is meant to provide guidance to designers and State, city, and town officials concerning the application of roadway lighting. Supplementing and referring to other resources developed by AASHTO, IES, and CIE this document contains information on:
Policy and Guidance – discussing references, policy, and recommendations used by FHWA in evaluating and administering funds for roadway and street lighting projects.
Basic Terms and Concepts – discussing descriptions of significant terms and concepts used in roadway and street lighting projects.
Warranting Criteria – including various warranting methods available when considering lighting.
Lighting Impacts – discussing various impacts (both positive and negative) of lighting systems and ways to control and mitigate.
Application Considerations – supplementing information provided in the reference documents.
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Policy and Guidance

This section discusses the references, policy, and recommendations used by the Federal Highway Administration in evaluating and administering funds for roadway and street lighting projects.

1 Purpose of Lighting

1.1 Purpose of Handbook

This handbook supplements the guidance provided by AASHTO and IES

This handbook has been prepared to provide guidance 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 need, benefits, and applicable references when considering a roadway or street lighting system. Documents available from organizations such as the American Association of State Highway and Transportation Officials (AASHTO), the Illuminating Engineering Society (IES), 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 provide supplemental information on topics not addressed in those documents.

The document is divided into six areas of discussion. These areas include:

Policy and Guidance – discussing references, policy, and recommendations used by FHWA in evaluating and administering funds for roadway and street lighting projects.

Basic Terms and Concepts – discussing descriptions of significant terms and concepts used in roadway and street lighting projects.

Warranting Criteria – including various warranting methods available when considering lighting.

Lighting Impacts – discussing various impacts (both positive and negative) of lighting systems and ways to control and mitigate.

Application Considerations – supplementing information provided in the reference documents.

Other Systems and Issues – discussing additional lighting and non-lighting elements impacting the roadway user.

This handbook is an update to the 1978 FHWA Lighting Handbook 78-15 as well as the 1983 addendum to chapter 6 of the handbook.

Key documents that provide guidance and criteria for roadway lighting and associated applications are listed below. The latest versions of these documents should be used as references for design projects.

AASHTO GL-6 Roadway Lighting Design Guide (www.transportation.org)

ANSI/IES RP-8 Standard Practice for Roadway Lighting (www.ies.org)

ANSI/IES RP-22 Standard Practice for Tunnel Lighting (www.ies.org)

ANSI/IES RP-22 Standard Practice for Tunnel Lighting (www.ies.org)

IES DG-19 Design Guide for Roundabout Lighting (www.ies.org)

FHWA-RD-01-103 Highway Design Handbook for Older Drivers and Pedestrians (www.fhwa.dot.gov)

FHWA-SA-07-010 Railroad-Highway Grade Crossing Handbook (www.fhwa.dot.gov)

FHWA-HRT-08-053 Informational Report on Lighting Design for Midblock Crosswalks (www.fhwa.dot.gov)

TAC Guide for the Design of Roadway Lighting 2006 Edition (www.tac-atc.ca)

NCHRP 672 Roundabouts: An Informational Guide – Second Edition (www.trb.org)

Additional useful documents include:

AASHTO RSDG-3 Roadside Design Guide 4th Edition 2011 (www.transportation.org)

AASHTO Highway Safety Manual (www.highwaysafetymanual.org)

AASHTO A Policy on Geometric Design of Highways and Streets 6th Edition 2011 (www.transportation.org)

1.2 Purpose of Roadway and Street Lighting

Driving or walking on, or across, a roadway is less safe in darkness than in a lighted area, due to the reduced visibility of hazards and pedestrians. Though the number of fatal crashes occurring in daylight is about the same as those that occur in darkness, only 25 percent of vehicle-miles traveled occur at night. Because of that the nighttime fatality rate is three times the daytime rate, as illustrated in Figure 1a. Figure 1b shows the difference in the number of fatal crashes on lit and unlit roadways.

Studies have shown a reduction in nighttime fatal crashes of up to 60% with the use of roadway lighting [5]

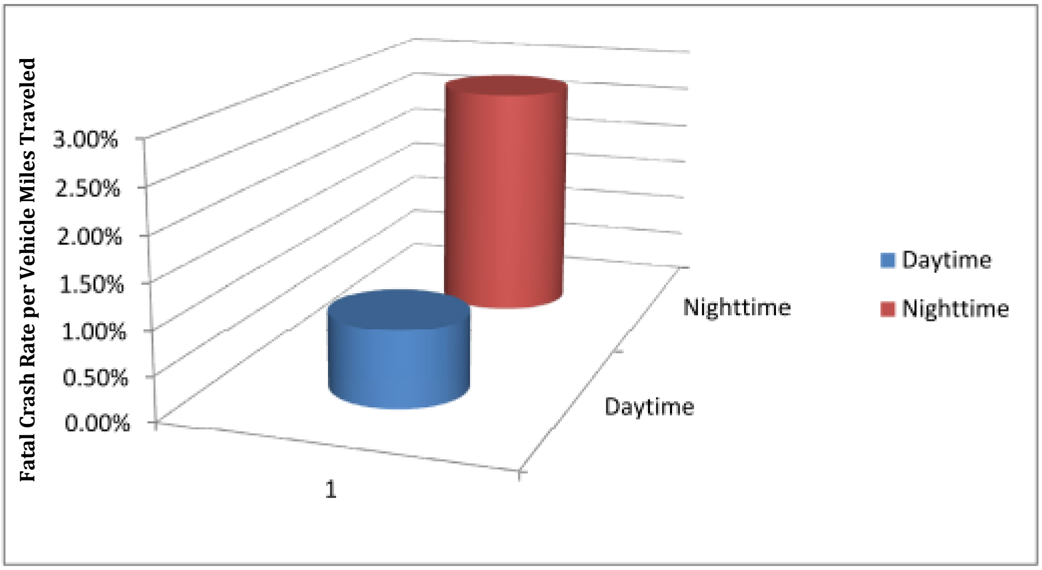

Figure 1a - Fatal Crash Rates per VMT for Day and Night (2009 FARS and NHTS data)

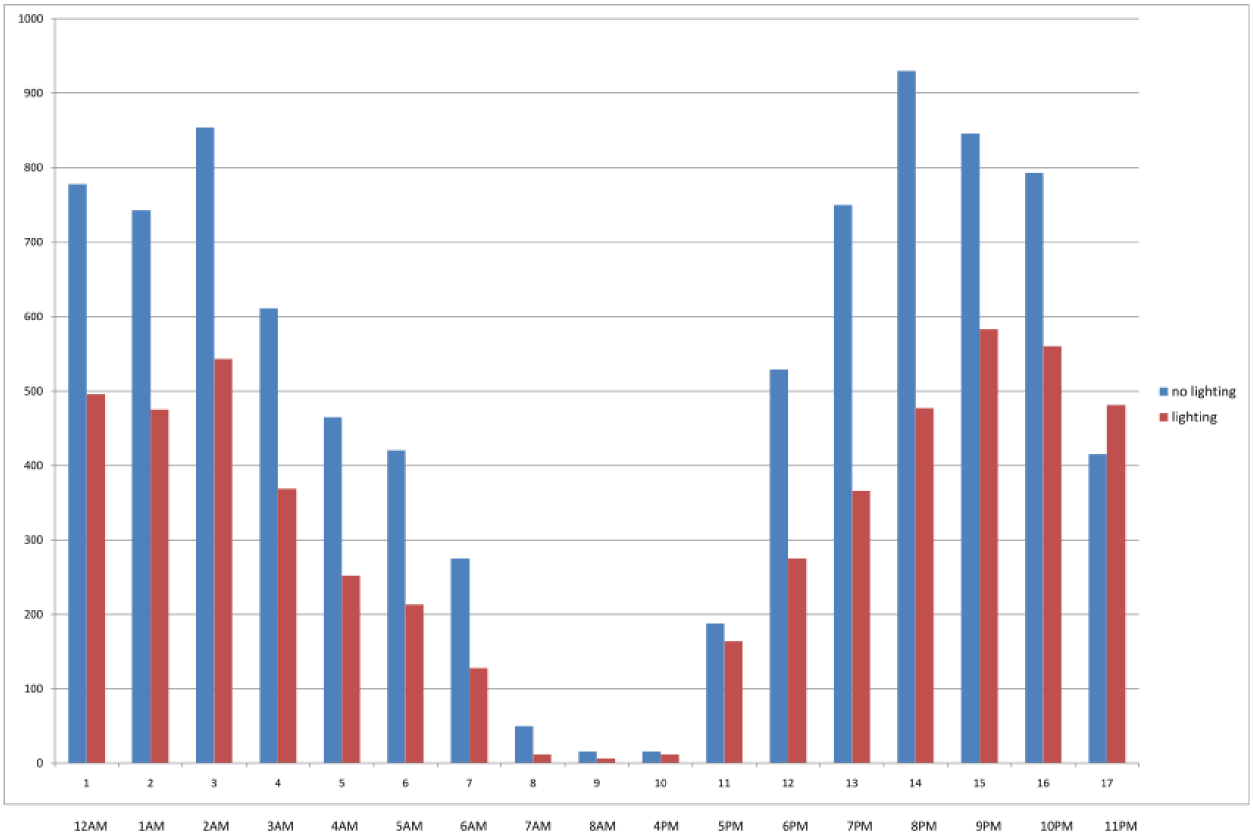

Figure 1b - Fatal Crashes during Darkness by Lighting Condition (2009 FARS data)

On a fundamental level, driving is largely a visual task. Being able to adequately see the road/street ahead and observe conflicting traffic and the behavior of other highway users is integral to the driving task. Lighting significantly improves the visibility of the roadway, increases sight distance, and makes roadside obstacles more noticeable to the driver, and therefore more avoidable.

Roadway lighting is a proven safety countermeasure. The positive safety effects of lighting have been documented in various reports and publications. For example, an FHWA/AASHTO international scan documented (1) that many countries showed a 20 to 30 percent reduction in the number of crashes when lighting was installed. More recently, the FHWA Signalized Intersection Informational Guide (3) reported that adding lighting can reduce nighttime crashes by 50 percent and reduce fatal crashes by 43 percent. There have been many other studies that document similar safety benefits of lighting.

In addition to traffic safety, adequate lighting provides clear benefits in terms of personal security. Roadway lighting often serves the purpose of safeguarding personal safety for pedestrians, bicyclists, and transit users as they travel along and across roadways. Deep shadows or darkness reduce personal security, and walking, bicycling or commercial activities may become uncomfortable or unsafe. Thus, ensuring that the lighting provides minimum acceptable levels of illumination is of great importance to all users of a roadway environment.

Noteworthy research included as part of the FHWA CMF Clearinghouse discussing the effects of road lighting on safety and driver performance includes:

- Elvik and Vaa (2004)(4) reviewed 38 studies comparing the impact of lighting on previously unlit roads and found a 64 percent reduction of fatal crashes, 28 percent reduction in injury crashes, and 17 percent reduction in property-damage-only crashes after the roadways were lit.
- Per Ole Wanvik (2009)(5) used various study methods and literature review to determine the usefulness of road lighting as a countermeasure, and found that the mean effect of roadway lighting is a 28 percent reduction in injury crashes, a 60 percent reduction in fatal crashes, a 45percent reduction in injury crashes involving pedestrians, a 35 percent reduction in injury crashes at rural intersections, and a 50 percent reduction in injury crashes on freeways.

Other research of note include:

- Lipinski and Wortman (1976)(6) showed a 45 percent reduction in the night crash rate at rural at-grade intersections.
- Walker and Roberts (1976)(7) found a 52 percent reduction in nighttime crashes at 47 intersections in a 6-year before-and-after study.
- The Minnesota Local Road Research Board (2006)(8), comparing rural intersection locations before and after lighting had been installed, indicated that 44 percent of the intersections showed a reduction in the number of nighttime crashes after lighting was installed.

2 Federal Guidance and Recommendations Regarding Roadway Lighting

2.1 Determination of Lighting Need

The FHWA administers funding for State roadway lighting projects that meet certain requirements in terms of need. These projects are eligible under Section 148 of Title 23, United States Code (Highway Safety Improvement Program). 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 the IES will be used and met as part of the design.

The FHWA review process requires a warrant analysis, project criteria document, maintenance plan, and MOU

A safety analysis and study showing that a lighting system is a cost-effective safety alternative for the project may also be considered. There are various ways of executing a study of this type. One is to use the AASHTO Highway Safety Manual – 2010 (HSM)(25). The HSM has assembled currently available information on crash frequency and severity so that various improvements to roadways could be quantified and evaluated in terms of their effectiveness. Some of the effects of various treatments, such as geometric improvements or operational changes on roadways, are quantified as Crash Modification Factors (CMFs). CMFs represent the change expected in crash frequency due to a specific change in conditions.

For example, in looking at the impact of highway lighting on all roadway types that previously had no lighting, for nighttime injury crashes, the HSM reports that research has shown a resultant CMF of 0.72 (showing that there would be a reduction of 28 percent in nighttime injury crash types). So if the expected average crash frequency is 10 injury crashes/year for a no-lighting condition, then after implementation of a highway lighting system one would expect 10 X 0.72 CMF = 7.2 injury crashes/year.

The amount of information for crash analysis and evaluation is actively growing and can be found at the Crash Modification Factors Clearinghouse at www.cmfclearinghouse.org. In this clearinghouse the viewer can sort through data by the 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 with a system using a 1-5 star scale.

- Countermeasure: Illumination

CMF	CRF(%)	Quality	Crash Type	Crash Severity	Roadway Type	Area Type	Reference
0.62 [8]	38	★★★★☆	All	Serious injury,Minor injury	Not specified	Not specified	Elvik, R. and Vaa, T., 2004
0.72	28	★★★★☆	All	Serious injury,Minor injury	All	All	Elvik, R. and Vaa, T., 2004
0.69	32	★★★★☆	All	Serious injury,Minor injury	All	Urban	Elvik, R. and Vaa, T., 2004
0.73	27	★★★★☆	All	Serious injury,Minor injury	Principal Arterial Other Freeways and Expressways	All	Elvik, R. and Vaa, T., 2004
0.8	20	★★★☆☆	All	Serious injury,Minor injury	All	Rural	Elvik, R. and Vaa, T., 2004

Figure 2 - Example of Data from the Crash Modification Factors Clearinghouse

2.2 Determination of System Maintenance

FHWA requires that federally funded lighting systems be adequately maintained. The Federal Regulations (23 CFR 1.27) 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."

2.3 Design for Older Drivers

The FHWA has prepared a *Highway Design Handbook for Older Drivers and Pedestrians* (9) that "provides practitioners with a practical information source that links older road user characteristics to highway design, operational, and traffic engineering recommendations by addressing specific roadway features." The handbook "supplements existing standards and guidelines in the areas of highway geometry, operations, and traffic control devices."

Included in the handbook are recommendations for fixed lighting installations at intersections and interchanges for the older driver. This handbook is not intended to constitute a new standard of required practice, but to provide a resource to practitioners and owners during the decision-making process.

The recommendations for intersections include the following:

> Wherever feasible, fixed lighting installations are recommended as follows:
>
> 1. Where the potential for wrong-way movements is indicated through crash experience or engineering judgment.
> 2. Where twilight or nighttime pedestrian volumes are high.
> 3. Where shifting lane alignment, turn-only lane assignment, or a pavement-width transition forces a path-following adjustment at or near the intersection

The handbook also recommends regular cleaning of lamp lenses, and lamp replacement when output has degraded by 20 percent or more of peak performance (based on hours of service and manufacturer's specifications), for all fixed lighting installations at intersections.

The recommendations for interchanges state:

> Complete interchange lighting (CIL) is the preferred practice, but where a CIL system in not feasible to implement, a partial interchange lighting (PIL) system comprised of two high-mast installations (e.g. 18- to 46-m- [60- to 150-ft-] high structures with 2 to 12 luminaires per structure) per ramp is recommended, with one fixture located on the inner ramp curve near the gore, and one fixture located on the outer curve of the ramp, midway through the controlling curvature.

2.4 Railroad Grade Crossings

The FHWA has a handbook (10) dealing with railroad-highway crossings that is meant to "provide a single reference document on prevalent and best practices as well as adopted standards relative to highway-rail grade crossings." The abstract states: "The handbook provides general information on highway-rail crossings; characteristics of the crossing environment and users; and the physical and operational improvements that can be made at highway-rail grade crossings to enhance the safety and operation of both highway and rail traffic over crossing intersections. The guidelines and alternative improvements presented in this handbook are primarily those that have proved effective and are accepted nationwide."

The recommendations for lighting state:

> "Illumination at a crossing may be effective in reducing nighttime crashes. Illuminating most crossings is technically feasible because more than 90 percent of all crossings have commercial power available. Illumination may be effective under the following conditions:
>
> - Nighttime train operations.

- Low train speeds.
- Blockage of crossings for long periods at night.
- Crash history indicating that motorists often fail to detect trains or traffic control devices at night.
- Horizontal and/or vertical alignment of highway approach such that vehicle headlight beam does not fall on the train until the vehicle has passed the safe stopping distance.
- Long dark trains, such as unit coal trains.
- Restricted sight or stopping distance in rural areas.
- Humped crossings where oncoming vehicle headlights are visible under trains.
- Low ambient light levels.
- A highly reliable source of power.

Luminaires may provide a low-cost alternative to active traffic control devices on industrial or mine tracks where switching operations are carried out at night.

Luminaire supports should be placed in accordance with the principles in the Manual for Assessing Safety Hardware (MASH) and NCHRP Report 350.117. If they are placed in the clear zone on a high-speed road, they should be designed with a breakaway base."

2.5 Crosswalks

FHWA has prepared an informational report on crosswalk lighting (FHWA-HRT-08-053: *Informational Report on Lighting Design for Midblock Crosswalks*)(11). The report "provides information on lighting parameters and design criteria that should be considered when installing fixed roadway lighting for midblock crosswalks. The information is based on static and dynamic experiments of driver performance with regard to the detection of pedestrians and surrogates in midblock crosswalks. Experimental condition variables included lamp type (high-pressure sodium and metal halide), vertical illuminance level, color of pedestrian clothing, position of the pedestrians and surrogates in the crosswalk, and the presence of glare. Two additional lighting systems, a Probeam luminaire and ground-installed LEDs, were also evaluated. The research found that a vertical illuminance of 20 lx in the crosswalk, measured at a height of 1.5 m (5 ft) from the road surface, provided adequate detection distances in most circumstances. Although the research was constrained to midblock placements of crosswalks, the report includes a brief discussion of considerations in lighting crosswalks co-located with intersections."

The results of this report were included in the revised IES RP-8 *Standard Practice for Roadway Lighting* (29)

2.6 Roundabouts

FHWA has prepared and informational guide on the design of roundabouts (NCHRP Report No. 672 : Roundabouts: An Informational Guide – Second Edition)(31). In this document it states that illumination is recommended for all roundabouts, including those in rural environments, and gives other advice for mitigation if lighting cannot be provided. The document also includes typical lighting levels for approach roadways which are then summed to determine the roundabout lighting levels.

Basic Terms and Concepts Related to Roadway Lighting

This section includes descriptions of key terms and concepts used in FHWA, AASHTO, and IES documents with regard to lighting, as well as some emerging concepts. Because they are already quantified in AASHTO and IES documents, or are still under study, these concepts are not quantified here. However, they merit close scrutiny in a discussion of roadway lighting.

3 Vision and Fundamental Concepts

3.1 Light and Vision

Many factors influence our ability to see an object while driving. These include the contrast of the object, both photometric and color (i.e., the difference between the object and its background); the driver's adaptation level (impacted by the brightness of the road and surrounds, how much glare is present from approaching vehicles and luminaires, etc.), and how long the driver has to view a hazard. Understanding these factors is vitally important to developing an effective design for roadway and street lighting.

3.1.1 Structure of the Eye

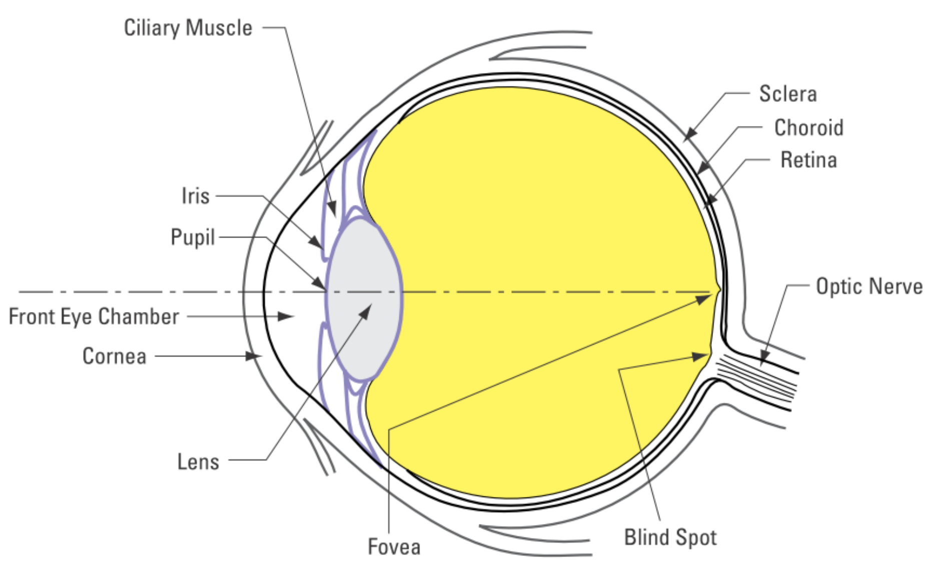

Figure 3 - Fundamental Structure of the Human Eye

The retina contains two types of photoreceptors, rods and cones. Rods, which are most numerous in the retina, are more sensitive and function at a lower light level than the cones. Rods are also not sensitive to color. Cones are sensitive to color and are divided into red (64 percent), green (32 percent), and blue (2 percent) cones. They are concentrated in the macula of the eye with most being in the center of that region, the fovea, which contains only cones.

In the 1990s a third type of photoreceptor was discovered and named "intrinsically photosensitive Retinal Ganglion Cells" (ipRGCs). More research is being conducted into the function of these photoreceptors as they relate to controlling adaptation, restriction of the pupil, and circadian rhythms. Their application to roadway lighting at this time is unclear.

Adaptation of the eye occurs in the retina, as the eye adjusts to the varying brightness of a scene caused by 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, where the adaptation luminance at the eye is 0.001 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 based on conditions, where the adaptation luminance at the eye is between 0.001 cd/m^2 and 3.0 cd/m^2. At this state of adaptation the eye is sensitive to color (more "blue" at the lower end of the adaptation range and more "red" at the higher).
- Photopic Vision – when predominantly cones are active and normal color vision is possible, where the adaptation luminance at the eye is 3.0 cd/m^2 and above.

3.1.2 Spectral Properties

Visible light is a limited range of electromagnetic radiation. Within this range, different wavelengths are seen as different colors. As Figure 4 demonstrates, radiation with a shorter wavelength on the visible spectrum is perceived as more "blue" in color, while radiation with a longer wavelength is perceived as more "red."

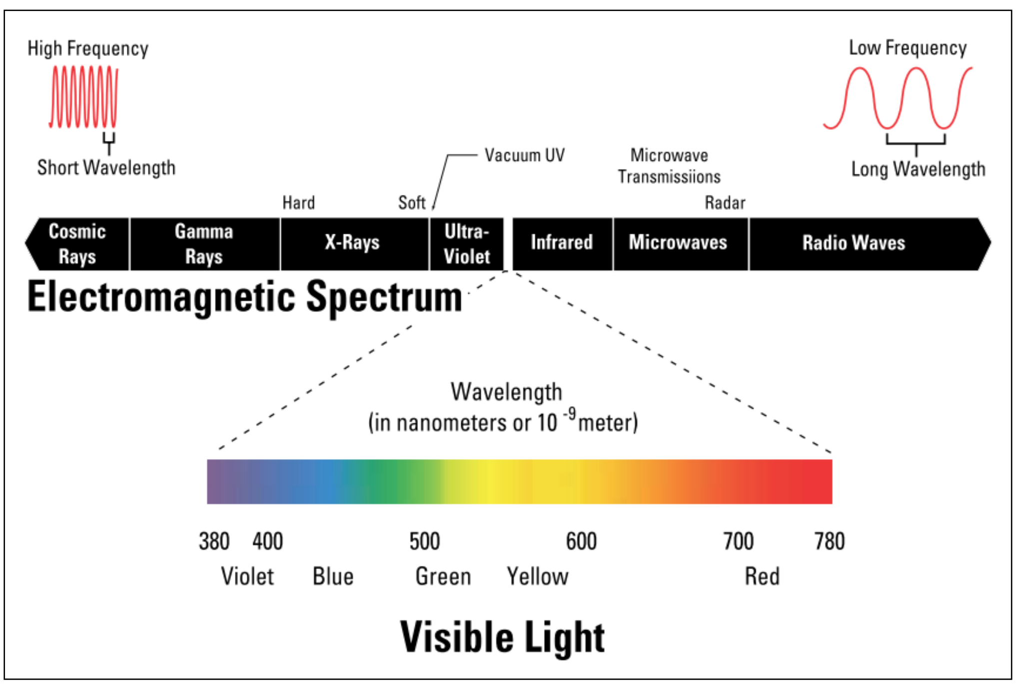

Figure 4 - Electromagnetic Spectrum and Visible Spectrum

The eye has varying sensitivity to different wavelengths within the visible spectrum depending on the state of adaptation.

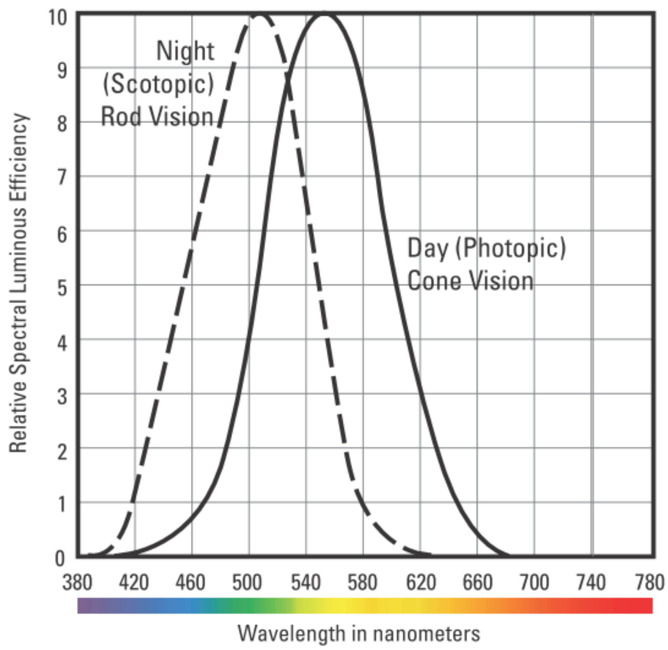

Figure 5 - Eye Sensitivity Curves

The solid curve in Figure 5 is referred to as the V Lambda V(λ) curve. This curve represents the spectral efficiency of a source when the eye is using photopic vision. Sources with wavelengths in the more "yellow" range, such as high pressure sodium, would be rated at a higher power value (lumen) than a source with the same amount of more "blue" content, such as metal halide of higher Correlated Color Temperature (CCT) LED sources.

The dashed curve represents the eye response when using scotopic vision. This shows that at very low light levels sources with more "blue" content would be allocated a higher lumen value.

3.2 Fundamentals of Visibility

3.2.1 Contrast

Objects are seen by "contrast," which is basically the visible difference between an object and its background. From a luminance perspective, an object that is darker than its background will be seen by "negative" contrast, and an object that is sufficiently brighter than its background will be seen by "positive" contrast. In Figure 6, 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 also changes along its length.

The formula for calculating contrast (Weber contrast) is:

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

L_{Object} = Luminance of the object

$L_{Background}$ = Luminance of the background

If we use the luminance values shown in the upper portion of the figure we can calculate that the lower portion of the cylinder, where the roadway is the background, has a contrast of (1-22)/22 = -0.95, with the negative value denoting that it is negative contrast.

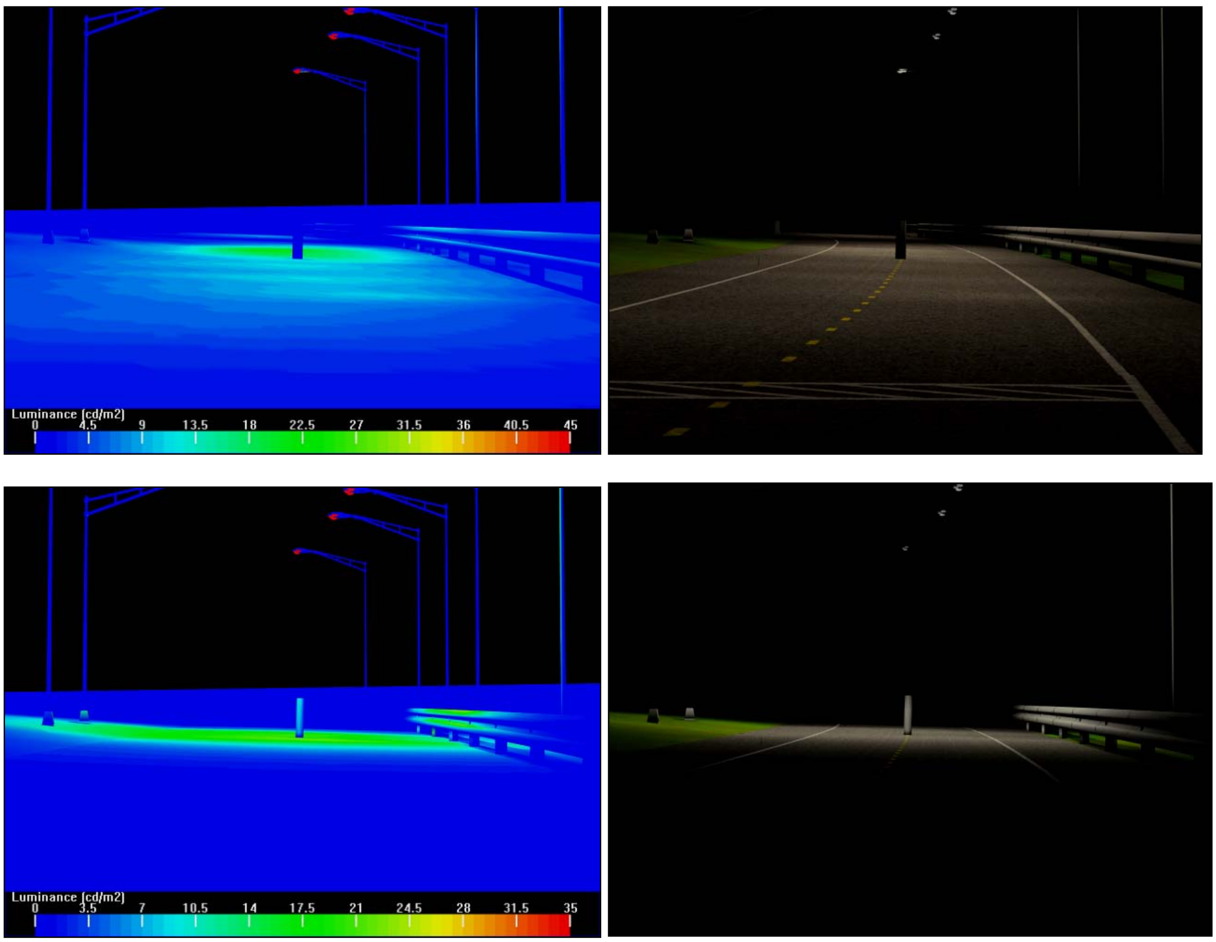

Figure 6 - Luminance Contrast (negative contrast above and positive below)

This contrast value is the luminance contrast of the object. How much contrast you need to see an object depends on a number of things, including the size of the object, how long you look at it, your age, and your adaptation luminance (determined by the luminance of the road, glare from lights, approaching headlights, and ambient lighting levels). This is called the threshold contrast and is based on the probability of detection of an object 50 percent of the time (Adrian, 1989) (12). The purpose of a roadway lighting system is to produce actual contrast of an object on the road greater than the threshold contrast required by the driver for detecting it. Studies

(Blackwell) (13) suggest that good visibility of objects can be achieved if the actual contrast is 3 to 4 times the required threshold contrast. Obtaining this contrast is primarily a function of the lighting placement and optical characteristics.

Applying contrast metrics to roadway lighting, however, is situational and depends on many variables. Designers should nevertheless be aware of the key elements under their control:

- Control/reduce the glare generated by the roadway lighting system.
- If possible, reduction of glare from approaching headlights by median widths and treatments will increase visibility.

Color also provides additive contrast benefits. As shown in Figure 7, the visibility of objects and pedestrians can be improved by color contrast. This is dependent upon the color of the object or clothing as well as the color rendering ability of the source used for roadway lighting. In looking at the pedestrian's red shirt or the approaching red vehicle in the left frame of Figure 7, we can tell that color contrast provides additional visibility. This effect is quite variable, however, so it is not quantified for roadway lighting.

Figure 7 - Effect of Color Contrast

3.2.2 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 driver proceeds, the adaptation level is constantly changing ("transient adaptation"). Roadway lighting thus aids the eye in adapting to an increased level of luminance than can be provided by headlights alone. Bright sources create other effects, collectively termed "glare," which should be avoided as much as is practical.

Disability Glare

Light rays passing through the eye are slightly scattered, primarily because of diffusion in the lens and the vitreous humor that fills the anterior chamber of the eye. When a light source of high intensity 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 task and background luminance, thus having the effect of reducing contrast. The effect is termed “disability glare” or “veiling luminance,” and it may be numerically evaluated by expressing the luminance of the equivalent luminous veil. A well-known example of this is trying to see beyond oncoming headlights at night. Because of contrast reduction by disability glare, visibility is decreased. Increasing luminance will counteract this effect by reducing the eye’s contrast sensitivity. A well designed roadway lighting system will minimize glare by employing luminaires that have proper optical design (e.g., cutoff or full-cutoff). Disability glare should be limited to the recommended veiling luminance ratios included in the AASHTO (26) and IES(28) recommendations.

Discomfort Glare

Discomfort glare is a further result of overly bright light sources in the field of view, and causes a sense of pain or annoyance. While its exact cause is not known, it may result from pain in the muscles that cause closing of 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. Discomfort glare, which can cause effects from an increased blink rate to tears and pain, does not reduce visibility. It is also generally accepted that reducing disability glare will reduce discomfort glare. It is possible, however, to reduce discomfort glare and increase disability glare. North American roadway lighting standards do not specify numerical limits for discomfort glare. Methods exist to quantify discomfort glare for roadway lighting, but are mostly subjective. Also, no instrument has been developed for the measurement of discomfort glare. The Commission Internationale de l’Eclairage (International Commission on Illumination - CIE) uses a “Glaremark System,” which is a graphical method using a scale of 1 to 10 to rate lighting systems. However, there is no current practical use or application of this method.

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

Nuisance Glare

The presence of extraneous light in the field of view may cause a nuisance or distraction to the driver, independent of the effects of disability and discomfort. Bright light sources tend to cause distraction, and the eye may be drawn to them. Lighting that is used for advertising, for example, may cause visual clutter and add complexity to the scene, making the driving task more challenging. There is no defined method or measurement system for assessing nuisance glare.

3.2.3 Perception-Reaction Time

Many components make up perception-reaction time. A motorist, in order to stop or avoid a hazard or person on a roadway, must first detect the object's presence, recognize or otherwise assess the object, then react to that determination. The mechanical operation of braking/steering mechanisms, as well as road/tire/vehicle performance conditions, also factor into perception-reaction time.

From a reaction time perspective, key elements include whether a situation is expected, cognitive load and distractions, personal physical response attributes, age, and other factors, Green (22) classified reaction times, adding an additional condition of "surprise", in the following way:

- Expected - The driver is alert and aware of the good possibility that braking will be necessary. This is the absolute best reaction time possible. The best estimate is 0.7 seconds (AASHTO Green Book (14) states it as approx. 0.6 seconds). Of this, 0.5 is perception and 0.2 is movement, the time required to release the accelerator and to depress the brake pedal.
- Unexpected - The driver detects a common road signal such as a brake from the car ahead or from a traffic signal. Reaction time is somewhat slower, about 1.25 seconds (AASHTO Green Book (14) states it is approx. 35% longer than the expected condition). This is due to the increase in perception time to over a second with movement time still about 0.2 second.
- Surprise - The driver encounters a very unusual circumstance, such as a pedestrian or another car crossing the road in the near distance. T here is extra time needed to interpret the event and to decide upon response. Reaction time depends to some extent on the distance to the obstacle and whether it is approaching from the side and is first seen in peripheral vision. The best estimate is 1.5 seconds for side incursions and perhaps a few tenths of a second faster for straight-ahead obstacles. Perception time is 1.2 seconds while movement time lengthens to 0.3 second."

For example a person traveling at 55mph is moving at approximately 80 ft/sec. The distance traveled during reaction time alone can be anywhere from 40' to 120'. When this is added to the distance covered during actual stopping, the total can be quite significant.

The AASHTO Policy on Geometric Design of Streets and Highways (14) include a method for determining stopping distance based on a number of factors including reaction time. Figure 8 shows examples of estimated Safe Stopping Sight Distance (SSSD) based on that AASHTO method with modifiers showing the impact of grades.

Metric							U.S. Customary						
Design Speed (km/h)	Stopping Sight Distance (m)						Design Speed (mph)	Stopping Sight Distance (ft)					
	Downgrades			Upgrades				Downgrades			Upgrades		
	3 %	6 %	9 %	3 %	6 %	9 %		3 %	6 %	9 %	3 %	6 %	9 %
20	20	20	20	19	18	18	15	80	82	85	75	74	73
30	32	35	35	31	30	29	20	116	120	126	109	107	104
40	50	50	53	45	44	43	25	158	165	173	147	143	140
50	66	70	74	61	59	58	30	205	215	227	200	184	179
60	87	92	97	80	77	75	35	257	271	287	237	229	222
70	110	116	124	100	97	93	40	315	333	354	289	278	269
80	136	144	154	123	118	114	45	378	400	427	344	331	320
90	164	174	187	148	141	136	50	446	474	507	405	388	375
100	194	207	223	174	167	160	55	520	553	593	469	450	433
110	227	243	262	203	194	186	60	598	638	686	538	515	495
120	263	281	304	234	223	214	65	682	728	785	612	584	561
130	302	323	350	267	254	243	70	771	825	891	690	658	631
							75	866	927	1003	772	736	704
							80	965	1035	1121	859	817	782

Figure 8 - Examples of AASHTO Calculated Safe Stopping Sight Distance with Variation Due to Grade

Although stopping distances are not applied to roadway lighting, with the exception of tunnel lighting systems, the distances shown demonstrate one of the benefits of roadway lighting. If we assume most low beam vehicle headlights have an effectiveness of approximately 300’ in front of the vehicle (Green, 2008) (23), speeds of 40 mph and above have stopping distances greater than that distance. In order for a driver to detect a pedestrian or road hazard in time to stop at higher speeds, the roadway lighting system needs to provide that necessary visibility.

At speeds above 40mph roadway lighting provides visibility of objects beyond the effective range of headlights

3.2.4 Spectral Effect Models

As discussed in the Light and Vision section of this handbook, the color of light (wavelength) produces different responses in the eye depending on its state of adaptation. There were established response curves for adaptation in the photopic and scotopic states, but none established for the mesopic state which would change depending on the adaptation luminance. However, models have been developed in recent years suggesting modifying factors which can be applied to adjust the calculated photopic luminance value to the expected mesopic luminance based on the source spectral distribution (Scotopic/Photopic –S/P- ratio). Ongoing discussion and further research is being performed in this area so these models are provided as information.

MOVE – Mesopic Optimisation of Visual Efficiency

The MOVE method was developed from tests conducted at the TNO (Netherlands), University of Veszprem (Hungary), Darmstadt University of Technology (Germany), City University (UK), and Helsinki University of Technology (Finland). From this research modifiers were developed for adaptation luminance and source S/P ratios of various values. Those modifiers are shown in Figure 9.

As an example, a high pressure sodium roadway fixture might have an S/P ratio of around 0.6; if lamped with pulse start metal halide it might be around 1.4; and with an LED roadway fixture it may be 2.0. So using the MOVE multipliers, if we assume the adaptation luminance is 1 cd/m^2 the mesopic luminance for the HPS luminaire would be approximately 0.93 cd/m^2, the MH luminaire would be approximately 1.06 cd/m^2, and the LED luminaire would be approximately 1.15 cd/m^2.

S/P	0.01	0.03	0.1	0.3	1	3	10
0.25	0.0025	0.0075	0.0640	0.2331	0.8735	2.8108	9.9095
0.35	0.0035	0.0133	0.0698	0.2430	0.8914	2.8372	9.9220
0.45	0.0045	0.0172	0.0751	0.2525	0.9090	2.8632	9.9344
0.55	0.0055	0.0201	0.0801	0.2616	0.9262	2.8888	9.9466
0.65	0.0065	0.0226	0.0848	0.2706	0.9431	2.9141	9.9587
0.75	0.0075	0.0249	0.0894	0.2792	0.9597	2.9391	9.9706
0.85	0.0085	0.0270	0.0937	0.2877	0.9760	2.9637	9.9825
0.95	0.0095	0.0290	0.0979	0.2959	0.9921	2.9880	9.9942
1.05	0.0105	0.0309	0.1020	0.3040	1.0079	3.0120	10.0058
1.15	0.0114	0.0328	0.1060	0.3119	1.0234	3.0356	10.0173
1.25	0.0122	0.0345	0.1099	0.3197	1.0387	3.0590	10.0286
1.35	0.0130	0.0362	0.1136	0.3273	1.0538	3.0822	10.0399
1.45	0.0138	0.0378	0.1173	0.3348	1.0686	3.1050	10.0510
1.55	0.0146	0.0394	0.1209	0.3421	1.0833	3.1276	10.0621
1.65	0.0153	0.0410	0.1245	0.3493	1.0978	3.1499	10.0730
1.75	0.0160	0.0425	0.1280	0.3565	1.1121	3.1720	10.0838
1.85	0.0167	0.0440	0.1314	0.3635	1.1262	3.1939	10.0945
1.95	0.0174	0.0455	0.1348	0.3704	1.1401	3.2155	10.1051
2.05	0.0180	0.0469	0.1381	0.3772	1.1539	3.2368	10.1156
2.15	0.0187	0.0483	0.1413	0.3840	1.1675	3.2580	10.1260
2.25	0.0193	0.0497	0.1445	0.3906	1.1810	3.2789	10.1363
2.35	0.0199	0.0511	0.1477	0.3972	1.1943	3.2997	10.1466
2.45	0.0205	0.0524	0.1509	0.4037	1.2075	3.3202	10.1567
2.55	0.0211	0.0538	0.1539	0.4101	1.2205	3.3405	10.1667
2.65	0.0217	0.0551	0.1570	0.4165	1.2334	3.3606	10.1766
2.75	0.0223	0.0564	0.1600	0.4228	1.2462	3.3806	10.1865

Figure 9 - Modifiers from MOVE Model

Rea et al - Unified System of Photometry

The unified system of photometry was developed by conducting a field study on a test road where subjects were asked to identify the orientation of various size Landolt rings displayed on small targets in the center of the roadway. Their reaction time was measured, as well as their subjective impressions of visibility. These results were then compared with various models for photometry in the mesopic region. The comparative models used are shown in Figure 10.

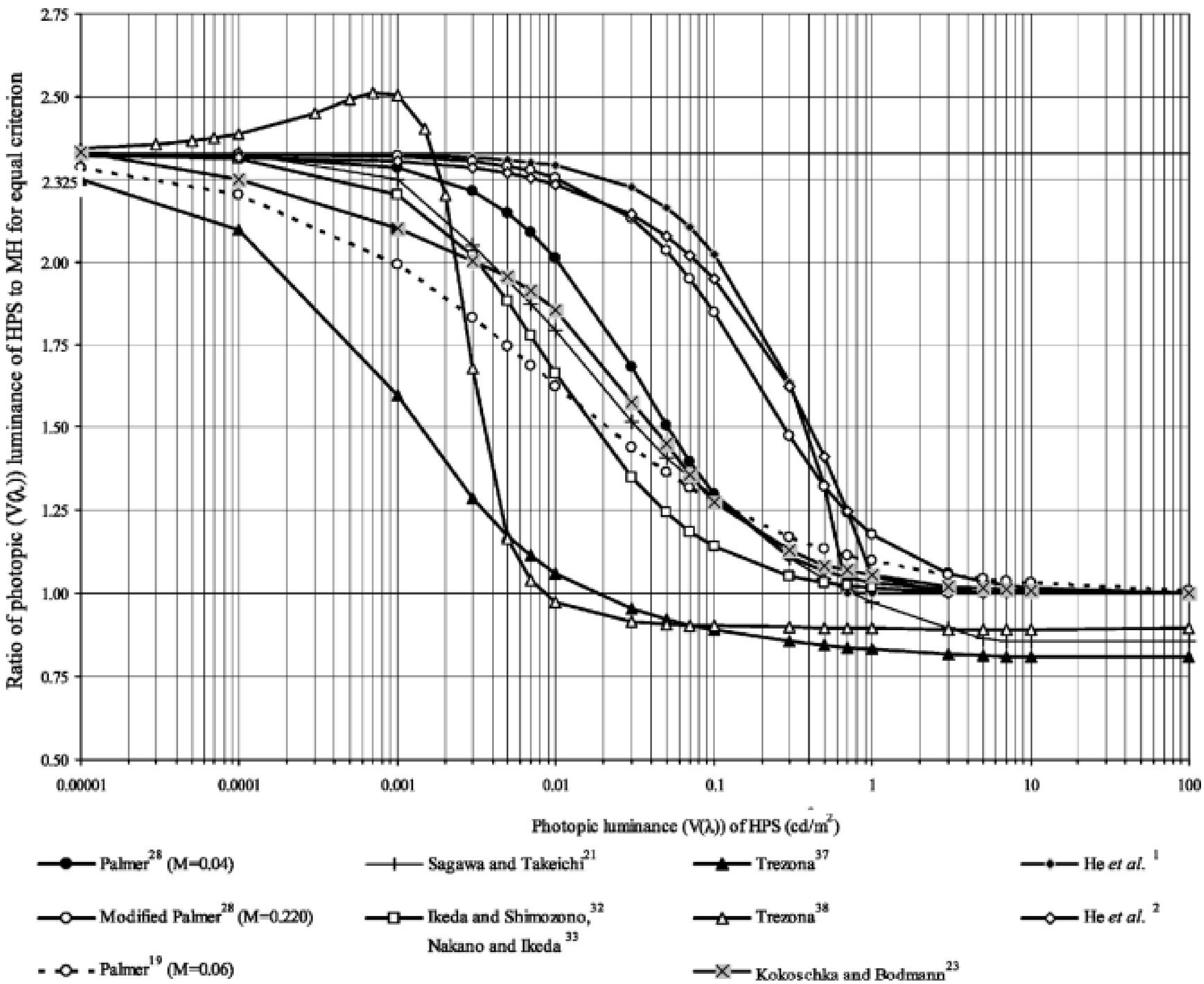

Figure 10 - Figure from Rea's "A proposed system of photometry" - Lighting Res. Tech. 36.2 (2004 pp. 85-111)

Rea's research also included a condensed summary of other research and models (shown in Figure 11) to allow for easy comparison'

Author	Method	Stimuli	Size of target	Position	Adaptation light levels	Model to obtain mesopic luminance
Palmer[19,30]	Heterochromatic brightness matching; monocular Maxwellian view of a 5°, 15° and 45° horizontally bisected circular field; 21° white surround	Nearly monochromatic to broad spectrum sources, covering the spectrum, reference tungsten light 2042 K	5°, 15° and 45°	foveal	0.000316 to 0.316 cd/m^2 in 0.5 log unit steps	Empirical, non-linear average of photopic and scotopic luminance, with a variable *M* that depends on visual size. Revised model using the same variables as the original
Ikeda and Shimozono,[32] Nakano and Ikeda[33]	Heterochromatic brightness matching; two-channel Maxwellian view of a 10° bipartie field	Four pairs of monochromatic combinations (460, 630; 490, 610; 470, 580; 500, 570mm) at different proportions from all of one to all of the other, white reference	10°	foveal	0.01, 0.1, 1, 10, 100 Td	Set of equations, with parameters defined for a 7 mm pupil and 10° field of view.
Sagawa and Takeichi[20,21]	Heterochromatic brightness matching; two-channel Maxwellian view of a 10° bipartite field; 3 mm artificial pupil	Monochromatic, 400 to 700 nm in 10 nm steps	10°	foveal	0.01 to 100 Td in 0.5 log unit steps	Graphic determination of mesopic luminance; uses brightness luminous efficiency functions normalized at 570 nm. One coefficient method for broad spectrum sources, two coefficients for monochromatic sources.
Kokoschka,[36] Kokoschka and Bodmann[23]	Brightness matching by direct comparison; bipartite fields of size 3°, 9.5° and 64°	Monochromatic sources from 400 to 700mm; reference 530 nm	3°, 9.5°, 64°	foveal	0.003 to 30 Td in one log unit steps	Iterative or graphic; utilizes four variables, one for each photoreceptor (rods and *L*, *M* and *S* cones)
Trezona[37,38]	Brightness matching; Maxwellian view of a 10° bipartite field	41 monochromatic and broad spectrum sources; reference 588 nm	10°	foveal	17 levels, from scotopic to photopic in 0.3 log unit steps	Set of equations based on hyperbolic tangent functions; utilizes four variables, one for each photoreceptor (rods and L, M and S cones); Trezona, 1991 presents refinements to previous model.
He *et al.*[1]	Reaction time; monocular view	MH and HPS light sources, target contrast 0.7	2°	foveal and 15° off-axis	0.003–10 cd/m^2	Iterative process; upper threshold of mesopic luminance 0.6 cd/m^2
He *et al.*[2]	Reaction time; binocular view	Monochromatic (436, 470, 510, 546, 630 nm), reference 589 nm, target contrast 0.7	2°	12° off-axis	0.3, 3, 10 Td	Iterative process; upper threshold of mesopic luminance 21 Td

Figure 11 - Summary of Various Studies of Vision at Mesopic Light Levels

(Rea et al, "A proposed unified system of photometry") (15)

The results of the model recommended by Rea (15) show an impact of using higher S/P ratio sources of moderate impact for most recommended roadway lighting levels with no difference in the visual efficacy multiplier for levels freeway lighting levels of around 0.6 cd/m^2 and more significant difference of over 20% for the lowest recommended lighting level streets like low pedestrian volume residential designed to 0.3 cd/m^2.

Figure 12 shows some S/P ratios from various light sources as reference. Figure 13 shows the different unified values which would result from applying Rea's unified method of photometry.

Low pressure sodium	0.25
High pressure sodium (HPS) 250 W clear	0.63
HPS 400 W clear	0.66
HPS 400 W coated	0.66
Mercury vapor (MV) 175 W coated	1.08
MV 400 W clear	1.33
Incandescent	1.36
Halogen headlamp	1.43
Fluorescent Cool White	1.48
Metal halide (MH) 400 W coated	1.49
MH 175 W clear	1.51
MH 400 W clear	1.57
MH headlamp	1.61
Fluorescent 5000 K	1.97
White LED[1] 4300 K	2.04
Fluorescent 6500 K	2.19

Figure 12 – Table showing S/P Ratios of Commercially Available Light Sources
(LRC ASSIST - Outdoor Lighting: Visual Efficacy, Volume 6, Issue 2, January 2009)

For example, if the photopic luminance level is 0.3 cd/m^2 is then under a source with an S/P ratio like low pressure sodium (S/P of 0.25) the equivalent mesopic luminance level would be 0.2012 cd/m^2. If instead the source was a metal halide lamp with an S/P ratio of 1.55, then the mesopic luminance level would be 0.3402 cd/m^2 .

	Base light level (photopic luminance (cd/m^2))											
S/P	**0.14**	**0.16**	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**	**0.34**	**0.36**
0.25	0.0573	0.0704	0.0849	0.1009	0.1184	0.1373	0.1574	0.1788	0.2012	0.2246	0.2487	0.2736
0.35	0.0728	0.0877	0.1037	0.1209	0.1392	0.1585	0.1787	0.1998	0.2217	0.2442	0.2674	0.2912
0.45	0.0864	0.1026	0.1197	0.1377	0.1565	0.1760	0.1963	0.2172	0.2387	0.2607	0.2831	0.3060
0.55	0.0983	0.1156	0.1335	0.1521	0.1713	0.1911	0.2113	0.2320	0.2532	0.2747	0.2966	0.3188
0.65	0.1092	0.1273	0.1459	0.1649	0.1844	0.2043	0.2245	0.2451	0.2659	0.2871	0.3085	0.3301
0.75	0.1191	0.1379	0.1570	0.1764	0.1961	0.2161	0.2363	0.2567	0.2773	0.2981	0.3190	0.3401
0.85	0.1283	0.1477	0.1672	0.1869	0.2068	0.2268	0.2470	0.2672	0.2876	0.3081	0.3286	0.3492
0.95	0.1368	0.1566	0.1765	0.1965	0.2165	0.2365	0.2566	0.2767	0.2969	0.3170	0.3372	0.3574
1.05	0.1448	0.1651	0.1853	0.2054	0.2255	0.2456	0.2656	0.2856	0.3055	0.3254	0.3452	0.3651
1.15	0.1523	0.1730	0.1935	0.2138	0.2339	0.2540	0.2739	0.2937	0.3135	0.3331	0.3526	0.3721
1.25	0.1593	0.1803	0.2010	0.2215	0.2417	0.2617	0.2816	0.3013	0.3208	0.3402	0.3594	0.3786
1.35	0.1661	0.1873	0.2082	0.2288	0.2491	0.2691	0.2888	0.3084	0.3277	0.3469	0.3658	0.3847
1.45	0.1724	0.1940	0.2150	0.2357	0.2560	0.2759	0.2956	0.3150	0.3341	0.3531	0.3718	0.3903
1.55	0.1785	0.2003	0.2215	0.2422	0.2625	0.2824	0.3020	0.3213	0.3402	0.3590	0.3774	0.3957
1.65	0.1843	0.2063	0.2276	0.2484	0.2687	0.2886	0.3081	0.3272	0.3460	0.3645	0.3827	0.4007
1.75	0.1899	0.2120	0.2335	0.2543	0.2746	0.2944	0.3138	0.3328	0.3514	0.3697	0.3877	0.4054
1.85	0.1952	0.2175	0.2391	0.2599	0.2802	0.3000	0.3193	0.3381	0.3566	0.3747	0.3924	0.4099
1.95	0.2003	0.2228	0.2444	0.2653	0.2856	0.3053	0.3244	0.3432	0.3615	0.3794	0.3969	0.4141
2.05	0.2053	0.2279	0.2496	0.2705	0.2907	0.3103	0.3294	0.3480	0.3661	0.3838	0.4012	0.4182
2.15	0.2100	0.2327	0.2545	0.2754	0.2956	0.3152	0.3341	0.3526	0.3706	0.3881	0.4052	0.4220
2.25	0.2146	0.2374	0.2592	0.2801	0.3003	0.3198	0.3387	0.3570	0.3748	0.3922	0.4091	0.4257
2.35	0.2190	0.2419	0.2637	0.2847	0.3048	0.3242	0.3430	0.3612	0.3789	0.3960	0.4128	0.4291
2.45	0.2233	0.2463	0.2682	0.2891	0.3092	0.3285	0.3472	0.3652	0.3828	0.3998	0.4164	0.4325
2.55	0.2275	0.2505	0.2724	0.2933	0.3134	0.3326	0.3512	0.3691	0.3865	0.4034	0.4198	0.4357
2.65	0.2315	0.2546	0.2765	0.2974	0.3174	0.3366	0.3551	0.3729	0.3901	0.4068	0.4230	0.4388
2.75	0.2354	0.2585	0.2805	0.3014	0.3213	0.3404	0.3588	0.3765	0.3936	0.4101	0.4261	0.4417

	Base light level (photopic luminance (cd/m^2))											
S/P	**0.38**	**0.40**	**0.42**	**0.44**	**0.46**	**0.48**	**0.50**	**0.52**	**0.54**	**0.56**	**0.58**	**0.60**
0.25	0.2990	0.3250	0.3514	0.3782	0.4053	0.4327	0.4604	0.4883	0.5164	0.5446	0.5730	0.60
0.35	0.3154	0.3400	0.3650	0.3904	0.4160	0.4419	0.4681	0.4944	0.5210	0.5477	0.5745	0.60
0.45	0.3293	0.3529	0.3768	0.4010	0.4254	0.4500	0.4749	0.4999	0.5251	0.5504	0.5759	0.60
0.55	0.3413	0.3640	0.3870	0.4102	0.4336	0.4571	0.4809	0.5047	0.5287	0.5528	0.5771	0.60
0.65	0.3519	0.3739	0.3961	0.4184	0.4409	0.4635	0.4862	0.5091	0.5320	0.5551	0.5782	0.60
0.75	0.3613	0.3827	0.4042	0.4258	0.4474	0.4692	0.4911	0.5130	0.5350	0.5571	0.5792	0.60
0.85	0.3700	0.3907	0.4116	0.4325	0.4534	0.4745	0.4955	0.5166	0.5378	0.5589	0.5802	0.60
0.95	0.3777	0.3980	0.4182	0.4385	0.4589	0.4792	0.4995	0.5199	0.5403	0.5606	0.5810	0.60
1.05	0.3849	0.4047	0.4244	0.4442	0.4639	0.4836	0.5033	0.5229	0.5426	0.5622	0.5818	0.60
1.15	0.3915	0.4109	0.4301	0.4494	0.4685	0.4876	0.5067	0.5257	0.5447	0.5637	0.5826	0.60
1.25	0.3976	0.4165	0.4354	0.4541	0.4728	0.4914	0.5099	0.5283	0.5467	0.5650	0.5833	0.60
1.35	0.4033	0.4219	0.4403	0.4586	0.4768	0.4949	0.5129	0.5307	0.5486	0.5663	0.5839	0.60
1.45	0.4087	0.4268	0.4449	0.4628	0.4805	0.4981	0.5156	0.5330	0.5503	0.5675	0.5845	0.60
1.55	0.4137	0.4315	0.4492	0.4667	0.4840	0.5012	0.5182	0.5351	0.5519	0.5686	0.5851	0.60
1.65	0.4184	0.4359	0.4532	0.4703	0.4873	0.5040	0.5207	0.5371	0.5534	0.5696	0.5857	0.60
1.75	0.4228	0.4400	0.4570	0.4738	0.4904	0.5067	0.5229	0.5390	0.5549	0.5706	0.5862	0.60
1.85	0.4271	0.4440	0.4606	0.4771	0.4933	0.5093	0.5251	0.5408	0.5562	0.5715	0.5867	0.60
1.95	0.4310	0.4477	0.4640	0.4802	0.4960	0.5117	0.5272	0.5424	0.5575	0.5724	0.5871	0.60
2.05	0.4348	0.4512	0.4673	0.4831	0.4987	0.5140	0.5291	0.5440	0.5587	0.5732	0.5876	0.60
2.15	0.4384	0.4545	0.4703	0.4859	0.5011	0.5162	0.5309	0.5455	0.5599	0.5740	0.5880	0.60
2.25	0.4419	0.4577	0.4733	0.4885	0.5035	0.5182	0.5327	0.5469	0.5610	0.5748	0.5884	0.60
2.35	0.4451	0.4607	0.4760	0.4910	0.5057	0.5202	0.5343	0.5483	0.5620	0.5755	0.5888	0.60
2.45	0.4483	0.4636	0.4787	0.4934	0.5079	0.5220	0.5359	0.5496	0.5630	0.5762	0.5892	0.60
2.55	0.4513	0.4664	0.4813	0.4957	0.5099	0.5238	0.5375	0.5508	0.5639	0.5768	0.5895	0.60
2.65	0.4541	0.4691	0.4837	0.4980	0.5119	0.5255	0.5389	0.5520	0.5649	0.5775	0.5899	0.60
2.75	0.4569	0.4716	0.4860	0.5000	0.5138	0.5272	0.5403	0.5531	0.5657	0.5781	0.5902	0.60

Figure 13 - Values of Unified Luminance for Various S/P ratios

In 2010 the Commission Internationale de l'Eclairage (CIE) issued the publication *CIE 191: Recommended System for Mesopic Photometry Based on Visual Performance*, which is essentially a compromise of the Rea and the MOVE methods.

At this time, FHWA does not make any recommendations concerning spectral effects or their associated models. Research is still underway and the results of this research are being worked into recommendations made by AASHTO and IES.

Higher S/P ratio "white" light sources do have an effect on visibility. The proper application of this effect is still under study.

3.3 Lighting Metrics

Illuminance

Illuminance is the amount of light that falls onto a surface. Illuminance is measured as the amount of lumens per unit area either in footcandles (lumens/ft^2) or in lux (lumens/m^2). Illuminance is variable by the square of the distance from the source. As a lighting metric, illuminance is simple to calculate and measure, not needing to take into account the reflection properties of the roadway surface and only requiring a fairly inexpensive illuminance meter 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 will be or how well a person can see.

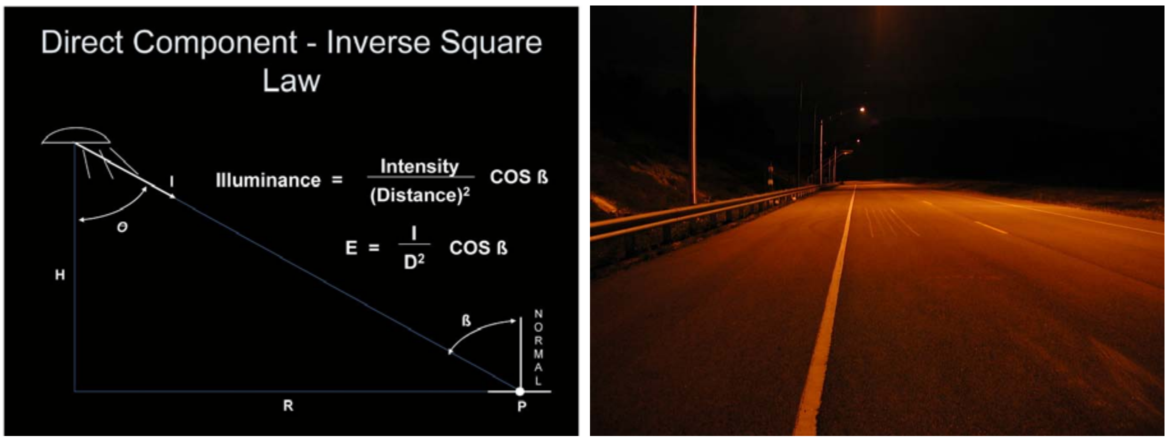

Figure 14 - Inverse Square Law Calculation at a Point

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. As it relates to roadway lighting, vertical illuminance is a reasonable criterion for determining the amount of light landing on pedestrians. It is also used as a criterion in determining adequate illumination for facial recognition. For roadway applications, vertical illuminance is most often used at a 1.5 meter height above the roadway or sidewalk. The 1.5 meter height is a commonly used metric in outdoor criteria as the height of a pedestrian’s face.

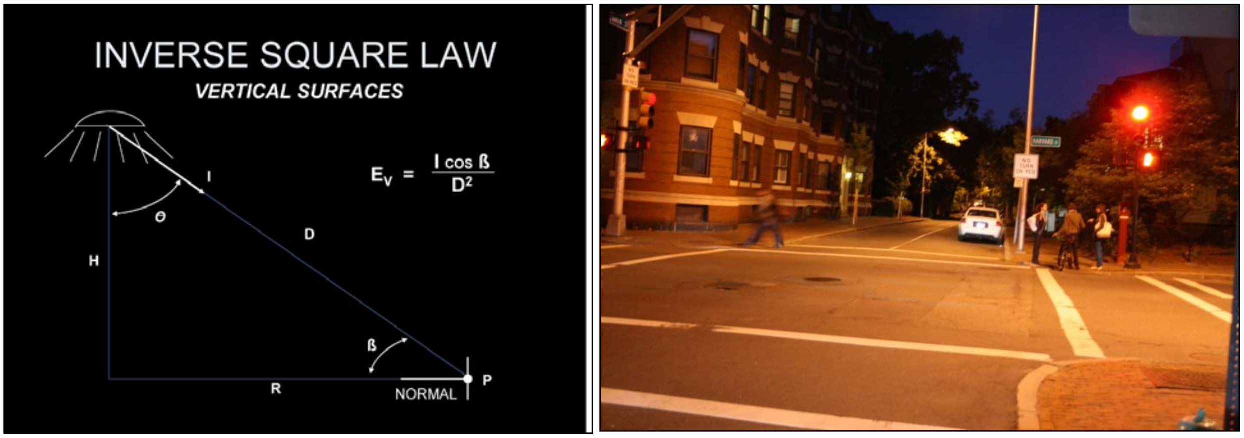

Figure 15 - Calculation of Vertical Illuminance

Luminance

Luminance is the amount of light that reflects from a surface in the direction of the observer. It is often referred to as the "brightness" of the surface, although apparent brightness has a number of other factors to take into consideration. It is, however, a more complete 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 towards the driver.

In Figure 16, the roadway has the same illuminance values across both lanes. The luminance values, however, are twice as high for the right lane, which is how the road appears to an observer

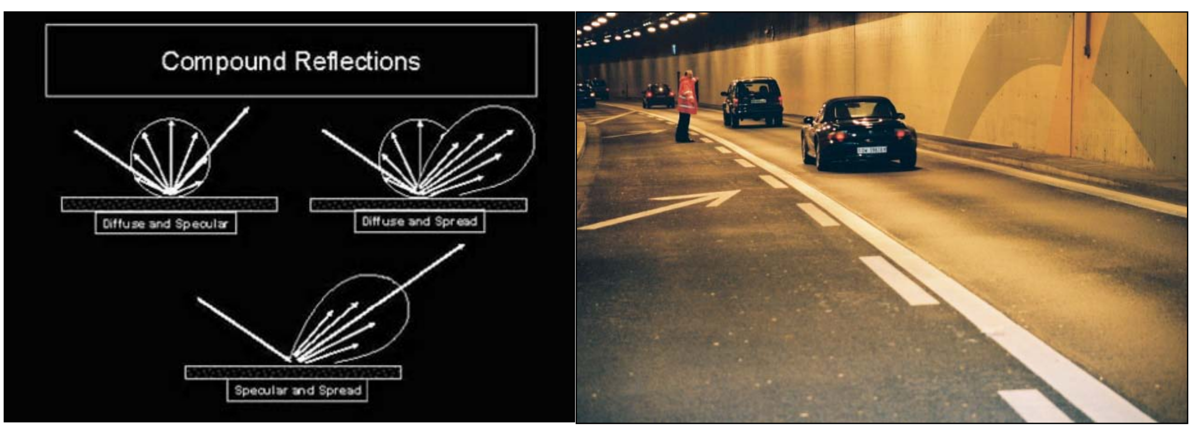

Figure 16 - Pavement Reflective Differences

Veiling Luminance Ratio

The veiling luminance ratio is a metric used by the IES and AASHTO to determine the amount of glare generated by a lighting system. The ratio is the maximum veiling luminance at the driver's eye divided by the average pavement luminance of the roadway. Because glare is a function of adaptation luminance, the road is used as the assumed scene from which the luminance reaches the eye.

For example, if a roadway lighting system was designed to a lighting level of 0.6 cd/m^2 using 250watt high pressure sodium fixtures of a certain distribution type, the glare would be a certain calculated veiling luminance ratio with the maximum veiling luminance probably being generated from the closest luminaire and the average roadway luminance being 0.6 cd/m^2. If the system was changed to use 400 watt lamps, you could expect the veiling luminance to increase by the change in output. But since the scene brightness (roadway luminance) will also increase by the proportional change in output, the veiling luminance ratio or glare of the lighting system will not change.

There are also other metrics which are used to express glare. CIE uses Threshold Increment (TI) as its primary method. TI is based on threshold contrast, which is the amount of contrast between and object and its background when the probability of detection is 50 percent. When glare is introduced, the probability of an object being seen drops below 50 percent, therefore not reaching threshold contrast, which means the contrast needs to be increased. TI is the percentage the contrast needs to be increased in order to achieve threshold contrast again.

Warranting Criteria

This section includes example 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 as well as for intersections have been included in this section for information.

It is important to note that warrants do not represent a requirement to provide lighting. Satisfaction of a lighting warrant shall not in itself require the installation of a lighting system.

4 Analysis for Lighting Needs

4.1 Warrants

Lighting warrants assist in evaluating locations where lighting will maximize benefit based on defined conditions or rating systems. Meeting these warrants does not obligate the state or other agencies to provide lighting. Conversely, using engineering judgment in addition to warrants, considering things such as roadway geometry, high crash rates, or frequent occurrences of poor weather conditions such as rain, fog, ice, or snow, may influence a decision on whether to install lighting.

Warrants indicate where lighting may be beneficial, but should not be interpreted as an absolute indication of whether or not lighting is required. The need for lighting should be determined by sound engineering judgment and rests with the agency having jurisdiction over the roadway.

Warrants do not represent a requirement to light, only an indication of situations where lighting should be investigated

4.2 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 (CFL), Complete Interchange Lighting (CIL) and Partial Interchange Lighting (PIL) based on warrant conditions including:

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

AASHTO believes it is desirable to provide lighting on long bridges in urban and suburban areas even if the approaches are not lighted. On bridges without full shoulders, lighting can enhance both safety and utility of the bridges, and is therefore recommended. Where bridges are provided with sidewalks for pedestrian movements, lighting is recommended for pedestrian safety and guidance.

4.3 Warranting Method Example for Collector/Major/Local Streets

The warrant system presented is based on the Transportation Association of Canada (TAC) Guide for the Design of Roadway Lighting (27) which was based on the 1978 Roadway Lighting Handbook published by the U.S. Department of Transportation.

The warrant system is based on factors grouped into geometric, operational, environmental, and crash factors. For each factor a numeric rating (R) from 1 to 5 corresponding to the defined criterion is defined. Each criterion is assigned a weight (W) to indicate its relative importance. The rating value (R) is multiplied by the weight (W) to obtain a point-score (R x W) for each criterion characteristic, indicating its 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.

When undertaking a warrant analysis, the length of roadway segment being analyzed should be as long as possible, and should take into account future development. Where 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.

Classification factors listed on the warrant sheets are defined as follows:

4.3.1 Geometric Factors

Includes key geometric factors listed for the length of roadway to which the warrant is being applied. These include:

- Number of lanes
- Lane width
- Number of median openings per kilometer
- Driveways and entrances per kilometer
- Horizontal curve radius
- Vertical grade
- Sight distance
- Parking

The worst-case rating factors (R) shall apply for the entire length of road being considered. The weighted value is very high for sharp horizontal curve radii.

4.3.2 Operational Factors

Includes operational factors for the entire length of roadway to which the warrant is being applied. These include:

- Signalized intersections
- Left turn lanes
- Median width
- Operating or posted speed
- Pedestrian activity (conflict) levels (ref to IESNA RP-8 for definition of high, medium or low activity)

The worst-case rating factors (R) shall apply for the entire length of road being considered. The weighted value is high for pedestrian activity level.

4.3.3 Environmental Factors

Includes environmental factors for the entire length of road to which the warrant is being applied. These include:

- Percentage of development adjacent to the roadway. Adjacent development must be a reasonable distance from the roadway and must tie into the roadway for which the warrant is being undertaken via a driveway or intersection which 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. As a general guide, the following ambient lighting definitions may be applied:
  - Sparse - Would typically include rural freeways and highways with little or no development outside of city boundaries.
  - Moderate - Would typically include 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 - Would typically be downtown commercial areas with well-lighted building exteriors adjacent to the roadway. Distracting lighting can also include that from fuel stations, automotive sales lots and other commercial development where lighting is used to attract attention to businesses.
  - Intense: Would typically be 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
- Ambient Lighting
- Raised median curb

The worst-case rating factors (R) shall apply for the entire length of road being considered. The weighted value is high for ambient lighting.

4.3.4 Crash Factors (Night and Day)

In the warranting forms crash factors are included using the night-to-day crash 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 night-to-day crash ratios, it is essential 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 where data is available.

Where a low number of crashes have been recorded (i.e., two at night, and one during the day), lighting may meet the warrant crash ratio; however, due to the low numbers it may be of less benefit than for other areas with similar ratios and higher numbers.

Excerpt from the TAC Guide for the Design of Roadway lighting (27)

Warrants for Lighting Arterial, Collector and Local Roads

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

Notes:

1. Lighting Warranted
2. Pedestrian Activity Level
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.

Lighting 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 regardless of the overall point-score.

Lighting may be prioritized solely on the basis of the point-scores, or in conjunction with a benefit/cost analysis. Benefits would typically be based on the potential reduction in crash frequency and severity. Depending on road authority practice, 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.

4.4 Warranting Method for Intersections

The Transportation Association of Canada Guide for the Design of Roadway Lighting includes a warranting system for intersection lighting. The warranting system is based on geometric, operational, environmental and crash factors. The critical factors determining the need for illumination are traffic volumes and night-time crashes. The warrant point score indicates whether full intersection lighting, partial lighting or delineation lighting is needed. Full intersection lighting denotes illumination covering an intersection in a uniform manner over the traveled portion of the roadway. Partial lighting is the illumination of key decision areas, potential conflict points, and/or hazards in and on the approach to an intersection. The illumination of vehicles on a cross street or median crossing, or lighting that marks an intersection location for approaching traffic, is referred to as sentry or delineation lighting.

The critical factors used to determine the need for illumination include the following:

- 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 its 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.

Based on the warrant analysis (the warranting form can be found in the TAC Guide for the Design of Roadway Lighting Document (27)), 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 indicated by comparing the point-score obtained from the warrant form categories to the following criteria:
  - Full Lighting - Is warranted where a total point-score of 240 or more points.
  - Partial Lightning - Is warranted where the point-score is between 151 and 239 points.
  - Delineation Lighting - Is warranted where the point-score is between 120 and 150.
  - No Lighting - Generally, a point-score under 120 indicates that lighting is not warranted. This score indicates 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 on the basis of the point-scores, 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 road authority practice, 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.

4.5 Other Examples of Intersection Warranting

Some authorities have looked at simple ways to prioritize lighting needs, particularly with rural intersections. Preston and Schoenecker (1999) (16) developed a system using traffic volumes on the major street by functional classification to give a priority to lighting intersections.

Major Street Functional Classification				
	Principal Arterial (TH)	Minor Arterial (TH or CSAH)	Collector (CSAH or CR)	Local (CR or TWN Rd)
Priority	Major street volumes in vehicles per day (% of major street volume that is recommended on the minor street)			
Low	0-2000 (10%)	0-1000 (10%)	0-500 (10%)	0-250 (10%)
Moderate	2,000-5,000 (15%)	1,000-2,000 (15%)	500-1,000 (15%)	250-500 (15%)
High	>5,000 (20%)	>2,000 (20%)	>1,000 (20%)	>500 (20%)

Figure 17 – Prioritization of Street Light Installations by Functional Class

Lighting Impacts: General Considerations

Lighting provides the benefit of improving safety for motorists and pedestrians; however, it also has a larger impact on our nighttime environment. Ongoing research demonstrates the impact of lighting at night as it relates to human health and to the condition of wildlife and plant life. As a result, revisions are being made in our approach to light control and recommended lighting levels. This research also affects the decision-making process on whether, and where, lighting is beneficial.

This section, which includes Chapter 5 – Considerations Concerning Lighting Systems and Chapter 6 – Lighting System Selection, discusses some general considerations regarding lighting impacts, and measures being taken to address them.

5 Considerations Concerning Lighting Systems

5.1 Environmental Impacts

The impact of lighting systems on the environment and abutters should be assessed in all roadway lighting designs

Nighttime lighting can impact humans, animals, and plants, both on and off the roadway.

5.1.1 Light Trespass

Light trespass (obtrusive lighting) is defined by three major interrelated elements. The three elements are:

- Spill light: Light that falls outside the area intended to be lit. It is typically measured in lux in a the vertical plane with the light meter oriented towards the light source.
- Glare: Light that is viewed at the light source (luminaire), which reduces one's visibility. Glare is further defined below.
- Sky glow: Light reflected from the light source, road or other surfaces up into the atmosphere. Sky glow in effect reduces one's ability to view stars in the night sky by casting unwanted light into the atmosphere. Though this is not a safety or security issue, groups such as the International Dark-sky Association (IDA) have mounted strong campaigns to reduce sky glow and protect visibility of our night sky.

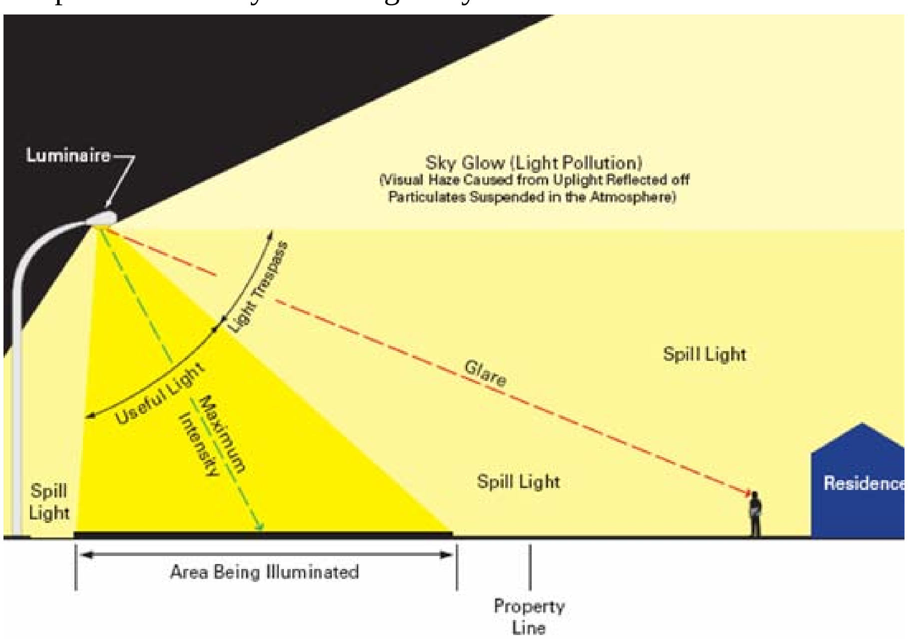

Figure 18 – Spill Lighting, Glare and Skyglow

Figure 19 – Example of Skyglow

Maintaining an effective balance between the reduction of light trespass and the provision of quality, beneficial lighting requires thoughtful design and the selection of luminaires with cut-off or full cut-off optical systems. Lighting design with full cut-off optics will typically reduce skyglow and spill lighting. Moreover, it will reduce veiling luminance (glare) from the luminaire on and off the roadway, thus improving overall visibility.

Figure 20 – Example of High Glare Street Lighting

Spill light levels have been developed and are documented in IESNA TM-11 *Lighting Trespass: Research, Results and Recommendations* and IESNA RP-33 *Lighting for Exterior Environments*. They are defined in the table below. Designations (LZ1 to LZ4) define the Light Zone and are further defined below. These levels are recommended by the IES where possible. They are typically calculated and measured from the residential boundary line, but are sometimes evaluated from the location of the residence being investigated.

Designation	Recommended Maximum Illuminance Level (Ee)	
	Pre-Curfew	Post-Curfew (Not Applicable to Roadway Lighting)
LZ 1	1.0 lux	0.0 lux
LZ 2	3.0 lux	1.0 lux
LZ 3	8.0 lux	3.0 lux
LZ 4	15.0 lux	6.0 lux

Figure 21 – Spill Light Levels

It is important to note that the reduction or elimination of light trespass must never take precedence over the provision of adequate roadway lighting. Lighting the area adjacent to roadway travel lanes (typically within or adjacent to the road right of way) can benefit a driver's peripheral vision. This can also provide better visibility of crossroads, driveways, and sidewalks. Lighting the area adjacent to the road can also help in the detection of large animals that may pose a safety hazard. Balancing the needs of the road user with any potential impacts of the lighting system can be difficult for many roadway types, but the issue needs to be approached holistically.

5.1.2 Lighting Zone Definitions

Zoning is a well-established practice in community planning. The fundamental idea behind zoning is that it allows a community to determine and regulate appropriate types of use in different areas within its jurisdiction—that is, to define acceptable land uses. Lighting zones work well with land use zones in determining the type and amount of lighting that can be used in different areas.

Lighting zones do not correspond with land use zones. They should be applied with engineering judgment for specific project conditions

The choice of an appropriate lighting zone is a matter of judgment based on community priorities for any given area. Among the factors that must be considered are neighborhood ambient conditions, lighting expectations, special environmental concerns, and how interior lighting may affect the exterior environment.

Because identifying the appropriate outdoor lighting zone is a matter of judgment and consensus, there is no automatic means of determining which zone is appropriate for a given area. The same type of lighting application may fall into different lighting zones in different jurisdictions. According to the IESNA Lighting Handbook, the lighting zones are defined as:

5.1.2.1 LZ1 Zone – Low Ambient Lighting

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, most lighting should be extinguished or reduced as activity levels decline.

5.1.2.2 LZ2 Zone - Moderate Ambient Lighting

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 extinguished or reduced as activity levels decline.

5.1.2.3 LZ3 Zone Moderately High Ambient Lighting

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 and/or convenience and it is often uniform and/or continuous. After curfew, lighting may be extinguished or reduced in most areas as activity levels decline.

5.1.2.4 LZ4 Zone - High Ambient Lighting

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 and/or convenience and it is mostly uniform and/or continuous. After curfew, lighting may be extinguished or reduced in some areas as activity levels decline.

5.1.3 Glare

Bright sources of light in the visual field create glare. Light is scattered in the human eye, resulting in a phenomenon known as “veiling luminance.” This results in a visual haze within the eye, reducing visibility. Veiling luminance that occurs when bright oncoming headlights significantly reduce one's vision is a common experience. Blocking the bright source or looking away from the visual field reduces the haze associated with veiling luminance, and vision is partially restored.

Figure 22 – Example of Glare

The perception of glare, however, varies greatly between observers. The IESNA define glare as "the sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility. The magnitude of the sensation of glare depends on such factors as the size, position, and luminance of a source, the number of sources, and the luminance to which the eyes are adapted."

Glare typically falls into one of the following categories:

- Disability Glare: The presence of an amount of glare so significant as to prevent an individual from seeing adequately. An example of disability glare is a driver's substantially reduced visibility caused by the headlights of an oncoming car.
- Discomfort Glare: The presence of glare that may over time causes a sense of pain or annoyance, and may increase blink rate or even cause tears.

Disability and discomfort glare are very different phenomena. Disability glare depends on the quantity of light falling on the eye and the angle from the line of sight. With discomfort glare the source luminance is a major factor; with disability glare the source intensity is a major factor. Typically, disability glare will apply to drivers on the roadway, and a numerical ratio has been developed referred to as the veiling luminance ratio which is applied to lighting design as part of IESNA RP-8. Veiling luminance is therefore a key criterion in undertaking lighting design. The effect of veiling luminance on visibility reduction is dependent upon the average lighting level, or average luminance level, of the pavement. A higher level of veiling luminance can be tolerated if the pavement luminance is high. Veiling luminance is calculated in terms of a ratio of the maximum veiling luminance experienced by the observer to the average pavement luminance.

IESNA TM-11 *Lighting Trespass: Research, Results and Recommendations* observes: "Source brightness had been generally identified as being the principal characteristic to which persons object. Spill light was seen as a less significant effect. It was decided, therefore, to design experimentation to identify quantitatively the relationship between source brightness and the degree to which the light source was found objectionable." Source intensity is a published method of evaluating the off-site discomfort glare. CIE has also produced a document (CIE 150:2003 *Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations*) that defines limitations for source brightness (intensity) and spill light for outdoor lighting applications. Figure 23 defines source intensity levels. This method will typically be applied where high-wattage light sources such as flood lighting or high mast lights are used. The environmental zone E1-E4 correspond to the lighting zones LZ1-LZ4 described in section 5.1.2.

Light Technical Parameter	Application Conditions	Environmental Zones			
		E1	E2	E3	E4
Luminous intensity emitted by luminaires (*I*)	Pre-curfew:	2 500 cd	7 500 cd	10 000 cd	25 000 cd
	Post-curfew hours:	0 cd*	500 cd	1 000 cd	2 500 cd

*NOTE: If the luminaire is for public (road) lighting then this value may be up to 500 cd.

Figure 23 – Source Intensity Levels

From the perspective of limiting the impact of a lighting system to both on- and off -road observers, a lighting system meeting the disability glare requirements of AASHTO and IES generally provides the needed control.

5.1.4 Animal and Plant Impacts

Lighting can have impacts on animals as well as humans, particularly since a good deal of animal activity takes place at night. Almost all small rodents and carnivores, 80 percent of marsupials, and 20 percent of primates are nocturnal. Lighting in environmentally sensitive areas with animal activity should minimize the duration, direct the light only where needed, and reduce intensity as much as possible. An example of the impact of lighting on wildlife can be found along the southern Atlantic coast of the United States. Sea turtle hatchlings in this area 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 on to lighted roadways. Local codes in this region may require the use of full cut-off light sources, controls, and other limitations on exterior nighttime lighting. Another impact to wildlife is the potential for bird strikes to illuminated structures, particularly when they are located along migration routes.

Plants have evolved a wide range of photoreceptors that perceive and respond to light signals in the ultraviolet, blue, red, and near-infrared regions of the electromagnetic spectrum. While there is not a significant body of research to explore and document the specific effects of electric lighting on plant life, there is little doubt that plants are affected in some degree by lighting.

5.1.5 Human Health Impacts

Since the beginning of the 1980's the effect of light on human performance and health has been a point of discussion and research. Disruptions to our circadian rhythms, the pattern of behavioral and physical processes including hormone secretion which is very dependent on light-dark cycles, has been linked to an increased risk to hormone dependent cancers such as breast and prostate cancer (Bartsch et al., 1985) (17). Bartsch also concluded that "melatonin controls not only the growth of well differentiated cancers, but also possesses anti-carcinogenic properties."

Research shows artificial lighting at night could also suppress melatonin (using 2500 lux of white light for between 2 to 4 hours).

The hormones responsible for the circadian rhythm in humans are melatonin, which is released in response to increasing levels of darkness and which promotes sleep, and cortisol, which is the biological opposite of melatonin and an indicator of the level of human activeness.

From an exterior lighting perspective, the question is whether levels and/or certain types of lighting can cause the suppression of melatonin levels at night through light trespass, producing a negative impact on the health of residents. The spectrum of the light can also have an influence, with shorter wavelength lighting having more of an impact. The amount of light needed has to be of sufficient level and applied for a sufficient amount of time to have an effect on melatonin levels.

Research reported in the Journal of Carcinogenesis (18) regarding the impact of light at night on residents from street lighting systems notes: "These light levels rarely exceed 10 lux at the cornea outdoors. Indoors, behind closed curtains, the levels would likely to be much lower. Further, the human eyelids transmit only about 1% to 3% in the short wavelength region of the visible spectrum….Given the available published data on human melatonin suppression in response to light, light trespass through residential windows is an unlikely cause of melatonin suppression, simply because the light levels are so low, particularly with the eyes closed."

Research into these topics is ongoing and not yet conclusive. Thresholds for these non-visual effects are not clearly established at this time. The complexities and interactions, along with the long-term aspects of these issues, make definitive statements elusive.

5.2 Lighting Impacts on the Aging Population

As we age, we are more susceptible to glare. Diseases such as glaucoma can also reduce peripheral vision. This is significant as our population ages and as life expectancy continues to increase. As we age, our eyes deteriorate considerably in their ability to adjust the pupil opening in proportion to the available light. The eye gate becomes smaller and smaller even in the daytime, but the critical feature is the inability to open up at twilight and in darkness to let in whatever little light might be available, particularly past the age of 60 (19).

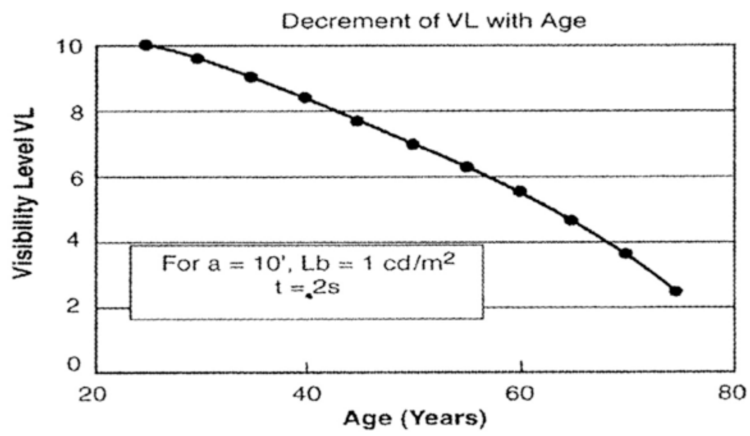

Figure 24 - Reduction in Visibility Level with Age

A vital factor is the ability to see the movement of objects that may represent a hazard from the corner of the eye. It has been found that the ability to see movement 40 and 80 degrees away from the line of sight is reduced as much as 60 percent for people over 60 (19). A younger person can typically see to some degree even with very little light, but this sensitivity to low brightness is reduced to approximately one half at 80+ years of age (19). It has been found that it can take up to 30 minutes for an 85-year-old person to adapt to lower outdoor night- time brightness after having been adapted to the higher interior brightness (19). This long period of eye adaptation can be greatly reduced with roadway lighting.

The visibility factors noted above also apply to pedestrians. Reduced visibility reduces pedestrians' ability to see motor vehicles and avoid crashes. This increases the risk that already exists due to the fact that reaction speed for both the driver and pedestrian is reduced with age.

Installations expecting an increased use by older drivers may consider increasing lighting levels and/or reducing glare

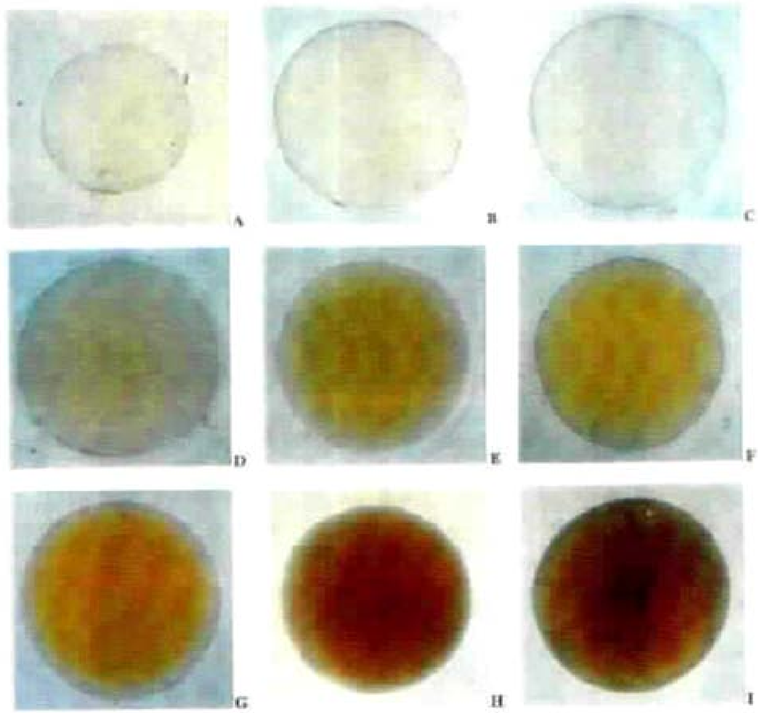

Fig. 3 Yellowing and transparency of the Human Lens from 6 month (A) to 8 years (B) , 12 years (C) , 25 years (D), 47 years (E), 60 years (F), 70 years (G), 82 years (H) and 91 years (I) of age.

Figure 25 - Effect of Aging on the Human Eye

Figure 25 shows the effect aging has on the human eye. As we grow older, the lens becomes discolored (darkens), thus reducing visibility.

Older drivers are also more susceptible to glare. Figure 26 shows that the amount of contrast needed to overcome the driver threshold contrast increases significantly with age. At a light level of 0.5 cd/m^2 a 65-year-old driver needs approximately 10 percent more contrast to be able to see an object.

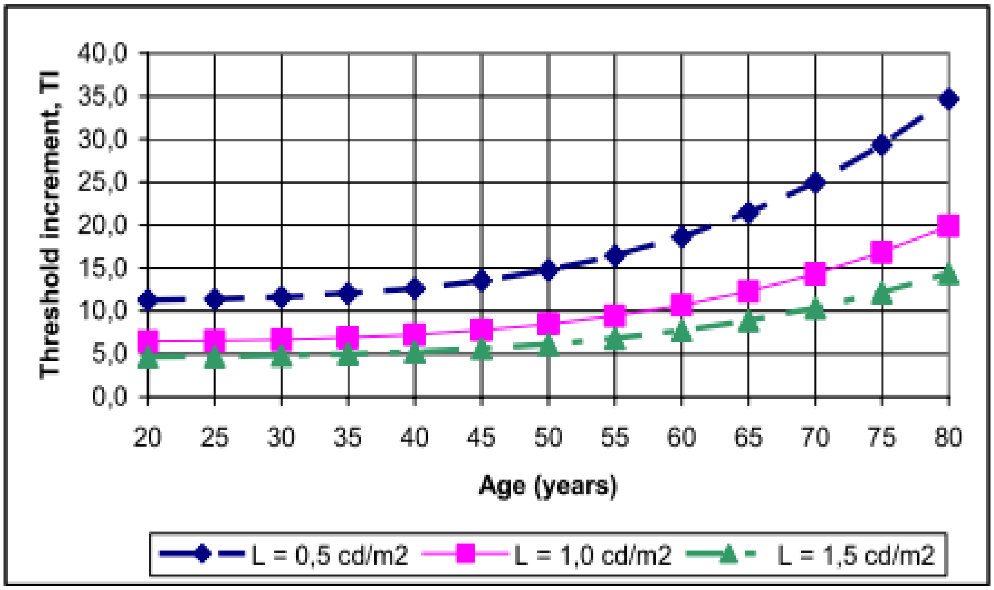

Figure 26 - Impact of Glare and Light Level on the Visibility of Aging Drivers

We do not currently design roadway lighting system with modifiers for age. A designer or agency, however, should be cognizant of the differences between younger and older drivers and may want to consider modifications, either a reduction in the amount of glare or an increase in the lighting levels, if the majority of the road users will be elderly.

6 Lighting System Selection

6.1 Design Considerations

In some cases, site conditions may dictate if roadway lighting can be installed, or may place certain constraints on the design. Therefore, the following site conditions should be investigated:

Lighting designs need to be performed in full coordination with the features of roadway and surrounds

- 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 in close proximity 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 in close proximity 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 – The presence of offsite glare, light trespass and skyglow should be taken into consideration in urban areas. The designer should consider these issues prior to undertaking any design and be aware of community concerns and local requirements. Local lighting ordinances may also dictate the type of lighting which may be installed, and may dictate 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. In some cases, products with a higher initial purchase cost can significantly reduce operating or maintenance costs over the life of the project. Products specified should be both corrosion-resistant and durable. All luminaires will require regular service for lamp replacement and cleaning. 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.
- Historical Safety Performance – It is recommended that historical crash data be reviewed in an effort to identify what may be problematic crash locations. This can be done by first driving, walking or cycling the road and establishing possible problematic locations. Municipal agencies, road authorities and maintenance contractors can be contacted to confirm whether these locations have any recorded crash statistics. Problem areas should be identified and solutions discussed with the owner.

Lighting systems should be selected based on the most beneficial life cycle cost of the system

6.2 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.

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 on its ability to satisfy stated or implied needs. While quality could be overlooked if low price is the primary criterion for product selection, it should always be a key consideration in product selection. In general, focusing on price alone will not deliver best value installations.

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

- Certification – Electrical products must be certified by an organization accredited by the Standards Council of Canada, and shall bear an appropriate label such as Underwriters' Laboratories (UL).
- Photometric Performance (for luminaires) – A photometric comparison of luminaires is critical to selecting the best product for a given application. Cobra head luminaries can be compared using the CSA 653 model. Comparisons should be based on photometric data provided by the supplier from an independent testing laboratory. The IESNA cutoff classification for luminaires should be known and deemed appropriate for the situation. In general, cutoff or full-cutoff optics should be used wherever possible.
- Durability – Durability is the capability of a product to resist deterioration, damage, and corrosion over time. Designers should understand the potential for vandalism and the corrosive nature of the project's environment, and relate those variables to the specific products under consideration.
- Aesthetics – Products selected should be aesthetically compatible with their surroundings. Manufacturers offer a wide range of equipment with respect to shape, configuration, 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. Also, they should 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, as well as maintenance frequency and level of service required over the product's anticipated useful life.
- Operations Cost – Similar products can result in varying cost of operations. 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.

The capital cost of an item (also known as the supply cost) is not listed above but is also an important consideration. Supply costs, however, should not be the primary factor when selecting products. To assess a product's true cost, other factors must be considered to confirm best value and performance, or life cycle of a product.

Whenever possible, individuals specifying products are encouraged to designate more than one manufacturer with similar or equal products to reduce costs via competitive bidding. All products proposed, however, should be reviewed for conformance to stated specifications and performance requirements. In some cases a specific product or manufacturer may need to be sole sourced because of the product's enhanced performance, special appearance, or the need to match existing adjacent conditions.

Specific luminaire requirements are as follows:

- Ingress Protection (IP) Rating - Optical systems should be well sealed to prevent the entry of dust and water. Luminaires should have an IP rating of 65 or 66 for maximum performance.
- Lens Material - Lenses should be composed of glass. Polycarbonate and acrylic materials, though more impact-resistant, tend to discolor over time, which will reduce light output and will often require replacement in about 5 years.
- Housing - The housing should be made of aluminum with a powder coat exterior finish. The luminaire should be designed for secure attachment to the pole. The luminaire should be designed for easy access for electrical and lamp changes via a tool-less entry
- Internal Electrical - Internal components will include a ballast, a starter and, a capacitor. The ballast should be a constant wattage auto-transformer (CWA) type.
- BUG Ratings – The luminaire optics should meet the specific BUG ratings where they are available.

6.3 Luminaire Classification

To assess and mitigate glare and to reduce skyglow, the IESNA have developed cut-off classifications for luminaries based on how they emit light.

The amount of glare generated by a luminaire is strongly influenced by the intensity (candlepower) emitted at angles close to the horizontal.

6.3.1 Luminaire Classification System

A new method referred to as the Luminaire Classification System (LCS) has been developed to define luminaire distribution and efficiency better. IESNA TM-15 *Luminaire Classification System for Outdoor Luminaires* defines this system in more detail. The LCS replaces the traditional IESNA luminaire cutoff classification system which uses designations like cutoff, non-off, semi-cutoff, and full cut-off. The traditional system was very limited as it only assessed the light distribution at very high angles and above horizontal.

The LCS defines a method of evaluation and comparison of outdoor luminaires. It provides a basic model which defines maximum lumens within defined angles within primary areas. The primary LCS areas are forward light, back light, and up-light zones as defined in Figure 27 (top left). Each of these zones is further broken into solid angles within the area. An example of the forward light zone is shown in Figure 27 (top right).

The sum of percentages of lamp lumens within these three primary areas is equal to the photometric luminaire efficiency. The LCS enables designers to evaluate and compare the distribution of lumens for various types of luminaire optics, thus assisting in the selection of the luminaire most appropriate for the application. An example of measurements for various luminaires is defined in Figure 28.

The benefit of this system, is that it allows a designer to better select the optimal optics for a given application while at the same time reducing light trespass impacts and sky glow. The new classification system is intended to be used as a tool to assess the light output of luminaires.

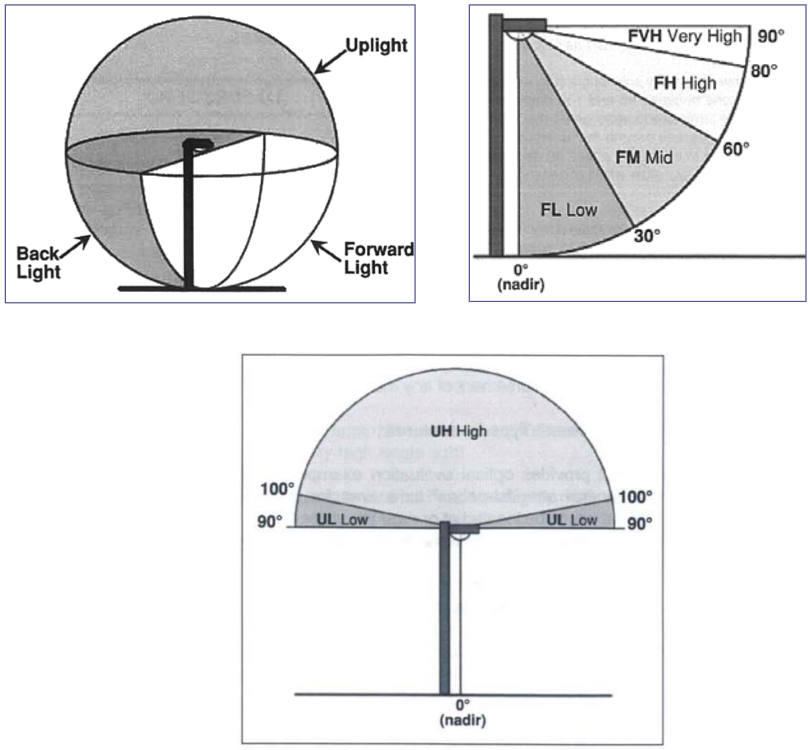

Figure 27 - Lamp Lumen Zones and Front Light Zone (from IESNA TM-15)

The LCS zones for various luminaire optical systems are calculated and shown in Figure 28. Through lighting photometric analysis software, a designer can use the LCS assess the percentage of lumen output in the various zones. This is very useful when comparing luminaire optical systems and how light is distributed from various luminaries.

Metal Halide	 Internal Refractor Optic (250 W Type V)	 External Refractor Optic (250 W Type V)	 Louvered Reflector Optics (250 W Type III)	 Hydro-formed Refractor Optics with Horizontal Lamp (250 W Type I)	 Sag Lens Refractor Optics (250 W Type III)	 Sag Lens Refractor Optics (250 W Type I)	 Sag Lens Refractor Optics (100 W Type I)
Forward Light							
Luminaire Lumens	4133.4	5405.6	6306.5	6487.6	10115.6	10557.0	3716.3
% Lamp Lumens	19.70%	25.70%	30.00%	29.50%	46.00%	48.00%	45.90%
FL (0˚-30˚)	0.20%	0.90%	1.20%	2.40%	7.40%	13.10%	12.60%
FM (30˚-60˚)	5.40%	3.70%	14.40%	15.30%	27.20%	24.80%	23.40%
FH (60˚-80˚)	8.90%	17.30%	12.90%	11.20%	11.20%	10.00%	9.60%
FVH (80˚-90˚)	5.10%	3.80%	1.40%	0.50%	0.20%	0.10%	0.20%
Back Light							
Luminaire Lumens	4133.4	5352.5	4220.2	4880.5	5384.3	7138.1	2465.6
% Lamp Lumens	19.70%	25.50%	20.10%	22.20%	24.50%	32.40%	30.40%
BL (0˚-30˚)	0.20%	0.90%	0.80%	2.30%	5.40%	7.70%	7.20%
BM (30˚-60˚)	5.40%	3.60%	9.40%	13.20%	14.50%	17.00%	16.10%
BH (60˚-80˚)	8.90%	17.10%	8.80%	6.00%	4.40%	7.60%	7.00%
BVH (80˚-90˚)	5.10%	3.90%	1.00%	0.70%	0.10%	0.10%	0.10%
Up-light							
Luminaire Lumens	9997.6	2477.0	957.5	163.2	0.0	0.0	0.0
% Lamp Lumens	47.60%	11.80%	4.60%	0.70%	0.00%	0.00%	0.00%
UL (90˚-100˚)	10.70%	2.40%	1.40%	0.50%	0.00%	0.00%	0.00%
UH (100˚-180˚)	37.00%	9.40%	3.20%	0.20%	0.00%	0.00%	0.00%

Figure 28 – LCS Comparison (IES TM-15-07)

6.3.2 BUG Rating System

Similar to the LCS, the IESNA developed the Backlight-Up-light-Glare (BUG) rating system which establishes back (B), up-light (U), and glare (G) zonal lumen limits for luminaires.

Each category (backlight, up-light, and glare) consists of specific regions that surround the luminaire. Each region has specific upper limit criteria that must be met to obtain the rating. All of the criteria must be met for a luminaire to obtain the generalized B, U, or G rating. So, the rating for a specific metric is set by the lowest (highest zonal lumen value) performance criterion within the metric. The limits vary according to the lighting zone (LZ1 – LZ4) in which the luminaire is located.

Once this calculation is performed for each of the three metrics, the composite BUG rating can be reported. Forward, Back and Up-light Zones and Forward Light Zones show the BUG regions. Solid angle references are based on a sphere of data points around a luminaire.

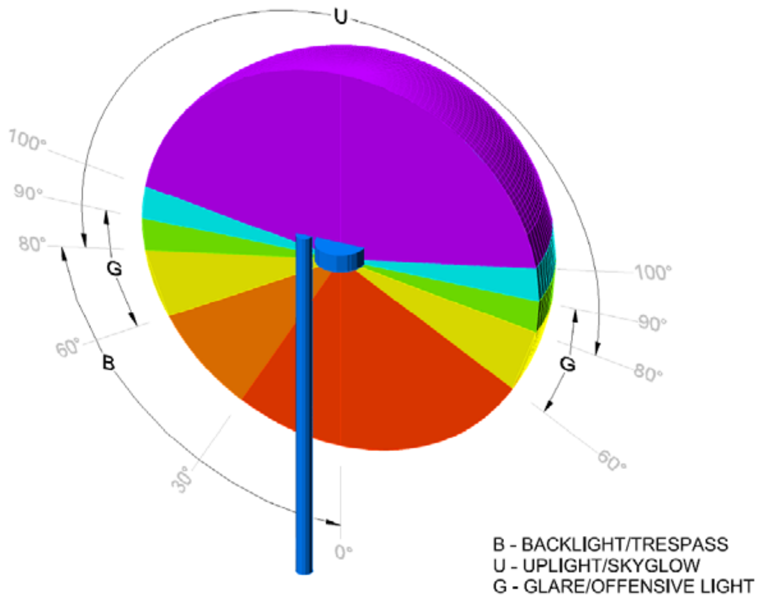

Figure 29 – Bug Zones (IES TM-15-07)

Backlight considers the light leaving a luminaire in the opposite direction from the main aiming angle of the light. This is the percent lamp lumens or the luminaire lumens distributed behind a luminaire between 0º vertical (nadir) and 90º vertical. Within a lighting zone, the backlight rating will change depending on the luminaire's proximity to the property line. Backlight is evaluated for high (60º–80º), medium (30º–60º) and low (0º–30º) areas.

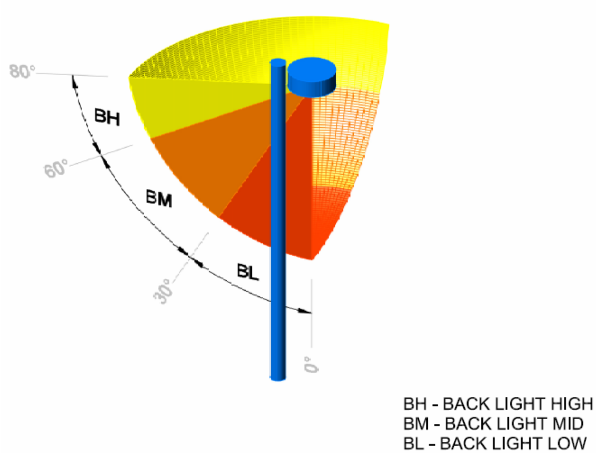

Figure 30 – BUG Backlight (IES TM-15-07)

Up-light measures the total light propagating from the luminaire in a near-horizontal or above-horizontal direction. This is an overall measure of the amount of light directly leaving the luminaire that may be associated with sky-glow. This measures the percent lamp lumens or the luminaire lumens distributed above a luminaire between 90º and 180º vertical. Up-light is evaluated for high (sky-glow: 100º–180º), low (90º–100º), forward light very high (80º–90º), and backlight very high (80º–90º).

Glare considers the light leaving a luminaire in the angles that are most likely to be a source of nuisance (or potentially disabling) to passers-by either within or outside the property boundaries. The light that causes glare is also sometimes presumed to be a source of light trespass problems. However, in most cases, glare complaints are due to the brightness of the source, and not because of spill light levels. For this reason, it is treated separately from the Backlight metric . Glare is evaluated for forward light very high and backlight very high (80º–90º), forward light medium (60º–80º), and backlight medium (60º–80º).

Note that the Up-light and Glare regions overlap as do the Glare and Backlight regions. While Glare is generally only considered important up to horizontal, the Up-light region has been shown to be important below horizontal, down to about 80°. Since these criteria regions are not intended to be additive or comprehensive to the complete output of the luminaire, this overlap is not a calculation inconsistency.

The region from directly below the luminaire forward to 60° is not considered in any of the criteria regions. This region is generally considered the ‘safe’ region of lumen output, where the light from a luminaire will be falling on the task area in an effective manner, and is also the region where the majority of lumens are outputted. Beyond this unmeasured region, the light may begin to be a source of glare, light trespass, sky-glow, or other concerns.

6.4 Lighting Master Plans

Lighting master plans are formal documents created through a study and planning process. They are based on input from municipal 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 also contain information regarding fixtures and poles, light sources, fixture cutoff, 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 take into account anticipated economic and cultural changes, a community’s public image and economic development goals, and technological advancements. The benefits of such plans include the coordination of the various municipal lighting functions, proactively planning lighting for the different areas of a community by recognizing their unique character and needs. The plans also provide 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 economics, contribute to beautification, and provide a secure environment for people and property. Transportation-related lighting is viewed as a key component of community management.

Lighting master plans are typically adopted by a jurisdiction through a bylaw, resolution, or similar measure, and as such 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 takes into account 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 and preserve the area's historical character, or that enhance the 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 (capital and operating).
- Aesthetics (daytime and nighttime).
- Lighting design criteria.
- Environmental issues and constraints, including the control of spill light, glare and skyglow.
- Energy use (through definition of unit power density).
- Potential for economic development and the enhancement of nighttime activities through lighting
- Preservation of areas of darkness, such as areas around observatories.
- Maintenance requirements.

Designers should check with local officials prior to beginning the design process to determine if a lighting master plan is in place, or is anticipated. Designers should be aware of the requirements of lighting master plans as they relate to the specific project under consideration. At the same time, under no circumstances should lighting master plan requirements dictate the quantity or quality of light for a roadway facility, since the safety of the roadway user is of paramount importance.

Lighting Application Considerations

AASHTO and IES provide recommendations for light levels and other considerations relating to roadway lighting.   This section discusses additional considerations, including design and calculations guidance, which may assist in proper evaluation and installation of lighting systems.

7 Lighting Application

7.1 System Layout and Geometry

The lighting industry has defined standard pole spacing layout designations. These standard pole spacing layout designations are one-sided lighting, opposite lighting, staggered lighting, and median lighting.

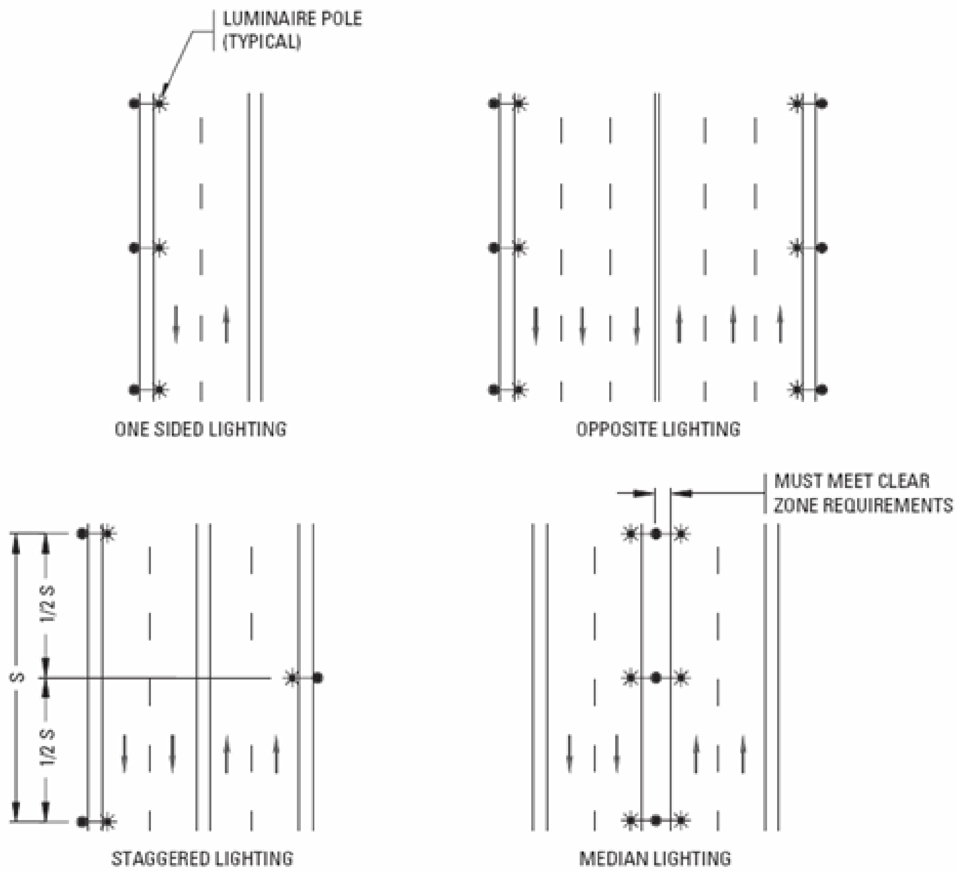

Figure 31 – Typical Pole Spacing

Typically, one-sided spacing is used on roadways with one to three lanes, staggered spacing is typically used on roadways with three to six lanes, and opposite spacing is typically used on roadways with five or more lanes. Median lighting is typically used where the median is wide enough to accommodate poles and meet clear zone requirements, or where the poles are protected by barriers. From a capital cost perspective, median lighting may be very cost-effective as the number of poles required may be reduced by 50 percent as opposed to opposite lighting. However, median lighting may cost more to maintain.

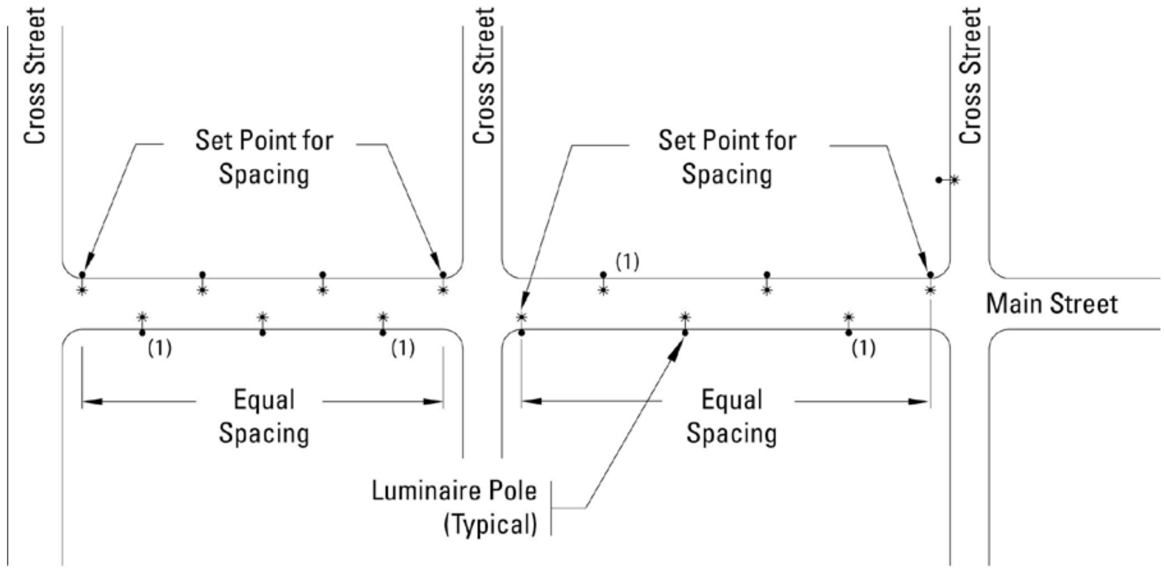

Figure 32 – Pole Spacing

To lay out poles, the designer must undertake lighting calculations to define optimal pole spacing. Once maximum pole spacing is defined, one can lay out poles on the road drawings using a calculator and scale rule. The design should lay out poles locating a pole at a start points such as cross street, then spacing the poles evenly within the maximum pole spacing defined by the calculations, as shown in Figure 32. The pole spacing may need to be adjusted to suit driveways and utility conflicts.

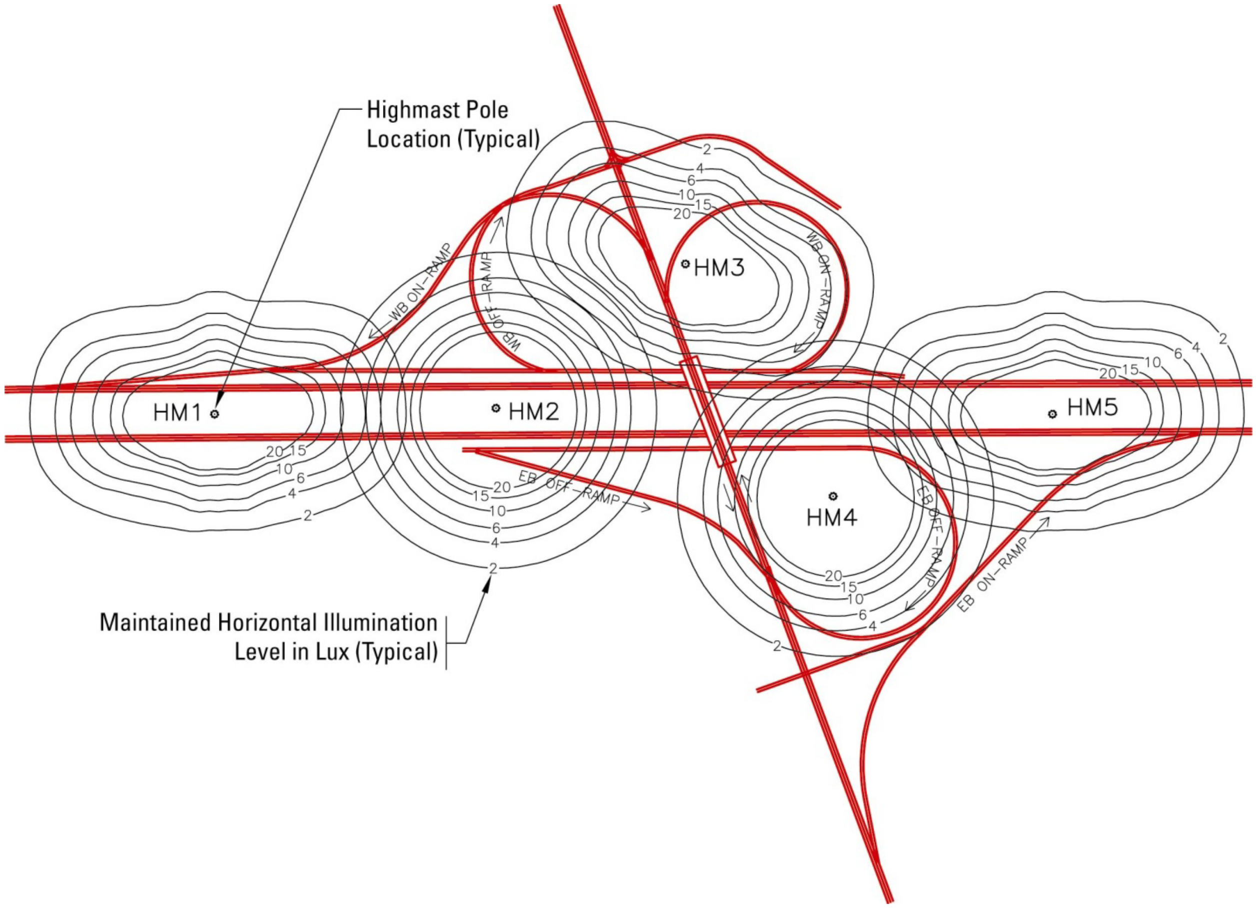

Figure 33 - Highmast Pole Spacing

For highmast lighting, the lighting calculation process is slightly different than it is for a typical roadway. It is recommended that the designer develop lighting templates for a variety of highmast pole arrangements using various fixture quantities and distributions. This can be accomplished using various combinations of individual luminaries clustered on a given pole to create the most effective overall distribution of light through trial and adjustment. By combining efficient templates, the designer is able to produce optimal light distribution for the given road geometry. The variables will include mounting height, number of luminaires, optics, and orientation of optics, wattage, light source, and photometrics.

The templates will show the pole location with luminance or illuminance levels using contour lines. The contour lines should represent different levels of illuminance or luminance. Typically, templates are developed in asymmetrical (long and narrow) or symmetrical (circular) patterns to suit road geometrics. The templates should be arranged on the site plan to show approximate pole locations, either digitally in a computer aided design (CAD) program as shown in Figure 33.

This method will give a rough pole layout and allow for optimization through trial and adjustment. Once the pole locations and pole distributions have been optimized, a lighting calculation should be undertaken for the entire interchange, defining lighting levels on the roadway. The lighting calculations will require further refinement, using trial and adjustment, until the desired levels are achieved. Highmast design will require many calculations and trial and adjustment cycles to provide an optimized design.

7.2 Scale and Inter-Relational Design

When determining pole heights, types, and luminaire wattages, the designer must consider the land use (residential, urban, downtown, commercial, industrial, etc.) and the road width. Pole height may also be limited by the reach of service vehicles used to maintain the lights. There is no exact formula for determining the optimal pole height and luminaire wattage for a given road. Factors such as pole spacing (one-sided, median, opposite, or staggered), luminaire photometrics, wattage, road geometrics, power line conflicts, lighting levels and uniformity, aesthetics, and obtrusive lighting issues are all appropriate considerations in defining optimal mounting height. In residential areas, the designer should select pole heights and fixture wattages to reduce spill light levels to those suitable for the lighting environmental zone (LEZ).

Determination of pole height and luminaire wattage is made using computer lighting design software to test different scenarios by a “trial and adjustment” process. Today’s computer lighting software allows a designer to undertake calculations in minutes, thus allowing the designer to explore many more options than were practical in the past. For an interchange, highmast lighting may prove to be more effective than conventional davit-style, mast-arm or truss-style lighting. In a downtown area, post-top lighting with a mounting height of 6.0 m or less may be preferred to provide lighting structures with a more human scale, meeting the requirement for improved aesthetics. For freeway ramps, intersections or a typical city roadway, davit-style, mast-arm or truss-style lighting may prove to be the most effective.

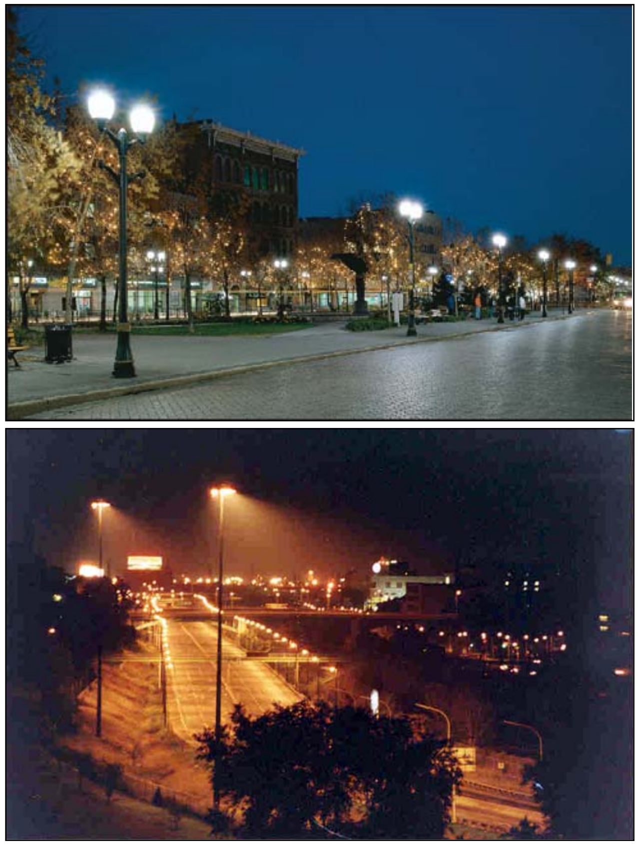

Figure 34 - Typical Lighting (Post-top and Highmast)

7.3 Adaptive Lighting

The need to reduce power consumption has stimulated significant research and product development in the field of roadway lighting. Adaptive lighting controls allow lighting levels to be reduced during off-peak periods. Simply put, a significant amount of power can be saved by varying the levels of lighting between peak and non-peak periods.

Lighting levels are established by applying criteria based on road classification (arterial, local, collector), type of pavement, pedestrian activity/conflict level. The higher the level of pedestrian conflict, the higher the level of lighting recommended. The present design practice is to use the highest pedestrian conflict/activity level for an area or segment of roadway to establish the minimum lighting levels for the portion of roadway under consideration. Once the minimum level of lighting is established, street lights have traditionally provided that level of lighting throughout the hours of darkness as adaptive technologies have been unavailable.

Pedestrian conflict levels do not necessarily remain constant throughout the hours of darkness, and in most instances the numbers of pedestrians present in a given area will be reduced in the late night and early morning hours when businesses are closed. Numbers of nighttime pedestrians may also be reduced based on the days of the week (weekday vs. weekend), seasonal factors, and other predictable dynamics. During hours of reduced pedestrian conflict, the level of lighting provided can be reduced and while meeting recommended criteria for the actual level of pedestrians present.

The amount of energy saving an adaptive lighting technology can provide depends on the variance of pedestrian conflict levels throughout the hours of darkness. During hours of reduced pedestrian conflict/activity, the level of lighting provided could be reduced (with reduced energy consumption) to the recommended criteria for the actual level of pedestrians present. An adaptive technology should not affect the distribution pattern of the luminaire, uniformity ratios are preserved, even with reductions in luminaire output. The reduction of lighting levels on local, collector and major roads can go from a high conflict to medium to low depending on predicted pedestrian activity anticipated during the course of the evening. In some cases where conflict has been designed to medium level then only a single to a low conflict/activity can be achieved. Where lighting is designed to a low pedestrian conflict then the recommended should be maintained to below those recommended.

Typically, the light output of the luminaire and lamp depreciates over their useful life, so designers must provide an initial level of lighting higher than the minimum maintained level. This compensation is achieved by applying a lighting loss factor to a lighting design. One of the components of light loss factor is lamp lumen depreciation, which defined based on lamp suppliers' published curves at the anticipated end of lamp life. This factor is typically 10 percent to 30 percent depending on the lamp type. Application of an adaptive technology may allow the street light to operate at its maintained level for the entire maintenance cycle, thus reducing power input and saving energy. One would not apply lumen depreciation to a lighting design, as the adaptive system would adjust the lamp output to maintain constant illumination on the roadway.

Because lamp wattages are fixed, some areas served by street lighting are over-lighted to meet uniformity criteria, which is the driving factor in luminaire spacing. This may be the result of the lack of a lamp in the appropriate wattage (e.g., the design requires a 160-watt lamp, which is not available so a 200-watt lamp is used), or because an owner has standardized a particular pole/luminaire combination for maintenance purposes. Many roads are in fact lighted to well above recommended levels. Examples are local, collector or arterial roads where lighting levels are higher than required to meet uniformity requirement. An adaptive system could be used to rectify this issue as well as reduce levels during off peak.

Variation of lighting levels is not recommended in all lighting scenarios. Listed below are scenarios where reducing lighting levels in off-peak periods is not recommended:

- Signalized Intersections - Signalized intersections typically include pedestrian crossings. Pedestrian conflicts with vehicles are very likely at signalized intersections even during low-pedestrian conflict periods.
- Mid-Block Crosswalks - The same rationale used for signalized intersections applies.
- Roundabouts - Due to the geometry in roundabouts and the effectiveness of fixed headlights within the roundabout circle, dimming should not be applied to these facilities.

- Rail Crossings - Rail crossing lighting is provided for detection of the trains and is not related to pedestrian conflict levels, therefore reducing lighting during off-peak periods is not recommended.

Engineering expertise is required in the application of an adaptive technology. Experienced roadway lighting designers will be able to assist owners in choosing the sites best suited for the technology. An adaptive technology is not for all roads and should be reviewed in accordance with the recommendations of IESNA RP-8 or TAC. Prior to installing an adaptive technology it is recommended a feasibility study be undertaken. The following should be included:

- Development of Design Criteria - The designer would establish design criteria for the municipality or agency for the proper application of dimming in line with standard practice.
- Inventory of Existing Facilities - An inventory of existing facilities will be required, including pole spacing, roadway classifications, pedestrian conflict levels, existing lighting levels and uniformities, configurations, etc.
- Undertake Computer Lighting Calculations - The engineer would provide calculations necessary to establish the applicability of dimming.
- Development of Cost Benefit Analysis - The engineer would assist the municipality or agency to develop and analyze the cost and benefits available.
- Development of Options and Rationale for Replacement or Retrofit of Luminaires - If existing luminaires are being retrofitted with the dimming technology, the engineer would establish criteria for evaluating where a new luminaire should be considered. Issues to be addressed would include age, condition, cost-effectiveness, etc.
- Verification and Testing - The engineer would provide independent verification of the performance of the dimming system.
- Master Planning (Recommended) to Optimize the Application of Dimming - Because communities and roadway networks are unique and operationally specific to an area, development of a dimming master plan is recommended. The master plan would define how dimming would be applied, and coordinate the retrofit of existing systems and new installations. In general, the application of dimming to new installations (new roadways or new lighting in conjunction with roadway improvements) should be prioritized to take advantage of energy savings, while retrofitting existing lighting may depend on a number of factors.
- Agreement Between Owner and Utility Companies Will Be Required - As most street lighting in North America is unmetered, an agreement between the utility company and the owner will normally be required for the owner to receive the monetary benefit associated with adaptive lighting.

An effective way to control lighting is via an adaptive lighting system. Adaptive lighting control systems can control, monitor and record the operating status of luminaires in a lighting system from a remote location using a desktop computer via the internet. Adaptive systems typically use miniature solid-state control devices that are installed in each new or existing luminaire. These systems are typically designed with software to allow an owner to build a database of the asset and monitor performance on an area-wide basis.

Additionally, luminaire locations can be identified by global positioning satellite (GPS) coordinates for easy identification, tracking and locating. With these system components in place, there is the potential to identify luminaire outages and schedule maintenance through the use of mapping software to identify and optimize maintenance routes. Using the system software, one can build up a database of the inventory and asset condition to improve scheduled maintenance.

7.4 Performance Based System Design Relating to Environmental Impacts (e.g. Outdoor Site-Lighting Performance - OSP)

Much work has been done in trying to establish a comprehensive method of determining the impact of a lighting installation for a road or site. Simply focusing on the distribution from a luminaire is insufficient, since this approach ignores the reflected light from the pavement or other direction components. The Outdoor Site-Lighting Performance method is a model developed by Brons et al (20) to try to quantify the total amount of light leaving a site and the lighting's impact on abutters and the community. Other models have also been developed, but this one is included here as an example of a more holistic approach to evaluating lighting impacts.

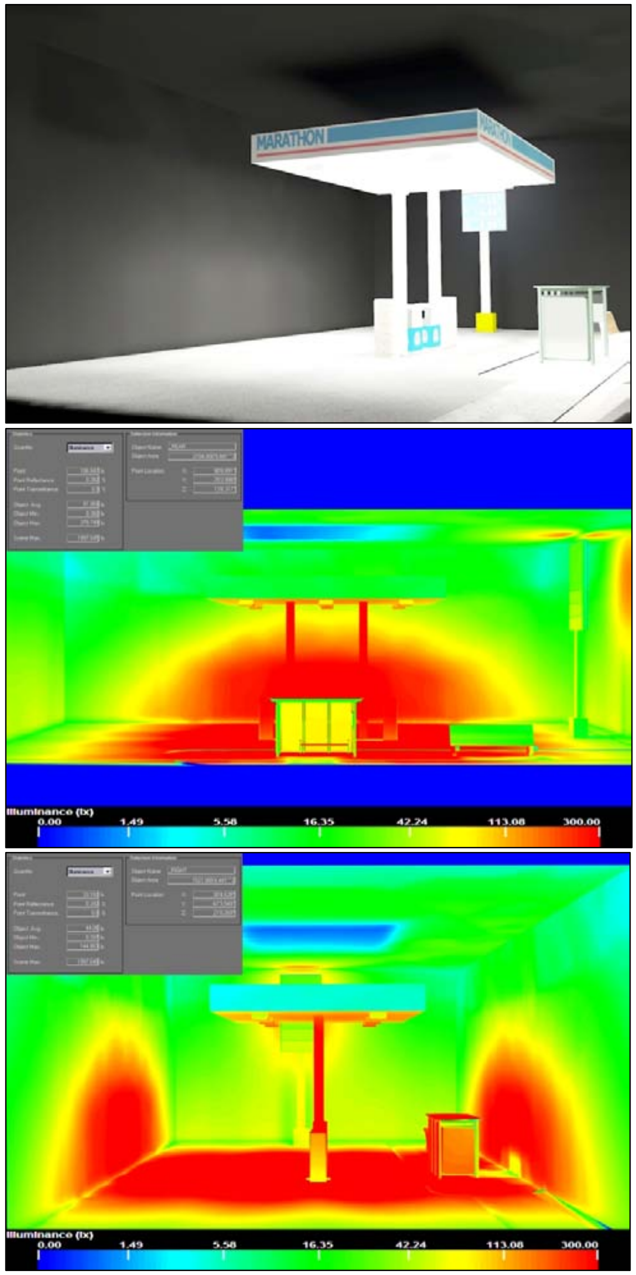

Figure 35 - Example Calculation of Lighting on Surfaces of Theoretical Box

The method essentially creates a box around a site or section of roadway and evaluates the amount of light on the sides and roof of the box as well as the maximum value of light on the vertical sides. Typical designs were investigated to get a range of values. Some provisional criteria values were then developed for discussion.

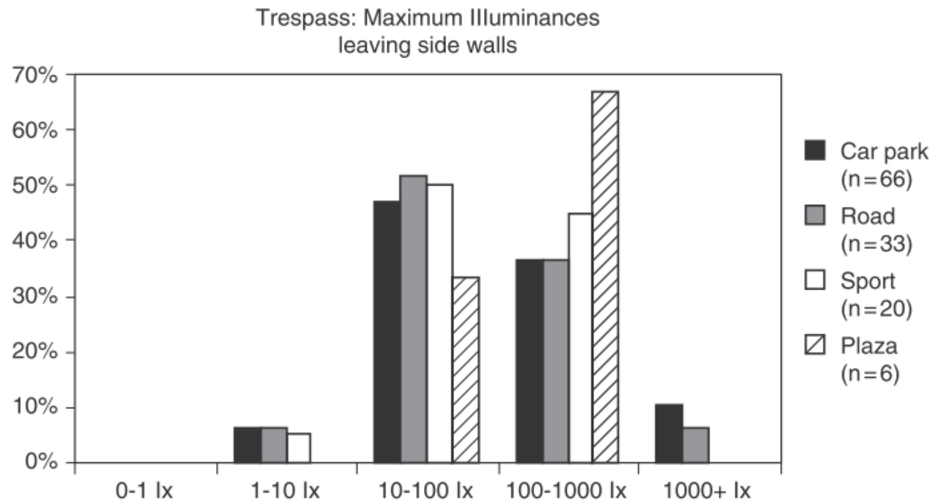

Figure 36 – Maximum Illuminance Level (Brons, 20)

	Before curfew		After curfew, glow limit (by lighting zone)							
	Criterion slope	(%) Pass	E4	(%) Pass	E3	(%) Pass	E2	(%) Pass	E1	(%) Pass
Car park	0.12	65.2		65.2		65.2		57.6		22.7
Roadway	0.14	63.6	30 lx	63.6	10 lx	63.6	3 lx	51.5	1 lx	21.2
Sport	0.22	65.0		35.0		5.0		0.0		0.0

Figure 37 – Proposed Glow Limits (Brons, 20)

7.5 Roadside Hazards

Clear zone is defined in the Roadside Design Guide 2011 as the total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles. Determining the clear zone is a function of design speed, traffic volumes, the presence of fill and cut slopes, the steepness of the slopes and the horizontal curvature of the road.

Although an unobstructed roadside is highly desirable from a roadside safety viewpoint, some appurtenances such as light poles must be placed near the travel way. As roadway lighting is a road safety enhancement, poles should be placed in such a way that they do not present a hazard to errant motor vehicles. All new and replacement Luminaire support poles should be selected from those that have been successfully crash-tested. Poles should not compromise the safety of the road user. Details for reducing impact severity with the use of suitable breakaway pole base design are included in the AASHTO Roadside Design Guide (21).

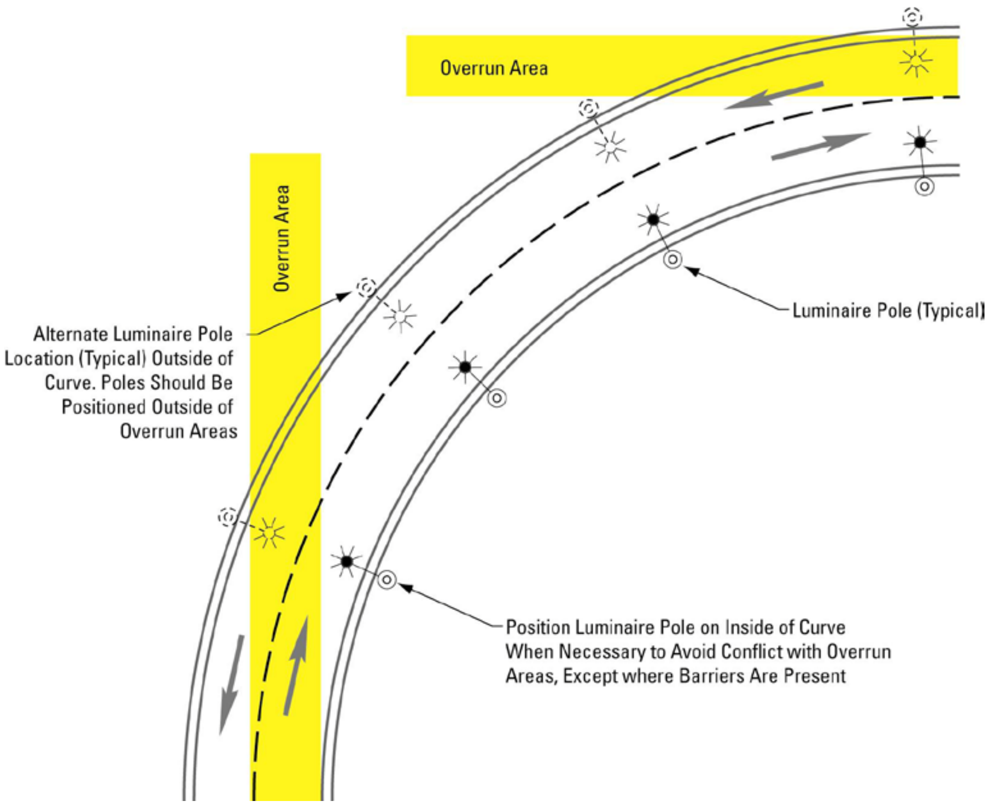

Figure 38 – Pole Spacing on Curves

Where lighting is required on roadways with small radius horizontal curvature, poles should be positioned on the inside of the curve to reduce the potential for impacts by errant vehicles that overrun the entry to the curve. If poles cannot be positioned on the inside of the curve, they should be located outside of the entry overrun areas defined in Figure 38.

Poles should be offset away from the roadway at a sufficient distance to minimize potential hazard to drivers. In urban areas with curbs and gutters, poles should be placed at the back of the sidewalks (when possible given locations of buildings and proper sidewalk width) to reduce the potential contact with motor vehicles. Breakaway base should always be used unless engineering judgment shows that pedestrian safety could be compromised. On highways and freeways, poles should be placed outside the clear zone or have a suitable breakaway device if placed within the clear zone.

A breakaway device typically attaches between the foundation and the pole to allow the pole to break away upon impact by a motor vehicle. Figure 39 illustrates breakaway base characteristics when a pole is struck by a motor vehicle. A stub height or 4 inches or less should be used to lessen the possibility for impacting vehicles to snag on the foundation of the breakaway support. Additionally the breakaway support should utilize electrical disconnects to reduce the risk of fire and electrical hazards after the structure is impacted by an errant vehicle.

Figure 39 – Pole with Breakaway Device

Other Systems and Issues Related to Roadway Lighting

This section discusses roadway-related items that impact the lighting system and roadway user.

8 Related Roadway Systems

8.1 Roadway Marking and Guidance

Retro-reflective markings, delineators, and signs can be a very cost-effective option for assisting a driver. When roadway lighting is not present, nighttime navigation generally depends upon on a road user's visibility of the roadway and pavement markings via vehicle headlamps. These types of systems do not directly help in the visibility of pedestrians, cyclists, or objects on the roadway but can greatly help in guidance and warning of known hazards.

Retro-reflective markings are designed to reflect light back to a road user's eye and improve visibility. High-performance pavement markings have been developed for both wet and dry road conditions.

Figure 40 - Retro-Reflective Pavement Markings

Post-mounted delineators (PMDs) are another effective method for providing delineation of roadway curves at night. PMDs consist of retro-reflective strips mounted on posts approximately 1.3 m above the pavement.

Figure 41 – Post-Mounted Delineators (PMDs)

PMDs are typically used for the benefit of marking out curves in a roadway. The Manual on Uniform Traffic Control Devices (MUTCD, 2009) defines typical spacing for PMDs.

Retro-reflective pavement markings and post-mounted delineators can be considered as alternatives to lighting for rural applications where pedestrians or other unexpected hazards are not anticipated.

8.2 Impact of Vehicle Headlamps

Vehicle headlamps improve a driver's visibility of objects on the roadway. However, this is not well quantified in the research. The effect of headlamps is not currently taken into account when undertaking lighting calculations and designing a roadway system. Typically, at higher speeds, the length of the safe stopping distance exceeds the distance from the vehicle in which headlamps give assistance to the driver.

In order to assess the speeds where headlamps alone may be sufficient, computer modeling was performed (Lutkevich, 2007) using available photometric files for low-beam headlights. The model suggests that vehicle headlamps alone may meet the lighting requirements for low-speed (lower than 30 mph), low-pedestrian-activity roadways. Because this was a limited analysis, however, and because many variables are involved in the decision to provide supplemental lighting, the designer and governing authority must decide whether lighting is warranted. Lighting has been proven as an effective countermeasure but headlamps are a consideration when evaluating a nighttime environment.

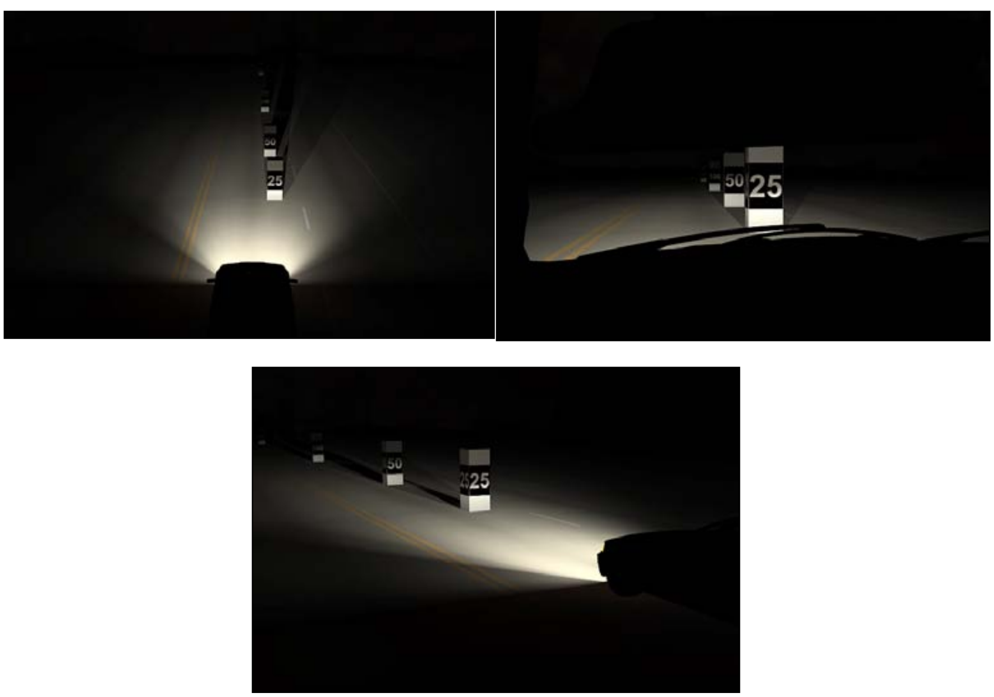

Figure 42 – Headlamp Modeling Example

8.3 Temporary Roadway and Work Zone Lighting

8.3.1 Temporary Roadway Lighting

Temporary roadway lighting is typically installed where a road detour is required. It is provided to aid traffic flow and improve driver and pedestrian visibility during road construction and detours. Temporary roadway lighting levels are similar to the requirements for permanent roadway lighting.

Highway construction projects frequently require detours, reduced shoulder widths, reduced lane widths, limited pull off areas, unusual maneuvering, temporary pavement and markings, rough pavement, and many other conditions that make navigating the construction zone difficult. Temporary roadway lighting can be an effective tool for improving guidance and aiding in the passage of road users through a construction site.

Temporary roadway lighting is considered when one or more of the following conditions are met:

- Where lighting exists but has to be removed for construction, and permanent lighting is not operational.
- The roadway does not meet geometric design standards for an extended period (more than a few weeks).
- Hazards are present during hours of darkness.
- Medium to high pedestrian activity occurs during hours of darkness.
- Devices such as pylons, delineators, barricades and barrels don’t provide sufficient guidance.

In the interest of economy, poles and luminaires designated for the permanent installation may be used for the detour and relocated to the permanent location. Highmast lighting is an efficient method of temporary roadway lighting since it lights areas well beyond the roadway, which may be used for temporary detour roads.

8.3.2 Work Zone Lighting

Work zone lighting is provided for construction activities and is not meant to serve as temporary roadway lighting. Work zone lighting typically involves the use of portable, high-intensity floodlights with portable generators to direct a high level of light onto the work area. Because work zone lighting is provided for worker safety, the warrant for this lighting should be dependent on the task at hand and the local worker safety regulations. Work zone illumination levels as recommended by National Cooperative Highway Research Program (NCHRP) Report 498 are recommended.

Category	Minimum Illuminance Level	Area of Illumination	Application	Example Areas and Activities for Illumination
1	54 lux	General illumination through spaces	Large size visual task; low accuracy; general safety requirements	Excavation; sweeping and cleaning; movement areas in work zones; movement between tasks
2	108 lux	General illumination of tasks around equipment	Medium size visual task; low to medium contrast; medium accuracy; safety on around equipment	Paving; milling; concrete work around paver, miller and other construction equipment
3	216 lux	Illumination on task	High size visual task; low contrast; high accuracy and fine finish	Crack filling; pot filling; signalization or similar work requiring extreme caution and attention

Figure 43 - Work Zone Lighting

Portable lighting equipment can often cause glare issues impacting a driver's visual performance passing through a work zone. To minimize that impact floodlights should be aimed away from travel lanes in a the work zone similar to the recommendation given in Figure 44. The possible addition of temporary roadway lighting may also be evaluated depending on locations and project conditions.

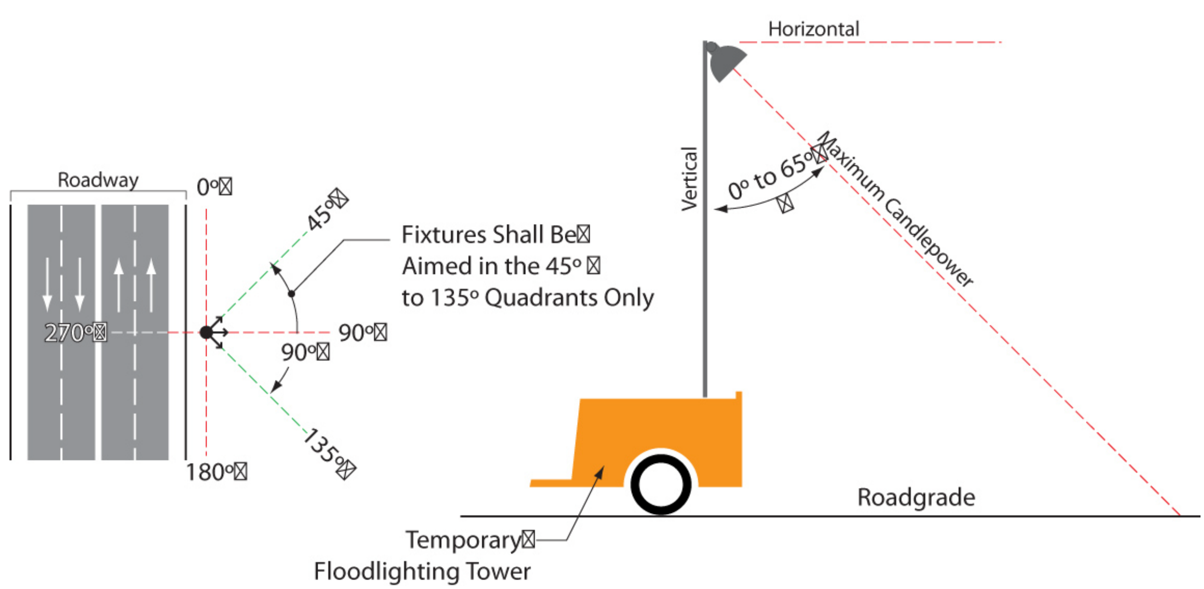

Figure 44 – Work Zone Floodlight Aiming

8.4 Impact of Architectural/Aesthetic Lighting System for Roadway Facilities

Lighting can produce distinctive visual effects, and can help to shape the identity of a place. Poles and luminaries can be provided in custom colors and shapes to complement street furniture such as benches, handrails, and trash bins. Spaces designed for visual effect involving such decorative elements are referred to as "streetscapes."

Typically, street lighting projects involve architects who define the aesthetic elements, including lighting. It is important that the lighting designer work in collaboration with the architect, since lighting features such as pole heights, arm length, luminaire optics, and location all have an impact on the overall design. For example feature lighting in the center island of a roundabout can not only enhance the nighttime aesthetic appearance but also increase vertical luminances on objects possibly enhancing visibility.

Figure 45 - Streetscape Lighting

Trees and other landscape features may be included as part of a streetscape design. The lighting designer should consult with the architect on items such as the location of plants and trees that may block lighting on the roadway, or tree roots that may interfere with underground conduits or other electrical equipment. Coordination will also be required regarding other architectural elements such as benches, planters, building canopies and awnings, and other street furniture, as well as parking stalls and signage. Architectural requirements should never take precedence over safe lighting requirements.

Streetscape projects are designed to meet both the visibility requirements for drivers and the more subjective security and comfort considerations for pedestrians. To meet sidewalk lighting requirements, pedestrian-scale lighting as shown in Figure 46 is typically be required. For wider roads, or in places where trees are present or proposed, taller poles with mast arms may be required to get lights out on the road.

Figure 46 - Pedestrian Scale Lighting

Typical light layouts are shown in Figure 47. For two lane roads, pedestrian-scale lighting may provide the required level of illumination for the street and sidewalk. However, if this does not produce the required results or if the roads are wider (4 or more lanes), pedestrian-scale lighting will typically have to be supplemented with taller overhead lighting poles. The main purpose of the overhead lighting is get the luminaries on mast arms extended over the road beyond to tree canopies to light the street. The pedestrian-scale lighting will provide illumination for the sidewalk.

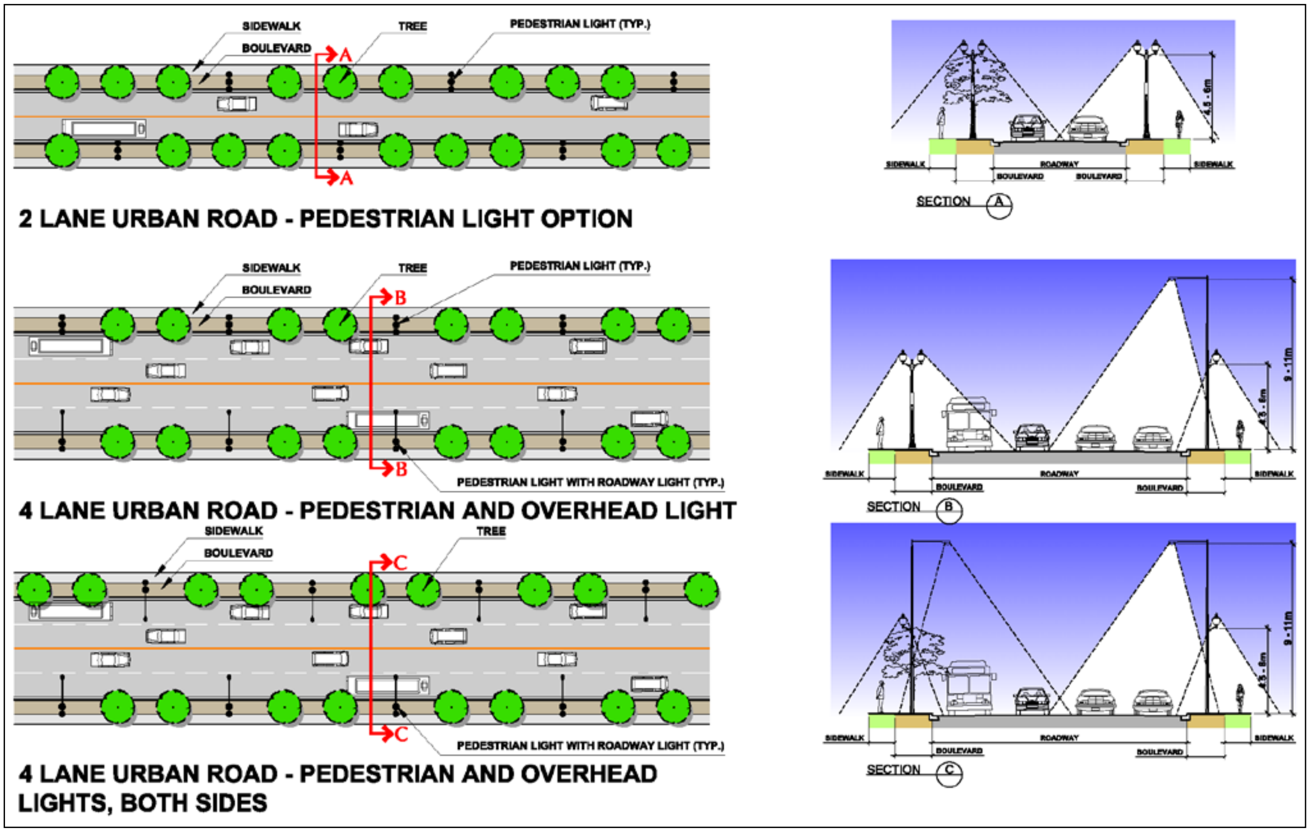

Figure 47 - Streetscape Lighting Layouts

Visibility on the sidewalk and streets can also be reduced if trees block the light and create shadows that reduce uniformity and visibility (Figure 48). A study titled *Trees, Lighting and Safety in Context Sensitive Design* (24) gave some examples of how a lighting system should be designed to allow for the presence of trees at all stages of maturity:

- The best design approach is to locate luminaires outside of the full growth lines of the species of tree along the roadway.
- When a roadway or pedestrian lighting project includes new or existing trees in close proximity to the lighting, an additional light loss factor should be included in the design to accommodate light loss due to shading. Insufficient research is available at this time to quantify the factor with precision, but an additional 10 - 20 percent is reasonable.

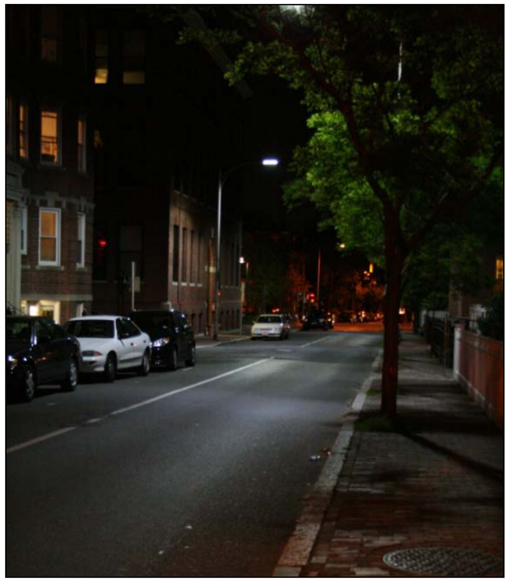

Figure 48 - Trees Blocking Light

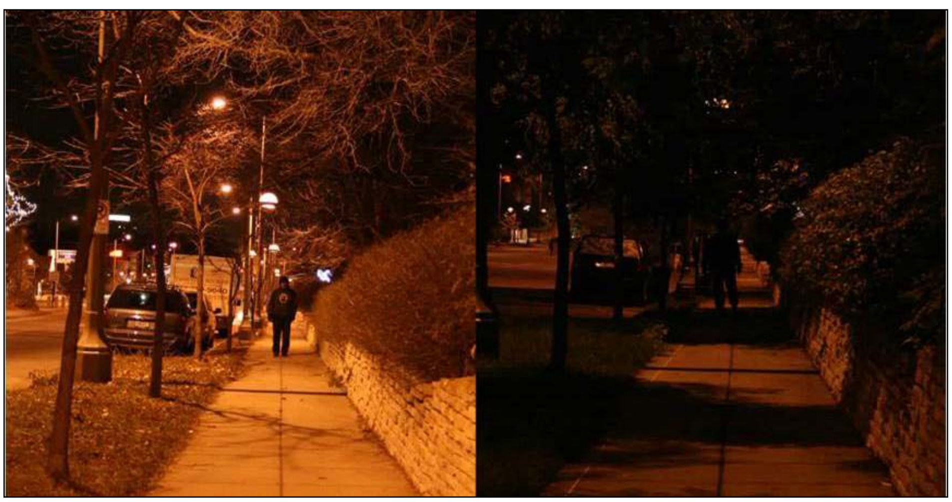

Figure 49 - Comparison of sidewalk areas in winter (without leaves) and summer (with leaves)

9 Summary

There are significant resources available for application and considerations relating to street and roadway lighting. These resources are constantly changing as research and practice evolve in the field of outdoor lighting. Much is left to learn about optimizing visibility for the roadway user while balancing the impacts and best cost/benefit of available safety improvements.

This handbook, with the research and documents referenced within it, provides a solid base for policy makers, owners, designers, and installers in the decision making process. Much is changing in this field. Research is ongoing in the areas of mesopic vision, adaptive lighting, spectral impacts to visibility/contrast, and better predictive models. New lighting sources continue to develop and emerge which are changing the way roadway lighting design is approached and designed. The user of this handbook is encouraged to remain current on the resources provided by FHWA, AASHTO, IES, CIE, and other technical organizations.

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Glossary of Terms

Accommodation: the process by which the eye changes focus from one distance to another.

Adaptation: the process by which the visual system becomes accustomed to more or less light or of a different color than it was exposed to during an immediately preceding period. It results in a change in the sensitivity of the eye to light.

Arrangement: the repeating pattern of luminaires on a roadway. Usually described as opposite, staggered, one-side, center-suspended, or median mounted.

Ballast: a device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current and waveform) for starting and operating.

Beacon lighting: a single luminaire that will identify the presence of an intersection or an interchange or potential conflict with other traffic and physical features and will serve as a warning or marker.

Bifurcation area: the triangular shaped area between two diverging lanes, beyond the point of physical separation of one lane from the other. This area is immediately beyond the decision point where a driver must commit to one lane or the other, and lies in the direct line of travel of an overrunning vehicle.

bidirectional reflectance-distribution function (BRDF): the ratio of the differential luminance of a ray reflected in a given direction to the differential luminous flux density incident from a given direction of incidence, which produces it.

Bikeway: any road, street, path, or way that in some manner is specifically designated as being open to bicycle travel, regardless of whether such facilities are designated for the exclusive use of bicycles or are to be shared with other transportation modes.

Brightness: see **luminance** and **subjective brightness.**

Candela, cd: the SI unit of luminous intensity. One candela is one lumen per steradian. Formerly candle.
(See **Figure 50**.)

Candela per square meter, Cd/m^2 :the SI unit of luminance equal to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square meter or the average luminance of any surface emitting or reflecting light at that rate.

Candlepower, cp: luminous intensity expressed in candelas. (It is no indication of the total lumen output)

Central (foveal) vision: the seeing of objects in the central or foveal part of the visual field, approximately two degrees in diameter. It permits seeing much finer detail than does peripheral vision.

Contrast sensitivity: the ability to detect the presence of luminance differences. Quantitatively, it is equal to the reciprocal of the contrast threshold.

contrast see **luminance contrast**.

Contrast threshold: the minimal perceptible contrast for a given state of adaptation of the eye. It also is defined as the luminance contrast detectable during some specific fraction of the times it is presented to an observer, usually 50 percent.

Conflict: A conflict occurs whenever the paths followed by vehicles diverge, merge or cross

Conflict Area: *Is* an area of a roadway where the motorist's special attention is required in order to interpret the functional features (e.g. bullnose) and / or activities (e.g. pedestrians, turning vehicles, railroad grade crossing) of the roadway, in order to make a decision on their driving routine. It is that area which encompasses all of the conflict points.

Conflict Points: Points at which conflicts can occur.

Continuous Lighting: A fixed overhead lighting system designed to provide a specific level of illuminance, luminance and uniformity of light on the roadway throughout a highway complex.

Crosswalk: see **pedestrian crosswalk**.

Diffuse reflectance: the ratio of the flux leaving a surface or medium by diffuse reflection to the incident flux.

Directional reflectance: the reflectance in a given direction from an incident ray reaching the surface or medium from a given direction. See **bidirectional reflectance-distribution function**.

Disability glare: glare resulting in reduced visual performance and visibility. It often is accompanied by discomfort. See **veiling luminance**.

Discomfort glare: glare producing discomfort. It does not necessarily interfere with visual performance or visibility.

Entrance Ramp Conflict Area: That area of an entrance ramp from the bullnose (covering both the ramp lane(s) and the right through lane) to the end of the ramp taper.

Exit Ramp Conflict Area: That area of an exit ramp *and the right through lane* from the beginning point of the bifurcation area (neutral area) to the end of the gore area and extended 15 to 40 meters- dependant on the design speed- <u>for both the ramp lane(s) and the right through lane.</u>

Footcandle, fc: the unit of illuminance when the foot is taken as the unit of length. It is the illuminance on a surface one square foot in area on which there is a uniformly distributed flux of one lumen, or the illuminance produced on a surface all points of which are at a distance of one foot from a directionally uniform point source of one candela.

Glare: the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility. See **disability glare**, **discomfort glare**.

Intersection: the general area where two or more roadways (highways) join or cross, including the roadway and roadside facilities for traffic movement within it.

Intersection Conflict Area: That area of an intersection that is extended to cover the conflict area

Lambertian surface: a surface that emits or reflects light in accordance with Lambert's cosine law. A Lambertian surface has the same luminance regardless of viewing angle.

Lamp: a generic term for an artificial source of light.

Lamp life: the average life of a lamp defined as the total operating hours at which 50 percent of any group of lamps is still operating.

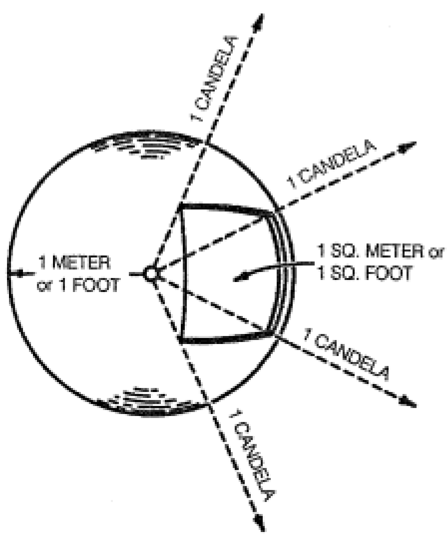

Figure 2 - Relationship between candelas, lumens, lux, and footcandles:

A uniform point source (luminous intensity or candlepower = one candela) is shown at the center of a sphere of unit radius whose surface has a reflectance of zero. The illuminance at any point on the sphere is one lux (one lumen per square meter) when the radius is one meter, or one footcandle (one lumen per square foot) when the radius is one foot. The solid angle subtended by the area A,B,C,D is one steradian. The flux density is therefore one lumen per steradian, which corresponds to a luminous intensity of one candela as originally assumed. The sphere has a total area of 4 (or 12.57) square units (square meters or square feet), and there is a luminous flux of one lumen falling on each unit area. Thus the source provides a total of 12.57 lumens.

High mast lighting: illumination of a large area by means of a group of luminaires which are designed to be mounted in fixed orientation at the top of a high support or pole (generally 20 meters or higher).

Illuminance, E: the density of the luminous flux incident on a surface; it is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated.

Illuminance (lux or footcandle) meter: an instrument for measuring illuminance on a plane. Instruments which accurately respond to more than one spectral distribution (color) are color corrected. Instruments which accurately respond to more than one spatial distribution of incident flux are cosine corrected. The instrument is comprised of some form of photo-detector with or without a filter, driving a digital or analog readout through appropriate circuitry.

Intensity: a shortening of the terms luminous intensity and radiant intensity.

Lamp lumen depreciation factor, LLD: the multiplier to be used in calculations to relate the initial rated output of light sources to the anticipated minimum output based on the relamping program to be used.

Lamp post: a support or pole provided with the necessary internal attachments for wiring and the external attachments for the bracket and/or luminaire.

Light loss factor, LLF: a factor used in a lighting calculation after a given period of time and under given conditions. It takes into account temperature and voltage variations, dirt accumulation on luminaire surfaces, lamp lumen depreciation, maintenance procedures, equipment and ballast variations. Formerly called maintenance factor.

Line of sight: the line connecting the point of observation and the point of fixation.

Lumen, lm: the SI unit of luminous flux. Radiometrically, it is determined from the radiant power. Photometrically, it is the luminous flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candela.

Luminaire: a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps and to connect the lamps to the power supply. Sometimes includes ballasts and photocells.

Luminaire cycle: the distance between two luminaires along one side of the roadway. Note: this may not be the same as luminaire spacing along the centerline considering both sides of the road. (See **spacing**.)

Luminaire dirt depreciation factor, LDD: the multiplier to be used in lighting calculations to reduce the initial light level provided by clean, new luminaires to the light level that they will provide due to dirt collection on the luminaires at the time at which it is anticipated that cleaning procedures will be instituted.

Luminance, L (cd/m^2): the quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. The luminous flux may be leaving, passing through, and/or arriving at the surface. Note: In common usage the term “brightness” usually refers to the strength of sensation which results from viewing surfaces or spaces from which light comes to the eye. This sensation is determined in part by the definitely measurable luminance defined above and in part by conditions of observation such as the state of adaptation of the eye.

Luminance contrast: the relationship between the luminances of an object and its immediate background.

Luminance meter: an instrument for measuring the luminance of an object or surface. Instruments which accurately respond to more than one spectral distribution (color) are color corrected. The instrument is comprised of some form of a lens system and aperture creating an image on a photodetector, driving a digital or analog readout through appropriate circuitry.

Luminous efficacy of a source of light: the quotient of the total luminous flux emitted by the total lamp power input. It is expressed in lumens per watt.

Luminous flux density at a surface: the luminous flux per unit area at a point on a surface. Note: this need not be a physical surface; it may equally well be a mathematical plane.

Luminous intensity, I (cd): the luminous flux per unit solid angle in a specific direction. Hence, it is the luminous flux on a small surface normal to that direction, divided by the solid angle (in steradians) that the surface subtends at the source.

Lux, lx: the SI unit of illuminance. It is the illuminance on a surface one square meter in area on which there is a uniformly distributed flux of one lumen, or the illuminance produced at a surface all points of which are at a distance of one meter from a uniform point source of one candela.

Mean lamp lumens: the mean lumen output of a lamp is calculated by determining the area beneath the lumen maintenance characteristic curve of that source over a given period of time and dividing that area by the time period in hours.

Mounting height, MH: the vertical distance between the roadway surface and the center of the apparent light source of the luminaire.

Overhang, OH: the horizontal distance between a vertical line passing through the luminaire light center and the curb or edge of the travelled roadway.

Partial Lighting: Partial Lighting refers to lighting installed at the decision areas of isolated interchanges and intersections whereby it provides visibility of potential conflicts with other traffic and physical features.

Pedestrian crosswalk: an area designated by markings for pedestrians to cross the roadway.

Pedestrian way: a sidewalk or pedestrian walkway, usually paved, intended for pedestrian usage.

Point of fixation: a point or object in the visual field at which the eyes look and upon which they are focused.

R-table: a table for a particular pavement type which provides reduced luminance coefficients in terms of the variable angles, beta and tan gamma.

Reaction time: the interval between the beginning of a stimulus and the beginning of the response of an observer.

Setback: the lateral offset of the pole center from the face of the curb or edge of the travelled way.

Spacing: the distance between successive luminaires measured along the center line of the street. See **luminaire cycle**.

Spacing-to-mounting height ratio, S/MH: the ratio of the distance between luminaire centers, along the center line of the street, to the mounting height above the roadway.

Subjective brightness: the subjective attribute of any light sensation given rise to the perception of luminous intensity, including the whole scale of qualities of being bright, lightness, brilliant, dim, or dark.

Traffic conflict area: area on a road system where a strong potential exists for collisions between vehicles or between vehicles and pedestrians.

Veiling luminance: a luminance superimposed on the retinal image which reduces its contrast. It is this veiling effect produced by bright sources or areas in the visual field that results in decreased visual performance and visibility.

Visibility: the quality or state of being perceivable by the eye. In many outdoor applications, visibility is sometimes defined in terms of the distance at which an object can be just perceived by the eye. In indoor and out- door applications it usually is defined in terms of the contrast or size of a standard test object, observed under standardized view-conditions, having the same threshold as the given object.

Visibility index, VI: a measure closely related to **visibility level** sometimes used in connection with road lighting applications.

Visibility level, VL: a contrast multiplier to be applied to the visibility reference function or provide the luminance contrast required at different levels of task background luminance to achieve visibility for specified conditions relating to the task and observer.

Visual angle: the angle subtended by an object or detail at the point of observation. It usually is measured in minutes of arc.

Walkway: a sidewalk or pedestrian way.