Guidelines for the Implementation of Reduced Lighting on Roadways

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FOREWORD

The Federal Highway Administration's Office of Safety Research and Development serves the highway safety community by conducting research that advances safety goals while accommodating practical considerations. The development of methodologies and tools that result from this research can assist practitioners who are looking to make safety-based decisions in the real world. The guidelines presented in this report address the need to maintain the safety effects of roadway lighting while alleviating the budgetary strains associated with the maintenance of the lighting infrastructure.

This report establishes a new set of criteria for practitioners to apply to their roadway environment that will identify appropriate lighting levels for given roadway characteristics and usage. Specifically, these guidelines identify the appropriate applications of adaptive lighting on roadways while maintaining the optimal level of safety. The methodology for applying the criteria is based on existing international standards that accommodate different roadway characteristics and usage. Therefore, practitioners will be familiar with the application of the results but will benefit from an enhanced data collection and statistical approaches when considering adaptive lighting applications.

The adaptive lighting criteria identified in this report are the first to utilize real-world lighting data collection and robust statistical analysis of crash histories of the associated roadways. Ultimately, these Guidelines will provide practitioners with the evidence-based criteria they need to determine the appropriate application of adaptive lighting systems in their jurisdictions. This allows for the unique opportunity to provide significant cost savings while maintaining the optimal level of safety for roadway users.

Monique R. Evans
Director, Office of Safety
Research and Development

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This report provides guidelines for the implementation of an adaptive lighting system for roadway lighting. Based on the analysis of crashes and lighting performance, a series of criteria and the associated design levels have been developed to provide an approach for light level selection and the adjustability of the light level based on the needs of the driving environment. The application, the technology needs, the benefit cost, and the legal implications of adaptive lighting are also considered in this guideline document.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ADT	average daily traffic
CIE	Commission Internationale de L'Eclairage (International Commission on Illumination)
FAA	Federal Aviation Administration
FTCA	Federal Tort Claims Act
IESNA	Illuminating Engineering Society of North America
ILE	Institute of Lighting Engineers
ITS	intelligent transportation system
LCC	lifecycle cost
LOS	level of service
LZ	Lighting Zone
mcd/m^2 lx	millicandela/meter squared lux
NPV	net present value
RP-8	Recommended Practice for Roadway Lighting
TAC	Transportation Association of Canada
vph	vehicles per h

INTRODUCTION

The impact of road lighting has been well documented, and its implementation is overwhelmingly regarded as positive; both drivers and pedestrians recognize the safety of being able to detect potential hazards at night. During the energy crisis in the 1970s, which affected metropolitan and rural areas, the removal of roadway lighting was hotly debated. Several studies conducted during this time assessed the impact of the presence or absence of roadway lighting. Other studies anticipated the installation of lighting along highways and evaluated the before-and-after effects of the lights. The results of these studies were not surprising: the presence of roadway lighting makes roads generally safer, while the removal of lighting decreases safety.

However, energy concerns continue to loom today, and the expenses associated with roadway lighting are typically a significant component of a transportation agency budget. New lighting and control technologies provide the ability to adapt the output of lighting systems based on road-user needs. Adaptive lighting allows lighting to be turned off or reduced when few or no vehicles or pedestrians are using the roadway; lighting can then be turned on or increased when needed. This process allows a reduction in the amount of energy consumed by lighting while maintaining the current level of safety that lighting provides to roadway users.

Current guidelines for roadway lighting already allow some adaptability. The Illuminating Engineering Society of North America (IESNA) Recommended Practice for Roadway Lighting (RP-8) defines the lighting level in terms of roadway type and potential for pedestrian interaction.(1) The Commission Internationale de L'Eclairage (CIE) provides a roadway lighting selection guide based on the characteristics of the roadway.(2) These two guidelines have been reviewed and are incorporated into the requirements defined as part of this document.

PURPOSE OF THIS DOCUMENT

These *Guidelines for the Implementation of Reduced Lighting on Roadways* provide a process by which an agency or a lighting designer can select the required lighting level for a road or street and implement adaptive lighting for a lighting installation or lighting retrofit. This document supplements existing lighting guidelines. It is expected that the reader has knowledge of lighting design and the issues associated with the implementation of roadway lighting.

ADAPTIVE LIGHTING PHILOSOPHY

The objective of adaptive lighting is to use lighting only when it is required and at the appropriate level to provide for the safety of roadway users. Streets and roads are often overlighted, meaning that more light is used than the road users require. The reasons are threefold:

- The output from a luminaire is quantized based on the wattage of the light source. As a result, the minimum-wattage criterion for a light source design may cause the luminaire to produce more light than the application requires.

- Lighting designs are intended to maintain given levels of illumination. During the design process, lighting levels are calculated to account for depreciation factors such as dirt and age. Consequently, a new installation provides greater illumination than is needed based on the design criteria. As the system ages, the output will fall off until it reaches the design value. This could take a significant amount of time.

- Roadway lighting design levels are selected based on worst-case scenarios. The current method for selecting a lighting design level uses the maximum requirements for the roadway. For example, in a retail district, the lighting level is selected and designed for times when there are high pedestrian volumes. Without an adaptive system, the lighting level remains the same even after the retail activities have closed for the night.

The philosophy behind adaptive lighting is to provide lighting only when and where it is needed, essentially managing the roadway lighting level as an asset. The light level on a roadway can be managed and controlled in two ways.

The first approach is to reduce the light output from the luminaire to the level required by the lighting design. This approach, typically referred to as "right sizing," avoids the output quantization problem by selecting a light source of appropriate size for the application. It is noteworthy that a right-sizing application typically includes a light level monitoring system to provide feedback for the control of the luminaire. This approach mitigates some of the maintenance issues by monitoring the light output over time and responding to deprecations in luminaire performance from dirt or lamp depreciation.

The second method is to adjust the light level based on current road conditions, which may include use of criteria such as traffic volume, vehicle mix, pedestrian activity, and weather. This document provides guidance on how to implement an adaptive lighting design, because it is more responsive to roadway user needs and provides greater efficiencies for the system owner/operator.

POTENTIAL BENEFITS OF ADAPTIVE LIGHTING

The obvious and primary benefit of adaptive lighting is the reduction of energy use, which has been shown to be between 20 and 40 percent with adaptive lighting.(3) The other potential benefits of adaptive lighting are reductions in the following:

- Maintenance costs.
- Lamp and driver replacement cost as a result of extended luminaire performance.
- Traffic and travel interruptions due to maintenance operations.
- Possibility of tort issues resulting from system maintenance issues.
- Over-lighting.
- Light trespass.
- Skyglow.
- Glare from roadway lighting installations.

ADAPTIVE LIGHTING SYSTEMS REQUIREMENTS

For an adaptive lighting solution to produce a financial benefit, the lighting system must have the following components:

- Control system, either central or localized on each luminaire.
- Dimmable-controls-ready luminaire.
- Localized metering or a negotiated adaptive lighting electricity rate.

The control systems are the primary component of the adaptive lighting methodology and are generally monitored and managed from a central location. A general outline of a lighting control system is shown in figure 1. Here, each individual luminaire is controlled from a central hub. Generally, each luminaire has an addressable control module that turns the luminaire on and off and manages any dimming requirements. This module communicates to a node controller that may manage as many as 2,000 or more luminaires. The node controllers then communicate with a central management system. The method of communication can be wired, via a power line carrier, or wireless. Wireless communication is a popular method, particularly for retrofits, because it does not rely on a formal network but can be created using self-healing mesh network techniques. Other sensors, such as weather detectors and ambient light monitors, may also be linked into the system to provide additional data for lighting management. This approach to lighting management falls under the general description of Electrical and Lighting Management Systems, and the National Transportation Communications for Intelligent Transportation System Protocol 1213 has been developed to provide commonality among the control systems.[(4)] It is also important to note that these systems may be part of the intelligent transportation system (ITS) of an agency and may need to comply with Federal requirements found in 23 Code of Federal Regulations 940.

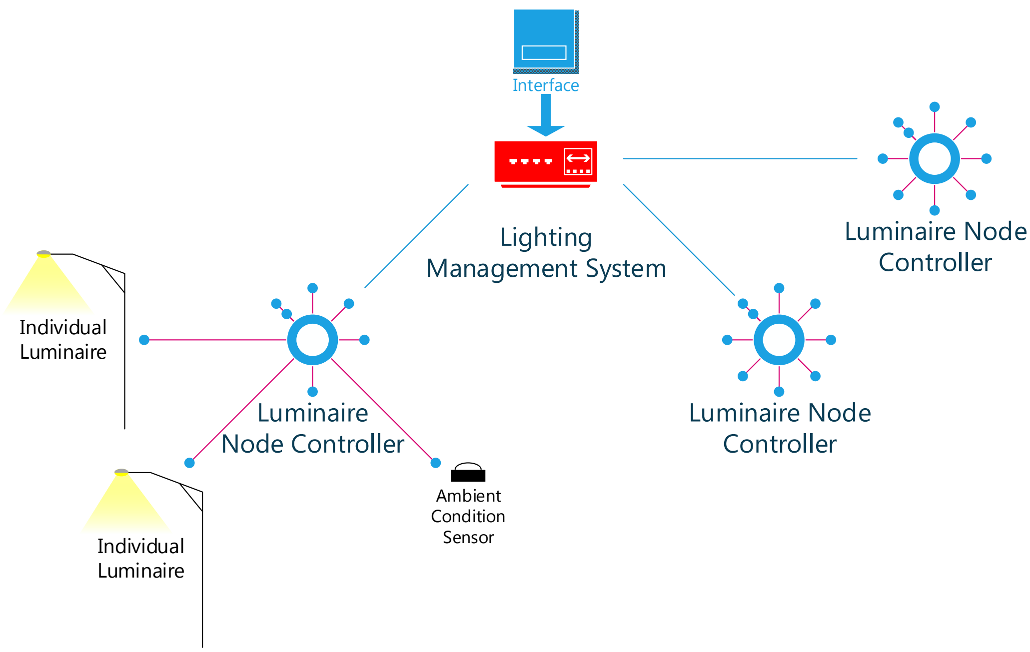


Figure 1. Illustration. General structure of a lighting control system.

The second aspect of the adaptive system is the luminaire itself. The luminaire must be able to respond to the output of the control system and provide dimming. Dimming is the recommended method for adaptive lighting. In the past, reduced lighting on roadways has been accomplished through switching or "half-code" lighting, in which every other luminaire or the luminaires on one side of the roadway are turned off or removed. It is not possible to meet all of the existing design criteria for uniformity and glare control using half-code lighting scenarios. By contrast, dimming a luminaire allows the light level to be adjusted without upsetting the other design criteria. Dimming luminaires are typically capable of dimming from 100-percent output to anywhere between 50 and 10 percent of maximum output, depending on the light source technology. A controls-ready luminaire is one that is typically equipped with a driver that can be dimmed through a standard controller connection. The typical dimming control for a luminaire is a 0–10-volt control input that adjusts the light output based on the input voltage. Recently developed technologies can provide dimming and luminaire control to the individual luminaire via a module attached through the photo-control receptacle on the luminaire.

The final component of the adaptive system involves negotiation with the electrical utility. Most lighting systems are either owned by the electrical utility or are charged at a flat rate to the roadway agency when connected to an unmetered source such as the utility secondary feeders. To reap the financial benefits of an adaptive lighting system, the roadway agency must negotiate with the utility for a reduced rate or a rate based on metering of the electrical usage by the lighting system. Some control systems provide utility-grade metering that can be used for this purpose. However, it is vital that this aspect of the adaptive lighting system be negotiated before the system is implemented.

CURRENT ROADWAY AND ADAPTIVE LIGHTING RECOMMENDATIONS

Several methods of classifying roadways and recommended lighting performance are available throughout the world. In addition to the IESNA, examples include the Transportation Association of Canada (TAC), the Institute of Lighting Engineers (ILE) in the United Kingdom, and the CIE.

The typical method for selecting a lighting level has been to first choose the road classification and then the potential for conflict. The IESNA RP-8 provides tables for this methodology of light-level selection; TAC has a similar system and levels. However, the applicability of this method to adaptive lighting on high-speed roads is limited, because the criteria that establish the potential for conflict do not change with time of day.

For street lighting, however, IESNA RP-8 uses peak hour pedestrian counts as the criterion for potential conflict. A volume greater than 100 pedestrians is classified as high, a volume between 10 and 100 pedestrians is classified as medium, and a volume of 10 or fewer pedestrians is classified as low. Table 1 shows IESNA RP-8 recommended lighting values for various street classifications based on these pedestrian volumes.

Table 1. Street lighting levels from IESNA RP-8.

Road and Area Classification		Average Luminance L_{avg} (cd/m^2)	Maximum Uniformity Ratio L_{avg}/L_{min}	Maximum Uniformity Ratio L_{max}/L_{min}	Maximum Veiling Luminance Ratio L_{vmax}/L_{avg}
Road	**Pedestrian Area Classification**				
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

The recommended light level for a collector road with high pedestrian volumes is 0.8 cd/m^2. If pedestrian volumes fall into a lower category during certain times at night, the overall classification of the street can change. Assuming the pedestrian volumes declined to less than 10 pedestrians per h, the lighting level on the roadway could be reduced to 0.4 cd/m^2 using the existing IES RP-8 recommendations.

The lighting values in the American Association of State Highway and Transportation Officials (AASHTO) *Roadway Lighting Design Guide* are essentially the same as those in IESNA RP-8.(5) Instead of using pedestrian volumes as a subcategory for selecting a light level, the AASHTO guide uses the land use groups of commercial, intermediate, and residential. These land use categories were substituted for the pedestrian volume values of IESNA RP-8, but the values were all derived from the same initial recommended values. Changing the land use category used in the AASHTO guide would be the same as changing the expected pedestrian volume used in IESNA RP-8. Because the land use category does not change with time of day, it is difficult to use the AASHTO guide as a basis for adaptive lighting recommendations.

IESNA RP-8 also includes a pedestrian-volume-based criterion for the sidewalk areas adjacent to the roadways. Table 2 through table 4 show the lighting levels for streets with high, medium, and low pedestrian usage.

Table 2. IESNA RP-8 street lighting levels for high-volume pedestrian areas.

Maintained Illuminance Values for Walkways			
Units	**E_{avg} (lux/fc)**	**E_{Vmin} (lux/fc)**	**E_{avg}/E_{min}**
Mixed Vehicle and Pedestrian	20.0/2.0	10.0/1.0	4.0
Pedestrian Only	10.0/1.0	5.0/0.5	4.0

Table 3. IESNA RP-8 street lighting levels for medium-pedestrian areas.

Maintained Illuminance Values for Walkways			
Units	**E_{avg} (lux/fc)**	**E_{Vmin} (lux/fc)**	**E_{avg}/E_{min}**
Pedestrian Areas	5.0/0.5	2.0/0.2	4.0

Table 4. IESNA RP-8 street lighting levels for low-pedestrian areas.

Maintained Illuminance Values for Walkways			
Units	**E_{avg} (lux/fc)**	**E_{Vmin} (lux/fc)**	**E_{avg}/E_{min}**
Rural/Semi-Rural Areas	2.0/0.2	0.6/0.06	10.0
Low-Density Residential (2 or fewer dwelling units per acre)	3.0/0.3	0.8/0.08	6.0
Medium-Density Residential (2.1 to 6.0 dwelling units per acre)	4.0/0.4	1.0/0.1	4.0

Adaptive lighting techniques can also be applied to these recommendations, reducing both the horizontal and vertical illuminance values for the sidewalk based on expected pedestrian volumes. This method of determining lighting levels to be applied in adaptive technology is somewhat useful, but it is limited by its simplistic classification of roadways and street types.

CHAPTER 1. ROADWAY LIGHTING LEVEL SELECTION

Regardless of the adaptability of a lighting system, the selection of the appropriate lighting level for the given roadway is the key component for the implementation of the system. This document provides a new method for the selection of a lighting level based on the relationship between lighting and safety.

A more complete classification system than that of the IESNA and AASHTO is needed to obtain the benefits of adaptive lighting for all types of roadways. The AASHTO and IESNA lighting guides do not provide methods to calculate changes to the recommended light levels for high-speed roads in response to changes in the driving environment. The classification methods used by the ILE and CIE evaluate such factors as traffic volume and geometry in addition to pedestrian volumes. After evaluating these classification systems and the data from the current research, a new methodology has been developed based on an analysis of vehicle crashes and lighting levels. The proposed methodology is a modification of the method currently recorded in CIE Document 115.(2)

This proposed approach has been developed from the results of an analysis of crashes and lighting levels on the roadway. For this analysis, lighting data were measured *in situ* on a variety of roadways in seven different states. Crash data were then used to determine the relationship of the lighting data to the crash rate. From these results, a variety of criteria were determined to be significant to the lighting–safety relationship, including traffic volume and roadway type. Other criteria were added to the selection process based on design approaches and relevant literature. An accompanying document, *Design Criteria for Adaptive Roadway Lighting*, provides more detail on the criteria listed here.(6)

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

- Roadway lighting is provided for freeways; expressways; limited-access roadways; and roads on which pedestrians, cyclists, and parked vehicles are generally not present. The primary purpose of roadway lighting is to help the motorist remain on the roadway and aid detection of obstacles within and beyond the range of vehicle headlamps (figure 2).

Figure 2. Photo. Roadway lighting.

- Street lighting is provided for major, collector, and local roads on which pedestrians and cyclists are generally present. The primary purpose of street lighting is to help motorists identify obstacles, provide adequate visibility of pedestrians and cyclists, and assist road users in visual search tasks both on and adjacent to the roadway (figure 3).

Figure 3. Photo. Street lighting.

- Residential/pedestrian area lighting is provided primarily for the safety and security of pedestrians, not specifically for drivers. These facilities typically have driving speeds slower than 25 mi/h (40 km/h), where vehicle headlights provide adequate lighting for drivers (figure 4).

Figure 4. Photo. Residential/pedestrian area lighting.

Because these three facility types—roadway, street, and residential/pedestrian—form the basis for the lighting requirement selection methodology, each is characterized as an H (roadway), S (street), or P (residential/pedestrian) class. Each of these classes has a specific set of criteria for the selection of the lighting requirements.

As with the method in CIE Document 115, once the facility type has been selected and the class identified, the characteristics of the facility are used as weighting factors to determine the requirements of the lighting system. The equation for the lighting design class is shown in figure 5.

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

Figure 5. Equation. Lighting class.

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

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

PARAMETERS

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

Speed

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

Traffic Volume

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

The hourly traffic volume of a roadway is a recommended parameter for the application of adaptive lighting because it is indicative of current roadway conditions. For hourly traffic volume parameters, the level of service (LOS), as defined by the *Highway Capacity Manual*, is used to determine the traffic flow level criteria for the adaptive lighting level.(7)

The capacity of a roadway is determined by the roadway speed, the number of lanes, the percentage of trucks, and a factor for the geometry of the roadway. This capacity is then characterized by an LOS grouping (i.e., Levels A through F, with A being low-traffic volume and F being high-traffic volume). The LOS of the roadway is determined by the density of the vehicles per lane. The *Highway Capacity Manual* should be referenced for additional information.(7) For the three roadway types used for these guidelines (i.e., roadway, street, and residential/pedestrian), the LOS calculations were based on the assumptions in table 5.

Table 5. Assumptions made for the LOS calculation.

Variable	Roadway	Street	Residential
Speed (mph)	65	45	25
Number of Lanes per Direction	2	2	1
Percentage of Trucks (%)	5	3	0
Terrain Effects[1]	1.5	1.5	1.5

[1]This value accounts for speed and capacity changes resulting from the impact of hills and curves.

The resulting calculations for the threshold traffic volume based on the LOS are shown in table 6.

Table 6. Threshold traffic volume based on LOS.

LOS	Threshold Density	Roadway	Street	Residential
A to B	11	1,310	900	N/A
B to C	18	2,150	1,520	N/A
C to D	26	2,990	2,200	290
D to E	35	3,730	2,910	760
E to F	45	4,320	3,560	990

N/A = not applicable.

As a result of these calculations, the criteria to be used for an hourly adjustment of the lighting level based on traffic volume are shown for roadways, streets, and residential/pedestrian areas in table 7, table 8, and table 9, respectively. These values are rounded values based on the transition from LOS B to C and the transition from LOS C to D. These levels were selected because they represent when the road reaches maximum free flow (B to C) and when crash rates begin to increase (C to D).[(8)] Note that the traffic volume values listed in the tables are for single-direction travel. Thus, the values would have to be doubled when applied to undivided roads.

Table 7. Hourly traffic flow criteria for roadways.

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

Table 8. Hourly traffic flow criteria for streets.

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

Table 9. Hourly traffic flow criteria for residential/pedestrian roads.

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

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

Median

The median parameter defines the presence of a median barrier. Typically, a median is present on large roadways to separate the two directions of travel. The median must have a barrier or be designed such that the light from opposing headlamps is limited and not visible to drivers approaching each other. The AASHTO *Roadside Design Guide* defines a median width of 49.2 ft (15 m) where a barrier is not required in a roadway, and this median width is suitable to limit glare between vehicles.(9) Median widths between 32.8 to 49.2 ft (10 to 15 m) require a design review with engineering judgment.

Intersection/Interchange Density

The intersection/interchange density parameter refers to the number of intersections and entrances into the roadway per mi or km. This parameter represents the possibility of vehicles interacting in the roadway. It includes not only other roadways but driveways and other entrance areas.

Ambient Luminance

The brightness and amount of light in the surrounding area affects the lighting requirements for the roadway and is accounted for in the lighting level selection. To differentiate lighting and ambient zones, the IESNA has developed Lighting Zones (LZ) describing different ambient lighting conditions.(10)

LZ0: No Ambient Lighting

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

LZ1: Low Ambient Lighting

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

LZ2: Moderate Ambient Lighting

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

LZ3: Moderately High Ambient Lighting

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

LZ4: High Ambient Lighting

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

Guidance

The guidance parameter refers to the presence and quality of the other non-lighting-related visibility and guidance tools on the roadway. In particular, the quality of the pavement markings has been shown to interact with the lighting in terms of driver performance. The criterion presented here for guidance is the retroreflectivity of the pavement markings in millicandela/meter squared lux (mcd/m^2 lx).

Pedestrian/Bicycle Interaction

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

Parked Vehicles

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

Facial Recognition

The facial recognition parameter refers to the requirement of a driver or pedestrian to recognize the facial characteristics of a person walking in the roadway or on the sidewalk (figure 6 and figure 7). This function is related to the feeling of safety and security of the roadway users. Typically, facial recognition can be expected to always be an important aspect of the roadway environment.

Figure 6. Photo. Facial recognition under low lighting.

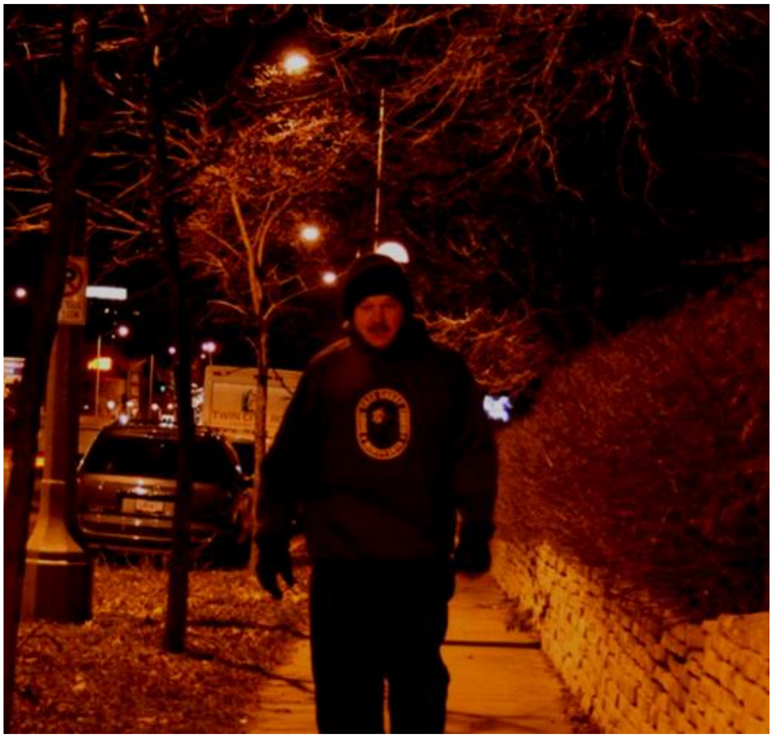


Figure 7. Photo. Facial recognition under high lighting.

Conflict Areas

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

DESIGN CRITERIA AND LUMINANCE SELECTION

The parameters described above are used to determine the lighting level. Table 10, table 12, and table 14 show the weighting parameters, while table 11, table 13, and table 15 show the recommended lighting design levels (based on the lighting class) for roadway, street, and residential/pedestrian facilities, respectively. The base values for each of the facility types are also provided for each classification. It is important to note that the lighting design criteria for the residential/pedestrian areas are horizontal and vertical illuminance, not luminance. Road luminance is the criterion for both roadway and street facilities.

It is also important to note that, as the weighting values change, the lighting level can change. For example, the traffic volume or the number of pedestrians can change, which affects the weighting value of that parameter. This, in turn, may change the roadway lighting class;

therefore, the lighting level requirements may change as well. This is particularly critical with respect to the traffic volume and pedestrian levels.

Design Criteria for Roadways (H-Class)

Base value for class: 5

Table 10. Roadway design level selection criteria.

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

Table 11. H-class lighting design levels.

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

Design Criteria for Streets (S-Class)

Base value for class: 6

Table 12. Street design level selection criteria.

Parameter	Options	Criteria	Weighting Value
Speed	High	> 45 mi/h (70 km/h)	1
	Moderate	35–45 mi/h (55–70 km/h)	0.5
	Low	< 35 mi/h (55 km/h)	0
Traffic Volume	High	> 15,000 ADT	1
	Moderate	5,000–15,000 ADT	0
	Low	< 5,000 ADT	-1
Median	No	No median present	1
	Yes (or one-way)	Must be glare blocking	0
Intersection/ Interchange Density	High	> 5 per mi (1.6 km)	1
	Moderate	1–5 per mi (1.6 km)	0
	Low	< 1 per mi (1.6 km)	-1
Ambient Luminance	High	LZ3 and LZ4	1
	Moderate	LZ2	0
	Low	LZ1	-1
Guidance	Good	> 100 mcd/m^2 lx	0
	Poor	< 100 mcd/m^2 lx	0.5
Pedestrian/Bicycle Interaction	High	> 100 pedestrians per h	2
	Moderate	10–100 pedestrians per h	1
	Low	< 10 pedestrians per h	0
Parked Vehicles	Yes	Parked vehicles present	1
	No	Parked vehicles not present	0

Table 13. S-class lighting design levels.

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

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

Base value for class: 6

Table 14. Residential/pedestrian design level selection criteria.

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

Table 15. P-class lighting design levels (E = illuminance).

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

EXAMPLE OF LIGHTING DESIGN CRITERIA SELECTION

The following example illustrates how to select a roadway lighting class. The parameters are the following:

- Speed limit of 70 mi (113 km).
- Equivalent of 35,000 ADT.
- 39-ft (12-m) median between opposing directions with no barrier.
- An average of 2 mi between interchanges.
- Zoned as an LZ3 lighting area.
- Has brand-new pavement markings measuring at 425 mcd/m^2 lx.

The resulting weighting functions are shown in table 16.

Table 16. Example lighting level selection process for a roadway facility.

Parameter	Options	Criteria	Weighting Value
Speed	Very High	> 60 mi/h (97 km/h)	1
Traffic Volume	High	> 30,000 ADT	1
Median	No	No median present	1
Intersection/Interchange Density	Moderate	1.5–4 mi (2.4–6.4 km) between intersections	0
Ambient Luminance	High	LZ3 and LZ4	1
Guidance	Good	> 100 mcd/m^2 lx	0
Sum of Weights			4

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

If this design was for an active adaptive system, the lighting design level would be changed based on the roadway conditions. For example, if the traffic volume of the roadway decreased from 35,000 to 15,000 ADT, the weighting value of traffic volume would decrease from 1to 0, and the road class would change from H1 to H2, allowing for a decrease in the lighting level from 1.0 to 0.8 cd/m^2 (shown in table 10 and table 11).

An alternative method for defining the traffic volume is to use hourly traffic volume. For example, if the hourly traffic volume was 4,100 vehicles per h (vph), the weighting value would be 1 (table 7). This would still result in an H1 class, assuming the same variables listed in table 16 are used. If the hourly traffic volume dropped to 1,000 vph, the weighting value would be -1, and the roadway classification would drop to H3.

A similar example is provided for a street facility. The design level criteria are shown in table 17. Here, a change in the number of pedestrians per h could result in a change in the recommended lighting level.

Table 17. Example lighting level selection process for a street facility.

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

The sum of the weighting values is 6 in this example, which would be subtracted from the base value of 6, resulting in a value of 0. This value would infer the use of the lighting class S1 (table 13). If the traffic volume changed to less than 5,000 vehicles per day and the pedestrian volume changed from more than 100 pedestrians per h to less than 10 per h, the sum would change from 6 to 4, allowing for a reduction in light levels at the S2 class.

CHAPTER 2. ADAPTIVE LIGHTING APPLICATION

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

WHERE TO ADAPT LIGHTING

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

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

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

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

- For roadway facilities, each roadway should be assessed individually, but drivers should not experience greater than a one-level change in the lighting class per mi of travel.
- For streets, each street should be evaluated in terms of the lighting needs. However, the difference in lighting classes for streets in a given vicinity should be no greater than two.
- Residential/pedestrian areas should be adapted to a single lighting level.

WHEN TO ADAPT LIGHTING

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

When ITSs are not available, such as on smaller streets and residential/pedestrian areas, curfews are typically established to determine when the lighting system can be dimmed. The following criteria can be used to establish a curfew:(11)

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

It is important that exceptions to the curfew (e.g., for sporting or entertainment events) be considered, providing an agency with the ability to override the adaptive lighting program on demand.

It is not advisable to adapt the lighting system during periods of adverse weather. The impact of dimming lighting during fog, snow, and rain is not clear. Some research has shown that visibility on a wet roadway is negatively affected by dimming of luminaires.[(12)] Further investigations are under way.

CHAPTER 3. LEGAL IMPLICATIONS OF ADAPTIVE LIGHTING

The parties most concerned with the legal implications of an adaptive lighting system are the owners and designers of the system. The owner is likely the government agency responsible for drafting the regulations defining the system and for implementing it. The designers include the engineers and design professionals working for the owner or agency. The legal concerns range from the agency justification for implementing such a system to the legal liability of the owners and designers in the event of a personal injury lawsuit attributed to the adaptive lighting system.

JUSTIFICATION OF AGENCY DECISION

The implementation of an adaptive lighting system likely require the promulgation or revision of highway safety regulations and the exercise of agency decisionmaking procedures. Such agency action is typically regulated by a statute outlining administrative procedures. (See, for example, 5 U.S.C. 553, informal rulemaking procedures of the Federal Administrative Procedures Act, and Wash. Rev. Code § 34.05.510, judicial review of agency action under State of Washington Administrative Procedure Act.) [13,14]

The action of an agency in promulgating or revising highway safety standards may be challenged if it can be shown to be "arbitrary, capricious, an abuse of discretion, or otherwise not in accordance with law." (See *Motor Vehicle Mfrs. Ass'n of U.S., Inc.* v. *State Farm Mut. Auto. Ins. Co.*, 463 U.S. 29, 41 [1983], reviewing order of National Highway Traffic Safety Administration rescinding crash protection requirements of the Federal motor vehicle safety standard.) [15] In the *Motor Vehicle Mfrs.* case, the decision of the agency was challenged because it failed to present an adequate basis and explanation for rescinding certain requirements relating to the use of seatbelts and airbags in motor vehicle passive restraint systems under its regulations.[15] The U.S. Supreme Court stated the following:

> There are no findings and no analysis here to justify the choice made, no indication of the basis on which the [agency] exercised its expert discretion. . . . Expert discretion is the lifeblood of the administrative process, but 'unless we make the requirements for administrative action strict and demanding, *expertise*, the strength of modern government, can become a monster which rules with no practical limits on its discretion.' (*Id.* at 48, quoting *New York* v. *United States*, 342 U.S. 882, 884 [1951], Black, J., dissenting)[15]

Most important is that the agency "cogently explain[s] why it has exercised its discretion in a given manner."[15]

For the agency implementing an adaptive lighting system, demonstrating the basis for the application of its expert discretion is crucial if the regulations are to survive. Supporting the decision with empirical data strengthens the case for needing the system, as does adherence to industry-accepted guidelines during the design of the system. A narrative explanation of the reasons the agency decided to implement the system—written or endorsed by the engineers with the particular expertise required—leaves little doubt regarding the basis for the new system. A well-supported agency decision will receive substantial deference from a reviewing court.

TORT LIABILITY OF AGENCY OR ENGINEER

An agency implementing an adaptive lighting system, or the engineer designing such a system, may face tort liability for personal injury resulting from such a system on the theory of negligent design.

Negligence is "conduct which falls below the standard established by law for the protection of others against unreasonable risk of harm" (Restatement [Second] of Torts, § 282). (16) Engineers and other design professionals must act according to the standard of care set by their particular profession:

> Architects, doctors, engineers, attorneys, and others deal in somewhat inexact sciences and are continually called upon to exercise their skilled judgment in order to anticipate and provide for random factors which are incapable of precise measurement. The indeterminable nature of these factors makes it impossible for professional service people to gauge them with complete accuracy in every instance. . . . Because of the inescapable possibility of error which inheres in these services, the law has traditionally required, not perfect results, but rather the exercise of that skill and judgment which can be reasonably expected from similarly situated professionals. (*Klein* v. *Catalano*, 386 Mass. 701, 718–19 [1982], citing *Mounds View* v. *Walijarvi*, 263 N.W.2d 420, 424 [Minn. 1978]; *Trustees of Union College* v. *Kennerly, Slomanson & Smith*, 167 N.J. Super. 311, 318 [1979]; and *Broyles* v. *Brown Eng'r Co.*, 275 Ala. 35, 39 [1963]).(17)

In designing an adaptive lighting system, an agency or engineer does not breach this duty of care if the agency or engineer performs according to industry-accepted guidelines (e.g., Federal highway standards). That is, if the engineer does what every other engineer would do in the same situation, a plaintiff will be hard pressed to argue that the engineer was negligent.

SOVEREIGN IMMUNITY

Sovereign immunity is a legal doctrine by which the government cannot commit a legal wrong and is immune from civil suit without its consent. The government has waived its immunity in most States, although discretionary policy decisions of employees of Federal and State agencies are still protected from suit. This protection does not extend to consulting engineers or other design professionals working on behalf of the agency.

The Federal government has waived its sovereign immunity to a limited extent under the Federal Tort Claims Act (FTCA, 28 U.S.C. 1346[b], 2671–2680).(18) Under the FTCA, the United States is liable for the following:

> … injury or loss of property, or personal injury or death caused by the negligent or wrongful act or omission of any employee of the government while acting within the scope of his office or employment, under circumstances where the United States, if a private person would be liable to the claimant in accordance with the law of the place where the act or omission occurred.(18)

The United States may be held liable under the FTCA for torts of employees of the executive, legislative, and judicial branches, but not for torts of government contractors (28 U.S.C. 2671).[19]

A significant exception to the FTCA immunizes the United States government from claims "based upon the exercise or performance or the failure to exercise or perform a discretionary function" (28 U.S.C. 2680[a]), even if the Federal employee acted negligently in the performance or nonperformance of his discretionary duty.[20] The U.S. Supreme Court has held that the discretion protected by the exception:

> …is the discretion of the executive or administrator to act according to one's judgment of the best course. … It … includes more than the initiation of programs and activities. It also includes determinations made by executives or administrators in establishing plans, specifications or schedules of operations. Where there is room for policy judgment and decision there is discretion. It necessarily follows that acts of subordinates in carrying out the operations of government in accordance with official directions cannot be actionable. (*Dalehite* v. *United States*, 346 U.S. 15 [1953])[21]

Elsewhere, the Supreme Court has stated that "[j]udicial intervention in [agency] decisionmaking through private tort suits would require the courts to 'second-guess' the political, social, and economic judgments of an agency exercising its regulatory function" (*United States* v. *Varig Airlines*, 467 U.S. 797, 820 [1984]).[22] Hence, the Court protected employees of the Federal Aviation Administration (FAA) from suit brought by victims of airplane accidents, alleging that the FAA employees had acted negligently in certifying certain airplanes for operation.[22]

Sovereign immunity also applies at the State level. Similar to the Federal government, Alaska has barred tort claims against a State agency or its employees relating to the discretionary functions of those employees (Alaska Stat. § 09.50.250[1]).[23] Case law distinguishes between "planning level" and "operational level" decisions, attaching immunity to the former but not the latter (*Wainscott* v. *State*, 642 P.2d 1355, 1356 [Alaska 1982]).[24] A planning decision involves policy formulation, while an operational decision involves policy implementation (*Alaska Dept. of Trans. and Pub. Facilities* v. *Sanders*, 944 P.2d 453, 456 [1997]).[25] Thus, the decision of an agency to follow a certain policy is protected from suit, but the actual implementation of the policy is not protected. (See *Moloso* v. *State*, 644 P.2d 205, 218 [Alaska 1982], stating that "[o]nce the state decided to and did undertake the task of re-routing the highway for better road maintenance, travel, and safety, it was obligated to use due care in its design and construction.")[26]

Texas has a similar sovereign immunity statute to that of Alaska, in which the State does not waive immunity for discretionary acts. (See Tex. Civ. Prac. & Rem. Code Ann. § 101.056 and 101.060.)[27] This protection has been specifically applied to highway design and safety features. (See *State* v. *Miguel*, 2 S.W.3d 249, 251 [Texas 1999], stating that "[d]ecisions about highway design and about what type of safety features to install are discretionary policy decisions" for which the government cannot be held liable.)[28] Also as in Alaska, immunity does not extend to the negligent implementation of a policy decision. (See Tex. Civ. Prac. & Rem. Code Ann. §101.021.)[29]

The State of Washington also has a discretionary function exemption to sovereign immunity, but "its applicability is limited to high-level discretionary acts exercised at a truly executive level" (*McCluskey* v. *Handorff-Sherman*, 125 Wash.2d 1, 12 [1994]; see also Wash. Rev. Code § 4.92.090).[30,31] Still, decisions involving traffic or highway planning are entitled to immunity. (See *Jenson* v. *Scribner*, 57 Wash. App. 474 [2012], holding that collection of accident data to plan and prioritize highway projects at a 2-year interval is part of the planning process and is, therefore, protected by sovereign immunity.)[32] However, this protection does not extend to negligent design and construction. (See *State* v. *Stewart*, 92 Wash.2d 285 [1979], holding that, while the decision to construct a bridge was a policy-level decision, the State was negligent in its planning and design of the bridge because of the lack of lighting; also see *Riley* v. *Burlington Northern, Inc.*, 27 Wash. App. 11, 17 [1980], holding that the angle of how a road approached a railroad track was a design issue, not a policy determination, and the State could not avail itself of sovereign immunity when sued for an accident related to the dangerous angle.)[33,34]

Based on the foregoing, the decision of an agency to follow an adaptive lighting regime would likely be protected by Federal or State sovereign immunity. However, the agency would remain open to suit if the implementation or installation of an adaptive lighting system was negligent in some way. Moreover, neither the Federal exemption nor the State exemptions extend the immunity protection to engineers and design professionals who are not direct government employees but are only agents of the government. Accordingly, the engineers or design professionals creating an adaptive lighting system would not be protected from suit by sovereign immunity and would have to rely on a typical negligence defense concerning the standard of care.

CHAPTER 4. COST BENEFIT ANALYSES OF ADAPTIVE LIGHTING

To determine the financial benefits to be expected from an adaptive lighting system, a lifecycle cost (LCC) analysis should be considered. A simple payback method of analysis could be used, but this method ignores operating and maintenance expenses, which are key components in evaluating lighting control systems and their expected benefits.

LCC is a simple calculation relating to the energy savings and the equipment required for the implementation of adaptive lighting. It does not consider the cost of a crash or a vehicle-caused fatality, and it assumes that the safety level of the roadway is not affected by the changes to the lighting level.

FIRST STEP: QUANTIFY COSTS

The first step in preparing an LCC is to quantify all of the costs associated with the lighting system. These costs include the following:

- Installation cost of the system.
- Expected reductions in energy costs (or change in rate structure offered by the electricity utility).
- Expected reduction or increase in maintenance costs for the lighting system, as well as the control equipment and support network.
- Expected life of the equipment.
- Any energy incentives that may be available for the installation.

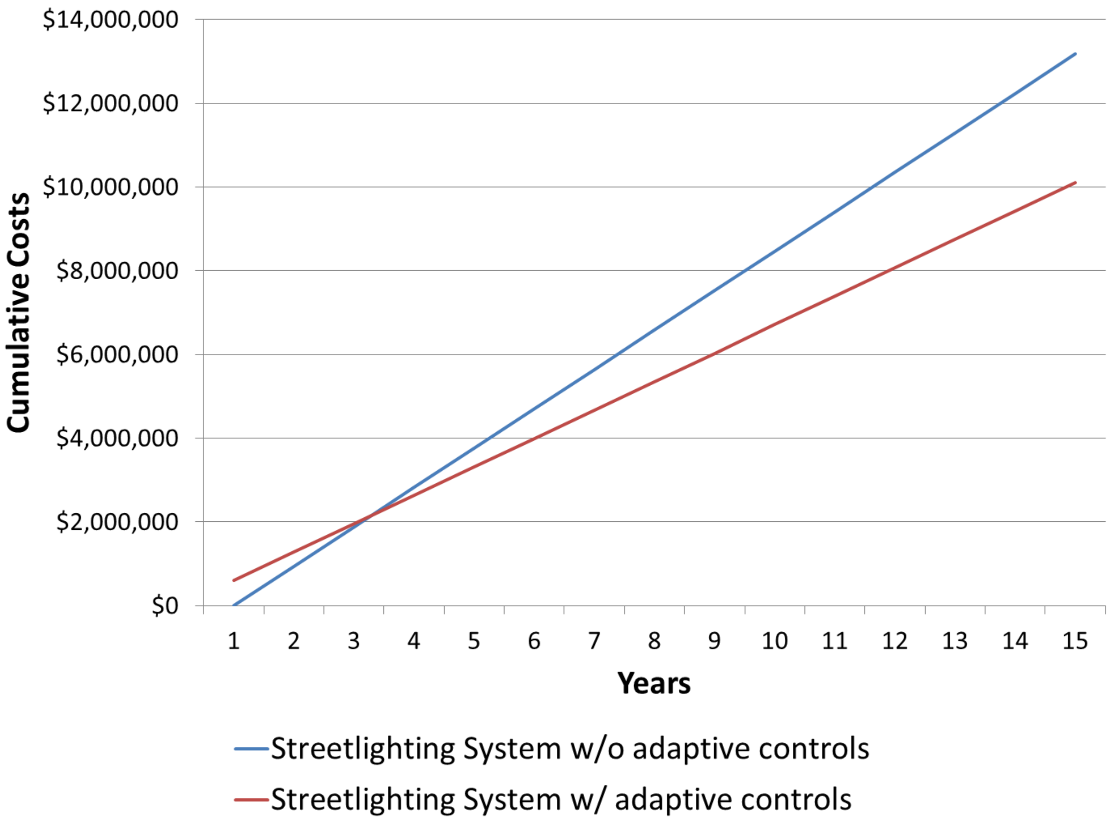
SECOND STEP: TABULATE THE COSTS

After the initial costs have been collected, assemble a simple tabulation of costs over a period of time, without inflation or time-value of money elements. A fixed period of time (e.g., 20 years) can be used, and system replacement costs can be added to the costs depending on expected component life. Another option is to use the expected life of the system and equipment being evaluated as the period of time.

For example, assume that an adaptive control system is being added to a light-emitting diode street lighting system already equipped with dimming drivers and an acceptable photocell receptacle with sufficient pins for control and power connections. The assumed equipment life is 15 years, and the simple LCC analysis is set to that time frame. An example is shown in table 18 and figure 8.

Table 18. Example cost information for an adaptive lighting system.

Type of Cost	Existing System Without Adaptive Control	Adaptive Control System Costs
Installed Cost	$0	$600,000
Annual Energy Cost	$841,000	$589,000
Annual Maintenance Cost	$100,000	$90,000
15-year Total Cost	$14,115,000	$10,785,000



w/o = without

Figure 8. Graph. Example system costs by year for standard and adaptive lighting systems.

THIRD STEP: CONVERT COSTS TO PRESENT VALUE

To obtain a better picture of the actual costs, the cost of capital and future costs should be brought into the present day by converting them to the present value based on the assumed discount rate. Figure 9 presents the formula for this conversion:

$$Present\ Value = Future\ cost \cdot \frac{1}{(1 + discount\ rate)^n}$$

Figure 9. Equation. Present value.

For the example above, a cash flow analysis is shown in table 19 using a 5-percent interest rate.

Table 19. Cash flow comparison for an adaptive lighting system.

Term	Street-Lighting System Without Adaptive Controls			Street-Lighting System With Adaptive Controls		
Years	Cash Flow	Total Expense	Present Value	Cash Flow	Total Expense	Present Value
0	$0	$0	$0	$600,000	$600,000	$600,000
1	$941,000	$941,000	$896,190	$679,000	$1,279,000	$1,218,095
2	$941,000	$1,882,000	$1,707,029	$679,000	$1,958,000	$1,775,964
3	$941,000	$2,823,000	$2,438,614	$679,000	$2,637,000	$2,277,940
4	$941,000	$3,764,000	$3,096,652	$679,000	$3,316,000	$2,728,081
5	$941,000	$4,705,000	$3,686,491	$679,000	$3,995,000	$3,130,187
6	$941,000	$5,646,000	$4,213,132	$679,000	$4,674,000	$3,487,811
7	$941,000	$6,587,000	$4,681,258	$679,000	$5,353,000	$3,804,277
8	$941,000	$7,528,000	$5,095,247	$679,000	$6,032,000	$4,082,695
9	$941,000	$8,469,000	$5,459,193	$679,000	$6,711,000	$4,325,970
10	$941,000	$9,410,000	$5,776,924	$679,000	$7,390,000	$4,536,819
11	$941,000	$10,351,000	$6,052,015	$679,000	$8,069,000	$4,717,777
12	$941,000	$11,292,000	$6,287,808	$679,000	$8,748,000	$4,871,214
13	$941,000	$12,233,000	$6,487,421	$679,000	$9,427,000	$4,999,339
14	$941,000	$13,174,000	$6,653,765	$679,000	$10,106,000	$5,104,217
15	$941,000	$14,115,000	$6,789,556	$679,000	$10,785,000	$5,187,769

The net present value (NPV) is shown in figure 10. The results show that the return on investment for this example is less than 3 years.

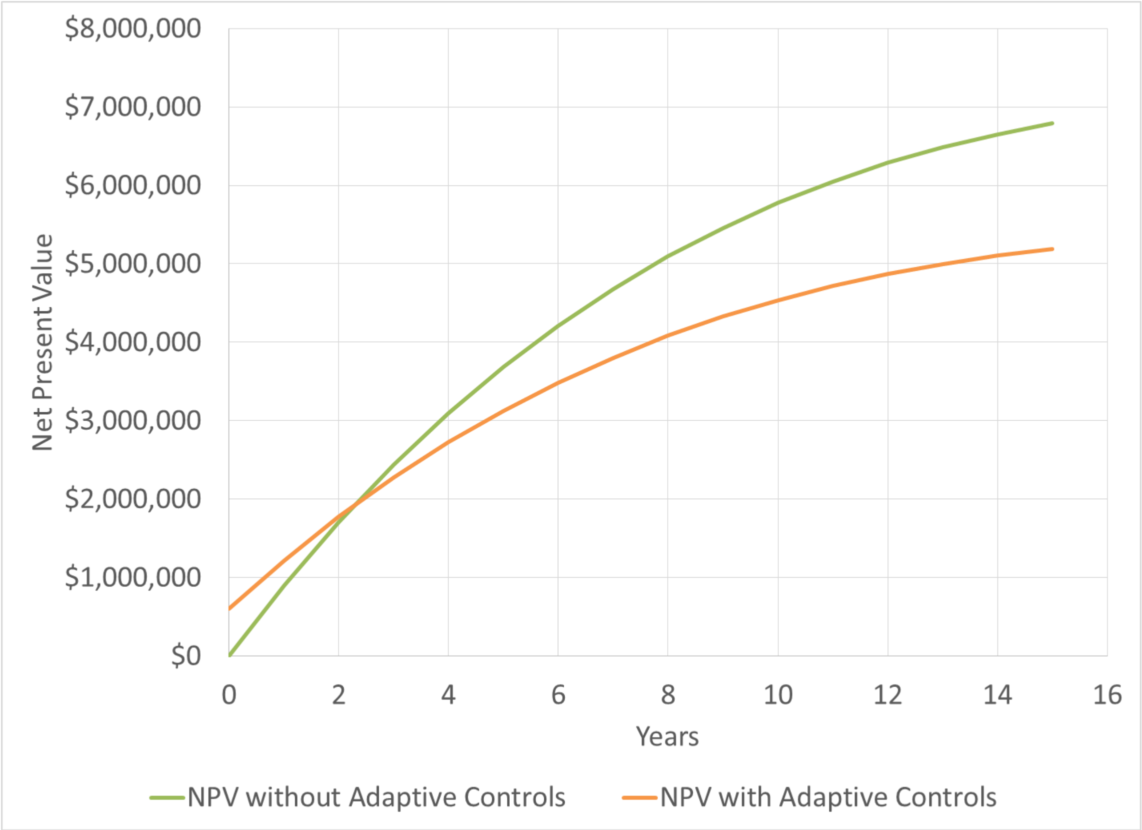


Figure 10. Graph. Example NPV for standard and adaptive lighting systems.

CHAPTER 5. SUMMARY

These guidelines have been developed to provide a designer or a roadway agency with a complete review of all aspects of the implementation of adaptive lighting on roadways. Through the development of a relationship between crashes and lighting, criteria have been chosen that affect the selection of the lighting level on a roadway. A lighting level selection methodology has been developed with these parameters. These parameters can also be used to actively determine a lighting level, meaning that the lighting system could be changed to adapt to the current needs of the driver and the roadway. The implementation of these systems requires a lighting control system and dimmable luminaires.

It is expected that the application of these design methods will sustain the current safety levels on roadways while reducing the use of unwanted light, the waste of energy, and the overall impact of the lighting system on the environment.

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