Study on Illumination for State Highways

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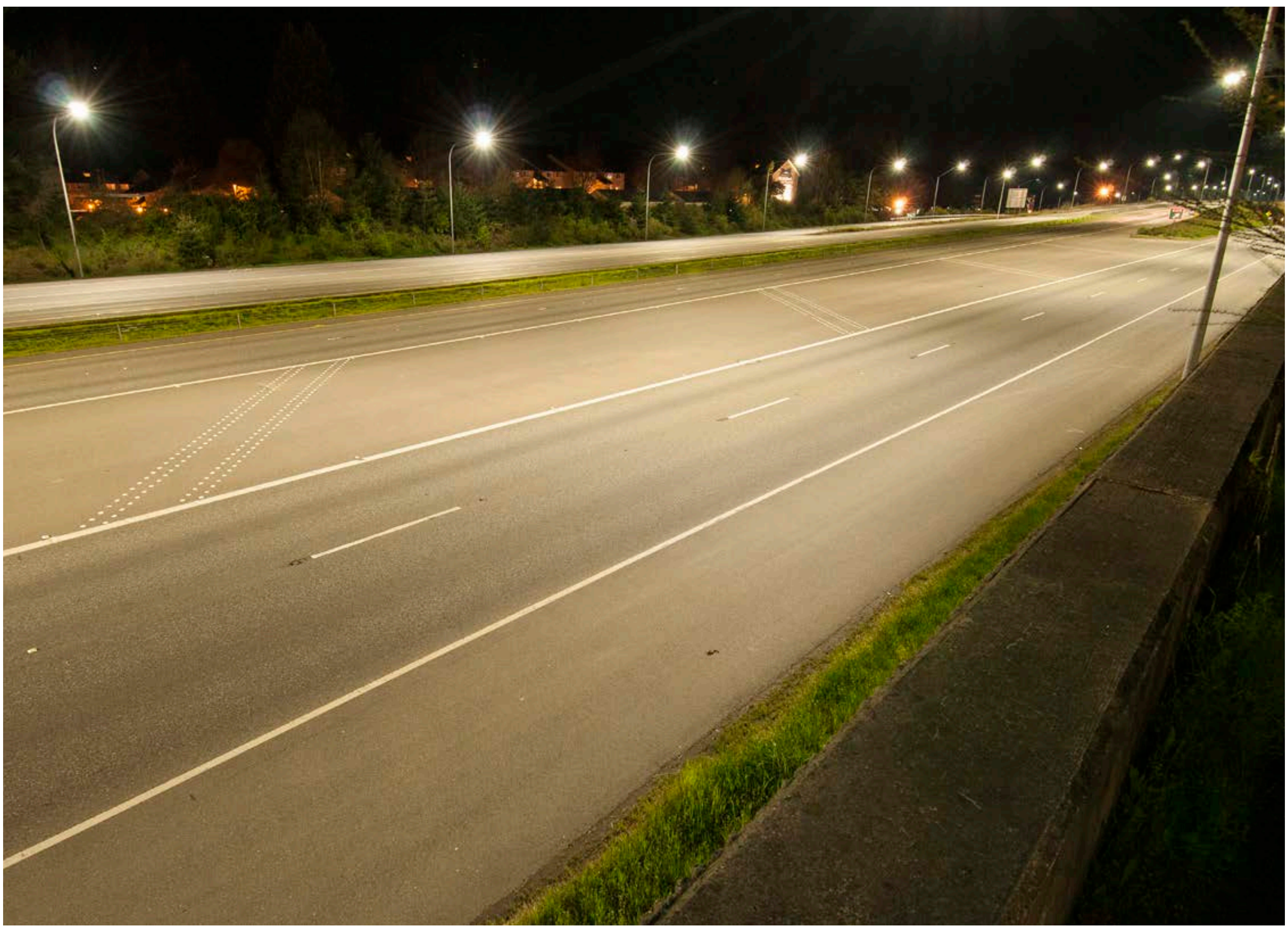

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WSDOT Research Report

Research Report
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Study on Illumination for State Highways

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16. ABSTRACT

Increasing budget pressures are causing the Washington State Department of Transportation (WSDOT) to look for ways to reduce costs. WSDOT currently owns and operates illumination fixtures on state freeways and highways with annual operating costs measured in millions of dollars. Given the pressures to reduce the WSDOT budget, it is important to have a complete understanding of the means available to reduce operating and capital costs with the least negative impact on service, safety and sustainability. There are several ways that the WSDOT can reduce expenditures on illumination. One way is to use more efficient lighting technologies. A second is to operate illumination more judiciously. Another option is to install fewer luminaires, remove superfluous luminaires and consolidate luminaires. Executing these options effectively requires the WSDOT to collect additional information regarding current and near future illumination practices and technologies.

A natural way in the process of revising and adapting WSDOT's illumination standards is examining how the WSDOT standards compare to other state DOTs, utilities, cities, counties and other public entities internationally. Given the work required to revise, publish and promulgate a new illumination standard, it is advisable to examine the current state of practice in illumination standards in order to inform comprehensive updates. Toward that end, a comprehensive review of illumination design standards, LED illumination technologies and illumination control systems is useful for revising illumination standards.

To address these aspects of illumination operation and design, a thorough literature review of existing illumination products, illumination control systems, and illumination spectrum technologies is conducted. This report reviewed existing public agency illumination standards domestically and internationally and outlined the difference in designing standards. An overview of existing luminaire technology performance, as well as operational and maintenance characteristics are provided. In addition, available illumination control and spectrum technologies for performance characteristics are summarized. The results of this literature review are useful for design and business case decisions regarding illumination installation, maintenance, and operation.

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Table of Contents

Executive Summary

Increasing budget pressures are causing the Washington State Department of Transportation (WSDOT) to look for ways to reduce costs. WSDOT currently owns and operates illumination fixtures on state freeways and highways with annual operating costs measured in millions of dollars. There are several aspects of roadway illumination that must be considered when revising the illumination design standards. These include evaluating why existing illumination design standards have been adopted and which luminaire technology and control technology have been employed. It is important that current standards include up to date evaluations of existing technology and the safety implications of design decisions. Specifically, the objectives of this research are:

- Review existing public agency illumination standards domestically and internationally and outline recommend modifications of alternative design standards;
- Provide an overview of existing light-emitting diode (LED) luminaire technology performance, as well as operational and maintenance characteristics;
- Examine available illumination control technologies for performance characteristics, luminaire compatibility, and overall capacity to function as a comprehensive asset management system; and
- Provide information regarding luminaire technology spectrum, scotopic and mesopic reduction factors, color rendering index (CRI), perceived light levels, and uniformity levels.

With other agencies facing similar budget pressures and seeing the same changes in illumination technologies, a review of other illumination practices was conducted by research team to give perspective on the tradeoffs between cost, operations and safety that other states are making. Specifically, the illumination design standard used by following public agencies were reviewed and compared: City of Seattle, New York City DOT, CalTrans, Minnesota DOT, TxDOT, Transportation Association of Canada, Oregon DOT, Illinois DOT and City of Los Angeles.

There are numerous currently available and emerging lighting technologies that may be used in luminaries. The selection of a given technology has implications for energy use, color of light, light levels, uniformity, maintenance, and control characteristics such as speed of ignition, and dimming. This study focused on LED luminaire technology. To inform changes in design practice, the research team focused on the following characteristics of LED products from eleven manufacturers: drivers, dimming control modules and luminaire types, compatibilities with different control systems and costs, life span, manufacturer warranty, ongoing preventative maintenance requirements, inrush current, illumination spectrum, energy use and efficiency, operating voltages, cased studies, etc.

Conventional illumination control tends to be very simple, with luminaires commonly being activated and deactivated based on time of day, individual photocells located on or near the luminaire fixture, or one master photo control located near the electrical service cabinet. Control technologies are becoming increasingly sophisticated with new options allowing dimming, motion based activation, and other control schemes. To inform the selection of a comprehensive control technology, the research team reviewed available literature, case studies, and vendor documentation for available illumination control systems to determine operational benefits, luminaire compatibility, impacts on maintenance and efficiency and overall effectiveness of the control technology as a comprehensive asset management system.

Each luminaire technology produces a different spectrum of light. Even with significantly lower overall illumination levels, whiter light and associated color rendering index (CRI) generally resulted in better perceived quality of illumination. To assist the modification and adoption of alternative design standards given different illumination spectra, the research team conducted a review of literature regarding how light is perceived and the impacts of different levels of light.

In summary, the results of this comprehensive literature review are useful for design and business case decisions regarding illumination installation, maintenance, and operation.

1 Introduction

Increasing budget pressures are causing the Washington State Department of Transportation (WSDOT) to look for ways to reduce costs. WSDOT currently owns and operates illumination fixtures on state freeways and highways with annual operating costs measured in millions of dollars. Given the pressures to reduce the WSDOT budget, it is important to have a complete understanding of the means available to reduce operating and capital costs with the least negative impact on service, safety and sustainability. There are several ways that the WSDOT can reduce expenditures on illumination. One way is to use more efficient lighting technologies. A second is to operate illumination more judiciously. Another option is to install fewer luminaires, remove superfluous luminaires and consolidate luminaires. Executing these options effectively requires the WSDOT to collect additional information regarding current and near future illumination practices and technologies.

A natural starting point in the process of revising and adapting WSDOT's illumination standards is examining how the WSDOT standards compare to other state DOTs, utilities, cities, counties and other public entities internationally. Given the work required to revise, publish and promulgate a new illumination standard, it is advisable to examine the current state of practice in illumination standards in order to inform comprehensive updates. Toward that end, a comprehensive review of illumination standards is an excellent starting point for revising illumination standards.

Recent advances in illumination technologies, such as LED luminaires, offer potential ways to reduce operating costs. However, before any of these new illumination technologies can be implemented, several operational details must be considered to ensure that service, safety and sustainability are not negatively impacted. First, each technology has a different upfront cost. Second, each technology has a different efficiency. Third, ongoing preventative maintenance and associated product warranties play a role. Forth, the lifespan and serviceability of components in each system will vary. Fifth, the qualifications and fiscal stability of the manufacturer and associated vertical supply chain have a long term financial risk component. Finally, the quality of light, particularly with regard to light level, uniformity and color, may have safety implications that should be considered.

Just as lighting technologies have advanced, so too have illumination control systems. It is now practical to exercise central control on illumination for entire corridors, turn luminaires on and off by time of day, use motion detectors to activate luminaires, and dim lights to reduce energy consumption and extend life since lighting systems are typically designed for end of life performance which equates to providing more light than necessary for a significant portion of their life. Many of these technologies can be implemented separately or in combination. The ability to exercise greater control on illumination offers an opportunity to reduce operating costs and extend life without an apparent loss of service or adverse safety impacts.

In light of budget constraints, it is also prudent to examine the guidelines for installing new illumination. Since the goal of providing illumination is primarily a matter of safety, and considering the high percentage of fatal accidents that occur in darkness (Griffith (1994)), it would be instructive to determine under which conditions illumination provides the greatest safety benefits. In many respects illumination is focused around providing safety and security for pedestrians. With this in mind, there are many locations, time periods, and seasons where pedestrian volumes are low or nonexistent resulting in a reduced need for illumination during those periods. Once these conditions have been identified, current standards can be revised to recommend illumination in locations with high potential impact.

To address these aspects of illumination operation and design, a thorough literature review of existing illumination products, illumination control systems, and safety implications due to illumination is conducted. The results of this literature review are useful for design and business case decisions regarding illumination installation, maintenance, and operation.

Section 2 reviewed existing public agency illumination standards domestically and internationally and outlined the difference in designing standards.

Section 3 provided an overview of existing luminaire technology performance, as well as operational and maintenance characteristics.

Section 4 examined available illumination control technologies for performance characteristics, luminaire compatibility, and overall capacity to function as a comprehensive asset management system.

Section 5 provided information regarding luminaire technology spectrum and a review of literature regarding how light is perceived and the impacts of different levels of light.

2 State Illumination Design Standard Review

With other agencies facing similar budget pressures and seeing the same changes in illumination technologies, it is reasonable to expect that there may be innovations in their illumination standards worth considering for inclusion in WSDOT standards. In this section, a review of illumination practices by other state agencies is conducted to give perspective on the tradeoffs between cost, operations and safety that other states are making. As WSDOT is facing many of the same design tradeoffs and can benefit from any innovative design aspects, it is an important first step to examine other public agency design standards.

2.1 TxDOT lighting guidelines

WSDOT defines two types of roadway lighting systems, required illumination and additional illumination. For TxDOT, they define two basic types of roadway lighting systems — "continuous illumination" and "safety lighting." TxDOT uses criteria called warrants to justify the need for roadway lighting at eligible locations. To determine if an eligible location meets the relevant warrant, TxDOT assesses roadway conditions in terms of criteria called "cases."

The TxDOT Illumination Manual (2003) states that full access-controlled urban multi-lane freeways and partial access-controlled urban multi-lane arterials are eligible for continuous lighting. Non-access-controlled roadways are not eligible for continuous lighting and continuous lighting for bikeways and pedestrian ways are determined based on the funding availability. TxDOT does not normally light frontage roads.

Individual warranting criteria for continuous lighting in the TxDOT guidelines are categorized into three groups: traffic volume criteria, roadway related criteria, and safety criteria. TxDOT assesses eligibility of roadway conditions for lighting under four scenarios, and continuous lighting may be warranted under any one of four scenarios. Case 1 (CL-1) describes the requirement for average daily traffic; Case 2 (CL-2) and Case 3 (CL-3) describe the requirements of roadway related criteria; and Case 4 (CL-4) describes requirements of the ratio of night-to-day crash rate. Table 2-1 provides the continuous lighting warrants from the TxDOT 2003 Illumination Manual.

Table 2-1 Continuous lighting warrants from the TxDOT 2003 Illumination Manual

Individual Criteria	Case No.	TxDOT Warrants
Traffic Volume	CL-1	Average daily traffic (ADT) ≥ 30,000 vpd
	CL-2	≥ 3 interchanges with average spacing ≤ 1.5 miles and adjacent to substantial urban areas
Roadway Related Factors	CL-3	≥ 2 miles freeway segment passing through areas with two or more of the following characteristics: • Lit street grid visible from the freeway;• A series of developments, e.g., streets, residential and parking areas;• Lit cross streets ≤ 0.5 mile apart; • Width of freeway cross-section elements below desirable levels
Safety	CL-4	Night-to-day crash rate ratio ≥ 2.0 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

Safety lighting consists of three types: partial interchange/intersection, complete interchange/ intersection, and spot. The safety lighting may be installed at any interchange, highway intersection, decision-making point or points of nighttime hazard. Warranting safety lighting depends on the type of roadway (for example, freeway, express-way, or other designated on-system highway) and the type of proposed lighting (partial interchange, complete interchange, or spot).

For the continuous lighting, TxDOT may consider both AASHTO 1984 and AASHTO 2005 lighting guides as the reference for setting lighting levels, and this is different from the illuminance level and uniformity ratio chart used by WSDOT. Table 2-2 provides a summary of lighting levels from the two guides to compare the requirements for lighting level.

Table 2-2 Summary of lighting levels from AASHTO 1984 and AASHTO 2005 (source: AASHTO 1984 and AASHTO 2005)

Roadway Type	General Land Use	Illuminance Method			Luminance Method			Additional
		Eavg* (lux) (min)	Emin (lux) (min)	Uniformity Eavg/Emin (max)	Lavg (cd/m^2) (min)	Uniformity Lavg/Lmin (Max)	Uniformity Lmax/Lmin (Max)	Veiling Luminance ** Lv(max)/Lavg (Max)
AASHTO 1984 Lighting Guide								
Freeway	All	6~9	2	3:1 or 4:1	0.4~0.6	3.5:1	6:1	0.3:1
Expressway	Commercial	10~14	As uniformity ratio allows	3:1	1	3:1	5:1	0.3:1
	Intermediate	8~12			0.8	3:1	5:1	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Major Arterial	Commercial	12~17		3:1	1.2	3:1	5:1	0.3:1
	Intermediate	9~13			0.9	3:1	5:1	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Collector	Commercial	8~12		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	6~9			0.6	3.5:1	6:1	0.4:1
	Residential	4~6			0.4	4:1	8:1	0.4:1
Local	Commercial	6~9		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	5~7			0.5	6:1	10:1	0.4:1
	Residential	3~4			0.3	6:1	10:1	0.4:1
Alleys	Commercial	4~6		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	3~4			0.3	6:1	10:1	0.4:1
	Residential	2~3			0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	10~14		3:1	Use illuminance requirements			
	Intermediate	6~9		4:1				
	Residential	3~4		6:1				
Pedestrian / Bike Lanes		12~22		3:1				
AASHTO 2005 Lighting Guide								
Interstate and Other Freeways	Commercial	6~12	2	3:1 or 4:1	0.4~1.0	3.5:1	6:1	0.3:1
	Intermediate	6~10	2	3:1 or 4:1	0.4~0.8	3.5:1	6:1	0.3:1
	Residential	6~8	2	3:1 or 4:1	0.4~0.6	3.5:1	6:1	0.3:1
Principle Arterial	Commercial	12~17	As uniformity ratio allows	3:1	1.2	3:1	5:1	0.3:1
	Intermediate	9~13			0.9	3:1	5:1	0.3:1
	Residential	6~9			0.6	3.5:1	6:1	0.3:1
Minor Arterial	Commercial	10~15		4:1	1.2	3:1	5:1	0.3:1
	Intermediate	8~11			0.9	3:1	5:1	0.3:1
	Residential	5~7			0.6	3.5:1	6:1	0.3:1
Collector	Commercial	8~12		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	6~9			0.6	3.5:1	6:1	0.4:1

	Residential	4~6			0.4	4:1	8:1	0.4:1
Local	Commercial	6~9		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	5~7			0.5	6:1	10:1	0.4:1
	Residential	3~4			0.3	6:1	10:1	0.4:1
Alleys	Commercial	4~6		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	3~4			0.3	6:1	10:1	0.4:1
	Residential	2~3			0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	10~14		3:1	Use illuminance requirements			
	Intermediate	6~9		4:1				
	Residential	3~4		6:1				
Pedestrian / Bike Lanes		15~22		3:1				

* The required minimum level of average maintained horizontal illuminance varies by pavement types, with the lowest values for Portland cement concrete surface and the highest values for rough asphalt surface
** The veiling luminance ratio is the ratio of veiling luminance $L_{v(max)}$ to the average maintained luminance L_{avg}.

For safety lighting, the light level required by TxDOT is different from the requirements of light level for continuous lighting. Note that TxDOT suggests that careful design should be considered to avoid excessive glare.

Standard pole heights for WSDOT are normally 20 – 50 feet. TxDOT considered two types of light standards, the conventional lighting and high mast lighting. The conventional lighting is about 50 feet or less. High mast lightings can be 100 feet or more. Selection between conventional and high mast units depends on several factors: installation and maintenance costs, traffic volume, possibility of lighting pollution, etc. Conventional lighting usually requires less installation cost on non-interchange roadway segments. High mast lighting is less expensive for interchange areas because fewer lighting fixtures and poles are required. The maintenance cost of high mast lighting is also less because it requires less traffic control. The TxDOT Illumination Manual (2003) recommends that high mast lighting should be used for complete interchange lighting and for tangent segments of freeways with initial ADT of 70,000 or greater.

Lighting poles may be installed between curb and right-of-way line, called house side mounting, or on medians, called median mounting. Although the TxDOT Illumination Manual (2003) does not specify the location of high mast poles, the high mast poles are typically house side mounted. If the median width is wide enough to treat each direction of main lanes as a separate roadway, the high mast poles may also be installed on wide medians. Placement of conventional lighting poles depends on the following factors: the type of poles (non-breakaway or breakaway), clear zone requirement, or hazard of falling poles to surrounding properties (for example, roadway users, vehicles etc.).

2.2 Illinois DOT lighting guidelines

The WSDOT defines two types of roadway lighting systems, required illumination and additional illumination. Illinois DOT provides highway lighting based on the following factors: reasonable engineering judgment, recommendations, and guidelines in the AASHTO Roadway Lighting Design Guide (2005) and NCHRP Report No. 152 Warrants for Highway Lighting (1974).

For Illinois state maintained freeway facilities, Illinois DOT provides three types of lighting. They are continuous lighting, complete interchange lighting and partial interchange lighting. According to Illinois highway lighting manual (2013), continuous lighting consists of all mainline and direct connections, and provides complete lighting of all associated interchanges. Lighting poles can be high-mast poles, conventional poles, or a mixed use of both. The conditions need to be considered for continuous freeway lighting (CFL) are summarized in Table 2-3. The continuous lighting warrants in Table 2-3 are from the Illinois DOT highway lighting design.

Table 2-3 Continuous lighting warrants from the Illinois DOT highway lighting design

Individual Criteria	Illinois Warrants
Freeway Volume	Average daily traffic ≥ 30,000 vpd
	≥ 3 interchanges with average spacing ≤ 1.5 miles and adjacent to substantial urban areas
Roadway Related Factors	≥ 2 miles freeway segment passing through areas with two or more of the following characteristics: • Lit street grid visible from the freeway;• A series of developments, e.g., streets, residential and parking areas;• Lit cross streets ≤ 0.5 mile apart; • Width of freeway cross-section elements below desirable levels
Safety	Night-to-day crash rate ratio ≥ 2.0 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

Complete interchange lighting (CIL) are generally applied in the following scenarios: the freeway's through traffic lanes within the interchange area, the traffic lanes of all ramps, the acceleration and deceleration lanes, all ramp terminals, and the crossroad between the outermost ramp terminals. Table 2-4 lists the complete interchange lighting warrants from the Illinois DOT highway lighting design (2013).

Table 2-4 Complete interchange lighting warrants from the Illinois DOT highway lighting design

Individual Criteria	Illinois Warrants
Ramp Volume	Average daily traffic ≥ 10,000 vpd for urban conditions, ≥ 8,000 vpd for suburban conditions and ≥ 5,000 for rural conditions.
Crossroad Volume	current ADT on the crossroad≥ 10,000 vpd for urban conditions, ≥ 8,000 vpd for suburban conditions and ≥ 5,000 for rural conditions
Roadway Related Factors	Consider CIL at locations on unlighted freeways where existing substantial commercial or industrial development, which is lighted during hours of darkness, is located in the immediate vicinity of the interchange, or where the crossroad approach legs are lighted for 0.5 miles (1 km) or more on each side of the interchange.
Safety	Night-to-day crash rate ratio ≥ 1.5 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

Partial interchange lighting (PIL) generally is usually used at the decision-making areas. This type of lighting consists of a few luminaires located in the vicinity of all ramp terminals. Table 2-5 lists the partial interchange lighting warrants from the Illinois DOT highway lighting design.

Table 2-5 Partial interchange lighting warrants from the Illinois DOT highway lighting design

Individual Criteria	Illinois Warrants
Ramp Volume	Average daily traffic ≥ 5,000 vpd for urban conditions, ≥ 3,000 vpd for suburban conditions and ≥ 1,000 for rural conditions.
Freeway Volume	current ADT on the crossroad≥ 25,000 vpd for urban conditions, ≥ 20,000 vpd for suburban conditions and ≥ 10,000 for rural conditions
Safety	Night-to-day crash rate ratio ≥ 1.25 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

When determining the lighting needs of streets and highways other than freeways, the following factors (i.e., urban and rural conditions, traffic volumes, intersections, turning movements, signalization, channelization, and varying geometrics) should be considered (as recommended in Illinois highway lighting manual, 2013).

Standard pole heights for WSDOT are normally 20 – 50 feet. Illinois DOT considered two types of light poles: conventional light pole and light towers. Conventional highway light pole's mounting heights range from approximately 30 ft to 50 ft. Light towers generally range from 80 ft to 160 ft.

WSDOT normally uses the cobra head-style, high-pressure sodium vapor luminaire with Type III, medium cut-off light distribution as the normal light source. Similarly, Illinois DOT also uses high-pressure sodium for roadway lighting unless permission is obtained from Illinois DOT for a different light source. But control of light distribution can be cutoff or full cutoff. In Illinois, LED lighting fixtures have not become effective for most roadway applications although LED is a popular light source due to their long life and low electrical energy usage.

In highway lighting design, the illuminance design criteria considered by Illinois DOT are provided in Table 2-6, which are different from the light level and uniformity ratio chart used by WSDOT. The pavement classifications R1, R2 , R3 and R4 are defined in Table 2-7.

Table 2-6 Illuminance design criteria considered by Illinois DOT (Source: Illinois highway lighting manual, 2013)

Roadway Facility Classification	Area Classification	Pedestrian Conflict Area	Average Maintained[1 3] Horizontal Illuminance (E_h) Footcandle (Lux)			Uniformity Ratio (Ave./Min.)	Veiling Luminance Ratio Lvmax/Lavg
			Pavement Classification				
			R1	R2 & R3	R4		
Freeway [2]	Class A		0.6 (6)	0.9 (9)	0.8 (8)	3:1	0.3
	Class B		0.4 (4)	0.6 (6)	0.5 (5)		
Expressway [2]	Commercial	High	1.0 (10)	1.4 (14)	1.3 (13)		
	Intermediate	Medium	0.8 (8)	1.2 (12)	1.0 (10)		
	Residential	Low	0.6 (6)	0.9 (9)	0.8 (8)		
Major	Commercial	High	1.2 (12)	1.7 (17)	1.5 (15)		
	Intermediate	Medium	0.9 (9)	1.3 (13)	1.1 (11)		
	Residential	Low	0.6 (6)	0.9 (9)	0.8 (8)		
Collector	Commercial	High	0.8 (8)	1.2 (12)	1.0 (10)	4:1	0.4
	Intermediate	Medium	0.6 (6)	0.9 (9)	0.8 (8)		
	Residential	Low	0.4 (4)	0.6 (6)	0.5 (5)		
Local	Commercial	High	0.6 (6)	0.9 (9)	0.8 (8)	6:1	
	Intermediate	Medium	0.5 (5)	0.7 (7)	0.6 (6)		
	Residential	Low	0.3 (3)	0.4 (4)	0.4 (4)		
Alleys	Commercial		0.4 (4)	0.6 (6)	0.5 (5)		
	Intermediate		0.3 (3)	0.4 (4)	0.4 (4)		
	Residential		0.2 (2)	0.3 (3)	0.3 (3)		
Rest Areas And Weigh Stations							

Ramp Gores & Interior Roadways	ALL		0.4 (4)	0.6 (6)	-	3:1 to 4:1	0.4
Parking & Major Activity Areas	ALL		0.8 (8)	1.1 (11)	-		
Minor Activity Areas	ALL		0.4 (4)	0.5 (5)	-	6:1	

Notes:

1. Average illuminance on the traveled way.
2. Both mainline and ramps.
3. The illuminance values are minimum maintained averages. Higher levels than shown in the tables may be justified, consult the AASHTO Roadway Lighting Design Guide for details.

Table 2-7 Definition of the pavement classifications R1, R2 , R3 and R4.

Pavement classifications	Definition
Class R1	Class R1 pavement has a mostly diffuse mode of reflectance. R1 pavements include portland cement concrete road surfaces and asphalt road surfaces with a minimum of 12% of the aggregates composed of artificial brightener (e.g., Synopal) aggregates (e.g., labradorite, quartzite).
Class R2	Class R2 pavement has a mixed diffuse and specular mode of reflectance. R2 pavements include asphalt road surfaces with an aggregate composed of a minimum of 60% gravel with a size greater than 0.40 in (12 mm).
Class R3	Class R3 has a slightly specular mode of reflectance. R3 pavements include asphalt road surfaces, both regular and carpet seal coats, with dark aggregates (e.g., trap rock, blast furnace slag) and exhibit a rough texture after some months of use. Class R3 pavement represents typical asphalt highways and is used on most highway lighting projects.
Class R4	Class R4 pavement has a mostly specular mode of reflectance. R4 includes asphalt road surfaces with a very smooth texture.

2.3 City of Los Angeles lighting guidelines

According to the design standards and guidelines (2007), the recommendations for lighting levels adopted by City of Los Angeles are different from the light level used by WSDOT. Specifically, the recommended values used by City of Los Angeles are summarized in the following Table 2-8.

Table 2-8 Recommendations for lighting levels adopted by City of Los Angeles (source: design standards and guidelines, 2007)

Road and Pedestrian Conflict Area		Pavement Classification (Minimum maintained Averaged Values)			Uniformity Ratio ($E_{Ave.}/E_{Min.}$)	Veiling Luminance Ratio L_{vmax}/L_{avg}
Road	Pedestrian Conflict	R1 fc/lux	R2 & R3 fc/lux	R4 fc/lux		
Freeway Class A		0.6 (6)	0.9 (9)	0.8 (8)	3:1	0.3
Freeway Class B		0.4 (4)	0.6 (6)	0.5 (5)		
Expressway	High	1.0 (10)	1.4 (14)	1.3 (13)		
	Medium	0.8 (8)	1.2 (12)	1.0 (10)		
	Low	0.6 (6)	0.9 (9)	0.8 (8)		
Major	High	1.2 (12)	1.7 (17)	1.5 (15)		
	Medium	0.9 (9)	1.3 (13)	1.1 (11)		
	Low	0.6 (6)	0.9 (9)	0.8 (8)		
Collector	High	0.8 (8)	1.2 (12)	1.0 (10)	4:1	0.4
	Medium	0.6 (6)	0.9 (9)	0.8 (8)		
	Low	0.4 (4)	0.6 (6)	0.5 (5)		
Local	High	0.6 (6)	0.9 (9)	0.8 (8)	6:1	
	Medium	0.5 (5)	0.7 (7)	0.6 (6)		
	Low	0.3 (3)	0.4 (4)	0.4 (4)		

For City of Los Angeles, Table 2-9 provides the recommended illuminance for the intersection of continuously lighted urban streets. The recommended lighting levels for intersection are different from values provided by the illumination design manual used by WSDOT.

Table 2-9 Recommended illuminance for the intersection of continuously lighted urban streets (source: design standards and guidelines, 2007)

Illuminance for intersections				
Functional Classification	Average Maintained Illumination at Pavement by Pedestrian Area Classification lux/fc			E_{avg}/E_{min}
	High	Medium	Low	
Major/Major	34.0/3.4	26.0/2.6	18.0/1.8	3
Major/Collector	29.0/2.9	22.0/2.2	15.0/1.5	3
Major/Local	26.0/2.6	20.0/2.0	13.0/1.3	3
Collector/Collector	24.0/2.4	18.0/1.8	12.0/1.2	4
Collector/Local	21.0/2.1	16.0/1.6	10.0/1.0	4
Local/Local	18.01/1.8	14.0/1.4	8.0/0.8	6

Besides the highways and intersections, City of Los Angeles also considers different design standards from WSDOT for bikeways, midblock pedestrian crossings, railroad crossings, parking lots and bus stop facilities. For these design areas, the recommended illumination levels considered by City of Los Angeles are summarized in Table 2-10.

Table 2-10 Recommended illumination levels considered by City of Los Angele for different design areas

Design area	Recommended illumination levels
Bikeways	Minimum average horizontal illumination Bikeways (Class 1) with High Pedestrian Conflict Areas are 10 Lux (1.0 fc) with uniformity ratio of 4:1.
Midblock pedestrian crossings	Crosswalks traversing roadways in the middle of blocks without signalization should be provided with additional illumination. The average illumination level in the crosswalk area should at least be equal to that provided at the intersection of two major streets; i.e., about 34 lux (3.4Fc). The uniformity ratio should be no more than 3:1.
Railroad crossings	Illumination level over track area, starting 100 feet (30 meters) before the crossing and ending 100 feet (30 meters) beyond the crossing, should be in accordance with Table D1 and table D2 on RP-8-2000, but never less than 9 Lux (0.9FC). The uniformity ratio should be no more than 4:1.
Parking lots	Illumination levels for parking lots should have an average illumination level of 22 Lux (2.0 fc) for LA DOT open parking lots and uniformity ratio of 3:1.
Bus stop facilities	Illumination levels over a Bus Stop area should have an average illumination level of 25 lux (2.5FC).The uniformity ratio is at 3:1 .Lighting levels should be in addition to the level provided by the regular street lighting system. Typically these facilities are 80’ in length and are provided with three lighting fixtures attached at 15’ height.

In designing street lighting systems, City of Los Angeles uses an overcurrent device (i.e., a fuse or circuit breaker) to protect the street lighting system. The minimum size fuse and circuit breaker used for a service point shall be 30 amps. The minimum size fuse for electroliers is 10 amps.

2.4 New York City DOT lighting design guidelines

New York City (NYC) DOT (Street design manual, 2004) uses guidelines established by the Illuminating Engineering Society of North America (IES) to provide sufficient lighting levels and uniformity to produce a comfortable and safe street environment. The recommendations for lighting levels adopted by New York City DOT (see Table 2-11) are different from the light level used by WSDOT.

Table 2-11 Recommendations for lighting levels adopted by New York City DOT

	Average Illuminance	Illuminance Uniformity
Roadways		
Collector	8 – 12 lux (.74 – 1.11 footcandles)	4:1
Local	6 – 9 lux (.56 – .84 footcandles)	6:1
Intersections		
Collector/Collector	16 – 24 lux (1.49 – 2.23 footcandles)	4:1
Collector/Local	14 – 20 lux (1.30 – 1.86 footcandles)	4:1
Local/Local	12 – 18 lux (1.11 – 1.67 footcandles)	4:1
Plazas, Walkways,& Bikeways	5 – 10 lux (.46 – .93 footcandles)	4:1

New York City DOT categorizes streetlights as standard, distinctive, historic, and pilot. For standard streetlights, the current standard fixtures are the 100W and 150W HPS Cobra Head for street lighting and the 70W and 100W HPS Cobra Head for pedestrian lighting (WSDOT also use cobra head-style, HPS as stand luminaire). However, New York City DOT is phasing in 110W LED Cobra Heads for street lighting and 75W LED Cobra Heads for pedestrian lighting. For historic streetlights in historic districts or in neighborhoods with substantial, intact historic fabric, the streetlights are currently used with only the teardrop and shielded teardrop fixtures, with a 150W LED lamp or 250W HPS. Any streetlights other than those that are listed as standard or historic are considered distinctive. Pilot streetlights are being tested by NYC DOT and are not yet approved for wider use in New York City. Tables 2-12 and 2-13 summarize the usage and applications of poles and fixtures currently used in New York City.

Table 2-12 Pole types currently used in New York City

Poles	Usage	Applications	Compatible Fixture
Davit Round Octagonal	Standard streetlight	Streetlight Pole: Streets and highways Single and twin mounting Pedestrian Pole: Parks, plazas, esplanades, pedestrian bridges, walkways, and bikeways	Cobra Head, Helm, Stad
Flatbush Avenue	Distinctive streetlight	Commercial and residential streets Single or twin mounting (center medians) Streets with roadway width of 36 feet or more	Helm, Stad, Teardrop and Shielded Teardrop
Triboro Bridge	Distinctive	Streetlight Pole:	Stad,

Tunnel Authority	streetlight	Commercial and residential streets Single or twin mounting Streets with roadway width of 36 feet or more Pedestrian Pole: Parks, plazas, esplanades, pedestrian bridges, walkways, and bikeways	Teardrop and Shielded Teardrop

Table 2-13 Fixture types currently used in New York City

Fixtures	Usage	Applications	Lamp/Optics
Cobra Head	Standard streetlight	Street light: Streets and highways; single or twin mounting Pedestrian light: Parks, esplanades, pedestrian bridges, walkways, ramps, under elevated trains, and bikeways; single mounting only	Road: 100W HPS, Medium Semi–Cutoff, IES Type I 150W HPS, Medium Semi–Cutoff, IES Type II Pedestrian: 70W and 100W HPS, Medium Semi–Cutoff, IES Type I
Standard LED	Standard streetlight	Street light:Streets and highways; single or twin mounting Pedestrian light: Parks, esplanades, pedestrian bridges, walkways, ramps, under elevated trains, and bikeways; single mounting only	Road: 110W LED Medium Semi-Cutoff, IES Type I Pedestrian: 75W LED (being phased in) Cutoff, IES Type II or III
Helm	Distinctive streetlight	Commercial districts	90W and 140W Cutoff or Semi-Cutoff, IES Type II or III

Stad	Distinctive streetlight	Commercial districts Pedestrian fixture: Parks, plazas, esplanades, pedestrian bridges, walkways, and bikeways Single or twin mounting	Road: 90W and 140W Pedestrian: 60W and 90W Cutoff or Semi-Cutoff, IES Type II or III
Teardrop and Shielded Teardrop	Historic streetlight	Selected historic districts	250W HPS 150W LED Teardrop: Non-Cutoff Shielded Teardrop: Cutoff IES Type III or V

The NYC DOT street design manual states that NYC DOT has decreased the maximum allowable wattage to 150W (watts) in 2009; and NYC DOT is now phasing in the 110W Standard LED fixture for all streetlights; this will further reduce the energy load of streetlight fixtures.

2.5 Oregon DOT lighting design guidelines

The Oregon DOT Traffic Lighting Design Manual (2009) addresses items not included in the AASHTO Roadway lighting design guide (2005). Oregon DOT uses guidelines established by the national standards (i.e., AASHTO 2005 and IESNA) to provide reasonable illumination levels. However, at critical decision points of the roadway, the Oregon DOT has specific illumination level requirements as summarized in Table 2-14.

Table 2-14 Illumination levels for different critical decision points

Critical decision points	Increase the illumination levels to
Gore areas	11 to 16 lux (1.0 to 1.5 fc)
Weaving lanes	9 to 11 lux (0.8 to 1.0 fc) average
Intersections	Sum of illuminance levels of the crossing roads, or up to 1.5 times of main street illuminance
Underpasses	Up to 1.5 times of roadway illuminance level

Standard pole heights for WSDOT are normally 20 – 50 feet. Oregon DOT uses 40 foot mounting height for freeways, interchanges and other state highways. And the poles are usually installed 30 foot away from edge of travel lane (where no barriers are installed) for freeways, interchanges and other state highways. Oregon DOT's Traffic Lighting Design Manual recommends that slip base steel poles should be installed within "clear zones" on freeways and expressways. And fixed base poles must meet "clear zone" requirements for all highways or be protected.

For interchange lighting, Oregon DOT provides roadway lighting on essential parts of the interchange. The standards are described here (Traffic Lighting Design Manual, 2009):

1) On Ramps - Standard of two poles at merging sections. Ramps in developed urban or suburban areas and ramps with high truck traffic may need more coverage. Ramps with longer acceleration lanes or complex alignment may need more coverage.

2) Off-Ramps - Standard of three poles to cover gore area. Ramps with complex alignment or roadside features may need additional coverage or pull through light.

3) Ramp Terminals - Standard of two poles at the intersection. One pole may be sufficient in rural area or T shape intersections. A wide intersection with crosswalk or raised island and a crossroad with physical median controls or channelization may need more coverage.

2.6 Caltrans lighting design guidelines

WSDOT uses two types of roadway lighting systems, required illumination and additional illumination. California DOT considers safety lighting for freeway and conventional highways. The warrants for the safety freeway lighting for different design areas are summarized in Table 2-15.

Table 2-15 Warrants for the safety freeway lighting for freeway

Design Area	Safety lighting warrants
Freeway interchange safety lighting	Safety lighting is considered to be warranted under either of the following conditions: a. Where the total sum of the ADT ramp traffic entering and leaving the freeway within the interchange area exceeds 5,000 under urban conditions, 3,000 under suburban conditions and 1,000 under rural conditions. b. Where the ADT on the freeway exceeds 25,000 for urban conditions, 20,000 for suburban conditions and 10,000 for rural conditions.
Freeway ramp-surface street intersection safety lighting	Use the same warrants considered for the freeway interchange
Lighting of existing local streets within the limits of the freeway project	The local street is lighted to modern standards up to the freeway right of way and the local agency agrees to assume ownership and cost of maintenance.
Exclusive pedestrian	The lighting is considered warranted at the following

facilities within the freeway	locations: a. Separated walkways (not sidewalks) and crosswalks within the interchange areas. b. Bicycle paths at roadway crossings and at underpasses. c. Bus stops within the interchange areas. d. Pedestrian overcrossings and undercrossings.

The warrants for the conventional highway safety lighting for different design areas are summarized in Table 2-16.

Table 2-16 Warrants for the safety freeway lighting for conventional highway

Design area	Safety lighting warrants
Existing Intersections	Safety lighting may be provided if one of the following conditions is fulfilled: a. A minimum vehicular volume, an interruption of continuous traffic or minimum pedestrian volume traffic signal warrant is satisfied for any single hour which may be in darkness in winter months. b. Four or more nighttime accidents in any recent consecutive 12-month interval or six or more nighttime accidents in any recent consecutive 24-month interval. c. Where a traffic signal or an intersection flashing beacon is installed. d. Where combinations of sight distance or horizontal or vertical curvature of the roadway, channelization or other factors constitute a confusing or unsatisfactory condition that may be improved with lighting.
New Intersections	Safety lighting may be provided at new intersections on expressways or conventional highways if there are indications that any of the warrants listed for existing intersections above will be fulfilled within five years after the opening of the project to traffic.
Railroad Grade Crossings	Safety lighting may be provided at railroad grade crossings where a substantial amount of railroad operation is conducted at night, particularly where train speeds are low, where crossings are blocked for long periods, or a study indicates that motorists experience difficulty in seeing trains or traffic control devices during the hours of darkness.

For the highway safety lighting installed at intersections on conventional highways (including the intersection of a freeway ramp with a local street), the minimum maintained horizontal illuminance should satisfy the following specification:

1. In urban areas and expressways, 1.6 horizontal lux on the area normally bounded by the crosswalks, and 6.5 horizontal lux at the intersection of centerlines of the entering streets.

2. In rural areas, 1.1 horizontal lux on the area normally bounded by the crosswalks, and 3.2 horizontal lux at the intersection of centerlines of the entering streets.

Normally, the luminaire for a new installation of safety lighting on State highways is a full-cutoff type using a high pressure sodium lamp. For WSDOT, The cobra head-style, high-pressure sodium vapor luminaire with Type III, medium cut-off light distribution is the commonly used light source.

2.7 Mn DOT lighting design guidelines

The lighting warrants used by Mn DOT are primarily from AASHTO's Roadway lighting design guide. Some modifications and additions to these warrants are summarized in Tables 2-17, 2-18, 2-19.

Table 2-17 Warrants for continuous freeway lighting (CFL)

Individual Criteria	Case	Mn DOT Warrants
Traffic Volume	CFL-1	Average daily traffic (ADT) ≥ 30,000 vpd
	CFL-2	≥ 3 interchanges with average spacing ≤ 1.5 miles and adjacent to substantial urban areas
Roadway Related Factors	CFL-3	≥ 2 miles freeway segment passing through areas with two or more of the following characteristics: • Lit street grid visible from the freeway;• A series of developments, e.g., streets, residential and parking areas;• Lit cross streets ≤ 0.5 mile apart; • Width of freeway cross-section elements below desirable levels
Safety	CFL-4	Night-to-day crash rate ratio ≥ 2.0 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

Table 2-18 Warrants for complete interchange lighting (CIL)

Individual Criteria	Case	Mn DOT Warrants
Ramp Volume	CIL-1	Average daily ramp traffic ≥ 10,000 vpd for urban conditions, ≥ 8,000 vpd for suburban conditions and ≥ 5,000 for rural conditions.
Crossroad Volume	CIL-2	Current ADT on the crossroad≥ 10,000 vpd for urban conditions, ≥ 8,000 vpd for suburban conditions and ≥ 5,000 for rural conditions.
Roadway Related Factors	CIL-3	Consider CIL at locations on unlighted freeways where existing substantial commercial or industrial development, which is lighted during hours of darkness, is located in the immediate vicinity of the interchange, or where the crossroad approach legs are lighted for 0.5 miles (1 km) or more on each side of the interchange.
Safety	CIL-4	Night-to-day crash rate ratio ≥ 1.5 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

Table 2-19 lists the partial interchange lighting warrants from the Mn DOT highway lighting design.

Table 2-19 Warrants for partial interchange lighting (PIL)

Individual Criteria	Case	Mn DOT Warrants
Ramp Volume	PIL-1	Average daily traffic ≥ 5,000 vpd for urban conditions, ≥ 3,000 vpd for suburban conditions and ≥ 1,000 for rural conditions.
Freeway Volume	PIL-2	Current ADT on the crossroad≥ 25,000 vpd for urban conditions, ≥ 20,000 vpd for suburban conditions and ≥ 10,000 for rural conditions
Safety	PIL-3	Night-to-day crash rate ratio ≥ 1.25 times state average for unlit similar sections, and study indicates lighting would reduce night crash rate

WSDOT does not list specific warrants for roundabout lighting. For Mn DOT, the warrants for roundabout lighting are described in details. The warrants for illumination vary based on the location of the roundabout and are described in Table 2-20.

Table 2-20 Warrants for roundabout lighting

Location	Warrants
Urban Conditions	Illumination should be provided in an urban condition since most or all of the approaches of an urban roundabout are typically illuminated and to improve the visibility of pedestrians and bicyclists.

Suburban Conditions	Illumination should be installed for safety reasons when any of the following conditions are present. • One or more approaches are illuminated. • Competing non-roadway illumination in the vicinity can distract the driver's attention (i.e. highly illuminated parking lots, car lots or filling stations). • Heavy nighttime traffic is anticipated. • Pedestrian and/or bicycle traffic is anticipated (approaches have sidewalks).
Rural Conditions	Illumination is recommended for rural roundabouts but it is not mandatory. Illumination can be costly if there is no power supply near the intersection.

Mn DOT uses Table 2-21 to determine the design level of illumination at roundabouts and other intersections.

Table 2-21 Recommended level of illumination at roundabouts and other intersections

Recommended illuminance for Intersections				
Roadway Classification (Street A/Street B)	Average Maintained Illuminance at Pavement			Uniformity Ratio(E_{avg}/E_{min})
	Pedestrian/Area Classification			
	High lux (fc)	Medium lux (fc)	Low lux (fc)	
Major/Major	34.0 (3.2)	26.0 (2.4)	18.0 (1.7)	3
Major/Collector	29.0 (2.7)	22.0 (2.1)	15.0 (1.4)	3
Major/Local	26.0 (2.4)	20.0 (1.9)	13.0 (1.2)	3
Collector/Collector	24.0 (2.2)	18.0 (1.7)	12.0 (1.1)	4
Collector/Local	21.0 (2.0)	16.0 (1.5)	10.0 (0.9)	4
Local/Local	18.0 (1.7)	14.0 (1.3)	8.0 (0.7)	6

In Minnesota, the shallow glass "cobra head" style, “vertical” head style, or “high mast” style are the normally used luminaires for roadway lighting. And in certain circumstances, "shoebox" style luminaires can be used. Different roadway lighting lamps have been used by Mn DOT. A description of the lamp and its usage is provided in Table 2-22 below.

Table 2-22 Description of the lamp and its usage

Lamp	Mn DOT practice regarding the use of this type of lamp
Incandescent or Filament	The incandescent lamp is rarely if ever used for roadway lighting because of its low efficiency and short lamp life in comparison with High Intensity Discharge light sources.

Fluorescent	No longer used for new roadway and sign lighting installations
Mercury Vapor	No longer used for new roadway and sign lighting installations
Metal Halide (MH)	Are occasionally used on Mn/DOT projects because of the elimination of the mercury vapor luminaires. Installations are in rest areas and weigh stations. Some are in operation as part of high mast tower lighting and rest area lighting.
High Pressure Sodium (HPS)	The most commonly used by Mn/DOT. Very efficient and is the best for most roadway lighting. Not good for use on signs because the light it produces does not render the proper colors on standard signs.
Low Pressure Sodium (LPS)	Mn/DOT does not use LPS light sources.
Induction	Mn/DOT has used this in Rest Areas.
Light Emitting Diode	Mn/DOT has used this in Rest Areas, on the I-35W Bridge and is investigating for use on highways.

For Mn DOT, the typical pole heights are 30 feet, 40 feet, and 49 feet. However, high mast tower lighting may replace conventional lighting units at locations with complex roadways and high mast tower luminaires have mounting heights varying from 100 feet to 140 feet (Roadway Lighting Design Manual, 2010). Table 2-23 provides the standard luminaire and support system types approved for Mn DOT use.

Table 2-23 Standard luminaire and support system types approved for Mn DOT use

Standard Luminaire and Support System Types	Components
Davit Pole/Cobra Head Luminaire	· 250 - 400 watt HPS lamp · 6 foot - 12 ft davit style mast arm · 40 foot – 49 ft round tapered (16 sided) stainless steel or round tapered aluminum pole, or · 40 foot – 49 ft galvanized steel pole (bridges, retaining walls and median barriers)
Bent Straw Pole/Shoebox	· 250 watt HPS lamp · 6 foot straight tapered mast arm· 30 foot - 40 foot painted square tapered stainless steel or galvanized aluminum pole
Tenon Top Pole/Vertical Mount Luminaire	· 250 - 400 watt HPS lamp · Pole top or twin bullhorn bracket mount · 40 - 49 foot round tapered (16 sided) stainless steel or round straight aluminum pole
High Mast Towers	· 1000 watt HPS lamp · 3 - 6 luminaires per tower · 100 foot - 140 foot corten steel pole with

	stainless steel luminaire support ring
Rest Area	· Walkway light poles with 12" arm and shoebox luminaire · 400 watt MH, induction or LED in parking lot · 12-foot painted 4" square steel poles · Mn/DOT is working on standardizing all rest area lighting styles to make maintenance easier and avoid a mix of styles due to the availability of products. Discuss with the District Office to confirm the standard.

Table 2-24 contains the minimum average maintained illumination and maximum uniformity ratios by facility classification and pavement classification.

Table 2-24 Illumination requirements by facility classification and pavement classification

Roadway and Walkway Classification		R1		R2 & R3		R4		Max Unif.
		footcandles	Lux	footcandles	Lux	footcandles	Lux	avg/min
Interstate and Other Freeways	Commercial	0.6 - 1.1	6 - 12	0.6 - 1.1	6 - 12	0.6 - 1.1	6 - 12	3:1 or 4:1
	Intermediate	0.6 - 0.9	6 - 10	0.6 - 0.9	6 - 10	0.6 - 0.9	6 - 10	3:1 or 4:1
	Residential	0.6 - 0.8	6 - 8	0.6 - 0.8	6 - 8	0.6 - 0.8	6 - 8	3:1 or 4:1
Other Principal Arterials	Commercial	1.1	12	1.6	17	1.4	15	3:1
	Intermediate	0.8	9	1.2	13	1	11	3:1
	Residential	0.6	6	0.8	9	0.8	8	3:1
Minor Arterial	Commercial	0.9	10	1.4	15	1	11	4:1
	Intermediate	0.8	8	1	11	0.9	10	4:1
	Residential	0.5	5	0.7	7	0.7	7	4:1
Collectors	Commercial	0.8	8	1.1	12	0.9	10	4:1
	Intermediate	0.6	6	0.8	9	0.8	8	4:1
	Residential	0.4	4	0.6	6	0.5	5	4:1
Local	Commercial	0.6	6	0.8	9	0.8	8	6:1
	Intermediate	0.5	5	0.7	7	0.6	6	6:1
	Residential	0.3	3	0.4	4	0.4	4	6:1
Alleys	Commercial	0.4	4	0.6	6	0.5	5	6:1
	Intermediate	0.3	3	0.4	4	0.4	4	6:1
	Residential	0.2	2	0.3	3	0.3	3	6:1
Sidewalks	Commercial	0.9	10	1.3	14	1.2	13	3:1

	Intermediate	0.6	6	0.8	9	0.8	8	4:1
	Residential	0.3	3	0.4	4	0.4	4	6:1
Pedestrian Ways and Bike Ways		1.4	15	2	22	1.8	19	3:1
Rest Areas	Roadways	-	-	0.6 - 0.8	6 - 9	-	-	3:1 or 4:1
	Parking Areas	-	-	1	11	-	-	3:1 or 4:1

Where: R1 = cement/concrete; R2 = asphalt/gravel & R3 = asphalt/rough texture (typical highway); R4 = asphalt/smooth texture.

2.8 Seattle DOT lighting design guidelines

For Seattle DOT lighting design guidelines, the street lighting design criteria describe the electrical systems and electrical materials for illumination. For Seattle DOT, luminaires are normally “cobrahead” style. For less than 200 watts luminaire, light distribution pattern is Type III medium cutoff and for 200 watts and more, light distribution pattern is Type II short cutoff. For designing street lights, Seattle DOT considers the following design criteria (Table 2-25).

Table 2-25 Design criteria considered by Seattle DOT

Design area	Design Criteria
New or relocated street lighting—non-arterial streets	Street lighting for non-arterial streets should be designed using the most recent edition of the recommended IES guidelines, unless otherwise approved by Seattle City Light.
Arterial Street lighting	Use design guidelines established by Seattle DOT for arterial street lighting. Existing street light systems may be required to meet the design criteria and new street light systems shall be designed to them.
Pedestrian lighting	Pedestrian lighting illuminates the pedestrian walkway and is typically mounted 12 -14 feet above the sidewalk. This lighting should be considered when calculating the maintained foot candles and uniformity of roadway lighting.

2.9 NJDOT lighting design guidelines

The warrants used by NJDOT for freeway lighting are summarized in Table 2-26. The warrants listed in Table 2-26 can be also found in AASHTO’s Roadway lighting design guide.

Table 2-26 Warrants used by NJDOT for freeway lighting

Design area	One of the following warrants must be met for lighting

Continuous Freeway Lighting	• CFL-3[1] • CFL-4 • Special considerations
Complete Interchange Lighting	• CIL-1[2] plus CIL-2. • CIL-3 • CIL-4 • Special considerations
Partial Interchange Lighting	• PIL-1[3] plus PIL-2 • PIL-3 • Special Considerations
Additional lighting for ramps	• Inside radius of entrance or exit ramp is less than 150 feet. • Accident data in the ramp area indicates a problem exists.
Additional lighting for Acceleration Lanes	• Stop before acceleration lane. • Grade and/or curvature presents a visibility problem, which cannot be corrected through other means. • Sidewalks exist to permit pedestrians to cross at the entrance or terminal of a ramp.
Additional lighting for Main Line	• Grade and/or curvature presents a visibility problem, which cannot be corrected through other means. • Bridges without shoulders.

[1] see definition of CFL-3 in Table 2-17;
[2] see definition of CIL-1 in Table 2-18;
[3] see definition of PIL-1 in Table 2-19.

The NJDOT currently uses two types of highway lighting systems: high mast lighting system and conventional lighting system. The high mast lighting system is defined as a system consists of a mounting pole of 100 feet and a maximum of eight 400 watt high pressure sodium luminaires. And the conventional lighting system is a system consists of mounting pole of 26 feet with 150 watt, 40 feet with 250 watt high pressure sodium conventional luminaires. NJDOT recommends that high mast lighting system with a 400 watt cutoff type luminaire should be considered for full interchange lighting. And conventional lighting (full cutoff luminaires) should be considered as a second choice for full interchange lighting. Conventional lighting (full-cutoff, cutoff & semi-cutoff) shall be considered as the first choice for continuous mainline or partial interchange lighting. A 40 foot mounting height standard with 250 watt luminaire is recommended for mainline and a 26 foot mounting height standard with 150 watt luminaire is recommended for ramps. For mainline highways and ramps, an average horizontal illuminance of 0.6 to 0.8 footcandles should be provided. Design for uniformity of illuminance on various highways shall produce a uniformity ratio of 3:1 to 4:1 or better with a 0.2 footcandle minimum level.

The warrants used by NJDOT for intersection lighting are summarized in Table 2-27.

Table 2-27 Warrants used by NJDOT for intersection lighting

Design area	Lighting warrants

Signalized intersections	All signalized intersections need to be illuminated.
Non-signalized Major intersections	Must meet one of the criteria 1. Four lane highway. 2. Warrants (dusk to dawn): • Any right turn movement on to the highway greater than 75 VPH*. • Any left turn movement on to the highway greater than 25 VPH/Leg. • Through movement for the intersecting roadway greater than 50 VPH in either leg.

* The VPH warrants for lighting are based on the highest VPH count in a given nighttime hour.

2.10 Transportation association of Canada lighting design guidelines

WSDOT defines two types of roadway lighting systems, required illumination and additional illumination. Transportation association of Canada (TAC) uses different warrants to justify the need for roadway lighting at eligible locations.

For roadway and interchange, the transportation association of Canada adopts the warrants summarized in Table 2-28. The warrants are based on criterion grouped into geometric, operational, environmental, and collision factors. For each criterion characteristic of the candidate installation, the warrant uses a numeric rating (total point-score) corresponding to the relative degree of hazard presented or indicated by the feature (Guide for the Design of Roadway Lighting, 2006). The higher the number, the greater the hazard. Table 2-28 provides the types of warranted lighting.

Table 2-28 Warrants for roadway and interchange

Lighting scenarios	Criteria
Full lighting	Full lighting is warranted where a total point-score of 60 or more is achieved. If the night-to-day collision ratio is 2.0:1 or greater, lighting is automatically warranted, regardless of the overall point-score.
Partial lighting	Partial lighting may be considered for freeway on-ramps and off-ramps where a point-score is less than 60 or the night to-day collision ratio is less than 2.0:1 and any of the following conditions apply: 1. There are three or more through lanes in one direction on the freeway at the ramp. 2. There are two or more ramp lanes. 3. The ramp traffic volume is greater than one-quarter of the through traffic volume or the traffic volume exceeds 9000 AADT. 4. Geometric design standards for the ramp are below

	recommendations outlined in the TAC Geometric Design Standards for Canadian Roads or below those set out by the road authority.
No lighting	Generally, full or partial lighting is not warranted if the warranting point score is under 60, a night-to-day collision ratio is less than 2.0:1, or none of the partial lighting warranting conditions are met.

Luminance is the recommended method for roadway and interchange lighting calculations. The luminance levels, uniformity and veiling luminance ratios are given in Table 2-29 for roadways and interchanges for the roadway surface.

Table 2-29 Luminance requirements for roadways and interchanges (Source: Guide for the Design of Roadway Lighting, 2006)

Road Area and Pedestrian Activity		Average Luminance cd/m^2	Average to Minimum Uniformity Ratio	Maximum to minimum uniformity ratio	Maximum to average veiling luminance ratio
Road Type	Pedestrian Activity				
Freeway	-	>=0.6	<=3.5	<=6.0	<=0.3
Partial lighting of Interchange on-Ramps/Off-Ramps	-	>=0.6	<=3.5	<=6.0	<=0.3
Expressway-Highway	High	>=1.0	<=3.0	<=5.0	<=0.3
	Medium	>=0.8	<=3.0	<=5.0	<=0.3
	Low	>=0.6	<=3.5	<=6.0	<=0.3
Arterial	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/Alleyway	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

For TAC, intersections should be illuminated when at least one of the following conditions is met: 1) the intersection is signalized; 2) the intersection meets warrant criteria noted in the

TAC Illumination of Isolated Rural intersections. The TAC Illumination of Isolated Rural intersection is based on geometric, operational, environmental, and collision factors. For each criterion of the candidate intersection, the warrant uses a rating (R) of 0 to 4. The ratings correspond to the relative degree of hazard presented by the intersection feature. Each criterion is assigned a weight (W), ranging from 3 to 30, to indicate its relative importance. The rating value (0 to 4) is then multiplied by the weight (3 to 30) to obtain a point-score for each criterion characteristic, indicating its relative significance. The critical factors used to determine the need for illumination include the following: traffic volumes (particularly on the cross street); the presence of crosswalks; night time collisions that may be attributed to the lack of illumination; the extent of raised medians. Table 2-30 provides the types of warranted lighting.

Table 2-30 Warrants for intersections

Lighting scenarios	Criteria
Full lighting	Full illumination is always warranted if the intersection is signalized. Full illumination is warranted where a total point-score of 240 or more points is achieved, indicating the likely presence of two or more critical warranting factors. Full intersection lighting denotes illumination covering an intersection in a uniform manner over the traveled portion of the roadway.
Partial lighting	Partial or delineation lighting may be considered at intersections with a point-score greater than or equal to 120 points, but less than 240 points. The type of lighting may be determined with reference to category classification subtotals: 1. If at least 80 of the minimum 120 points are achieved in the geometric score, partial lighting should be considered to illuminate the geometric features that contributed most to the score. Partial lighting refers to the illumination of key decision areas, potential conflict points, and/or hazards in and on the approach to an intersection. 2. If 120 points or more are achieved in the operational score, delineation lighting should be considered. Delineation lighting refers to "beacon" lighting that marks an intersection location for approaching traffic, for the illumination of vehicles on a cross street or median crossing, or for the illumination of pedestrians. 3. If 120 points are achieved in the collision score, a review of the collision history should be conducted to identify the causes of collisions. If the causes cannot be rectified, partial or delineation lighting may be considered to address collisions that may be avoided by adding lighting. 4. If the total point-score reflects the presence of several secondary warranting factors, the highest scoring individual factors should be reviewed to identify circumstances contributing to the score. Lighting may be appropriate to address these factors.

No lighting	Generally, a point-score under 120 indicates that illumination is not warranted. This score indicates that neither the critical operational warranting factor (substantial traffic volumes) nor the critical collision warranting factor (repeated night time collisions) is present.

The values included in Table 2-31 are the recommended minimum average maintained illuminance levels for fully-lighted intersections based on road classification and pedestrian volumes. The table is based on an R2/R3 pavement type. The values for full intersection lighting represent the sum of the recommended values for the intersecting streets.

Table 2-31 Recommended minimum average maintained illuminance levels for fully-lighted intersections (Source: Guide for the Design of Roadway Lighting, 2006)

Roadway Classification	Average Maintained Illuminance at Pavement by Pedestrian Conflict (lux)			Average to Minimum uniformity ratio
	High	Medium	Low	
Arterial/Arterial	34	26	18	3
Arterial/Collector	29	22	15	3
Arterial/Local	26	20	13	3
Expressway-Highway/Arterial	31	25	18	3
Expressway-Highway/Expressway-Highway	28	24	18	3
Expressway-Highway/Collector	26	21	15	3
Expressway-Highway/Local	23	19	13	3
Collector/Collector	24	18	12	4
Collector/Local	21	16	10	4
Local/Local	18	14	8	6

Partial lighting should meet the lighting levels for the type of road where the intersection is located. The values included in Table 2-32 are the recommended average maintained lighting levels for the area being lighted based on the road classification and pedestrian volumes. The table is based on R2/R3 pavement type.

Table 2-32 Recommended minimum average maintained illuminance levels for partial lighting (Source: Guide for the Design of Roadway Lighting, 2006)

Roadway Classification	Average Maintained Illuminance at Pavement by Pedestrian Conflict (lux)			Average to Minimum uniformity ratio
	High	Medium	Low	
Arterial	17	13	9	3
Expressway-highway	14	12	9	3

Collector	12	9	6	4
Local	9	7	4	6

For TAC, the warrants for other facilities (roundabout, mid-block crossing, at-grade railway crossing and parking lot) are summarized in Table 2-33.

Table 2-33 Warrants for other facilities

Facilities	Warrants
Roundabout	Urban area should always be lighted. Rural area should be lighted in most cases. Typically illuminated when one or more of the entry roads are also illuminated. Heavy nighttime traffic volumes may also be a factor that warrants illumination.
Mid-block	It is recommended that all pedestrian crosswalks with nighttime pedestrian traffic be illuminated.
At-grade railway crossing	An at-grade railway crossing should have fixed lighting to illuminate the roadway approaches (horizontal lighting) and the sides of the train (vertical illumination) during hours of darkness if all of the following conditions are met: • The railway crossing is an unrestricted grade crossing. • No grade crossing warning system (warning signals and/or gates) or interconnected traffic signals are present. • The posted speed on the roadway is 50 km/h or greater. • Routinely, during hours of darkness, there are switching operations, trains, engines, or any other railway equipment which stops on the crossing or travels over the crossing at 24 km/h (15 mph) or less.
Parking lot	To enhance public safety, parking lots should be illuminated in areas where there is nighttime usage.

3 LED Luminaire Technology Review

In this section, available literature, case studies, and vendor documentation were reviewed to determine the availability, characteristics, costs, and operational characteristics of each identified luminaire technology. We focused on the following characteristics: drivers, dimming control modules and luminaire types, compatibilities with different control systems and costs, life span, manufacturer warranty, ongoing preventative maintenance requirements, inrush current, illumination spectrum, energy use and efficiency, operating voltages, cased studies, etc.

3.1 Cooper lighting

The Cooper lighting provides LED and controls solutions to commercial, retail, institutional, residential and utility markets. The history of Cooper Lighting goes back to 1956. Table 3-1 summarizes the key characteristics for cooper lighting's LED products.

Table 3-1 Key characteristics of cooper lighting's LED products

LED product	CAX Series	OVF LED Roadway Large Cobrahead	OVH LED	Trailmaster™ Dusk-to-Dawn/Site/Roadway Luminaire
Description	LED Lamping Exit Lighting	Streetworks Roadway Luminaire	Streetworks Roadway Luminaire	High performance LED Dusk-to-Dawn, Site/Area, and Roadway Luminaire
Drivers	N/A	electronic LED Driver	electronic LED Driver	electronic LED Driver

Dimming control modules	N/A	Twistlock Photocontrol Receptacle	Twistlock Photocontrol Receptacle	Twistlock Photocontrol Receptacle
Luminaire types	Overhead Sign	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	N/A	Photocontrol	Photocontrol	Photocontrol
Life span	an estimated life of 25 years or more	60,000 hours	60,000 hours	60,000 hours
Warranty	a firm one year warrant against defect in material and workmanship	Five-year limited warranty	Five-year limited warranty	Five-year limited warranty
Maintenance requirements	No maintenance need under normal conditions	Die-cast aluminum door frame features integral hinges for tool-less maintenance access	Die-cast aluminum door frame features integral hinges for tool-less maintenance access	Tool-less entry, full cutoff hinged removable power tray door for easy maintenance

Inrush current	Very low	7 LED lightbar: 0.13-1.3 A; 21 LED lightbar: 0.1-1.24 A	7 LED lightbar: 0.13-0.86 A; 21 LED lightbar: 0.13-0.81 A	120V: 0.44 A; 277V: 0.19A
Illumination spectrum/ effective projected area ?	N/A	0.87 Square Feet	0.80 Square Feet	0.89 Square Feet
Efficiency	very low input wattage	7 LED lightbar: 27 - 154 watt; 21 LED lightbar: 27-146 watt	7 LED lightbar: 27 - 101 watt; 21 LED lightbar: 27-95 watt	53 watt
Operating voltages	120/277 V	120-277V; 347V; 480V	120-277V; 347V; 480V	120-277V;

Table 3-1 Key characteristics of cooper lighting's LED products (continued)

LED product	VAL Valet LED Tunnel	XNV LED Luminaire	Quadcast™ LED Parking Garage and Canopy Luminaire	TopTier LED

Description	Streetworks Tunnel/Underpass/parking Garage Luminaire	Streetworks Roadway Luminaire	for illuminating parking garages, canopy and stairwells	for illuminating parking garages
Drivers	Electronic LED Driver	Electronic LED Driver	Electronic LED Driver	Electronic LED Driver
Dimming control modules	N/A	dimming driver	Photocontrol Sensor	0-10V dimming driver
Luminaire types	trunnion / wall / pendant mount	Pole/Arm Mounted - Area and Roadway	Ceiling Mount	Ceiling Mount
Compatibilities	N/A	Photocontrol	Photocontrol	
Life span	50,000 + hour	60,000 hours	60,000 hours	60,000 hours
Warranty	Five-year limited warranty	Five-year limited warranty	Five-year limited warranty	Five-year limited warranty
Maintenance requirements	N/A	Tool-less entry, hinged removable power tray door for easy maintenance.	N/A	N/A

Inrush current	7 LED lightbar: 0.13-0.86 A; 21 LED lightbar: 0.13-0.81 A	120V: 0.25 -0.44 A; 277V: 0.11 -0.19 A.	0.17 -0.46 A	0.14 - 0.91 A
Illumination spectrum/ effective projected area ?	N/A	0.59 Square Feet	N/A	N/A
Efficiency	7 LED lightbar: 27 - 101 watt; 21 LED lightbar: 27- 95 watt	30- 53 watt	56 watts	34-108 watts
Operating voltages	120-277V; 347V; 480V	120-277V; 347V; 480V	120-277V; 347V.	120-277V; 347V; 480V

Case study 1

Carroll EMC, headquartered in Carrollton, Georgia, partnered with Cooper Lighting to retrofit its corporate parking lot with LED lighting. The project included retrofitting the existing 100W-400W HPS and 1000W MH fixtures with Cooper Lighting Streetworks Talon Medium LED luminaires (146W), OVF LED Roadway Large Cobraheads (146W), Traditionaire LED luminaires (58W) and Generation Series (58W) LED luminaires. After installing the new LEDs, the utility's electrical load was reduced by 72% (6.6 kW) for that area, resulting in an estimated annual energy savings of $2,600 (28,900 kWh) with a 3.6 year payback.

Case study 2

There is a need to upgrade the parking garage lighting at Hartsfield-Jackson Atlanta International Airport. After comparing multiple LED products with different manufacturers, they selected the Valet LED luminaire.

Officials at Hartsfield-Jackson Atlanta International Airport decided to replace each of the 4,342 175-watt metal-halide fixtures that consumed 210-watts with 80-watt Valet LED fixtures in its north and south parking decks. This can lead to greater energy-efficiency as well as cost savings of about $500,000 each year. The Valet LED fixtures can reduce maintenance costs as they are designed to last more than 50,000 hours.

3.2 Acuity brands lighting

Acuity Brands, Inc. is one of the world's leading providers of lighting solutions for both indoor and outdoor applications. Table 3-2 summarizes the key characteristics of LED products provided by Acuity Brands.

Table 3-2 Key characteristics of Acuity Brands's LED products

LED product	AUTOBAHN ATB0	AUTOBAHN ATB2	SERIES 247 LED - AMERICAN REVOLUTION	SERIES AVPL - VALIANT LED
Description	for lighting streets and highways	for lighting streets and highways	for lighting sidewalk	for lighting sidewalk
Drivers	Electronic driver	Electronic driver	Electronic driver	Electronic driver
Dimming control modules	0V - 10V dimmable driver	0V - 10V dimmable driver	0V - 10V dimmable driver	Photocontrol Receptacle
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Decorative
Compatibilities	the ROAM® smart controls system	the ROAM® smart controls system	the ROAM® smart controls system	Photocontrol
Life span	100,000 hours	100,000 hours	100,000 hours	70,000 hours
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	N/A	5-year limited system warranty standard
Maintenance requirements	Includes standard AEL lineman-friendly features such as tool-less entry, tool-less NEMA photocontrol receptacle, terminal block and quick disconnects. Bubble level located inside	Easy to Maintain: Includes standard AEL lineman-friendly features such as tool-less entry, tool-less NEMA photocontrol receptacle, terminal block and quick	Hinged hood and captive thumb screws provision afford quick, easy access to electrical and optical area for servicing	Easy to Maintain: Includes standard AEL lineman-friendly features (such as a tandem tool-less cupola and photocontrol receptacle, a terminal block and quick disconnects). The electrical platform and

	the electrical compartment for easy leveling at installation	disconnects. Bubble level located inside the electrical compartment for easy leveling at installation.		durable housing materials provide superior longevity and reduce the need for maintenance
Inrush current	0.35 A to 1 A	0.525 to 1 A	0.35 to 1.05 A	0.35 to 0.7 A
Illumination spectrum/ effective projected area ?	0.76 sq ft	0.78 sq ft	1.6 sq. ft	2.4 sq. ft
Efficiency	22 to 108 Watts;	70 to 284 Watts	13 to 72 Watts	35 to 78 Watts;
Operating voltages	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.

Table 3-2 Key characteristics of Acuity Brands's LED products (continued)

LED product	Series 245 LED - Contempo	AL25 LED	Resonance 1.5 LED
Description	for lighting sidewalk	for architectural site and roadway lighting.	For outdoor Area, Parking, Roadway, Sidewalk
Drivers	0V-10V dimmable driver	Electronic driver	Electronic driver
Dimming control modules	0V-10V dimmable driver	Photocontrol Receptacle	dimming drivers are available
Luminaire types	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Area and Roadway
Compatibilities	the ROAM smart controls system	Photocontrol	N/A
Life span	100,000 hours	100,000 hours	60,000 hours

Warranty		5-year limited system warranty standard	
Maintenance requirements	Hinged hood and captive screw latching provision afford quick, easy access to electrical and optical area for servicing	N/A	The hinged roof/ reflector housing is furnished with captive screws for access to the light engine. The light engine is furnished with a quick-disconnect plug. The driver assembly is furnished with a quick-disconnect plug.
Inrush current	0.35 to 1.05 A	0.525; 0.7 A	0.35 to 0.7 A
Illumination spectrum/ effective projected area ?	1.3 sq. ft	1.3 sq. ft	1.8 sq feet
Efficiency	13 to 72 Watts;	77 Watts	42 to 194 watts
Operating voltages	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.

Table 3-2 Key characteristics of Acuity Brands's LED products (continued)

LED product	ATL23 LED	AS1 LED	AST1 LED	MRT1 LED
Description	for architectural site and roadway lighting.	For parking areas, streetlighting, walkways and car lots	For parking areas, streetlighting, walkways and car lots	For parking areas, streetlighting, walkways and car lots
Drivers	Electronic driver	Electronic driver	Electronic driver	Electronic driver
Dimming control modules	Photocontrol Receptacle	dimming driver	dimming driver	dimming driver
Luminaire types	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	Photocontrol	the ROAM® smart controls system	N/A	N/A
Life span	50,000 hours	100,000	100,000 hours	100,000

		hours		hours
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard
Maintenance requirements	N/A	N/A	N/A	N/A
Inrush current	0.525; 0.7 A	0.35 to 0.53 A	0.35 to 0.53 A	0.35 to 0.53 A
Illumination spectrum/ effective projected area ?	1.3 sq. ft	0.7 sq ft	0.7 sq ft	0.54 sq ft
Efficiency	77 Watts	59 -109 Watts;	59 -109 Watts;	59 -108 Watts;
Operating voltages	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.

Table 3-2 Key characteristics of Acuity Brands's LED products (continued)

LED product	MRT2 LED	MR1 LED	MR2 LED
Description	For streets, walkways, parking areas lighting.	For parking areas, streetlighting, walkways and car lots	For parking areas, streetlighting, walkways and car lots
Drivers	Electronic driver	Electronic driver	Electronic driver
Dimming control modules	dimming driver	dimming driver	dimming driver
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	the ROAM® smart controls system	N/A	the ROAM® smart controls system
Life span	100,000 hours	100,000 hours	100,000 hours
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard
Maintenance requirements	N/A	N/A	N/A
Inrush current	0.7 to 1 A	0.35 to 0.53 A	0.7 to 1 A
Illumination spectrum/ effective projected area ?	0.9 sq ft	0.54 sq ft	0.9 sq ft
Efficiency	132 to 206 Watts;	59 to 108 Watts;	132 to 206 Watts;
Operating voltages	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.	120-277V; 347V ; 480V.

Case study 1

Officials in Chula Vista, San Diego, decided to retrofit the city's 150- and 250-watt high pressure sodium cobrahead lighting system. Autobahn LED Series Roadway Luminaires from American Electric Lighting were the selected lighting fixtures to meet the technical specifications for the lighting fixtures. Chula Vista installed 3,987 70-watt ATBO Series luminaires with 30 LEDs to replace the 150-watt HPS units and 140-watt ATB2 Series luminaires with 40 LEDs to replace the 250-watt fixtures. Luminaires were mounted on existing steel, concrete or wooden poles set in the curb along the roadway or mounted on the median. The lighting design meets IESNA RP-8 standard for roadway lighting, with illumination levels an average .84 footcandles with the ATBO Series luminaires and 1.10 footcandles with the ATB2 fixtures. The color rendering index (CRI) is 70. Autobahn luminaires are controlled by photocell and operate 4,150 hours per year, or approximately 11 hours per day, which is the standard operating average established for the region by San Diego Gas & Electric. The fixtures reduce energy consumption by more than 45 percent and have an expected payback of eight years.

Case study 2

The Maine state's old high pressure sodium fixtures consumed 3,000-watts per tower (or $200 monthly on each tower). After assessing two fixtures in the field, MaineDOT selected the Holophane HMAO LED high mast from Acuity Brands. The HMAO LED high mast fixtures use prismatic glass optics to help eliminate the potential for dark spots. The new LED high mast fixtures consume significantly less wattage than the previous fixtures. The HMAO LED uses only 290-watts and has an expected life of 25 years. Furthermore, the LED fixtures include multiple light sources for backup lighting capabilities. Each new lighting tower costs $66 per month. The Maine DOT estimates after all 105 towers are upgraded with LED fixtures, the department will save $135,000 annually in energy.

3.3 GE lighting

GE Lighting is a division of General Electric headquartered in Ohio, United States, employing 17,000 people and GE was founded in 1911. Table 3-3 summarizes the key characteristics for GE lighting's LED products.

Table 3-3 Key characteristics of GE lighting's LED products

LED product	Evolve LED Roadway	ERX1	Evolve™ LED Post Top - Avery StreetDreams™ – EPAS	Evolve™ LED Post Top
Description	for lighting streets and highways	for lighting streets and highways	Roadway, site, area, and general lighting	Roadway, site, area, and general lighting
Drivers	N/A	N/A	N/A	N/A
Dimming control modules	GE Monitor Stand-Alone Controller	GE Monitor Stand-Alone Controller	GE dimming/ Photo electric sensors	GE dimming/ Photo electric sensors
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Decorative
Compatibilities	GE LightGrid™ Outdoor Wireless Control System	GE LightGrid™ Outdoor Wireless Control System	Photocontrol	Photocontrol
Life span	50,000 hour life	50,000 hour life	50,000 hour life	50,000 hour life
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard
Maintenance requirements	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should be established with frequency dependent	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should be	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should

	on local conditions. Use a mild soap or detergent which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.	be established with frequency dependent on local conditions. Use a mild soap or detergent which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.	established with frequency dependent on local conditions. Use a mild soap or detergent which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.	be established with frequency dependent on local conditions. Use a mild soap or detergent which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.
Inrush current	525 mA	700 mA	N/A	N/A
Illumination spectrum/ effective projected area ?	ERS1: 0.5 square feet; ERS2 0.7 square feet; ERS3 1.0 square feet; ERS4 1.0 square feet;	0.7 sq ft	1.4 sq ft	1.6 sq ft
Efficiency	ERS1 43 to 74 Watts; ERS2 82 to 140 Watts;ERS3 148 to 218 Watts; ERS4 209 to 287 Watts;	39 to 71 Watts	49 to 94 watts	49 to 94 watts
Operating voltages	120-277 volt and 347-480 volt available	120-277 volt.	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available

Table 3-3 Key characteristics of GE lighting's LED products (continued)

LED product	Evolve™ LED Post Top - Contemporary Conical – EPCC	Evolve™ LED Post Top - Contemporary Twin Support - EPTC	Evolve™ LED Flood Light - Wide, Billboard & Spot – EFMR	Evolve™ LED Garage Light - Medium Square - EGMS
Description	Roadway, site, area, and general lighting	Roadway, site, area, and general lighting	General flood requirements, bulletin/billboard	Garage, warehouse, walkway and stairway lighting
Drivers	N/A	N/A	N/A	N/A
Dimming control modules	GE dimming/ Photo electric sensors	GE dimming/ Photo electric sensors	Photo electric sensors	GE dimming
Luminaire types	Pole/Arm Mounted - Decorative	Pole/Arm Mounted - Decorative	Overhead Sign	Parking Garage / Canopy
Compatibilities	Photocontrol	Photocontrol	Photocontrol	N/A
Life span	50,000 hour life	50,000 hour life	50,000 hour life	50,000 hour life
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard
Maintenance requirements	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should be established with frequency dependent on local conditions. Use a mild soap or detergent which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash	In order to maintain high efficiency of reflectors and refractors, a regular cleaning cycle should be established with frequency dependent on local conditions. Use a mild soap or detergent	N/A	Occasionally it will be necessary for the refractor to be cleaned to maintain appearance and light levels. The frequency of cleaning will be dependent on the ambient dirt level and

	outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.	which is essentially neutral, nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash outside thoroughly, using a soft cloth, or brush if necessary. Rinse in clean, cold water and wipe dry.		minimum light level required. Refractor and housing should be washed with a solution of warm water and mild household detergent, rinsed with clean water, and wiped dry
Inrush current	N/A	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	1.6 sq ft	1.12 sq. ft	2.26 sq ft	N/A
Efficiency	63 to 96 watts	49-93 watts	90 watts	60 - 131 watts
Operating voltages	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available	120 volt	120-277 volt and 347-480 volt available

Table 3-3 Key characteristics of GE lighting's LED products (continued)

LED product	Evolve™ LED Area Light - Modular Small & Medium Fixtures	Evolve™ LED Area Light - Scalable Wall Pack – EWS1	Evolve™ LED Area Light - Scalable – EASA
Description	site, area, and general lighting	site, area, and general lighting	site, area, and general lighting
Drivers	N/A	N/A	N/A
Dimming control modules	GE dimming/ Photo electric sensors	Non-dimming	GE dimming/ Photo electric sensors
Luminaire types	Parking Garage /	Wall mounted	Parking Garage /

	Canopy		Canopy
Compatibilities	Photocontrol	N/A	Photocontrol
Life span	50,000 hour life	50,000 hour life	50,000 hour life
Warranty	5-year limited system warranty standard	5-year limited system warranty standard	5-year limited system warranty standard
Maintenance requirements	Occasionally it will be necessary for the refractor to be cleaned to maintain appearance and light levels. The frequency of cleaning will be dependent on the ambient dirt level and minimum light level required. Refractor and housing should be washed with a solution of warm water and mild household detergent, rinsed with clean water, and wiped dry	Occasionally it will be necessary for the refractor to be cleaned to maintain appearance and light levels. The frequency of cleaning will be dependent on the ambient dirt level and minimum light level required. Refractor and housing should be washed with a solution of warm water and mild household detergent, rinsed with clean water, and wiped dry	Occasionally it will be necessary for the refractor to be cleaned to maintain appearance and light levels. The frequency of cleaning will be dependent on the ambient dirt level and minimum light level required. Refractor and housing should be washed with a solution of warm water and mild household detergent, rinsed with clean water, and wiped dry
Inrush current	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	1.35 sq ft		0.97 sq ft
Efficiency	100 - 213 watts	43 - 74 watts	62- 433 watts
Operating voltages	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available

Case study

Las Vegas estimates that the installation of new LED streetlights can reduce electricity use by more than 20 million kilowatt hours (save about $1.7 million annually). Las Vegas selected GE Evolve™ LED Roadway fixtures to replace the current lighting fixtures. Nearly 6,600 GE Evolve™ LED Roadway fixtures were replaced mercury vapor and high-pressure sodium (HPS) lights on arterial streets and residential thoroughfares throughout Las Vegas. In early

2012, Las Vegas installed 35,000 additional Evolve™ LED Roadway fixtures. After the completion of project, more than 80% of Las Vegas' 50,000 streetlights are GE LED fixtures. GE's new Evolve™ LED Roadway fixtures have a estimated life of more than 11 years at 12 hours of use per day. The city calculates the total cost savings (combined annual energy and maintenance) to $2.7 million.

3.4 Cree/ Beta

Cree leads the LED lighting revolution and is advancing the use of energy-efficient, environmentally friendly LED lighting. Table 3-4 summarize the key characteristics for Cree/Beta lighting's LED products.

Table 3-4 Key characteristics of Cree/Beta lighting's LED products

LED product	Cree XSP Series LED Street Light	LEDway Street Lighting Products	LEDway SLM™ IP66 Streetlight	LEDway SLM™ Series
Description	The XSP series is an ideal replacement for outdated high-pressure sodium fixtures and is applicable to any street/roadway	roadway lighting	LEDway SLM IP66 is sleek, low profile LED luminaires designed to replace existing traditional cobrahead systems along residential streets	LEDway SLM is sleek, low profile LED luminaires designed to replace existing traditional cobrahead systems along residential streets
Drivers	LED driver	LED driver	LED driver	LED driver
Dimming control modules	ROAM dimming control module/Photocell Receptacle	ROAM dimming control module/Photocell Receptacle	ROAM dimming control module/Photocell Receptacle	ROAM dimming control module/Photocell Receptacle
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	ROAM/Photocontrol	ROAM/Photocontrol	ROAM/Photocontrol	ROAM/Photocontrol
Life span	100,000 hours	120000 hours	87000 hours	87000 hours
Warranty	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish
Maintenance requirements	State of the art flow through heat sink technology delivers years of near maintenance-free performance	Quick disconnect harness suitable for mate and break under load provided on power feed to driver for ease of maintenance.	N/A	N/A
Inrush current	XSP1: 0.2 - 0.44 A.;XSP2 : 0.39 -	20-30 LED: 0.07-0.61 A; 40-60	0.1 -1.19 A	0.1 -1.19 A

	0.84 A.	LED: 0.11 - 1.17 A; 70-90 LED: 0.2 - 1.69 A; 100-120 LED: 0.26 -2.31 A.		
Illumination spectrum/ effective projected area ?	XSP1: 0.714 sq. ft.;XSP2 : 0.692 sq. ft.;	20-30 LED: 0.565 sq ft; 40-60 LED: 0.685 sq ft.70-90 LED: 0.706 sq ft; 100-120 LED: 0.82 sq ft	1.36 sq ft.	1.06 sq ft
Efficiency	XSP1: 53 watts; XSP2: 101 watts.	20-30 LED: 25 -72 watts; 40-60 LED: 45 - 139 watts. 70-90 LED: 75 - 210 watts. 100-120 LED: 111 - 272 watts.	38 - 142 watts	38 - 142 watts
Operating voltages	120–277V	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available

Table 3-4 Key characteristics of Cree/Beta lighting's LED products (continued)

LED product	THE EDGE® Transportation Mount	Aeroblades™ LED Area Light	BetaLED SLM™ IP66 Area Lighting	THE EDGE®-LED Area Lighting
Description	THE EDGE® TSP is designed for bridges, overpasses, roadways and tunnels.	walkways, roadways and parking applications.	walkways, roadways and parking applications.	pathways, large common spaces and parking lots applications.
Drivers	LED driver	LED driver	LED driver	LED driver
Dimming control modules	0–10V dimming control	0–10V dimming control	0–10V dimming control/Photocell Receptacle	0–10V dimming control/Photocell Receptacle
Luminaire types	Ceiling Mount	LED area &parking lights	LED area &parking lights	LED area &parking lights
Compatibilities	N/A	N/A	Photocontrol	Photocontrol
Life span	>100,000 hours	>60,000 hours	>87,000 hours	> 111,000 hours

Warranty	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish
Maintenance requirements	N/A	N/A	N/A	N/A
Inrush current	40-100 LEDs: 0.12 -1.18 A;120-160 LEDs: 0.28 - 2.29 A;200-240 LEDs: 0.49 - 4.49 LEDs.	0.1 -1.17 A	0.1 -1.19 A	0.07 - 2.30 A
Illumination spectrum/ effective projected area ?	N/A	0.90 sq ft.	1.25 sq ft.	0.66 sq ft.
Efficiency	40-100 LEDs: 47 - 172 watts;120-160 LEDs: 132 - 265 watts;200-240 LEDs: 234 - 539 watts.	39 - 138 watts	38 -142 watts	26- 265 watts.
Operating voltages	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available

Table 3-4 Key characteristics of Cree/Beta lighting's LED products (continued)

LED product	THE EDGE® Round-LED Area Lighting	THE EDGE® Parking Structure lighting	304 Series LED Parking Structure Lighting
Description	pathways, parks, and parking lots applications.	parking garages and underpasses applications.	parking structure and underpass applications.
Drivers	LED driver	LED driver	LED driver
Dimming control modules	0–10V dimming control/Photocell Receptacle	20 LED: Non-dimming; 40-100 LED: 0–10V dimming control	0–10V dimming control
Luminaire types	LED area &parking lights	LED parking lights	LED parking lights
Compatibilities	Photocontrol	N/A	N/A
Life span	> 111,000 hours	20 LED: >150,000 hours; 40-100 LED: 111,000 hours	122000 hours

Warranty	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish	5 years on luminaire / 10 years on finish
Maintenance requirements	N/A	N/A	N/A
Inrush current	0.12 - 1.76 A	20 LED: 0.1 - 0.2 A; 40-100 LED: 0.12-1.47 A	0.11-1.26 A
Illumination spectrum/ effective projected area ?	0.53 sq ft.	N/A	N/A
Efficiency	47 - 204 watts.	20 LED: 26 watts; 40-100 LED: 47 - 172 watts.	47-141 watts.
Operating voltages	120-277 volt and 347-480 volt available	20 LED: 120-277 volt; 40-100 LED: 120-277 volt and 347-480 volt available	120-277 volt and 347-480 volt available

Case study

Town of Danville in California decided to convert 262 high-pressure sodium streetlights to LED. After comparing the streetlights from various manufacturers, LEDway streetlights (LEDway streetlights with 60 and 80 LED) were installed along a five-mile section of the heavily traveled arterial roadway corridor.

It is estimated that LEDway streetlights consume 44 - 53% less energy per year compared to the conventional HPS system. In addition, more than 50,000 hours of maintenance-free operation with lumen depreciation of less than 2% per year compared to HPS systems with an average lumen depreciation rate of approximately 8% per year.

3.5 Philips

Philips Lighting is the leader in lighting, driving the digital lighting revolution. Table 3-5 summarizes the key characteristics for Philips lighting's LED products.

Table 3-5 Key characteristics of Philips lighting's LED products

LED product	RoadView Series	StreetView	RoadStar Series	MetroScape
Description	for lighting streets and highways	for lighting streets and highways	for lighting streets and highways	Outdoor Lighting
Drivers	Philips Xitanium driver	Dimmable driver 0-10V	Philips Dynadimmer driver	Dimmable driver 0-10V
Dimming control modules	Programmable step-dimming/ Dimming driver	dimmable driver	dimmable driver	dimmable driver
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	photocontrol receptacle/Philips smart lighting control system	Photo-cell Control/ Digital Addressable Lighting Interface control system	Photo-cell Control/Dynadimmer control	Photo-cell Control/ Digital Addressable Lighting Interface control system
Life span	Up to 100,000 hour rated life	100,000+ hour rated life	70,000 hours	Up to 100,000 hour rated life
Warranty	not provided	ten-year	not provided	not provided
Maintenance requirements	removable power door for easy maintenance	N/A	Easily replaces cobraheads. No special tooling required.	N/A
Inrush current	RVS 0.31 - 1.08 A; RVM 0.88 - 2.17 A.	0.085 - 0.86 A	570mA	350 - 530 mA
Illumination spectrum/ effective projected area ?	RVS: 0.53 -0.6 square feet; RVM: 0.71 - 0.78 square feet	0.51 sq ft	GPLS: 0.76 square feet; GPLM :1.1 square feet.	1.97 sq ft

Efficiency	RVS 35- 135 watts; RVM 110-270 watts	18 to 156 watts	GPLS: 40 to 90 Watt; GPLM 105 to 180 Watt.	35 - 129 Watts
Operating voltages	120 - 277V; 347V; 480V;	120V; 277V; 347V; 480V;	120 / 208 / 240 / 277	120V; 208V;240V; 277V; 347V; 480V;

Case study

Due to the inefficient light, high energy consumption and high maintenance cost of HPS fixtures, officials at Cherokee, NC decided to use new LEDs. The old HPS fixtures were replaced by highly efficient Philips LED fixtures. A 7-mile long road along with adjacent parking lots was included in the project, and there are totally 250 to 275 fixtures. 85 Transit luminaires, fitted with 82w 54-LED and 90w 49-LED LifeLED™ light engines designed and manufactured by Philips Lumec have been installed. The newly installed LED can reduce Cherokee's energy and maintenance bills by $23,000 annually.

3.6 Dialight

Dialight is a British-based electronics business specializing in LED lighting. It is headquartered in Newmarket and operates in North America, the United Kingdom and mainland Europe. It is listed on the London Stock Exchange. Table 3-6 summarizes the key characteristics for Dialight's LED products.

Table 3-6 Key characteristics of Dialight's LED products

LED product	StreetSense	DuroSite® LED Low Bay Fixture	DuroSite LED High Bay fixtures _UL	DuroSite LED High Bay fixtures _CE
Description	Street Lighting	parking decks	tunnel	tunnel
Drivers	LED driver	N/A	N/A	N/A
Dimming control modules	Photo controller receptacle only/Streetlight control module	dimming control cable pre-installed	dimming control cable pre-installed	dimming control conductor
Luminaire types	Pole/Arm Mounted - Area and Roadway	parking garage	Tunnel-Ceiling mount	Tunnel-Ceiling mount
Compatibilities	Photo controller receptacle/Dialight Street Light Control System	N/A	N/A	remote control
Life span	N/A	>100,000 hours	>100,000 hours	>100,000 hours
Warranty	7 year full performance warranty	5 year full performance warranty	5 year full performance warranty standard	10 year full performance warranty standard
Maintenance requirements	N/A	Maintenance free	Maintenance free	Maintenance free
Inrush current	N/A	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	0.6 - 1.13 sq ft.	0.6 sq ft.	N/A	N/A
Efficiency	43 - 252 Watts.	45 - 140 Watts.	124 - 270 Watts.	146 - 270 watt.
Operating voltages	100- 277 V; 347 - 480V.	100-277V	100- 277 V; 347 - 480V.	100-277V

Case study

Along the Missouri Highway 74 corridor through downtown Cape Girardeau, over 100 250W high-pressure sodium street lights require frequent maintenance and bulb changes. Officials in Cape Girardeau, Missouri decided to replace these 104 high-pressure sodium street lights with Dialight's new StreetSense™ LED street lights. The city has replaced 104 of its 250W HPS lights with the more efficient 120W Dialight LED units along Highway 74 and North Kings highway. In addition to the maintenance savings, it is estimated that the new LED units can reduce the energy consumption from about 160,000 KWH to 89,000 KWH.

3.7 Leotek Electronics

Leotek Electronics USA Corp., located in California's Silicon Valley since 1997, is a globally recognized LED lighting manufacturer. Table 3-7 summarize the key characteristics for Leotek's LED products.

Table 3-7 Key characteristics of Leotek's LED products.

LED product	ECobra-head™ LED Roadway Luminaire	EC LED Dusk-to-Dawn Area Luminaire	Arieta™ LED Area Luminaire
Description	street and roadway lighting	general area lighting	general area lighting
Drivers	N/A	N/A	N/A
Dimming control modules	Photocontrol receptacle	Photocontrol receptacle	Photocontrol for A13 and A18/ motion sensor for A13
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	Photocontrol	Photocontrol	Photocontrol
Life span	100,000 hours of life	100,000 hours of life	100,000 hours of life
Warranty	10-year limited warranty	10-year limited warranty	10-year limited warranty
Maintenance requirements	N/A	N/A	N/A
Inrush current	0.35 - 0.7 A	0.35 - 0.7 A	0.35 - 0.7 A
Illumination spectrum/ effective projected area ?	0.4 - 0.63 sq ft.	0.4 - 0.63 sq ft.	AR13: 0.47 ; AR18: 0.55 sq ft.
Efficiency	19 - 260 watts	18 - 89 watts.	AR13: 18 -172 watts; AR18: 25 - 246 watts.
Operating voltages	120-277V; 347-480V	120-277V; 347-480V	120-277V; 347-480V

Table 3-7 Key characteristics of Leotek's LED products (continued).

LED product	GreenCobra™ LED Street Light	EnduraLux™ LCN3 LED Canopy Luminaire	LCN1 Single-Skin LED Canopy Luminaire
Description	general area lighting	Entryways, and Drive-Throughs	Entryways, and Drive-Throughs

Drivers	N/A	N/A	N/A
Dimming control modules	Photocontrol receptacle	N/A	N/A
Luminaire types	Pole/Arm Mounted - Area and Roadway	Ceiling mount	Ceiling mount
Compatibilities	Photocontrol	N/A	N/A
Life span	100,000 hours of life	70,000 hours of life	60,000 hours of life
Warranty	10-year limited warranty	5-year limited warranty	5-year limited warranty
Maintenance requirements	N/A	N/A	Electrical easily accessible with three thumb/knurl screws and hinged door for future maintenance.
Inrush current	0.35 - 0.7 A	0.53, 0.7 A	N/A
Illumination spectrum/ effective projected area ?	GC1: 0.9 sq ft.; GC2: 1 sq ft.	N/A	N/A
Efficiency	N/A	104 - 208 Watts.	91, 143 Watts
Operating voltages	120-277V; 347-480V	120-277V; 347-480V	120-277V

Case study
Caltrans selected the Leotek GreenCobra™ LED luminaire to replace the high pressure sodium roadway lights on the Dumbarton Bridge over San Francisco Bay.

The GreenCobra™ features a precision micro-lens optical system designed to place light on the roadway and not waste spill light off of the bridge. This optical system provides a uniform light pattern assuring excellent visibility and improved safety on the bridge. Caltrans replaced their 400W HPS units (utilizing 465 system watts) with 183 watt GreenCobra™ LED luminaires, realizing an energy savings of over 60%. The new LED luminaires have the advantage that there is virtually no moisture intrusion to degrade the LEDs. This feature is necessary for San Francisco Bay considering its salt environment, constant vibration, and famous fog.

3.8 King Luminaire

Established in 1953, the King Luminaire is the oldest, most reliable manufacturer of spun concrete poles in North America. King Luminaire also manufactures high quality decorative outdoor lighting fixtures, fabricated metal poles, arms, and site furnishings. Table 3-8 summarizes the key characteristics for King Luminaire 's LED products.

Table 3-8 Key characteristics of King Luminaire 's LED products

LED product	K902 Centurion Luminaire	K700 Series Luminaires	K800 Series Luminaires	K580 Skyline Luminaires	K118R Washington LED Luminaire
Description	street lighting	street lighting	street lighting	street lighting	street lighting
Drivers	Electronic driver	Electronic driver	Electronic driver	LED universal dimmable driver	LED universal dimmable driver
Dimming control modules	photo button cell	photo button cell	N/A	photo receptacle	photo receptacle
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	photo control	photo control	N/A	photo control	photo control
Life span	50,000 hours	50,000 hours	50,000 hours	80,000+ hours	50,000 hours
Warranty	N/A	N/A	N/A	7 year limited warranty	7 year limited warranty
Maintenance requirements	Ease of Maintenance	Ease of Maintenance	N/A	Complete tool-less maintenance	Complete tool-less maintenance
Inrush current	N/A	N/A	N/A	0.315-0.467 A	0.292 - 0.667 A
Illumination spectrum/ effective projected area ?	1 - 1.42 sq ft.	N/A	N/A	K581: 0.48 sq ft; K582: 0.52 sq ft; K583: 0.75 sq ft; K584: 0.66 sq ft.	1.6 sq ft.
Efficiency	60 - 165 Watts.	40 - 70	60 - 165	75 - 200	40-120

		Watts	Watts.	Watts.	Watts.
Operating voltages	100-277 V	100-277 V	100-277 V	100-277 V	100-277 V; 480V

3.9 EvoLucia LED Lighting

EvoLucia LED Lighting has been existence since 2005. Table 3-9 summarize the key characteristics for EvoLucia's LED products.

Table 3-9 Key characteristics of EvoLucia's LED products

LED product	LED COBRAHEAD 40W-100W	LED COBRAHEAD 200W	LED COBRAHEAD SLIM PROFILE SERIES	LED ARCHITECTURAL SHOEBOX SERIES
Description	street lighting	street lighting	street lighting	parking and area lighting
Drivers	LED driver	LED driver	LED driver	N/A
Dimming control modules	Standard with 0-10v 10% dimming/Twist-lock photocell receptacle	Standard with 0-10v 10% dimming/Twist-lock photocell receptacle	Twist-lock photocell receptacle	Optional Photocell
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	photo control	photo control	photo control	photo control
Life span	50,000 hours	50,000 hours	50,000 hours	50,000 hours
Warranty	10 year limited warranty	10 year limited warranty	5 year limited warranty	5 year limited warranty
Maintenance requirements	N/A	N/A	N/A	N/A
Inrush current	N/A	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	0.81 sq ft.	N/A	0.7 sq ft.	N/A
Efficiency	60-100 Watts.	200 Watts.	44 - 178 Watts.	150 and 300 Watts.
Operating voltages	100-277 V; 347V; 480V	100-277 V; 347 - 480V	100-277 V; 347V; 480V	100-277 V.

Table 3-9 Key characteristics of EvoLucia's LED products (continued)

LED product	LED CONTRACTOR SHOEBOX SERIES	LED NIGHTWATCH AREA SERIES	LED Dusk to Dawn	LED PARKING GARAGE -PS14
Description	parking and area	street lighting	street lighting	parking

	lighting			lighting
Drivers	N/A	N/A	N/A	N/A
Dimming control modules	Optional Photocell	Optional Photocell	N/A	Optional Photocell
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Parking Garage / Canopy
Compatibilities	photo control	photo control	N/A	photo control
Life span	50,000 hours		50,000 hours	70,000 hours
Warranty	5 year limited warranty	5 year limited warranty	5 year limited warranty	5 year limited warranty
Maintenance requirements	N/A	N/A	N/A	N/A
Inrush current	N/A	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	N/A	N/A	N/A	N/A
Efficiency	75 and 110 Watts.	25, 50 & 75 Watts	45 Watts.	82 Watts
Operating voltages	100-277 V.	100-277 V.	100-277 V.	100-277 V.

Case study

Nearly 1100 metal halide and high-pressure sodium streetlights throughout U.S. Marine Base Camp Lejeune have been replaced with 75- and 105-watt EvoLucia™-brand LED lights, reducing energy just below 50% compared to the metal halide or sodium lights. The EvoLucia LED cobra head luminaires are maintenance-free, requiring no lamp replacements for more than 12 years of nighttime use.

3.10 Schreder Lighting

Schréder is an international lighting group, specializing in outdoor lighting and is represented in 33-countries. Since its founding in Belgium in 1927, Schréder has acquired know-how and technical expertise for a wide range of products to become a market leader. The North American facility has been serving the local market for over 10-years. Known for its superior photometric performance and quality, Schréder is the reference in lighting for: roadway, urban, flood, industrial, tunnel lighting and special applications. Table 3-10 summarizes the key characteristics for Schreder Lighting's LED products.

Table 3-10 Key characteristics of Schreder Lighting's LED products

LED product	HESTIA LED	PIANO	TECEO	AKILA
Description	street lighting	street lighting	street lighting	street lighting
Drivers	LED driver	LED driver	LED driver	LED driver
Dimming control modules	photocell/ dimming system/	photocell/ dimming system/	photocell/ dimming system/	dimming system
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	photo control / Dimming system/ complete remote Owlet management system	photo control / Dimming system/ complete remote Owlet management system	photo control / Dimming system/ complete remote Owlet management system	Dimming system/ complete remote Owlet management system
Life span	100,000 hours of life	100,000 hours of life	100,000 hours of life	100,000 hours of life
Warranty	5 year limited warranty	10 year limited warranty	10 year limited warranty	10 year limited warranty
Maintenance requirements	N/A	Both the photometric engine and the electrical power supply can be replaced on-site to take advantage of any future	The optical unit can be easily removed, allowing real on-site replacement at the end of its service life in order to take advantage	FutureProof photometric engine, easily removed and replaced to take advantage of future technological developments

		technological developments	of future technological developments.	
Inrush current	0.35; 0.5 A	0.35; 0.5; 0.7 A	0.35; 0.5; 0.7 A	0.35; 0.5; 0.7 A
Illumination spectrum/ effective projected area ?	N/A	N/A	N/A	N/A
Efficiency	53 - 75 Watts	Mini: 19 - 55Watts; Midi: 36- 123 Watts; Maxi: 80 -196 Watts.	18 - 107 Watts.	58 - 465 Watts.
Operating voltages	120-277 V.	120-277 V.	120-277 V.	120-277 V.

Table 3-10 Key characteristics of Schreder Lighting's LED products (continued)

LED product	AMPERA	ISLA LED	MODULLUM
Description	street lighting	Squares and pedestrian areas	Squares and pedestrian areas
Drivers	LED driver	LED driver	N/A
Dimming control modules	dimming system	photocell/ dimming system/	N/A
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway
Compatibilities	Dimming system/ complete remote Owlet management system	photo control / Dimming system/ complete remote Owlet management system	N/A
Life span	100,000 hours of life	100,000 hours of life	N/A
Warranty	10 year limited warranty	5 year limited warranty	5 year limited warranty
Maintenance requirements	Both the photometric engine and the electrical power supply can be replaced on-site	Both the photometric engine and the electrical power supply can be replaced on-site	Thanks to a direct access (one screw) on the rear door of each module, the maintenance

	to take advantage of any future technological developments	to take advantage of any future technological developments	operations of the modullum are very easy. The door swivels around a hinge and remains attached to the column to facilitate the technical interventions.
Inrush current	N/A	0.35; 0.5 A	0.35; 0.5; 0.7 A
Illumination spectrum/ effective projected area ?	N/A	N/A	N/A
Efficiency	Mini: 10- 55 Watts; Midi: 36- 139 Watts; Maxi: 86 -279 Watts.	19 -51 Watts.	Mini: 11 -30 Watts; Midi: 25- 54 Watts; Maxi: 26 -96 Watts.
Operating voltages	120-277 V.	120-277 V.	120-277 V.

Case study

Barreiro Retail Planet (shopping center in Canada) selected the lighting fixtures for the car parking lot to provide high quality lighting with the lowest possible energy consumption. After various comparative studies, the Piano was selected. A total of 51 luminaires equipped with neutral white 58W high-power LEDs were installed on 5 meter high posts. The lighting scheme provides energy savings of 13% in comparison with a lighting solution using a 60W HPS lamp.

3.11 Trastar

Located in Richardson, Texas, TraStar, Inc. manufactures and supplies LED related green products since 1993. Table 3-11 summarizes the key characteristics for Trastar's LED products.

Table 3-11 Key characteristics of Trastar's LED products

LED product	Tool-less Entry Cobra Head	LED Luminaire Shoebox Style	LED Parking Garage Lights	LED High Bay Light	Wal-Pak Area Lighting
Description	Street/area Lighting	Street/area Lighting	Street/area Lighting	Street/area Lighting	Street/area Lighting
Drivers	N/A	N/A	N/A	N/A	N/A
Dimming control modules	Twist-lock photocell included/ dimmable option	N/A	Dimming and Motion Sensor options available	Dimming and Motion Sensor options available	N/A
Luminaire types	Pole/Arm Mounted - Area and Roadway	Pole/Arm Mounted - Area and Roadway	LED parking lights	Ceiling Mount / Underdeck	Ceiling Mount / Underdeck
Compatibilities	Photo control	N/A	N/A	N/A	N/A
Life span	100,000 hours of life	100,000 hours of life	100,000 hours of life	100,000 hours of life	80,000 - 100,000 hours of life
Warranty	5 year limited warranty	5 year limited warranty	N/A	N/A	N/A
Maintenance requirements	Tool-less entry feature to allow for easy field maintenance	N/A	N/A	N/A	N/A
Inrush current	N/A	N/A	N/A	N/A	N/A
Illumination spectrum/ effective projected area ?	0.85 sq ft.	N/A	N/A	N/A	N/A
Efficiency	40 - 250 Watts.	85, 135 Watts.	55, 80 Watts.	150, 180 Watts.	50 -250 Watts.
Operating	120-277 V; 480 V	120-277 V;	120-277 V;	120-277	120-277

voltages		480 V	480 V	V; 480 V	V; 480 V

4 Illumination Control Technology Review

In this section, available literature, case studies, and vendor documentation for different illumination control systems were reviewed to determine operational benefits, luminaire compatibility, impacts on maintenance and efficiency and overall effectiveness of the control technology as a comprehensive asset management system.

4.1 ROAM (a subsidiary of Acuity Brand Controls)

ROAM stands for remote operation asset management. The ROAM system controls individual streetlights within a municipal area. Through building a network, system operators can view, monitor and control each individual streetlight remotely. This kind of asset management can minimize the operation costs of street lighting, and improve the efficiency. The networks of streetlights of Acuity's ROAM monitoring system are built using a radio frequency-enabled photo control. ROAM is currently compatible with many fixtures, including: HID, LED, CFL, induction, and incandescent. The ROAM system has the option to operate: 1) turn on/off or dim streetlights manually by the operator; 2) issue a scheduled operation to turn on/off or dim streetlights.

The ROAM system consists of the following components:

Table 4-1 Component of ROAM system

Component	Feature Description
Smart Photocontrols	• Commands onboard dimming control modules • Compatible with any outdoor LED, HID or other fixtures • Spacing can be up to 1000 feet apart • Provides enhanced surge protection for durability • Optional power measurement capability provides +/-2% accuracy
ROAM gateways	• Receives data and transmits commands to nodes • Communicates with up to 2000 devices, reducing installed cost • Uplinks via cellular or Ethernet communication • Mounts on pole or building
Network Operation Center (NOC)	• Receives and stores all data from Gateways • Analyzes and stores fixture data on secure data servers • Uses encryption scheme
Customer Portal	• Provides secure web-based user GIS map or dashboard graphic interface • Displays operating conditions and performance data • Controls and schedules ON/OFF/TRIM/DIM for individual fixtures or groups • Manages lighting at one or multiple sites

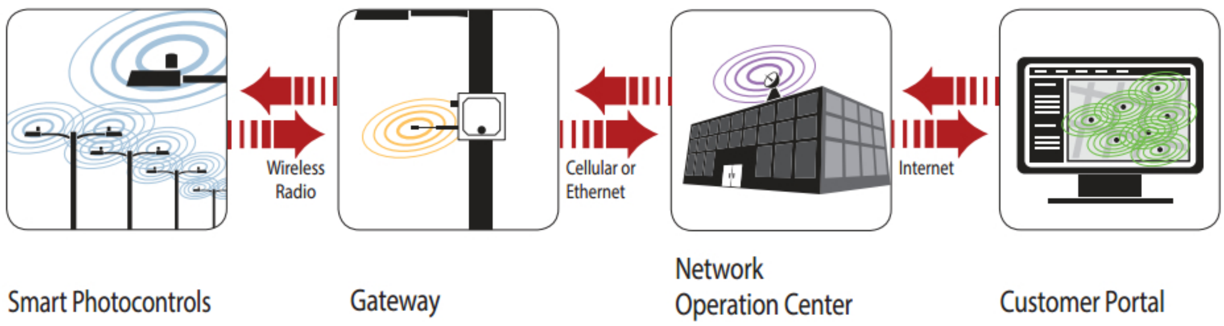

Figure 4-1 Basic system architecture diagram for ROAM system (source: ROAM Enterprise Sell Sheet)

Hardware and controls details

ROAM uses a diagnostic photocontrol (+/- 2% accuracy per ANSI C12.1 & 12.20) to collect operational information from the lighting fixture and transmit the information wirelessly to the gateway and then the NOC. The following conditions can be detected and recorded by the ROAM photocontrol.

Table 4-2 Conditions detected by the ROAM photocontrol

Condition	Description
1	Fully operational
2	Fixture malfunction
3	No communication
4	Unspecified malfunction
5	Partial report
6	Unregistered
7	No power at activation
8	Low wattage
9	Operational with issues (cycling, day burner, group control, excessive power, low voltage high voltage, high current, etc.)

The ROAM gateway collects the information from multiple nearby ROAM photocontrols. Then, the ROAM transmits information between the photocontrols within the network and the NOC through internet connection. Note that one gateway can manage 2000 or fewer photocontrols. The ROAM technology can convey dimming commands to ROAM enabled fixtures. The dimmable electronic ballast/driver and ROAM dimming control module (ROAM DCM) are integrated in the fixture. The ROAM DCM is compatible with any fixture that has a 0-10V enabled diming driver available from a ballast manufacturer. Table 4-3 summarizes the specification for the ROAM components.

Table 4-3 Specification for the ROAM components

Component	Specification
Product warranty	3 years
Design life	8 years
Annual failure rate for photocontrols	0.76%
Actual field failure rate	1%
Photocontrol wattage	1.6W, maximum = 2.2 W
Gateway wattage	5.5W, maximum = 12 W

Network design

The ROAM gateway collects the information from multiple ROAM photocontrols. ROAM nodes work at 2.4 GHz using IEEE 802.15.4 standard protocols, and have a range of 1000 feet with a clear line of sight (Shackelford et al., 2010). The gateway communicates with the NOC by using 1) cellular uplink; 2) Ethernet connection. Users can select the most economical uplink choice based on the available access and cost.

Network management interface

When using the ROAM system, users can get access to lighting data from the secure customer portal. A user ID and password are required to access lighting data from the web portal. The ROAM system can detect the following conditions: fixtures which are fully functional; fixture malfunctions; fixtures which are functioning but that have an operational issue, etc (Shackelford et al., 2010).

From the web portal, operators can command and schedule the streetlights to turn on/off or dim; archive repair, maintenance and equipment replacements records. A screenshot from ROAM’s web portal is shown in Figure 4-2.

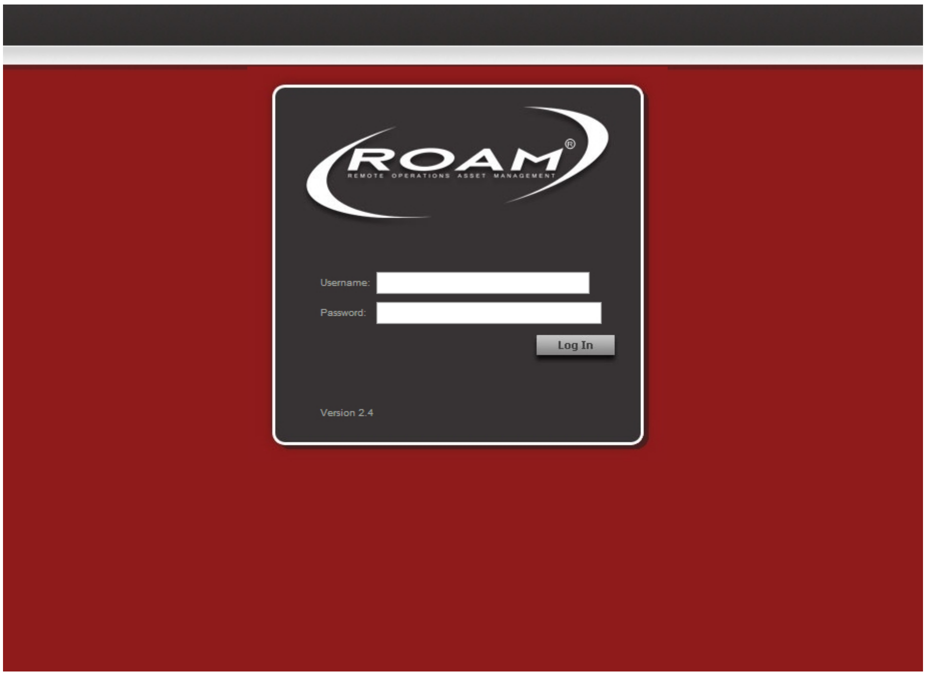

Figure 4-2 ROAM's web portal

Case studies

- In 2007, the City of New Orleans Department of Public Works installed 1,000 ROAM units in a pilot project to evaluate the technology's effectiveness.
- In 2007, 18500 ROAM photocontrols were installed in the City of Glendale, AZ. After installing the new system, the city reduced their rate of system-wide outages and malfunction from 20% of fixtures to less than 4%. ROAM nodes were installed on each streetlight fixture. During the installation, detailed information about the streetlight, including fixture location, fixture type, and wattage was recorded and entered into the ROAM system.
- The Plymouth Public School District started an energy saving program to monitor and reduce the energy consumption. The ROAM system was installed at eight of the District's 15 buildings. ROAM nodes were installed on each outdoor fixture in parking areas. 160 new LED luminaires and approximately 260 ROAM nodes were installed during the lighting upgrade program.
- Circuit of the Americas (COTA) in Austin installed 139 ROAMview control nodes across approximately 375 acres of the facility. Most of the nodes were installed on metal halide fixtures within parking lots, the main street and roadways.
- ROAM remote monitoring system was selected for the city of Austin, Texas's street lighting upgrade project. The ROAM monitoring system was selected as the control system. After completing the project, the city of Austin can control each of the 70,000 streetlights using the ROAM web portal. The ROAM remote monitoring system can approximately save more than $1,000,000 annually in combined energy and maintenance costs.

4.2 Lumewave

Lumewave provides a wireless, remote control and monitoring system for street lights, parking lot and pathway lighting. This system can improve the energy usage efficiency by using various nighttime dimming or switching profiles during evening hours, and verifying system performance for individual fixtures.

Lumewave's wireless, remote control system is compatible with LED, Induction, Plasma, eHID lighting, and standard HID. Compared with simple on/off lighting, the dimming option and adaptive controls can save energy by 40%-50% and enhance safety and security by illuminating roadways for the users. Additional public safety functions of the Lumewave's system include the ability for police to raise light levels from nearby streetlights using their onboard computers for incident clean up purpose.

Hardware and controls details

Lumewave's TOP900 series Wireless Control Modules include two products with different installation procedures: TOP900-TN and TOP900-TL. For TOP900-TN model, the threaded nipple allows for installation directly to poles, fixtures, or other enclosures by simply attaching through the ½" knock out or opening (TOP900TN, Cut Sheet). For TOP900-TL model, the module mounts to the Lumewave supplied, twist-lock photocell type connector installed either by the fixture manufacturer, or during fixture retro-fit (TOP900TL, Cut Sheet).

Both models provide a 5 mile range to devices when mounted on poles twenty feet or higher. Lumewave's TOP900 series Wireless Control Modules do not require additional penetration of the fixture.

(a)

(b)
Figure 4-3 (a) TOP900-TN model; (b) TOP900-TL model

Lumewave installs the LED fixtures with its IEEE 802.15.4 based spread spectrum wireless control modules. Lumewave uses a centralized command system to remotely control fixtures individually or by groups based on time of day and traffic patterns or simply the need to set a level as desired. Users can drop the lighting level through multi-level dimming or based on input from traffic monitors or other systems and sensors.

Network management interface

The LumeStar Software allows the user to identify and control devices installed on fixtures through the Lumewave's Gateway. Using the simple tree based drop down menus, the LumeStar software let users choose control functions and group assignments. The LumeStar Software allows the user to control devices and easily change the lighting to any level. Real time monitoring allows owners to reduce outage times. Other important functions of LumeStar software include: adjustment of photocell thresholds, additional time of day functions, scheduling of performance, failure reports and work order details. The LumeStar Program is shown in Figure 4-4.

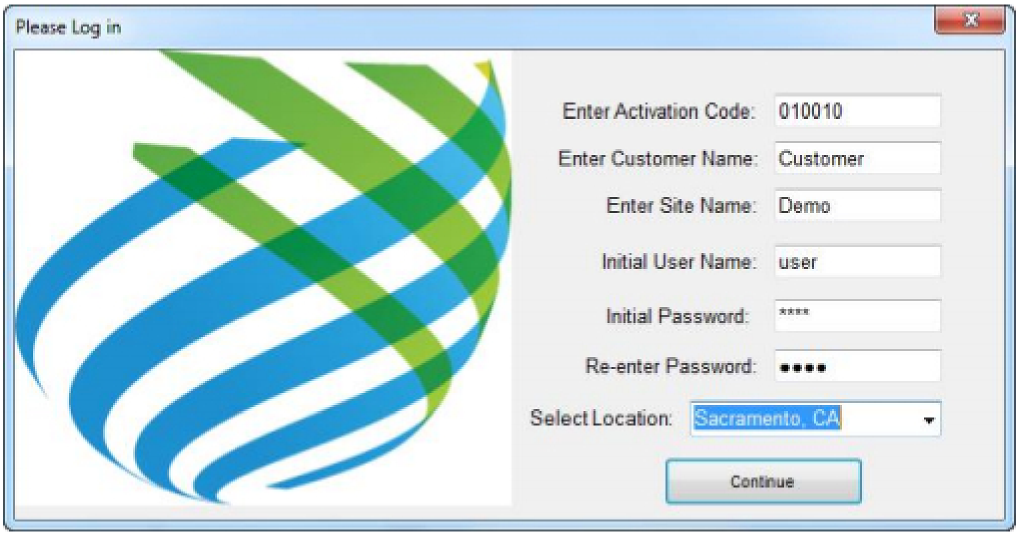

Figure 4-4 LumeStar Program

Access to detailed fixture operating functions provides information about the condition and performance of light fixtures for maintenance purpose. Thus, there is no need for maintenance personnel to drive around at night looking for streetlight outages since the abnormal fixtures are automatically detected. Figure 4-5 shows how to add control schedule.

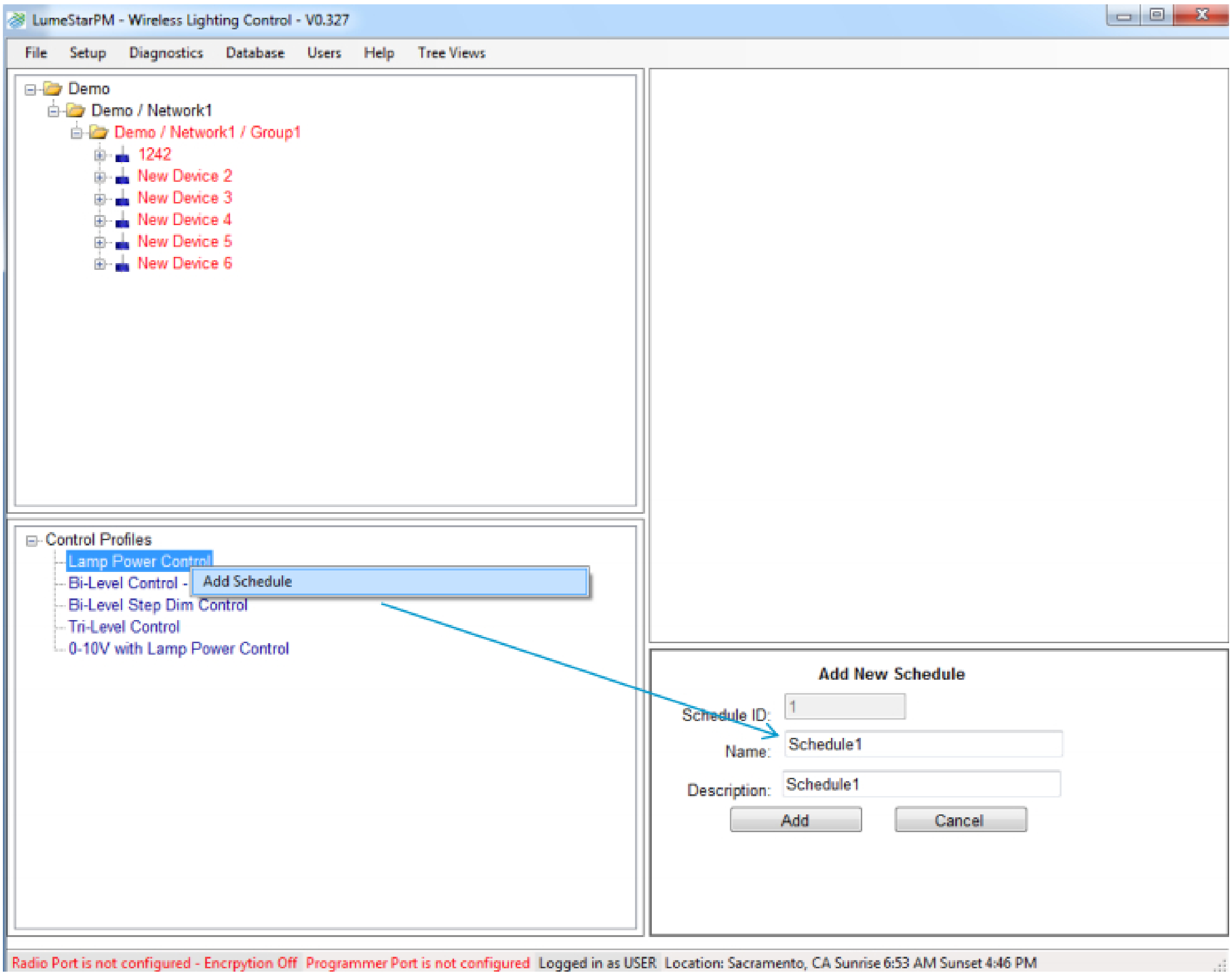

Figure 4-5 Adding control schedule in LumeStar Program

Network design

Lumewave's wireless lighting control network is assembled from three components: 1) Wireless control modules; 2) Gateway; 3) Control Software. There are some topologies that can be used: 1) Cellular to gateway (Figure 4-6); 2) Ethernet to gateway (Figure 4-7); 3) Wi-Fi to gateway (Figure 4-8); 4) USB to gateway (Figure 4-9).

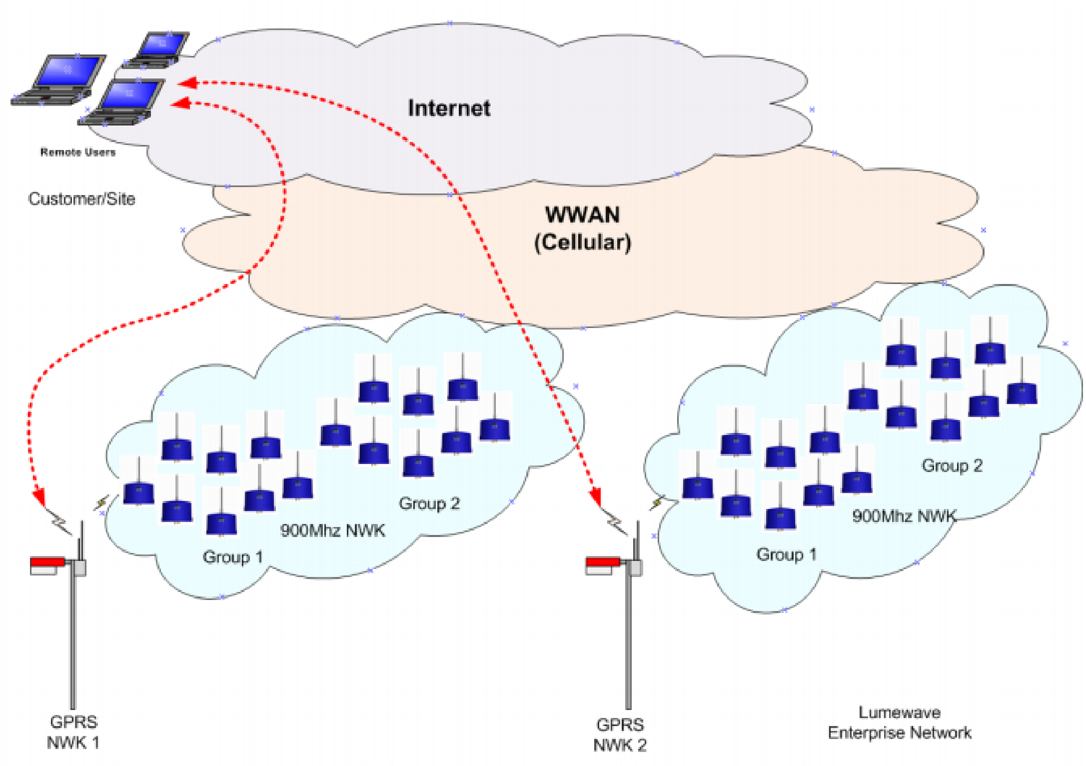

Figure 4-6 Example of Enterprise Level Network Using Cellular Gateways (Source: Lumewave Network Architecture)

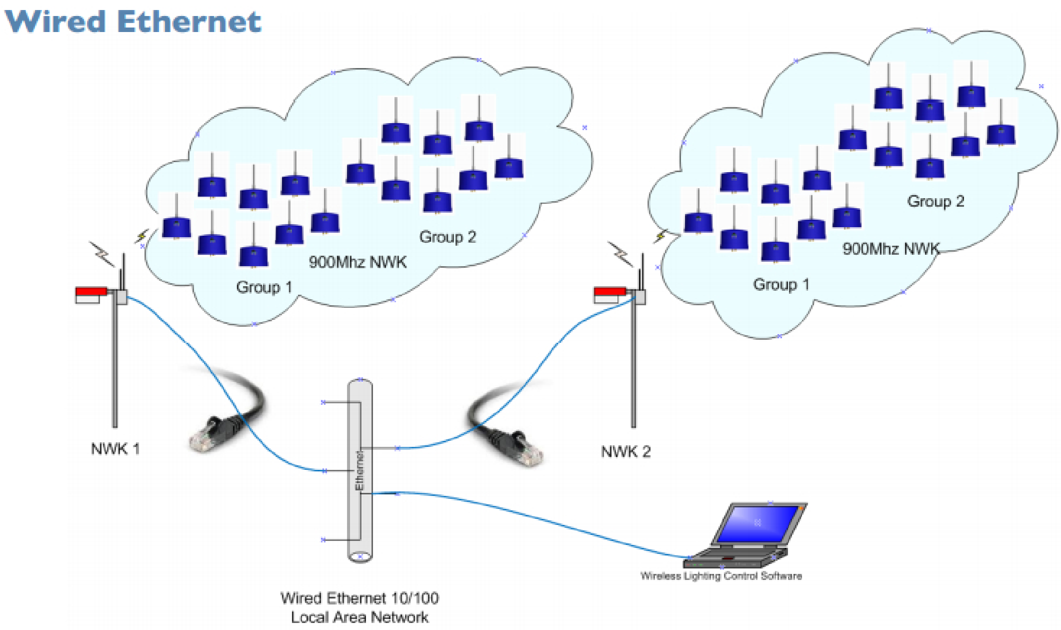

Figure 4-7 Example of Enterprise Level Network Using wired Ethernet Gateways (Source: Lumewave Network Architecture)

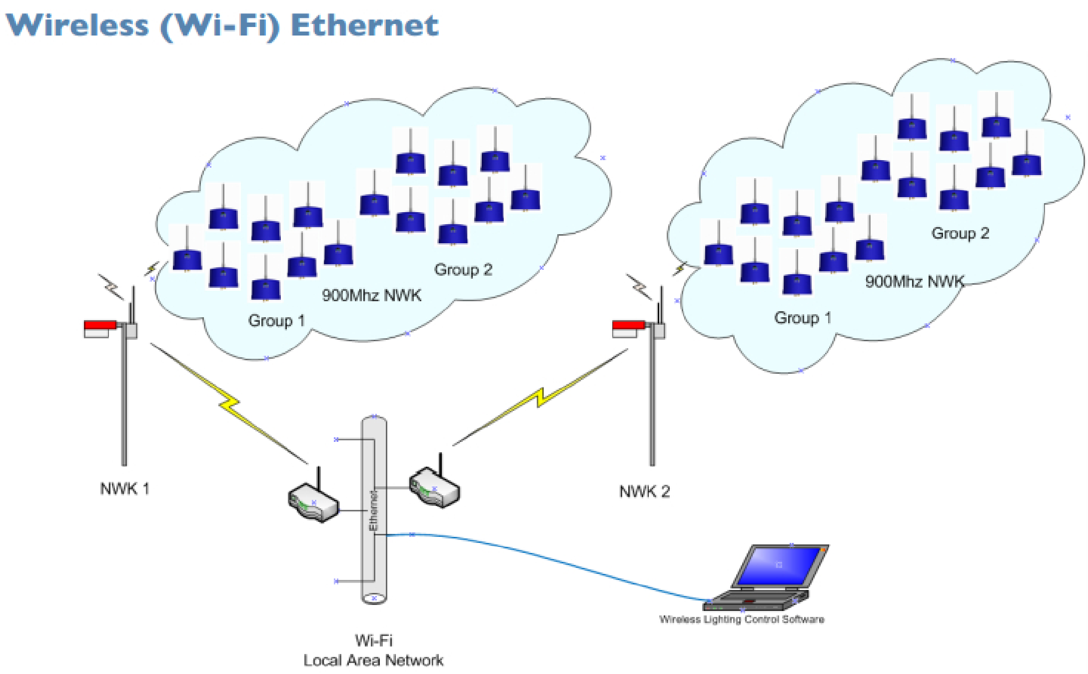

Figure 4-8 Example of Enterprise Level Network Using Wi-Fi Ethernet Gateways (Source: Lumewave Network Architecture)

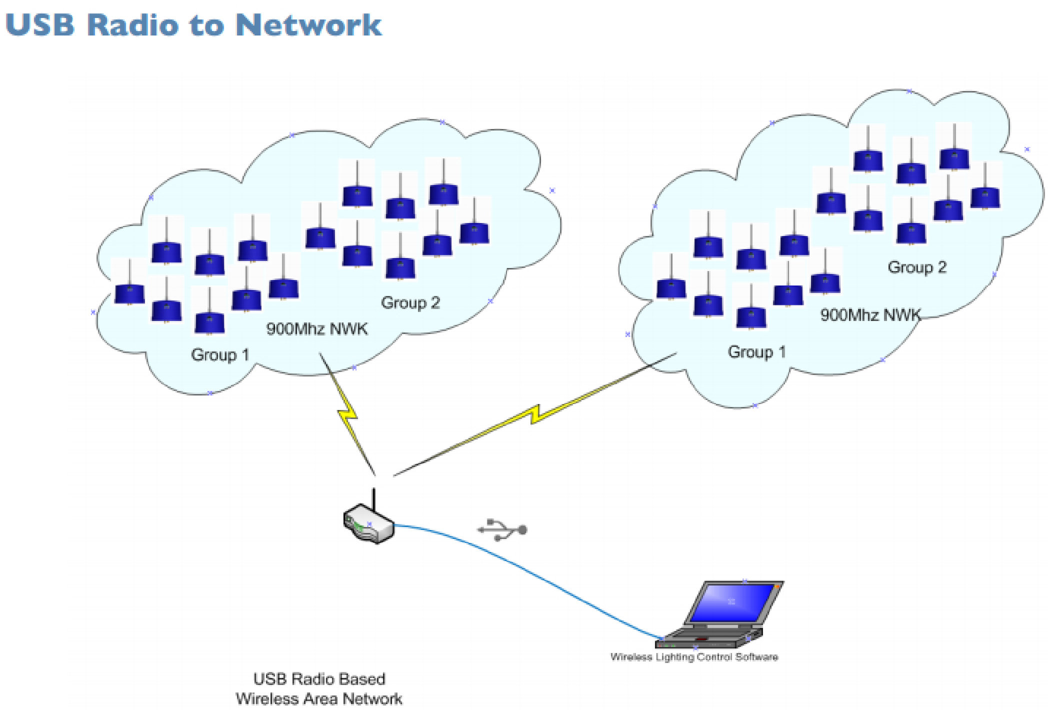

Figure 4-9 Example of Enterprise Level Network Using USB Gateways (Source: Lumewave Network Architecture)

Case studies
Lumewave was selected by the San Francisco Public Utility Commission (SFPUC) to install its system in 2 areas of San Francisco. The system was installed and managed by the SFPUC since November 19, 2013. The Lumewave system offers control access to the city's streetlights remotely from a central location and via mobile devices. The SFPUC manages and maintains over half the city's street lights (about 25,000 fixtures) and conducted a project to replace 18,500 of its high pressure sodium cobra-head style light fixtures with efficient much more LED luminaires. The Lumewave control system is designed to operate via gateways connected to a central location via LAN or Cellular and provides connection to more than 100,000 modules installed throughout a city over a wide area broadcast system.
The university of California-Davis campus installed one wireless system to control 1400+ exterior fixtures on campus. The adaptive campus control system developed by Lumewave operates a variety of adaptive fixtures, including bollards, wall packs, pathway luminaires and streetlights. The installed control system can increase the energy saving by 40%. This system installs radio frequency network and utilizes motion sensors to automatically adjust lighting.

4.3 LSI Virticus

LSI Virticus provides innovative and informative systems to control outdoor lighting systems. By utilizing the lighting control system from LSI Virticus, it is possible to reduce energy and maintenance costs by 30-50%. LSI Virticus' wireless, remote control system is compatible with LED.

Hardware and controls details

LSI Virticus uses a Rialto lighting controller to remotely manage the network lighting systems. Rialto can record the real-time power consumption, and abnormal behavior and burnt-out lamps can be detected in real time. Rialto also provides a pre-determined schedule. If the administrator loses control over the Rialto, the pre-determined schedule can enable a continuance of proper operation.

Network management interface

LSI Virticus provides the user a web-based, enterprise-class software platform to control the lighting networks across multiple physical sites. This platform is named Malibu and it can be accessed anywhere. Malibu has a detailed inventory and real-time status of a lighting network by using an advanced GPS tracking database. This software can identify network issues and electronic problems.

Network design

LSI Virticus's wireless lighting control network consists of three components: 1) Rialto controller module inside each light; 2) Ventura site manager; 3) Malibu web portal. The

Ventura site manager is a communication infrastructure which can be remotely accessed via any internet-based connection (e.g., cellular modem, cable, etc.). Each Ventura site manager can individually manage up to 3000 lights. The system architecture diagram for LSI Virticus is provided in Figure 4-10.

Figure 4-10 system architecture diagram for LSI Virticus (Source: LSI Virticus Network Architecture)

Case studies

The city of Portland, OR installed LSI Virticus' wireless control system for its streetlights to replace the photocells. The LSI Virticus system allows the city's Department of Transportation Center to observe and control streetlights located in multiple sites. Through the Malibu web portal, the system operator can see the light status and remotely adjust the levels of the lights and record the detailed energy consumption.

The West Edmonton Mall in Alberta, Canada, installed LSI Virticus' wireless control system to manage 412 120W LED fixtures. Prior to the installation of LSI Virticus system, the site consumed about 1500 KWH per day with a peak demand of 80KW. After conversion, the daily consumption reduced to 470 KWH and a daily peak of 24KW. The control system can save the energy by 375,950 KWh/year (equivalently $45,047/year).

Sports arena parking lot in San Diego, CA installed LSI Virticus' wireless control system to manage 293 LED fixtures. The control system can save the energy by 160,765 KWh/year (equivalently $30,545/year).

4.4 GE LightGrid™ outdoor wireless lighting control system

The GE LightGrid outdoor wireless lighting control system can remotely operate and monitor all the connected fixtures through a web central management system. This system has several features: 1) identify the exact location of controllers and fixtures using a GPS chip; 2) a pre-determined schedule can be programmed to enable a continuance of proper operation in case of network outage. The GE LightGrid outdoor wireless lighting control system is compatible with LED and HPS.

Network management interface

LightGrid server is a web-based interface that can be hosted remotely to record the lighting data for every fixture. LightGrid server provides real-time status of the lighting network, allows programmed/manual dimming plans, and automatically sends notifications when a fixture malfunctions.

Network design

The GE LightGrid outdoor wireless lighting control system consists of three components: 1) lighting fixture with LightGrid node; 2) LightGrid gateway; 3) server. Each LightGrid wireless gateway can control a network with up to 500 nodes. The gateway has a 500 meter line-of-sight range. The system architecture diagram for LightGrid system is provided in Figure 4-11.

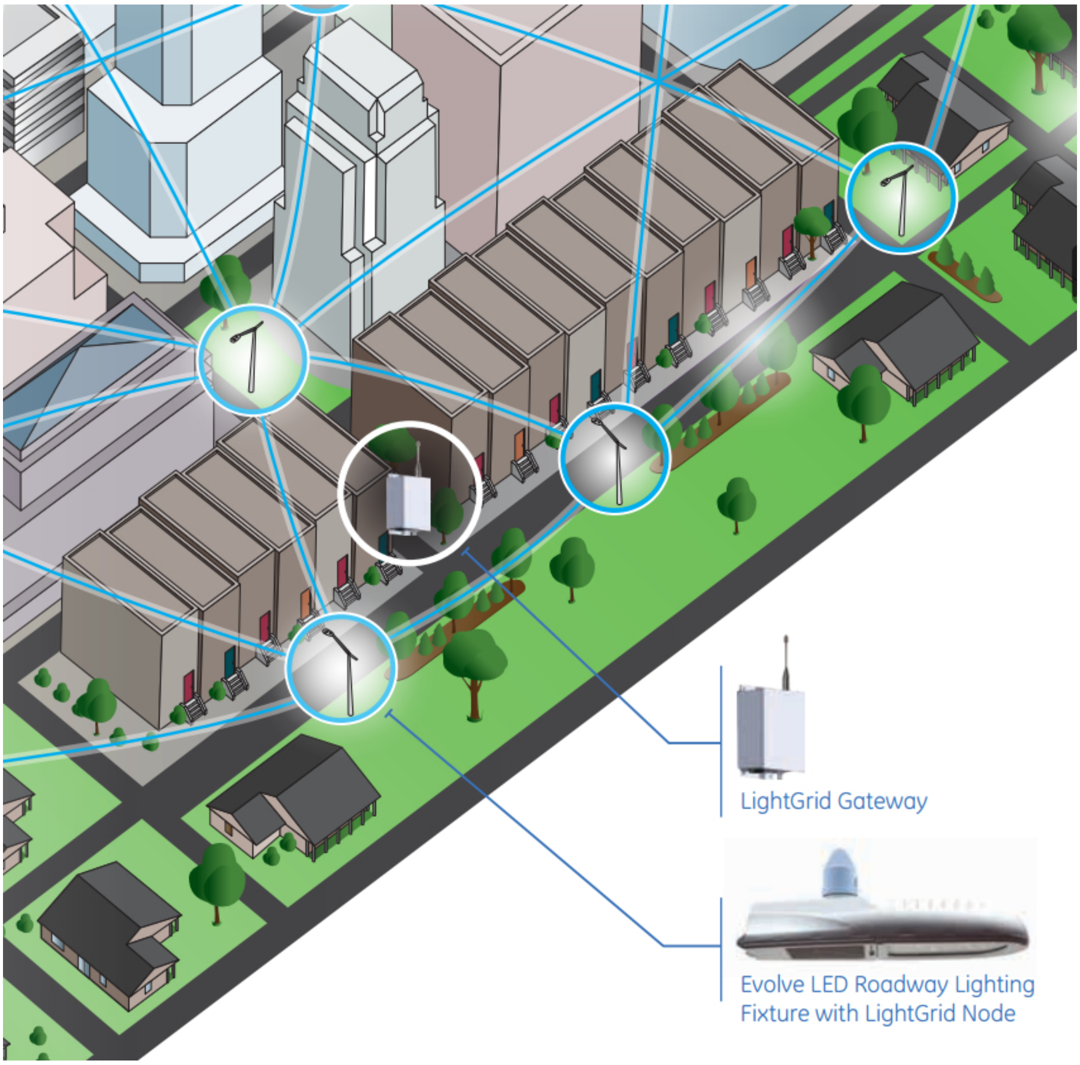

Figure 4-11 system architecture diagram for LightGrid system (Source: LightGrid system)

Case studies

The LightGrid™ Outdoor Wireless Control System was installed in San Diego to help manage the GE's Evolve™ LED lighting fixtures. Approximately 3,000 new GE lighting fixtures were installed to replace the high pressure sodium lamps save the energy cost, which is about $254,000 annually.

4.5 Echelon

Echelon's street lighting network system can remotely manage the lighting fixtures and conduct the following tasks: 1) pre-determined schedule; 2) different dimming options; 3) failure detection and maintenance tracking; 4) individual streetlight and network-level energy report. The street lighting network system uses the power line carrier technology to connect the streetlights and the network.

Hardware and controls details

To be compatible with the street lighting system, the ballast or drivers of the lighting fixtures should have the following capabilities: 1) dimmable; 2) can detect electrical failures; 3) can measure the working status; 4) can receive the dimming commands from a streetlight segment controller. Echelon's street lighting network system uses a SmartServer as the streetlight network segment controller, which can manage up to 200 streetlights through the power line carrier technology.

Network management interface

Echelon's street lighting network system can be managed and monitored using a web-based interface and streetlight monitoring system. The dimming options of the control system allow 100 to 25% of the maximum power output. For each fixture, detailed information (i.e., runtime, lamp burn hours, total energy consumption, etc.) can be recorded in the system. The overall network-wide energy consumption can be also reported.

Case studies

In 2009, the City of San Jose installed 118 55W LED streetlight to replace the LPS streetlights. The new LED fixtures are controlled using the Echelon network control system.

In China, over 16,000 lights were equipped with Echelon PLC transceivers and were managed using the Echelon energy control network system. The new control system can increase efficiency, reduce the energy cost with dimming options and lower maintenance costs.

5 Illumination Spectrum Effectiveness Literature Review

5.1 Fundamentals of visibility

There are many factors play important roles in influencing the performance of human's eyes to perceive objects while driving. These factors include the difference in photometric and color between the object and background, the glare, etc. If an object is brighter than the surrounding background, then this object has a higher probability to be perceived. The contrast (difference in photometric and color between the object and background) can be calculated using the following equation.

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

where, L_{object} = Luminance of the object

$L_{Background}$ = Luminance of the background.

Adrian (1989) proposed the concept of threshold contrast which is the probability of seeing an object 50% of the time. The value of threshold contrast depends on a number of factors, for example, the distance between the object and the eyes, the eyesight, the age, etc. Blackwell found that if the contrast is 3 times larger than the required threshold value, then the object can be clearly observed by the driver. Thus, the good contrast requires the proper installation of roadway lighting system.

Glare caused by the bright sources can impair the ability of eyes. There are three types of Glare (i.e., disability glare, discomfort glare, nuisance glare). Disability glare is a luminous haze over eyes caused by a high intensity light source. The disability glare can be minimized by an appropriate luminaires with cutoff or full-cutoff optical design. Too bright light sources in the view field can cause discomfort glare for eyes, and discomfort glare usually causes eye tears, but does not impair visibility. Very often, disability glare and discomfort glare are present simultaneously. The discomfort glare can be also minimized or avoided through improving the luminaire lighting. Nuisance glare is generally caused by an extraneous light. For example, advertising lights may distract driver's view.

5.2 Spectral properties and lighting metrics

Human eyes can see certain light with a limited range of wavelength (from 380 nanometers to 780 nanometers). Figure 5-1 shows the visible colors with different wavelengths. At days and nights, eyes have different sensitivity to some colors.

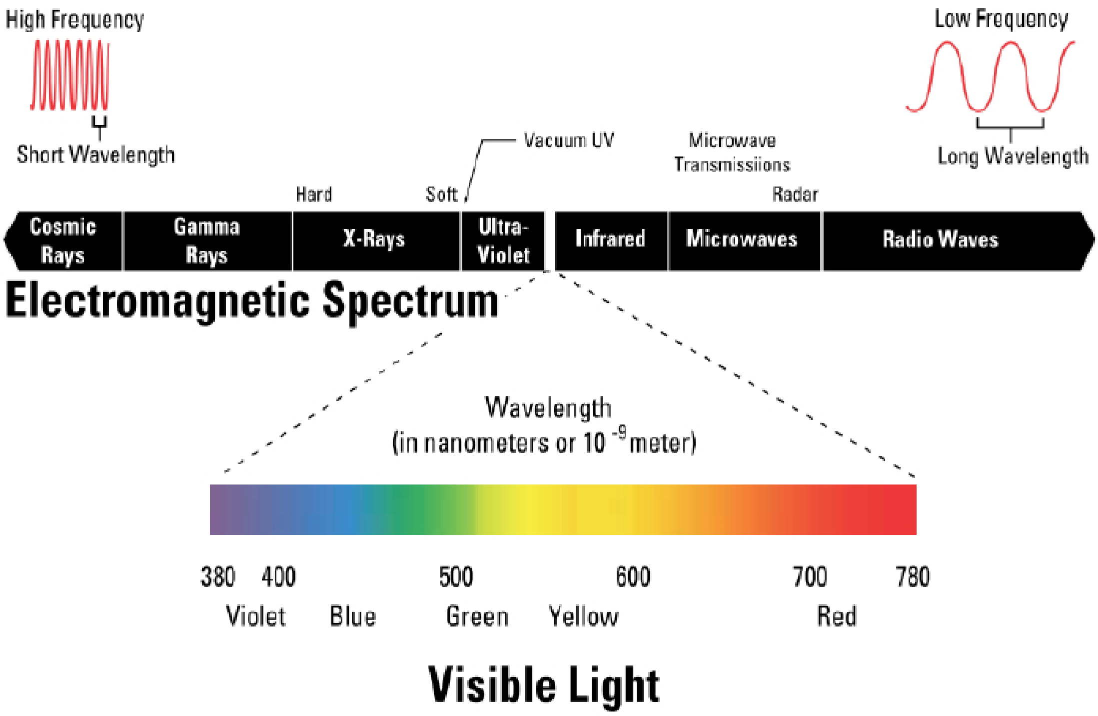

Figure 5-1 Visible Spectrum and electromagnetic radiation (source: FHWA lighting handbook)

Different lighting metrics are introduced and described in Table 5-1. These metrics include illuminance, vertical illuminance, luminance, veiling luminance ratio, etc.

Table 5-1 Definitions of different lighting metrics

Metric	Definition
Illuminance	Illumination can be defined as the amount of light on a surface. The unit for illuminance is footcandles (lumens/ square feet), which is the amount of lumens per square feet.
Vertical illuminance	Vertical illuminance can be defined as the amount of illuminance on a vertical surface. The unit for vertical illuminance is footcandles(lumens/ square feet).
Luminance	Luminance is defined as the amount of light that reflects from a surface to the observer. This term can be also referred to as the brightness of the surface.
Veiling luminance ratio	Veiling luminance ratio is defined as the maximum veiling luminance at the driver's eye divided by the average pavement luminance of roadway

Color rendering index (CRI)	Color rendering index describes how well a light source renders color compared to a reference light source of similar color temperature.
Coefficient of variation (CV)	Coefficient of variation is defined as the disparity between the actual values of all measured points and the average of those values. It measures the uniformity of all points across the test entire area. And lower coefficient of variation indicates a more uniform distribution.
Average to minimum uniformity (AMU)	This measure is the ratio of single lowest value over the average of all measured values.
Maximum to minimum uniformity (MMU)	This measure is the ratio of single lowest value over the single highest measured value.
Grid points illuminated	The percentage of total test area grid points that were measurably illuminated (> 0.05 footcandles)

5.3 Case studies about illumination levels given different illumination intensities

LED street lighting and network controls

Shackelford et al. (2009) conducted a study to examine the performance of LED luminaries with network controls in street lighting applications. In their project, 118 55W nominal low-pressure sodium (LPS) fixtures (American Electric Lighting Roadway-Area-SRX Type II fixtures) were replaced with dimmable 75W BetaLED LEDway luminaires (BLD-STR-T2-HT LEDway™ Streetlight – Type II) in San Jose, California. A 400 ft stretch of roadway was selected as the test area to compare the lighting performance under different dimming settings. The lighting and energy performance of four luminaires are summarized in Table 5-2.

Table 5-2 Lighting and energy performance of four luminaires (source: Shackelford et al., 2009)

Luminaire	Luminaire Power	Initial Lumens (luminaire)	Luminaire Efficacy (lm/W)	CCT (K)
LPS	80	5171	64.6	1800
LED (100% power setting)	75	3793	50.6	6497

LED (75% power setting)	60.3	3280	54.4	6413
LED (50% power setting)	36.2	2186	60.4	6235

In their study, the photopic and scotopic illuminance were measured at a height of 18 inch. There are 104 measurement points in an area of 390 feet × 15 feet at spacing of 180 feet and 210 feet. Illuminance was measured for the LPS luminaires and the LED luminaires at 100%, 75%, and 50% power settings.

As shown in Table 5-3, photopically, the LED at 50% generally provides smaller average illuminance than the LPS, but at 75% and 100% power level, the LED provides larger average illuminance than the LPS. In addition, all metrics (gird points illuminated, average illuminance, CV, AMU and MMU) decrease as the power setting drops from 100% to 50%. Scotopically, the LED provides larger average illuminance than the LPS and all metrics (gird points illuminated, average illuminance, CV, AMU and MMU) decrease as the power setting drops from 100% to 50%.

Table 5-3 Photopic illuminance (source: Shackelford et al., 2009)

Luminaire	Spacing	Grid Points Illuminated	Average Illuminance (fc)	Coefficient	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
LPS	180'	100%	0.24	0.51	2.4	6
LED (100% Power)		100%	0.33	0.74	3.31	10
LED (75% Power)		95.83%	0.27	0.68	2.69	7
LED (50% Power)		95.83%	0.19	0.59	1.85	5
LPS	210'	98.21%	0.2	0.52	1.93	5
LED (100% Power)		82.14%	0.26	0.93	2.63	9
LED (75% Power)		87.50%	0.23	0.81	2.27	7
LED (50% Power)		69.64%	0.13	0.95	1.34	5

Table 5-4 Scotopic illuminance (source: Shackelford et al., 2009)

Luminaire	Spacing	Grid Points Illuminated	Average Illuminance (fc)	Coefficient	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
LPS	180'	78.72%	0.1	0.65	0.96	2
LED (100% Power)		100.00%	0.72	0.72	7.19	22
LED (75% Power)		100.00%	0.59	0.68	5.92	16

LED (50% Power)		100.00%	0.33	0.63	3.25	10
LPS	210'	62.50%	0.08	0.89	0.75	2
LED (100% Power)		100.00%	0.58	0.88	5.79	21
LED (75% Power)		98.21%	0.51	0.77	5.11	16
LED (50% Power)		69.64%	0.22	1.01	2.2	9

Application assessment report on LED street lighting

Cook et al. (2008) conducted a study to compare four LED products from four different manufacturers. The objectives of their study were to examine energy and lighting performance of LED luminaires. Illuminance (photopic and scotopic), uniformity and correlated color temperature were used the measures to evaluate the lighting performance. These four LED street light products are used as a replacement for 100 Watt HPS cobrahead fixtures. The lighting and energy performance of four luminaires are summarized in Table 5-5.

Table 5-5 Lighting and energy performance of four luminaires (source: Cook et al.,2008)

Luminaire	Power	Lumens/watt	CCT (K)	CRI
LED A	58.6	54.7	6227	75
LED B	54.4	18.7	14628	74
LED C	36.7	71.2	5210	68
LED D	73.3	46.9	6052	72

A brief description of each demonstration LED product is provided in Table 5-6.

Table 5-6 Description of four LED luminaires

Luminaire	Description	Rated LED life	Warranty
LED A	Type II, full cutoff luminaire; 30 LEDs with individual clear optics below each, arranged in three, 10 LED light bars, in an aluminum housing with no enclosure.	117,000	5
LED B	Type II, full cutoff luminaire; 14 white LEDs in a specular aluminum housing with clear plastic cover.	50,000	2
LED C	Type III, cutoff luminaire; 36 LEDs in a cast aluminum housing, with a specular metal lens frame, molded gray reflector and clear plastic enclosure.	50,000	5

LED D	LED D: Type III, cutoff luminaire; 24 LEDs in 4 rows, tilted 35 degrees from vertical with individual hemispherical integral lenses and formed reflectors, housed in extruded aluminum with a specular interior.	70,000	7

In their study, 20 LED luminaires for each of four LED products were installed on four different streets. Spacing of the installed luminaires was 150 feet or 200 feet (on alternating sides of street). The height of luminaire ranges from 24 feet to 34 feet. The photopic and scotopic illuminance were measured at a height of 18 inch. There are 280 measurement points in an area of 350 feet × 45 feet. The testing beds were 38th, 41st, 42nd and 44th avenue in San Francisco and each LED luminaire was tested on one street. Note that due to variations between the test areas, the lighting performance of four LED luminaires cannot be directly compared using the measured metrics.

For LED luminaire A, the photopic illuminance and scotopic illuminance were measured at different spacing levels on 41st Ave, and the metrics were summarized in Tables 5-7 and 5-8. As shown in Table 5-7, for 150 feet spacing, photopically, LED A has smaller average illuminance, better CV and larger AMU and MMU values. For 200 feet spacing, LED A has smaller average illuminance, better CV and AMU and MMU values. Then, as shown in Table 5-8, scotopically, LED A has larger average illuminance, better CV and larger AMU and MMU values, for both 150 and 200 feet spacing. Overall, this LED luminaires can provide more uniform lighting distribution than the HPS luminaires.

Table 5-7 LED A photopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	100%	0.5	0.79	2.5:1	10.5:1
LED A (150')	100%	0.3	0.61	3.6:1	12:1
HPS (200')	73%	0.4	1.15	5.6:1	21:1
LED A (200')	92%	0.3	0.91	3.2:1	10:1

Table 5-8 LED A scotopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	100%	0.4	0.8	3.9:1	16:1
LED A (150')	100%	0.7	0.67	7.6:1	28:1
HPS (200')	67%	0.3	1.2	4.5:1	16:1
LED A (200')	91%	0.5	1.07	6.5:1	23:1

For LED luminaire B, the photopic illuminance and scotopic illuminance were measured on 38th Ave, and the measured values were summarized in Tables 5-9 and 5-10. As shown in Table 5-9, photopically, LED B has smaller average illuminance, worse CV and smaller AMU and MMU values. Then, as shown in Table 5-10, scotopically, LED B has larger average illuminance, worse CV and larger AMU and MMU values, for both 150 and 200 feet spacing.

Table 5-9 LED B photopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	100%	0.6	0.66	5.7:1	17:1
LED B (150')	63%	0.2	1.18	4.7:1	12:1
HPS (200')	76%	0.4	0.99	5.3:1	18:1
LED B (200')	51%	0.2	1.51	3.4:1	12:1

Table 5-10 LED B scotopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	100%	0.4	0.7	4.4:1	14:1
LED B (150')	71%	0.5	1.3	8.7:1	35:1
HPS (200')	72%	0.3	1.05	4.0:1	13:1
LED B (200')	51%	0.4	1.59	8.5:1	32:1

For LED luminaire C, the photopic illuminance and scotopic illuminance were measured on 42nd Ave, and the measured values were summarized in Tables 5-11 and 5-12. As shown in Table 5-11, photopically, LED C has smaller average illuminance, better CV and smaller AMU and MMU values. For Table 5-12, scotopically, LED C has smaller average illuminance, better CV, smaller AMU and MMU values.

Table 5-11 LED C photopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	100%	0.7	0.84	7.1:1	28:1
LED C (150')	99%	0.2	0.62	2.4:1	7:1
HPS (200')	63%	0.5	1.32	8.0:1	28:1
LED C (200')	72%	0.2	1.03	2.7:1	8:1

Table 5-12 LED C scotopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	94%	0.5	0.86	5.6:1	20:1
LED C (150')	100%	0.3	0.61	4.0:1	13:1
HPS (200')	57%	0.4	1.38	6.7:1	26:1
LED C (200')	73%	0.3	1.08	4.4:1	13:1

For LED luminaire D, the photopic illuminance and scotopic illuminance were measured on 44th Ave, and the measured values were summarized in Tables 5-13 and 5-14. As shown in Table 5-13, photopically, LED D has smaller average illuminance, worse CV. Scotopically, LED D has smaller average illuminance, worse CV, larger AMU and MMU values.

Table 5-13 LED D photopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	97%	0.6	0.87	5.9:1	21:1
LED D (150')	83%	0.4	0.95	5.2:1	18:1
HPS (200')	100%	0.4	1.03	4.4:1	23:1
LED D (200')	53%	0.3	1.53	5.1:1	18:1

Table 5-14 LED D scotopic illuminance (source: Cook et al., 2008)

Luminaire (Spacing)	Grid Points Illuminated	Average Illuminance (All Measured Points, footcandles)	Coefficient of Variation	Average to Minimum Uniformity (Illuminated Points Only)	Maximum to Minimum Uniformity (Illuminated Points Only)
HPS (150')	90%	0.4	0.88	4.7:1	15:1
LED D (150')	83%	0.7	1.01	10.1:1	38:1
HPS (200')	95%	0.3	1.02	3.4:1	17:1
LED D (200')	51%	0.5	1.58	10.6:1	35:1

5.4 Discussion

To decide whether the LED luminaires are feasible replacements for the existing luminaires, commonly accepted guidelines for street lighting (for example, AASHTO 2005 lighting guide) should be used. As demonstrated in the two case studies, LED luminaires generally provided more uniform and measurable illumination over a larger area than the existing HPS luminaires. Note that one limitation of HPS luminaries is that they over-light the area directly below (which is called "hotspot") in order to maintain minimum levels further away, which creates uneven lighting distribution. In this case, the MMU values should be used to evaluate the lighting performance of HPS and LED luminaires. High MMU values over the entire testing area may indicate that the increased average illuminance values are caused by hotspots for HPS luminaires. In addition to variation in photometric metrics, the LED luminaires varied greatly in other metrics such as Color Rendition Index. As tested in Cook et al. (2008), all of the four LED luminaires showed higher CRI over the base case HPS luminaires. The LED luminaire types A, B, C and D had CRIs approximately 75, 74, 68, and 72 respectively. And the reported CRI for HPS lamps was only 22.

Overall, different LED luminaries varied greatly in their lighting performance and LED products from different manufacturers should be evaluated independently. With dimming options, the LED streetlight can be remotely controlled to save some energy over the HPS streetlight. However, as all lighting metrics (gird points illuminated, average illuminance, CV, AMU and MMU) decrease as the power setting drops, careful examination should be conducted to ensure that the street lighting requirements are satisfied.

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