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Kansas Highway LED Illumination Manual: A Guide for the Use of LED Lighting Systems

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The research project was aimed to assist the Kansas Department of Transportation (KDOT) in the development of a Highway LED Illumination Manual for guiding the upcoming implementation of successful LED roadway lighting systems in Kansas to replace the existing High Intensity Discharge (HID) roadway lighting systems. A prequalified products list (PQL) of 146 LED roadway luminaires was collected and evaluated over 28 specifications. All products were then tested via computer simulations in the AGi32 software for optimized roadway layout and luminaire placement and the performance of illuminance and uniformity calculations. Based on this acceptance testing, an approved products list (APL) of 83 luminaires was compiled, which met the requirements for Kansas uses. To provide Kansas with a short list of luminaires intended to be highly recommended, this APL was further reduced to 13 standard pole and three high-mast LED luminaires based on their efficacy, technological innovation, availability of manufacturer sales representative, and payback time period for roadway implementation in Kansas. A lighting economics calculator was developed to compare the short list products to their equivalent existing HID (high intensity discharge) luminaire counterparts. This cost-benefit analysis revealed significant energy cost savings and 12-year life cycle cost savings for Kansas of approximately $18.89 to $71.22 with an average of $47.68 per year per light over their lifecycle. The calculated average payback time period was 1.5 to 7.1 years, averagely 2.9 years. Guidelines on the use of the selected LED illumination systems in Kansas cover the responsibilities of the KDOT divisions and districts, eligibility and warrant for installations, construction and maintenance, inspection and servicing, and lighting curfew. A pilot run program was also conducted to test and evaluate the selected LED roadway luminaires installed on K-10 over their useful life of 10-12 years. The new Kansas Highway LED Illumination Manual will assist Kansas in the implementation of the selected LED roadway lighting systems on the APL, especially the short-listed products that show the most potential for energy and total cost savings.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

The authors and the state of Kansas do not endorse products or manufacturers. Trade and manufacturers names appear herein solely because they are considered essential to the object of this report.

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Abstract

The research project was aimed to assist the Kansas Department of Transportation (KDOT) in the development of a Highway LED Illumination Manual for guiding the upcoming implementation of successful LED roadway lighting systems in Kansas to replace the existing High Intensity Discharge (HID) roadway lighting systems. A prequalified products list (PQL) of 146 LED roadway luminaires was collected and evaluated over 28 specifications. All products were then tested via computer simulations in the AGi32 software for optimized roadway layout and luminaire placement and the performance of illuminance and uniformity calculations. Based on this acceptance testing, an approved products list (APL) of 83 luminaires was compiled, which met the requirements for Kansas uses. To provide Kansas with a short list of luminaires intended to be highly recommended, this APL was further reduced to 13 standard pole and three high-mast LED luminaires based on their efficacy, technological innovation, availability of manufacturer sales representative, and payback time period for roadway implementation in Kansas. A lighting economics calculator was developed to compare the short list products to their equivalent existing HID (high intensity discharge) luminaire counterparts. This cost-benefit analysis revealed significant energy cost savings and 12-year life cycle cost savings for Kansas of approximately $18.89 to $71.22 with an average of $47.68 per year per light over their lifecycle. The calculated average payback time period was 1.5 to 7.1 years, averagely 2.9 years. Guidelines on the use of the selected LED illumination systems in Kansas cover the responsibilities of the KDOT divisions and districts, eligibility and warrant for installations, construction and maintenance, inspection and servicing, and lighting curfew. A pilot run program was also conducted to test and evaluate the selected LED roadway luminaires installed on K-10 over their useful life of 10-12 years. The new Kansas Highway LED Illumination Manual will assist Kansas in the implementation of the selected LED roadway lighting systems on the APL, especially the short-listed products that show the most potential for energy and total cost savings.

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Appendices available upon request to library@ksdot.org:

List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ANSI	American National Standards Institute
APL	Approved Products List
CCT	Correlated Color Temperature
CE	Conformance European
CFL	Continuous Freeway Lighting
CIE	Commission Internationale de L'Eclairage (International Commission on Illumination)
CIL	Complete Interchange Lighting
CRI	Color Rendering Index
CSA	Canadian Standards Association
DOE	Department of Energy
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
HID	High Intensity Discharge
HPS	High-Pressure Sodium
IES	Illuminating Engineering Society
IEC	International Electrotechnical Commission
KDOT	Kansas Department of Transportation
LCC	Lifecycle Cost
LEED	Leadership in Energy and Environmental Design.
LED	Light-Emitting Diodes
LZ	Lighting Zone
MH	Metal Halide
MHL	High-Mast Lighting
NEMA	National Electrical Manufacturers Association
NFL	Non-Freeway Lighting
PIL	Partial Interchange Lighting
PQL	Prequalified Products List
RoHS	Restriction of Hazardous Substances
UL	Underwriters Laboratories

Glossary

BUG rating: a quantitative measure to help prevent light trespass and sky glow, referring to Backlight, Uplight, and Glare (BUG).

cUL: Canadian certificate of UL

Energy Star: (trademarked ENERGY STAR) is an international standard for energy efficient consumer products originated in the United States.

ETL: originally a mark of ETL Testing Laboratories, now a mark of Intertek Testing Services

IES file: photometric test file of luminaires for computer simulation

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

IP rating: Ingress Protection Rating

LEED: a green building certification program that recognizes best-in-class building strategies and practices.

Lighting Zones (LZ): lighting environmental zones, including LZ1 with dark ambient lighting (e.g., state parks, recreation areas, and wildlife preserves), LZ2 with low ambient lighting (e.g., rural areas), LZ3 with medium ambient lighting (e.g., urban areas), and LZ4 with high ambient lighting (e.g., metropolitan areas).

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

Luminance: the quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction.

Luminaire efficacy: lumen/Watt, or lm/W

Useful life (L_{70}): the estimated time at which LED light output depreciates to 70% of its initial rating. This is different from the life of 50% mortality of HPS or MH lamps that burn

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Chapter 1: Introduction

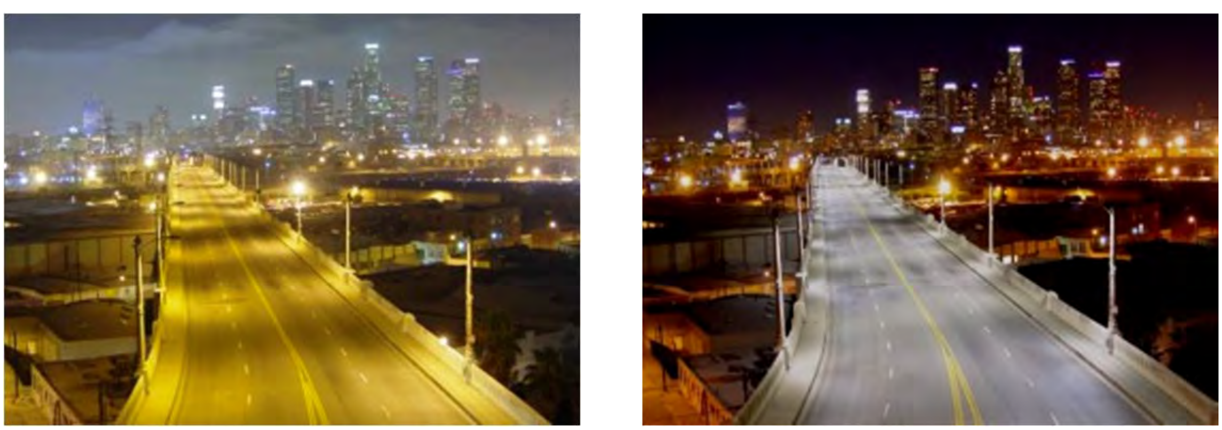
City sprawl and population growth result in an expansion of transport infrastructure. More streetlights will be installed on the roads. Over the past decade, roadway illumination systems have undergone a transformation from conventional high intensity discharge (HID) lamps to light-emitting diodes (LED). LED roadway luminaires have six major advantages over the conventional HID roadway luminaires, including useful life, luminaire efficacy, photometric performance due to the low profile of the LEDs and their directional light output that are easy to control, color rendering performance, compatibility with advanced digital controls (e.g., continuous dimming, motion sensor controls, photoelectrical controls), and environment friendliness since LEDs do not contain mercury and lead.

The LED luminaires have large energy saving potential for roadway lighting. The Department of Energy (DOE) projects that, by 2020, LED lamp efficacies will approach 170 lumens per Watt [1-3]. Meanwhile, the price of LED luminaires is dropping. The current rate of cost decline for LED lighting systems is approximately 20% every year. This cost reduction will lead to a greater market penetration, projecting LED technology to represent 48% of the lumen-hour sales of the general illumination market by 2020. By 2030, white-light LEDs will have a market share of 74% of lumen-hour sales in the U.S. and save 297 terawatt-hours in electricity consumption [1]. Based on these promising predictions, outdoor lighting energy consumption is expected to reduce by 15% in 2020, increasing to 40% by 2030 [1, 4]. This would result in a 3 quad savings, which is equivalent to 261 terawatt-hours of energy. This amount of energy is enough to provide 24 million homes across the United States with their daily electrical energy needs for the whole year use.

Reduction in electric energy consumption on road is critical for our sustainable roadway environment. The total U.S. energy-related emissions of carbon dioxide by the electric power sector in 2014 were a staggering 2,043 million metric tons—which is about 38% of the total U.S. energy-related carbon dioxide emissions [5]. Switching to LEDs over the next two decades has the potential to save the country $250 billion in energy costs [4]. This could reduce electricity consumption by 50%, thereby avoiding 1,800 million metric tons of carbon emissions.

There are already cities throughout the United States that have implemented successful LED roadway lighting systems. Los Angeles, California, is one of those. The scope of the Los Angeles project includes 4,500 miles of illuminated roads with 210,000 total roadway luminaires. Of the 210,000 luminaires, Los Angeles proposed replacing 140,000 luminaires with new LED roadway luminaires in phase one of the project. The 70,000 remaining decorative luminaires were proposed to be updated in the second phase of the project. Thirty-six (36) months after phase one implementation in 2013, Los Angeles [6] published an update on their LED roadway system with results as follows: 114,067 units replaced and $5,325,793 annual electricity savings, which totals to 63.3% electricity savings compared to the pre-existing high-pressure sodium (HPS) roadway lighting system. Before the new LED roadway lighting system was implemented, the HPS repair and maintenance events numbered 70,000, which fell to 46,300 after the LED implementation. Also, the failure rate of LED luminaires after 36 months was 0.2% compared to the HPS luminaires, which had a failure rate of about 10%. Based off this information, Los Angeles expects to save $2.5 million on annual maintenance costs.

Not only did the new LED roadway lighting system save money, it was also safer. The conversion was reported by Los Angeles citizens to have improved visibility, and was positively encouraged by the police department after a noticeable decrease in crime rate. Figure 1 shows the aesthetic differences of the pre-existing HPS lighting system versus the new LED lighting system, and the improved visual properties are very evident.



HPS LED

Figure 1: Visual Comparison of HPS vs. LED Lighting
Source: [6]

Los Angeles is not the only city to have implemented successful LED roadway lighting programs. More and more cities across the U.S. are adopting these systems. Pretty soon, based on the projections, LED roadway lighting is going to be the norm rather than the trendy innovation. Street lighting can account for up to 40% of a city's electricity bill. It is expected that, by 2030, LEDs will replace all HID lamps used on highways and in all other transportation illumination systems, resulting in significant reduction in electrical energy consumption and maintenance costs.

As a result, more and more LEDs will be mounted on roads in Kansas. If Kansas were to adopt an LED roadway lighting system, they would be doing their part to decrease emissions as well as save money that could be utilized elsewhere. This project is intended to help the State of Kansas Department of Transportation (KDOT) realize a new LED roadway lighting system.

The current KDOT lighting handbook that deals with HID luminaires is no longer useful for guiding new or retrofit roadway lighting projects that deploy LED luminaires. Kansas needs a highway LED illumination manual to evaluate the cost-effectiveness of the LED roadway lighting systems in Kansas, judge their eligibility and warranty, guide the selection and use of LED luminaires, and lower the maintenance costs. Many LED vendors and sales representatives have approached the Kansas Department of Transportation (KDOT) for their LED roadway lighting products. A new highway LED illumination manual is thus needed in Kansas.

Chapter 2: How to Use This Manual

This highway LED illumination manual was prepared for guiding the use of selected qualified LED lighting systems, with a short list of highly recommended products, for not only replacing the conventional high-intensity discharge (HID) roadway lights with LEDs in retrofit projects but also new constructions of LED lighting projects in Kansas. The lighting specialists, highway engineers, designers, planners, maintenance crews, and policy makers in the Kansas Department of Transportation (KDOT), local counties, and cities in Kansas may use this manual to guide their selection of LED roadway lighting products, their technical specifications, lighting design and layout, lighting curfew, field construction and maintenance, inspection and servicing, and cost-effectiveness evaluation, etc.

The manual can be divided into five major parts, as follows.

1. Fundamentals of LED roadway lighting technologies, design and layout, and lighting criteria.
2. Selection of qualified LED roadway lighting systems, an approved products list (APL), with a short list of highly recommended products, for Kansas roadways.
3. Potential payback evaluation and a lighting economics calculator.
4. Guidelines on using the selected LED illumination systems in Kansas.
5. A pilot run program.

The LED technologies are upgrading on a daily basis. Although this manual focuses on guiding the selection and installation of LED roadway luminaires currently available in the U.S. market as of 2015 for uses on roads in Kansas, the underlying principles and the proposed methods and techniques for testing and selection of qualified LED lighting products as well as their cost-effectiveness analysis can be continuously used for evaluating future LED products. However, with upgrading LED market over time, it is reasonable to assume that an update and reaffirmation is necessary over a reasonable period of time, e.g., 10 years (or at the end of the 12-year life cycle of current LED lighting products), when the LED technologies have undergone break through changes.

In addition, the manual can be used as training materials for any personnel involved in new and retrofit LED roadway lighting projects in Kansas. A highway LED illumination training course on this manual will be offered in the end of this project for lighting specialists, highway engineers, designers, planners, maintenance crews, and policy makers in KDOT and local counties and cities in Kansas who are involved with highway illumination.

On the other hand, while this manual presents many useful outcomes, it is important to understand that those outcomes are based upon some assumptions. Every LED roadway project is inherently different, and without knowing the specific details of the project that KDOT or local cities plan to undertake, this manual is intended to guide through the decision-making process in general, rather than present a cut-and-dry design solution. The lighting economics calculator developed in this project in particular was designed to allow changes of the design input, to tailor the cost-benefit analysis for any project in time to come.

The assumptions and limitations of this project are outlined below, which contribute to possible variations on how to use this manual:

- The size of the actual project that KDOT or the local county/city plans to undertake is unknown. If the project is too small, it might not have the same benefits as larger-scale projects, as suggested in this lighting economics calculator using a project size of 1,000 luminaires.
- The manual was prepared in a general and compressive way. It is limited by the overwhelming number of photometric test files (called IES files) of LED roadway luminaires on the market that haven't been tested. Acceptance testing was mainly based on four optimized roadway layouts of standard poles and high-mast lighting at intersections using standard luminaire spacing solutions, and attempted to cover all common roadway lighting plans.

- The lighting economics calculator was based on an assumed electricity and demand rate, energy-savings rebate rates were not taken into account, which could have the potential to save even more money. Other assumptions used in the calculator were based upon research studies of projects in other states, and standard costs according to RS Means. The variability of those assumptions with the actual KDOT project has the potential to effect the results in small ways, if not significantly.

Chapter 3: LED Roadway Lighting in General

3.1 LED Technology and LED Roadway Luminaires

As a solid-state lighting source, LEDs have the following five unique characteristics that other artificial light sources do not have.

a. Compared to traditional HID light sources used on roadways, LEDs are very energy efficient. The energy efficacy of LEDs available in the market as of 2015 is in a range of approximately 70-150 lumens per watt (lm/W), versus 71-145 lm/W of high pressure sodium (HPS) lamps, and 67-115 lm/W of metal halide (MH) lamps. In addition, the efficacy of LEDs is still increasing with the upgrade of the LED technologies.

b. An LED is a tiny and bright point light source, which can fit in a small space, e.g., light-emitting surface of the roadway luminaires. This small profile can benefit the LED roadway luminaires for more accurate photometric performance and reduced overall size.

c. LEDs generate light towards the forward direction. LEDs also generate a large amount of heat that is not radiated with the light but remains on the back of the diode itself. Traditional light sources generate light and heat in mixed energy flux towards the same direction. The LED heat will be conducted using heat sink and dissipated to the air.

d. While an LED’s light output is not as temperature sensitive as fluorescent, LEDs run most efficiently at a junction temperature less than 120°C. The lower the ambient temperature, the more efficient the LEDs. High ambient temperatures must be taken into account in the luminaire design for heat sinking. Humidity and dirt conditions of the environment must also be considered.

e. Most LEDs define their useful life (L_{70}) based on the estimated time at which LED light output depreciates to 70% of its initial rating. This is different from the life of 50% mortality of HPS or MH lamps that burn out.

Due to the unique characteristics of LEDs aforementioned, LED roadway luminaires also have unique characteristics that are different from the HPS roadway luminaires. LED roadway luminaires have six major advantages over the HPS luminaires, including:

a. High energy efficiency, which still increases over time with new improvement on LED technologies. Over next decade, the LED efficacy is predicted to reach approximately 219 lm/W by 2020 [7]. Such a high efficacy will enable a significant energy saving for highway LED illumination.
b. Long useful life L_{70} (typically 50,000-100,000 hours as of 2015), over which the light output of the LEDs gradually drops to 70% of the initial lumen. Note that the LEDs do not burn out at the end of its useful life, with still 70% light output remaining.
c. Good photometric performance due to the low profile and directional light output of the LEDs, which can effectively deliver more light to the demanded road surfaces while reducing light spill to the sky and the surrounding environment.
d. High color rendering performance (typically CRI is 70+ as of 2015). LEDs used for road lighting may eventually have CRI greater than 90, similar to those LEDs used inside the buildings.
e. Compatibility with advanced digital controls, e.g., continuous dimming controlled by occupancy sensors or photosensors to save energy while enhancing roadway safety.
f. Environment friendliness without harmful components like mercury and lead. Also, if well controlled, LED roadway luminaires do not produce light pollution to the sky and light trespass to the neighborhood.

On the other hand, LED roadway luminaires available in today's market may still have slightly higher initial cost than the conventional HPS luminaires. However, while the efficacy of LED luminaires is increasing, their cost is dropping. It is expected that LED roadway luminaires may be more affordable in the near future. Additionally, LED luminaires can reduce the costs in energy consumption and maintenance over their service life, which will offset the initial costs.

3.2 Typical Specifications of LED Roadway Luminaires

Many manufacturers are available in the U.S. market to provide LED roadway lighting systems, including luminaires and controls. Example manufacturers include Holophane, Philips, Acuity, Cooper, GE, Hubbell, Cree, Cree Canada, HE Williams, Kenall Manufacturing Co., LSI Industries, Sternberg Lighting, Zenaro Lighting Inc., American Electric Lighting, Selux, Stanpro Lighting Systems, Lumca, Tersen Lighting, Sentry Electric LLC, LED Roadway Lighting Ltd., Excellence Opto Inc., Green Image Tech, RAB Lighting, Lighting Science, Arani, and Sansi.

Table 1 summarizes the typical 28 specifications of LED roadway luminaires available in the current market of 2015, including voltage, current, wattage, dimensions, weight, lens, mount style, pole height, arm length, number of luminaires per pole, initial lumen, efficacy, CCT, CRI, light lateral distribution, cutoff, BUG rating, sensors, control technology, certificate, IP rating, useful life, etc., and their typical values.

Table 1: Typical Specifications of LED Roadway Luminaires as of 2015

Items	Specifications
Voltage (VAC)	120 – 277, 347 – 480
Drive current (mA)	350 – 2100 or more for low (dimmed) and high output
Wattage (Watts)	70 – 560 or more
Luminaire dimensions (L x W x H) (inches)	Various, e.g., 23.0 x 23.0 x 23.0, 26.5 x 18.3 x 6.3, 23.0 x 17.6 x 5.3, 25.5 x 25.5 x 42.2, 23.0 x 23.0 x 11.5, 15.9 x 11.0 x 4.1, 23.3 x 11.0 x 4.4, etc.
Luminaire weight (lb)	7.5 – 276
Lens	Glass materials, or polycarbonate, acrylic, or optical grade polymer materials, either clear or frosted, flat or in other shapes.
Mount style	Post-top or side-arm, most of them are armed mounted
Pole height (if post-top mounted) (ft)	8-40 or more for standard poles, 100-140 or more for high-mast lighting
Arm length, horizontal (not including luminaire length unless specified) (mm)	Various, e.g., 60, 65, 82, 90, 100, 130, 203, 254, 305, 521, 533, 622, 625, 634, 710, 748, 826, 1095, 1220, 1273, 1321, 2440, etc.
Luminaires per pole	Often 1-4, occasionally up to 6-10 for high-mast lighting
Number of LED modules per luminaire	Various, e.g., 2-7, 11, 14, 20, 30, 32, 36, 64-128, 136, 140, 160, etc.
Initial lumen (lm)	1600 – 34000
Efficacy (lumen/Watt)	50 – 140
Typical CCT (correlated color temperature) (K)	2700, 3000, 3500, 3800, 4000, 4100, 4500, 5000, 5250, 5600, 5700, 6000, 6200, etc.
CRI (color rendering index)	65 – 82, most of them are 70
Light lateral distribution	Type I, II, III, IV, V, and VS
Cutoff classification	Full cutoff, a few of them are cutoff
BUG rating	For standard poles roadside lighting, the best BUG rating is B0-U0-G0, while the worst bug rating is B5-U5-G5. For high-mast lighting, the best BUG rating is probably B3-U0-G0 for certain amount of backlight without causing glare and light pollution, while the worst BUG rating is probably B5-U5-G5
LED driver manufacturer	Various
Driver model #	Various
Dimming or non-dimming	Most of them are smooth continuous dimming for both constant-current and constant-voltage sources. A few are non-dimming
Sensor mount location	On luminaires or pole
Sensor types	Nearly all of the LED roadway luminaires come with photosensors for controlling the activation of the lights at dust and dawn. They may also be equipped with motion/occupancy sensors and temperature sensors, drive current sensors, voltage sensors for surge protection
Control technology	Thermal controls and energy saving control options, or photoelectric controls, surge protectors, photocontrols, heatsink, shorting caps
Coverage pattern	Rectangular or circular 360°
Luminaire certificate	UL, cUL, CSA, ETL, 3G, 4G, IC, IDA, DLC, RoHS, FCC, CE, Pb, HG, etc.
Luminaire IP rating	At least IP65, IP66, most of them are rated IP67
Luminaire life L_{70} (hours)	50,000-350,000, most of them are in a range of 60,000 – 100,000 in the current (2015) market

More details of the specifications are expounded as follows.

3.2.1 Wattage

Wattage of the LED roadway luminaires is the SI unit of power, equivalent to one joule per second. LEDs require less power to operate. Therefore, the corresponding wattage of LED roadway luminaires is a lot lower than that of the conventional HPS roadway standard pole and high-mast lighting luminaires commonly used on Kansas roads.

As shown in Table 1, the LED roadway luminaires available in the current market run on different voltages, typically from 120-277 or 347-480 VAC. The drive current also varies approximately from 350-2100 mA or more for low (dimmed) light output or high output (non-dimmed). The wattage of the LED roadway luminaires available in the market is in a wide range of 70-560 Watts or more.

3.2.2 Dimensions/Weight

For each LED roadway luminaire, it is important to record its dimensions and weight as input information for shipping, field installation, and maintenance. Typically, the bigger and heavier the luminaire will result in a higher cost for shipping and installation costs up front. LEDs are tiny and bright light sources, thus, LED roadway luminaires could be made much smaller than the HPS luminaires without compromising their photometric performance.

The LED roadway luminaires available in the current market have different sizes, e.g., 23.0” x 23.0” x 23.0” (584 mm x 584 mm x 584 mm), 26.5” x 18.3” x 6.3” (674 mm x 466 mm x 161 mm), 23.0” x 17.6” x 5.3” (584 mm x 447 mm x 135 mm), 25.5” x 25.5” x 42.2” (648 mm x 648 mm x 1072 mm), 23.0” x 23.0” x 11.5” (584 mm x 584 mm x 291 mm), 15.9” x 11.0” x 4.1” (404 mm x 280 mm x 104 mm), 23.3” x 11.0” x 4.4” (591 mm x 279 mm x 111 mm), etc. The weight of the luminaires also varies from 7.5-276 pounds.

3.2.3 Lens

A lens is necessary for all roadway luminaires for better light distribution on the road pavement. Because of the tiny size of LEDs and their directional light output, LED roadway luminaires by design do not need a big Sag lens (Figure 2) commonly seen in HPS roadway luminaires to cover the whole cobra head. Most LED roadway luminaires use small individual lens covering each LED, or a whole piece of flat lens (Figure 2) to cover the entire light-emitting surface of the LED luminaire. Flat lenses are flush with the outside metal casing, while sag lenses drop below. The different sag choices allow for different distribution angles.

Sag lens   Flat lens   Individual lens on each LED module

Figure 2: Different Types of Lens Commonly Specified in the Current Roadway Luminaires

The lens of the LED roadway luminaires may be glass, polycarbonate, acrylic, or optical grade polymer materials, either clear or frosted, flat or in other shapes. Most luminaires available in the current market specify acrylic or polycarbonate lenses. These lenses prove to be more durable than the traditional glass lenses. There are also some lenses in the list that are specified as prismatic. Prismatic lenses provide economy and efficiency but only limited control of light distribution—the majority of the light is directed downward within a given distribution, but a portion of the light is refracted into the higher angles.

3.2.4 Mounting, Pole Height, Arm Length

The mounting style of the LED luminaires includes post-top or arm mounted, and most of them are arm mounted. Nearly all LED roadway luminaires are specified on poles with varying arm lengths, as shown in Figure 3. The pole height and arm length vary between luminaires, especially between standard versus high-mast luminaires. The arm length is the dimension from the pole to the luminaire, which helps place the light closer to the target surface—the road pavement. The mounting of roadway luminaires is fairly standard, with the head of the luminaire facing directly towards the ground, illuminating the roadway. Figure 4 also shows the high-mast lights lowered to the ground level for re-lamping.


Long arm [8]


Pole top [9]

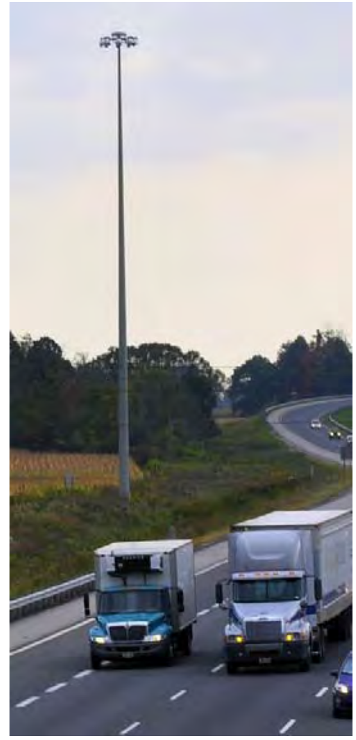

High-mast lighting [10]

Figure 3: Different Mounting of Standard and High-Mast LED Roadway Luminaires

Figure 4: Technicians Lower the High-Mast Lights to the Ground Level for Re-Lamping
Source: [11]

Dimensions vary based on the luminaire. The arm length is in a range from 2.4” (60 mm), 2.6” (65 mm), 3.2” (82 mm), 3.5” (90 mm), 3.9” (100 mm), 5.1” (130 mm), 8.0” (203 mm), 10.0” (254 mm), 12.0” (305 mm), 20.5” (521 mm), 21.0” (533 mm), 24.5” (622 mm), 24.6” (625 mm), 25.0” (634 mm), 28.0” (710 mm), 29.4” (748 mm), 32.5” (826 mm), 43.1” (1095 mm), 48.0” (1220 mm), 50.1” (1273 mm), 52.0” (1321 mm), and 96.0” (2440 mm). The standard pole height of the LED luminaires is 8-40 feet or more, typically 40 feet in Kansas. For high-mast lighting, the pole height can be 100-140 feet, typically 100-120 feet in Kansas.

3.2.5 Luminaires per Pole and LEDs per Luminaire

Most luminaires specify just one luminaire per pole. However, some specify two luminaires per pole to accommodate median roadway lighting for two roads. Also, there are options available for some intersections to have four luminaires per pole, but these are more common in parking areas and are not very common in roadways. In conclusion, on each pole, there might be one to four LED lights mounted for roadway lighting for both standard poles and high-mast towers. Occasionally, there might be six to 10 LED lights for high-mast lighting. In Kansas, most standard poles have only one luminaire, and often three fixtures symmetrically mounted on the top of a high-mast tower.

The number of LEDs per luminaire varies widely in the LED roadway luminaires available in the current market. The more LEDs that are in an array, the higher the resulting lumen output will be. Some LEDs specify the number of LEDs per chip, and have multiple chips in a single luminaire. In general, the number of LEDs per luminaire ranges from 2-160 and even more, including several (2-6), 7, 11, 14, 20, 30, 32, 36, 64, 68, 80, 84, 96, 104, 120, 128, 136, 140, 160 and more LED modules in the roadway luminaires available in the current market.

3.2.6 Initial Lumens

Initial lumen output is the amount of light output from a lamp (i.e., initial lamp lumen) or a luminaire (i.e., initial fixture lumen) when it is brand new. A lumen is the SI unit of luminous flux, a measure of the total “amount” of visible light emitted by a source, equal to the amount of light emitted per second weighted against the spectral sensitivity (luminous efficacy) of the human eye. The initial lumen of the LED luminaires available in the current market as of 2015 is in a range from 1,600-34,000 lumen.

3.2.7 Luminaire Efficacy

The efficacy of LED roadway luminaires is measured as the total initial fixture lumens per Watt (lm/W). Compared to traditional HID roadway luminaires commonly used on roads in Kansas, LED roadway luminaires are very energy efficient. When comparing the efficacy for LED and conventional products, it is vital to consider the system as a whole. The efficacy of LED roadway luminaires considers the entire lighting system including driver, thermal, and optic losses. The average efficacy of LED roadway luminaires was around 80 lm/W in mid-2013, but is now closer to 100 lm/W, according to the U.S. Energy Information Administration. In the current market of 2015, the efficacy of LED luminaires is in a range from 50-140 lm/W. Moreover, LED roadway luminaires is expected to make substantial increases in efficacy in the near future when the LED efficacy is predicted to reach 219 lm/W over the next decades [7].

3.2.8 Correlated Color Temperature (CCT)

CCT stands for correlated color temperature and is measured in Kelvins (K). CCT is single number that is a measure of light source color appearance defined by the proximity of the light source's chromaticity coordinates to the blackbody locus. CCT can be found by extending an isotemperature line from the blackbody locus out to the chromaticity coordinates of the source. The CIE 1976 chromaticity diagram shown in Figure 5 shows six isotemperature lines commonly used by the LED manufacturers. The correlated color temperature (CCT) of the LED roadway luminaires available in the current market typically uses 2700K, 3000K, 3500K, 3800K, 4000K, 4100K, 4500K, 5000K, 5250K, 5600K, 5700K, 6000K, 6200K.

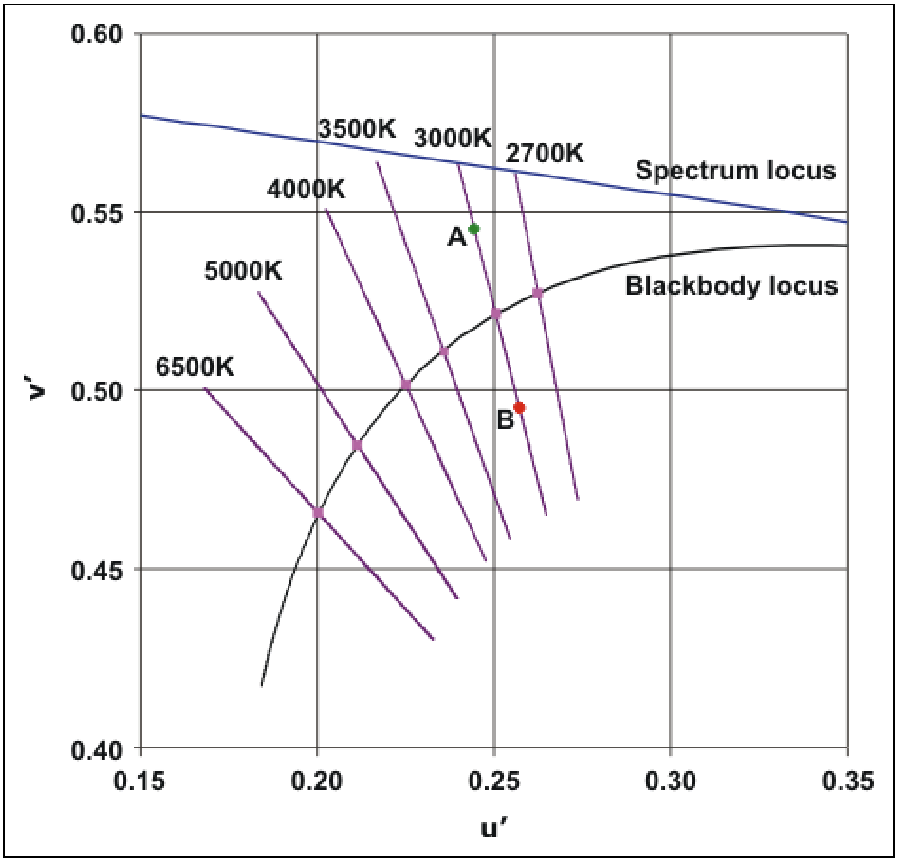


Figure 5: The CIE 1976 Chromaticity Diagram Showing Six Isotemperature Lines Commonly Used by the LED Manufacturers
Source: [12]

Also, as seen in Figure 6, a higher CCT color temperature in Kelvin results in a light that is "cooler," casting a cool light toward the bluish end on objects, while a lower CCT color temperature in Kelvin results in a light that is "warmer," casting a warmer light toward the yellowish end on objects. Most LED roadway luminaires cast a much cooler light on the road pavement compared to conventional HPS lights which emit yellow light, as shown in Figure 7.

On the other hand, the cool white LED roadway lights have spectrum that contains more short wavelength ("blue") light component which will largely enhance the mesopic vision of roadway environment at night under low light levels (e.g., 0.5-1 fc). As a result, the drivers and pedestrians can actually see better under the LED lighting even at the same light levels on the pavement as that under the conventional HPS lights.

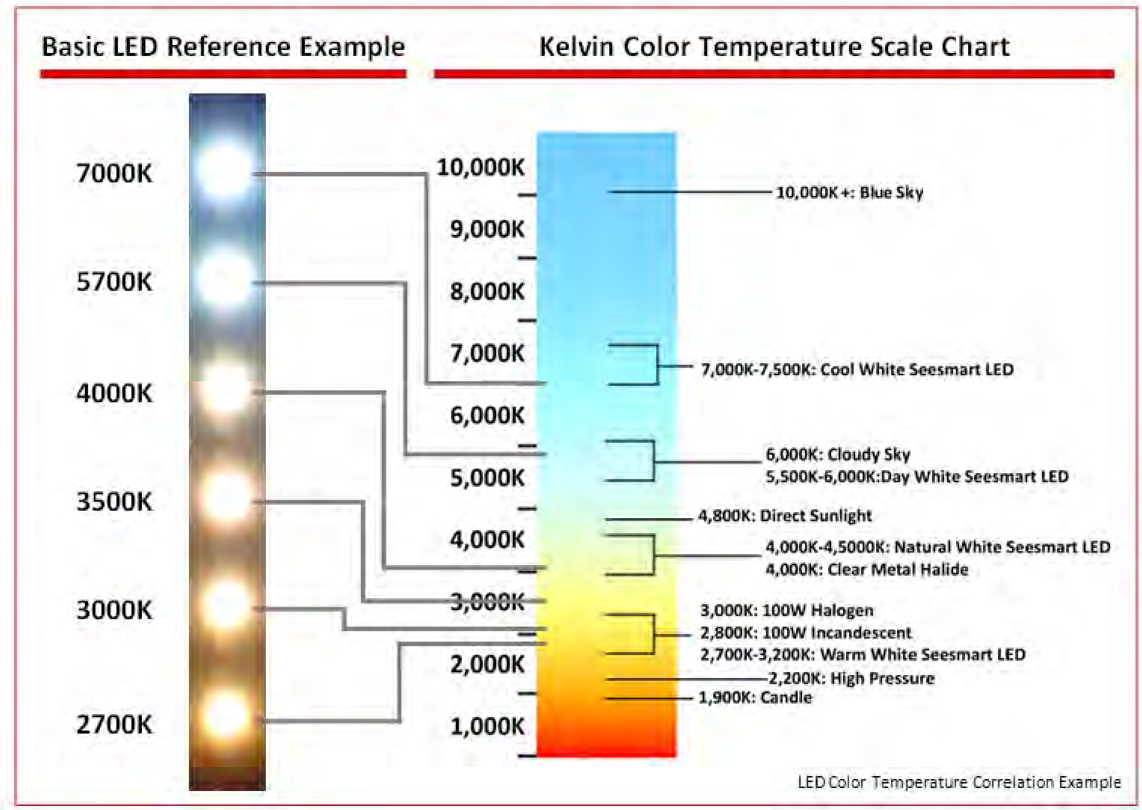


Figure 6: Different CCT Values and the Kelvin Color Temperature Scale Chart
Source: [13]

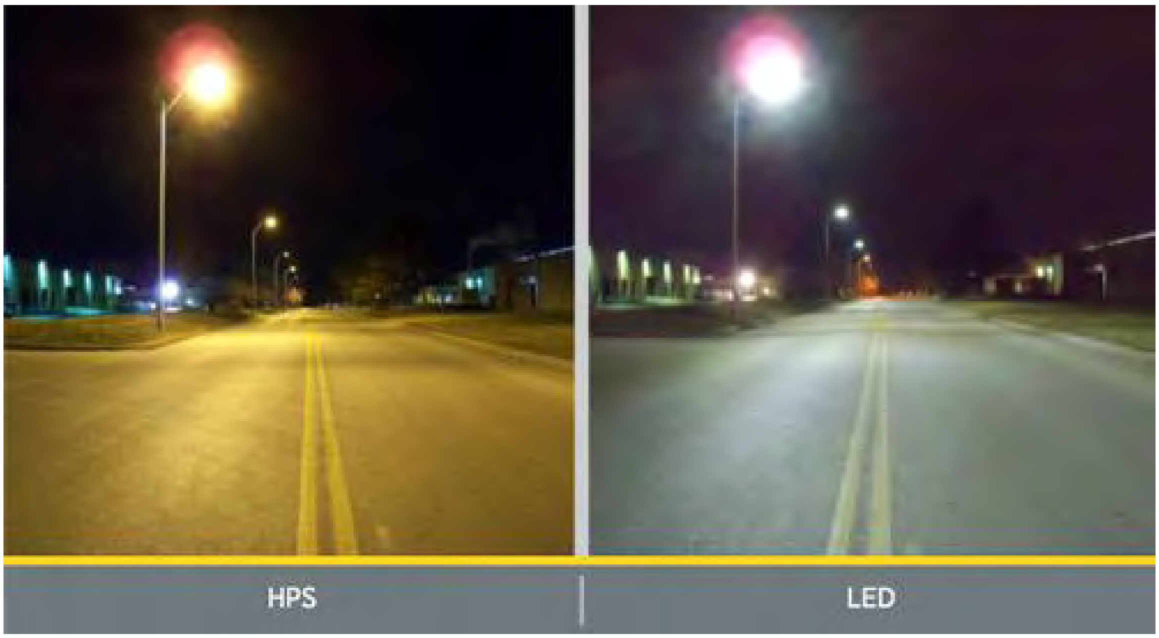


Figure 7: The Yellowish Light of HPS Light versus the Cool White Light of LED Roadway Lights
Source: [14]

3.2.9 Color Rendering Index (CRI)

CRI stands for the color rendering index, which is a quantitative measure of a light source's ability to show object colors "realistically" or "naturally" compared to a familiar reference source, such as incandescent or daylight. CRI is calculated from the differences in the chromaticities of eight CIE standard color samples (as defined in the CIE 1995 color space) when illuminated by a light source and by a reference illuminant of the same CCT. The smaller the difference in chromaticities, the higher the CRI will be. A CRI of 100 represents the maximum value, and lower CRI values indicate that some colors may appear unnatural when illuminated by the lamp. Figure 8 shows how low CRI's versus high CRI's can affect the naturalness of color appearance.

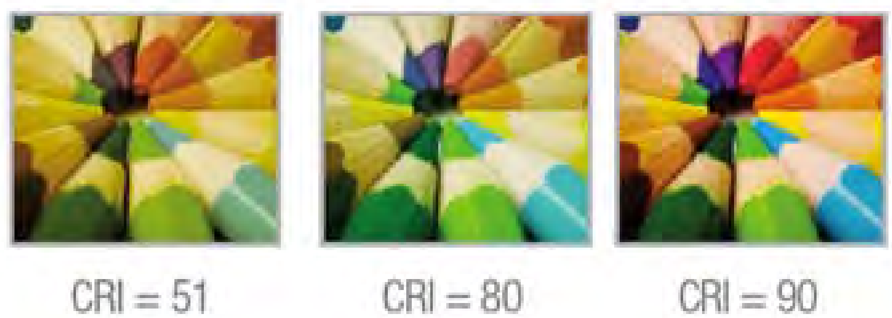


Figure 8: Color Rendering Performance Evaluated Using CRI Values
Source: [15]

High-pressure sodium lights have a typical CRI of 49, and fluorescents are in the 60-70 range. Both of these lamps do a poor job at accurately reproducing color. Most LEDs available in the current market for architectural illumination have CRI in the range of 80s-90s. It is worth mentioning that most LED luminaires for interior uses have CRI values equivalent to or greater than 90. The LED roadway luminaires often have a typical CRI values in a range of 65-82, and most of them are 70 as of 2015, which is a trade off of high lumen efficacy. It is expected that in the near future, LED roadway luminaires will have CRI values greater than 90 as well, similar to those LEDs used inside the buildings.

3.2.10 Light Lateral Distribution Types

There are six light lateral distribution types for area lighting, as shown in Figure 9 for a visual representation of each type. Sometimes type VS is incorporated in Type V. Different types are expounded below.

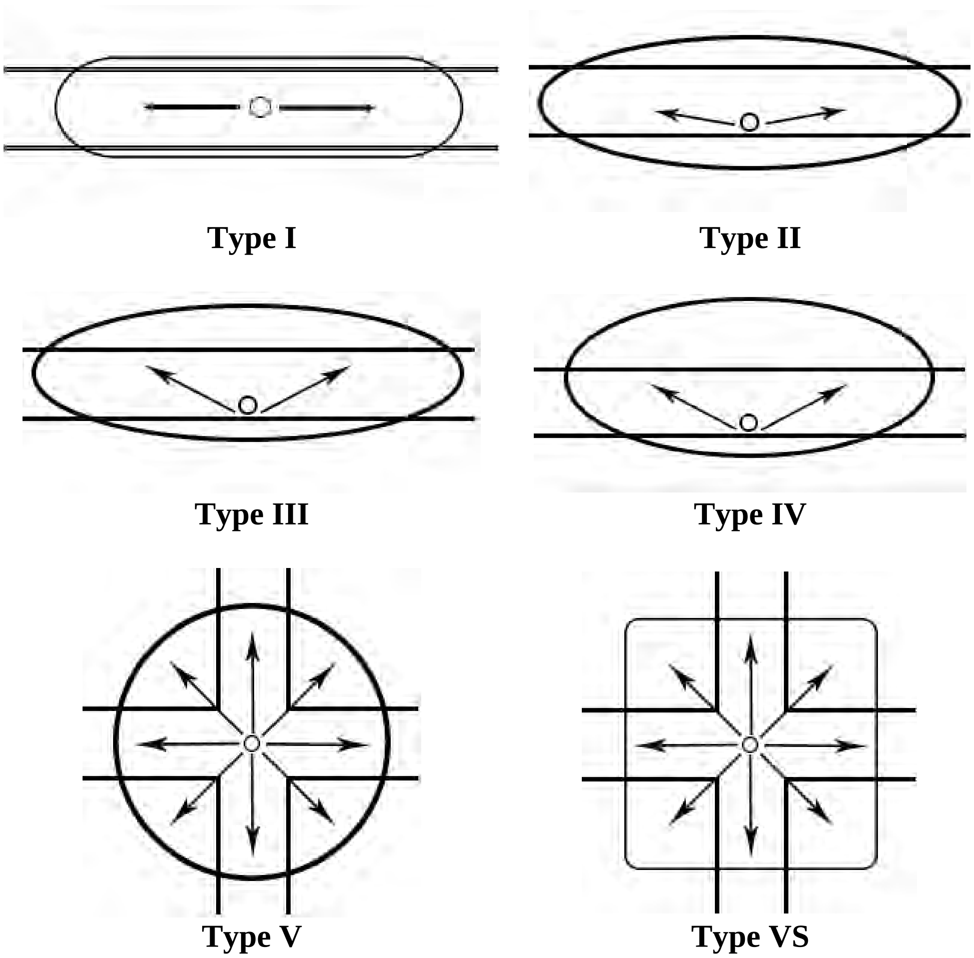


Figure 9: Light Lateral Distribution Types of Typical Area and Roadway Lighting
Source: [16]

Type I distribution is great for lighting walkways, paths, and sidewalks. This type of lighting is meant to be placed near the center of the pathway, and is a two-way lateral distribution having a preferred lateral width of 15 degrees in the cone of maximum candlepower. The two principal light concentrations are in opposite directions along a roadway.

Type II distribution is typically used for wide walkways, ramps, and entrance roadways. This distribution is meant for lighting larger areas and is usually located near the roadside, on smaller side streets or jogging paths. Type II distribution has a preferred lateral width of 25 degrees, and is generally applicable where the roadway does not exceed 1.75 times the designed mounting height.

Type III distribution is meant for roadway lighting, general parking areas, and other areas where a larger area of lighting is required. This distribution type is intended to be placed to the side of the area, allowing the light to project outward and fill the area. Type III distributions have a preferred lateral width of 40 degrees, and are best in areas where the width of the roadway or area does not exceed 2.75 times the mounting height.

Type IV distribution produced a semicircular light pattern for mounting on the sides of buildings and walls. It is best for illuminating the perimeter of parking areas and businesses. This distribution type has the same intensity at angles from 90 to 270 degrees, and the preferred lateral width of this distribution is 60 degrees. This distribution type is intended for roadways where the width does not exceed 3.7 times the mounting height.

Type V lighting distribution produces a circular distribution that has the same intensity at all angles. It is intended for luminaire mounting at or near the center of roadways, center islands of parkway, and intersections. This distribution type is also meant for large, commercial parking lot lighting as well as areas where sufficient, evenly distributed light is necessary.

Type VS (square), is the last type of lighting distribution that has a square distribution that has the same intensity at all angles. It is intended for luminaire mounting at or near the center of roadways, center islands of parkways, and intersections. Type VS lighting distribution is similar to Type V lighting distribution, but is used in areas where a more defined edge is necessary.

The light lateral distribution types of current LED luminaires include all types (I, II, III, IV, V, and VS). However, it is recommended to use only Types III, IV, and V for standard roadside poles, and Types V and VS for standard roadside poles and high-mast lighting. Types I and II are deemed inappropriate for roadway lighting in Kansas discussed in this manual.

3.2.11 Cutoff Classification

According to the Illuminating Engineering Society (IES), there are four different classifications for luminaires pertaining to their glare control and high-angle brightness. These classifications are called full cutoff, cutoff, semi-cutoff, and non-cutoff, as shown in Figure 10.

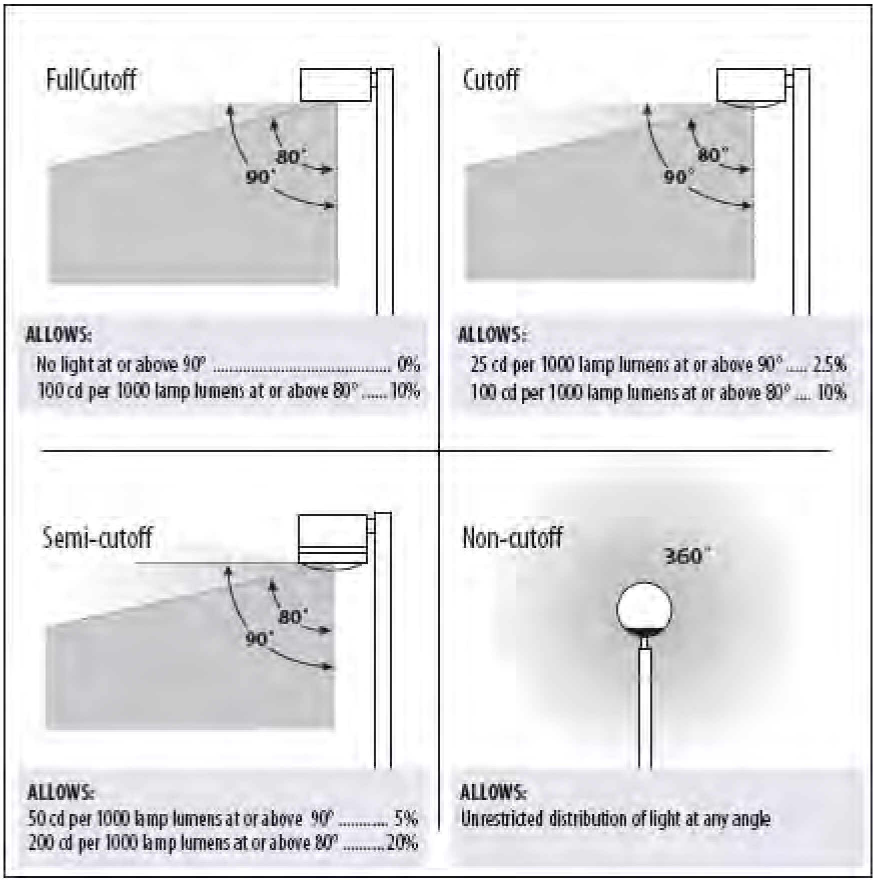


Figure 10: Cutoff of the Roadway Luminaires
Source: [17]

Full cutoff specifies zero intensity at or above horizontal, and limited to a value not exceeding 10% of lamp lumens at or above 80 degrees. Cutoff specifies the intensity at or above horizontal to be no more than 2.5% of lamp lumens, and no more than 10% of lamp lumens at or above 80 degrees. Semi-cutoff specifies the intensity at or above horizontal to be no more than 5% of lamp lumens and no more than 20% of lamp lumens at or above 80 degrees. Non-cutoff has no limitations on light distribution at any angle.

The cutoff classification for nearly all LED roadway luminaires is "full cutoff," and a few of them are "cutoff." In this project we will only suggest luminaires that are full cutoff in order to preserve the darkness of the night sky, preventing light pollution and sky glow.

3.2.12 BUG Rating

The BUG rating is also a quantitative measure to help prevent light trespass and sky glow, referring to Backlight, Uplight, and Glare (BUG). Backlight creates light trespass onto adjacent sites opposite from the area intended to be lighted. Backlight is measured by the amount of light in the BL, BM, BH, and BVH zones (Figure 11). Uplight causes artificial sky glow, mainly due to light in the UL zone. Light in the UH zone is mostly energy waste and should also be avoided. Glare can be annoying, but also visually disabling. The G rating takes into account the amount of light in the FH, FVH, BH, and BVH zones.

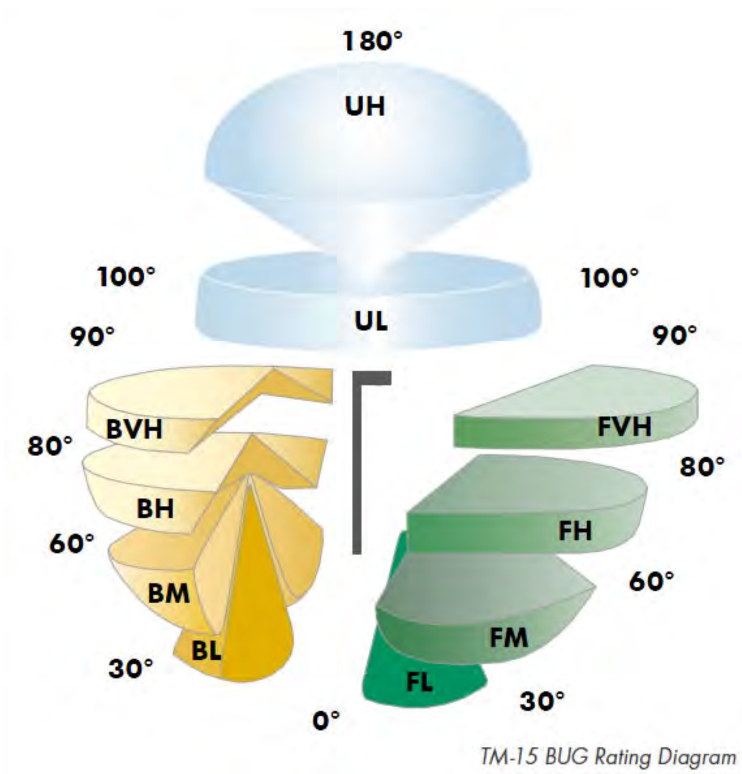


Figure 11: IES TM-15 BUG Rating Diagram, Backlight is Measured by the Amount of Light in the BL, BM, BH, and BVH Zones
Source: [18]

The BUG rating itself is based on zonal lumen calculations for secondary solid angles defined in the Addendum A for the IES publication TM-15-11 [19]. The zonal lumen thresholds are based on data from photometric testing procedures approved by IES for outdoor luminaires (LM-31 or LM-35).

For standard poles roadside lighting, the best BUG rating is B0-U0-G0, while the worst bug rating is B5-U5-G5. For high-mast lighting, the best BUG rating is probably B3-U0-G0 for a certain amount of backlight without causing glare and light pollution, while the worst BUG rating is probably B5-U5-G5.

3.2.13 Driver

An LED driver is a device that manages power and controls the current flow for an LED lighting product. Because LED doesn't require high voltage, LEDs could even use batteries or solar power, depending on the application. An important factor that affects the choice of a particular driver is the way in which multiple LEDs are actually wired together.

The three wiring configurations are: series, parallel, and series/parallel. Series refers to LEDs connected to form a chain, cathode to anode. Parallel refers to LEDs that are connected so as all cathodes are connected together and all anodes are connected together. The mixture of the two in series/parallel is when LEDs are connected in series to form a chain and then the chains are wired in parallel. There are three LED driver topologies (the way in which electronic parts are interrelated) that are typically used. "Buck" is stepping down a higher input voltage to a lower output voltage. "Boost" is stepping up an input voltage to a higher output voltage. "Buck/Boost" allows the input voltage to vary—it can be greater than, less than, or equal to the output voltage.

3.2.14 Dimming

There are drivers available that can dim LEDs from 100% to 1% output, offering smooth continuous dimming for both constant-current and constant-voltage sources. The dimming range of a product, either a lamp or a fixture, is based solely on the driver, including the low-end light level performance. Choosing the right dimming control allows for the reduction of flicker, pop-on, or drop-out. All dimmers are related to a maximum load in volts, amps, and/or Watts that must not be exceeded. Similarly, some LED drivers may not perform well if they are required to control a very minimal load. While a few of the LED roadway luminaires are non-dimming, most of them are dimmable, which is optimal for controls, and nearly all of the LED roadway luminaires come with photosensors for controlling the on-and-off of the lights at dust and dawn.

3.2.15 Sensors and Controls

Daylight photosensors can be used to detect the prevailing light levels, allowing the luminaire to be turned on only when daylight levels are not adequate. Photosensors can be used to adjust the electric lighting based on the available daylight in the space. In an open-loop system, the photosensor detects the amount of available daylight only, and can be positioned on the luminaire facing the daylight. In a closed-loop system, the photosensor detects the total photometric amount of light, from both daylight and electric sources in the space. For this reason, most roadway luminaires are installed in an open-loop system. These daylighting photosensors have significant potential to save energy in a typical roadway lighting system.

Occupancy sensors are control devices that detect occupancy of a space by people and turns lights on or off automatically. These sensors are typically intended for use in indoor spaces, and are not very practical for roadway lighting applications. The occupancy sensors have three control technologies, as follows.

a. Passive infrared control technology works on heat movement and detection, calibrated to detect infrared radiation radiated by the human body. Based on this detection, the sensor operates and starts lighting loads connected to it.
b. Ultrasonic control technology is similar to radar—it works on the Doppler shift principle. It will send high frequency sound waves in an area and will check for their reflected patterns. If the reflected pattern is changing continuously, then it assumes that there is occupancy and the lighting load is turned on. If the reflected pattern is the same for a present time then it assumes there is no occupancy and the lighting load is switched off.

c. Dual technology sensors combining both passive infrared and ultrasonic are usually the most effective way of controlling lighting loads. However, as previously stated, this type of occupancy sensor is not very ideal for roadway lighting.

There are different types of coverage patterns for lighting sensors, the most common are circular and rectangular. It is important for the coverage patterns of luminaires to overlap, ensuring that there are no areas that are not covered. The rectangular coverage pattern would be most useful for roadway luminaires.

Nearly all of the LED roadway luminaires come with photosensors for controlling the on-and-off of the lights at dust and dawn. They may also be equipped with motion/occupancy sensors and temperature sensors, drive current sensors, and voltage sensors for surge protection. The controllers use thermal controls and energy saving control options, or photoelectric controls, surge protectors, photocontrols, heatsink, and shorting caps. The coverage patterns of those sensors are either rectangular or 360° circular.

3.2.16 Certificates

LED roadway luminaires, as well as other traditional ones, are required to meet the general requirements of certificate, including NEMA, ANSI, IEC, Underwrite (e.g., UL, CSA, ETL, CE, FCC), LEED, ENERGY STAR, and IP rating. Their full names and symbols are listed in Table 2.

In the U.S., the most common and important type of luminaire certification is UL. UL operates under its own authority as an independent, not-for-profit, nongovernmental organization. To establish certification, samples of a product submitted by manufacturers for certification are tested and evaluated. If UL decides the product fulfills all applicable requirements, it authorizes the manufacturer to apply a certification mark to production of the samples submitted, or issues a certificate or notification that the product is now certified by UL. If only a component of a product is tested by UL, an UL affiliated “ ” certificate is awarded to the manufacturer for labeling that component.

A report of the evaluation is provided to the manufacturer, and before the manufacturer releases products with the certification mark, UL must initiate follow-up service in which UL field representatives complete periodic audits of products at the factory. Certification continues until the manufacturer requests termination or fails to fulfill a requirement. UL must evaluate modifications to certified products before the modified product is authorized to be considered certified. UL is financially funded by the fees it charges manufacturers of the products submitted for certification. Fees are charged for the initial evaluation process, as well as ongoing maintenance fees for follow-up service. For this reason, getting a luminaire UL certified is not a cheap process, and many small manufacturers cannot afford it.

Table 2: The Certificates of LED Luminaires and Their Symbols

Certificate	Full name	Symbol
NEMA	National Electrical Manufacturers Association	
ANSI	American National Standards Institute	
IEC	International Electrotechnical Commission	
UL	Underwriters Laboratories	
CSA	Canadian Standards Association	
ETL	Originally a mark of ETL Testing Laboratories, now a mark of Intertek Testing Services	
CE	Conformance European	
FCC	Federal Communications Commission	

Most of the LED roadway luminaires available in the current market are certified with UL, cUL, CSA, ETL, RoHS, FCC, CE, etc.

3.2.17 IP Rating

IP rating stands for Ingress Protection Rating. It is a numerical rating system of IP followed by two digits and one optional letter. As defined in IEC 60529 [20], it classifies the degrees of protection provided against the intrusion of solid objects including: body parts, dust, accidental contact, and water in electrical enclosures. The standard aims to provide users more detailed information than vague marketing terms like "waterproof."

The digits of IP rating indicate conformity with the conditions summarized in the tables below. The first digit refers to solids, while the second digit refers to liquids. Table 3 shows the detailed meaning of the first and second digits. The IP rating of the LED roadway luminaires should be at least IP65, IP66, and most of them available in the current market are rated IP67.

3.2.18 Life

One of the main selling points of LEDs is their long life. The measurement of LED useful life is usually determined through lumen depreciation. The life rating is usually demarcated L_{70}, which is the lifetime of the luminaire based upon the amount of time it takes for the lumens to depreciate to 70% of the original output. The primary cause of LED lumen depreciation is heat generated at the LED junction. The typical lifespan of a HPS lamp is on average 20,000 hours. The service life of LED roadway luminaires available in the current market is ranged from 50,000 hours to 350,000 hours, most of them are in a range of 50,000-100,000 hours. Compared to the burn out failing mode, the LED light diminishes gradually, as shown in Figure 12. LEDs prove to be the most cost effective when it comes to lifespan in comparison to all other lamp types, and technology is continuing to get better and better.

Table 3: IP Rating Number Designations: The Meaning of the First and Second Digits

Level	Object Size Protected Against	Effective against
	FIRST DIGIT	
0	Not Protected	No protection against contact and ingress of objects
1	>50mm	Any large surface of the body, but no protection against deliberate contact with a body part
2	>12.5mm	Fingers or similar objects
3	>2.5mm	Tools, thick wires, etc.
4	>1mm	Most wires, screws, etc.
5	Dust Protected	Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment; complete protection against contact
6	Dust Tight	No ingress of dust; complete protection against contact
	SECOND DIGIT	
0	Not Protected	
1	Dripping Water	Dripping water (vertically falling drops) shall have no harmful effect
2	Dripping Water When Tilted Up to 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position
3	Spraying Water	Water falling as a spray at any angle up to 60° from the vertical shall have no harmful effect
4	Splashing Water	Water splashing against the enclosure from any direction shall have no harmfull effect
5	Water Jets	Water projected by a nozzle (6.3mm) against enclosure from any direction shal have no harmful effect
6	Powerful Water Jets	Water projected in powerful jets (12.5mm nozzle) against the enclosure from any direction shall have no harmful effects
7	Immersion up to 1m	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time
8	Immersion beyond 1m	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. Normally, this will mean that the equipment is hermetically sealed. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects.

Source: [21]

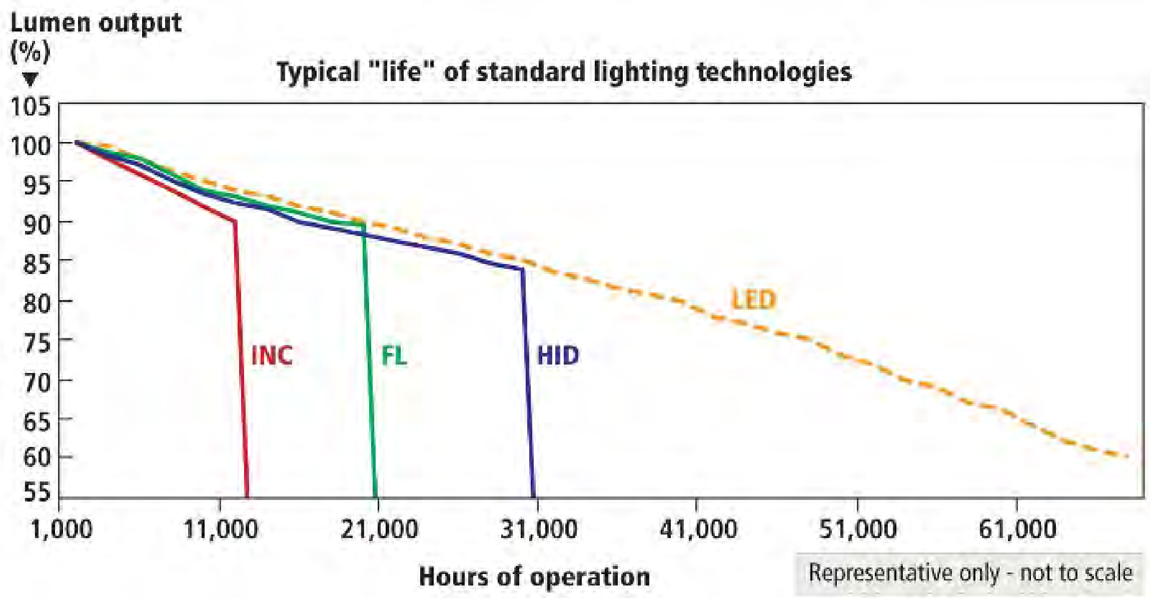


Figure 12: LED Life L_{70} and the Light Diminishes Gradually Over Time versus Conventional Light Sources Which Burn Out at the End of Their Life
Source: [22]

3.3 Implementation Benefits of LED Roadway Luminaires

Implementation of more LED roadway luminaires in Kansas to replace those HPS roadway lights is expected to have three significant benefits to the Kansas Department of Transportation (KDOT), districts and cities, and the driving public [23].

Reduced operating and maintenance costs. LEDs have an outstanding operational life of typically 50,000-100,000 hours in 2015, which is 11-22 years of 50% operation on roads (at night only). Such a long life largely reduces the maintenance frequency of the roadway illumination systems and the associated costs. In addition, most LEDs today have an estimated light utilization efficiency of up to 80%, which is rapidly increasing in the latest LEDs. The high efficiency of LEDs can largely reduce the operating cost of large scale roadway illumination projects. Moreover, LEDs are extremely durable and built with sturdy components that are highly rugged and can withstand even the roughest conditions. LEDs are ideal for operation under cold and low outdoor temperature settings in Kansas. The savings on operating and maintenance costs in Kansas could be very impressive based on other states' data, e.g., $1.35 million in 10 years for high-mast lighting solely [3].

Safety and efficiency. The LED roadway luminaires have elongated life and reliability in wide range of operating temperatures and more short-wavelength light in the full light spectrum to enhance visibility of vehicle operators, which can promote safer and more efficient highway operations year around than the existing HPS counterparts. They can enhance safety for the motoring public at night.

Benefits on toxic substances control. All conventional HID lamps on road contain mercury that is dangerous for the environment. Mercury can be evaporated into the air, deposited into the soil, and leaked into the water. LED lights are free of toxic chemicals, e.g., mercury and lead. Replacing HID lamps with LEDs can effectively lower the mercury pollution in the environment. LED lights are 100% recyclable, and will help Kansas to reduce carbon footprint by up to a third.

Chapter 4: Roadway Lighting Design and Layout

4.1 Review of Roadway Lighting Systems

To guide the roadway lighting design and layout, the AASHTO, FHWA, IES, and CIE requirements are reviewed for the roadway lighting systems and summarized below.

4.1.1 Classification of Roadway and Pavement

For lighting, the Illuminating Engineering Society (IES) classified the road into the following categories [24]. Among them, the most interesting ones to Kansas at this moment for LED lighting and addressed in this manual are bolded and underlined.

- **<u>Freeway</u>**
- **<u>Expressway</u>**
- **<u>Major</u>**
- Collector
- Local
- Alley
- Sidewalk
- Pedestrian Walkway
- **<u>Isolated Interchange</u>**
- **<u>Isolated Intersection</u>**
- **<u>Isolated Traffic Conflict Area</u>**
- Bikeway

In addition, for lighting purpose, IES classified the road pavement into four classes, as shown in Table 4 [24]. Note that wet roadway conditions are not covered in Table 4. Obtained from this table is the value Q_0, the representative mean luminance coefficient, which is used in the calculations for this project. Different pavement has different mode of reflectance for lighting calculations, and thus, different values of Q_0. Mostly, an R1 pavement classification with a corresponding Q_0 of 0.1 is a common design value for Kansas LED roadway lighting. Other values may also be possible.

Table 4: Pavement Classifications

Class	Q_0	Description	Mode of Reflectance
R1	0.1	Portland cement concrete road surface. Asphalt road surface with a minimum of 12% of the aggregates composed of artificial brightener aggregates	Mostly Diffuse
R2	0.07	Asphalt road surface with an aggregate composed of a minimum 60% gravel (size greater than 0.4 in.). Asphalt road surface with 10-15% artificial brightener in aggregate mix.	Mixed (Diffuse and Specular)
R3	0.07	Asphalt road surface with dark aggregates and rough texture after some months of use.	Slightly Specular
R4	0.08	Asphalt road surface with very smooth texture	Mostly Specular

4.1.2 Pole Placement Guidelines

AASHTO published some guidelines for pole placement [25], as follows:

a. Structural support.
    - Poles of the LED roadway luminaires should be designed and located so that they do not distract the attention of the motorists or interfere with their view of the roadway and other important roadway features.
    - Supports should be placed so that they do not obstruct the view of signs.

b. Height restriction.
    - Lighting poles placed adjacent to airports and in their landing zones should comply with the height restrictions of federal aviation administration.

c. Median location advantages. Locating poles for LED roadway luminaires within a median area can have multiple advantages as follows.
    - Reduce half of the required lighting poles for house side lighting.
    - Reduce the amount of wiring.
    - The back light of the LED roadway luminaires, which is otherwise wasted on the house side, is used for lighting the opposite roadway.
    - Reduce construction and maintenance costs.
    - Improve visibility on the high-speed lanes.

d. Gore areas.
    - Locating poles within the clear zone at a gore area is not usually desirable, unless located behind or atop a longitudinal traffic barrier or behind a crash cushion.

4.1.3 Lighting System Selection

A typical LED roadway lighting design has the following considerations [26]:

- Availability of Power
- Proximity to Aircraft Landing Facilities
- Proximity to Railroads
- Presence of Overhead Distribution and Transmission Lines
- Environmental Issues
- Maintenance and Operations Considerations
- Roadside Safety Considerations
- Historical Safety Performance

For selection of the LED roadway luminaires, often the following factors need to be taken into account [26]:

- Quality
- Certification
- Photometric Performance (for luminaires)
- Durability
- Aesthetics
- Availability
- Maintenance Requirements
- Operations Cost

In particular, the LED roadway luminaires to be mounted in Kansas, there are some specific luminaire requirements as follows [26]. Whenever possible, individuals specifying products are encouraged to designate more than one manufacturer with similar or equal products to reduce costs via competitive bidding.

- Ingress Protection (IP) Rating
    - Optical systems should be well sealed to prevent the entry of dust and water. Luminaires should have an IP rating of 65 or 66 for maximum performance.
- Lens Material
    - Lenses should be composed of glass. Polycarbonate and acrylic materials, though more impact-resistant, tend to discolor over time, which will reduce light output and will often require replacement in about 5 years.
- Housing
    - The housing should be made of aluminum with a powder coat exterior finish. The luminaire should be designed for secure attachment to the pole. The luminaire should be designed for easy access for electrical and lamp changes via a tool-less entry.

- Internal Electrical
    - Internal components usually include an LED driver, a photosensor, and even a temperature sensor.
- BUG Ratings
    - The luminaire optics should meet the specific BUG ratings where they are available. For standard poles roadside lighting, the best BUG rating is B0-U0-G0, while the worst BUG rating is B5-U5-G5. For high-mast lighting, the best BUG rating is probably B3-U0-G0 for certain amount of backlight without causing glare and light pollution, while the worst BUG rating is probably B5-U5-G5.

4.1.4 LED Lighting System Layout and Geometry

Typical standard pole spacing layout is shown in Figure 13. These standard pole spacing layout designations include one-sided lighting, opposite lighting, staggered lighting, and median lighting [26], as detailed below.

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

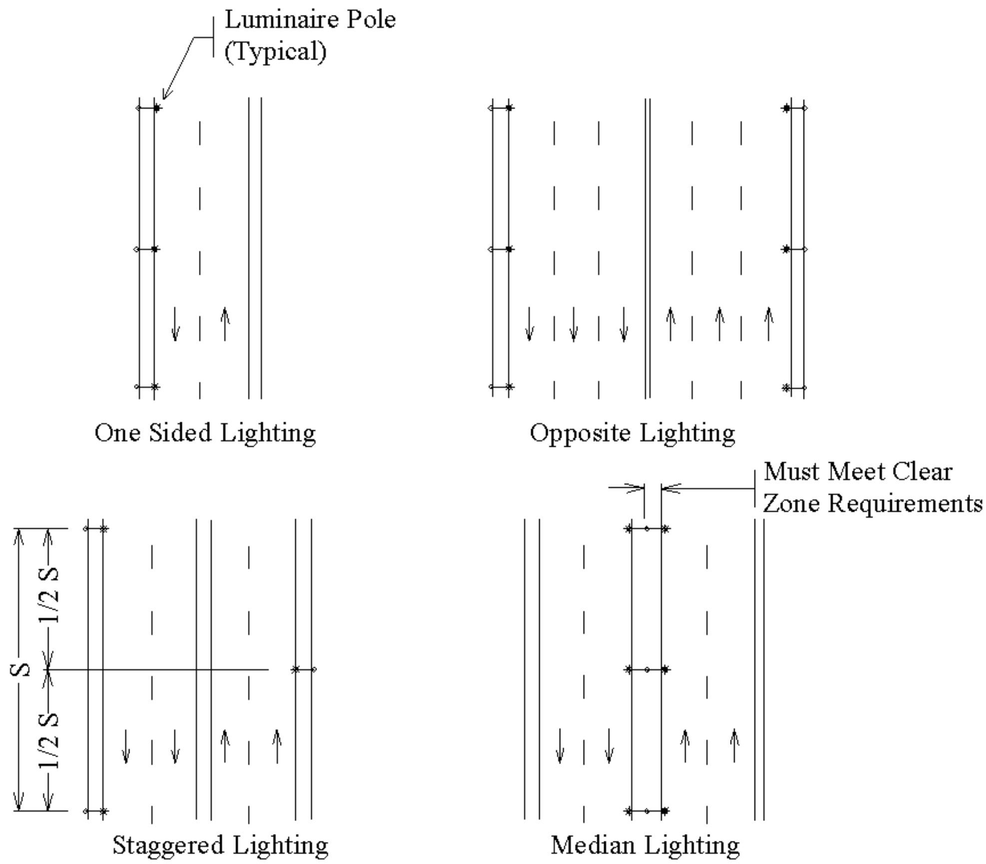


Figure 13: Typical Standard Pole Spacing Layout Designations
Source: [26, Figure 31]

To lay out poles, the designer must undertake lighting calculations to define optimal pole spacing. Once maximum pole spacing is defined, one can lay out poles on the road drawings using a calculator and scale rule. The design should lay out poles locating a pole at a start point such as cross street, then spacing the poles evenly within the maximum pole spacing defined by the calculations, as shown in Figure 14. The pole spacing may need to be adjusted to suit driveways and utility conflicts [26].

There are commonly used geometries for the luminaires support systems, including pole height, spacing, arm length, etc. These numbers are summarized in Table 5. Mast arms support the luminaire at a lateral dimension from the pole. Mast arm length is usually 6 feet, 9 feet, or 12 feet. Typical pole heights are 30 feet, 40 feet, and 49 feet. Freeway pole mounting height is in a range of 25-40 ft. The spacing to mounting height ratio on freeway start with a 5:1 value and modify accordingly to meet criteria design issues. On municipal streets, the mounting height of standard poles are often 20-30 ft, while the spacing to mounting height ratio starts with a 5:1 and modify accordingly to meet criteria design issues. For freeways, pole for conventional lighting should be spaced as the longitudinal spacing between poles: 140-220 ft for 250W HPS cutoff or equivalent on 40 ft pole, and 220-270 ft for 400W HPS cutoff on 50 ft pole. Distance from luminaire to farthest edge of pavement is 0-50 ft for 250W HPS cutoff or equivalent on 40 ft pole, and 50-60 ft for 400W HPS cutoff on 50 ft pole. High-mast tower luminaires have mounting heights often varying from 100 feet to 140 feet.

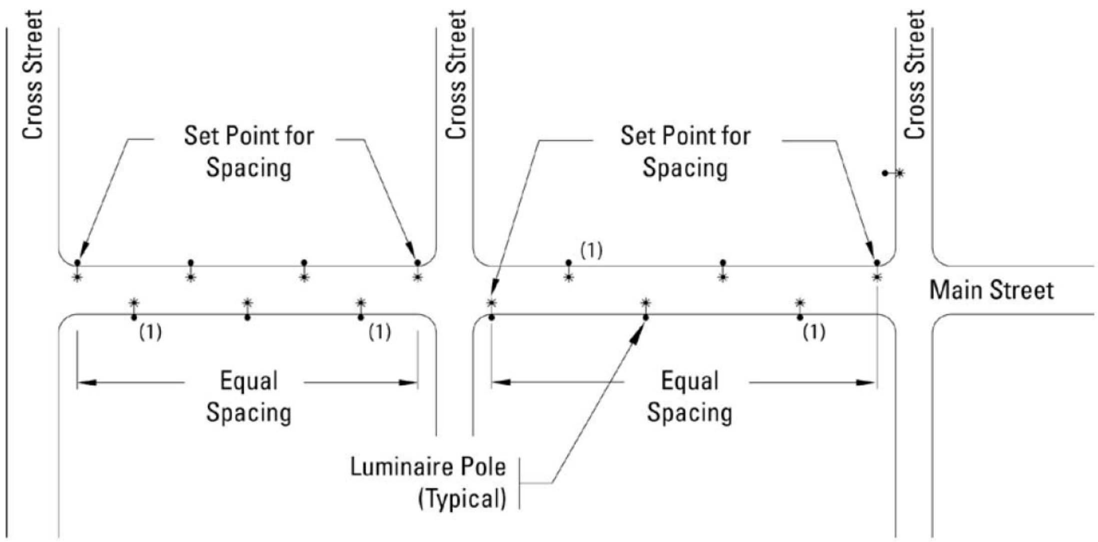


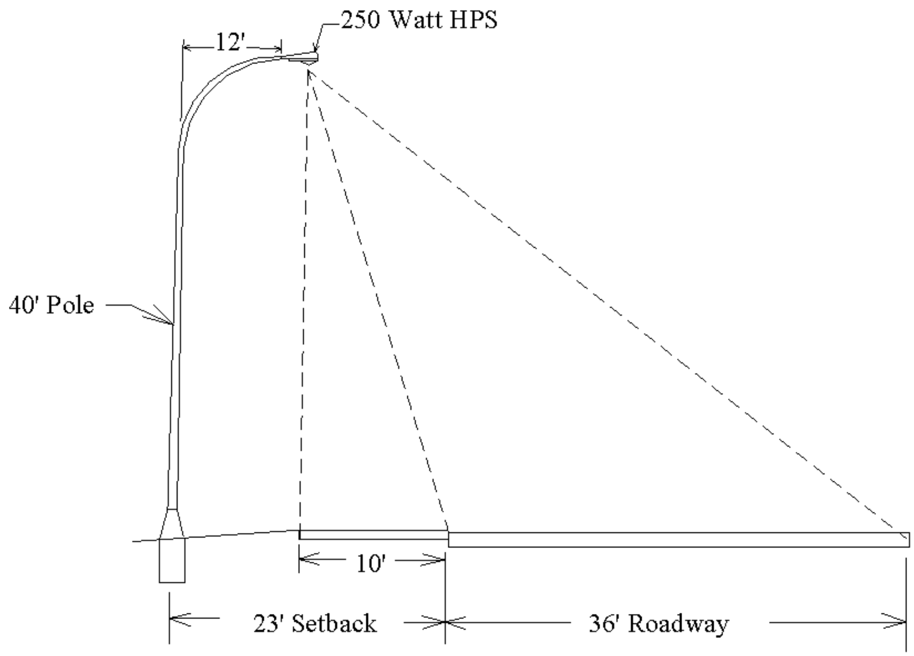
Figure 14: Typical Standard Pole Spacing Layout
Source: [26, Figure 32]

Table 5: Typical Geometries for the Luminaire Support Systems

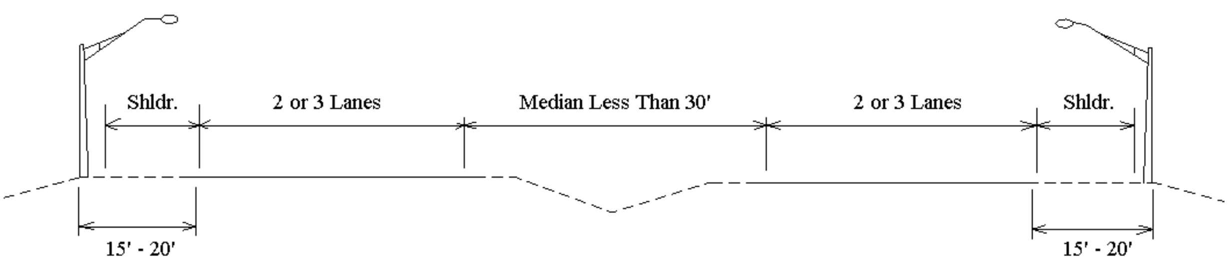
Support system	U.S.		Kansas
Pole height	Overall	30, 40, 49 ft	40 ft
	Freeway	25-40 ft	40 ft
	Municipal streets	20-30 ft	
Mast arm length	6, 9, 12 ft		15 ft
Longitudinal spacing between poles	Overall	Spacing to mounting height ratio starts with a 5:1, and modify to meet criteria	
	Freeway	140-220 ft for 250W HPS with cutoff or equivalent on 40 ft pole; 220-270 ft for 400W HPS with cutoff on 50 ft pole.	150 ft for 150W HPS on 40 ft pole
Setback distance from luminaire to the nearest edge of pavement	Overall	15-20 ft, 23 ft	No further than 6 ft from the edge of the nearest traffic lane in curb & gutter section or 2 ft from shoulder
Distance from luminaire to the farthest edge of pavement	Freeway	Up to 50 ft for 250W HPS with cutoff or equivalent on 40 ft pole; 50-60 ft for 400W HPS with cutoff on 50 ft pole	
High-mast tower height	100 to 140 ft		Typically 100 -120 ft

Source: [26]

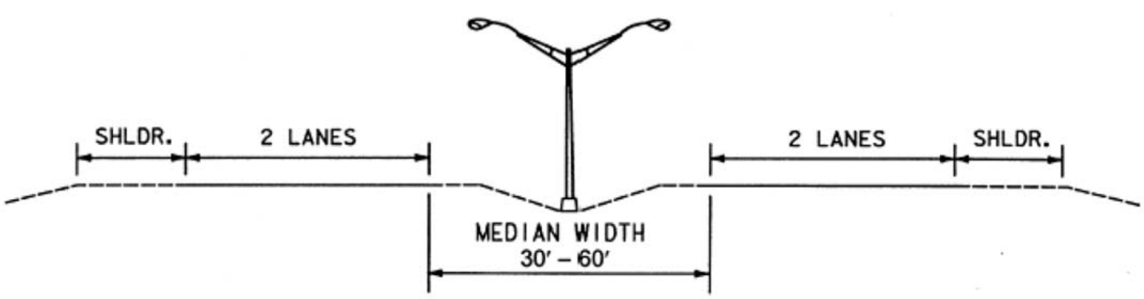
Figure 15 lists the typical geometries for the luminaire support systems, including those used across the U.S. and those specifically used in Kansas. In Kansas, the typical standard pole height is 40 ft (vs. 25-49 ft in the U.S.). Mast arm length for standard poles is often 15 ft in Kansas (vs. 6-12 ft in the U.S.). High-mast tower luminaires have mounting heights of 100-120 ft in Kansas (vs. 100-140 ft in the U.S.). The longitudinal spacing between poles is often 150 ft for 150W HPS mounted on 40 ft pole on freeway in Kansas (vs. 140-270 ft in the U.S.). In Kansas, the distance to the luminaire is no further than 6 ft from the edge of the nearest traffic lane in curb and gutter section, or 2 ft from the shoulder. In the U.S., the setback distance from the luminaire to the nearest edge of pavement is often 15-23 ft and up to 60 ft to the farthest edge of pavement for freeways.



(a) Typical one-sided lighting layout

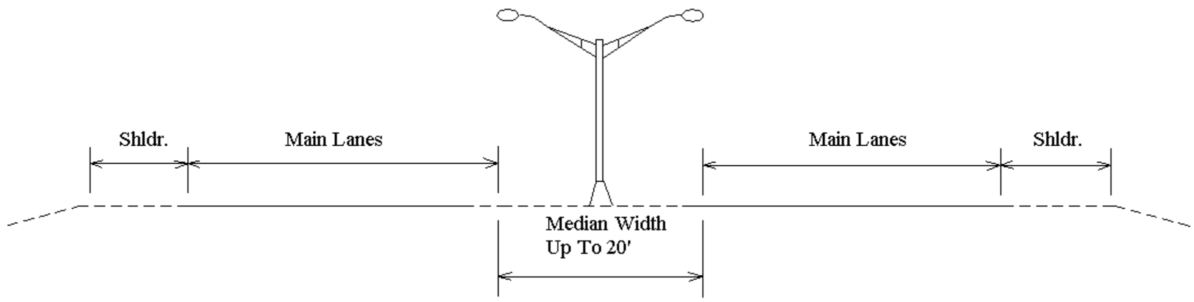


(b) Typical house-side lighting for controlled access highway (the 250 Watt HPS lamps mounting height is 40 ft, spacing varies).

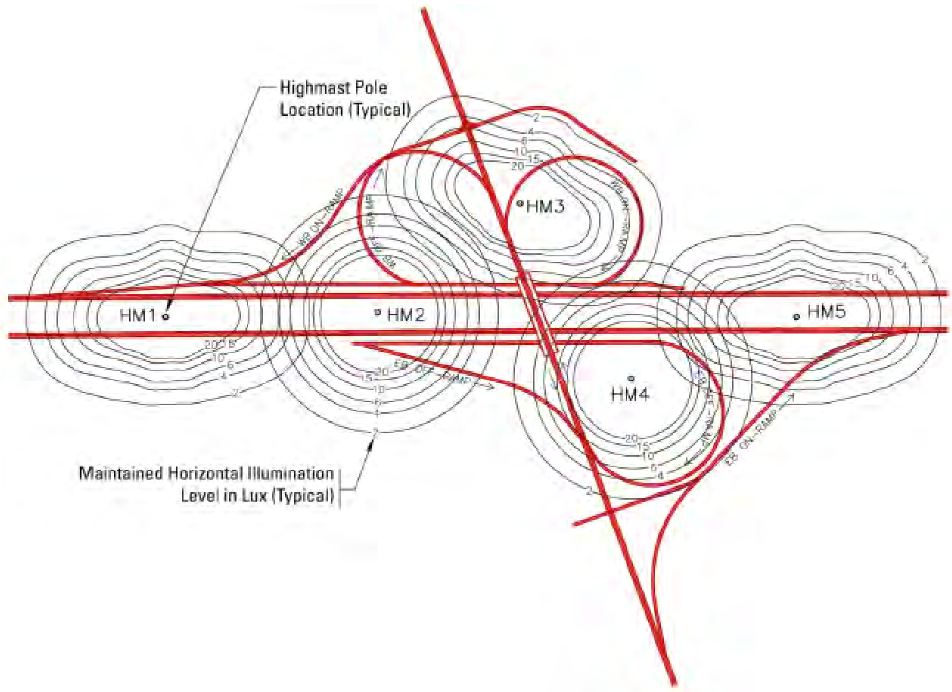


(c) Typical median lighting with breakaway poles (when the median width exceeds 60 ft, it may be necessary to treat each main lane as a separate roadway, using two rows of poles in the median or house sides).

Figure 15: Typical Pole Designations and the Geometries
Source: [26, Figures 6-8, 6-9, 6-10, 33]



(d) Typical median lighting with concrete median barrier



(e) Typical high-mast pole spacing

Figure 15: Typical Pole Designations and the Geometries (Continued)
Source: [26, Figures 6-8, 6-9, 6-10, 33]

Moreover, when determining pole heights, types, and luminaire wattages, the designer must take the land use (residential, urban, downtown, commercial, industrial, etc.) and the road width into account. Pole height may also be limited by the reach of service vehicles used to maintain the lights. There is no exact formula for determining the optimal pole height and luminaire wattage for a given road. Factors such as pole spacing (one-sided, median, opposite, or staggered), luminaire photometrics, wattage, road geometrics, power line conflicts, lighting levels and uniformity, aesthetics, and obtrusive lighting issues are all appropriate considerations in defining optimal mounting height. In residential areas, the designer should select pole heights and fixture wattages to reduce spill light levels to those suitable for the lighting environmental zones (LZ1-LZ4) [26].

Determination of pole height and luminaire wattage is made using computer lighting design software, e.g., AGI32, to test different scenarios by a "trial and adjustment" process [26].

For an interchange, high-mast lighting may prove to be more effective than conventional davit-style, mast-arm, or truss-style lighting. For freeway ramps, intersections or a typical city roadway, davit-style, mast-arm, or truss-style lighting may prove to be the most effective [26].

4.1.5 Adaptive Lighting Controls

Adaptive lighting controls allow lighting levels to be reduced during off-peak periods. Considering LED roadway luminaires are superb in dimming controls, a significant amount of power can be saved by varying the levels of lighting between peak and non-peak periods.

4.2 Lighting Design and Layout

The manual collects all lighting codes, standards, and ordinances for regulating the proper lighting design and layout for each type of LED roadway lighting systems on the Approved Products List (APL). As part of this task, technical support from the University of Kansas lighting research laboratory will also be provided upon request for field lighting measurements and the assessment of driver's visual performance, etc.

4.2.1 Roadway Lighting Design Criteria

There are two principal tasks facing the highway lighting specialist when designing an LED roadway lighting installation. First, there is the choice of overall quality, related to the function of the road/area to be lit. Second, there is the selection and positioning of the LED luminaires, and the positioning of the latter above the roadway to give the desired level, spread and uniformity of luminance. At the same time, the designer has to minimize the amount of glare from light entering the road user's eyes directly [27]. There are certain design criteria that the highway lighting engineer may need to follow, which are summarized as below.

4.2.1.1 Standard Pole Lighting

The overall quality of an LED lighting installation is usually evaluated using the following lighting metrics [24, 25, 27]:

- Minimum maintained average illuminance (E) on road pavement
- Average luminance L_{avg}
- Maximum allowed illuminance uniformity ratio of E_{avg}/E_{min}
- Maximum allowed luminance uniformity ratio of L_{avg}/L_{min}
- Maximum allowed veiling luminance ratio L_{vmax}/L_{avg}
- Overall uniformity of luminance, or illuminance, both across and along the roadway, defined as the minimum divided by the average, and designated L_{min}/L_{avg} or E_{min}/E_{avg} U_0.
- Uniformity of luminance, or illuminance, along the axis of the road which coincides with a typical driver's eye position. Defined as the ratio of the minimum to the maximum, and designated L_{min}/L_{max} or E_{min}/E_{max} U_1.
- Glare. As glare has the effect of reducing contrast, a luminaire's "glare performance," or optical control, can be expressed in terms of the increase in background luminance necessary to compensate (threshold increment, *TI*). The lower the figure the better. In highly motorized countries 10% is specified for motorways, with 15% and even 30% allowed for general traffic routes. These percentages are determined by the amount of light the luminaires project near the horizontal. This light also causes problems of sky-glow (see later).

For standard roadside pole lighting, the recommended lighting criteria on the pavement of different types of road are listed in Tables 6 and 7, respectively [24, 25, 27]. Tables 6 and 7 cover the following illumination metrics for different types of road and pavement classification or different roadway & pedestrian conflict areas, including Minimum maintained average illuminance (E) on road pavement, Maximum allowed illuminance uniformity ratio of E_{avg}/E_{min}, Maximum allowed veiling luminance ratio L_{vmax}/L_{avg}, Average luminance L_{avg}, Maximum allowed luminance uniformity ratio of L_{avg}/L_{min} and L_{max}/L_{min}.

Most roadways in Kansas considered for LED lighting may be in the Expressway road type category in a Low pedestrian conflict area. This corresponds to a minimum maintained illuminance value of 6.0 lux (0.6 footcandles), a uniformity ratio of 3.0, and a veiling luminance ratio of 0.3. However, other roadway types and pavements may also be possible.

Table 6: Recommended Illuminance and Uniformity on Road Pavement

Road and Pedestiran Conflict Area		Pavement Classification (Minimum Maintained Average Values)			Uniformity Ratio Eavg/Emin	Veiling Luminance Ratio Lvmax/Lavg
Road	Pedestrian Conflict Area	R1 lux/fc	R2 & R3 lux/fc	R4 lux/fc		
Freeway Class A		6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Freeway Class B		4.0/4	6.0/0.6	5.0/0.5	3.0	0.3
Expressway	High	10.0/1.0	14.0/1.4	13.0/1.3	3.0	0.3
	Medium	8.0/0.8	12.0/1.2	10.0/1.0	3.0	0.3
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Major	High	12.0/1.2	17.0/1.7	15.0/1.5	3.0	0.3
	Medium	9.0/0.9	13.0/1.3	11.0/1.2	3.0	0.3
	Low	6.0/0.6	9.0/0.9	8.0/0.8	3.0	0.3
Collector	High	8.0/0.8	12.0/1.2	10.0/1.0	4.0	0.4
	Medium	6.0/0.6	9.0/0.9	8.0/0.8	4.0	0.4
	Low	4.0/4	6.0/0.6	5.0/0.5	4.0	0.4
Local	High	6.0/0.6	9.0/0.9	8.0/0.8	6.0	0.4
	Medium	5.0/0.5	7.0/0.7	6.0/0.6	6.0	0.4
	Low	3.0/0.3	4.0/0.4	4.0/0.4	6.0	0.4

Source: [24, Table 2]

Table 8 lists the recommended light metrics for overall uniformity of luminance, or illuminance, both across and along the roadway, the uniformity of luminance, or illuminance, along the axis of the road which coincides with a typical driver's eye position, and a luminaire's "glare performance" expressed in terms of the increase in background luminance necessary to compensate (threshold increment, *TI*). For recognized traffic routes the figures are for luminance, but roughly equivalent values of illuminance for moderately dark road surfaces are given in parenthesis [27].

In addition, AASHTO [25] recommend a bit different illuminance and luminance values on road, as shown in Tables 9 and 10 below:

Table 7: Recommended Luminance and Uniformity on Road Pavement

Road and Pedestrian Conflict Area		Average Luminance Lavg (cd/sq.m.)	Uniformity Ratio Lavg/Lmin (max. allowed)	Uniformity Ratio Lmax/Lmin (max. allowed)	Veiling Luminance Ratio Lvmax/Lavg (max. allowed)
Road	Pedestrian Conflict Area				
Freeway Class A		0.6	3.5	6.0	0.3
Freeway Class B		0.4	3.5	6.0	0.3
Expressway	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
Major	High	1.2	3.0	5.0	0.3
	Medium	0.9	3.0	5.0	0.3
	Low	0.6	3.5	6.0	0.3
Collector	High	0.8	3.0	5.0	0.4
	Medium	0.6	3.5	6.0	0.4
	Low	0.4	4.0	8.0	0.4
Local	High	0.6	6.0	10.0	0.4
	Medium	0.5	6.0	10.0	0.4
	Low	0.3	6.0	10.0	0.4

Source: [24, Table 3]

Table 8: Recommended Overall Uniformity Cross and Along the Roadway, Along the Axis of the Road Which Coincides with a Typical Driver's Eye Position, and the Threshold Increment for Glare Compensation

Category	Average level	L_{min}/L_{avg} or E_{min}/E_{avg}	L_{min}/L_{max} or E_{min}/E_{max}	TI (threshold increment)
Residential areas, pedestrians and many non-motorized vehicles	1-2 lux	0.2, E_{min}/E_{avg}	n/a	n/a
largely residential but some motorized vehicles	4-5 lux	0.2, E_{min}/E_{avg}	n/a	n/a
Major access roads, distributors and minor main roads	0.5 cd/m^2 (~8 lux)	0.4, L_{min}/L_{avg}	0.5, L_{min}/L_{avg}	n/a
Important rural and urban traffic routes	1.0 cd/m^2 (~15 lux)	0.4, L_{min}/L_{avg}	0.6, L_{min}/L_{avg}	20%
High-speed roads, dual carriageways	1.5 cd/m^2 (~25 lux)	0.4, L_{min}/L_{avg}	0.7, L_{min}/L_{avg}	15%

Source: [27]

Table 9: Illuminance and Luminance Recommendations (Metric)

Roadway and Walkway Classification	Off-Roadway Light Sources	Illuminance Method						Luminance Method			Additional Values (both methods)
		Average Maintained Illuminnace				Min. Illuminance	Illuminance Uniformity Ratio	Average Maintained Luminance			Veiling Luminance Ratio
		R1	R2	R3	R4			Lavg	Uniformity		
	General Land Use	(min. lux)	(min. lux)	(min. lux)	(min. lux)	(lux)	(max. avg/min)	(min. cd/sq.m.)	max. Lavg/Lmin	(max. Lmax/Lmin)	(max. Lvmax/Lavg)
Principal Arterials											
Interstate and other freeways	Commercial	6 to 12	6 to 12	6 to 12	6 to 12	2	3:1 or 4:1	0.4 to 1.0	3.5:1	6:1	0.3:1
	Intermediate	6 to 10	6 to 10	6 to 10	6 to 10	2	3:1 or 4:1	0.4 to 0.8	3.5:1	6:1	0.3:1
	Residential	6 to 8	7 to 8	8 to 8	9 to 8	2	3:1 or 4:1	0.4 to 0.6	3.5:1	6:1	0.3:1
Other Principal Arterials (partial or no control of access)	Commercial	12	17	17	15	As Uniformity Ratio Allows	3:1	1.2	3:1	5:1	0.3:1
	Intermediate	9	13	13	11.0		3:1	0.9	3:1	5:1	0.3:1
	Residential	6	9	9	8		3:1	0.6	3.5:1	6:1	0.3:1
Minor Arterials	Commercial	10.0	15.0	15.0	11.0		4:1	1.2	3:1	5:1	0.3:1
	Intermediate	8.0	11.0	11.0	10.0		4:1	0.9	3:1	5:1	0.3:1
	Residential	5.0	7.0	7.0	7.0		4:1	0.6	3.5:1	6:1	0.3:1
Collectors	Commercial	8	12	12	10		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	6	9	9	8		4:1	0.6	3.5:1	6:1	0.4:1
	Residential	4	6	6	5		4:1	0.4	4:1	8:1	0.4:1
Local	Commercial	6	9	9	8		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	5	7	7	6		6:1	0.5	6:1	10:1	0.4:1
	Residential	3	4	4	4		6:1	0.3	6:1	10:1	0.4:1
Alleys	Commercial	4	6	6	5		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	3	4	4	4		6:1	0.3	6:1	10:1	0.4:1
	Residential	2	3	3	3		6:1	0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	10	14	14	13		3:1	Use illuminance requirements			
	Intermediate	6	9	9	8		4:1				
	Residential	3	4	4	4		6:1				
Pedestrian Ways and Bicycle Ways	All	15	22	22	19		3:1				

Notes:

1. Meet either the illuminance design method requirements or the luminance design method requirements and meet veiling luminance requirements for both the illuminance and the luminance design methods

2. Assumes a separate facility. For Pedestrian Ways and Bicycle Ways adjacent to roadway, use roadway design values. Use R3 requirements for walkway/bikeway surface materials other than the pavement types shown. Other design guidelines such as IESNA or CIE may be used for pedestrian ways and bikeways when deemed appropriate.

3. Lv(max) referes to the maximum point along the pavement, not the maximum in lamp life. The maintenance factor applies to both the Lv term and Lavg term.

4. There may be situations when a higher level of illuminance is justified. The higher values for freeways may be justified when deemed advantageous by the agency to mitigate off-roadway sources.

5. Physical roadway conditions may require adjustment of spacing determined from the base levels of illuminance indicated above.

6. Higher uniformity ratios are acceptable for elevated ramps near high-mast poles.

7. See AASHTO publication entitled, "A Policy on Geometric Design of Highways and Streets" for roadway and walkway classifications.

Source: [25, Table3-5b]

Table 10: Illuminance and Luminance Recommendations (English)

Roadway and Walkway Classification	Off-Roadway Light Sources	Illuminance Method						Luminance Method			Additional Values (both methods)
		Average Maintained Illuminnace				Min. Illuminance	Illuminance Uniformity Ratio	Average Maintained Luminance			Veiling Luminance Ratio
		R1	R2	R3	R4			Lavg	Uniformity		
	General Land Use	(min. fc)	(min. fc)	(min. fc)	(min. fc)	(fc)	(max. avg/min)	(min. cd/sq.m.)	max. Lavg/Lmin	(max. Lmax/Lmin)	(max. Lvmax/Lavg)
Principal Arterials											
Interstate and other freeways	Commercial	0.6 to 1.1	0.6 to 1.1	0.6 to 1.1	0.6 to 1.1	0.2	3:1 or 4:1	0.4 to 1.0	3.5:1	6:1	0.3:1
	Intermediate	0.6 to 0.9	0.6 to 0.9	0.6 to 0.9	0.6 to 0.9	0.2	3:1 or 4:1	0.4 to 0.8	3.5:1	6:1	0.3:1
	Residential	0.6 to 0.8	0.6 to 0.8	0.6 to 0.8	0.6 to 0.8	0.2	3:1 or 4:1	0.4 to 0.6	3.5:1	6:1	0.3:1
Other Principal Arterials (partial or no control of access)	Commercial	1.1	1.6	1.6	1.4	As Uniformity Ratio Allows	3:1	1.2	3:1	5:1	0.3:1
	Intermediate	0.8	1.2	1.2	1.0		3:1	0.9	3:1	5:1	0.3:1
	Residential	0.6	0.8	0.8	0.8		3:1	0.6	3.5:1	6:1	0.3:1
Minor Arterials	Commercial	0.9	1.4	1.4	1.0		4:1	1.2	3:1	5:1	0.3:1
	Intermediate	0.8	1.0	1.0	0.9		4:1	0.9	3:1	5:1	0.3:1
	Residential	0.5	0.7	0.7	0.7		4:1	0.6	3.5:1	6:1	0.3:1
Collectors	Commercial	0.8	1.1	1.1	0.9		4:1	0.8	3:1	5:1	0.4:1
	Intermediate	0.6	0.8	0.8	0.8		4:1	0.6	3.5:1	6:1	0.4:1
	Residential	0.4	0.6	0.6	0.5		4:1	0.4	4:1	8:1	0.4:1
Local	Commercial	0.6	0.8	0.8	0.8		6:1	0.6	6:1	10:1	0.4:1
	Intermediate	0.5	0.7	0.7	0.6		6:1	0.5	6:1	10:1	0.4:1
	Residential	0.3	0.4	0.4	0.4		6:1	0.3	6:1	10:1	0.4:1
Alleys	Commercial	0.4	0.6	0.6	0.5		6:1	0.4	6:1	10:1	0.4:1
	Intermediate	0.3	0.4	0.4	0.4		6:1	0.3	6:1	10:1	0.4:1
	Residential	0.2	0.3	0.3	0.3		6:1	0.2	6:1	10:1	0.4:1
Sidewalks	Commercial	0.9	1.3	1.3	1.2		3:1	Use illuminance requirements			
	Intermediate	0.6	0.8	0.8	0.8		4:1				
	Residential	0.3	0.4	0.4	0.4		6:1				
Pedestrian Ways and Bicycle Ways	All	1.4	2	2	1.8		3:1				

Notes:

1. Meet either the illuminance design method requirements or the luminance design method requirements and meet veiling luminance requirements for both the illuminance and the luminance design methods
2. Assumes a separate facility. For Pedestrian Ways and Bicycle Ways adjacent to roadway, use roadway design values. Use R3 requirements for walkway/bikeway surface materials other than the pavement types shown. Other design guidelines such as IESNA or CIE may be used for pedestrian ways and bikeways when deemed appropriate.
3. Lv(max) referes to the maximum point along the pavement, not the maximum in lamp life. The maintenance factor applies to both the Lv term and Lavg term.
4. There may be situations when a higher level of illuminance is justified. The higher values for freeways may be justified when deemed advantageous by the agency to mitigate off-roadway sources.
5. Physical roadway conditions may require adjustment of spacing determined from the base levels of illuminance indicated above.
6. Higher uniformity ratios are acceptable for elevated ramps near high-mast poles.
7. See AASHTO publication entitled, "A Policy on Geometric Design of Highways and Streets" for roadway and walkway classifications.

Source: [25, Table3-5a]

4.2.1.2 High-Mast Lighting

High-mast lighting is also commonly used for lighting interchanges and complex intersections in both urban and rural areas and tangent sections with more than six lanes [24]. The recommended illuminance for intersections is listed in Table 11.

Table 11: Recommended Illuminance for the Intersection of Continuously Lighted Urban Streets, Based on the Values in Table 6 for R2 and R3 Pavement Classifications

Illuminance for Intersections				
Functional Classification	Average Maintained Illumination at Pavement by Pedestrian Area Classification (lux/fc)			Eavg/Emin
	High	Medium	Low	
Major/Major	34.0/3.4	26.0/2.6	18.0/1.8	3.0
Major/Collector	29.0/2.9	22.0/2.2	15.0/1.5	3.0
Major/Local	26.0/2.6	20.0/2.0	13.0/1.3	3.0
Collector/Collector	24.0/2.4	18.0/1.8	12.0/1.2	4.0
Collector/Local	21.0/2.1	16.0/1.6	10.0/1.0	4.0
Local/Local	18.0/1.8	14.0/1.4	8.0/0.8	6.0

Source: [24, Table 9]

High-mast lighting typically consists of clusters of three to six or more luminaires mounted on rings, which can be mechanically lowered to near ground levels for servicing [24]. In Kansas, the number of luminaires on the pole top is typically three (3). Kansas often uses three 1000 Watt HPS lamps per tower.

Design for high-mast lighting can utilize the illuminance method or via computer simulation, e.g., in AGI software program. High-mast lighting LED luminaires with both symmetrical and asymmetrical light distributions can be used [24]. Full cutoff and cutoff LED luminaires are desirable to avoid excessive glare, while full cutoff is already recommended. Conventional HPS lamps consuming up to 1000 watts are sometimes employed, while LED luminaires usually consume much less wattage (50% or less).

High-mast lighting for interchanges is frequently less expensive to install than standard pole lighting due to the reduced complexity of conduit, conductor and the smaller number of luminaires and poles required [24]. Note that other than these interchange locations, conventional standard pole lighting usually requires a smaller initial cost.

4.2.1.3 Spill Light Level

Spill light level criteria are developed and documented by the IES [28, 29]. Classification factors that will be listed on the warrant sheets of the LED lighting installation are defined as follows [26]:

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

Based on these factors, different lighting zones are defined for light trespass classification as listed below.

- LZ1 Zone - Dark Ambient Lighting (e.g., state parks, recreation areas, and wildlife preserves)
- LZ2 Zone - Low Ambient Lighting (e.g., rural areas, as defined by the 2000 U.S. Census)
- LZ3 Zone - Medium Ambient Lighting (e.g., urban areas, as defined by the 2000 U.S. Census)
- LZ4 Zone - High Ambient Lighting (e.g., metropolitan areas)

In the designated Lighting Zone (LZ1 to LZ4), the design values for spill light levels are shown in Table 12. These levels are recommended by the IES where possible. They are typically calculated and measured from the residential boundary line, but are sometimes evaluated from the location of the residence being investigated [26]. Since most of Kansas is rural, most LED lighting projects assume the lighting zone LZ2, which is the designation for low ambient illumination. The recommended maximum illuminance spill light level is 3.0 lux, pre-curfew.

Table 12: Spill Light Levels

Designation	**Recommended maximum illuminance level (E_e)**	
	Pre-Curfew	**Post-Curfew (Not Applicable to Roadway Lighting)**
LZ1	1.0 lux	0.0 lux
LZ2	3.0 lux	1.0 lux
LZ3	8.0 lux	3.0 lux
LZ4	15.0 lux	6.0 lux

Table 13 lists the lower threshold luminous intensity of roadway luminaires, without cutoff, to be considered glare sources [26]. Any intensity higher than those values will cause glare to the vehicle operators or pedestrians. This method will typically be applied where high-wattage light sources such as flood lighting or high-mast lights are used [26].

Table 13: Source Intensity Levels that Cause Glare

Light Technical Parameter	Application Conditions	Environmental Zones			
		LZ1	LZ2	LZ3	LZ4
Luminous intensity (I) emitted by luminaires	Pre-Curfew:	2500 cd	7500 cd	10000 cd	25000 cd
	Post-Curfew	500 cd*	500 cd	1000 cd	2500 cd

*Note: for public (road) lighting, otherwise, it will be 0 cd.
Source: [26]

4.2.2 Roadway Lighting Layout Computer Calculation

Roadway lighting layout of a real project could be simulated in computer software programs, e.g., AGI32. This project conducted a great deal of work in computer simulations to evaluate and select the qualified LED roadway products for Kansas use. Nonetheless, this manual does not cover the actual procedure and technical details of how to conduct computer simulation. Assistance in computer calculations and rendering is available in the University of Kansas lighting research laboratory upon request.

In AGi32, the calculation grid is often set at 3 x 3 feet across the road surfaces. Calculation results include the horizontal illuminance, vertical illuminance, spill light levels, and driver's eye luminance. The horizontal calculation points are located on the pavement, while the vertical calculation points are placed 5 feet above the pavement. The spill light levels are calculated in the single row of calculation points surrounding the roadway. The driver's eye luminance levels are calculated in the vertical calculation points at both the top and bottom of the roadway.

For all of the luminaire simulations completed in AGi32, a simulation report can be compiled in order to summarize the performance of the luminaire. For standard pole lighting, each report includes a page summarizing 1) the luminaire properties, 2) the one-sided lighting calculation results, 3) the staggered lighting calculation results, 4) the opposite lighting calculation results, and 5) the median lighting calculation results. For high-mast lighting, the report could cover lighting performance evaluation for highway interchanges or major intersections.

Chapter 5: Selection of Qualified LED Roadway Luminaires

5.1 Specifications of Qualified LED Roadway Lighting Systems

5.1.1 List of Factors for Specifications

The specifications of qualified LED roadway lighting products, poles, and supporting electrical systems should at least comply with the requirements of AASHTO (American Association of State Highway and Transportation Officials), FHWA (Federal Highway Administration), IES (Illuminating Engineering Society), and CIE (International Commission On Illumination) standards, and also comply with state and local specifications.

A complete list of specifications of qualified LED roadway lighting systems may include the following:

- Manufacturer
- Luminaire model #
- Voltage (DC/AC)
- Drive current (mA)
- Wattage
- Luminaire dimensions (L x W x H) / Length & Height
- Luminaire weight
- Lens (glass)
- Mount style (post-top, side-arm, etc.)
- Pole height (if post-top mounted)
- Pole spacing (vary with different layout)
- Arm length, horizontal (not including luminaire length unless specified)
- Luminaires per pole
- Number of LEDs per luminaire
- Initial lumen
- Uniformity (on the pavement)
- Efficacy (Lumen/Watt)
- CCT (K)

- CRI
- Light lateral distribution (Type I - V)
- Cutoff classification (full cutoff, cutoff, semi-cutoff, non-cutoff)
- BUG rating
- LED driver manufacturer
- Driver model #
- Control technology (passive infrared, Ultrasonic, or dual tech, etc.)
- Dimming or non-dimming
- Light curfews
- Sensor types (daylight photosensor, occupancy, etc.)
- Sensor mount location
- Coverage pattern (circle 360 degree, rectangular, etc.)
- Luminaire certificate (UL, CSA, ETL, etc.)
- Luminaire IP rating
- Luminaire life L_{70}
- Costs
- Warranty

In addition, a list of specifications of the roadway environment may include the following:

- Surrounding land use
- Surrounding lighting
- Traffic flow
- Traffic management interaction
- Safety and security concerns
- Sky glow and light trespass issues, etc.

While all those factors are important for the specifications of qualified LED roadway lighting systems in certain road environments, there are some key factors that are frequently used in roadway lighting design and layout. Those key factors are listed below.

- Initial lumen
- Uniformity (on the pavement)
- Efficacy (Lumen/Watt)
- CCT (K)
- CRI
- Light lateral distribution (Type I - V)
- Cutoff classification (full cutoff, cutoff, semi-cutoff, non-cutoff)
- BUG rating
- Control technology (passive infrared, Ultrasonic, or dual tech. etc.)
- Dimming or non-dimming
- Luminaire certificate (UL, CSA, ETL, etc.)
- Luminaire IP rating
- Luminaire life L_{70}
- Costs
- Warranty

5.1.2 Recommended Specifications for Qualified LED Roadway Luminaires

During the design stage of LED lighting, designers need to determine the minimum required value of the most essential property of each roadway luminaire to comply with the recommended levels by codes and standards (aforementioned). While all those factors listed in Table 1 before are important for the specifications of qualified LED roadway lighting systems in certain road environments, there are several key factors that are most frequently used in roadway lighting design and layout, including initial lumen output, luminaire efficacy, CCT, CRI, light lateral distribution, cutoff, light levels on the pavement and the uniformity, lighting zone, spill light, BUG rating, control technology, dimming, certificate, IP rating, life, cost, and warranty.

The specifications of qualified LED roadway lighting products, poles, and supporting electrical systems should comply with the requirements of AASHTO (American Association of State Highway and Transportation Officials) [25], FHWA (Federal Highway Administration) [26], IES (Illuminating Engineering Society) [28-32], CIE (International Commission On Illumination) [33] standards, and also comply with Kansas state [34] and local city specifications if any.

A pilot run of the computer simulation tests of sample products in more than 140 product families was also conducted. In the pilot run of computer simulations, a standard luminaire layout was tested for each roadway type (one-sided, staggered, opposite, median) based off of the most respected codes and standards. The luminaire layout is as follows:

- Luminaire Spacing: 60 feet
- Mounting Height: 40 feet
- Arm Length: 15 feet
- Luminaire Offset: 5 feet from roadway shoulder

It was determined in the pilot run that a minimum lumen output of about 4000 lumen (at least 3700 lm, ideally 4000 or more lm) is required to satisfy the horizontal illuminance required of 0.6 footcandles but with fluctuations depending on the luminaire design and distribution pattern. The minimum luminaire efficacy is recommended as $\geq$ 60 lm/W. Also, light lateral distribution should be types III, IV, V, and VS. Types I and II are tested inappropriate for typical highway lighting.

Based on a thorough review of those requirements and results of the pilot run of the computer simulation tests, the key specifications of qualified products were identified. Table 14 lists the values required for qualified LED roadway lighting products on the Approved Products List (APL) for roadways in Kansas. Table 15 is the recommended specifications for qualified LED roadway luminaires.

Table 14: Required Specifications for Qualified LED Roadway Luminaires for Kansas

Key Specifications	Values
Initial lumen (lm)	At least 3700, ideally 4000 or more
Luminaire efficacy (lm/W)	At least 60, ideally 80-120, the higher, the better
CCT (K)	3000-5700
CRI	At least 70
Light lateral distribution	Types III, IV, V, and VS
Cutoff classification	Full cutoff
Minimum maintained average light level on the pavement	6 lx
Average maintained illuminance on pavement for intersections	13-34 lx
Light uniformity ($E_{avg.}/E_{min.}$ ratio) on the pavement	Maximum 3
The Lighting Zone designations	LZ1, LZ2, LZ3, LZ4, typically LZ2 for low ambient illumination in Kansas for highway.
Maximum illuminance spill light level	3 lx, pre-curfew
BUG rating	Ideally B3-U3-G3 or lower
Control technologies	Photosensors, motion sensors, temperature sensors, drive current sensors, or voltage sensors for surge protection
Dimming or non-dimming	Dimmable
Luminaire certificate	UL, CSA, ETL, etc.
Luminaire IP rating	IP66 or above
Luminaire life L_{70}	50,000 – 100,000 hours, or more
Costs	The lower, the better
Warranty	At least 5-10 years, ideally 12 years or more

Table 15: Recommended Specifications for Qualified LED Roadway Luminaires

Key Specifications	Values
Initial lumen	Ideally 4000 lumen or more
Light uniformity Avg./Min ratio on the pavement	Maximum 3
Efficacy (Lumen/Watt)	At least 60 lm/W, ideally 80 – 120 lm/W, the higher, the better.
CCT (K)	3000 K – 5700 K
CRI	At least 70
Light lateral distribution (Type I - V)	Types III, IV and V
Cutoff classification (full cutoff, cutoff, semi-cutoff, non-cutoff)	Full cutoff
BUG rating	Max. B3U3G3, ideally B1U0G1 or lower
Control technology	Passive infrared, Ultrasonic, dual tech.
Dimming or non-dimming	Dimmable
Luminaire certificate	UL, CSA, ETL
Luminaire IP rating	IP66 or above
Luminaire life L_{70}	50,000 – 100,000 hours, or more
Costs	The lower, the better
Warranty	5-10 years or more

5.2 Prequalified Product List (PQL)

The compilation of the Prequalified Product List (PQL) was the first task completed in the project. Many manufacturers make LED roadway lighting systems, including luminaires and controls, whose specification details are often available online. The research team conducted a comprehensive search of all LED roadway luminaires available in the current U.S. market. In addition, the manufacturer's sales representatives, with their best technologies on the market, aided the project team in gaining the most recent information of the LED roadway luminaires. Through compiling product specification sheets and communications with sales representatives, the PQL was made. As seen in Appendix A, the PQL contains a total of 146 LED roadway luminaires from various manufacturers in the United States and Canada.

Nonetheless, the 146 LED roadway luminaires on the PQL are too many for practical implementation. They were evaluated based on the information provided by the manufacturers, thus, their photometric performance need to be tested in this project for roadway uses in Kansas. The project team conducted the second task—the acceptance testing—to test all products on the PQL to find the qualified LED luminaires that are most appropriate for roadway lighting in Kansas.

5.3 Acceptance Testing in AGi32

All of the 146 LED luminaires on the Prequalified Product List (PQL), each with various models, were screened over the key specifications listed in Table 2. Their photometric performance was tested via computer simulation in the AGi32 software for optimized roadway layout and luminaire placement. Luminaire photometric performance analyses include calculating horizontal illuminance and uniformity on the pavement, vertical illuminance, and spill light levels. The test results were compared to the key specifications summarized in Table 2 for judgment of their compliance with the codes and standards. Additionally, AGi32 was used for visualization of the lighting systems to predict the roadway lighting effect in real world.

In the AGi32 simulation, ideally every single model (with its individual IES file) of the 146 LED luminaires should be tested on typical roadway layouts in Kansas. Such testing configurations include typical roadway types, typical pole spacing, and typical geometries of the luminaire support systems. The roadways in Kansas that need LED luminaires first include freeway (class A, B), expressway, and major roads. Most roadways need standard poles, while the interchanges and large intersections in both urban and rural areas as well as tangent sections with more than six lanes may need high-mast lighting.

In practice, the obsolete HID streetlights are to be swapped with the LED luminaires mounted on the same poles. The pole spacing, mounting height, and mast arm length would not be changed for cost savings. This results in a concern that the upgraded LED roadway lighting may or may not meet the requirement of light uniformity ($E_{avg.}/E_{min.}$ ratio ≤ 3) on the pavement. Therefore, for the acceptance testing of the 146 LED luminaires on the PQL, the project team undertook lighting calculations in AGi32 to define an optimal pole spacing of every LED luminaire that surely meets the criteria listed in Table 2. The optimal pole spacing may not be exactly 150 ft as currently used in Kansas for 150W HPS mounted on 40 ft poles.

In the AGi32 simulation, the Roadway Optimizer tool was used to optimize the luminaire spacing and layouts based on the recommended minimum maintained average illuminance of 6 lx on pavement and the maximum uniformity $E_{avg.}/E_{min.}$ ratio of 3 [24, Table 2; 25, Tables 3-5a] that apply to most roads in Kansas. The recommended average maintained illuminance on pavement is in a range of 13-34 lx with a maximum $E_{avg.}/E_{min.}$ ratio of 3 that is appropriate for intersections in Kansas [32, Table 9]. Since most of Kansas is rural, the recommended maximum spill light level is 3 lux, pre-curfew for Lighting Zone designations of LZ2, which is the designation for low ambient illumination [28, 29]. The spill light levels were typically calculated and measured from the boundary line of the simulated project site.

Table 16 summarizes the typical layout specifications used in the AGi32 simulation for the four types of roadway lighting calculations (i.e., one-sided, staggered, opposite, median lighting), including an optimal spacing that varies with different IES files, mounting height, tilt angle, arm length, setback distance, total width, number of lanes, shoulder width, and median width if applicable. The calculation grid in AGi was set at 3 x 3 ft across the road surfaces. The horizontal calculation points were located on the pavement, while the vertical calculation points for spill light were placed 5 ft above the pavement along the boundary line surrounding the roadway. The calculated values were then compared to the criteria listed in Table 14 for compliance check with the codes and standards.

Table 16: The Layout Specifications for the Four Types of Roadway Lighting in the AGi32 Simulation

Layout specifications	Types of roadway lighting layout			
	One-sided	**Staggered**	**Opposite**	**Median**
Pole spacing (ft)	Varies	Varies	Varies	Varies
Mounting height (ft)	40	40	40	40
Tilt angle (deg)	0	0	0	0
Arm length (ft)	15	15	15	15
Setback (ft)	5	5	5	5
Total road width (ft)	40	72	93	76
# of lanes	2	4	6	4
Shoulder width (ft)	8	8	8	8
Median width (ft)	N.A.	N.A.	4	12

After dozens of luminaires were tested in AGi32, the research team noticed a pattern with the lower threshold luminaires' lumen output of at least 3700 lumens and other recommended specifications (e.g., luminaire efficacy ≥ 60 lm/W, light lateral distribution Types III, IV, V, and VS) listed in Table 14 to pass the acceptance testing. This finding was very useful to reduce the overall computer simulation time. Given that there are a total of 146 products on the PQL list, each has a large number (approximately 10-60) of IES files to be tested in AGi32, the computer simulation time would otherwise need an overwhelming 1,500-2,100 hours. The project team came up with a strategy to reduce the computer simulation time. All products were quickly screened over the judging criteria listed in Table 2 based on their photometry data published on their specification sheets into three groups: those will surely pass the acceptance tests, those will surely fail, and those unknown. The team conducted computer simulation tests only for products fallen in the "unknown" group to dramatically reduce time for testing the 146 LED luminaires on the PQL.

Moreover, AGI simulation was conducted for testing multiple high-mast LED luminaires on the PQL, which would replace the HPS or Metal Halide high-mast lights currently installed in the interchanges in Kansas. In Kansas, typically three lights are symmetrically mounted on the top of the high-mast tower. For future expansion, those high-mast LED luminaires may also be used in various large intersections or tangent sections with more than six lanes. To speed up the AGI simulation, no specific interchanges or intersections were modeled, since their geometries vary dramatically, for testing three high-mast LED luminaires symmetrically mounted on the top of the tower. Instead, only a single high-mast LED luminaire of each model was mounted on the 100 ft high tower and tested in AGi32 to measure its light distribution in one-sided and median lighting layouts with multiple lanes. The simulated uniform light distribution will most likely apply for different types of interchanges or large intersections.

For all of the luminaire simulations completed in AGi32, a simulation report was compiled to summarize the performance of the luminaires. The passing luminaires were added to the Approved Products List (APL).

5.4 Approved Products List (APL)

Based on the acceptance testing, an approved products list (APL) was compiled, reducing the number from 146 luminaires on the PQL down to 83 on the APL that met the requirements for Kansas uses. Appendix B shows the specifications of the 83 LED luminaires on the APL. Although it is good for Kansas to have many choices of qualified LED products to use for their roadway lighting, the APL is too long for practical implementation. Therefore, KDOT requested a short list of highly recommended LED luminaires for efficient implementation in the future.

5.5 Short List of Highly Recommended Products

Based on the luminaire efficacy, technological innovation, availability of manufacturer sales representatives, and payback time period for roadway implementation in Kansas, the APL with 83 LED luminaires was further reduced to 13 standard pole and three high-mast LED luminaires. This short list is summarized in Table 17.

Table 17: Recommended Short List of Approved Products, All Full Cutoff and Dimmable

#	Manufacturer	Luminaire model #	Voltage (VAC)	Wattage (W)	Initial lumen (lm)	Efficiency (lm/W)	CCT (K)	CRI
				Standard Pole				
1	Acuity	Autobahn ATB0	120-277, 347-480	37-92	3800-11100	82-103	4000, 5000	70
2	Acuity	Autobahn ATB2	120-277, 347-480	94-187	7027-25254	79-107	4000, 5000	70
3	GE	Evolve LED Roadway Scalable Project Grade Cobrahead	120-277,	42-269	3700-22800	75-91	4000, 5700	70
4	GE	Evolve LED Roadway Scalable Specification Grade Cobrahead	120-277, 347-480	31-285	2800-22400	75-100	4000, 5000	70
5	Cree	LEDway Series Street Lights	120-277, 347-480	47-274	3730-26707	79-97	3000, 4000, 5700	70
6	Cree	XSL LEDway High Output Street Light	120-277, 347-480	136	13021-13784	95-101	3000, 4000, 5700	70 80
7	Philips	RoadView (RVM)	120-277, 347-480	105-260	10500-23700	91-100	4000	70
8	Philips	RoadView (RVS)	120-277, 347-480	37-129	3700-12400	96-100	4000	70
9	Philips	RoadStar (GPLM)	120-277, 347-480	119-204	8200-12500	61-69	4000	70
10	Philips	RoadStar (GPLS)	120-480	45-102	3152-6217	61-70	4000	70
11	Philips	RoadFocus Cobra Head - L	120-277, 347-480	145-241	15700-28600	113-119	4000	70
12	Philips	RoadFocus Cobra Head - M	120-277, 347-480	73-161	8100-16800	93-118	4000	70
13	Philips	RoadFocus Cobra Head - S	120-277, 347-480	38, 54	3900-5500	96-110	4000	70
				High Mast Lighting				
1	Holophane	HMAO-LED II	120-277, 347-480	249-498	30700-61400	123	4000	70
2	Cree	Edge High Output High Mast	120-277, 347-480	267-831	17200-72500	64-83	4000, 5000	70
3	Cooper Lighting	Galleon LED (High Mast)	120-277, 347-480	30-528	5100-53500	101-170	3000, 4000, 6000	70

Chapter 6: Potential Payback Evaluation

6.1 Introduction

The research team conducted economic studies on potential payoff evaluation of all LED roadway lighting systems listed in the Approved Products List (APL). Such evaluation includes estimation of initial, operating and maintenance costs, cost-benefit analysis on a lifetime cycle basis, and payback period calculations. The results will be recommended for internal use by the KDOT employees and districts and cities in Kansas, or other authorized users. The results are not available to vendors or manufacturers.

As a result, this manual includes a lighting economics calculator developed in the economic studies. The goal of the lighting economics calculator is to provide KDOT a useable spreadsheet in order to estimate the costs and payback periods of implementing a new LED roadway lighting system. The spreadsheet is based off of several changeable assumptions that can be adapted to a particular project. The user has the ability to customize many factors, including: 1) operating hours, 2) luminaire quantity, 3) maintenance cost, 4) luminaire installation costs, 5) luminaire prices, 6) average lifecycle, and 7) electricity/demand costs, among others.

6.2 Implementation Cost Analysis and Results

A lighting economics calculator was then developed to compare the short list products to their equivalent existing HPS luminaire counterparts, for an assumed project size of 1,000 luminaires. The goal of the lighting economics calculator was to provide KDOT a useable spreadsheet to estimate the costs and payback time periods of implementing a new LED roadway lighting system in Kansas. The lighting economics calculator was designed to allow the user to make necessary changes of design input that could be adapted to a particular project, including (a) operating hours, (b) average lifecycle, (c) luminaire quantity, (d) luminaire price, (e) maintenance cost, (f) luminaire installation cost, and (g) electricity/demand cost. The KDOT lighting specialists can reuse the spreadsheet for a variety of projects across the state. Design inputs for different projects will automatically update the cost analysis results.

The lighting economics calculator was developed based on some presumptions, including lifecycle of the roadway lighting system, its annual operating hours, typical specifications of the pre-existing lighting systems, average maintenance and installation costs, prices of the LED and HPS roadway luminaires, and energy rates charged by the local electric utility provider. These presumptions came from the specifications of the 83 LED luminaires on the APL, the electric utility provider, and reviews of some case studies from states that have already implemented new LED roadway lighting systems to replace their existing systems. These states include Missouri [35], Minnesota [36], Arizona, and California. The presumptions are detailed as follows.

The overall lighting economics calculator was based on a reasonable 12-year lifecycle for the roadway lighting system, calculated with a minimum useful life of 50,000 hours for the LED luminaires on the APL and the presumed annual operating hours. The operating hours for the roadway luminaires were based on operation times of approximately ½ hour before sunset and ½ hour after sunrise, estimated to be 11 hours per day for 365 days, totaling 4,015 hours per year. Note that the useful life of the existing HPS luminaires is often 20,000 hours, and 10,000 hours for the existing high-mast metal halide luminaires installed in Kansas. As a result, re-lamping of the existing HID roadway luminaires is expected over the 12-year lifecycle.

In this calculator, the pre-existing standard pole luminaires were the typical 150 W HPS with a typical pole spacing of 150 ft and a typical lumen output of typically 16,000 lm. The pre-existing high-mast lights were the typical 400 W Metal Halide luminaires with a typical mounting height of 100 ft and a typical lumen output of 32,000 lm. Both lighting systems are commonly mounted in Kansas. The replacement LED luminaires used in the calculators were those from the APL short list (including 13 standard pole lights and three high-mast lights) with minimum wattage and lumen output that could pass the photometric requirements of the codes and standards as listed in Table 2. Note that the actual wattages of the HID and LED lighting systems would be a bit more than the lamp wattages considering the extra power consumed by the electronic devices like the ballasts or drivers.

The average maintenance cost ($225/luminaire) and installation cost ($110/luminaire, $800/pole) for Kansas roadway lighting were used, based on the RS Means [37]. The price of LED luminaires was calculated from a normalized average cost of $4 per Watt, based on the lighting economics studies of other states. Additionally, the DOE developed Equations (1) and (2) for HPS roadway luminaire price. Equations (1) and (2) were also used to estimate the prices of the MH high-mast luminaires.

$$HPS\ Lamp\ =\ 3.6562\ *\ FW^{0.525} \qquad \textbf{Equation (1)}$$

$$HPS\ Lum. =\ 0.0944\ *\ FW\ +\ 204.18 \qquad \textbf{Equation (2)}$$

Where:

HPS Lamp = HPS lamp price in $;

HPS Lum. = HPS luminaire price in $;

FW = fixture Watts.

For this project, the Commercial and Industrial Pricing Rates, such as Small General Service, Medium General Service, and High Load Factor Electric Rate, were used from the largest electric utility provider in Kansas—Westar Energy headquartered in Topeka, Kansas [38]. The Small, Medium, and Large Power Service rates are based on the kilowatt (kW) demand and load factor (hours of use versus maximum kW load). Assuming the lighting usage for KDOT highways is larger than 1,000 kW, it falls under Westar’s High Load Factor rate. Based on this billing information, the energy rates for Energy Cost (EC) and Demand Cost (DC) are $0.0149/kWh and $12.327/kW, respectively.

Table 18 lists the constants used in this project. Those presumed values are editable by the user of the economics calculator to apply to a variety of different projects. This allows the KDOT lighting specialists to input their project-specific data later.

Table 18: Values of Typical Factors Presumed in this Project

Factor	Symbol	Values
Energy Cost rate	*EC*	$0.0149/kWh
Demand Cost rate	*DC*	$12.327/kW
Operating hours	*OH*	4,015 hours/year
Total luminaire quantity in this project	*Qty*	1,000
Average maintenance cost in $/luminaire	*Avg. MC*	$225/luminaire
Pole installation cost in $/pole	*Pole IC*	$800/pole
Luminaire installation cost in $/luminaire	*Lum. IC*	$110/luminaire
Avg. LED Luminaire Cost in $/Watt		$4/Watt
Project lifecycle	*Avg. LC*	12 years

The lighting economics calculator was made using Microsoft Excel. The spreadsheet identifies energy and demand usage of the existing HPS luminaires compared to those of the LED roadway luminaires on the APL short list (Table 4). In addition to energy and demand cost, maintenance and installation costs were taken into account to determine the total lifecycle and annualized cost for each luminaire. Based on these calculations, the cost savings results and the simple payback time period were calculated for each of the LED products on the APL short list.

In addition to aforementioned Equations (1) and (2), other equations used in the excel spreadsheet calculations are listed below.

$$Avg.NLR = \frac{Avg.LC}{Avg.Life/OH}$$ **Equation (3)**

$$EU = \frac{Qty.*OH*FW}{C1}$$ **Equation (4)**

$$LEC = EU * EC * Avg.LC$$ **Equation (5)**

$$DU = \frac{Qty.*FW}{C1}$$ **Equation (6)**

$$LDC = DU * DC * Avg.LC$$ **Equation (7)**

$$LLMC\ LED = Qty.* NLR * (Avg.MC + (Avg.\ LED\ Lum.Cost * FW))$$ **Equation (8)**

$$LLMC\ HPS = Qty.* NLR * (Avg.MC + HPS\ Lamp)$$ **Equation (9)**

$$EIC\ LED = Qty.* ((Avg.LED\ Lum.Cost * FW) + Lum.IC + Pole\ IC)$$ **Equation (10)**

$$EIC\ HPS = Qty.* (HPS\ Lum. + Lum.IC + Pole\ IC)$$ **Equation (11)**

$$TLC = LEC + LDC + EIC + LLMC$$ **Equation (12)**

$$AC = \frac{TLC}{Avg.LC}$$ **Equation (13)**

$$AECS = \frac{(HPS\ LEC + HPS\ LDC) - (LED\ LEC + LED\ LDC)}{Avg.LC}$$ **Equation (14)**

$$ASPS = \frac{HPS\ AC - LED\ AC}{Qty.}$$ **Equation (15)**

$$TAS = HPS\ AC - LED\ AC$$ **Equation (16)**

$$LCS = TAS * Avg.LC$$ **Equation (17)**

$$SPB = \frac{AC}{TAS}$$ **Equation (18)**

Where:
HPS = high pressure sodium
LED = light-emitting discharge
NLR = number of lifecycle lamp replacements
EU = energy usage in kWh/year
C1 = constant = 1000 Watts/kW
LEC = lifecycle energy cost in $
DU = demand usage in kW/year
LDC = lifecycle demand cost in $
LLMC = lifecycle lamp maintenance cost in $
EIC = initial equipment and installation cost in $
TLC = total lifecycle cost in $
AC = annualized cost in $
AECS = annual energy cost savings in $
ASPS = annual cost savings per streetlight in $
TAS = total annual savings in $
LCS = lifecycle cost savings in $
SPB = simple payback in years

Using the lighting economics calculator, the cost savings and simple payback time period were calculated for the 13 standard and three high-mast LED luminaires in Table 19, and then compared to their HID luminaire counterparts—a pre-existing standard pole 150 Watt HPS luminaire and a pre-existing high-mast 400 Watt HPS luminaire—for a project size of 1,000 luminaires. Table 19 shows the minimum wattages and corresponding initial lumens of the LED luminaires as well as their useful life that are most cost-effective for implementation in Kansas. The lower threshold wattages of those LED luminaires whose lumen output still met the codes and standards were used to maximize the energy cost savings. For the same LED luminaire but with different wattages (and thus corresponding initial lumens) used for different projects, the calculated results will be different.

The desired outcomes of this lighting economics calculator for those short list products include: (a) high energy cost savings, (b) high total lifecycle cost savings, and (c) low simple payback time period. A high annual energy cost savings will save KDOT money on their energy bill every year, even after the new LED roadway luminaire system has been paid off. The total lifecycle cost savings should be high, encouraging KDOT to see the positive outcomes that implementing this new LED roadway lighting system will have. The less the payback time, the more benefits KDOT will obtain in practice.

Table 19: APL Short List LED Luminaires Used in the Calculation with Minimum Wattages, Corresponding Initial Lumens, and Useful Life

Proposed LED Luminaire	Watts (Min.)	Lumens (Min.)	Life (hrs)
Acuity; Autobahn ATBO	49	4,747	100,000
Acuity; Autobahn ATB2	94	9,461	100,000
GE; Evolve LED Roadway Scalable Project Grade Cobrahead	54	4,200	50,000
GE; Evolve LED Roadway Scalable Specification Grade Cobrahead	45	4,000	50,000
Cree; LEDway Series Street Lights	53	5,032	100,000
Cree; XSL LEDway High Output Street Light	136	13,021	50,000
Philips; RoadView RVM	105	10,516	100,000
Philips; RoadView RVS	56	5,327	100,000
Philips; RoadStar GPLM	119	8,174	70,000
Philips; RoadStar GPLS	73	5,189	70,000
Philips; RoadFocus Cobrahead - L	145	15,700	100,000
Philips; RoadFocus Cobreahead - M	73	8,100	100,000
Philips RoadFocus Cobrahead - S	38	4,167	100,000
Holophane; HMAO-LED II (high-mast)	249	28,000	175,000
Cooper Lighting; Galleon LED (high-mast)	210	22,276	300,000
Cree; Edge High Output (high-mast)	267	22,829	350,000

The calculation results are shown in Table 20 for a project size of 1,000 luminaires, including annual energy cost savings ($2,159.82 to $16,198.62, with an average of $8,162.31), and total annual cost savings (on initial equipment, installation, and maintenance costs) of $18,890.35 to $71,223.62, with an average of $47,677.22. Over the assumed 12-year life cycle, KDOT will have the potential to save an average of $572,126.64, within a range of $226,684.23 to $854,683.42. Also, the payback time periods for the new LED roadway lighting system are in a range of 1.47 to 7.13 years with an average of 2.94 years. Figure 16 shows how much cost each individual LED luminaire may save per year over its lifecycle.

Table 20: Implementation Cost Analysis for the APL Short List Luminaires

Proposed LED Luminaire	Watts (Min.)	Lumens (Min.)	Annual Energy Cost Savings - AECS (qty=1000)	Total Annual Savings for LED - TAS (qty=1000)	Life Cycle Cost Savings - LCS (qty=1000)	Simple Payback (years) - SPB
Acuity; Autobahn ATBO	49	4747	$9,071.23	$57,801.77	$693,621.18	1.7
Acuity; Autobahn ATB2	94	9461	$5,831.50	$39,562.04	$474,744.49	2.9
GE; Evolve LED Roadway Scalable Project Grade Cobrahead	54	4200	$8,711.26	$55,775.13	$669,301.55	1.8
GE; Evolve LED Roadway Scalable Specification Grade Cobrahead	45	4000	$9,359.20	$59,423.07	$713,076.89	1.6
Cree; LEDway Series Street Lights	53	5032	$8,783.25	$56,180.46	$674,165.48	1.7
Cree; XSL LEDway High Output Street Light	136	13021	$2,807.76	$22,538.30	$270,459.57	5.8
Philips; RoadView RVM	105	10516	$5,039.57	$35,103.44	$421,241.30	3.4
Philips; RoadView RVS	56	5327	$8,567.27	$54,964.47	$659,573.70	1.8
Philips; RoadStar GPLM	119	8174	$4,031.66	$29,428.86	$353,146.32	4.2
Philips; RoadStar GPLS	73	5189	$7,343.38	$48,073.91	$576,886.95	2.2
Philips; RoadFocus Cobrahead - L	145	15700	$2,159.82	$18,890.35	$226,684.23	7.1
Philips; RoadFocus Cobreahead - M	73	8100	$7,343.38	$48,073.91	$576,886.95	2.2
Philips RoadFocus Cobrahead - S	38	4167	$9,863.16	$62,260.36	$747,124.37	1.5
Holophane; HMAO-LED II (High Mast)	249	28000	$13,390.86	$55,415.86	$664,990.29	3.2
Cooper Lighting; Galleon LED (High Mast)	210	22276	$16,198.62	$71,223.62	$854,683.42	2.3
Cree; Edge High Output High Mast	267	22829	$12,094.97	$48,119.97	$577,439.61	3.8

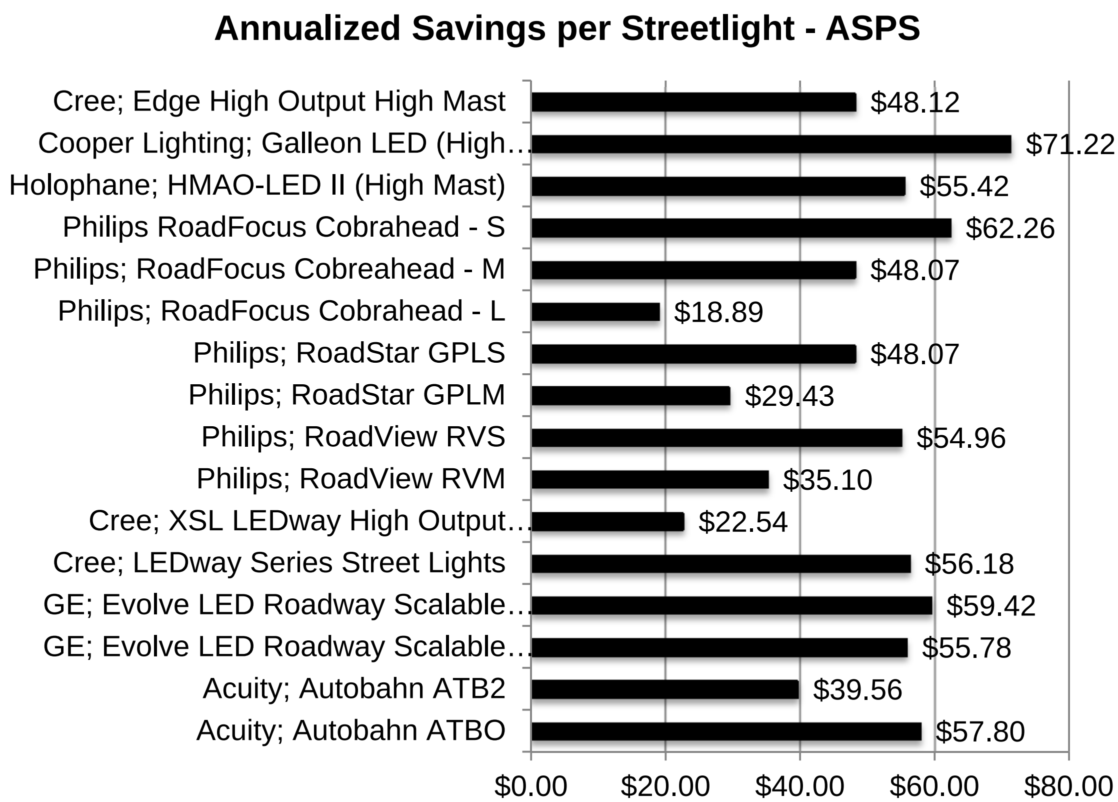


Figure 16: Annualized Savings per Streetlight over its Lifecycle of 12-Years

Chapter 7: How to Use the Selected LED Illumination Systems in Kansas

The selected qualified LED roadway luminaires on the APL, especially the short-listed highly recommended luminaires with cost-effectiveness analysis, are ready to be implemented on Kansas roads by KDOT and local districts and cities. This section summarizes the protocol and guidelines on using the selected LED illumination systems, including:

a. Responsibilities of the KDOT divisions and districts.
b. Eligibility and warrants for KDOT and the six districts of Kansas to install and maintain LED lighting systems.
c. Submission of the request for LED illumination and the process.
d. Guidelines on construction and maintenance of the LED roadway luminaires.
e. LED roadway lighting inspection and servicing on the project sites.

They are detailed below.

7.1 Responsibilities

This section outlines the responsibilities of the KDOT divisions and districts in regard to the selection, evaluation, installation, inspection, and maintenance of different types of LED roadway lighting systems in Kansas. The responsibilities may slightly change over time in the future.

7.1.1 Division of Transportation Planning

The Division of Transportation Planning in the Bureau of Transportation Safety & Technology (BTST) will prepare policies, procedures, and standards for LED lighting systems; develop and maintain LED lighting agreement forms; review and process plans, specifications, and estimates for LED lighting projects; assist districts with design, construction, and maintenance problems associated with LED lighting systems; review and approve shop drawings for LED standard pole lighting and LED high-mast lighting assemblies (unless the district chooses to handle the matter); assist districts with luminaire pole shop drawings and submittal review of LED lighting; and conduct electrical and illumination design training. The contact is below.

Highway Lighting Specialist
Bureau of Transportation Safety & Technology
Phone: (785) 296-0356

7.1.2 Division of Engineering and Design

The Division of Engineering and Design will assist the KDOT lighting specialist and relevant engineers in the design of the structure, lighting poles and footing, details of pole changes, etc. The contact is below.

Signing and Lighting Structures Engineer
Phone: (785) 296-4316

7.1.3 Districts

The districts in Kansas will be responsible for LED lighting projects constructed within their district, regarding the following tasks.

- Review lighting and electrical field changes.
- Construct LED illumination projects in accordance with plans.
- Maintain LED illumination systems.
- Operate LED illumination systems.
- Ensure that standard designs are compatible with and applicable to plans.
- Prepare and submit FAA Form 7460-1 “Airway-Highway Clearance Form.”

The current contact for the six districts of Kansas is listed below.

District 1: Northeast Kansas

District 1 Office
121 SW 21st Street
Topeka, Kansas 66612
(785) 296-3881

District 2: North Central Kansas

District 2 Office
1006 N. Third
Salina, Kansas 67402-0857
(785) 823-3754

District 3: Northwest Kansas

District 3 Office
312 S. Second
Norton, Kansas 67654-0350
(785) 877-3315

District 4: Southeast Kansas

District 4 Office
411 W. Fourteenth
Chanute, Kansas 66720-0498
(620) 431-1000

District 5: South Central Kansas

District 5 Office
500 N. Hendricks
Hutchinson, Kansas 67504-
0769
(620) 663-3361

District 6: Southwest Kansas

District 6 Office
121 N. Campus Dr.
Garden City, Kansas 67846-6603
(620) 276-3241

7.2 Eligibility and Warrant

This section describes for different types of LED lighting systems (e.g., standard poles and high-mast lighting), which roadways are eligible for those systems, and the conditions that warrant each system. KDOT can only install and maintain LED lighting systems on **eligible** roadways where the conditions **warrant** such installation. However, meeting of the warrants does not obligate the KDOT and districts to provide LED lighting (e.g., due to other considerations like high costs or restrictive subjective values for local use). The eligibility requirements and warranting criteria to specify the types of highways eligible for the spending of state funds on proposed LED roadway lighting systems are thus identified. Such eligibility requirements and warrants are intended to assist the KDOT and local districts in considering LED lighting on Kansas roads.

7.2.1 Eligibility

Eligibility covers the requirements specify the types of highways eligible for the spending of Kansas state funds on each type of LED lighting system (e.g., standard pole lighting, high-mast lighting). The major highway types in Kansas currently desirable for implementation of LED lighting include:

- Freeways — continuous freeway lighting
- Interchanges — partial or complete interchange lighting
- Other highways — street lighting
- Other highways — intersection lighting

Table 21 summarizes the eligibility requirements for installation of LED lighting systems on different types of roadways in Kansas. Note that in Kansas, 5000 is coded for urban areas of average daily traffic (ADT) of 5000, likewise, 3000 is coded for suburban areas, and 1000 is coded for rural areas.

Table 21: Eligibility Requirements for Installation of LED Lighting Systems on Different Types of Roadways in Kansas

Roadway types	Eligibility requirements
Standard pole lighting	
Freeways – 5000	Urban freeways that are multi-lane divided facilities for which full control of access is provided. Heavy nighttime traffic is anticipated.
Interchanges – 5000	Urban interchanges with one or more approaches illuminated. Heavy nighttime traffic is anticipated. An illuminated area in the vicinity can distract the driver's view.
Interchanges – 3000	Suburban interchanges with one or more approaches illuminated. An illuminated area in the vicinity can distract the driver's view, or heavy nighttime traffic is anticipated.
Highways – 5000	Heavy nighttime traffic is anticipated. Multi-lane arterial highways with partial control of access where the following conditions exist: a. Access is provided to abutting property b. At-grade crossings are provided at minor streets and roads c. Where grade separation structures are provided at major crossings of arterial highways, streets, and roads
Highways – 3000	Illumination is necessary to improve the visibility of pedestrians and bicyclists for safety.
Intersections – 5000	Heavy nighttime traffic is anticipated. Illumination is necessary to improve the visibility of pedestrians and bicyclists for safety.
Intersections – 3000	Illumination is necessary to improve the visibility of pedestrians and bicyclists.
High-mast lighting	
Freeways - 5000	Urban freeways that are multi-lane divided facilities for which full control of access is provided. Heavy nighttime traffic is anticipated.
Interchanges – 5000	Urban interchanges with one or more approaches illuminated. Heavy nighttime traffic is anticipated. An illuminated area in the vicinity can distract the driver's view.
Interchanges – 3000	Suburban interchanges with one or more approaches illuminated. An illuminated area in the vicinity can distract the driver's view, or heavy nighttime traffic is anticipated.
Intersections – 5000	Heavy nighttime traffic is anticipated. Illumination is necessary to improve the visibility of pedestrians and bicyclists.
Intersections – 3000	Illumination is necessary to improve the visibility of pedestrians and bicyclists.

Source : [39, 40, 41]

7.2.2 Warrants

Warrants are the criteria used to justify the need for and expense of LED lighting at eligible locations (Table 21). To determine if an eligible location meets the relevant warrant, KDOT assesses roadway conditions in terms of criteria called “cases.” These cases are coded for ease of reference (i.e., CFL-1, CIL-2, PIL-1, MHL-2). When roadway conditions meet or exceed one or more of the relevant cases, then the roadway in question warrants the LED lighting—in other words, the warrant is met. After the warrant is met, KDOT may enter into a partnership agreement with the city or local government (if necessary) and program the financing [25, 39, 40].

In Kansas, the following cases will be adopted for warrants of LED illumination for continuous freeway lighting (CFL), complete interchange lighting (CIL), partial interchange lighting (PIL), non-freeway lighting (NFL), and high-mast lighting (MHL). Such warrants could be further justified for modification in case of local conditions, such as frequent fog, ice, snow, roadway geometry, ambient lighting zones, sight distance, signing, etc. [25].

7.2.2.1 Continuous Freeway Lighting (CFL)

A continuous freeway lighting system often uses standard pole lights to provide relatively uniform lighting on all main lanes and direct connections. Note that it is not expected in the near future that continuous freeway LED lighting would be used in Kansas. However, this manual still includes continuous freeway lighting for future expansion. Continuous freeway LED lighting should be considered for all median barriers on roadway facilities in urban areas. In rural areas each location must be individually evaluated as to its need for illumination. Table 22 lists the warranting conditions for continuous freeway lighting (CFL) in Kansas.

Table 22: Warranting Conditions for Continuous Freeway Lighting (CFL)

Case	Warranting conditions
CFL-1	Sections in and near cities where the current average daily traffic (ADT) is 30,000? or more.
CFL-2	Sections where three or more successive interchanges are located with an average spacing of 1.5 miles or less, and adjacent areas outside the right of way are substantially urban in character.
CFL-3	Sections of 2 miles or more passing through a substantially developed suburban or urban area in which one or more of the following conditions exist: a. Local traffic operates on a complete street grid having some form of street lighting, parts of which are visible from the freeway; b. The freeway passes through a series of developments such as residential, commercial, industrial and civic areas, colleges, parks, terminals, etc., which includes roads, streets and parking areas, yards, etc., that are lighted; c. Separate cross streets, both with and without connecting ramps, occur with an average spacing of 0.5 miles or less, some of which are lighted as part of the local street system; and d. The freeway cross section elements, such as median and borders, are substantially reduced in width below desirable sections used in relatively open country.
CFL-4	Sections where the ratio of night to day crash rate is at least 2.0 times the statewide average for all unlighted similar sections since a study indicates that lighting may be expected to result in a significant reduction in the night crash rate. Where crash data are not available, rate comparison may be used as a general guideline for crash severity. (Note that because the ratio of night to day crash rates for a given section of roadway cannot always be statistically verified, this measure must be considered as an aid to design rather than an absolute rule. Engineering judgment should be exercised when using this warrant.)

Source: [25]

7.2.2.2 Complete Interchange Lighting (CIL)

Likewise, Table 23 lists the warranting conditions for complete interchange lighting (CIL).

Table 23: Warranting Conditions for Complete Interchange Lighting (CIL)

Case	Warranting Conditions
CIL-1	Where the total current average daily traffic (ADT) ramp traffic entering and leaving the freeway within the interchange areas exceeds 5000 for urban conditions, 3000 for suburban conditions, or 1000 for rural conditions.
CIL-2	Where the current ADT on the crossroad exceeds 5000 for urban conditions, 3000 for suburban conditions, or 1000 for rural conditions.
CIL-3	Where existing substantial commercial or industrial development that 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 mile or more on each side of the interchange.
CIL-4	Where the ratio of night to day crash rate within the interchange area is at least 1.5 times the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in significant reduction in the night crash rate. Where crash data are not available, rate composition may be used as a general guideline for crash severity.

Source: [25]

7.2.2.3 Partial Interchange Lighting (PIL)

Table 24 lists the warranting conditions for Partial Interchange Lighting (PIL). Partial interchange lighting covers only the parts of the interchange that are most critical to the night drivers, including the merge-diverge areas of the ramp connections, intersections, and other critical roadway features.

Table 24: Warranting Conditions for Partial Interchange Lighting (PIL)

Case	Warranting Conditions
PIL-1	Where the total current ADT ramp traffic entering and leaving the freeway within the interchange areas exceeds 5,000 for urban conditions, 3,000 for suburban conditions, or 1,000 for rural conditions.
PIL-2	Where the current ADT on the freeway through traffic lanes exceeds 25,000 for urban conditions, 20,000 for suburban conditions, or 10,000 for rural conditions.
PIL-3	Where the ratio of night to day crash rate within the interchange area is at least 1.25 times the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night crash rate.

Source: [25]

7.2.2.4 Non-Freeway Lighting (NFL)

The AASHTO *Roadway Lighting Design Guide* [25] gives no specific warrants for continuous lighting of roadways other than freeways (roads with fully controlled access, no at-grade intersections), but does suggest some general criteria that may apply when considering the installation of lighting. Based on AASHTO, in Kansas, lighting of at-grade intersections is warranted if the geometric conditions mentioned in the AASHTO *Roadway Lighting Design Guide* exist or if one or more of the following conditions exists:

a. <u>Volume</u> — The traffic signal warrant volumes for the minimum vehicular volume warrant, the interruption of continuous traffic warrant, or the minimum pedestrian volume warrant are satisfied for any single hour during conditions other than daylight, excluding the time period between 6:00 a.m. and 6:00 p.m.
b. <u>Crashes</u> — There are three or more crashes per year occurring during conditions other than daylight.
c. <u>Intersecting Roadway</u> — The intersecting roadway is lighted.
d. <u>Ambient Light</u> — Illumination in areas adjacent to the intersection adversely affects the drivers' vision.
e. <u>Channelization</u> — The intersection is channelized and the 85th percentile approach speed exceeds 40 miles per hour. A continuous median is not considered as channelization for the purpose of this warrant.
f. <u>School Crossing</u> — Scheduled events occurring at least once per week during the school year make it necessary for 100 or more pedestrians to cross at the school crossing during any single hour in conditions other than daylight, or a traffic engineering study indicates a need for lighting.
g. <u>Signalization</u> — The intersection is signalized.
h. <u>Flashing Beacons</u> — The intersection has a flashing beacon.

7.2.2.5 High-Mast Lighting (MHL)

The principal benefits of high-mast lighting applications are the ability to provide uniformity of illumination and reduce glare with a substantially smaller number of pole locations. This is especially true in interchange and other complex road areas. High-mast lighting makes a contribution to safety and aesthetics by reducing the number of poles that would be required for a conventional system and through locating poles out of the recovery area adjacent to the driving lanes. Also, their remote location eliminates the need for maintenance vehicles obstructing traffic on the roadway, or the requirement for maintenance personnel to be near the high-speed traffic lanes. Table 25 lists the warranting conditions for high-mast lighting (HML).

Table 25: Warranting Conditions for High-Mast Lighting (HML)

Case	Warranting Conditions
HML-1	Where continuous lighting is desirable such as interchange lighting, lighting of toll plazas, rest areas and parking areas, general area lighting, and for continuous lighting on highways having wide cross sections and a large number of traffic lanes.
HML-2	Where there is minimal residential and where maintenance of conventional lighting units may be a hazard to the traveling public and the maintenance personnel.

However, attention should be paid to residential activity to avoid unnecessary light pollution to neighborhoods that lead to local citizen complaints, since some installations of high-mast lighting have resulted in glare and light trespass due to the amount of lighted area and the visibility of the bright LEDs.

7.2.3 Submission and Process

The districts should submit data substantiating that warrants are met with the request for programming or financing to the lighting specialist with the KDOT Bureau of Transportation Safety & Technology (BTST).

The format of the substantiating data is listed in Table 26 for eligibility and warrants of a new LED roadway lighting project.

When an LED lighting project is proposed (by a local government, citizens, or KDOT personnel), the lighting specialist in the Bureau of Transportation Safety & Technology (BTST) then first determines the eligibility of the roadway. If the roadway is eligible, then the lighting specialist assesses conditions to determine if the lighting system is actually warranted. Only after both eligibility and the warrant (warranting conditions) are established, can the lighting specialist execute an agreement with the local government (if necessary) and proceed with design and installation.

Table 26: Format of the Submission for Eligibility and Warrants of a New LED Roadway Lighting Project

The LED lighting system	Type of the LED lighting system	Standard poles High-mast lighting
	LED luminaire specification	
	Existing or new poles	
Eligibility	The following roadways are eligible for such LED lighting systems	
	Type	e.g., Interchanges – 5000
	Location	
Warrant	The following roadway conditions meet or exceed the relevant cases to warrant the LED lighting	
	Case #:	e.g., CIL-3
	Case #:	

7.3 Construction and Maintenance

This section addresses issues of concern to construction and maintenance personnel for implementation of the selected LED roadway luminaires in Kansas, including review and approval of shop drawings, pole placement, electrical system requirements, and maintenance considerations. They are detailed below.

7.3.1 Review and Approval of Shop Drawings

Typical shop drawings for implementation of the short listed LED luminaires in Kansas include the following two types:

a. Product specification sheets of the LED luminaires, electronic devices and equipment, and light poles provided by the contractors, suppliers, or manufacturers, and

b. The installation and coordination drawings of the electrical systems of the new or retrofit roadway lighting projects.

Suppliers must submit shop drawings for LED roadway luminaires and their supportive electronic devices and lighting poles on purchase requisition for the review and approval. For breakaway poles, manufacturers are required to submit shop drawings with the structural strength test results and the breakaway certification [40].

Shop drawings for implementation of new LED luminaires on Kansas roadways at the district level may be reviewed and approved by the districts with assistance from the lighting specialist of the KDOT Bureau of Transportation Safety & Technology (BTST) for both contract projects and district-oriented purchase requisitions. Shop drawings for roadway light poles may also be reviewed and approved by the districts with coordination of the KDOT Division of Engineering and Design and the Bureau of Transportation Safety & Technology (BTST).

Shop drawings for high-mast lighting needs to be reviewed by the lighting specialist with the Bureau of Transportation Safety & Technology (BTST) in coordination with the KDOT Division of Engineering and Design and the districts where the high-mast lighting is installed. Districts desiring to review the shop drawings themselves may include a general note in the plans to that effect. However, due to the complicated and critical nature of high-mast assemblies, it is recommended that the Bureau of Transportation Safety & Technology (BTST) in coordination with the KDOT Division of Engineering and Design review these shop drawings.

Shop drawings should be marked as “approved” or “approved except as noted” or “returned for correction.” Approval marking should be on the drawing itself instead of only by an accompanying letter [40].

7.3.2 Pole Placement Guidelines

Most of the LED luminaires will be mounted on the top of the existing poles on Kansas roads unless a new construction is considered for using new poles. Whether new poles are installed or not depends on the need of new poles for optimal light distribution on the roadway pavement and the corresponding layout of the luminaires, which will be judged jointly by the lighting specialist with the KDOT Bureau of Transportation Safety & Technology (BTST), the

Division of Engineering and Design, as well as the district where the project is located. Once new poles are to be installed, the pole placement should follow the guidelines as follows [25]:

a. Structural supports—poles for lighting units should be designed and located so that they do not distract the attention of the motorists or interfere with their view of the roadway and other important roadway features. Supports should be placed so that they do not obstruct the view of signs.
b. Height restriction. The federal aviation administration may have certain highest restrictions for lighting poles place adjacent to airports and in their landing zones.
c. Locating structural supports for lighting units within a median area can have multiple advantages.
    i. Reduce half of the required lighting poles for house side lighting
    ii. Reduce the amount of wiring
    iii. Lighting otherwise wasted on the house side is used instead on the opposite roadway
    iv. Reduce construction and maintenance costs
    v. Improve visibility on the high-speed lanes
d. Gore areas—locating poles within the clear zone at a gore area is not usually desirable, unless located behind or atop a longitudinal traffic barrier or behind a crash cushion. In Kansas, poles need to be 35 ft height or more, and must be out of the clear zone.

7.3.3 Electrical System Requirements

Construction and maintenance of the electrical systems of the LED roadway lighting should abide by the latest National Electrical Code and the AASHTO publication entitled “Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals” for wiring, disconnection, grounding, and voltage drop.

7.3.4 Maintenance Considerations

LED lighting system has reduced maintenance loads due to its elongated life and robust performance in wide range of roadway environments. Major maintenance considerations of the LED roadway lighting include luminaire dirt depreciation, lamp lumen depreciation, support structure maintenance, electrical distribution and control system maintenance, and the replacement of the LED luminaires and electronic devices at the end of their useful life.

Maintenance of LED illumination systems on Kansas roads is usually provided by cities and districts under agreement with the KDOT. However, any maintenance problems involving electrical and illumination design and materials should be brought to the attention of the lighting specialist of the Bureau of Transportation Safety & Technology (BTST) so that possible solutions can be provided or alterations can be made on this manual.

LED luminaires often have a useful life of 50,000-100,000 hours or more (> about 12 years). Considering the LED technologies upgrade in every 2-3 years, those LED roadway luminaires will be replaced at their end of life with new generation of technology. Group re-lamping on a regular schedule of 3-5 years is no longer needed. As a result, the costs for labor, traffic control, and equipment use are expected to be greatly reduced.

Note that LED roadway lighting may have other maintenance needs, such as replacement of electronic devices (e.g., driver, photosensors, which may have shorter useful life than the LEDs) and cleaning. Cleaning of the luminaires, which involves wiping the dirt from the LED lenses, may be performed during a recommended time interval by the Illuminating Engineering Society or KDOT. This periodic cleaning of the fixtures reduces the depreciation of light due to the accumulation of dirt and allows the delivery of more light per lighting dollar.

At the end of its useful life, replacement LED fixtures for standard pole or high-mast lighting must be obtained by special order. Each fixture could be replaced with an upgraded generation. The order should be reviewed and approved by the lighting specialist of the Bureau of Transportation Safety & Technology (BTST) to make sure the critical photometric performance of the new fixture will be satisfactory, with assistance from the University of Kansas lighting research laboratory.

7.4 LED Roadway Lighting Inspection and Servicing

LED roadway lighting inspection and service on the project sites involves luminaire malfunction report and information gathering, troubleshooting guide for LED luminaire and photocontrols, inspection of lighting poles and assemblies, proper preventive maintenance, the inspection and servicing routine, and responsibility of cities and districts, etc. Figure 17 is a flow chart of a typical LED roadway lighting system inspection. The inspection and service routine should be performed at a reasonable interval or every time the LED lighting system is maintained (e.g., cleaning) or (for high-mast lighting) the ring is lowered for any reason.

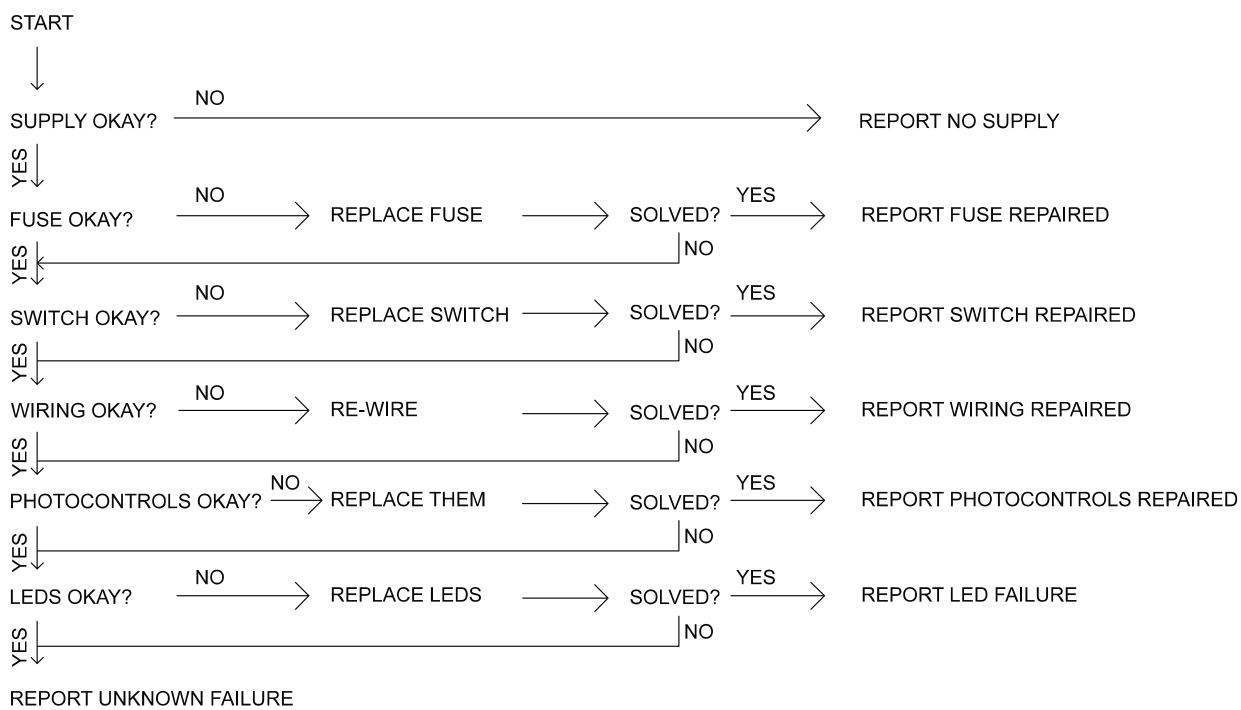


Figure 17: Flow Chart of Test Procedure for Analyzing Faults in a Typical LED Lighting System

Personnel carrying out inspections of standard pole or high-mast LED lighting should document their findings using an Inspection Record form. Items to be checked and maintained during these inspections are listed on the Form as checklist. Districts must retain these completed inspection forms for a minimum of three years.

Inspection and service of the standard pole or high-mast LED lighting assemblies, by agreement, are the maintenance responsibility of a city and district. This work may be performed by the city or its agent. When this inspection and servicing is performed by the city or its agent, districts should occasionally check that the work is performed correctly. Districts should provide a copy of the shop drawings, submittals, and "as built" plans to cities that are maintaining high-mast lighting. Further assistance with LED lighting inspection and service may be obtained from the lighting specialist of the Bureau of Transportation Safety & Technology (BTST).

7.5 Lighting Curfews

This section provides guidance on the use of modern controls to turn on/off or dim the selected LED roadway lighting systems on the approved product list (APL) as permitted by reduced traffic flow, favorable weather conditions, and other local conditions for energy savings, greater flexibility in resource allocation, and reduction of light pollution like light-trespass and sky glow [25]. However, for officials implementing such options in Kansas, KDOT and local cities should be aware of its consequences and conduct meaningful studies of costs and benefits in advance [40].

7.5.1 Background

Over 50% of all motor vehicle fatalities occur in darkness even though only 25% of all travel occurs at night [42]. Warrants for lighting are empirically derived and based on traffic volume. It is generally accepted that lighting reduces crashes when traffic volumes are high. However, the frequencies and severities of road crashes are dependent on a host of geometric and traffic factors including the volume of traffic utilizing the road, the road's capacity, and the complexity of the driver's visual search task [42].

Motor vehicle crash data from the National Highway Traffic Safety Administration's Fatality Analysis Reporting System (FARS) [43] and the General Estimates System (GES) [44] show that 90% of fatal and injury crashes that occur on the roadway are multiple vehicle crashes, where lighting should be placed. However, the number of overall crashes reduces substantially after midnight on weekdays and after 4:00 a.m. on weekends. At these late hours, most of the crashes are single vehicle off roadway crashes, where continuous lighting may not help except only at decision making points such as ramp gores, intersections, and merge areas. It may be reasonable to turn off the continuous roadway lighting or dim the complete/partial interchange lighting when traffic volumes subside.

On the other hand, crash rates can increase where lighting systems are turned off or every other luminaire is turned off (rather than dimming) resulting in poor uniformity ratios. The issue of drivers' needs and safety versus energy conservation efforts should be closely examined by KDOT when considering curfews. Poorly conceived conservation efforts may contribute to excessive increases in traffic crashes and operational problems resulting in higher overall costs.

7.5.2 Reasons for Curfews

Government entities around the world are considering lighting curfews for the following reasons [25]:

- <u>Low late-hours traffic volumes</u>. AASHTO warrants for highway lighting are based, among other things, on traffic volume. When the high traffic volumes and high usage drop off in later hours of the night, it is reasonable to turn off or dim the LED lighting after such drop-offs.
- <u>To free up resources for greater overall safety</u>. Lowering the operational costs of lighting systems by reducing electrical and maintenance costs through curfews may allow more lighting systems or other crash countermeasure to be installed, thereby reducing the overall nighttime crash rate within the jurisdiction of the master lighting plan.
- <u>LED Technology now practical</u>. Modern controls technology of LED lights, e.g., DALI (digital addressable lighting interface) as a protocol set out in the technical standard IEC 62386, allows digital and precise control of individual or groups of LED luminaires at reasonable costs.
- <u>Positive study results</u>. Light dimming and turn-off curfews are viable options for management of public lighting systems, including roadway lighting. Although past studies showed unfavorable increases in traffic crash rates because of turning off lighting, those studies were performed on conventional lighting systems where the HID lamps were turned off or

partially turned off for the entire nighttime period. New LED lighting systems could be continuously dimmed to a reasonable low level when the traffic volumes are low without jeopardizing roadway safety. Yet new research is needed to validate this conservation potential for Kansas.

- Energy savings. Energy costs are still high. Dimming or turning off LED lights on Kansas roads may largely reduce energy uses.
- Sky glow issues. Sky glow issues are of increasing importance to the health of citizens and local environments like nocturnal animals.

7.5.3 Considerations Before Implementation

Normal traffic volumes, special events (e.g., regularly scheduled sports events and other large traffic generators), weather, and other local considerations should be included in the decision to implement curfews of LED lighting systems in Kansas. For example, reduced freeway lighting tactics normally should not be implemented before about 11:00 p.m. in most urban areas, since traffic density typically remains relatively high until that time. Cities with little or no evening activity might allow an earlier light reduction. Implementation of lighting curfews should occur through traffic management centers in Kansas and should be monitored to gain experience as to the best operational procedures [42].

Old light reduction techniques dealing with conventional HID lighting systems during lighting curfews have a problem that lighting was reduced or eliminated during the entire nighttime period, rather than only when traffic volume was low. In addition, HID lighting systems could not be continuously dimmed like modern LED lighting systems do.

By providing full lighting during periods when volumes are high and the roadway operates near capacity and providing reduced lighting as the traffic decreases, considerable energy savings could be achieved while still providing the benefits of full or dimmed lighting at critical locations (e.g., interchanges) and at times (i.e., high volumes) where driver decision-making is the most critical and the greatest visibility is required [42].

From a safety standpoint, lighting curfew may lower drivers' hazard detection performance, which theoretically implies some reduction in safety. However, this implied reduction in safety is statistically significant for all off and one side only lighting tactics that were commonly used by the conventional HID lighting systems, but may not be statistically significant for the continuously dimmed tactics that LED lighting systems typically deploy. Unfortunately, it is not possible at this time to quantify, under LED lighting curfews, the exact decrease in safety in terms of the frequency of nighttime accidents, the night accident rate, or the night-to day accident ratio. Further research is needed for an evaluation of the impact of lighting curfews on long-term installations of LED lighting systems in Kansas [42].

Chapter 8: A Pilot Run Program of the Selected LED Roadway Luminaires

A pilot run program was conducted in the end of this project to install and test a total of four selected LED roadway luminaires on the short list of highly recommended products (Table 17). The selection of the tested luminaires was based on their photometric specifications and availability as free samples provided by the local sales representatives.

The four LED luminaires installed and tested in this pilot run include (i) Cooper Galleon LED and Holophane HMAO-LED II for high-mast lighting, and (ii) Philips RoadFocus Cobra Head–M and GE Evolve LED Roadway Scalable Specification Grade Cobrahead–ERS1 for standard pole lighting. Table 27 lists the four LED luminaires and their installation locations on K-10 east of Lawrence (Figure 18(a)), KS, at the intersections of K-10 & E 1900 Road (Figure 18(b)) and intersections of K-10 & E 2300 road (Figure 18 (c)). The key specifications of those four LED luminaires are summarized in Table 28.

Table 27: Selected LED Luminaires for Field Tests in the Pilot Run Program

Location	Lighting type	LED luminaire	Look
Intersections of K-10 & E 1900 road (Figure 18 (b))	High-mast lighting	Cooper Galleon LED	
	Standard pole lighting	Philips RoadFocus Cobra Head - M	
Intersections of K-10 & E 2300 road (Figure 18 (c))	High-mast lighting	Holophane HMAO-LED II	
	Standard pole lighting	GE Evolve LED Roadway Scalable Specification Grade Cobrahead - ERS1	

(a)

(b)

(c)

Figure 18: Field Test Location of the Pilot Run LED Luminaires, (a) The Sites on K-10, East of Lawrence, (b) Intersection of K-10 & E 1900 Road, (c) Intersections of K-10 & E 2300 Road

Table 28: Key Photometric Specifications of the Four LED Luminaires Tested in the Pilot Run Program

Luminaire model	GE Evolve LED Roadway Scalable Specification Grade Cobrahead (Standard Pole)	Philips RoadFocus Cobra Head – M (Standard Pole)	Holophane HMAO-LED II (High-Mast)	Cooper Lighting Galleon LED (High-Mast)
Voltage (VAC)	347-480	347-480	347-480	347-480
Wattage (Watt)	60	106	500	528
Initial lumen (lm)	5000	12279	60,990	53356
Efficacy (Lumen/Watt)	83	116	122	101
CCT (K)	4000	4000	4000	4000
CRI	70	70	70	70
Luminaire life L_{70} (hrs)	50,000	100,000	175,000	350,000

The four LED luminaires replaced four legacy luminaires on the same high-mast towers or the standard poles. The legacy luminaires were swapped with their LED counterparts without any other changes of the poles or the electrical cabinets on site. The Cooper Galleon LED fixture and the Holophane HMAO-LED II fixture were used to replace one Metal Halide (MH) fixture on top of the high-mast tower at each test site, respectively. Note that there are often three MH lights on each high-mast tower. As a result, each high-mast tower at the two test sites has one LED high-mast light and two legacy MH lights side by side. The replacement LED high-mast light was mounted close to K-10 facing the traffic lanes. For standard poles, which have only a single cobrahead light mounted, the Philips RoadFocus Cobra Head-M LED fixture and the GE Evolve LED Roadway Scalable Specification Grade Cobrahead-ERS1 LED fixture replaced the legacy High Pressure Sodium (HPS) cobrahead on the top of the standard pole at each site, respectively. The four LED luminaires will be tested and evaluated in the field for a long time over their useful life of 10-12 years.

Before the replacement of the legacy fixtures with the four LED luminaires, the lighting conditions at the two test sites were carefully measured at night. After the replacement, a follow-up field measurement was conducted at night to evaluate the photometric performance of the test LED luminaires at the two test sites. Both measurements were taken on dry pavement under clear night sky. A total of 10 points along the solid white line (pavement marking) between the shoulder and the roadway on the south and north sides of K-10, as shown in Figure 19 (a), were measured at each site under the high-mast lighting. The measurement points were spaced by 100 feet. Four more points were measured at the four corners of the intersections at each site under the standard pole cobrahead light, as shown in Figure 19 (b). Selection of those points was to evaluate light levels along the boundary of the lighting zone and also avoid interruption on traffic for safety. At each measurement point, both horizontal light level on the pavement and vertical light level at 4 ft high above the ground from the driver's eye position and orientation (e.g., how much light enters the driver’s eye) were measured using a Minolta CL-200A Chroma meter. At each point, the light color temperature was recorded simultaneously with the light level. The geometries including the pole height, arm length, and luminaire mounting distance from the road were also measured in the field. The results are summarized in Tables 29-32. Data analyses were conducted in Figures 20 to 23 to show the changes of the lighting conditions at each test site before and after the replacement of the legacy luminaires with their LED counterparts.

(a)

Figure 19: Layout of Field Measurement Points, Including Point 1-10 for High-Mast Lighting and Point 11-14 for Standard Pole Cobrahead Light, (a) Measurement Points at the Intersection of K-10 & E 1900 Road, (b) Measurement Points at the Intersections of K-10 & E 2300 Road

(b)

Figure 19: Layout of Field Measurement Points, Including Point 1-10 for High-Mast Lighting and Point 11-14 for Standard Pole Cobrahead Light, (a) Measurement Points at the Intersection of K-10 & E 1900 Road, (b) Measurement Points at the Intersections of K-10 & E 2300 Road (Continued)

Table 29: Field Measurement Data of the High-Mast Lighting at the Intersection of K-10 & 1900th Road Before and After the Luminaire Replacement

Location: K-10 & 1900th				
Luminaire Type	Metal Halide High Mast		Cooper Galleon LED High Mast	
Luminaire Mounting Location	Close to south roadway			
Pole Height	100 ft			
Luminaire setback distance from south roadway at Point 3	23 ft			
Luminaire distance from measurement Point 8	182 ft			
Average CCT	4004 K		4140 K	
Measurement Points	Before - Horizontal Illuminance (on pavement) (lux)	Before - Vertical Illuminance (4 ft above the ground) (lux)	After - Horizontal Illuminance (on pavement) (lux)	After - Vertical Illuminance (4 ft above the ground) (lux)
P1	3.3	7.1	3.2	7.5
P2	9.5	11.9	9.8	12.3
P3	12.1	2.8	12.4	3.6
P4	6.7	0.7	7.4	0.8
P5	3.2	0.8	3.4	1.3
P6	1.1	2.8	0.8	3.3
P7	2.5	3.6	2.5	3.9
P8	3.4	1.2	4.2	1.6
P9	2.3	0.3	3.2	0.7
P10	1.1	0.2	1.3	0.6

Table 30: Field Measurement Data of the Standard Pole Cobrahead Lighting at the Intersection of K-10 & 1900th Road Before and After the Luminaire Replacement

Location: Intersection of K-10 & 1900th				
Luminaire Type	HPS Cobra Head		Philips RoadFocus Cobra Head - M Cobra Head	
Mounting Location	SE Corner			
Pole Height	35 ft			
Arm Length	15 ft			
Luminaire distance from road	5 ft			
Average CCT	None detected (for yellow light)		3835 K	
Measurement Points	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)
P11	5.2	0.5	14	1.2
P12	3.9	0.3	4.4	0.5
P13	0.8	1.2	0.9	1
P14	6.2	2.4	6.1	4.5

Table 31: Field Measurement Data of the High-Mast Lighting at the Intersection of K-10 & 2300th Road Before and After the Luminaire Replacement

Location: K-10 & 2300th				
Luminaire Type	Metal Halide High Mast		Holophane HMAO-LED II High Mast	
Mounting Location	Close to south roadway			
Pole Height	100 ft			
Luminaire setback distance from south roadway at Point 3	46 ft			
Luminaire distance from measurement Point 8	201 ft			
Average CCT	3215 K		4051 K	
Measurement Points	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)
P1	1.9	4.3	3.9	9.9
P2	6.3	8.2	13.7	14.8
P3	10.8	1.7	25.9	3.7
P4	5.9	0.6	7.1	0.7
P5	2	0.3	2	0.4
P6	0.8	2	1	2.6
P7	1.7	2.4	2.7	3.4
P8	2.4	0.8	5.3	2.2
P9	1.9	0.4	3.1	1
P10	0.9	0.3	1.3	0.6

Table 32: Field Measurement Data of the Standard Pole Cobrahead Lighting at the Intersection of K-10 & 2300th Road Before and After the Luminaire Replacement

Location: Intersection of K-10 & 2300th				
Luminaire Type	HPS Cobra Head		GE Evolve LED Roadway Scalable Specification Grade Cobrahead - ERS1 Cobra Head	
Mounting Location	SE Corner			
Pole Height	35 ft			
Arm Length	15 ft			
Luminaire distance from road	5 ft			
Average CCT	None detected (for yellow light)		3976 K	
Measurement Points	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)	Horizontal Illuminance (on pavement) (lux)	Vertical Illuminance (4 ft above the ground) (lux)
P11	6.1	1.6	8.5	1.1
P12	4.8	0.4	5.8	0.6
P13	3.7	4.1	6.7	7.1
P14	5.1	0.7	5.8	3.1

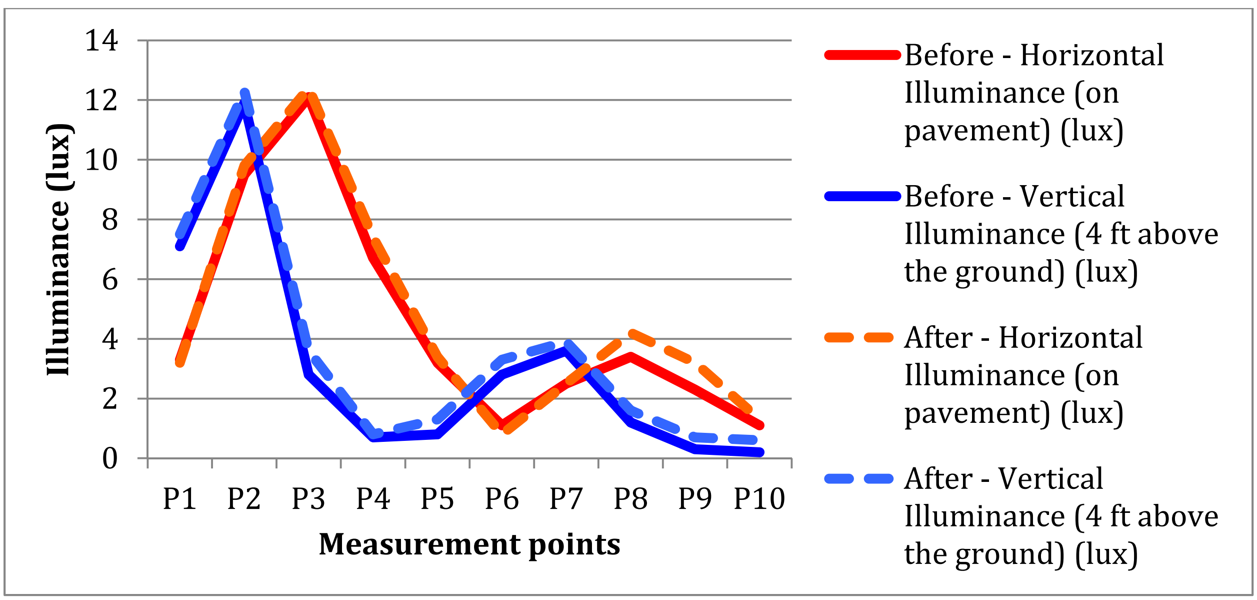


Figure 20: Comparison of High-Mast Lighting Conditions at the Intersection of K-10 & 1900th Road Before and After the Luminaire Replacement from Metal Halide to the Cooper Galleon LED

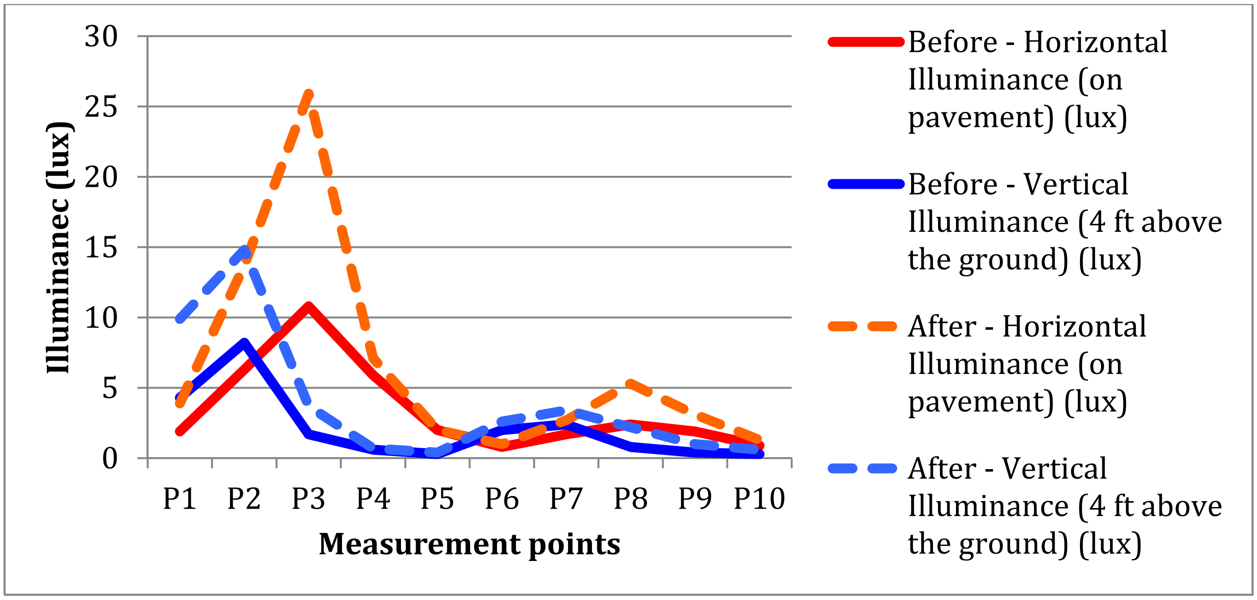


Figure 21: Comparison of High-Mast Lighting Conditions at the Intersection of K-10 & 2300th Road Before and After the Luminaire Replacement from Metal Halide to the Holophane HMAO-LED II

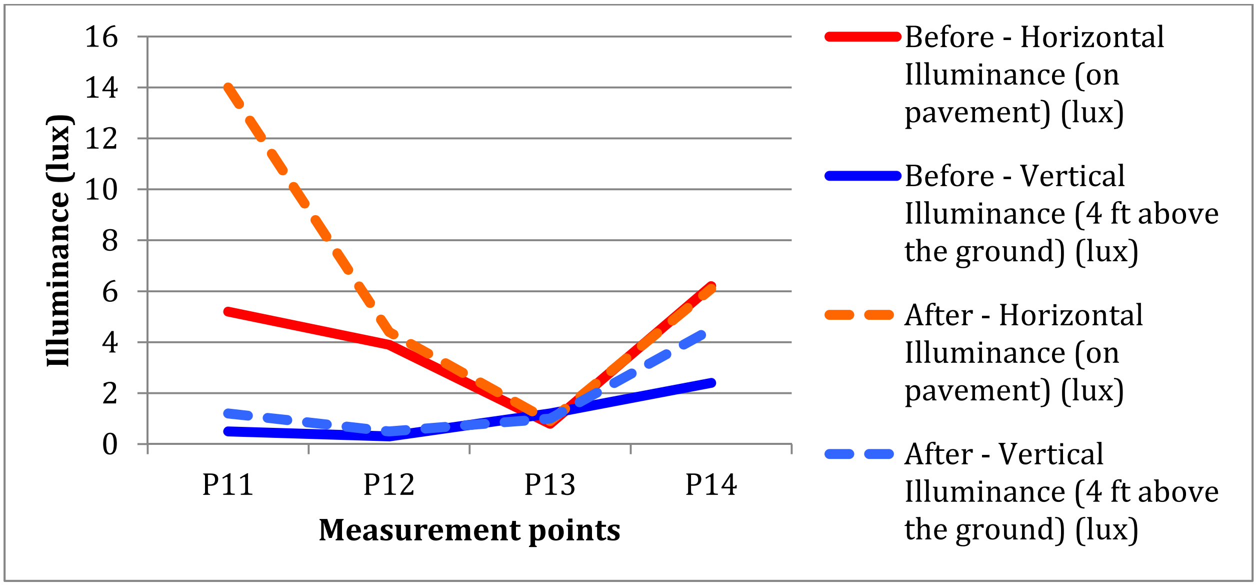


Figure 22: Comparison of Standard Pole Cobrahead Lighting Conditions at the Intersection of K-10 & 1900th Road Before and After the Luminaire Replacement from HPS to the Philips RoadFocus Cobra Head-M

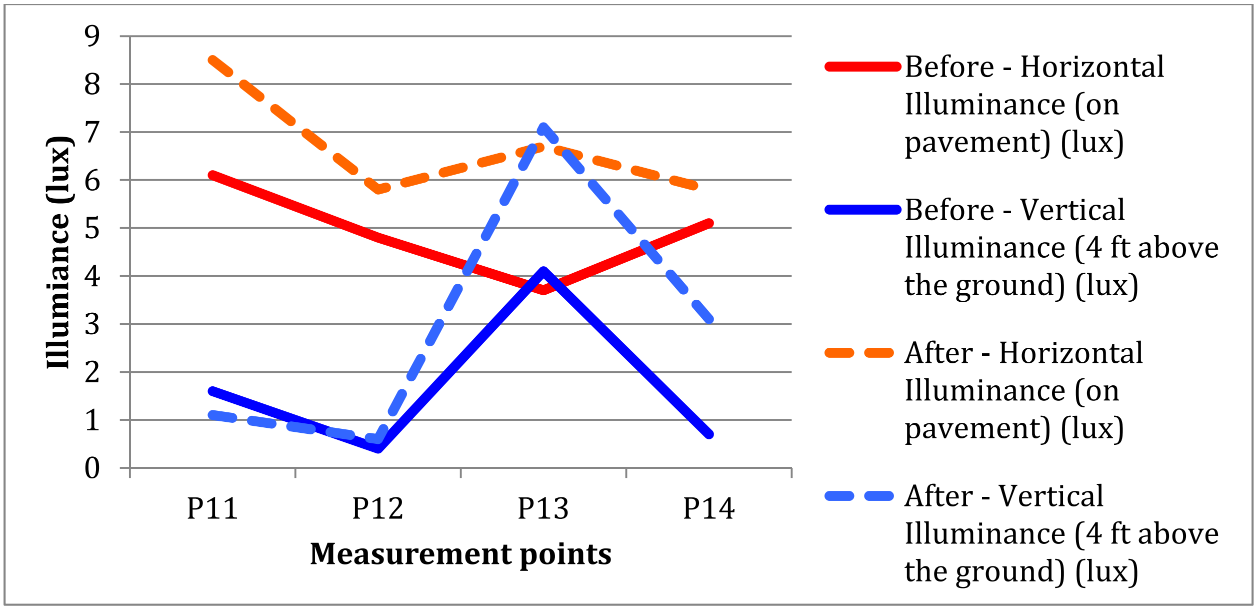


Figure 23: Comparison of Standard Pole Cobrahead Lighting Conditions at the Intersection of K-10 & 2300th Road Before and After the Luminaire Replacement from HPS to the GE Evolve LED Roadway Scalable Specification Grade Cobrahead-ERS1

Based on Figures 20 and 21, it was found that the lighting conditions under the high-mast lighting at both intersections before and after the replacement of luminaires were close (Figure 20, with a Cooper Galleon LED fixture) or slightly improved (Figure 21, with a Holophane HMAO-LED II fixture) after the replacement. It is worth mentioning that on the top of each high-mast tower with three Metal Halide (MH) fixtures, only one MH fixture (facing the road) was replaced with the LED counterpart. As a result, the measured lighting conditions after the replacement was actually a mixture of two MH lights and one LED light mounted on the tower. This explains why the lighting conditions have only slightly better improvements compared to the initial lighting conditions under the three MH fixtures. It is expected that the lighting conditions could have larger improvements once all three legacy MH fixtures are replaced with the proposed LED counterparts.

The expectation in that LED roadway lights have better light distribution was proven in Figures 22 and 23, when the legacy HPS cobrahead lights mounted on the standard poles were replaced with their LED counterparts. Based on Figure 22 (with a Philips RoadFocus Cobra Head-M fixture) and Figure 23 (with a GE Evolve LED Roadway Scalable Specification Grade

Cobrahead-ERS1 fixture), both the horizontal light level on the pavement and the vertical light level at the height of typical driver's eyes were increased after the replacement of fixtures.

Moreover, the visual perception of the roadway lighting conditions at both intersections was enhanced (visually brighter) with better color temperature of the light, especially when the HPS cobrahead lights (which emit yellowish light without color temperature measured by the meter) were replaced with the LED lights with a color temperature close to 4000 K.

Chapter 9: Conclusions and Discussions

The research project was aimed to assist the Kansas Department of Transportation (KDOT) in the development of a highway LED illumination manual for guiding the upcoming implementation of successful LED roadway lighting systems in Kansas to install at new locations and replace the existing HID roadway lighting systems. This project has five major outcomes, including:

a. The desired specifications of the LED roadway lighting systems that could be used in Kansas for roadway lighting and an approved product list (APL) with 83 LED luminaires.
b. The selection of a short list of 13 standard pole and three high-mast LED luminaires highly recommended for implementation in Kansas.
c. The development of a lighting economics calculator for those APL LED luminaires if implemented in Kansas, and the implementation cost analyses for the APL short-listed LED luminaires as examples.
d. Use of the selected LED illumination systems in Kansas covering the responsibilities, eligibility and warrant, construction and maintenance, LED roadway lighting inspection and servicing, and lighting curfew.
e. A pilot run program of the selected LED roadway luminaires installed on K-10. Those LED luminaires will be tested and evaluated in the field over their useful life of 10-12 years.

The five deliverables contribute to the major content of the new Kansas Roadway LED Illumination Manual. They will assist Kansas in the implementation of LED roadway lighting systems using the most highly recommended luminaires that show the most potential for energy and total cost savings, with a short payback time period.

In particular, the 83 LED luminaires on the APL, including the highly recommended short list of 13 standard pole and three high-mast LED luminaires, are expected to provide the KDOT and local cities in Kansas good options of LED lighting systems for practical implementation of LED roadway lighting in terms of energy efficacy (e.g., 61-170 lm/W), useful life (e.g., 50,000, 100,000 hours, and longer), photometric performance (e.g., lumen output of 4,000-72,500 lm, CCT of 3000-6000 K, light lateral distribution types of III, IV, V, and V-FT, full cutoff, low BUG ratings, IP $\geq$ 66), high color rendering performance (CRI $\geq$ 70), and advanced digital controls (e.g., continuously dimmable, photoelectric control, spill control). In addition, based on the example cost-benefit analyses conducted for the APL short list products, when replacing the HID roadway luminaire counterparts, the APL short listed LED luminaires may save approximately $18.89 to $71.22 with an average of $47.68 per year per light over their lifecycle (at least 12 years) with a payback period of 1.5-7.1 years, averagely 2.9 years.

The developed lighting economics calculator is a simple and useful tool for quick implementation cost analysis on replacing the traditional HID system with a new LED system, which could be used for any projects of different size in Kansas. It can be used for calculating factors such as (i) annual energy cost saving, (ii) initial equipment, installation, and maintenance cost savings, (iii) total annual cost savings, (iv) cost savings per luminaire, (v) life cycle total cost savings, and (vi) the simple payback time period. The calculator may also be used in other states as well with appropriate adjustments of inputs, such as localized costs of electricity and demand, operating hours, average maintenance and installation costs, etc.

While this project presents some useful outcomes, it is important to understand that the derivation of the deliverables was based upon several presumptions tailored to Kansas uses.

Nonetheless, every LED roadway project is inherently different. A small project may not have the same benefits as larger-scale projects, as suggested in this research. Without knowing the specific details of the project that KDOT plans to undertake, the outcomes summarized in this paper are intended to guide KDOT through the decision making process in general, rather than present a cut-and-dry design solution. The lighting economics calculator in particular was designed to allow KDOT lighting specialists to change the design input, to tailor the cost-benefit analysis for any project in time to come. Moreover, in the lighting economics calculator, energy-savings rebate rates that vary from time to time were not taken into account, which could have the potential to save even more money.

References

[1] Office of Energy Efficiency and Renewable Energy (EERE). 2012. Energy Savings Potential of Solid-State Lighting in General Illumination Applications. Washington, DC: U.S. Department of Energy.

[2] Office of Energy Efficiency and Renewable Energy (EERE). 2013. Adoption of Light-Emitting Diodes in Common Lighting Applications. Washington, DC: U.S. Department of Energy.

[3] Office of Energy Efficiency and Renewable Energy (EERE). 2013. Solid State Lighting Research and Development Multi-Year Program Plan. Washington, DC: U.S. Department of Energy.

[4] Office of Energy Efficiency and Renewable Energy (EERE). 2014. Energy Savings Forecast of Solid-State Lighting in General Illumination Applications. Washington, DC: U.S. Department of Energy.

[5] U.S. Energy Information Administration (EIA) Independent Statistics and Analysis. 2014. How Much of U.S. Carbon Dioxide Emissions Are Associated with Electricity Generation? http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11

[6] Gerdes, Justin. 2013. Los Angeles Completes World's Largest LED Street Light Retrofit. Forbes. Retrieved June 6, 2015, http://www.forbes.com/sites/justingerdes/2013/07/31/los-angeles-completes-worlds-largest-led-street-light-retrofit/

[7] Office of Energy Efficiency and Renewable Energy (EERE). 2011. Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. Retrieved June 6, 2015, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf

[8] Holophane. 2014. Mongoose LED roadway and area lighting luminaire. Retrieved July 21, 2015, http://www.acuitybrandslighting.com/library/HLP/Documents/otherdocuments/HL-2506%20Mongoose%20LED%20Brochure.pdf

[9] Holophane. n.d. Mongoose LED image gallery [Image of Mongoose LED fixtures alongside highway]. Retrieved July 21, 2015, http://www.holophane.com/led/MGLED/gfx/Gallery/MGLED-Highway1.jpg

[10] Wikipedia. n.d. High mast lighting used on Ontario highway 401 during the day. Retrieved July 21, 2015, http://en.wikipedia.org/wiki/High-mast_lighting#/media/File:Highway_401-Highway_402_interchange.jpg

[11] American city and county. 2013. [Image of Maine DOT traffic control electricians installing Holophane luminaires]. Retrieved July 21, 2015, http://americancityandcounty.com/site-files/americancityandcounty.com/files/imagecache/large_img/uploads/2013/09/holophanehrmainedotphoto-2.jpg

[12] Lighting Research Center, Rensselaer Polytechnic Institute. 2004. Light sources and color. Figure 8. The CIE 1976 chromaticity diagram. Lighting Answers 8(1). Retrieved June 6, 2015, http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/whatisCCT.asp

[13] Seesmart LED. n.d. Color temperature scale application. Retrieved July 21, 2015, http://www.seesmartled.com/kb/choosing_color_temperature/

[14] All LED Lighting. 2013. Retrieved June 6, 2015, http://img.deusm.com/allledlighting/2013/08/560818/163108_854448.jpg

[15] LEDspots. n.d. Color rendering performance. Retrieved July 21, 2015, http://ledspots.org/color-rendering-index/

[16] Eye Lighting International. n.d. LED distribution types. Retrieved May 16, 2015, http://www.eyelighting.com/resources/lighting-technology-education/led-basics/led-distribution-types/

[17] Apack. n.d. Street light cutoff classifications. Retrieved May 16, 2015, http://apack.net/kor/sub/Street_Light.html

[18] Praha Lighting. n.d. TM-15 BUG rating. Retrieved May 16, 2015, http://www.prahalighting.com/miniplatinum/fotometriasmini.html

[19] Illuminating Engineering Society (IES). 2011. Addendum A for IES TM-15-11: Backlight, Uplight, and Glare (BUG) Ratings. http://www.ies.org/PDF/Erratas/TM-15-11BUGRatingsAddendum.pdf

[20] National Electrical Manufacturers Association (NEMA). 2004. ANSI/IEC 60529-2004. Degrees of Protection Provided by Enclosures (IP Code) (identical national adoption). Rosslyn, VA: NEMA.

[21] DSM&T. n.d. Sample IP rating. Retrieved May 21, 2015, http://www.dsmt.com/resources/ip-rating-chart

[22] Richman, E. 2011. The elusive “life” of LEDs: How TM-21 contributes to the solution. LEDs Magazine. Retrieved May 21, 2015, http://www.ledsmagazine.com/articles/2012/11/the-elusive-life-of-leds-how-tm-21-contributes-to-the-solution-magazine.html

[23] LED Luxor. 2012. Top 10 Benefits of Using LED Lighting. Retrieved June 12, 2015, http://www.ledluxor.com/top-10-benefits-of-led-lighting

[24] Illuminating Engineering Society of North America (IESNA). 2000. American National Standard Practice for Roadway Lighting. ANSI/IESNA RP-8-00. New York, NY: IESNA.

[25]American Association of State Highway and Transportation Officials (AASHTO). 2005. Roadway Lighting Design Guide. GL-6. Washington, DC: AASHTO.

[26] Lutkevich, Paul, Don McLean, and Joseph Cheung. 2012. FHWA Lighting Handbook. Office of Safety. Washington, DC: Federal Highway Administration.

[27] International Commission on Illumination (CIE). 2007. Road Transport Lighting for Developing Countries. CIE 180-2007. Vienna, Austria: CIE.

[28] Illuminating Engineering Society of North America (IESNA). 2011. Technical Memorandum on Light Trespass: Research, Results, and Recommendations. TM-11-00. New York, NY: IESNA.

[29] Illuminating Engineering Society of North America (IESNA). 2014. Lighting for Exterior Environments: An IESNA Recommended Practice. IESNA RP-33-14. New York, NY: IESNA.

[30] Illuminating Engineering Society of North America (IESNA). 2011. Luminaire Classification System for Outdoor Luminaires. IES TM-15-11. New York, NY: IESNA.

[31] Illuminating Engineering Society of North America (IESNA). 2011. The Lighting Handbook: Reference and Application. New York, NY: IESNA.

[32] Illuminating Engineering Society of North America (IESNA). 2014. Roadway Lighting. ANSI/IESNA RP-8-14. New York, NY: IESNA.

[33] International Commission on Illumination (CIE). 1995. Industrial Colour-difference Evaluation. CIE 116-1995. Vienna, Austria: CIE.

[34] Kansas Department of Transportation (KDOT). 2003. Kansas Roundabout Guide. Chapter 7 - Traffic Design. Topeka, KS: KDOT.

[35] Long, Suzanna, Ruwen Qin, Curt Elmore, Tom Ryan, and Sean Schmidt. 2011. LED Roadway Luminaires Evaluation (TRyy1101) Final Report. No. cmr12-011. Jefferson City, MO: Missouri Department of Transportation. Retrieved May 21, 2015, http://library.modot.mo.gov/rdt/reports/tryy1101/cmr12011tryy1101.pdf

[36] Energy Management Solutions, Inc. 2012. Cost-Benefit Analysis of Energy Efficient Technologies Available for Use in Roadway Lighting. St. Paul, MN: Minnesota Department of Commerce. Retrieved July 13, 2015, https://www.cards.commerce.state.mn.us/CARDS/security/search.do?method=showPoup&documentId=%7BB9337BBA-09D3-43D3-81AB-0279CF28FB0F%7D&documentTitle=40203&documentType=6

[37] RSMeans. 2014. RSMeans Electrical Cost Data. 37th edition. Norwell, MA: RSMeans.

[38] Westar Energy. 2013. Small General Service, Medium General Service, and High Load Factor Electric Rate Summary. Retrieved June 16, 2015, https://www.westarenergy.com/Portals/0/Resources/Documents/Commercial%20Rates%20South.pdf

[39] Minnesota Department of Transportation. 2010. Roadway Lighting Design Manual. St. Paul, MN: Minnesota DOT.

[40] Texas Department of Transportation. 2003. Highway Illumination Manual. Austin, TX: Texas DOT.

[41] New Hampshire Department of Transportation. 2010. Highway Lighting Design Manual. Concord, NH: New Hampshire DOT.

[42] Staplin, L. K., M. S. Janoff, and L. E. Decina. 1985. Reduced Lighting on Freeways During Periods of Low Traffic Density. FHWA/RD-86/018. Washington, DC: Federal Highway Administration.

[43] National Highway Traffic Safety Administration (NHTSA). n.d. Fatality Analysis Reporting System (FARS). Retrieved May 20, 2015, http://www.nhtsa.gov/FARS

[44] National Highway Traffic Safety Administration (NHTSA). n.d. NASS General Estimates System. Retrieved May 20, 2015, http://www.nhtsa.gov/Data/National+Automotive+Sampling+System+(NASS)/NASS+General+Estimates+System

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