EMERGING LED TECHNOLOGIES AND USE WITHIN TUNNELS

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FINAL REPORT

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1.0 Executive Summary

Tunnel owners today are faced with the decision whether to embrace new LED lighting technology vs the continued use of long term, tried and tested High-Pressure Sodium and/or Fluorescent lighting sources. This research will document the differences in lighting sources and the issues related to use of LED lighting sources in roadway tunnels. Issues include potential changes in tunnel maintenance cycles and procedures, differences in color/brightness, distribution of light from LED luminaires and the higher initial capital cost.

A review of recent international and domestic design standards was performed and is documented in this report. It was noted that besides the literature published in the last year, there was no significant documentation of LED design guidelines or principles. In addition, a questionnaire was sent to twelve tunnel owners and six tunnel luminaire and control product manufactures. The responses to the questionnaire concluded that tunnel owners are adopting the use of LED lighting systems as their existing High-Pressure Sodium and/or Fluorescent lighting systems reach the end of their service life. The tunnel owners that have implemented LED lighting systems have acknowledged the benefits of reduced maintenance and energy consumption.

A life cycle cost analysis between HPS and LED luminaires was performed and was documented in the previous report. Research was also conducted to identify and evaluate existing LED systems that are used on roadways and tunnels, and evaluate their effectiveness. It was concluded that the benefits of LED luminaires become more prominent as technology advances. Additionally, these advances in technology, along with the availability of serviceable LED luminaires, have diminished previous shortcomings of LED roadway lighting systems. We see clear evidence of this as the market shifts from alternatives such as HPS luminaires to LED luminaires, particularly in tunnel lighting applications. Furthermore, when LED tunnel luminaires are controlled by an intelligent control system, continuous dynamic dimming of the LEDs is available to closely match the lighting requirements and reduce energy.

Guidelines developed in Task 6 have been used to develop and propose revisions to the AASHTO Roadway Lighting Design Guide, current version is Seventh Edition dated October 2018, with respect to tunnel lighting. Revisions are proposed to Chapter 1.7 Emerging Roadway Lighting Technologies, and Chapter 4 Tunnels and Underpasses. The revisions are included within this report with track changes highlighting the recommended updates.

It is expected that the adoption of LED lighting will become the norm for tunnel owners across the U.S. Tunnel owners currently consider several factors when determining the lighting source they will select: capital cost, durability, expected life of the product, safety (key factor) for the traveling public, reliability to keep the tunnel open, and life-cycle costs.

2.0 Introduction

Highway tunnels play an important role in our nation's transportation network. Tunnels provide vehicular access through critical links within the transportation system for a region; without them the remaining roadways would be overburdened, and travel would be longer and more indirect. Maintaining the lighting systems in a state of good repair and at peak performance is a critical element to maintaining the safe passage of vehicles on our transportation network. The enclosed space of a tunnel versus a highway brings its own unique challenges to the design and performance of a tunnel lighting system. The effect of tunnel lighting on drivers' eyes at tunnel entrances and exits must be considered in design, and the harsh environment caused by thermal fluctuations, high humidity levels and sodium chloride (road salt) must be considered as it impacts the performance of any lighting system.

LED tunnel lighting has evolved rapidly and has become economically competitive; LED technology can now successfully deliver and meet the stringent requirements of tunnel lighting. Tunnel lighting design guidelines, recommended practices, and international references have been around for some time and are fairly well developed, but LED technology for tunnels has been changing and it is only now becoming more standardized. This is one of many issues relative to LED technology for tunnel owners to consider when deciding upon a tunnel lighting system replacement. This project will address the issues associated with implementing LED lighting in tunnels while answering the questions that tunnel owners are asking when deciding if it is the right time to replace their lighting system and whether LED is the right technology.

Unlike normal roadway lighting, tunnel lighting is required to operate at its peak performance during daylight hours and react progressively to changes in exterior/ambient light levels throughout a complete solar day. The ability of tunnel lighting to allow motorists to enter, travel through, and exit a tunnel with the same degree of confidence and at the same travel speed as they would on an adjacent section of open road plays a key role in driver safety. A safe tunnel is a well-designed tunnel.

When drivers enter a tunnel during the day they are confronted with a physical need to adapt both spatially and visually. Upon approaching the tunnel, the field of vision narrows and is limited to an angle corresponding to the opening of the tunnel entrance. Visual adaptation occurs from a sudden high level of luminance at the tunnel entrance to a very low level inside the tunnel interior; consequently, the eye needs time to adapt. Proper lighting and controls will allow drivers' eyes the time to safely adapt to the changing light levels as they travel through the tunnel.

2.1 Goal for this Research Project

The goal for this research project is to develop proposed revisions to the AASHTO Roadway Lighting Design Guide, current version is Seventh Edition dated October 2018[(1)]. The revisions presented to AASHTO will (1) assemble a catalog of LED luminaire types; (2) identify benefits and issues related to implementation of LED lighting systems; (3) identify cost strategies related to capital and on-going maintenance and operation costs. The proposed guidelines will be applicable to the initial planning and final design of new LED tunnel lighting systems. This Final Report documents the compilation of all the research tasks and methodologies included in the proposed guidelines and proposed revisions to the design guide.

3.0 Literature Review of Design and Maintenance of LED Tunnel Lighting

To evaluate current methods and best practices employed for the design and maintenance of LED tunnel lighting, a review of existing international and domestic standards and other relevant documentation was performed. In addition, surveys with owners and manufacturers were conducted to document key aspects related to the current state of knowledge on the performance, cost and maintenance of LED tunnel lighting systems. Eight tunnel owners in the U.S. responded to the survey: Pennsylvania DOT, Metropolitan Transit Authority Bridges and Tunnels, Colorado DOT, Chesapeake Bay Bridge and Tunnel District, North Texas Tollway Authority, Pennsylvania Turnpike Commission, and Port Authority of Allegheny County. Four tunnel luminaire and control product manufactures responded to the survey: Kenall Lighting, Holophane Lighting, Schreder Lighting, and PLC Multipoint Controls. The results of these surveys are described in the sections below.

3.1 Technical Literature Review

Over the past four decades, the principles and standards for lighting road tunnels have evolved dramatically from the use of incandescent, to fluorescent, then high-pressure sodium, some limited use of induction light sources and new LEDs.

The recent research has been largely led by the luminaire manufacturers; they are on the cutting edge of this constantly evolving lighting source. As a result, their luminaire and control products are also constantly evolving, incorporating the latest LEDs and control features that enhance the luminaire performance and energy efficiency.

Stepping back to the market-recognized, published guidelines, in 1973 the Commission Internationale de l'Eclairage (CIE) published **International Recommendations for Tunnel Lighting**. These recommendations were revised and published as a new document: **The Guide for Lighting of Tunnels and Underpasses CIE 88-1990**, the recent version being **CIE 88-2004**(2). CIE 88-2004 is the most established international standard and is currently under revision. The current CIE standards do not address the use of LEDs. Switzerland and Austria are developing guidelines beyond the current CIE requirements that are anticipated to be tailored to the potential offered by LED tunnel lighting systems.

The domestic standard, **ANSI/IES RP-22-11(3) Tunnel Lighting** was published in 1987 with revisions in 1996, 2005 and 2011. In 2019, ANSI/IES RP-22-11 was rolled into **ANSI/IES RP-8-18**(4), the **Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting**. ANSI/IES RP-8-18 provides key information related to LED tunnel lighting. Key chapter elements that are applicable to tunnel lighting include:

- Chapter 2 – Vision and Fundamental Concepts: Discusses glare, how to calculate glare, maximum recommended levels and how utilizing luminaires with proper optical design will minimize glare.
- Chapter 3 – Calculations: Discusses tunnel lighting calculations and glare metrics.
- Chapter 6 – System Components: Discusses the selection of equipment including key selection criteria along with LED as a light source, luminaire photometric performance, LED system components, control technologies and adaptive lighting design and operation.
- Chapter 9 – Maintenance and Operations: Describes the life of solid-state light sources and factors affecting maintenance. Maintenance of Tunnel Lighting is discussed linking tunnel luminaire maintenance with ensuring that lighting levels are maintained allowing drivers to maintain speed and safely navigate in the tunnel.
- Chapter 14 – Tunnels: Discusses light distribution techniques for tunnel luminaires, tunnel lighting equipment, control systems and maintenance.

The technical specification, **NMF01- 2018 - LED Luminaires - Requirements-Ed.-1.0**(5), is a working document based on current European guidelines, four European Union road authorities, and ongoing work by the CIE technical work committees, International

Organization for Standardization (ISO), International Electrotechnical Commission (IEC) and European Committee for Standardization (CEN) standards and draft standards in progress. In large part this standard is a pre-cursor to the pending update of the CIE standards. It addresses many of the topics we anticipate including in the proposed guidelines resulting from this project research, including: photometric performance, useful service life, maintenance and light output factors, color temperature and rendering index. It is encouraging that the international standards are in the process of being updated in parallel with the research and anticipated proposed guidelines for this project.

The Belgium-based light manufacturer, Schréder, founded in 1907, has LED lighting systems, luminaires and controls, installed in various recent tunnels located in Europe, North America, Asia, Middle East and Australia. Schréder has published a document of their **Tunnel Lighting and Controls**(6) technology. Currently, the longest tunnel with Schréder's lighting systems is planned for the E4 Stockholm bypass, a new route for the European highway (E4) past the Swedish capital. The tunnel is 21 km (13 miles) in length with three travel lanes in each direction in two separate tunnel tubes. LED lighting and lighting controls are scheduled for installation along the entire route between 2021-2026. Additionally, the NorthConnex Tunnel is 9 km (5.6 miles) in length built with long term capacity for three lanes, initially operating with two lanes and a breakdown lane in each direction. The NorthConnex is scheduled for completion in mid-2020 having 4,500 LED luminaires. The tunnel lighting control system will dim the LED luminaires based on real-time electronic speed signs and traffic volume monitoring.

In 2017, Lorenzo Domenichini, Francesca La Torre, Dario Vangi, Antonio Virga & Valentina Branzi (2017) studied the influence of the lighting system on the driver's behavior in road tunnels. The published document from their study was **Influence of the lighting system on the driver's behavior in road tunnels: A driving simulator study**(7). Their work studied driver performance approaching, inside and exiting LED lighted tunnels compared to the behavior maintained in tunnels illuminated with a traditional lighting system. The results indicated that simulated LED lights often induced a better driving behavior under some aspects. The motorists were able to perceive in advance the critical situation and consequent maneuvers were carried out in a more effective manner. Additionally, drivers had better lateral trajectory control in transition areas.

MTA Bridges & Tunnel that operates both the Hugh L. Carey Tunnel and the Queens Midtown Tunnel experience higher traffic volumes during the AM and PM peak commuter periods. According to **2016 New York City Bridge Traffic Volumes**(8), between 7-8AM, the average vehicular volume through these tunnels into Manhattan is 3,000 and 3,500 respectively. In urban tunnels and as travel speeds become slower than normal during peak commute times, it is logical that owners begin considering the use of real-time data on traffic volume and speed to permit dimming the threshold and transition lighting which will result in decreased energy consumption and extend the life of the luminaires.

The American-based light manufacturer, Kenall, founded in 1963 and recently acquired by Legrand, has indicated that all tunnel lighting projects they are currently involved with are utilizing LED luminaires. They have also indicated that solid state lighting (SSL) is the only light source technology currently funded by the U.S. Department of Energy. According to Rennselaer Polytechnic Institute's Lighting Research Center, SSL has evolved to a point where the LED is now the preferred light source for many lighting applications, and the LED market transformation is estimated to approach 50% by 2025. This information was included in a presentation titled **New Considerations in LED Tunnel Lighting**(9) given by Michael N. Maltezos, MIES, who is Chairman of the IESNA Tunnel Committee.

Additional documents researched to date are listed in our References list. Documents ten through thirteen speak to LED technology in a general sense and document fourteen, though specific to tunnels, makes no mention of LED lighting technology.

4.0 Survey - Tunnel Owners and Other Stakeholders (Manufacturers)

Gannett Fleming conducted a survey of tunnel owners and manufacturers, asking them an array of questions related to specific topics relevant to this study. The responses provide an understanding of current knowledge regarding the performance of LED lighting installations including cost along with maintenance and operational components of an LED tunnel lighting system.

Specific experiences relevant to this study will be discussed, including although not limited to: ease of replacement of light engine and driver, equipment durability in tunnel environment, control of tunnel lighting system, maintenance and cleaning policy. The experience gained by agencies that have installed (or rejected) LED lighting have provided us with a database of lessons learned and a list of best practices for procurement, installation, and maintenance of LED tunnel lighting systems.

Key issues of tunnel owners: energy, re-lamping, and maintenance costs of High Pressure Sodium (HPS) and/or Fluorescent tunnel lighting systems are significant. With tunnel lighting projects, initial capital cost versus life cycle cost is always a concern. An additional concern is future technological developments rendering a system obsolete prior to its end of expected life. Replacement parts for legacy systems (T-12 fluorescent lamps as an example) are being phased out and will become difficult to find. Maintenance costs and challenges include accessibility to equipment while minimizing traffic disruption, tunnel washing, equipment damage from over-sized vehicles, water leaks, and equipment corrosion.

Equipment Manufacturer Questionnaire:
Questionnaires were sent to lighting luminaire and control system manufacturers. Discussions provided insight into materials, light distribution techniques, glare reduction, and future technological developments including the potential for analog dimming. To synthesize the results of the equipment manufacturer questionnaires, the results are presented in a comparison table form.

4.1 Owners Survey – Key Observations and Questions Response Summary

Key observations taken from the Owners Survey results include:

- Tunnel maintenance is generally performed in a cyclical time period. A change to LED would not change the owner's cyclical period but it is anticipated that luminaire maintenance would be dramatically reduced.
- While LEDs themselves have a 20+ year expected life, there are other components of the LED luminaire (i.e. driver) that need to be evaluated when calculating life-cycle cost.
- The durability of LED luminaires due to the harsh tunnel environment is a primary issue that tunnel owners review when selecting a luminaire.
- Tunnel owners are adopting or are considering adoption of advanced control strategies including dimming of luminaires.
- A proactive operational financial plan that considers life-cycle costs must be developed to address the need for preventive maintenance, system upgrades/replacements and energy performance

The proposed guidelines will address each of these key observations in addition to other key issues raised by the literature research and manufacturer's survey responses. See Section 5.0 of this Report for the outline of the proposed guidelines.

The survey was sent to the following tunnel owners, those marked in green text below responded to the survey as of the date on this report. Their responses are summarized below, see Appendix A for the questions and raw results from each owner.

TABLE 1: Listing of Tunnel Owners that Received Survey	
PA Turnpike	Kenneth L. Slippey
Port Authority of Allegheny County	Anonymous
PennDOT District 11	Ben DeVore
CBBT	Timothy Holloway
NTTA	Jeff Martinez
CDOT	Tyler Weldon
Triborough Bridge and Tunnel Authority (TBTA)	Kelley Bray
FDOT D6	Alberto Sardinas
PANYNJ	Dennis Stabile
Oregon DOT	Bruce Johnson
MdTA	John O'Neill
	Eric Morris
DDOT	Abdullahi Mohamed

Owners realize that tunnels can be challenging for drivers and that maintaining lighting throughout the tunnel assists in providing safe passage. Additionally, those who have installed LED lighting have experienced significant reduction in maintenance, specifically in manpower and lane closures, given the longer life of the LED light source because of the longer time between maintenance cycles.

1. How often do you perform maintenance (cleaning, lamp/ballast replacements) on your tunnel lighting luminaires? Would you anticipate reduction in these actions with a change to LED luminaires?
   Response Summary:
   Maintenance is performed on tunnel lighting luminaires between monthly to twice a year. A change to LED light source will not change their frequency of maintenance but the expected effort during each maintenance event will be reduced. Maintenance of tunnel lighting luminaires is performed during regularly scheduled tunnel closures for other maintenance activities.

2. Do you group re-lamp or replace individual lamps and ballasts as they fail?
   Response Summary:
   Maintenance is performed by replacing individual lamp/ballast on regularly scheduled maintenance periods for each tunnel.

3. Which of the following (if any) do you keep in stock as spare parts?
   Entire Fixtures, Lenses, Housing, Ballasts, Lamps, LED Boards, Surge Protective Devices, Drivers, Other?
   Response Summary:
   Spare parts range from entire fixtures to individual sub-components.

4. What are the key characteristics you consider important when determining a luminaire's durability?
   Response Summary:
   Primary characteristics that are critical to tunnel owners are: Environmental resistance to corrosives such as vehicle exhaust gases and salt/chlorides from either sea saltwater or from ice/snow melting products, moisture, water infiltration. Taking into consideration the material of the fixture is also critical as it relates to dissimilar metal between the fixtures and supporting systems.

5. Would your agency adopt dimming in lieu of switching groups of luminaires to automatically control threshold and transition zone light levels according to outdoor light?
   Response Summary:
   Tunnel owners utilize this control feature on their tunnel lighting systems or would consider the feature if proven through calculations to be beneficial.

6. As traffic speed increases, so does required maintained average pavement luminance levels. Would your agency consider using real-time data on traffic speed and/or traffic flow to dim threshold and transition zone lighting?
   Response Summary:
   The results to this question were mixed with just two owners that would consider this energy savings and control scenario.

7. Historically, tunnel lighting fixtures have been identified by their wattage (e.g. High-Pressure Sodium 250-Watt, 400 Watt). However, the recent market transition to LED fixtures shifts the focus to light output, measured in lumens. When establishing lighting values, does your agency identify fixtures by their lumen output as opposed to their wattage to account for these changes in technology?
   Response Summary:
   It was encouraging to see the responses indicate that owners acknowledge that luminaire light out (lumens) is the new design criteria point with the increased

use of LEDs as the light source. The response that suggested a conference/debate on the topic is aligned with the intended next steps of this research project during Tasks 6, 7 & 9 when we develop guidelines, propose revisions to the existing Guideline and present the recommended guidelines.

8. When considering future lighting system upgrades what results have you seen in life-cycle cost comparison of LED versus High Pressure Sodium systems?
   Response Summary:
   Based on the responses, there is an opportunity during this research project to increase knowledge in the industry about life-cycle cost comparison strategies and input criteria to be included in such calculations.

4.2 Other Stakeholders (Manufacturers) Survey – Key Observations and Questions Response Summary

Key observations taken from the Manufacturers Survey results include:

- LED luminaire durability is a key aspect of a manufacturer's product development including corrosion resistance, water/moisture/dust intrusion, lumen performance, ease of maintenance.
- The importance of addressing dissimilar metals is acknowledged as a critical element of manufacturers developing their product.
- Life-cycle cost data is still being captured and not fully developed given that LEDs have not been in place for as long as their expected life of about 20 to 30 years.
- Placement of lenses over the LED light chips are used to control glare as perceived by motorists.
- The expected life of LED luminaires is closely tied to the energy rating and number of hours each luminaire operates each day of a year.

The proposed guidelines will address each of these key observations in addition to other key issues raised by the literature research and owners survey responses. See Section 5.0 of this Report for the outline of the proposed guidelines.

The survey was sent to the following Manufacturers, those marked in green text below responded to the survey as of the date on this report. Their responses are summarized below, see Appendix A for the questions and raw results from each manufacturer.

TABLE 2: Listing of Other Stakeholders and Manufacturers that Received Survey	
Kenall	Michael Maltezos
Holophane	Ken Roth
Schréder	Francis Saint-Laurent
PLC Multipoint	Norm Dittmann
Nyx Hemera Technologies	Pierre Longtin
Phoenix Contact	Christophe Steppe

Manufacturers are advancing their products to enhance the durability, energy efficiency, resistance to corrosion and overall performance to deliver lighting to the unique characteristics of roadway tunnels.

1. What are the key characteristics you consider important when determining a luminaire's durability?
   Response Summary:
   Regarding durability, the primary characteristics luminaire manufacturers consider important are ability to withstand vibration, corrosion resistance, full insulation of dissimilar metals, ingress protection against dust and high-pressure jets, as well as protection against voltage surges. Additionally, the use of high-quality LEDs is critical as it relates to maintaining lumen output over the life of the luminaire.

2. What material are your existing lighting products made from; select all that apply?
   Response Summary:
   Stainless steel and aluminum are the primary material that manufacturers are using for tunnel luminaires. For aluminum, manufacturers are providing full insulation of dissimilar metals using nylon interfaces between luminaires and their supporting system.

3. If you answered 'Other' in question 3, please list other materials here:
   Response Summary:
   Manufacturers are using only aluminum or stainless steel. When using aluminum, the housing is properly finished with anodization, sealing and double layers of powder coating.

4. Have you addressed concerns in the market with the presence of dissimilar materials between luminaire mounting bracket and the fixture itself?
   Response Summary:
   Manufacturers are isolating dissimilar metals using nylon interfaces between luminaires and their mounting brackets.

5. What results have you seen in life-cycle cost comparison of LED versus High Pressure Sodium systems?
   Response Summary:
   Manufacturers have seen energy and maintenance cost savings of 50% over high pressure sodium. Furthermore, when coupled with a proper dimming control system, energy savings can reach as high as 60% over high pressure sodium even though initial installed power is similar for both.

6. Are your tunnel luminaires designed to be serviceable? Can components, driver and LED array be replaced?
   Response Summary:
   The results to this question were consistently yes.

7. Is your warranty for the life of the product and what does it cover?
   Response Summary:
   It is encouraging to see warranties of ten (10) years for both stainless steel and aluminum housings, excluding drivers which are covered for five (5) years. It was noted that warranties exclude labor required to install replacement parts.

8. What is the life of the drivers used in your LED tunnel luminaires?
   Response Summary:
   Generally, the standard warranty on drivers is five (5) years or 43,800 hours. Typical lifetime is published from 50,000 hours plus and one luminaire manufacturer indicates the electronic drivers used have an estimated minimum life of 100,000 hours. Since drivers have a shorter lifetime than LEDs, they continue to remain the weakest link inside the LED luminaire.

9. What is the life of the LED arrays used in your tunnel luminaires?
   Response Summary:
   In understanding the responses to this question, it first helps to know that the Illuminating Engineering Society's (IES) standard TM-21 'Projecting Long Term Lumen Maintenance of LED Light Sources' is the standard for extrapolation

calculations for the lumen maintenance measurement known as L70. L70 being hours at which the LEDs will still emit at least 70% of their initial light output. Manufacturer TM-21 test reports indicate L70 of:

- 150,000 hours or 17 years for 400-Watt luminaires
- 175,000 hours or 20 years for 300-Watt luminaires
- 225,000 hours or 26 years for 200-Watt luminaires
- 300,000 hours or 34 years for 100-Watt luminaires

10. What optical design techniques are utilized to limit glare from the light source?

    Response Summary

    In tunnels allowing luminaires to be installed overhead, a counter-beam light distribution reduces glare and provides high pavement luminance. Wall mounted installations rely more heavily on optical lenses and reflectors to control the distribution and minimize direct view of the LEDs. Furthermore, each individual LED within the array has its own optical lens which limits glare.

11. Which of the below light distributions are available in your LED tunnel luminaires:

    a. Symmetrical
    b. Asymmetrical – Negative Contrast also known as Counter-Beam
    c. Asymmetrical – Positive Contrast also known as Pro-Beam

    Response Summary

    Luminaires used to accomplish the required high light levels in tunnels typically have one of three light distribution types: symmetrical, counter-beam and pro-beam. The tunnel luminaire manufacturers responding to our questionnaire were Holophane, Schréder and Kenall. All three offer LED luminaires containing these distributions. Additionally, it was encouraging to see various other photometric distributions offered allowing for the best possible balance of luminance while limiting veiling luminance (disability glare) for each tunnel depending on the geometric shape of the tunnel and luminaire installation height.

5.0 Outline of Proposed Guidelines

1. Why is tunnel lighting different?
    - Operates at peak performance during daylight hours versus nighttime hours as with roadway lighting
    - Reacts to changes in ambient light levels throughout the entire day
    - Assists driver with visual adaptation as they enter/exit a tunnel
2. History of tunnel lighting
    - Advent of new vehicular tunnels. Conversion of railroad tunnels to roadway use
    - Advancement of Electric Lamps: sodium, fluorescent, induction, LED
3. Light source alternatives in today's tunnels
    - High pressure sodium (HPS), fluorescent, LED
    - Factors affecting the selection of light source.
        - Lumen output: Light sources are measured by their lumen output
        - Efficacy (lumens per watt)
        - Lumen depreciation: Lumen output of light sources depreciates over their expected life at different rates.
        - Restrike time: The time it takes for a HPS lamp to reach 90% of light output after it has been turned off and immediately reenergized.
        - Correlated color temperature (CCT): CCT is a measure of the visual "warmth" or "coolness" of light expressed in kelvins (K).
        - Color rendering index (CRI): CRI is an indication of the ability of the light source to render colors. The higher the CRI, the better the rendering of color.
4. Photometric classification for tunnel luminaires
    - Symmetrical, Pro-beam, Counter-beam
    - Glare mitigation
5. Environmental considerations
    - Dissimilar metals (Aluminum versus 304 Stainless Steel versus 316 Stainless Steel)
    - Luminaire housings: vibration; ingress protection from dust, water and jets; corrosion resistance
    - Ability to operate under the highest and lowest expected ambient temperatures
6. Safety & Crash Reduction
    - Traffic safety and behavior of drivers in tunnels

7. Lighting selection considerations
    - Lumen Output
    - Efficacy (lumens per watt)
    - Lumen depreciation
    - Maintenance
        - Lifetime of light source and luminaire components (i.e. LED drivers, HPS ballasts)
        - Advancing technology and ease of component replacement.
    - Controllability
        - Dimming
            - Precise tracking of the Transition Adaptation Curve for luminance reduction in Threshold and Transition Zones.
            - Enhanced energy management of LED lumen maintenance L70 values
        - Switching
            - Group/Circuit switching
            - Individual fixture switching
    - Costs:
        - Capital: Initial high cost
        - Operating: lower maintenance cost; labor and potential energy reduction
        - Life-cycle cost
8. Evolving technology
    - LED luminaires are relatively new and, as such, continually evolving and improving performance
9. Smart adaptive lighting
    - Light level verification
    - Predictive maintenance
    - Real time energy monitoring
    - ITS integration (traffic control)

6.0 <u>Life Cycle Cost Analysis</u>

Research was conducted under this task to evaluate alternative solutions for the replacement of an existing tunnel lighting system. An authentic tunnel model was generated which was used to create two tunnel lighting design solutions. The lighting design criteria for the tunnel was established per the requirements of the ANSI/IES RP-22-11. One of the tunnel lighting design solutions utilized HPS luminaires of various wattages and the other utilized LED luminaires. A simplified life cycle cost analysis was performed to compare the economics of a lighting system using HPS luminaires to a lighting system using LED luminaires. The analysis used current day unit pricing as well as current day ballast/lamp and driver replacement costs. The analysis did not account for potential methods of control (i.e. switching, dimming, etc.).

6.1 Basis of Analysis

For our research analysis, we have modeled a double box, vehicular tunnel that is approximately 864 feet long and runs in a North–South orientation. The tunnel carries vehicular and pedestrian traffic.

The tunnel is divided into two separate boxes, each providing unidirectional traffic Northbound and Southbound. Due to the pedestrian walkway on the northbound side, the tubes are not symmetrical. The larger Northbound tube is 31'-7" wide and the Southbound tube is 26'-10" wide. Both tunnel tubes have a height of 14'-3".

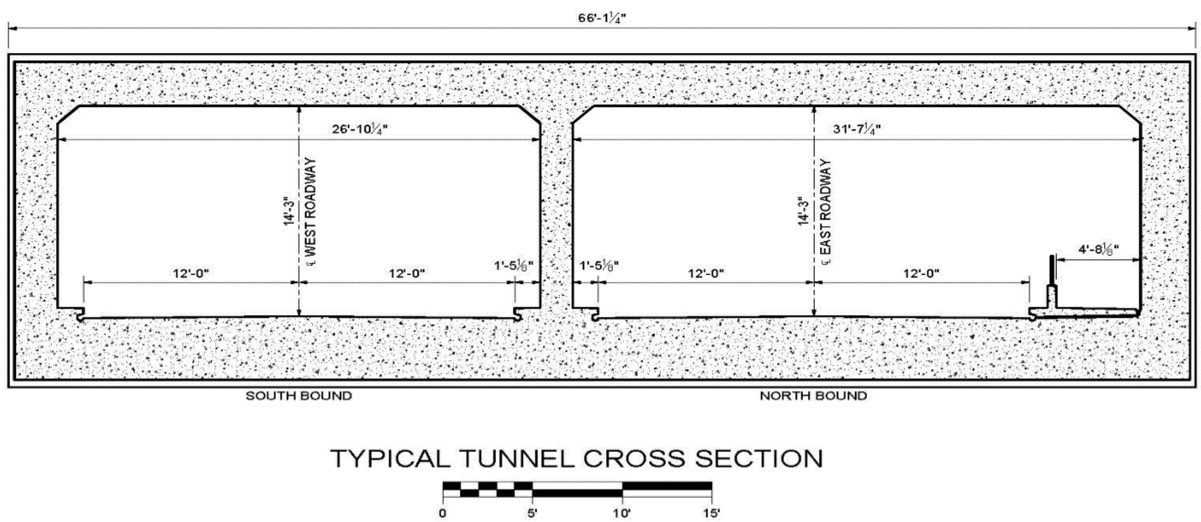

FIGURE 1: Tunnel Cross Section

6.2 Lamp Sources For Luminaires

High-Pressure Sodium

HPS is one of three main types of high intensity discharge (HID) lamps. HID lamps are characterized by small, bright arc tubes made from quartz or translucent/transparent ceramic materials. These arc tubes contain electric discharges of vaporized metals operating at relatively high temperatures and pressures.

Historically, HPS has been used in roadway lighting because its service life far exceeded the other available technologies that pre-existed its development. Additionally, lamp-to-lamp color variation for standard high-pressure sodium lamps is in the range of

1900-2200K (very warm, golden color) with a low Color Rendering Index of about 22. HPS lamps are offered in standard wattages, 35 up to 1,000 watts, and have a complete range of lumen packages. Efficacies range from 70-120 lumens/watt.

The HPS lamps used in the photometric lighting calculations, as well as the life cycle cost calculations, are of the clear, EPA Toxicity Characteristic Leaching Procedure (TLCP) Compliant type and suitable for mounting in all operating conditions.

The lamp characteristics are:
(Lamp Wattage, Bulb Shape, Minimum Initial Lumen Output, Rated Avg. Life in Hours)

- 100 / ED 23.5 / 9,500 / 24,000
- 250 / ED 18 / 27,000 / 24,000
- 400 / ED 18 / 50,000 / 24,000

Advantages of HPS lamp sources are:

- Very Good Efficacy (400W lamp - 108 lumens/watt)
- Standard Wattage and Lumen Output Ratings
- Very Good Light Distribution
- Lower Initial Cost
- Good lumen maintenance at end of lamp life
- Good ballast life at 60,000 hours

Disadvantages of HPS lamp sources are:

- Lower Lamp Life (24,000 hours, 5-7 years)
- Not Instant On, Restrike Time Required
- Switching Required, Not Dimmable
- Low Color Rendering Index
- Golden Color (2200 degrees Kelvin Color Temperature), less white light
- Heavy bulky fixtures
- No end of life warning of ballast or lamp failure
- Parts will become hard to find as manufactures are phasing them out

Light-Emitting Diodes

Light-emitting diodes are solid-state electronic devices that generate light via the transformation of electric energy to radiant energy within the crystalline structure of a semiconductor chip. Advances in phosphor technologies, particularly the addition of red enhanced phosphor coatings have enabled less bluish-white light and allowed for warmer white LEDs (color temperatures below 6,000 degrees Kelvin). Additionally, LED technology enables higher lumen outputs, which are ideal for the requirements of the Tunnel Threshold Zones for Roadway Lighting. Typically, LED luminaires do not provide notification of when the LEDs have reached their end-of-rated-life. Since LED light output decreases continually over time much beyond their 70% of rated life hours (L70), there is no indication of when the luminance on the roadway falls below the target criteria. However, several DOTs (Arizona, California, Colorado, Hawaii, Illinois, Massachusetts, Ohio, Virginia, and Washington) have, in recent years, adopted the use of LEDs for tunnel lighting applications.

The latest advances in LED electronic drivers provide features which can be programmed by luminaire manufacturers.

Such features of the latest drivers include:

- Constant Light Output (CLO), delivering constant lumens through the life of the luminaire.
- Over the Life (OTL) indicator, the driver provides an L70 or end of life signal. Upon reaching L70, the driver will flash for 2.5 seconds and then continue normal operation. LED flashing occurs every time at startup once L70 is reached.

Advantages of LED lamp sources are:

- No Flickering of Light
- Very Good Efficacy (104 lumens/watts)
- Very Good Lamp Life (L70 @ 100,000 hours), translates to lower operating cost
- Good Driver Life (50,000 hours)
- Precise Light Distribution and glare control
- Instant On
- No indication when roadway luminance falls below criteria (L70 notification can be provided via specialized sub-components)
- High Color Rendering Index

- Whiter light (4000-5000 degrees Kelvin Color Temperature)
- Dimmable (in lieu of switching) to achieve Tunnel Scenes
- Smaller profile
- Adaptive control interface to adjust light levels (dimming) through the day and changes in ambient weather conditions

Disadvantages of LED lamp sources are:

- No standard Wattage or Lumen Output Ratings
- Lumen maintenance decreases beyond L70 (Newest products are boasting L80 and L90 lumen maintenance criteria)
- Higher initial fixture cost
- No end of life warning of driver failure

6.3 Design Criteria – Recommended Light Levels per ANSI/IES RP-22-11

The preliminary Tunnel Lighting Design Criteria located in Appendix B was developed using methodology from ANSI/IES RP-22-11 Tunnel Lighting. When motorists enter a tunnel during the day, they are confronted with visual adaptation problems. One problem faced is when approaching the tunnel, the entrance to the tunnel represents a low percentage of their field of view. The second problem faced is that drivers suddenly go from a high level of luminance, daylight, to a very low level of luminance, measured in candela per meter squared (cd/m^2), inside the tunnel. Consequently, the eye needs time to adapt. The time for an individual's eyes to adjust varies and can be multiple seconds.

To neutralize the effect of these two situations, the first part of the tunnel, the Threshold Zone, is highly illuminated over a distance equal to the safe stopping distance. The higher the speed limit, the longer the safe stopping distance. The Threshold Zone is followed by Transition Zones in which the level of luminance is gradually reduced over a distance. This serves to support the curve of acceptability in IES RP-22-11 for the reduction in luminance perceived by the eye. The values below closely align with the curve of acceptability.

TABLE 3: Northbound Tunnel (South Portal) – Lighting Design Criteria

	Threshold Zone 1 148 ft	Threshold Zone 2 102 ft	Transition Zone 1 153 ft	Transition Zone 2 204 ft	Transition Zone 3 257 ft
Sunny (1,500* & above)	200 cd/m^2	167 cd/m^2	70 cd/m^2	30 cd/m^2	15 cd/m^2
Cloudy (500*to 1,500*)	160 cd/m^2	133 cd/m^2	55 cd/m^2	24 cd/m^2	12 cd/m^2
Overcast (50* to 500*)	115 cd/m^2	95 cd/m^2	40 cd/m^2	17 cd/m^2	9 cd/m^2
Dawn/Dusk (5* to 50*)	64 cd/m^2	53 cd/m^2	22 cd/m^2	9 cd/m^2	9 cd/m^2
Night (5* & below)	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2

TABLE 4: Southbound Tunnel (North Portal) – Lighting Design Criteria

	Threshold Zone 1 148 ft	Threshold Zone 2 102 ft	Transition Zone 1 153 ft	Transition Zone 2 204 ft	Transition Zone 3 257 ft
Sunny (1,500* &above)	190 cd/m^2	158 cd/m^2	66 cd/m^2	28 cd/m^2	14 cd/m^2
Cloudy (500*to1,500*)	152 cd/m^2	126 cd/m^2	53 cd/m^2	24 cd/m^2	12 cd/m^2
Overcast (50* to 500*)	108 cd/m^2	90 cd/m^2	38 cd/m^2	16 cd/m^2	9 cd/m^2
Dawn/Dusk (5* to 50*)	60 cd/m^2	50 cd/m^2	20 cd/m^2	9 cd/m^2	9 cd/m^2
Night (5* & below)	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2	2.5 cd/m^2

6.4 Summary of Lighting Calculation Results

The lighting calculations for this study were performed using the Lighting Analysts, Inc. AGi32, software package. AGi32 software was used to calculate average roadway luminance, measured in candela per square meter (cd/m^2) levels, and uniformity ratios. AGi32 utilizes calculation methodology and procedure techniques outlined in ANSI/IES RP-22-11 Tunnel Lighting as well as ANSI/IES RP-8-18 Roadway Lighting. Factors involved in the lighting analysis include luminaire type, mounting height, tilt, spacing and reflectance of tunnel surfaces.

TABLE 5: High Pressure Sodium – NB Tunnel Luminaire Schedule

Single row of luminaires located on both East and West Walls.
Mounting Height is 12 feet to center of fixture above roadway.

Luminaire Schedule

Qty	Lamp Lumens	LLF	Description	Distribution	Luminaire Watts
36	11,223	0.51	PD15AHP	Wide Vertical,	188
42	6,847	0.51	PD100HP	Wide	128
180	37,864	0.51	PF400HP	Horizontal	444
				Beam (Typical	
42	20,460	0.51	PF250HP	for All)	289

TABLE 6: HPS Lighting Calculation Results – Northbound Sunny

Northbound Sunny - All luminaires are turned on.								
Zone	Calc Type	Units	Target Avg	Calc Avg	Max	Min	Avg/Min	Max/Min
Threshold 1	Luminance	Cd/SqM	200	199.63	216.00	172.00	1.16	1.26
Threshold 2	Luminance	Cd/SqM	167	172.13	185.00	150.00	1.15	1.23
Transition 1	Luminance	Cd/SqM	70	74.56	81.00	65.00	1.15	1.25
Transition 2	Luminance	Cd/SqM	30	35.21	38.00	28.00	1.26	1.36
Transition 3	Luminance	Cd/SqM	15	20.08	22.00	17.00	1.18	1.29

TABLE 7: LED – NB Tunnel Luminaire Schedule

Luminaires are mounted on wall, mounting height is 13'-6" from roadway to center of luminaire. Luminaire tilt is 45 degrees from "facing straight down" position.

Qty ¦	Label	Lum. Lumens	LLF	Description	Distribution	Luminaire Watts
118 ¦	X Day	56,611	0.58	Tunnel Luminaire	Type 1 Very Short	530
36 ¦	Y Day	38,712	0.58	Tunnel Luminaire	Type 1 Very short	298
36 ¦	Y Night	38,712	0.58	Tunnel Luminaire	Type 1 Very Short	298

TABLE 8: LED Lighting Calculation Results – Northbound Sunny

Northbound Sunny - All luminaires are turned on.								
Zone	Calc Type	Units	Target Avg	Calc Avg	Max	Min	Avg/Min	Max/Min
Threshold 1	Luminance	cd/m^2	200	202.68	275.00	119.00	1.70	2.31
Threshold 2	Luminance	cd/m^2	148	149.49	210.00	82.00	1.82	2.56
Transition 1	Luminance	cd/m^2	82	83.62	117.00	47.00	1.78	2.49
Transition 2	Luminance	cd/m^2	36	39.06	55.00	22.00	1.78	2.50
Transition 3	Luminance	cd/m^2	18	19.49	28.00	11.00	1.77	2.55

Based on the calculations, both the HPS and LED luminaire solutions are compliant with the ANSI/IES RP-22-11 recommended practice. It can also be observed that the total number of fixtures used in the HPS luminaire solution for the Northbound tunnel is 300, while the total number of fixtures used in the LED luminaire solution is 190.

6.5 Summary of Life Cycle Cost Results

A fair comparison of available tunnel lighting systems must compare all aspects of a lighting system's capital and operating costs. To justify the use of an LED system, all energy savings and reduced maintenance/replacement costs must be evaluated. During this task, we have performed life cycle evaluations for LED and HPS, as HPS has historically been the most commonly used lamp type in North American tunnel lighting applications. Fluorescent and induction lighting are utilized in existing tunnels but would likely not be considered for a lighting system upgrade today. The analysis performed considered initial cost, expected lifetime, expected maintenance and operating costs, and energy savings. To clarify the results in the analysis, a table is included below. Complete tables and graphs, including back analysis, are provided Appendix D.

Below is the result of the life cycle cost comparing LED to HPS Lighting Systems with both lighting systems showing similar costs over the 20-year life cycle of the tunnel lighting system. One cost that was not represented in this analysis is maintenance of traffic. The inconvenience and cost associated with more frequent lane/tunnel closures to accommodate ballast/lamp replacements when maintaining an HPS lighting system is difficult to quantify. Though it is not represented, maintenance of traffic is an area where LED lighting systems can provide additional cost savings compared to HPS. Additionally, less maintenance frequency will minimize the potential of secondary crashes due to Maintenance of Traffic (MOT).

TABLE 9: 20 Year Life Cycle Cost Analysis

	LED	HPS
Initial Construction Cost	$1,008,434	$724,413
Annual Energy Cost (Electricity)	$76,801	$92,814
20 Yr. Lamp Replacement Costs	$0	$60,544
20 Yr. Replace Driver/Ballast Costs	$185,894	$123,446
Quantity of Luminaires	370	550
Lamp Replacement Period (hours)	100,000	24,000
Replace Driver/Ballast Period (hours)	50,000	60,000
Present Value Lifecycle Costs	$2,457,217	$2,434,618

Inflation Rate	3.00%
Discount Rate	5.00%
Time Frame for Analysis (years)	20
Electric Cost per KWH	$0.11
Annual Burning Hours	4,455

Inflation Rate - the percentage increase in general level of prices over a period.
Discount Rate - rate used to discount future cash flows in discounted cash flow (DCF) analysis.

6.6 Task Summary

The lighting calculations indicate the lighting can be replaced with either an HPS or LED luminaire solution that is compliant with the ANSI/IES RP-22-11 recommended practice. However, the energy efficiency of available LED luminaires is constantly increasing. According to prime tunnel lighting manufacturers, "Manufacturers have largely sunset the production of high-pressure sodium luminaires. Moreover, their integral components such as ballasts and igniters have become difficult and expensive for luminaire manufacturers to procure." Additionally, LED luminaires have superior options for control compared to HPS luminaires. For example, most LED luminaires have dimming capability which can provide a wide range of light levels. A similar, HPS solution would typically utilize on/off control for numerous fixtures of varying wattages via relays in order to achieve the same results. Dimming LED luminaire will result in even greater energy savings when compared to HPS luminaires. The added cost to replace drivers for LED luminaires offsets the savings in HPS lamp replacement costs, so the ultimate difference in technologies is the cost of energy.

7.0 <u>Identification and Evaluation of LED Systems</u>

Research was conducted under this task to identify existing LED systems that are generally used on roadways and tunnels, and evaluate their effectiveness on roadways regardless of whether they are feasible in tunnels. From the list of effective systems, we can identify those that could be used in tunnels, and develop a list of best practices for their use in tunnels. We can also identify any shortcomings that exist in available LED systems and provide recommendations to improve these shortcomings.

In 2017, an article in the journal of Illuminating Engineering Society of North America, ***Selection Methods and Procedures for Evaluation of LED Roadway Luminaires, LEUKOS, 13:3, 159-175***[15] developed key specifications of applicable LED roadway luminaires in the U.S. market as of 2015 (FIGURE 2). These values will to be updated over time to reflect the upgraded LED technologies implemented in the field.

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
Maximum illuminance spill light level	3 lx, precurfew
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 nondimming	Dimmable
Luminaire certificate	UL, CSA, ETL, et cetera
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

FIGURE 2: Image from *Selection Methods and Procedure for Evaluation of LED Roadway Luminaires, LEUKOS, 13:3, 159-175.*[15]

The mounting configurations for luminaires are truss or mast-arm mounting. These are the most common styles of luminaires used for roadways and are referred to as a "cobra head." Cobra head mounting consists of a slip fitter for over the tenon at the end of the mast-arm.

One of the key specifications mentioned in FIGURE 2 is light distribution as it is an essential factor in efficient roadway lighting. **ANSI/IES RP-8-18 Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting** (4) classifies luminaire light distribution according to several characteristics, among them:

- Longitudinal (along-road) light distribution
- Transverse (across-road) light distribution
- High-angle (glare producing) light distribution
- Upward light distribution
- Backward ("house side") light distribution

Classification of transverse (across-road) light distributions is based on the horizontal pattern it casts and the amount of light that reaches certain vertical angles. The Illuminating Engineering Society has classified the transverse (across-road) light distribution into five categories that range from Type I to Type V.

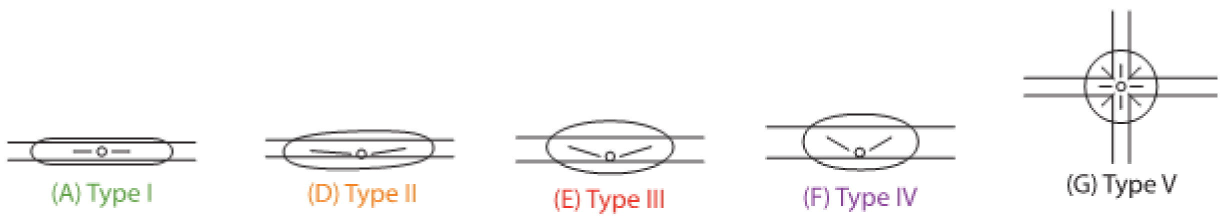

FIGURE 3: Transverse Lighting Classifications

Longitudinal (along-road) light distributions are divided into ranges; short, medium, and long. Additionally, distributions with maximum candela emission control at lower vertical angles in the longitudinal direction and are used to reduce system glare. Distributions with higher vertical angles of maximum candela emission are used in attaining required luminance uniformity where longer luminaire spacings are used as on roadways with light traffic.

In order to light various roadway widths, luminaire optical designs for roadway applications include an array of distributions mentioned above.

Additional information on roadway light distributions can be found in Chapter 2, Section 6 of **ANSI/IES RP-8-18 Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting** (4). Tunnel luminaires are available with many light distributions including IES Types I, II and III transverse distribution classifications with very short or short longitudinal distribution classifications. Additionally, symmetrical distributions distribute light similar in both longitudinal directions while asymmetrical luminaires distribute light either parallel to the flow of traffic (pro-beam) or against the flow of traffic (counter-beam). Luminaires are often fitted with reflectors for pro and counter beam solutions.

To create the light distribution patterns mentioned above, refracting devices are used to bend the light that passes through them. Today, many roadway and tunnel LED luminaires use lens-type refractors, where each LED point is associated with a specific lens that generates the complete photometric distribution of the luminaire and controls glare. This allows the manufacturer to interchange the LED photometric engines within luminaire housings to obtain any one of the desired light distributions mentioned above.

Luminaires are presently manufactured for both roadway and tunnel lighting applications, having various mounting configurations and housings capable of withstanding corrosion, high wind, vibrations, and hose down using powerful water jets. Additionally, they have a wide array of photometric distributions and lumen output packages for both roadway and tunnel applications.

An important task for the designer will be the selection and specification of equipment. Key considerations for selection and application of LED tunnel luminaires include:

- Luminaires shall be certified or listed by an organization such as Underwriters Laboratories, Underwriters Laboratories of Canada (ULC) or CSA Group [(4)].
- Photometric data shall be provided by the manufacturer from an independent testing laboratory [(4)].
- Vibration testing according to ANSI Standards
- Corrosion resistance
- Full insulation of dissimilar metals
- Ingress protection against dust and high-pressure jets (IP66 rating)
- Protection against voltage surges
- High quality LEDs with consistent
- Ability to replace individual LED array and driver
- 10-year warranty for housings and LED array
- 5-year warranty for drivers
- Glass lens
- Lensed optic principal. Each individual LED within the array has its own optical lens to mitigate glare

Innovations and emerging technology have been abundant in the past three years where many of the shortcomings that previously existed in available LED systems have been addressed by luminaire manufacturers.

7.1 Task Summary

The explorative findings in this task provide rational criteria for the selection of LED luminaires, both roadway and tunnel. The use of the established specifications for selecting LED roadway luminaires focuses on areas that will positively impact agency goals such as driver safety, system performance, cost, and reliability. Many of the criteria for roadway luminaires apply to tunnel luminaires. Subsequently, two preeminent tunnel luminaire manufacturers have customized their tunnel product for pole mounting in roadway lighting applications. Additionally, recent advances in technology, along with the availability of serviceable LED luminaires, have diminished previous shortcomings of LED roadway lighting systems.

EMERGING LED TECHNOLOGIES AND USE WITHIN TUNNELS GUIDELINES

Prepared for:

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8.0 Guidelines

8.1 Why is Tunnel Lighting Different?

Compared to open road, the visual environment of tunnels is particularly different. "The significant light contrast between daylight and tunnel luminance causes motorists to slow down as they approach the tunnel entrance."[1] This phenomenon is known as the "black hole" effect. To alleviate this effect, a higher, "reinforced" level of lighting is provided at the tunnel entrance. The amount of light required to avoid the black hole effect depends on the brightness outside the tunnel in sunny, overcast or cloudy weather. Luminance measurements outside the tunnel entrance are used to determine and adjust the light levels required for the tunnel entrance.

Tunnel lighting assists drivers with visual adaptation as they enter/exit a tunnel. "The human visual system can process information over an enormous range of luminance but not all at once. To cope with the wide range of illumination the retinal is exposed to, the visual system changes its sensitivity through a process called adaptation."2 The basic mechanisms responsible for controlling adaptation in the retina are complex. The designer should recognize this phenomenon; for instance, being outside on a sunny day and then walking into a darkened room results in temporary blindness. Similarly, adaptation occurs when moving from the dark into bright light. When a driver enters a tunnel during the day, they are confronted with the need to adapt visually. Addressing this phenomenon plays a key role in allowing motorists to enter, travel through and exit a tunnel with the same degree of confidence and at the same travel speed as they would on an adjacent section of open road. Once the driver is inside the tunnel and the eye is no longer exposed to exterior luminance, a transition can be made to a lower level of tunnel interior lighting. This transition allows for the visual system to physically adjust to lower levels of illumination.

Lighting designs address a variety of "scenes" which reflect times of the day and weather conditions (sunny, overcast, etc.). Lighting systems are designed with numerous fixtures near the entrance portals to accommodate the highest level of illumination required. Operation of the system, however, must react to changes in the ambient lighting conditions and engage the appropriate number of fixtures to develop the level of illumination needed.

While normal roadway lighting operates at peak performance during nighttime hours and at a lower lighting level. In contrast tunnel lighting is required to operate at its peak performance during daylight hours. The actual lighting level needed in a tunnel at nighttime is similar to that for normal roadway lighting. Unlike normal roadway lighting, tunnel lighting is required to operate at its peak performance during daylight hours. According to the International Commission on Illumination: "The lighting requirements of a tunnel are totally different by day and by night. At night the problem is relatively simple and consists in providing luminance levels on lit routes inside the tunnel equal to those outside the tunnel. The design of the lighting during daytime is particularly critical because of the human visual system. The driver outside the tunnel cannot simultaneously perceive details on the road under lighting levels existing in a highly illuminated exterior and a relatively dark interior."3

Furthermore, "light levels for a tunnel's threshold and transition zones are established for a motorist to safely enter the tunnel. Therefore, the design will demand that 100% of the luminaires in these zones be on for a sunny day".[4] It is known that these lighting conditions can vary not only throughout the day but also from day to day. As a result, there is no need to have 100% of the luminaires on full output all the time. Instead, through the use of an intelligent control system, lumen output can be adjusted to the Transition Adaptation Curve, Figure 14-12 in ANSI/IES RP-8-18 for different conditions of external brightness.

With tunnel lighting requirements for both daytime and nighttime lighting, it is easy to see how tunnel lighting contributes a significant portion of the cost of the overall operations of a highway tunnel.

8.2 History of Tunnel Lighting

"In the late 1700s people travelled by horse and carriage over log-surfaced roads and muddy terrain and by the 1800's they could travel by railroads and canals. As early as 1910, ideas arose to convert abandoned railway routes into motorways."[26]
Tunnel lighting has evolved significantly in the last century. Some of these railway tunnels have been converted to highway use, and the addition of lighting in these tunnels was typically incandescent. With the construction of the National Highway System beginning in the 1950's, highway tunnel construction grew, and the majority of tunnels existing in the US today were constructed over a 20-year period beginning in the mid-1950's. Fluorescent and high-pressure sodium lighting was often the choice for these tunnels. Through the years, these systems were replaced with upgraded with newer versions of fluorescent and high-pressure sodium lighting. Today, many tunnels exist in the U.S. still employ these light sources. With the advent of LED's with its many benefits, the availability of parts for the other lighting alternatives is greatly diminished.

Today's new tunnels are constructed to improve mobility while reducing traffic congestion and preserving urban space.

"The United States has approximately 72 mi (116 km) of road tunnels."[25] Recent road tunnel construction in the United States include:

The Central Artery Tunnel, Massachusetts Turnpike Authority
Port of Miami Tunnel
The Alaska Way Viaduct Tunnel, Washington State Department of Transportation
Hampton Roads Tunnel Expansion, Virginia Department of Transportation
Elizabeth River Tunnel, Virginia Department of Transportation
Devil's Slide Tunnel, California Department of Transportation
Caldecott Tunnel Fourth Bore, California Department of Transportation

The need for lighting tunnels was not necessary until tunnels were made for road traffic. "The engine-driver of a train only needs to pay attention to the signals, but the road user on the other hand needs light to steer by. Hardly had the sodium lamp appeared on the market when it was made use of in the Schelde River tunnel in Antwerp, Belgium in 1969. In 1964, lamp types suitable for tunnel lighting were sodium lamps with integral vacuum glass, high pressure mercury lamps with fluorescent bulb and fluorescent tubes."[27] Today the primary light source used in existing roadway lighting installations are lamps classified as high intensity discharge. In newly installed roadway lighting systems, LEDs are used. General characteristics of commonly used light sources can be found in Table 6-1 of ANSI/IES RP-8-18, Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting.

8.3 Light Source Options In Today's Tunnels

High pressure sodium (HPS), fluorescent, LED

- High pressure sodium (HPS) lamps offer a long lamp life expectancy of approximately 24,000 hours, a lumens per watt efficiency of approximately 125 lumens per watt, and a wide variety of lumen output options. The downside to high pressure sodium lamps is the correlated color temperature (CCT) of 2100K which gives the lamp an orange glow. Additionally high pressure sodium lamps have a restrike time which does not allow them to instantly turn on after they are turned off.
- Fluorescent lamps offer a wide range of lamp life expectancy ranging from approximately 20,000 to 36,000 hours, a wide variety of correlated color temperature (CCT) options ranging from 2700K to 6500K, and a wide variety of lumen output options. The downside to fluorescent lamps is the lumens per

watts efficiency of approximately 80 to 90 lumens per watt, which is less than other options. Fluorescent lamps and ballasts are also affected by cold temperatures which will cause them to output fewer lumens or potentially not work at all.

- Light-emitting diode (LED) offer a long lamp life expectancy ranging from approximately 50,000 to 100,000 hours, lumens per watt efficiency ranging from 125 to 150 lumens per watt, wide variety of correlated color temperatures (CCT) ranging from 3000k to 5000k, and a wide variety of lumen output options. The downside to light-emitting diodes (LED) is with the technology being relatively new and constantly evolving simply replacing a LED boards and drivers may not be as easy as replacing older technology lamps and ballasts.

Factors affecting the selection of light source.

- Restrike time: The time it takes for the gas in a high-pressure sodium (HPS) lamp to reach 90% of light output after it has been turned off and immediately reenergized. This issue can be mitigated with the use of restrike lamps within the fixture that help offset some of the lost lumen output.
- Correlated color temperature (CCT): CCT is a measure of the visual “warm” to “cool” of light expressed in kelvins (K).
  - Warm light sources have a low color temperature around 2200 to 3000K. These light sources emit more light in the red, orange, and yellow spectrum range which gives the light source that warm glow.
  - Cool light sources have a high color temperature over 4000K. These light sources emit more light in the blue spectrum range which gives the light source a very cool and crisp white glow.
- Color rendering index (CRI): CRI is an indication of the ability of the light source to render colors. The higher the CRI, the better the rendering of color.
- BUG rating is an acronym to describe the measurement of light trespass a light source produce. Light trespass accrues when the light source has poor directional control which causes light to spill over into unwanted locations.
  - Backlight – Looks at the amount of light a light source produces which end up behind the desired area.
  - Up-light - Looks at the amount of light a light source produces above the light source.
  - Glare – Looks at the glare potential a light source may produce at the light source. Glare is not only a light trespass issue but can also pose a safety issue by blinding individuals.

8.4 Photometric Classification For Tunnel Luminaires

Symmetrical, Pro-beam, Counter-beam

- Tunnel luminaires fall into three general photometric classifications. The first of these is symmetrical, with light distribution equally proportioned about the vertical centerline of the luminaire. These are suitable for use in both bidirectional and unidirectional tunnels. They may also be symmetrical about the horizontal centerline, but this is not necessarily the case. Luminaires may project more light above the horizontal centerline, which results in brighter wall and ceiling illumination or below the horizontal centerline, resulting in more illumination of the roadway surface. Either type may be preferred in certain tunnels.

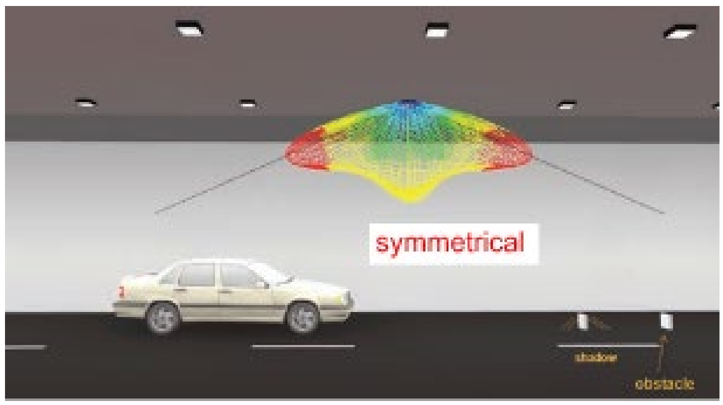

FIGURE 4: Symmetrical Light Distribution[4]

- The other general classifications are Pro-beam lighting (PBL), also referred to as Asymmetrical Light Distribution – Positive Contrast (ALD-PC) and Counter-beam lighting (CBL), also referred to as Asymmetrical Light Distribution – Negative Contrast (ALD-NC). These distributions find their utility in unidirectional tunnels where traffic flow is in a single direction within that portion of the tunnel.
- ALD-PC lighting distributions provide the larger portion of luminaire output in the same direction as traffic flow. The objective is to increase illumination of vertical surfaces such as vehicles and objects in the travel lanes to improve contrast between those objects and the roadway surface, resulting in a positive contrast between such objects and the roadway and facilitating discrimination of such objects.

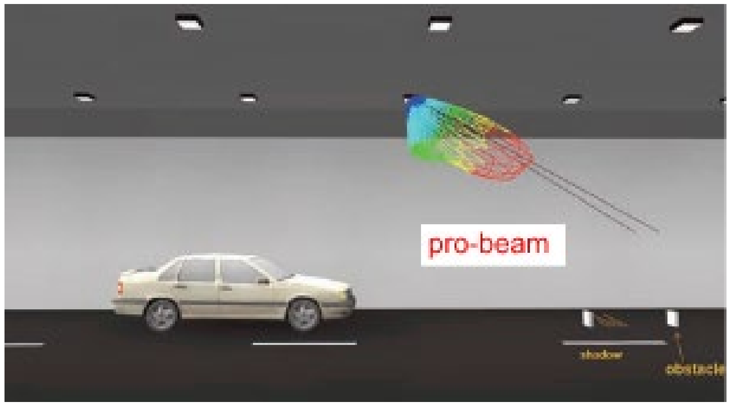

FIGURE 5: Pro-Beam Light Distribution[4]

- ALD-NC lighting takes the opposite approach, directing more illumination against the direction of traffic flow, always consistent with limiting visual impact on the drivers. The result is less illumination of the face of the objects facing the drives, resulting in negative contrast between the objects and the roadway surface, again facilitating discrimination of the objects.

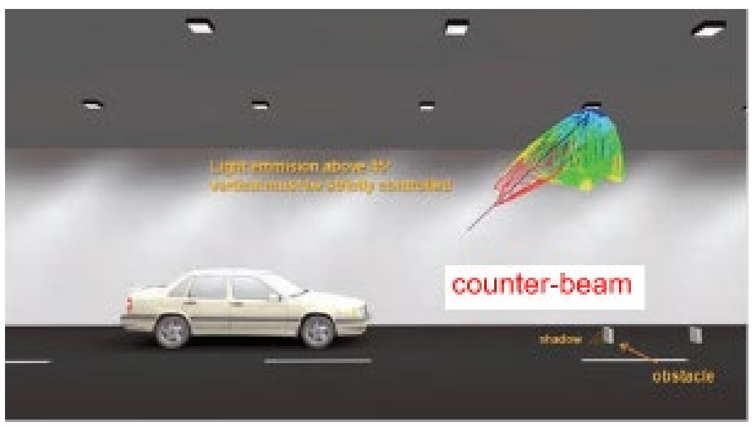

FIGURE 6: Counter-Beam Light Distribution[4]

- The choice of luminaire distributions is largely dependent on the nature of the roadway surface and is also conditioned by secondary factors such as the wall surfaces and any curvature of the tunnel that brings more of the wall surfaces into alignment with the driver's line of sight.

Glare mitigation

- As with conventional roadway lighting, mitigating glare that would impede the driver's ability to discriminate objects within the roadway is essential to the visual task. To that end, luminaire light distributions are tailored to cut off any illumination that would have a direct impact on the drivers and to limit contributions from specular reflection or other sources to yield a veiling luminance ratio to a value typically established as 0.3 for straight daytime interior portions or night-time portions of the tunnel.

8.5 Environmental Considerations

Dissimilar metals (Aluminum vs 304 Stainless Steel vs 316 Stainless Steel)

- When two different metals are in contact in a corrosive environment, one of the metals experiences accelerated galvanic corrosion while the other metal remains galvanically protected. Metals near each other in the galvanic series have little effect on each other. Generally, as the separation between metals in the series increases, the corroding effect on the metal higher in the series increases as well. Relative surface areas of contacting dissimilar metals is also relevant in determining which metal exhibits accelerated corrosion. It is undesirable to have a large cathode surface in contact with a relatively small anode surface.
- These different affinities create an electrical potential between the two metals, allowing current to flow. The metal higher in the galvanic series of metals, the anode, provides protection for the metal lower in the series, the cathode. With respect to contacting surface areas of the two metals, although the corrosion current that flows between the cathode and anode is independent of area, the rate of penetration at the anode does depends on current density. Thus, a large anode area in contact with a relatively small cathode area is generally not problematic. Regardless, environmental conditions remain large determinants of corrosion rates.

FIGURE 7: Anode and Cathode Material[18]

Applications to Tunnel Construction and Maintenance

- In tunnel applications, there are many different metals used for various features and systems in a tunnel. Such features/systems can include:
    - Light Fixtures
    - Lane Control Signs
    - Digital Message Signs (DMS)
    - CCTV Cameras
    - Jet Fans
    - Conduit and Supports for Power Supply, Communications, etc

Because there are a variety of metals used in housings for these materials, the proper selection of support systems that do not have dissimilar metal issues is critical to ensuring that corrosion of the fixtures or their supports is not accelerated in the harsh tunnel environment. Since some of the most common housings and support systems can be on the opposite ends of the galvanic spectrum, this is a serious issue during design.

For instance, an aluminum (anodic) light fixture housing attached to a tunnel wall with a stainless steel (cathodic) anchor bolt has the potential for increased corrosion. There can also be concerns about connections of galvanized members (zinc coated, anodic) in contact with stainless steel (cathodic). The corrosion of the more noble or cathodic metal (stainless steel) is decreased and that of the more active metal (zinc) is increased. However, when austenitic stainless steels (300 series) are in contact with zinc, neither material will suffer additional corrosion, or at the most, only slight corrosion. This is one exception to this based on the area of contact of the cathodic and anodic member. It is undesirable to have a large cathode surface in contact with a small anode surface (see Figure 1). However, when combining a zinc plate (large anode) with a stainless-steel rivet (small cathode) the area ratio is reversed, and the fastener should not fail because of corrosion (see Figure 2).

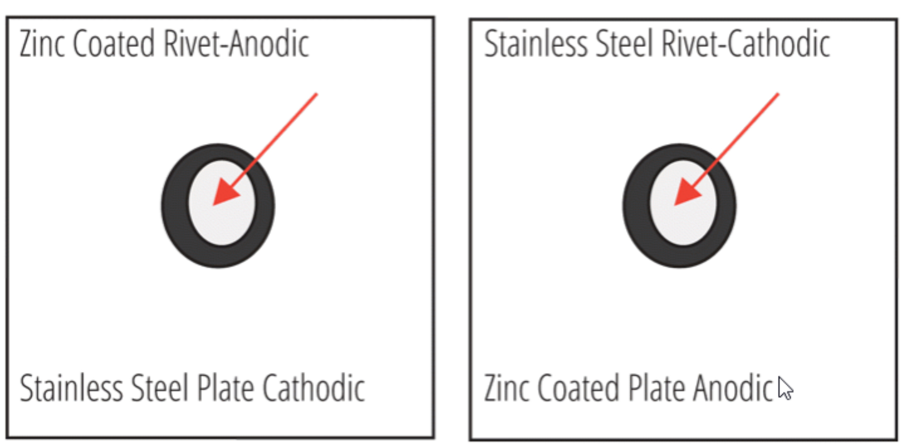

FIGURE 8: Anode and Cathode Surface Area[19]

This size correlation to corrosion rate is also shown in Table 10.

TABLE 10 - Contact Corrosion Between Dissimilar Metals

	*	Zinc	Stainless Steel
Zinc	Small Large	--- ---	S G
Stainless Steel	Small Large	G G	--- ---

* Refers to surface area of metal in left column relative to surface area of metals in top row.
S = Heavy corrosion of metal in row.
G = No or only slight corrosion of metal in row.

If a situation is encountered where two parts of dissimilar metals cannot be avoided, there are alternatives like a nylon sleeve (see Figure 6 - sleeve is green) that can provide separation of the dissimilar metals, but this application must be evaluated carefully for each situation. The designer of the lighting system (conductor raceway, luminaire and support systems) shall be responsible for evaluation of the materials specified to ensure dis-similar metals being in contact with each other is avoided.

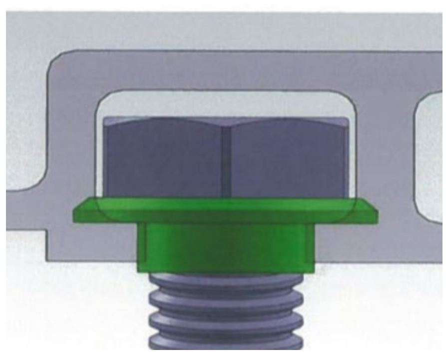

FIGURE 9: Non-Metallic Insulator

Luminaire housings: vibration; ingress protection from dust, water and jets; corrosion resistance

- There are various environmental factors to consider when selecting luminaires for tunnel lighting applications. Tunnel luminaires are often prone to high levels of vibration due to truck and trailer traffic and should be selected with adequate vibration ratings in accordance with the requirements of ANSI C136 31, American National Standard for Roadway Lighting Equipment – Luminaire Vibration.

- Tunnels become corrosive environments for luminaires due to exhaust fumes and brake dust. Depending on geographic location, humidity and road salt can also contribute to the corrosion of luminaires if they are not properly protected. Tunnel maintenance procedures often include cleaning of the tunnel walls and luminaires with high pressure hoses. These factors should be considered when selecting the luminaire housing. The material, coating, or finish of a luminaire housing can provide varying degrees of protection and an IP (Ingress Protection) rating, as published by the International Electrotechnical Commission (IEC), can be useful in selecting or specifying the correct luminaire for the environment.

Ability to operate under the highest and lowest expected ambient temperatures

- When evaluating luminaires for any outdoor application, including tunnels, the extremes on both ends of the ambient temperature range for the location should be identified. If luminaires are not capable of operating within the identified range, they will likely experience adverse effects or become non-functional. According to ANSI/IES RP-8-18, Design and Maintenance of Roadway and Parking Facility Lighting, LED light sources specifically can see significant loss in lifetime burn hours at elevated operating temperatures (3-3). The performance of all light sources is affected by ambient temperature and a specific ambient temperature maintenance factor should be determined and contribute to the total maintenance factor assigned to luminaires before performing lighting calculations.

8.6 Safety & Crash Reduction

Traffic safety and behavior of drivers in tunnels - Studies have shown that crash rates in tunnels are less than that of the open road; though when crashes do occur in tunnels, they are likely more severe, resulting in significantly higher rates of injury and even death[20,21]. As stated in an article published by the Journal of Transportation Safety & Security, "The analysis of accident reports inside and near road tunnels showed that the main causes of accident are due to behavioral aspects (e.g., safety distance, lane keeping, overtaking, speeding) and lack of vigilance (e.g., fatigue, distraction, inattention)"[6]. Furthermore, this article also states that "the realization of a lighting system (or the restoration of the functionality of the existing one) allows to reduce the crash rate by about 35%"[22,23]. Understanding this, the importance of a functional, well-designed lighting system cannot be overstated when prioritizing traffic safety in tunnels. A reduced maintenance frequency will minimize the potential of secondary crashes due to Maintenance of Traffic (MOT).

8.7 Lighting Selection Considerations

Lumen output for tunnel lighting luminaires is a function of the desired illumination levels combined with the need to maintain uniformity of illumination throughout the tunnel and to avoid luminaire spacings that can create flicker effects. As a result, luminaires with different outputs are typically used in different portions of the tunnel. Within the threshold zone and the earlier portions of the transition zone, the high illumination levels needed for visual adaptation during daylight hours will require luminaires with high lumen outputs. Within the interior of the tunnel and during nighttime, much less lumen output is required, and luminaire sizing is primarily dictated by providing sufficient lumen output at the maximum allowable spacing through these areas.

The efficacy (Lumens per watt) output of the luminaires is the largest portion of the total operating costs of a tunnel lighting system. To that end, luminaires with higher efficacy, consistent with meeting other requirements, have always been sought. From early incandescent lighting through a period where fluorescent luminaires prevailed, then on to gas discharge lighting sources such as high-pressure sodium (HPS) and low-pressure sodium (LPS), an objective has always been to deliver the necessary lumens at a reduced cost for energy. Some light sources, such as LPS, enjoy very high efficacy, approaching 200 lumens per watt, but the monochromatic yellow light emitted has been regarded as a significant detriment. In some instances, LPS luminaire have been used to supplement other light sources in portions of tunnels such as the threshold where very high levels of light are required during daytime conditions. HPS lamps reached efficacies of 120 lumens per watt and even more for very large lamps and so have been the preferred lighting source for applications such as roadway lighting where color rendering is not important. Today, efficacy of light emitting diode (LED) light sources has exceeded the efficacy of HPS lamps in many cases and some LED sources have been identified as having efficacies in excess of 200 lumens per watt, approaching the theoretical limits on the efficacy of such sources.

Lumen depreciation - All light sources depreciate to some degree during their lifetime. Most have reduced lumen output; LPS sources are an exception to this in that their current input increases as they age while they maintain an essentially constant lumen output. HPS lamps have lower depreciation than other discharge lamps and LEDs typically have even less depreciation over a given operating time as well as longer lifetimes than most other sources.

Maintenance - All light sources have a limited lifetime. Fluorescent lamps typically are good for 12K-16K hours of operation. HPS lamps are generally rated for 24K hours with some lamps with dual arc tubes rated for as many as 40K hours of operation.

Induction lamps (discharge lamps similar to fluorescent lamps) have demonstrated lifetimes of 100K hours but have other disadvantages that led to their use primarily in applications where re-lamping was extremely difficult. LED luminaires have demonstrated lifetimes of 50K to 100K hours or even more in current designs. Weighing against those numbers are the complications of renewing the light source in an LED luminaire versus re-lamping other types of luminaires. A related factor is the projected lifetime of other components of the luminaire. The ballasts for fluorescent and discharge lighting fixtures often have a lifetime in the range of 80K-100K hours. LED drivers have often had similar lifetimes. Thus, the prospect exists that the life of the LEDs in a luminaire may well equal or exceed the lifetime of other active components. Modular construction of luminaires can facilitate the replacement of failed components. However, a lack of standardization of LED luminaire components may cause replacement components to only be available from the luminaire manufacturer. If the needed parts are not available, complete replacement of a failed luminaire would be necessary.

Controllability - LED luminaires offer increased controllability in comparison to other light sources. While fluorescent luminaires may be dimmed to some degree, LED luminaires can offer virtually full range dimming from full output to 1% of output by control of the lamp drivers. This can be achieved by group dimming signals or by individually addressable commands to the drivers via technologies such as DALI. This opens the possibilities of precise tracking of the Transition Zone adaptation curves rather than step-wise switching of blocks of luminaires in these areas along with the prospect of monitoring the actual luminaire outputs to enhance energy management by limiting lumen output to that actually desired without allowing for future lumen depreciation. All this implies that control of individual luminaires can offer both technical and economic advantage as compared to the group/circuit switching of other types of luminaires

Costs:

- Capital costs: Over the past decade, the cost of LED luminaires for tunnel illumination has decreased to the point where they are not substantially more expensive that other tunnel luminaires. This is partly a result of the falling costs of the LED components and drivers and partly a result of the other portions of cost such as lenses and enclosures for tunnel luminaires being relatively constant regardless of light source due to the demanding environment in which they must operate.
- Operating costs: Operating costs represent two primary contributors: energy costs – a function of lumen efficacy along with control methodologies that allow reduced energy inputs to luminaires based on discrete control schemes and reduced energy input when luminaire output has not been depreciated due to

age of the system. The other cost is maintenance. General cleaning is necessary for all tunnel illumination systems and not significantly affected by the light source. The primary recurring cost is replacement of depreciated or failed components. This will include periodic re-lamping costs. Here the extended lifetime of LED sources and drivers has the potential to offer reduced cost, but these are partially offset by the inability to replace individual components on a preventative or as-needed basis. This can be offset to some degree by arranging for complete, easy replacement of failed luminaires followed by repair in a shop environment.

- Life cycle costs: Total Life Cycle Costs (TLCC) for tunnel illumination systems will consider initial capital costs, energy costs, and maintenance costs over the prospective lifetime of the proposed tunnel lighting system.

8.8 Evolving Technology

Light-emitting diode (LED) luminaries are a relatively new technology and as such is constantly evolving and improving. LED cost used to be a large concern but as the technology has improved so has the cost.

- LED luminaries offer:
  - Long life expectancy compared to legacy light sources.
  - Greater efficacy (lumens per watt) compared to legacy light sources.
  - Better light quality with more correlated color temperature (CCT) options.
  - Lumen level control with dimming systems.

8.9 Smart Adaptive Lighting

"Adaptive lighting involves varying lighting levels to suit activity levels during off-peak periods. This can result in energy savings and reduction in operating costs."[4] Networked lighting control systems have the ability to monitor, control and react to changing environments. In tunnels, adaptive lighting involves varying lighting levels to suit the real time luminaire performance, traffic volume and vehicle speed information.

High traffic volume or Average Annual Daily Traffic (AADT) implies a need to provide safe, efficient and orderly movement of traffic, as well as, minimize delays and congestion. "The perception by the motorist of the presence of light within the tunnel will encourage the motorist to maintain speed. Interior surfaces with high luminance levels will give motorists the impression of a bright tunnel." [4] Additionally, AADT is a component in determining tunnel luminance values.

Similarly, traffic speed is significant in determining luminance values at the tunnel entrance since visual adaptation is not instantaneous. For example, "a motorist approaching a tunnel entrance at a relatively low speed, e.g., 25 mph, and observing the tunnel portal at 492 feet will have a pre-adaptation period of 13 seconds before entry into the tunnel, permitting significantly lower luminance values in the threshold zone. A motorist traveling 50 mph will have only 6.5 seconds for eye pre-adaptation. Thus, the demand for visual adaptation will be more severe, and significantly higher luminance values will be required in the threshold zone." [4] Less time for eye pre-adaptation requires higher tunnel entrance luminous values.

LED Lumen Depreciation - LEDs rarely extinguish or burn out; although, during their lifetime, their lumen output gradually diminishes. An LED light source's rated life can be defined as when its lumen output declines to 70%, known as L70, of its initial output. Tunnel lighting systems are designed for maintained values; in other words, the target design values must be maintained at end of rated life. As a result, tunnels are over lighted until the point when lumen output depreciates by 30%.

Adaptive lighting controls will operate the tunnel lighting system at lower than full lumen output until L70 by monitoring LED lumen depreciation and adjusting lumen output accordingly. This approach reduces power input in the beginning, thus saving energy. Additionally, illuminance sensors can be located within the tunnel to measure and monitor interior illumination levels. Connecting the sensors to the tunnel lighting control system allows verification that light levels are maintained, overcoming light loss as a result of dirt depreciation between cleaning cycles. The system supports monitoring the electrical parameters of the tunnel luminaires as well as the entire tunnel lighting system resulting in optimization of operation and maintenance.

Predictive Maintenance - Monitoring and data collection of burn hours on each luminaire will assist in predictive maintenance. Additionally, equipment malfunctions can be identified quickly. "A control system can create component failure rate reports and the mean time between failures (MTBF) index by component type, luminaire model and by age category." [4]

Traffic Volume and Speed via Intelligent Transportation System (ITS) Integration - Tunnel lighting control systems can connect to a Supervisory Control and Data Acquisition (SCADA) network, thus integrating lighting control with intelligent transportation systems. Posted traffic speed affects lighting levels at the tunnel entrance; higher speed limits require higher lighting levels. As mentioned above, decreasing the maximum speed in a tunnel allows a decrease in the required luminance in the threshold and transition zones. Since the threshold and transition zone lighting is a major component of energy, reduction of luminance values in these zones decreases energy consumption. To accomplish this, reduction in posted traffic speed can be communicated to the tunnel lighting control system and light levels at the tunnel entrance can be adjusted accordingly.

EMERGING LED TECHNOLOGIES
AND USE WITHIN TUNNELS

PROPOSED REVISIONS TO THE
AASHTO LIGHTING DESIGN GUIDE

Prepared for:

National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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October 2020

9.0 Proposed Revisions to the AASHTO Lighting Design Guide

Revisions proposed to Chapter 1.7 Tunnels and Underpasses. The revisions are included below.

1.7 EMERGING ROADWAY LIGHTING TECHNOLOGIES

New roadway lighting technologies have inundated the market and are being promoted as having advantages over traditional lighting sources. Solid-state lighting (SSL)—principally light emitting diodes (LEDs), but also light emitting plasma (LEP), and other technologies—is being promoted as improving safety, conserving natu- ral resources, reducing energy consumption, and reducing life-cycle costs of roadway lighting operations. Until recently, the majority of roadway lighting was comprised of high-intensity discharge (HID) lighting, specifically high-pressure sodium (HPS). There are many differences between SSL and HID beyond the physical equipment differences. Examples include the following:

- light distribution,
- lighting output control (dimmability),
- spectral power distribution (SPD), and
- efficiency of lighting production suitable for human perception (luminous efficacy).

Research comparing the use of SSL to HID for roadway lighting has established some benefits in terms of energy consumption, luminous efficacy, color rendering, and adaptability.

The NCHRP technical report ~~*Analysis of New Highway Lighting Technologies*~~*Solid State Roadway Lighting Design: Volume 1 : Guidance and Volume 2: Research Overview* (Project No. 5-22~~20-7/305~~, published in 2020~~2013~~) *(2 & 3)* documents and presents the results from a study of solid state roadway lighting technologies, ~~including~~ primarily the use of LED sources. ~~and other light source types~~. A review of published research and case studies of new lighting technologies, as well as a comparison of roadway luminaire photometric performance, ~~suggests~~ confirmed that LED ~~technologies, while still rapidly developing,~~ technologies are viable for specifying energy efficient and visually effective roadway lighting systems. New metrics such as luminaire system application efficacy can allow engineers to make informed decisions about the roadway lighting system configurations (including luminaire selection, spacing, and mounting height) that will lead to the most economical system performance. The~~Research~~ research also ~~suggests that~~addresses a number of other metrics such as mesopic photometry, brightness perception, and spectral sensitivity for discomfort glare ~~could~~that are impacted by ~~assist the designer in selecting among~~ new lighting technologies, most of which have greater short-wavelength spectral output than conventional high-pressure sodium lighting. Evaluations of visual performance and visibility coverage areas from roadway lighting may also be of use in identifying appropriate adaptive control strategies for roadway lighting.

~~When considering any new technology, it is appropriate to carefully evaluate the benefit and potential risk asso- ciated with that product. In the case of LED highway lighting, great improvements have been made during the past few years. Manufacturers have developed creative solutions to concerns such as heat dissipation, light output, photometrics, and durability. For roadway lighting, the industry-wide trend appears to be away from HPS and towards LED systems. While light levels and distributions of LED roadway lighting luminaires are now similar or in some cases better than traditional luminaires, some of the unanswered questions include:~~

- ~~Does the higher color temperature of LED luminaries result in the need for less overall~~

illumination?

• Will LED luminaires last as long in the field as predicted by manufacturers? Does the higher color tem- perature of LED luminaires create any health concerns related to the effect of melatonin levels on sleep and alertness?

• Does the higher color temperature of LED luminaires create any environmental concerns related to negative impacts on fauna and flora?

NationalCooperativeHighwayResearchProject(NCHRP05-22), *Guidelines for Solid-State Roadway Lighting,*

is currently underway, with an expected completion date in 2019. Further updates to this Guide may occur after that report is published. Other research efforts related to health concerns are also underway. Regarding SSL/LED lighting, a list of items that still need research includes the following:

The research offers guidance on subjects that have been raised concerning SSL:

- metrics for assessing the effectiveness of roadway lighting, with and without headlights, to achieve adequate contrast;
- standardization and asset management for SSL replacement to simplify maintenance;
- potential revenue streams from data collection and barriers to their implementation;
- real-time asset management within the context of ITS framework;
- metrics to characterize the environmental and health effects of roadway light spectrum, amount, distribution, and timing;
- metrics for assessing light depreciation and means of determining end of useful life; and
- light and adverse weather.

One recommendation specific to solid state lighting in tunnels is the consideration of correlated color temperature (CCT) of the luminaires that are active during both daytime and nighttime conditions. The CCT of daylight can range from 5000 to 20,000K whereas HPS lighting has a CCT around 2100K. The research suggests that higher CCTs approximating the daytime color temperatures is more favorable for drivers during daylight hours. Such luminaires are likely to be more efficient as well. During nighttime, it is preferable that the tunnel luminaire CCT approximate the external roadway luminaire CCT. This implies CCTs of 3000K or less where HPS roadway luminaire exist, although the prospect of future replacement of these luminaires may affect this decision.

Volume 1 of the SSL Guide is formatted in a fashion intended to be compatible with this design guide while specifically directed at considerations when employing SSL

1.8 REFERENCES

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Washington, DC, 2010.

2. ~~Bullough, J.D. and L.C. Radetsky. *National Cooperative Highway Research Report 20-7/305: Analysis of New Highway Lighting Technologies.* NCHRP, Transportation Research Board, Washington, DC, 2013.~~National Academies of Sciences, Engineering, and Medicine 2020. *Solid-State Roadway Lighting Design Guide: Volume 1: Guidance.* Washington, DC: The National Academies Press. https//doi.org/10.17226/25678.

~~2.~~3. National Academies of Sciences, Engineering, and Medicine 2020. *Solid-State Roadway Lighting Design Guide: Volume 2: Research Overview.* Washington, DC: The National Academies Press. https//doi.org/10.17226/25679.

Revisions proposed to Chapter 4 Tunnels and Underpasses. The revisions are included below.

CHAPTER 4

TUNNELS AND UNDERPASSES

4.1 OVERVIEW

4.1.1 Introduction

The designer may review and become familiar with resources that exist related to the lighting design of underpass- es and tunnels. Literature is available on the technical aspects of visibility and lighting of vehicular tunnels. A re- view of the research material included in the references of this guide as well as other research efforts is encouraged and will provide considerably more detailed information than is possible in this guide. In addition to independent studies, ANSI/IES RP-8~~22~~-18~~11~~, American National Standard Practice for ~~Tunnel Lighting~~ Design and Maintenance of Roadway and Parking Facility Lighting *(2)*; International Com- mission on Illumination (CIE), Publication 88 *(4)*; and British Standard BS 5489-2 *(3)* offer recommendations for various tunnel and underpass lighting applications.

4.2 UNDERPASSES

4.2.1 General Scope and Guide Application

An underpass is defined as a portion of a roadway that extends through and beneath some natural or man-made structure, which, because of its limited length relative to its height, requires no supplementary daytime lighting. Underpasses of multiple highway structures will normally be treated separately where the space between these structures permit good penetration of daylight on the underpass roadways, rather than as one composite length. Daytime lighting may not be necessary in cases where the overhead structure allows relatively direct daylight penetration.

The specific geometry and roadway conditions, including vehicular and pedestrian activity, should be considered in evaluating the need for daytime lighting. These features are more fully covered in the tunnel lighting section.

Underpass lighting can be designed using the same method used for the roadway.

4.2.2 Warrants for Nighttime Underpass Lighting

Meeting minimum lighting levels through underpasses is warranted (1) in areas that have frequent nighttime pedestrian traffic or (2) where unusual or critical roadway geometry occurs adjacent to or in the underpass area.

Continuous lighting on the associated freeway lanes also warrants the continuation of minimum lighting levels through the underpass.

Minimum lighting levels may be met by using supplemental underpass lighting or with luminaires positioned adjacent to the underpass to provide adequate lighting.

4.2.3 Design Values for Underpass Lighting

Nighttime lighting levels and uniformities should target the lighting levels on the adjacent roadways. Higher levels of lighting may result because of luminaire mounting height and spacing limitations. Increased levels should not exceed approximately twice that of the roadway adjacent to the underpass.

High nighttime ambient brightness produced by lighting from other nearby sources may justify higher lighting levels.

4.2.4 Selection and Placement of Underpass Luminaires

Luminaires attached to the structure along the roadside in full or partial view of the motorist may necessitate glare control or the use of lower wattages. It is generally better to minimize source glare by using several lower output luminaires than to provide one or two high output luminaires. The use of lower lumen output fixtures tends to improve the uniformity of lighting while maintaining lighting levels.

Wall-mount luminaires are usually easier to maintain, and they are less affected by structure vibration.

4.3 VEHICULAR TUNNELS

4.3.1 General Scope and Guide Application

A structure of any type that surrounds a vehicular roadway and is longer than an underpass is recognized by this publication as a tunnel. Road tunnels as defined by the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee for Tunnels (T-20) are enclosed roadways with vehicle access that is restricted to portals regardless of type of the structure or method of construction." Tunnels normally require supplementary daytime lighting to provide adequate roadway visibility necessary for safe and efficient traffic operation.

Tunnel designs are typically designed using luminance methods. It is difficult to equate illuminance levels to luminance levels given the various surface reflectance and luminaire orientation possibilities. Surface reflectance, luminaire placement, and luminaire orientation affects the end design results. Future changes to pavement, wall, or ceiling surfaces that change reflectance should be avoided unless the lighting design allows for specific changes.

Figure 4-1. Example of a Vehicular Tunnel

4.3.2 Short Tunnels

A tunnel is considered "short" if the length from portal to portal is equal to or less than the wet pavement minimum stopping sight distance as recommended by the latest AASHTO Policy on Geometric Design of Highways and Streets (1) for the vehicle operating speeds of the tunnel roadway and approaches. A short tunnel has only one tunnel lighting zone. The zone begins at the tunnel portal and is called the threshold zone. The length is equal to the minimum stopping sight distance. The daytime lighting system is not required in the first 20 ft or last 50 ft of the tunnel as stated in ANSI/IES RP-8~~22-11~~18 (2).

4.3.3 Long Tunnels

A tunnel is considered "long" if the portal to portal length is greater than the minimum stopping sight distance. A long tunnel has more than one tunnel lighting zones which may include the threshold zone, transition zone, and interior zone. The transition zone is the area between the threshold zone and the interior zone. The luminance through the transition zone is incrementally reduced allowing the eyes of the motorist to adapt. The interior zone is the next zone and begins when eye adaptation is complete.

4.3.4 Warrants for Tunnel Lighting

The installation of daytime lighting is warranted when tunnel user visibility requirements are not met with sunlight. Tunnel visibility factors include such items as the geometry of the tunnel and its approaches, the traffic characteristics, the treatment of roadway and environmental reflective surfaces, the climate, and the orientation of the tunnel. The standards referenced in this chapter offer guidance on when supplemental daytime lighting is required. This guidance is based on the tunnel length, expected traffic volume, whether cyclists are present, if the tunnel is straight or curved, how much daylight penetration is present, and how reflective the interior surfaces are. Essentially, if the tunnel is less than 80 ft in length, no supplemental lighting is required. If it is greater than 410 ft in length supplemental daytime lighting is required. For lengths in between, there may be no or complete lighting recommendations based on the factors previously noted. It should also be noted that additional study is being conducted on the requirements for short tunnels, and revisions in this methodology are expected in future revisions to ANSI/IES RP-8-1822-11 *(2)*.

4.3.5 Visibility Optimization of the Tunnel and Approach Features

It is important in the physical design of a tunnel structure that due consideration be given to lighting needs. The physical features of a tunnel can have a significant effect on reducing the daytime lighting needs.

The items in Sections 4.3.5.1 through 4.3.5.4 contribute to improved tunnel visibility and should be explored in the development of daytime tunnel lighting designs.

4.3.5.1 Reduction of Ambient Daytime Brightness

Tunnel portals, adjacent walls, approach pavement, and other external features in the motorist's field of view should be darkened to the extent possible. Admixtures, overlays, vegetation, or other methods that result in low reflectance, non-specular surfaces are recommended. Dark features increase the degree of advance eye adaptation of the entering motorist and improves contrast with the lower luminance levels in the tunnel interior. Tunnels with a predominant sky background above the tunnel approach should be reviewed for the use of plantings, screens, or panels that increase the size of the darkened area above the portals.

4.3.5.2 Portal Design Factors

Upsweep ceilings may increase daylight penetration but can result in increased tunnel structure costs.

Sunscreens have not been effective. Dirt accumulation, permanent depreciation of reflective and light-transmit- ting properties, and snow and ice accumulation have posed serious problems. The high initial costs of sunscreens coupled with high maintenance costs have practically eliminated their use.

4.3.5.3 Visibility Optimization of Tunnel Interiors

It is recommended that ceiling and wall surfaces consist of an easily maintained finish with a non-specular reflective efficiency of at least 70 percent. High wall brightness is of great value in meeting visibility needs in tunnels that have curved roadways or approach roadways. Such surface type also results in using fewer luminaires to light the tunnel. Relatively narrow tunnels where the width-to-height ratios are approximately three or less will develop inter-reflectivity that can enhance tunnel visibility as a result of the reflected light from the walls.

Natural sunlight penetration in entrance portal areas can be improved by the use of wall, ceiling, and roadway surface texture control. The use of vertical wall corrugations, coarse finished pavements, or other treatments which produce surface relief, increase the retro-reflection of light entering the portal over that of smooth surfaces.

4.3.5.4 Types of Pavement Surfaces

The use of bituminous concrete on the approach road surface to the tunnel portal and portland cement concrete on the road surface inside the portal for a distance at least equal to the minimum stopping sight distance may reduce the luminance contrast between the outside and the inside of the tunnel. This will in turn reduce threshold zone luminance. The selection of future resurfacing should account for the luminance and illuminance used in the lighting design of the originally designed roadway surface.

4.4 DAYTIME LIGHTING OF TUNNEL INTERIORS

4.4.1 Short Tunnels—Silhouette Visibility

Short vehicular tunnels that have relatively straight and level approach alignments with corresponding straight and level tunnel roadways may offer adequate visibility to the entering motorist by silhouette viewing of other vehicles and objects on the roadway against the far side exit portal. These tunnels are treated as underpasses in this guide. Silhouette visibility should be carefully evaluated with respect to the tunnel geometry to provide visi- bility of objects within the tunnel. The roadway surface details will normally be indiscernible to the motorist with silhouette visibility.

In multi-lane one-way tunnels or in unseparated two-way tunnels, lighting should be provided to the extent the motorist can distinguish lane markings or other delineation important to safe travel through the tunnel.

4.4.2 Tunnel Approach at Entrance Portal

The most critical portion of a tunnel that affects visibility is at the portal. This is commonly called the "black hole" effect. Visibility of the tunnel approach zone, while still outside the tunnel, is essential to the motorist in identify~~-~~ing and safely reacting to the presence of vehicles and objects that may be present on the tunnel roadways. This is accomplished by lighting the threshold zone in proper proportion to the outside ambient luminance to which the motorists' eyes are adapted.

The luminance of the approach pavement, adjacent landscape, sky, the presence of the sun in or near the tun- nel approach, and the portal area itself, are all integrated over time by the motorist's eyes in adapting to overall

ambient conditions. It is suggested that an evaluation of brightness conditions be made for the actual roadway and tunnel prior to establishing a lighting design.

A model simulation may be necessary for new facilities in order to duplicate the anticipated tunnel approach conditions. The motorist's field of view of adapted luminance should be evaluated at a location along the approach roadway equal to the minimum stopping sight distance in advance of the portal. See the CIE 88 (4) or ANSI/IES RP-~~22-11~~8-18 (2) tunnel lighting design guides for extensive discussion of these details.

Two and three lane one-way tunnels having favorable alignments of the approaches and tunnel structure, and which are of relatively short length, have been adequately lighted with relatively low artificial lighting levels. The optimization of approach portal conditions, in some cases, has produced adequate approach visibility at artificial luminance levels in the range of about 100 to 200 candelas per square meter reflected from an in-service roadway surface.

Threshold zone lighting levels should be designed to accommodate the greatest ambient luminance expected at the location. The stopping sight distance defined previously determines the length of threshold zone lighting. Most tunnel approach roadways, except for extreme cases of vertical and horizontal curvature, have approach characteristics such that a point relatively close to the tunnel portal will confine the motorist's view to the pre- dominance of the darkened tunnel structure. It is an acceptable practice to include this "fixation" distance in the minimum stopping sight distance to reduce the length of the threshold zone lighting.

4.4.3 Interior Tunnel Lighting

If the tunnel is classified as a short tunnel, the threshold zone lighting level applies throughout its entire length. However, in long tunnels, lighting beyond the minimum stopping sight distance should be reduced progressively through the transition zone until an established interior zone light level is reached. This reduction is based on the time it takes the eye to adapt to the lower interior values of the tunnel. Both ANSI/IES RP-~~22-11~~8-18 *(2)* and CIE-88 *(4)* include time/level curves to determine the length of the required threshold and transition zones.

4.4.4 Nighttime Tunnel Lighting

Nighttime lighting should, if practical, make use of a portion of the daytime lighting system rather than be a sep- arate system. Nighttime levels in a tunnel should be somewhat higher, but not exceeding three times that of the lighting requirements for the roadways adjacent to the tunnel. Uniformity of lighting should closely match that of the requirements for the adjacent roadways.

Tunnels located on non-continuously lighted roadways should be lighted to the minimum standards required for the highway type and character as contained in this guide.

4.4.5 Emergency and Egress Lighting Systems

For long tunnels, emergency and egress lighting systems are sometimes required. These systems are defined and described in NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways.

4.4.6 Selection and Placement of Tunnel Luminaires

The choice of particular types of tunnel luminaires and light sources should be made by considering such items as luminous efficacy, source glare, light distribution characteristics, physical placement limitations, frequency

of maintenance, resistance to damage, and have an ingress protection (IP) rating suitable for wet locations and capable of resisting spray wash. An important consideration in the placement of tunnel luminaires is to avoid the stroboscopic effect of alternate bright-dark areas where luminaires do not provide a continuous line of luminance. Frequencies in the range of 5 to 10 cycles per second have been observed to result in eye annoyance (flicker) and should be avoided at the particular design speed of the tunnel.

Also note that LED luminaires have greater control over the light distribution because of the individual lenses around the LEDs. As a result, they can have sharper cut-off of the distributions. This can reduce glare, but must also be considered in regard to illumination provided on surfaces adjacent to the roadway such as tunnel walkways and walls.

4.4.7 Tunnel Lighting Control Systems

Lighting levels for the threshold zone may be adjusted to match the ambient conditions created due to varying light levels from season to season and during cloudy or inclement weather. If such system variances are deter- mined to be economical and feasible, lighting levels in subsequent tunnel zones should vary in the same propor- tion. Lighting systems for tunnels should be designed as fail safe as practical to reduce the possibility of a total tunnel outage in the event of a circuit failure or other malfunction.

Lighting levels were historically controlled by the switching of groups of luminaires to approximate the desired levels for varying conditions. The ability of solid state (LED) luminaires to be controlled individually and continuously yield possible advantages for consideration:

Lighting levels may be tailored to current conditions without concerns such as restrike time of luminaires.

Due to the spacing of active luminaires that are block/group switched may negatively impact flicker considerations. This problem can be reduced or eliminated with continuous individual control of fixtures simultaneously.

4.4.8 Maintenance Factor for Tunnel Lighting Design

The reduction of initial lighting levels becomes an important factor in tunnel lighting design. Initial design levels should consider the frequency and degree of maintenance that is to be performed. Factors in the range of 50 per- cent are commonly applied to tunnel lighting designs. Lighting is required to deliver at least the minimum target lighting levels with the impact of both dirt and lumen level depreciation over time fully considered.

Adaptive lighting controls monitoring actual roadway lighting levels can, in conjunction with the continuously variable control of light output possible with solid state (LED) luminaires, can allow for reductions of luminaire output when such depreciation does not fully apply, resulting in energy savings over substantial periods of time. As an additional advantage of such controls, operation of luminaires at reduced output may extend the life of both the LEDs and the drivers beyond that forecast for full-on operation.

4.4.9 Material Considerations for Tunnel Lighting Systems

Tunnels present a particularly arduous environment for the luminaires and other components of a tunnel lighting system. Three items are worthy of particular consideration:

The high levels of moisture often present in combination with corrosive agents such as road deicing chemicals in northern climates and salt fog in coastal areas pose a higher risk of deterioration to system components. This has been combated by both enclosure design and choices of materials. One special concern that has presented itself via failures in a number of installations is dissimilar metal corrosion. This can be resisted by avoiding the placement of metals likely to react in contact with each other or limiting the contact of metals that act as cathodic elements to small areas. Another effective strategy is the separation of different metallic components (e.g., aluminum luminaire housings and stainless-steel mounting bolts and brackets) with non-metallic dielectric insulating components.

Mechanical anchors are often used for attachments to concrete surfaces in tunnels. Failures of epoxy adhesive anchors have occurred and potential for failures under fire conditions also exists with these anchors. Use of anchors which do not depend on adhesives to maintain structural integrity is generally prescribed for luminaires and lighting system components within the travel ways of tunnels.

Temperatures within tunnels can be higher than outdoor temperatures, particularly near the tunnel ceiling. The luminaires must have temperature ratings suitable for such conditions if they exist.

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Disclaimer

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Appendix A – Owners Survey and Other Stakeholders (Manufacturers) Responses

Owners' Survey
Manufacturers' Survey

How often do you perform maintenance (cleaning, lamp/ballast replacements) on your tunnel lighting luminaires? Would you anticipate reduction in these actions with a change to LED luminaires?	
Penn DOT, District 11-3 Tunnel Maintenance	Cleaning lenses 1x per year, lamp/ballast replacements as needed (typically once 1% of lights are out in a tunnel - usually equals one shift of work at night). This happens 5-10 times per year. Change to LED would probably eliminate need for lamp/ballast replacement for 10 years.
Metropolitan Transit Authority Bridges and Tunnels	In frequently required.
Metropolitan Transit Authority Bridges and Tunnels	Bi-monthly lens cleaning. Routine maintenance has been reduced since the conversion to LED luminaires in 2017.
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Twice per year cleaning and washing. Each time takes 3-5 days. No we'll continue to clean tunnel walls and lights for road grime and deicer residue.
Chesapeake Bay Bridge and Tunnel District	We relamped our tunnels approximately once every 4 to 6 weeks. This would take approximately 4 nights for two tunnels. One night per side, per 1 mile tunnel. Yes, which is why we are now installing LEDs in our tunnels now. While everyone focuses on the reduction in power useage, the savings in man power and lanes closures are significant.
North Texas Tollway Authority	Quarterly during scheduled closures. Changing to LED would not change schedule but we would expect to have to perform fewer replacements.
Pennsylvania Turnpike Commission	Washing and spot relamping is performed twice per year at a minimum. Washing will remain at this level. Intervals of maintenance would be adjusted if fixtures
Port Authority of Allegheny County	Quarterly maintenance on tunnel luminaires.
Do you group re-lamp or replace individual lamps and ballasts as they fail?	
Penn DOT, District 11-3 Tunnel Maintenance	As the fail and it equals a shift's worth of work.
Metropolitan Transit Authority Bridges and Tunnels	Replace components.
Metropolitan Transit Authority Bridges and Tunnels	Individual lamps.
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Yes. Not worth the time to do it otherwise
Chesapeake Bay Bridge and Tunnel District	We re-lamp as they fail.
North Texas Tollway Authority	Quarterly as they fail
Pennsylvania Turnpike Commission	Both practices are used on cycled intervals.
Port Authority of Allegheny County	Typically, individual lamps/ballasts were replaced as they fail. However, as new projects allow the installation of LEDs, the hope is that requirement will be reduced.
Which of the following (if any) do you keep in stock as spare parts? Entire Fixtures, Lenses, Housing, Ballasts, Lamps, LED Boards, Surge Protective Devices, Drivers, Other	
Penn DOT, District 11-3 Tunnel Maintenance	Entire Fixtures;Lenses;Housings;Ballasts;Lamps;Other;
Metropolitan Transit Authority Bridges and Tunnels	Entire Fixtures;Lenses;Housings;LED Boards;Surge Protective Devices;Drivers ;
Metropolitan Transit Authority Bridges and Tunnels	Entire Fixtures;
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Lenses;Housings;Ballasts;Lamps;
Chesapeake Bay Bridge and Tunnel District	Other;
North Texas Tollway Authority	Entire Fixtures;Lenses;Housings;Ballasts;Lamps;LED Boards;Drivers ;
Pennsylvania Turnpike Commission	Entire Fixtures;Lenses;Ballasts;Lamps;LED Boards;Drivers ;
Port Authority of Allegheny County	Ballasts;Lamps;
If you answered 'Other' in question 4, please list other materials here.	
Penn DOT, District 11-3 Tunnel Maintenance	Fuses
Metropolitan Transit Authority Bridges and Tunnels	
Metropolitan Transit Authority Bridges and Tunnels	
Colorado DOT - Eisenhower Johnson Memorial Tunnels	
Chesapeake Bay Bridge and Tunnel District	We are in an intermittent change over period. One of the pushes to find an alternative came when our light manufacturer went out of business and spare parts were no longer available. Prior to that, we stocked fixtures, lenses, housings, etc.
North Texas Tollway Authority	
Pennsylvania Turnpike Commission	
Port Authority of Allegheny County	

Appendix A – Owners Survey and Other Stakeholders (Manufacturers) Responses

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What are the key characteristics you consider important when determining a luminaire's durability?	
Penn DOT, District 11-3 Tunnel Maintenance	Ability to hold up in tunnel envirnoment.
Metropolitan Transit Authority Bridges and Tunnels	Length of time between install and replacement.
Metropolitan Transit Authority Bridges and Tunnels	Water tightness and durability/rivers and LEDs.
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Resistence to cold, water, chlorides and power outage
Chesapeake Bay Bridge and Tunnel District	The CBBT is an extremely corrosive environment, nestled in the mouth of the Chesapeake Bay and Atlantic Ocean. It is not uncommon to have over 100 MPH winds driving sand and grit with it. Durability of the fixture itself is paramount. All metal items on our facility must be 316 SS or marine grade aluminum such as 6063-T6 or similar. Equally important is the longevity of the lighting apparatus as re-lamp processes during night time lane closures is an expensive endeavor.
North Texas Tollway Authority	Resistance to corrosion/chemicals/hydrocarbons (soot) Resistance to insect infestation and bird nesting
Pennsylvania Turnpike Commission	Dissimilar metals, in particular cast aluminum.
Port Authority of Allegheny County	Life expectancy, suitable for damp/wet environments, ease of component access.
Would your agency adopt dimming in lieu of switching groups of luminaires to automatically control threshold and transition zone light levels according to outdoor light?	
Penn DOT, District 11-3 Tunnel Maintenance	Yes
Metropolitan Transit Authority Bridges and Tunnels	Have that feature already.
Metropolitan Transit Authority Bridges and Tunnels	Yes
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Yes
Chesapeake Bay Bridge and Tunnel District	Yes, we currently do this with both the previous light systems and the new LED fixtures.
North Texas Tollway Authority	Would analyze both in design process but believe that dimming would probably be the recommendation
Pennsylvania Turnpike Commission	If it were proven through competent calculation.
Port Authority of Allegheny County	Overall, yes. We utilize dimming and switching groups for light level transitioning.
As traffic speed increases, so does required maintained average pavement luminance levels. Would your agency consider using real-time data on traffic speed and/or traffic flow to dim threshold and transition zone lighting?	
Penn DOT, District 11-3 Tunnel Maintenance	We would probably be more inclined to match outside lighting levels but the minimum light level should be based on the requirement for vehicle speed.
Metropolitan Transit Authority Bridges and Tunnels	Not at this time.
Metropolitan Transit Authority Bridges and Tunnels	No
Colorado DOT - Eisenhower Johnson Memorial Tunnels	Yes
Chesapeake Bay Bridge and Tunnel District	No
North Texas Tollway Authority	No
Pennsylvania Turnpike Commission	If it were proven through competent calculation.
Port Authority of Allegheny County	No. Our owned/maintained roadways are restricted access. Speeds and flow are negligible due to a fixed number of vehicles.
Historically, tunnel lighting fixtures have been identified by their wattage (e.g. High Pressure Sodium 250 Watt, 400 Watt). However, the recent market transition to LED fixtures shifts the focus to light output, measured in lumens. When establishing lighting values, does your agency identify fixtures by their lumen output as opposed to their wattage to account for these changes in technology?	
Penn DOT, District 11-3 Tunnel Maintenance	Fixtures are identified by wattage but lumen level is what has been used for determining if LED's are viable.
Metropolitan Transit Authority Bridges and Tunnels	Yes
Metropolitan Transit Authority Bridges and Tunnels	Yes
Colorado DOT - Eisenhower Johnson Memorial Tunnels	We've only replaced T-8s in kind, expense, compatibility and availability is the biggest consideration for the HID lights replacements. HID's are being replaced
Chesapeake Bay Bridge and Tunnel District	This would be a great two day conference/debate topic. Within my own facility, I do not find a common verbiage used as we did for previous HPS fixtures and bulbs. When discussing in the field, the wattage equivalent is one animal, lumen output is another, the actual measured foot candles on the ground is another and then light color with eye perception of light is yet another. When applying this to tunnels, the reflective properties of the tunnel surface, thus in many cases the cleanliness of the tile surface, also plays a significant part. It will be interesting to see what terminology emerges as a standard.
North Texas Tollway Authority	Yes, we identify LEd fixtures by lumen output
Pennsylvania Turnpike Commission	Yes
Port Authority of Allegheny County	We typically will have foot-candle levels designed based on the fixture's characteristics. That will identify if a fixture meets the needs of the project.

Owners' Survey
Manufacturers' Survey

When considering future lighting system upgrades, what results have you seen in life cycle cost comparisons of LED versus High Pressure Sodium systems?	
Penn DOT, District 11-3 Tunnel Maintenance	The break even was at 26 years for Ft Pitt Tunnel and the current light fixtures are only thru 1/2 of their expected life expectancy so it didn't make sense to make the switch yet.
Metropolitan Transit Authority Bridges and Tunnels	Efficient
Metropolitan Transit Authority Bridges and Tunnels	Not applicable - new system was installed in 2017.
Colorado DOT - Eisenhower Johnson Memorial Tunnels	We haven't done this analysis yet.
Chesapeake Bay Bridge and Tunnel District	LEDs have been installed for just a short time period and continue to be installed. With the prices of fixtures coming down and the proven durability increasing, we are projecting the life cycle costs to be very positive for LEDs. The projected overall durability of the fixture and lights over time, with the potential to significantly reduce re-lamp costs will be the crux, as the energy reduction is more of a known factor.
North Texas Tollway Authority	In the past decade our design engineers have done various studies. Around 2014 the life cycle cost flipped in favor of LED. We would expect that trend to continue barring new technologies.
Pennsylvania Turnpike Commission	Potential justification in favor of LED.
Port Authority of Allegheny County	We do not have hard numbers yet to make strong comparisons.

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What are the key characteristics you consider important when determining a luminaire's durability?	
Holophane, a Division of AcuityBrands Lighting	Min 3G rating per ANSI C136.31 Corrosion resistance evaluated to pass minimum of 5000 hours rating in Salt spray test ASTM B117 20kV/10kVA surge protection ANSI/IEEE C62.41 IP 66 rating IEC60529 Listed for wet and marine locations (UL/CUL 1598) Pass high pressure hose down and scrub down washing procedures used in the specific application Suitable for application in areas having 50-degrees C ambient temperature
PLC-Multipoint	Product Life Cycle including: -Replacement component availability -Firmware upgradeability -Ease of component maintenance and replacement
Schréder	A high rating on the ASTM-D1654 scale when neutral salt spray tested according to ASTM-B117 after 5000 hours. Separate compartments for replaceable components for service outside of a tunnel in order to avoid contamination when exposed to airborne contaminants. Ideal calorimetric density of LEDs/PCBAs VS metal volume for efficient heat dissipation without requiring the need for external radiators in order to prolong the life of said LEDs and minimize the depreciation of luminous flux over time. This is to minimize the risk associated with the accumulation of contaminants and solids over time in the external radiators which reduce the thermal dissipation qualities of a luminaire. The use of high quality, latest generation LEDs. The use of Aluminium plates for the PCBAs to avoid using thermal paste to create a thermal bridge. Direct aluminium on aluminium contact offers the best dissipation. Again, this helps to minimize depreciation of flux and failures over the life of the product. High Quality alloys with proper pretreatment (anodization, sealing + double layer of powder coat) Full insulation of dissimilar metals through the use of nylon interfaces. Minimum Impact rating of IK08 for any glass protector (while retaining fragmentation properties)
Kenall Manufacturing Co.	- Corrosion resistance - L70 Performance - TM21 Performance
What material are your existing lighting products made from; select all that apply?	
Holophane, a Division of AcuityBrands Lighting	Aluminum;Stainless Steel;Other;
PLC-Multipoint	Other
Schréder	Aluminum;Stainless Steel;
Kenall Manufacturing Co.	Aluminum;Stainless Steel;
If you answered 'Other' in question 3, please list other materials here:	
Holophane, a Division of AcuityBrands Lighting	Generally the Aluminum is the housing and it is properly finished with a TGIC thermoset powder coat finish. Other finishes are available if required. Separation of dissimilar metals to provide is provided. Mounting hardware is 316 Grade Stainless steel.
PLC-Multipoint	We manufacture lighting controls. Our system devices include: Tunnel Lighting Control Cabinets, located along roadway near portal-l316 Stainless Remote Dimming Enclosures, located in tunnel or air plenum -316 Stainless Luminance meters, located along roadway near portal - Aluminium
Schréder	
Kenall Manufacturing Co.	
Have you addressed concerns in the market with the presence of dis-similar materials between luminaire mounting bracket and the fixture itself?	
Holophane, a Division of AcuityBrands Lighting	Yes
PLC-Multipoint	NA
Schréder	Yes, all of our equipment requires the insulation of dissimilar metals through the use of nylon bushings, grommets and washers.
Kenall Manufacturing Co.	Yes; Kenall always physically/galvanically isolates dissimilar metals.
What results have you seen in life cycle cost comparisons of LED versus High Pressure Sodium systems?	
Holophane, a Division of AcuityBrands Lighting	Energy and maintenance savings of 50% over HPS
PLC-Multipoint	We have only been controlling LED fixtures for the last 5 years - with 40,000 hours of experience. Certainly, early LED components, such as drivers are already obsolete , when compared with the performance of current products. Performance improvements and software support are two factors which limit the life of early LED products.
Schréder	LEDs present a TCO that is much lower than HPS when coupled with a proper dimming control system (an impossibility for HPS). Many strategies for various scenarios are available on the market which can lead to power savings of 60 to 70% vs HPS even though the initial installed power is very similar for both.
Kenall Manufacturing Co.	LED technology is still relatively new, so true historical maintenance data over a 20-30 year period does not yet exist. Still, if I had to make an educated guess, Based on current test reports: LED technology should be a far better value than HPS, especially when considering re-lamping and maintenance costs over time.

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Are your tunnel luminaires designed to be serviceable? Can components, driver and LED array be replaced?	
Holophane, a Division of AcuityBrands Lighting	Yes. Procedures are described in the installation instructions for LED, Surge protection, and LED Driver replacement.
PLC-Multipoint	NA
Schréder	Yes, on all counts.
Kenall Manufacturing Co.	Yes; components are modular, and can be popped in and out as needed.
Is your warranty for the life of the product and what does it cover?	
Holophane, a Division of AcuityBrands Lighting	5 Years when properly applied. If the Product(s) fail to comply with the terms of this Warranty, Acuity, at its option, will repair or replace the Product(s) with the same or a functionally equivalent Product(s) or component part(s). This Warranty excludes labor and equipment required to remove and/or reinstall original or replacement parts. This Warranty extends only to the Product(s) as delivered to, and is for the sole and exclusive benefit of, the original end user of the Product(s) at the original location. This Warranty may not be transferred or assigned by the original end user. The repair or replacement of any Product(s) or component part within the Product(s) is the sole and exclusive remedy for failure of the Product(s) to comply with the terms of this Warranty and does not extend the Warranty period. Warranty claims regarding the Product(s) must be submitted in writing within (30) days of discovery of the defect or failure to an authorized Acuity post-sales or customer service representative. Product(s) or component part(s) may be required to be returned for inspection and verification of non-conformance by Acuity, but no Product(s) or component part(s) will be accepted for inspection, verification or return unless accompanied by a "return authorization number" which can be obtained only from an authorized Acuity post-sales or customer service representative. Acuity is not responsible for any costs and expenses incurred in connection with shipment of Product(s) to Acuity, but Acuity shall bear all cost and expense incurred in connection with shipment of replacement Product(s) to the customer.
PLC-Multipoint	Our warranty for control components is 5 years on material and software. This means that we will evaluate a defective product to determine what the component failure was. If it is a material or workmanship defect, the product is repaired or replaced. We provide software support for our products for 5 years. Our support is based upon the product implementation at the time of commissioning, and will be replaced by a compatible product.
Schréder	The standards warranty is for 10 years for the complete unit (parts only) excluding the drivers which are covered for 5 years. Longer spans are available at a reasonable premium. Loss of 10% or more luminous flux during this period would warrant a full replacement of the luminaire as opposed to parts only.
Kenall Manufacturing Co.	For stainless steel housing fixtures, 10-year warranty covering everything except drivers (5 years or per driver manufacturer) and labor. For aluminum housing fixtures, 5-year warranty covering everything except labor.
What is the life of the drivers used in your LED tunnel luminaires?	
Holophane, a Division of AcuityBrands Lighting	Electronic drivers used have an estimated minimum life of 100,000 hours.
PLC-Multipoint	NA
Schréder	The life span is dependent on too many factors for a simple answer (power quality, climate, environment, etc). The standard warranty offered by all driver manufacturers is 5 years. some manufacturers offer extended warranties at a reasonable premium.
Kenall Manufacturing Co.	We use Mean Well HVGC Series Drivers. Mean Well advertises a 5-year warranty, >50,000 hours lifetime. Based on Mean Well MTBF Reports, we see typical expected lifetime of 20 years+.
What is the life of the LED arrays used in your tunnel luminaires?	
Holophane, a Division of AcuityBrands Lighting	We continue to monitor and test the LEDs in the Tunnel Pass using TM21 to estimate the life. While we expect 100k hours, this exceeds the allowed 6 time extrapolation limit. Improvements to LEDs are continuing to replace older generations. What I can say for certain is the applications of the TunnelPass product has been successful. Response to installations have been positive, and our earliest installation in the BAY Bridge tunnel in San Francisco is still operating to the satisfaction of the authority.
PLC-Multipoint	NA
Schréder	Tricky question... The only standardized/objective tool to calculate depreciation over time does not provide an estimation of lifespan. TM-21 grids tell us that our tunnel luminaires will depreciate by roughly 10 % over 300K+ hours but this does not guarantee a lifespan of 300K+ hours. We estimate at least 30 years of use before a product may need to be replaced.
Kenall Manufacturing Co.	To L70, based on TM21 Test Reports: - Typically 300,000 hours for low output fixtures (100W or less) - Typically 225,000 hours for low-med output fixtures (200W or less) - Typically 175,000 hours for medium output fixtures (300W or less) - Typically 150,000 hours for med-high output fixtures (400W or less) - Typically 125,000 hours for high output fixtures (600W or less)

Owners' Survey
Manufacturers' Survey

What optical design techniques are utilized to limit glare from the light source?	
Holophane, a Division of AcuityBrands Lighting	Borosilicate glass refractor in conjunction with internal reflectors control the distribution minimizes direct view of the LEDs. The prismatic glass refractor provides a spreads the LED "brightness" over a large area minimizing visual discomfort.
PLC-Multipoint	NA
Schréder	Very tight control of peak angles through the use of reflectors when the luminaires are installed over head for counter beam distributions. For wall mounted installations, this is complex. Our strategy is to offer dozens of different photometric distributions in order to have the best possible balance of pertinent luminance generation VS veiling luminance for each possible user case (depending on the geometrical shape of the tunnel, the installation height, possibility of tilt, etc)
Kenall Manufacturing Co.	Lensed optics over the LEDs; best way to limit glare. Also, on some fixtures, opaque fixture lenses.
Which of the below light distributions are available in your LED tunnel luminaires: Symmetrical, Asymmetrical Negative Contrast also known as Counter-Beam, Asymmetrical Positive Contrast also known as Pro-Beam.	
Holophane, a Division of AcuityBrands Lighting	Symmetrical; Asymmetrical Negative Contract also known as Counter-Beam; Asymmetrical Positive Contrast also know as Pro-Beam
PLC-Multipoint	NA
Schréder	Symmetrical; Asymmetrical Negative Contract also known as Counter-Beam; Asymmetrical Positive Contrast also know as Pro-Beam
Kenall Manufacturing Co.	Symmetrical; Asymmetrical Negative Contract also known as Counter-Beam; Asymmetrical Positive Contrast also know as Pro-Beam

Appendix B – Tunnel Lighting Design Criteria

Henry E. Kinney Tunnel Lighting Design Criteria and Summary

(Two 2 – Lane Tunnels)

1. Tunnel Data:

Length ..... Approx. 864'

Width
- Tunnel No. 1 – Northbound (including curbs, barrier, walkway and roadway) ..... 31'-5"
- Tunnel No. 2 – Southbound (including curbs and roadway) ..... 26'-10"

Height at Portal ..... 14'-3"

Orientation ..... North-South

Approach Characteristics (ANSI/IES RP-22-2011)
- South Approach/Portal (Travel direction Northbound) ..... Scene 4, Urban
- North Approach/Portal (Travel direction Southbound) ..... Scene 4, Urban

Class of Road Surface
- Dirty/Stained Concrete (Asphalt appearance) ..... $S1 = 1.11$ & $Q_0 = 0.07$

Reflectance
- Wall – Ceramic Tile ..... r = 0.50
- Ceiling – Ceramic Tile ..... r = 0.50
- Curb ..... r = 0.30

2. Traffic Data:

Traffic Speed (Posted) ..... 35 mph
Average Annual Daily Traffic (Future Year 2034) 72,003
Safe Stopping Sight Distance (Wet Pavement):
- 5.5% Downgrade[1] to Tunnel Approach, Northbound (South Portal) ..... @ 35 mph = 271'
- 5.6% Downgrade[1] to Tunnel Approach, Southbound (North Portal) ..... @ 35 mph = 271'

3. Tunnel Lighting Data:

Light Source: LED

Total Maintenance Factor: ..... 0.58 (LED)
- LED lumen depreciation (L90) 0.90
- Luminaire dirt depreciation 0.80
- Tunnel surface reflectance depreciation 0.80

Luminaire Type:
Wall Mount ..... Type I Very Short Distribution

Design Uniformity on Roadway ..... Average to Minimum 2 to 1
Maximum to Minimum 3.5 to 1

Design Uniformity on Wall ..... Max Avg Road Luminance to Avg Wall Luminance Ratio 2.5 to 1
(Up to 6' – 6" above roadway)

4. Tunnel Lighting Staging/Design Values:
Design Values

Northbound Tunnel (South Portal)

	Threshold Zone 1 148 ft	**Threshold Zone 2 102 ft**	**Transition Zone 1 153 ft**	**Transition Zone 2 204 ft**	**Transition Zone 3 257 ft**
Sunny (1,500* & above)	200 cd/m²	148 cd/m²	82 cd/m²	36 cd/m²	18 cd/m²
Cloudy (500*to 1,500*)	160 cd/m²	118 cd/m²	65 cd/m²	28 cd/m²	14 cd/m²
Overcast (50* to 500*)	115 cd/m²	85 cd/m²	47 cd/m²	21 cd/m²	10 cd/m²
Dawn/Dusk (5* to 50*)	64 cd/m²	47 cd/m²	26 cd/m²	12 cd/m²	6 cd/m²
Night (5* & below)	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²

Southbound Tunnel (North Portal)

	Threshold Zone 1 148 ft	**Threshold Zone 2 102 ft**	**Transition Zone 1 153 ft**	**Transition Zone 2 204 ft**	**Transition Zone 3 257 ft**
Sunny (1,500* &above)	190 cd/m²	141 cd/m²	77 cd/m²	34 cd/m²	17 cd/m²
Cloudy (500*to1,500*)	152 cd/m²	112 cd/m²	62 cd/m²	27 cd/m²	14 cd/m²
Overcast (50* to 500*)	108 cd/m²	80 cd/m²	44 cd/m²	20 cd/m²	10 cd/m²
Dawn/Dusk (5* to 50*)	60 cd/m²	44 cd/m²	24 cd/m²	11 cd/m²	6 cd/m²
Night (5* & below)	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²	2.5 cd/m²

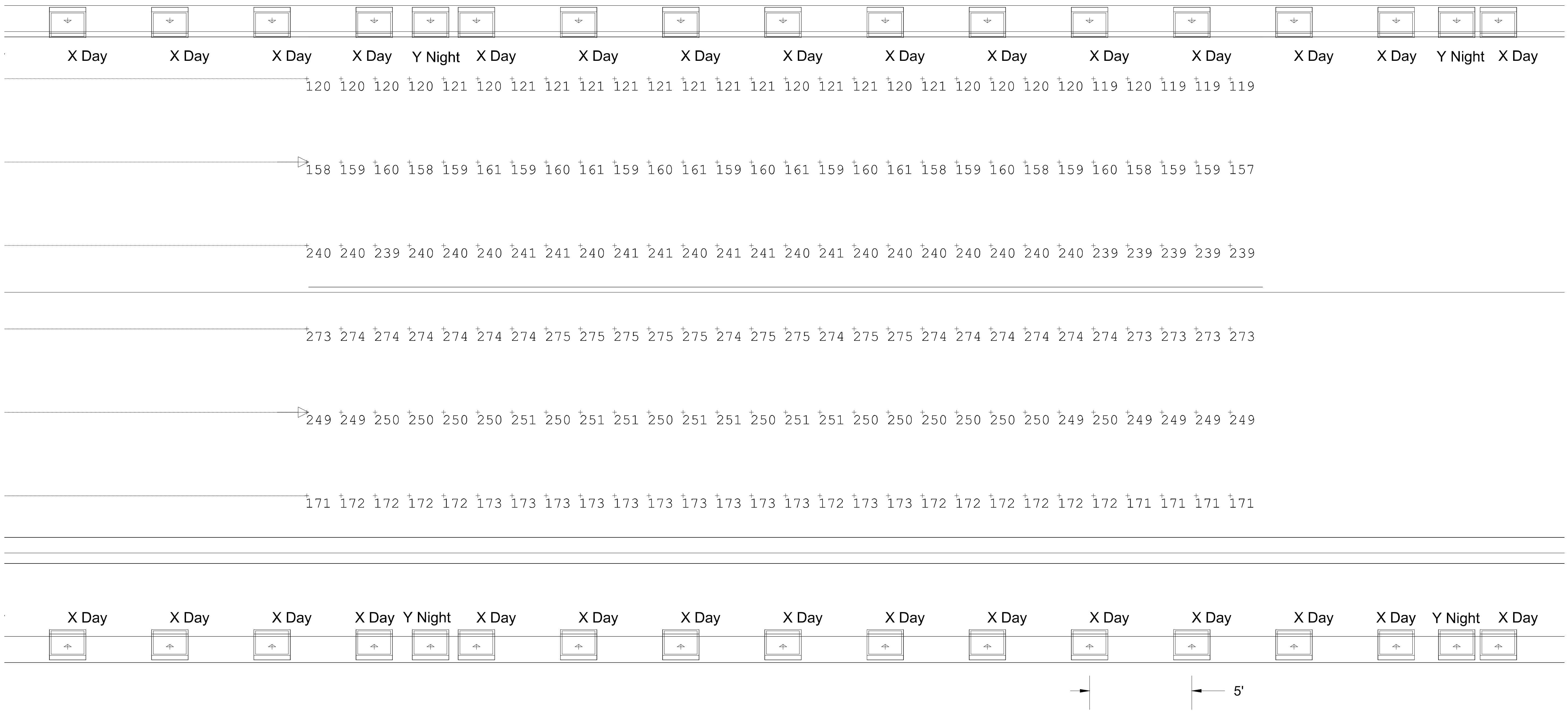
* Denotes Tunnel Portal illuminance

5. Flicker:

Disturbing Flicker Frequency Range ..... 4 to 11 Hz
This restriction is only valid where the phenomenon lasts more than 20 seconds. At 35 mph a vehicle will travel 51 feet/second and in 20 seconds will have traveled 1,020 feet and have exited the tunnel. Therefore, this spacing restriction does not have to be taken into account per the practices in IES RP-22-11

Luminaire Spacing ***d*** for Avoidance of Flicker Frequencies:
At Traffic Speed of 20 to 35 mph ..... 12.8 ft < ***d*** < 2.7 ft

[1] Source: A Policy on Geometric Design of Streets & Highways, AASHTO. Chapter 3 Elements of Design, Table 1: AASHTO Stopping Sight Distance (Wet Pavement), 6% Downgrade column



NORTHBOUND TUNNEL - DAY SCENE, TH1 (THRESHOLD ZONE 1)

5' 0 5' 10'

1" = 5'-0"

LUMINAIRES ARE MOUNTED 13', CENTER OF LUMINAIRE, TILTED 45° FROM CENTER OF ROADWAY FROM "FACING STRAIGHT DOWN" POSITION.
NIGHT LUMINAIRES ARE TURNED OFF FOR THIS CALCULATION.

Calculation Summary									
Scene: Daylighting									
Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Min	ActQVal	Roadway Standard
TH1 Northbound_Luminance	Luminance	Cd/Sq.m	202.68	275	119	1.70	2.31	0.07	IES RP-22-2011

REVISIONS			
DATE	DESCRIPTION	DATE	DESCRIPTION

ROAD NO.	COUNTY	FINANCIAL PROJECT ID

TUNNEL LIGHTING
PHOTOMETRIC CALCULATIONS

CALCULATION NO.

HPS

	0	1	2	3	4	5	6
Present Value of Cost	**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**
Initial Construction Cost	$724,413						
Annual Energy Cost (Electricity)		$95,599	$98,467	$101,421	$104,464	$107,597	$110,825
Lamp Replacement Costs		$0	$0	$0	$0	$0	$29,854
Replace Ballast Costs		$0	$0	$0	$0	$0	$0
Annual Cash Flow	$724,413	$95,599	$98,467	$101,421	$104,464	$107,597	$140,680
Discount Factors	1.0000	0.9524	0.9070	0.8638	0.8227	0.7835	0.7462
Discounted Cash Flow	**$724,413**	**$91,047**	**$89,312**	**$87,611**	**$85,942**	**$84,305**	**$104,977**

	7	8	9	10	11	12	13
Present Value of Cost	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**
Initial Construction Cost							
Annual Energy Cost (Electricity)	$114,150	$117,575	$121,102	$124,735	$128,477	$132,331	$136,301
Lamp Replacement Costs	$0	$0	$0	$0	$34,610	$0	$0
Replace Ballast Costs	$0	$0	$0	$0	$0	$0	$0
Annual Cash Flow	$114,150	$117,575	$121,102	$124,735	$163,086	$132,331	$136,301
Discount Factors	0.7107	0.6768	0.6446	0.6139	0.5847	0.5568	0.5303
Discounted Cash Flow	**$81,124**	**$79,579**	**$78,063**	**$76,576**	**$95,353**	**$73,687**	**$72,283**

	14	15	16	17	18	19	20
Present Value of Cost	**Year 14**	**Year 15**	**Year 16**	**Year 17**	**Year 18**	**Year 19**	**Year 20**
Initial Construction Cost							
Annual Energy Cost (Electricity)	$140,390	$144,602	$148,940	$153,408	$158,010	$162,751	$167,633
Lamp Replacement Costs	$0	$0	$0	$41,326	$0	$0	$0
Replace Ballast Costs	$244,415	$0	$0	$0	$0	$0	$0
Annual Cash Flow	$384,805	$144,602	$148,940	$194,734	$158,010	$162,751	$167,633
Discount Factors	0.5051	0.4810	0.4581	0.4363	0.4155	0.3957	0.3769
Discounted Cash Flow	**$194,353**	**$69,556**	**$68,231**	**$84,962**	**$65,657**	**$64,406**	**$63,179**

Present Value Lifecycle Costs	**$2,434,618**

LED

	0	1	2	3	4	5	6
Present Value of Cost	**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**
Initial Construction Cost	$1,008,434						
Annual Energy Cost (Electricity)		$79,105	$81,478	$83,922	$86,440	$89,033	$91,704
Lamp Replacement Costs		$0	$0	$0	$0	$0	$0
Replace Driver Costs		$0	$0	$0	$0	$0	$0
Annual Cash Flow	$1,008,434	$79,105	$81,478	$83,922	$86,440	$89,033	$91,704
Discount Factors	1.0000	0.9524	0.9070	0.8638	0.8227	0.7835	0.7462
Discounted Cash Flow	**$1,008,434**	**$75,338**	**$73,903**	**$72,495**	**$71,114**	**$69,760**	**$68,431**

	7	8	9	10	11	12	13
Present Value of Cost	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**
Initial Construction Cost							
Annual Energy Cost (Electricity)	$94,455	$97,289	$100,207	$103,214	$106,310	$109,499	$112,784
Lamp Replacement Costs	$0	$0	$0	$0	$0	$0	$0
Replace Driver Costs	$0	$0	$0	$0	$0	$333,839	$0
Annual Cash Flow	$94,455	$97,289	$100,207	$103,214	$106,310	$443,339	$112,784
Discount Factors	0.7107	0.6768	0.6446	0.6139	0.5847	0.5568	0.5303
Discounted Cash Flow	**$67,127**	**$65,849**	**$64,595**	**$63,364**	**$62,157**	**$246,868**	**$59,812**

	14	15	16	17	18	19	20
Present Value of Cost	**Year 14**	**Year 15**	**Year 16**	**Year 17**	**Year 18**	**Year 19**	**Year 20**
Initial Construction Cost							
Annual Energy Cost (Electricity)	$116,168	$119,653	$123,242	$126,940	$130,748	$134,670	$138,710
Lamp Replacement Costs	$0	$0	$0	$0	$0	$0	$0
Replace Driver Costs	$0	$0	$0	$0	$0	$0	$0
Annual Cash Flow	$116,168	$119,653	$123,242	$126,940	$130,748	$134,670	$138,710
Discount Factors	0.5051	0.4810	0.4581	0.4363	0.4155	0.3957	0.3769
Discounted Cash Flow	**$58,673**	**$57,555**	**$56,459**	**$55,383**	**$54,328**	**$53,294**	**$52,279**

Present Value Lifecycle Costs	**$2,457,217**

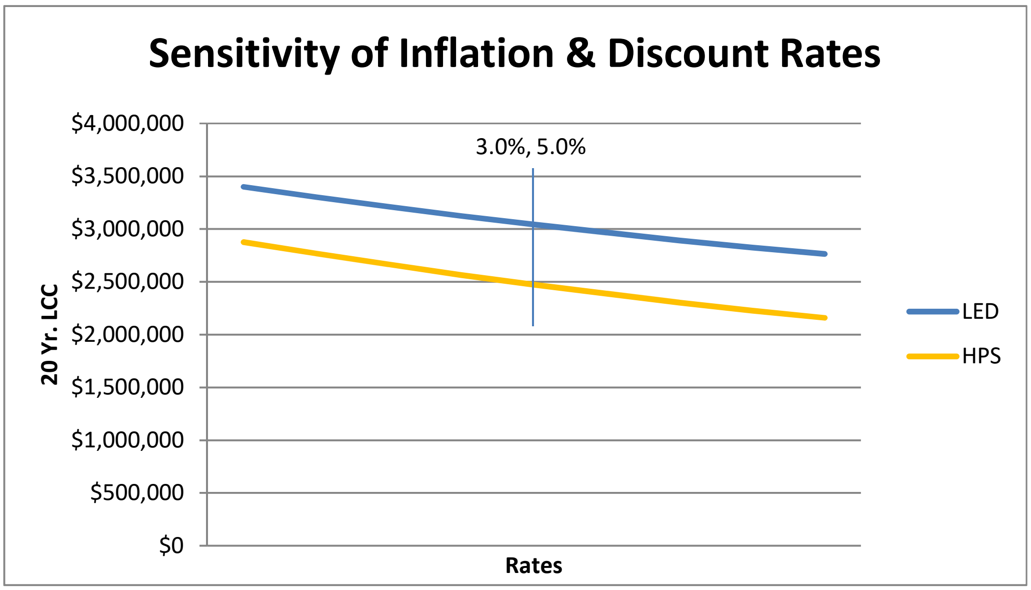
20 Year Life Cycle Cost Analysis

	LED	HPS
Initial Construction Cost	$1,008,434	$724,413
Annual Energy Cost (Electricity)	$76,801	$92,814
20 Yr. Lamp Replacement Costs	$0	$60,544
20 Yr. Replace Driver/Ballast Costs	$185,894	$123,446
Quantity of Luminaires	370	550
Lamp Replacement Period (hours)	100,000	24,000
Replace Driver/Ballast Period (hours)	50,000	60,000
Present Value Lifecycle Costs	$2,457,217	$2,434,618

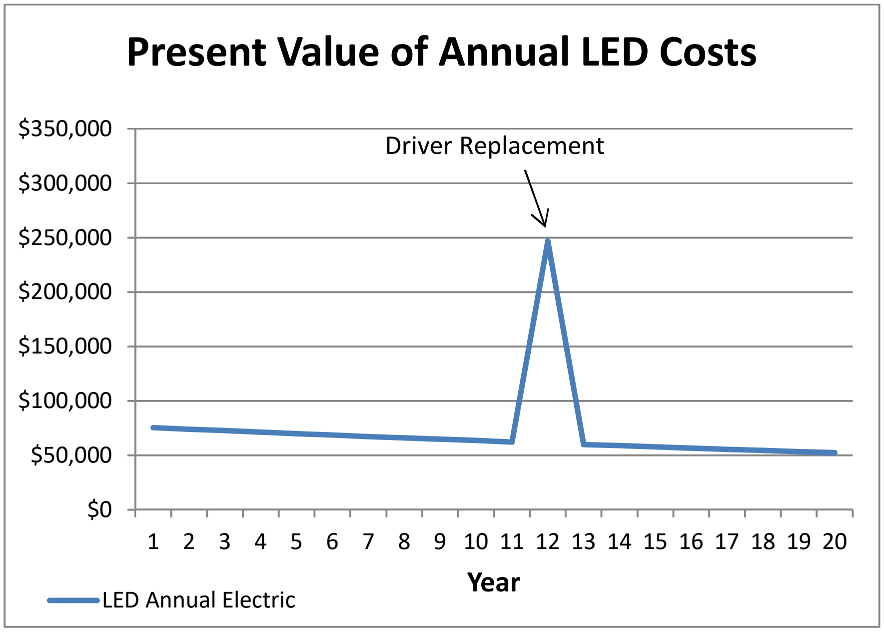
Inflation Rate	3.00%
Discount Rate	5.00%
Time Frame for Analysis (years)	20
Electric Cost per KWH	$0.11
Annual Burning Hours	4,455

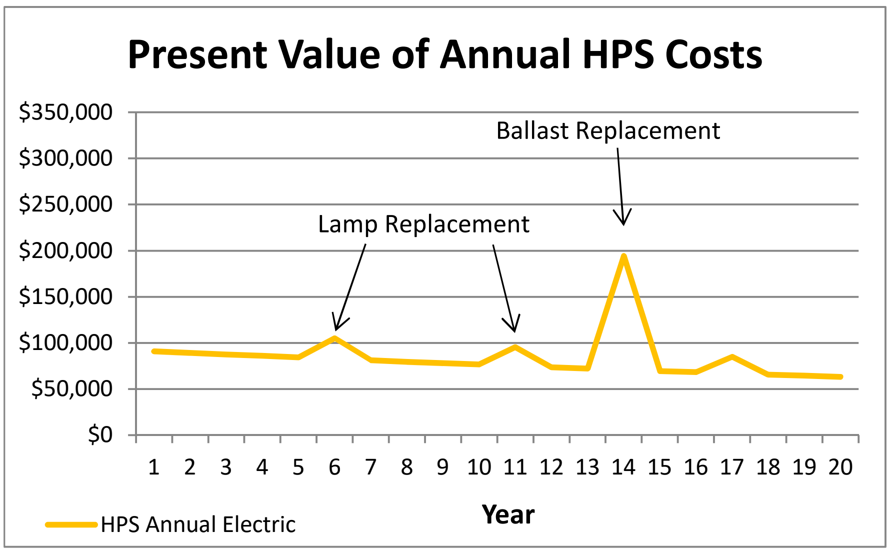
Sensitivity of Inflation and Discount Rates

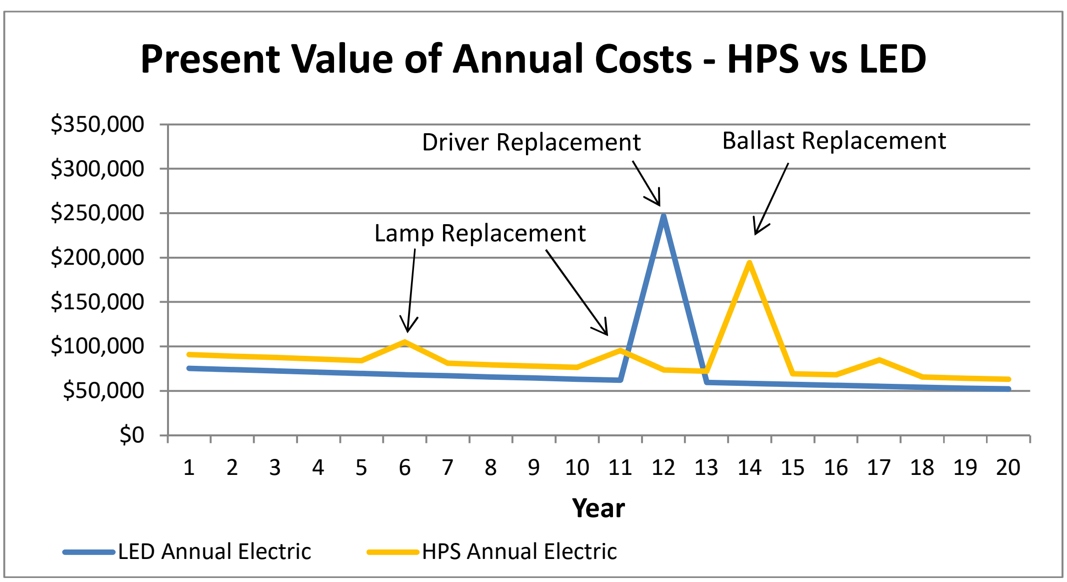
Inflation	Discount	LED	HPS
4.5%	4.5%	$3,399,496	$2,876,280
4.5%	5.0%	$3,302,395	$2,766,304
4.5%	5.5%	$3,211,730	$2,663,714
3.0%	4.5%	$3,123,435	$2,563,902
3.0%	**5.0%**	**$3,043,320**	**$2,473,427**
3.0%	5.5%	$2,968,404	$2,388,910
1.5%	4.5%	$2,892,295	$2,303,140
1.5%	5.0%	$2,826,071	$2,228,593
1.5%	5.5%	$2,764,047	$2,158,852



The impact of sensitivity graph visually demonstrates the impact of present value lifecycle costs caused by the fluctuation of inflation and discount rates. For this study, an average inflation rate of 3.00% and current discount rate of 5.00% have been chosen. Because of the difficulty predicting future rates over the next 20 years, the present values costs were additionally estimated with a 1.5% fluctuation for the interest rate and 0.5% for the discount rate to help compensate for this uncertainty. This graph simply portrays how sensitive the 20 year present value costs are to changes in the interest and discount rates. If over this 20 year period the average difference is greater than 4% or less than 0% of the discount to inflation rate, further calculations or extrapolation of this graph will be necessary.


Present Value of Annual LED Costs
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0
Driver Replacement
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Year
LED Annual Electric


Present Value of Annual HPS Costs
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0
Ballast Replacement
Lamp Replacement
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Year
HPS Annual Electric


Present Value of Annual Costs - HPS vs LED
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0
Driver Replacement
Ballast Replacement
Lamp Replacement
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Year
LED Annual Electric
HPS Annual Electric

LED

Basic Information	
Time Frame for Analysis (years)	20
Inflation Rate	3.00%
Discount Rate	5.00%
Electric Cost per KWH	$0.11
Annual Burning Hours	4455

Relevant Information	
Initial Construction Cost	$1,008,434
Annual Energy Cost (Electricity)	$76,801
20 Yr. Lamp Replacement Costs	$0
20 Yr. Replace Driver/Ballast Costs	$185,894
Lamp Replacement Period (hours)	100,000
Replace Driver/Ballast Period (hours)	50,000

Present Value Lifecycle Costs	**$2,457,217**

HPS

Basic Information	
Time Frame for Analysis (years)	20
Inflation Rate	3.00%
Discount Rate	5.00%
Electric Cost per KWH	$0.11
Annual Burning Hours	4455

Relevant Information	
Initial Construction Cost	$724,413
Annual Energy Cost (Electricity)	$92,814
20 Yr. Lamp Replacement Costs	$60,544
20 Yr. Replace Driver/Ballast Costs	$123,446
Lamp Replacement Period (hours)	24,000
Replace Driver/Ballast Period (hours)	60,000

Present Value Lifecycle Costs	**$2,434,618**

First Year Energy Cost Calculations

LED

	Luminaire Quantity	Lamp Sizes	Luminaire Wattage	Total Power (kW)
	230	9 LEDs 1050mA	500	115.0
	140	6 LEDs 1050mA	298	41.7
Total	370			156.7

Burning Hours (assumes all luminaires are on during 4,455 annual hours of sunlight)	4455
Energy Cost per KWH	$0.11
Total First Year Energy Cost	$76,801

First Year Energy Cost Calculations

HPS

	Luminaire Quantity	Lamp Sizes	Luminaire Wattage	Total Power (kW)
	84	100W HPS	128	10.8
	68	150W HPS	188	12.8
	70	250W HPS	289	20.2
	328	400W HPS	444	145.6
Total	550			189.4

Burning Hours (assumes all luminaires are on during 4,455 annual hours of sunlight)	4455
Energy Cost per KWH	$0.11
Total First Year Energy Cost	$92,814

Appendix D – Life Cycle Cost Calculations

Cost Data - December 2019

Initial Construction Cost

ITEM	QUANTITY		MATERIAL		LABOR		EQUIP		TOTAL COST
	No. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	PER UNIT	TOTAL	
LED									
500W	230	EA	$2,366	$544,094	$372	$85,654	$91	$20,902	$650,650
298W	140	EA	$2,092	$292,923	$372	$52,137	$91	$12,723	$357,783
									$1,008,434
HPS									
100W	84	EA	$742	$62,311	$372	$31,282	$91	$7,634	$101,227
150W	68	EA	$746	$50,750	$372	$25,324	$91	$6,180	$82,254
250W	70	EA	$921	$64,437	$372	$26,069	$91	$6,362	$96,868
400W	328	EA	$891	$292,105	$372	$122,150	$91	$29,809	$444,064
									$724,413

Driver/Ballast Replacement Cost

ITEM	QUANTITY		MATERIAL		LABOR		EQUIP		TOTAL COST
	No. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	PER UNIT	TOTAL	
LED									
500W	230	EA	$378	$86,931	$164	$37,718	$91	$20,902	$145,552
298W	140	EA	$378	$52,915	$164	$22,959	$91	$12,723	$88,597
									$234,148
HPS									
100W	84	EA	$74	$6,220	$80	$6,718	$91	$7,634	$20,572
150W	68	EA	$101	$6,867	$80	$5,438	$91	$6,180	$18,485
250W	70	EA	$148	$10,367	$80	$5,598	$91	$6,362	$22,327
400W	328	EA	$135	$44,162	$80	$26,232	$91	$29,809	$100,203
									$161,587

Lamp Replacement Cost

ITEM	QUANTITY		MATERIAL		LABOR		EQUIP		TOTAL COST
	No. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	PER UNIT	TOTAL	
LED									
500W	432	EA	--	--	--	--		$0	$0
298W	108	EA	--	--	--	--		$0	$0
									$0
HPS									
100W	84	EA	$32	$2,714	$9	$792	$91	$7,634	$3,506
150W	68	EA	$34	$2,289	$9	$641	$91	$6,180	$2,930
250W	70	EA	$35	$2,450	$9	$660	$91	$6,362	$3,110
400W	328	EA	$38	$12,365	$9	$3,091	$91	$29,809	$15,457
									$25,003