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TRANSPORTATION RESEARCH BOARD

Designing solid-state roadway lighting

Tuesday, March 31, 2020
2:00-3:30 PM ET

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RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Learning Objectives

At the end of this webinar, you will be able to:

- Describe how to apply SSL to roadway environments
- Design SSL effectively

Introduction

Project No. NCHRP 05-22

GUIDELINES FOR SOLID STATE ROADWAY LIGHTING

FINAL REPORT

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

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMICS OF SCIENCES, ENGINEERING AND MEDICINE

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August 2019

http://www.trb.org/Main/Blurbs/180129.aspx

SOLID STATE LIGHTING GUIDE

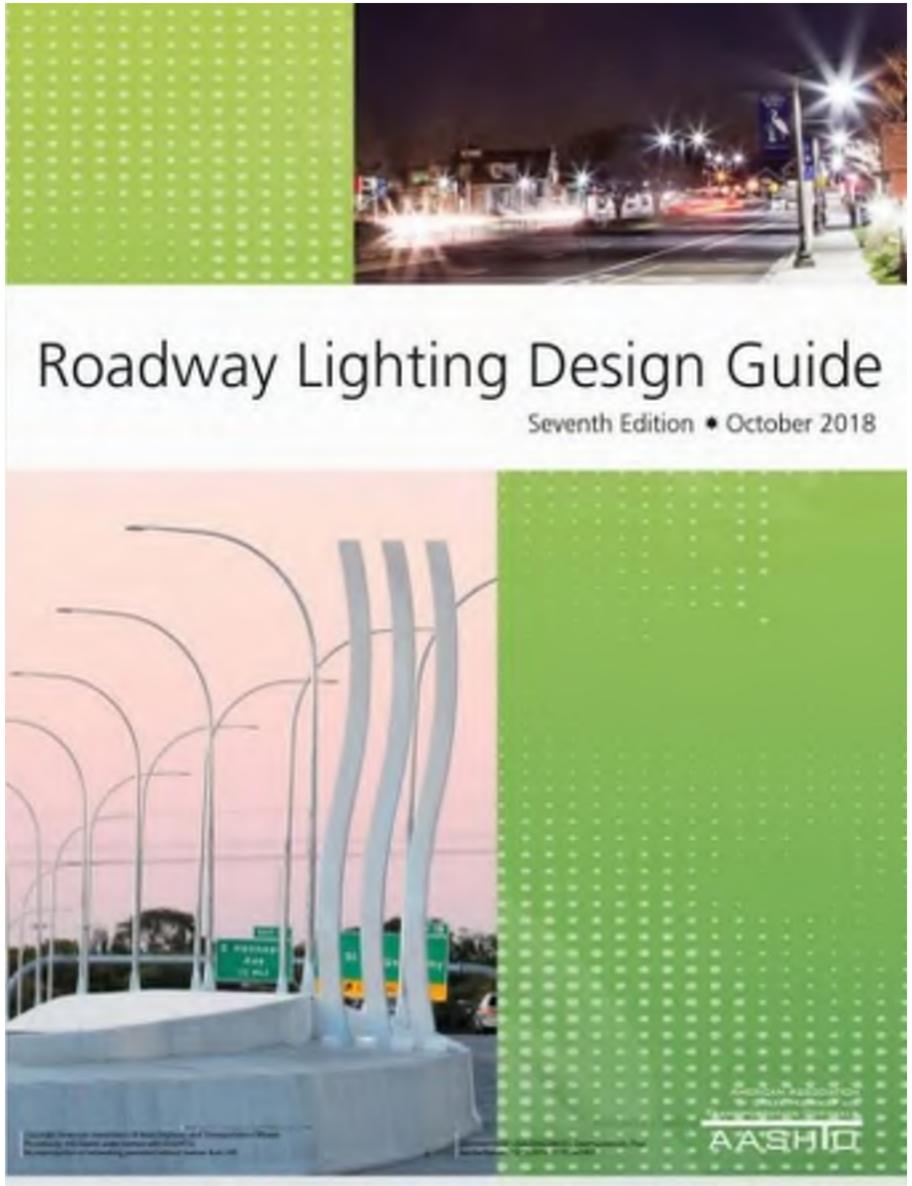
Final – August 2019

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS
AASHTO

http://www.trb.org/Main/Blurbs/180128.aspx

Supplemental Solid State Guide

- Chapter 1 – Introduction
- Chapter 2 – Master Lighting Plan
- Chapter 3 - Technique of Lighting Design
- Chapter 4 - Tunnels and Underpasses
- Chapter 5 - Work Zone Lighting and Temporary Roadway Lighting
- Chapter 6 – Roundabouts, Interchanges, and Intersections
- Chapter 7 – Electrical System Requirements
- Chapter 8 – Safety Rest Areas
- Chapter 9 – Roadway Sign Lighting
- Chapter 10 – Operation and Maintenance Considerations
- Chapter 11 – Potential Environmental Impacts
- Annex A – Design Examples
- Annex B – Solid State Lighting Sample Specifications



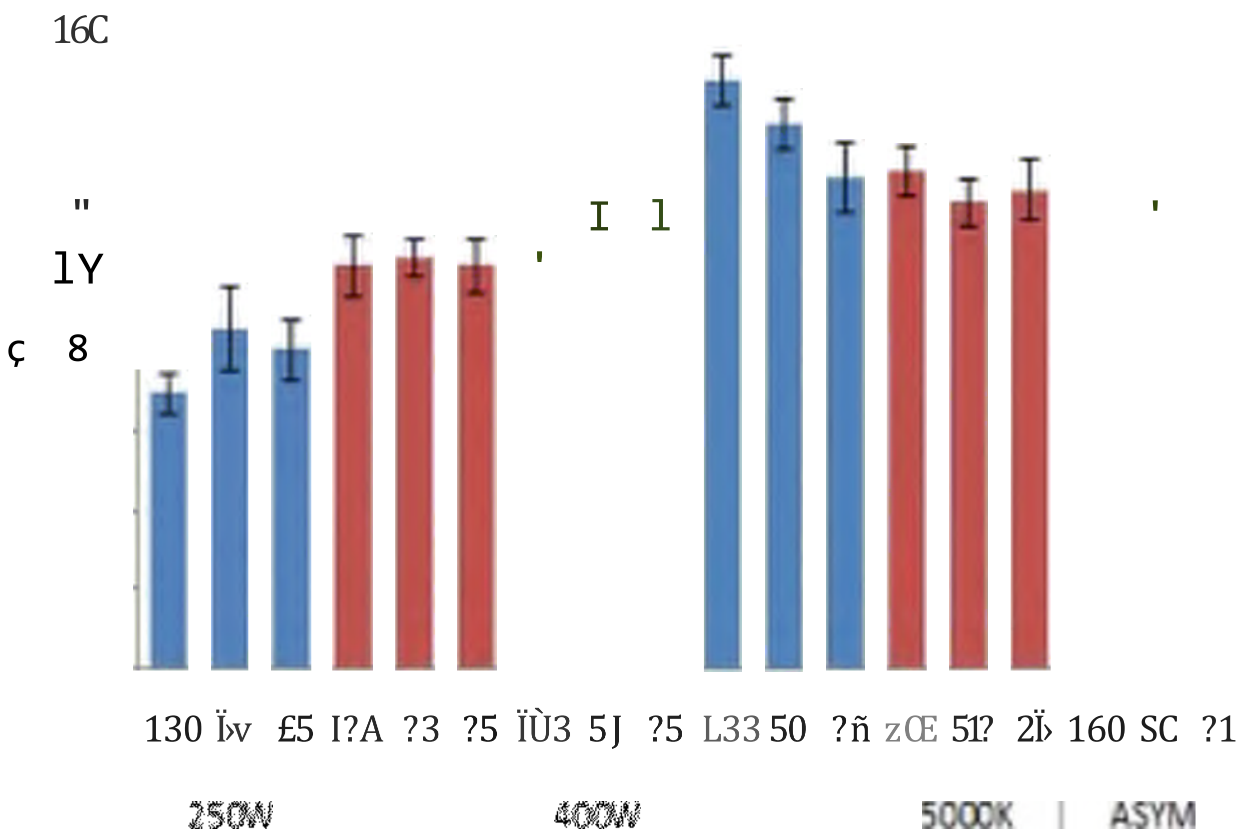
Planning and Use of Solid State Lighting

Prior research, as well as research for this project, show differences in driver detection distances, with 4000K sources showing some advantages.

Key Differences Between Solid State and Traditional Light Sources

- Spectral content and effectiveness vary. CCT only partially describes LED source spectral content.
- Photometric distribution can greatly vary with HID sources as well as among LED products.
- Rated life of luminaires is based on different performance requirements.
- Solid state components require different considerations relating to electrical components and operations.
- Solid state luminaires allow for much greater flexibility regarding control, output, and optical distribution. These flexibilities offer potential benefits over HID and HPS.
- Solid state luminaires can create impacts relating to glare, environmental impacts, and subjective preferences which should be understood and mitigated.

Figure 14. Comparison of Different CCT Streets



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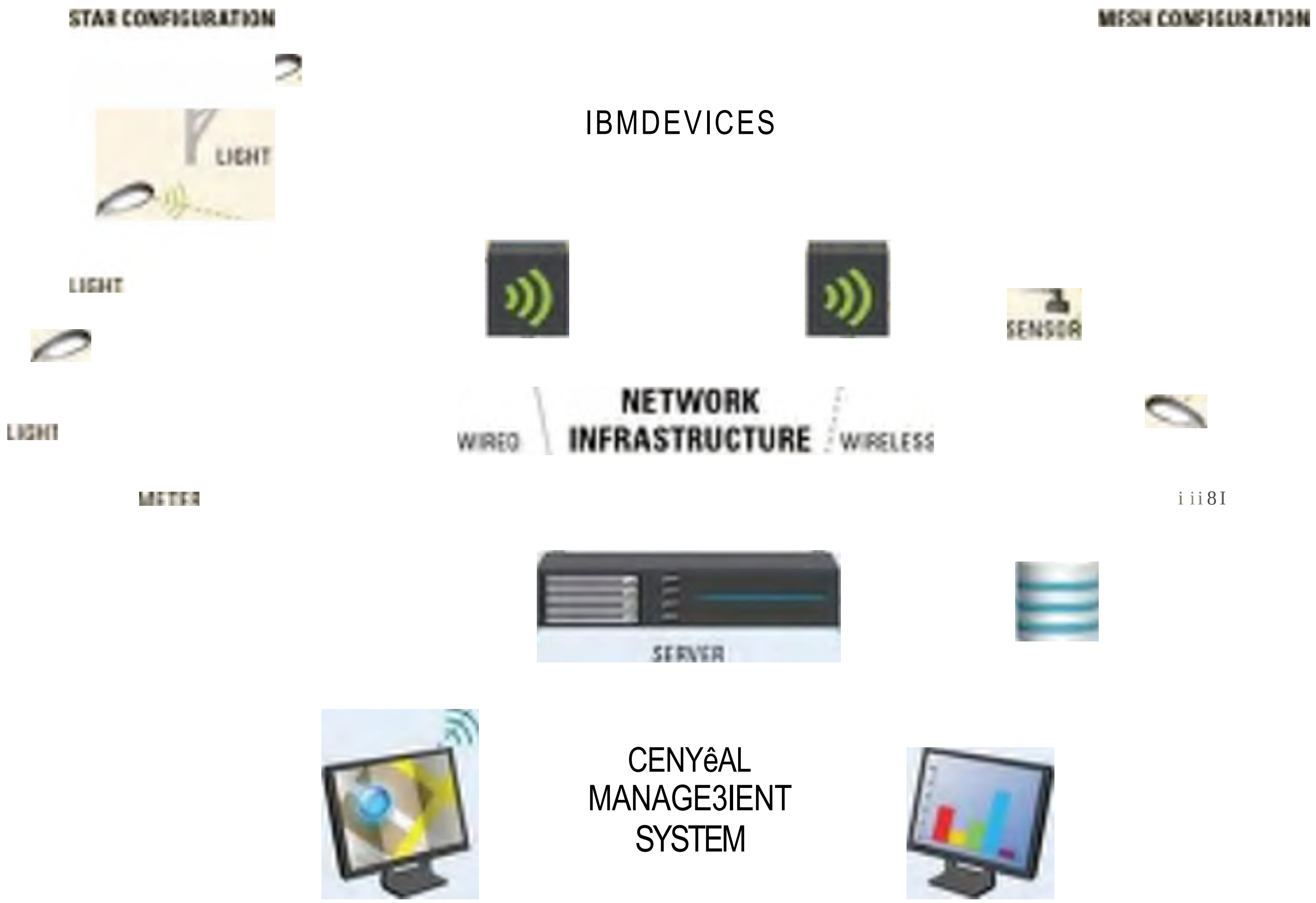

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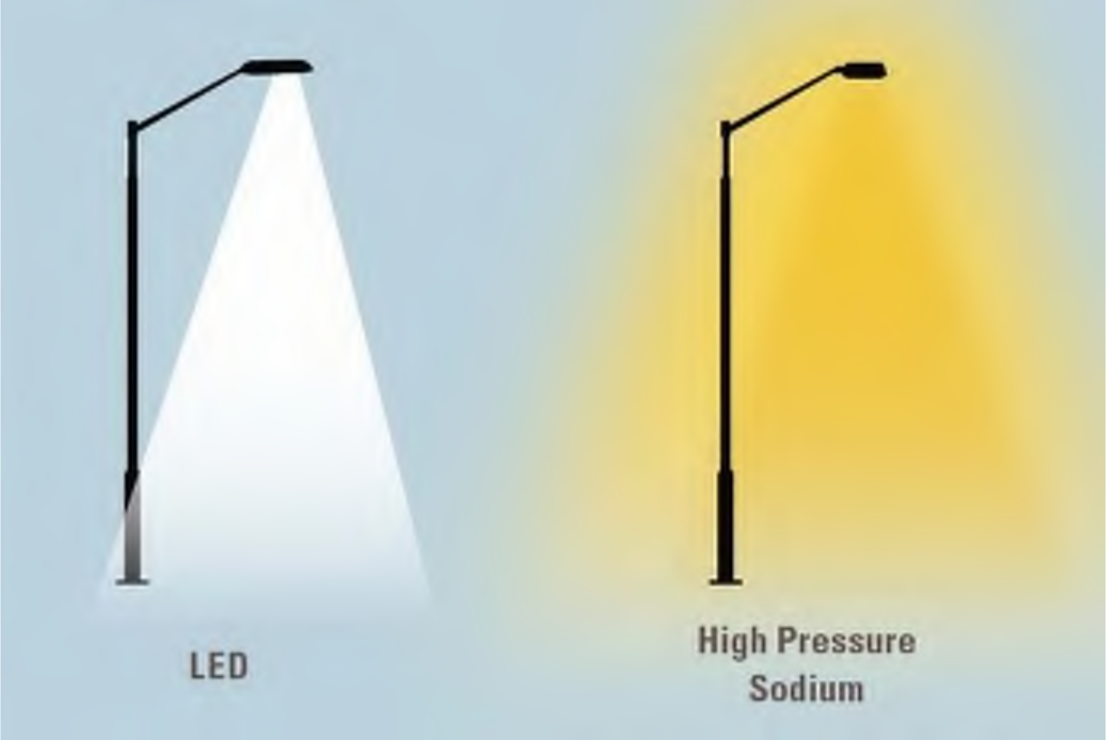
(Image Credit: California Lighting Technology Center, UC Davis)

Criteria for Solid-State Roadway Lighting

Existing Recommendations for Light Levels on Roadways

- Based on legacy sources like HPS – Poor Optical Distribution Control



For HPS, light adjacent to the roadway could have been unintended safety benefit

Anchorage. Photo by Wayne Johnson, ML&P

How to deal with it in the age of LEDs

- **Does additional lighting beyond the roadway help the drivers in seeing better?**
- **If yes..**
  - **How much light do we need?**
  - **How do we specify it?**
  - **Implications for sidewalks and bicycle paths**

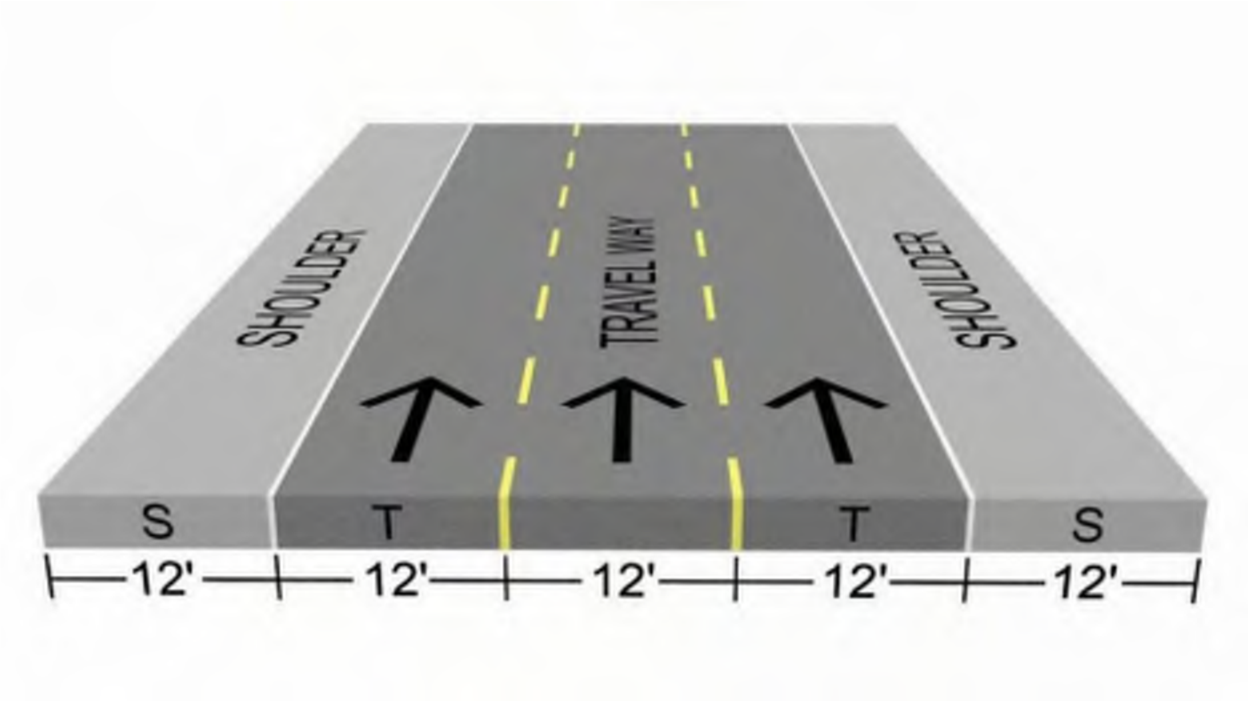
  - **This is the focus of NCHRP Project 5-22**

What is Surround Ratio?

"Ratio of the average horizontal illuminance on the two longitudinal strips each adjacent to the two edges of the carriageway to the average horizontal illuminance on two longitudinal strips each adjacent to the two edges of the carriageway" **- CIE 140: 2000**

What is Surround Ratio?

$$\text{Surround Ratio} = \frac{\text{Edges}}{\text{Lanes}}$$



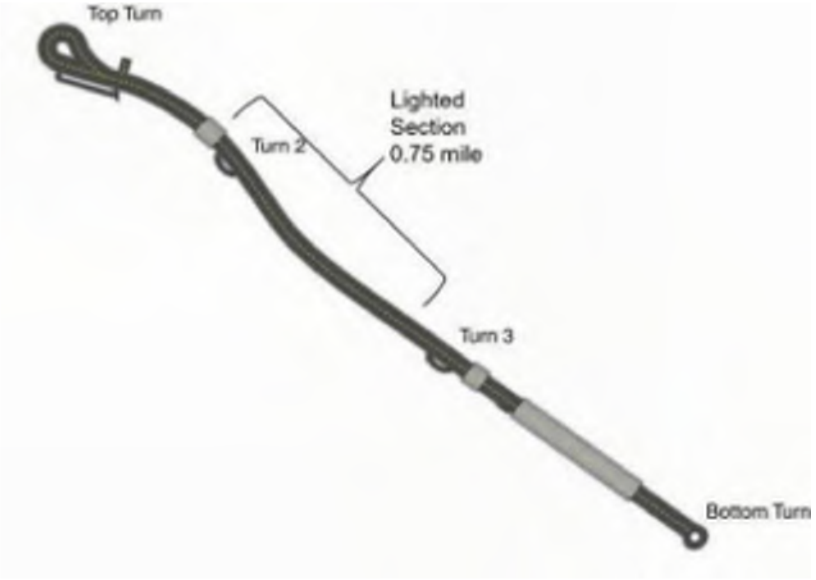
Objectives

How does changing the surround ratios affect driver visual performance?

- Pedestrian location on the roadway
- Speed
- Light level
- Uniformity

Experimental Procedure – Virginia Smart Road

- 60 Participants – Age and Gender Balanced
- Object detection task on the Virginia Smart Road
- Control system to dim
- 80 meter spacing
- 15 meter mounting height



Experimental Design – Independent Variables

Independent Variable	Level
Light Spectral Power Distribution	3000 K LED 4000 K LED 5000 K LED
Light Level (Avg. Luminance)	High: 1.5 cd/m^2 Medium: 1.0 cd/m^2 Low: 0.7 cd/m^2
Surround Ratio (Avg. Shoulder to Avg. Lane Luminance)	High (0.8) Low (0.45)
Uniformity Ratio (Avg. to Min Luminance)	High (1.8) Low (1.3 to 1.4)
Speed	High (55 mi/h) Low (35 mi/h)
Age	Old (65 and older) Young (18 to 35 years)

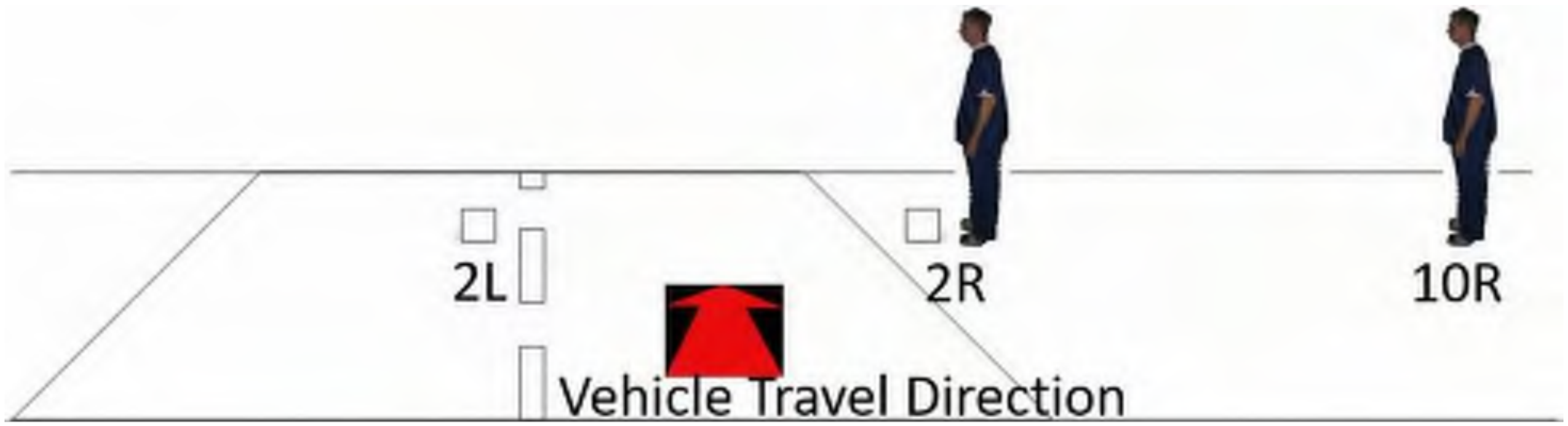
Surround and Uniformity Ratios

Dependent Measures – Detection Distances

- Targets (18 cm by 18 cm)

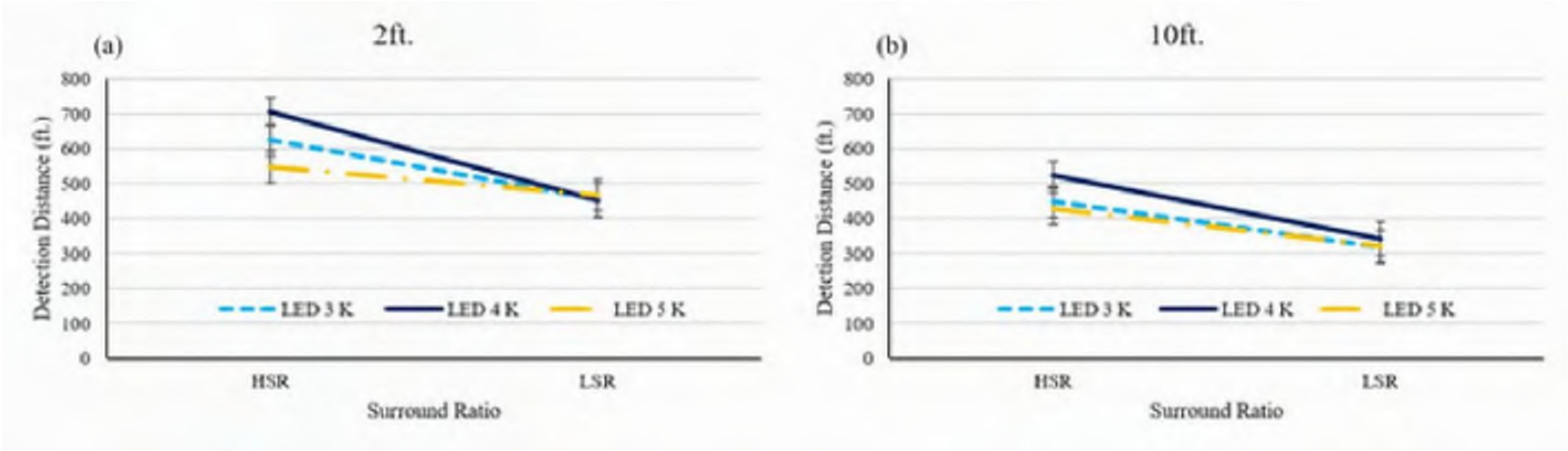
- Pedestrians

Object Locations – Detection Task

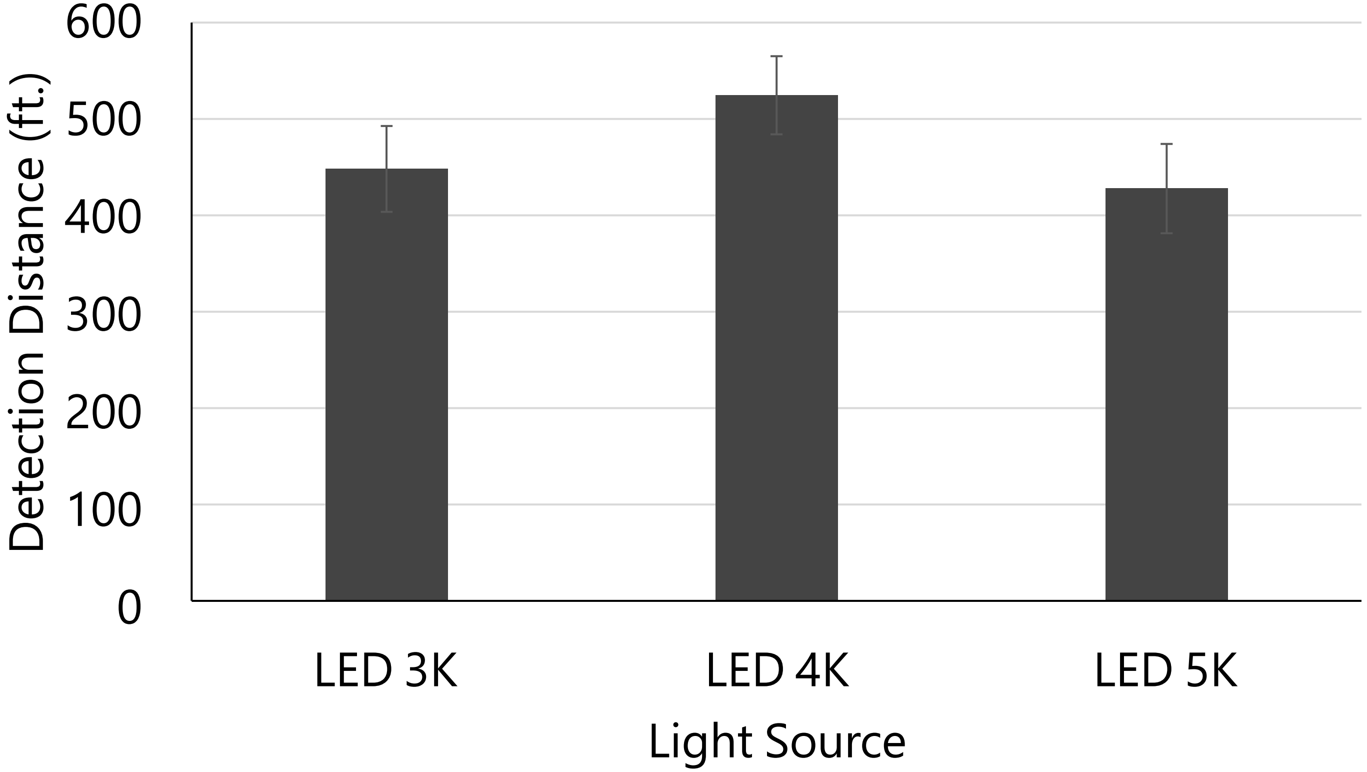


How does Surround Ratio affect Visual Performance Across LEDs and Offset Distances?

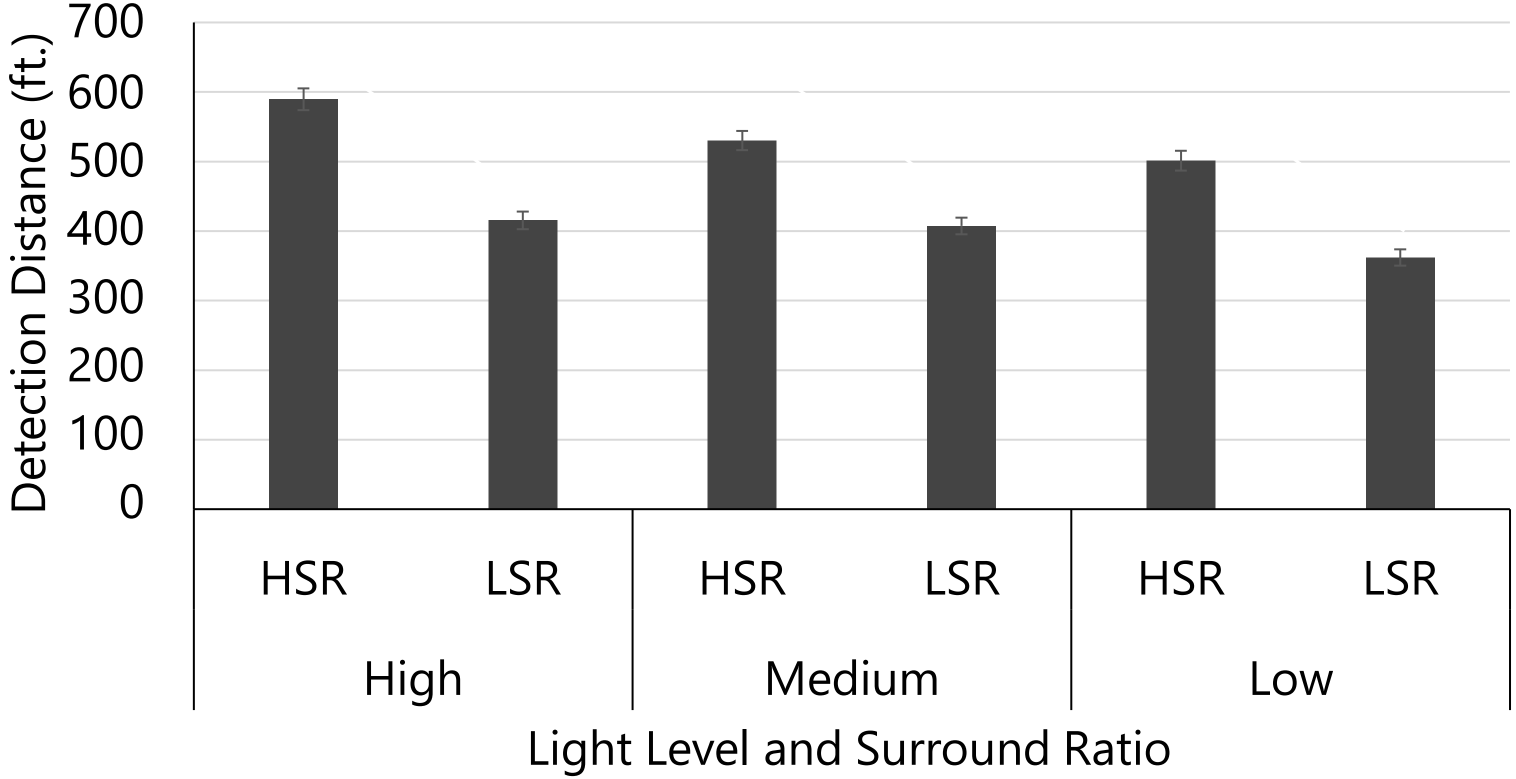
- Lower surround ratios had lower detection distances
  - Lowest at 10ft. offset
- Consistent across all LEDs



For Higher Surround Ratio, 4000 K LED increased detection distances for off-axis pedestrians



How does Surround Ratios affect visual performance across Light Levels?



Odds the driver can detect the pedestrian from a “safe” distance?

Independent Variable	Level	Reference Level	Odds Ratio	95% Confidence Limits	
Light Level	High	Low	1.7	1.3	2.3
	High	Medium	1.4	1.1	1.8
Surround Ratio	HSR	LSR	2.6	1.3	5.0
Uniformity Ratio	HUR	LUR	2.3	1.2	4.4
Age	Younger	Older	5.6	2.7	11.4
Clothing Color	Blue	Black	1.3	1.0	1.8
	Gray	Black	1.6	1.2	2.2
	Red	Black	3.3	2.4	4.6
Offset	2 ft.	10 ft.	3.4	2.7	4.3
Speed	35 mi/h	55 mi/h	37.7	27.8	51.1

Conclusions – Light Source Type

- No significant differences between LEDs and between LED and HPS
  - For Both Pedestrians and Targets
- 4000K typically had a higher response level
  - HPS had significantly higher uncertainty and higher non-uniformity
  - Higher speeds
- SPD of the light source might not majorly influence driver visual performance at speeds greater than 35 mi/h

Conclusions – Surround Ratio

- Higher Surround Ratios (SRs) increased visual performance (esp. for Pedestrians)
    - Longer detection distances
    - Higher odds of detection from safe distance
    - All offset distances
    - All light levels
    - All LEDs
- Higher SRs for 4000 K LEDS
    - only condition that had detection distance greater than SSD at 55 mph
    - longest detection distances for all offset distances
- Higher surround ratios increased off-axis visual performance
    - Increased light on the shoulder → more information for drivers
- A Surround Ratio of at least 0.8 will ensure good visual performance

Techniques for SSL Design

Key Issues During Lighting Design

- Consider an adaptive lighting system (or at least provide a controls-ready system) and establish light levels for dimming.
- Select CCT for the installation based on visibility differences for certain spectral content sources as well as preferences determined by the DOT or Authority. Generally, 4000K provides consistent results but consider other factors as discussed in other sections of this guide.
- Include the shoulders adjacent to the roadway in lighting design. When pedestrians and/or cyclists are present, consider the AASHTO recommendations for those areas as part of the design. For highways and freeways, adjacent areas should meet the SR levels discussed in this chapter.
- Consider warrants and other factors as part of the decision process for roadway safety improvements.
- Consider high-mast lighting, which can create more light trespass and perceived brightness issues from abutters, only for large area lighting or very wide roadway cross sections.
- Identify sensitive receptors and housing areas close to the roadway right-of-way early in design.
- Consider shielding in lighting system design.
- Because individual LED shields perform better than luminaire shields for high-mast lighting, carefully select shielding types.
- LED luminaires may help reduce structural requirements (fewer fixtures/weight/EPA) for poles.
- Consider longer periods between needed access to luminaires.

Adaptive Lighting Methods

Road Classification	Average Luminance L_{avg} (cd/m^2)	Average Uniformity Ratio L_{avg}/L_{min}	Maximum Uniformity Ratio L_{max}/L_{min}	Maximum Veiling Luminance Ratio $L_{V,max}/L_{avg}$
Freeway Class A	0.6	3.5	6.0	0.3
Freeway Class B	0.4	3.5	6.0	0.3
Expressway	1.0	3.0	5.0	0.3

Table Notes:

L_{avg}: Maintained average pavement luminance

L_{min}: Minimum pavement luminance

$L_{V,max}$: Maximum veiling luminance

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

Table Notes:

* Pedestrian Activity Classifications are defined in Section 11.3.3.

L_{avg}: Maintained average pavement luminance

L_{min}: Minimum pavement luminance

$L_{V,max}$: Maximum veiling luminance

Figure 9. Excerpt from RP-8-18 showing Roadway and Street Lighting Levels

Adaptive Lighting Methods

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

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

Figure 11. Excerpt from FHWA Adaptive Lighting Report - Classification Method for Highways (S class = 5- weighting factors)

Use of Surround Ratio

Research perfomed for tbis yojec-I shows that detection distances are increased 1t'hen li@tiii9 is usefi in areas adjacent to the roadway'. Therefore, c-Dnsider SR as a criterion. T'he céteiia for SR fihDtlld b« o.g, hi@ei l a n that used @ CIE. and be the ratio oftk.• as'eraRe i£ixninance of an area adjacent to th» 4avel ›saj' of 12 fe£it (fi) (3 fi meti3rS [I+i]) and aa'e-f8R R illuminaiice of Ae lane of the 6ai'ol is'aj' adjacent to it. For example, tUmR the configuration shDssn in Fi¡(ine 20, the an=ora9e illumination of the at-ea shosi» as shoulder dis4d Rd8j' the ax'eraee illumination of the adjacent lane shoulfi be 0.8 or ereater.

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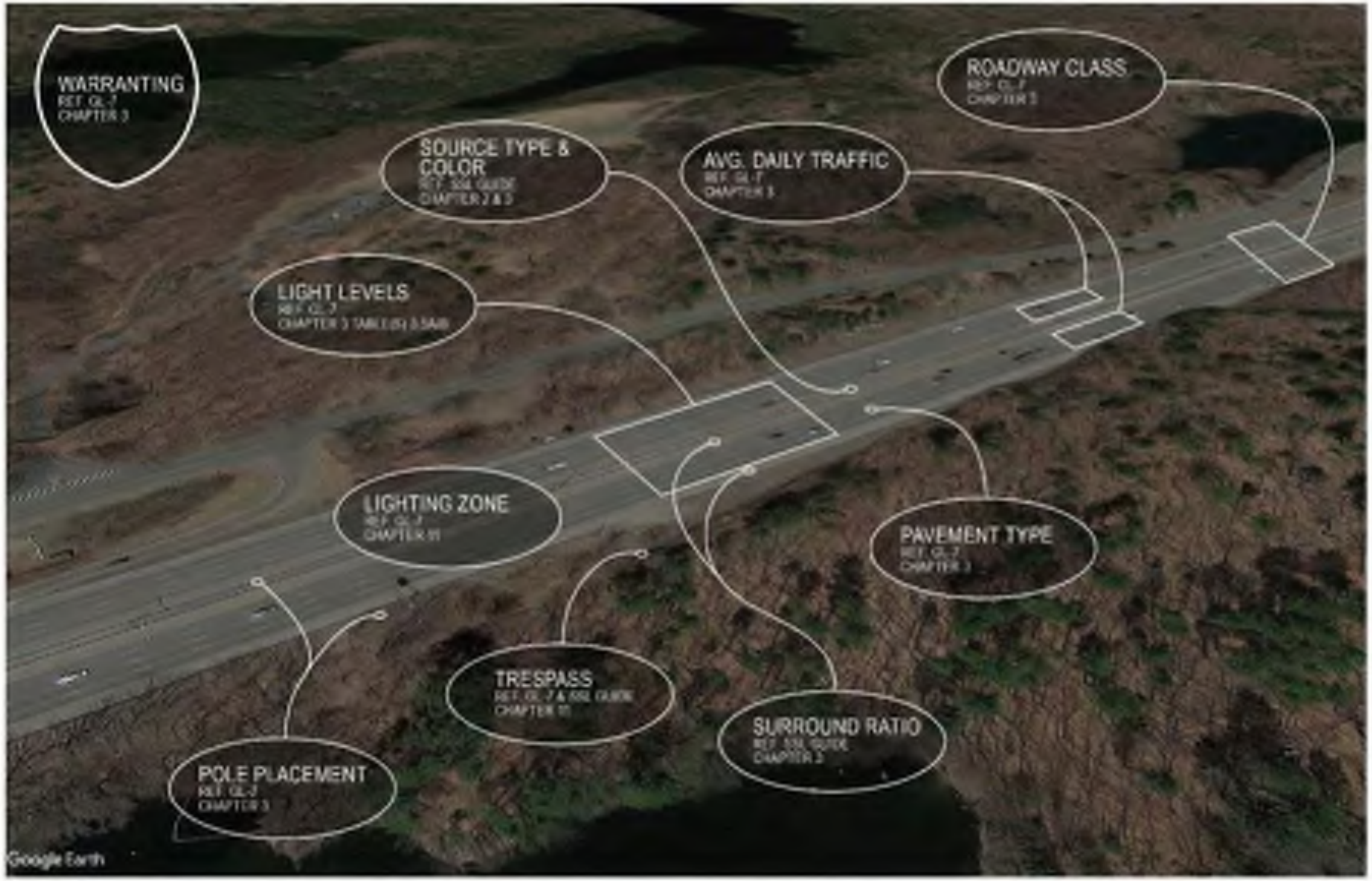
Design Examples



Step 2a - Determine Illuminance or Luminance Design

Example Result: Both Illuminance and Luminance will be used for freeway calculations.

Step 2b – Determine the road surface classification to properly design a roadway lighting system.

Example Result: Asphalt, Class R3

Table 3-1 R«Jart Sr‹rface bi DSsifir <J°ion?

Class	Q_0*	Description	Mode of Reflectance
R1	0.10	Portland cement concrete road surface. Asphalt road surface with a minimum of 12 percent of the aggregates composed of artificial brightener (e.g., Synopal) aggregates (e.g., labradorite, quartzite).	Mostly diffuse
[redacted]	[redacted]	Asphalt road surface with an aggregate composed of	Mixed (diffuse and specular)
R3	0.07	Asphalt road surface (regular and carpet seal) with dark aggregates (e.g., trap rock, blast furnace slag); rough texture after some months of use (typical highways)	Slightly specular
R4	0.08	Asphalt road surface with very smooth texture.	Mostly specular

Example Result: Warranting condition, sections in and near cities where the current average daily traffic (ADT) is 30,000 or greater, CFL-1. Warranting conditions can also be applied from the SSL Guideline for crash modification factors. Lighting was decided to be added.

Case	Warranting Conditions
CFL-1	Sections in and near cities where the current average daily traffic (ADT) is 30,000 or greater.
CFL-2	Sections where three or more successive interchanges are located with an average spacing of 1.5 mi or less, and adjacent areas outside the right-of-way are substantially urban in character.
CFL-3	Sections of two miles or more passing through a substantially developed suburban or urban area in which one or more of the following conditions exist: a) local traffic operates on a complete street grid having some form of street lighting, parts of which are visible from the freeway b) the freeway passes through a series of developments—such as residential, commercial, industrial and civic areas, colleges, parks, terminals, etc. that include lighted roads, streets, parking areas, yards, etc.—that are lighted c) separate cross streets, both with and without connecting ramps, occur with an average spacing of 0.5 mi or less, some of which are lighted as part of the local street system d) the freeway cross section elements, such as median and borders, are substantially reduced in width below desirable sections used in relatively open country.
CFL-4	Sections where the ratio of nighttime to daytime crash rate is at least 2.0 times the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night crash rate. Where crash data are not available, rate comparison may be used as a general guideline for crash severity.

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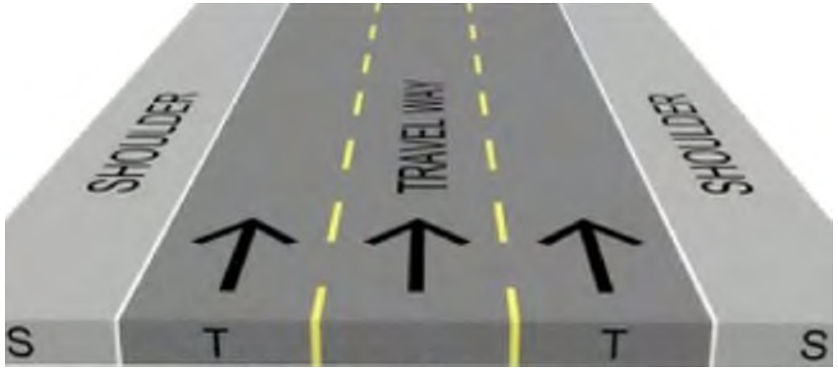
Table 3-5a. Illuminance and Luminance Design Values (U.S. Customary)

Roadway and Walkway Classification				
Principal Arterials:				
Interstate and other freeways				
Other Principal Arterials (partial or no control of access)				
Minor Arterials				
Collectors				
Sidewalks	Commercial	0.9	1.3	1.3
	Intermediate	0.6	0.8	0.8
	Residential	0.2	0.4	0.6
Pedestrian Ways and Bicycle Ways	All	1.4	2.0	2.0

Step 2g - Consider SR as part of design

Example Results: Surround ratio will be included SR – 0.8



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Example Results: SSL specific Maintenance Factors LDD: 0.9, LLD: 0.82, LATF:1 = LLF .738

Example Result: LZ2

LZ0: No ambient lighting—Areas where the natural environment will be seriously and adversely affected by lighting.

LZ1: Low ambient lighting—Areas where lighting might adversely affect flora and fauna or disturb the character of the area.

LZ2: Moderate ambient lighting—Areas of human activity where the vision of human residents and users is adapted to moderate light levels. Lighting may typically be used for safety, security, or convenience but is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.

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

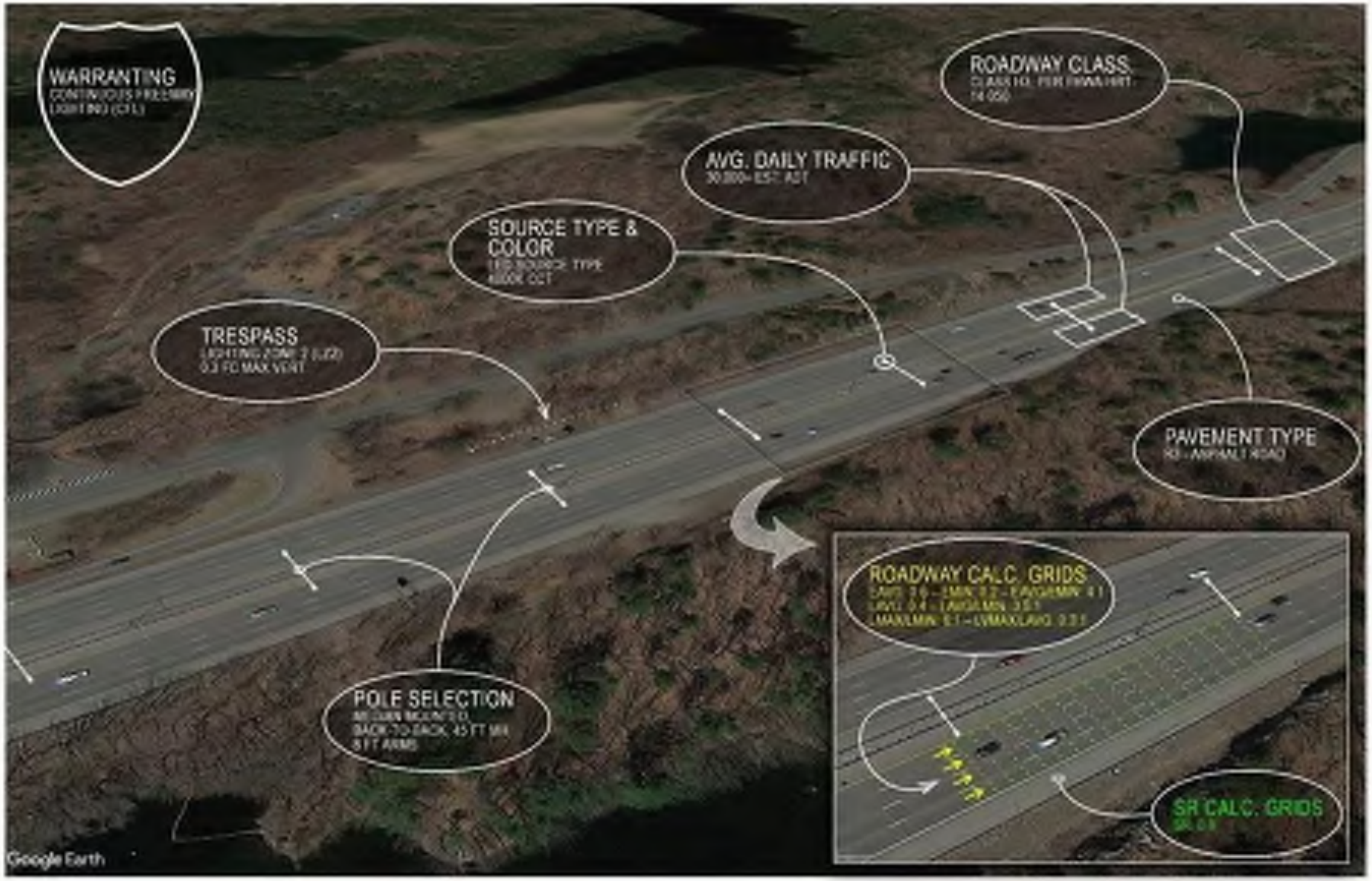
LZ4: High ambient lighting—Areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security, or convenience and is mostly uniform or continuous, or both. After curfew, lighting may be reduced in some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

Step 4b - Determine mitigation of sky glow and trespass

Example Result: Maximum Illuminance 0.3 fc

Table 11-1. Maximum Values of Lighting Zones

Lighting Zone LZ0	Lighting Zone LZ1	Lighting Zone LZ2	Lighting Zone LZ3	Lighting Zone LZ4
0.05 fc (0.5 lux)	0.1 fc (1.0 lux)	0.3 fc (3.0 lux)	0.8 fc (8.0 lux)	1.5 fc (15.0 lux)


WARRANTING
SOURCE TYPE &
COLOR
AVG. DAILY TRAFFIC
ROADWAY CLASS.
TRESPASS
PAVEMENT TYPE
POLE SELECTION
ROADWAY CALC. GRIDS
SR CALC. GRIDS
Google Earth


WARRANTING
SOURCE TYPE & COLOR
CHAPTER 2 & 3
LIGHT LEVELS
REF. GL-7
LIGHTING ZONE
REF. GL-7
CHAPTER 11
ROADWAY CLASS.
AVG. DAILY TRAFFIC
PAVEMENT TYPE
POLE PLACEMENT
TRESPASS
REF. GL-7 & SSL GUIDE
CHAPTER 11
SURROUND RATIO
SIDEWALKS
REF. SSL GUIDE
Google Earth


WARRANTING
ROADWAY CLASS
AVG. DAILY TRAFFIC
SOURCE TYPE &
COLOR
TRESPASS
PAVEMENT TYPE
POLE SELECTION
ROADWAY CALC. GRIDS
SIDEWALK GRIDS
Google Earth

Tunnels and Underpasses

Key Issues for LED in Tunnels

- Use an adaptive control system with luminance sensors outside the tunnel for better control of required threshold and transition zone lighting.
- Evaluate source CCT and potential benefits.
- Evaluate tunnel luminaires and operating characteristics relating to temperature and expected environment of the installed luminaires.

Lpsation

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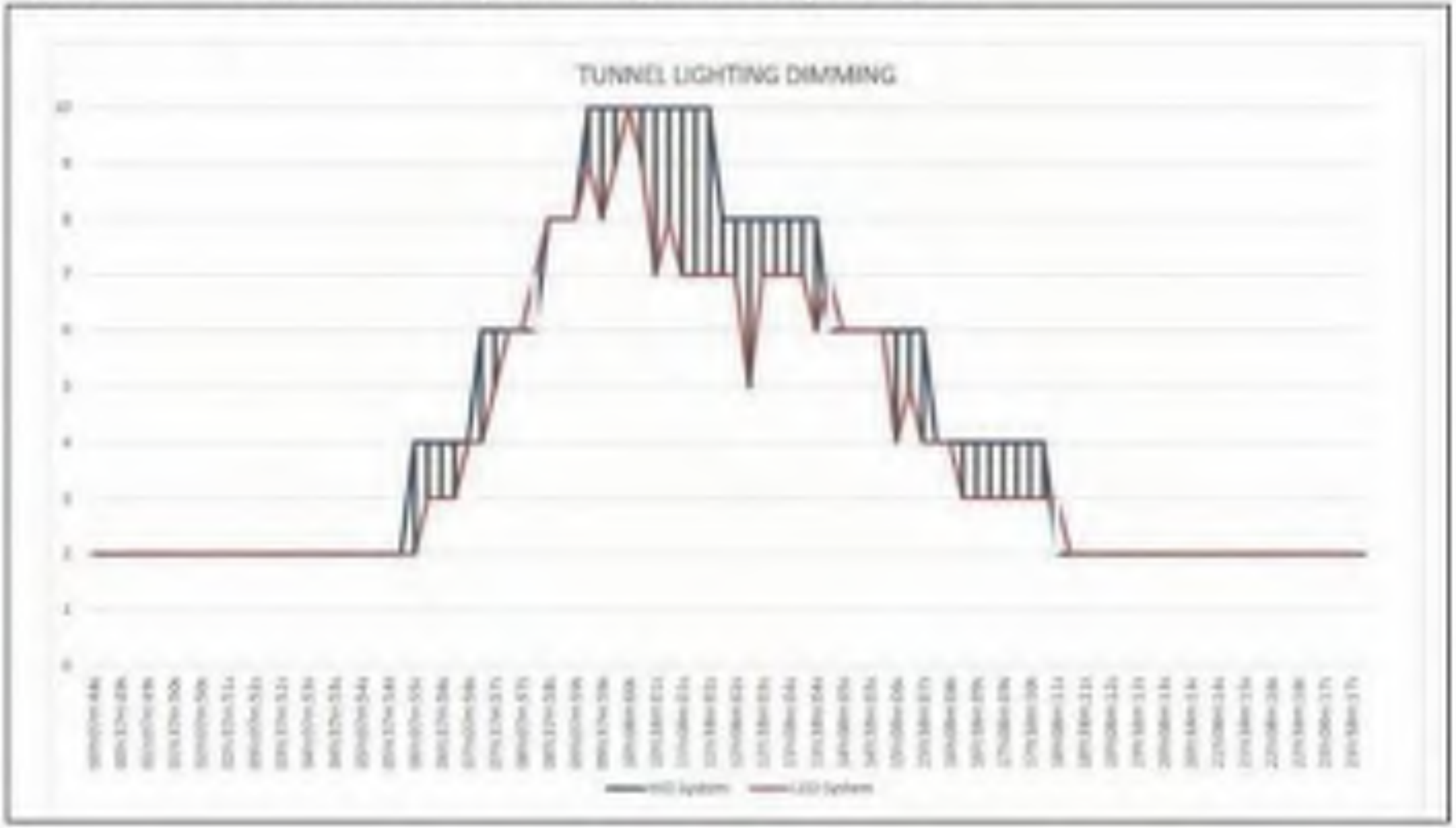
Controls

Figure 26. Differences in Step Switching vs an Adaptive System



Work Zone and Temporary Lighting

Key Issues for Work Zone Lighting with LED Light Fixtures

- Base work zone lighting on the ambient environment in which it is used and illuminate the roadway in the work zone to AASHTO lighting requirements.
- Limit glare in work zones by proper selection of equipment and its use. Use the glare limits included in this document to assess when work zone glare would become an issue.

Work Zone Lighting Plan modified from ATSSA

1. Identify work zone and tasks
2. Measure ambient illuminance level
3. Select types of luminaires
4. Select illuminance level
5. Check light tower orientation
6. Perform horizontal illuminance level check
7. Perform objective glare measurement
8. Check design for adequacy
9. Perform field check and maintenance

Horizontal Light Levels in Work Zones – NCHRP 498

Category	Recommended for
[redacted]	

Category II 108 lx (10-foot candles)	• Illumination on and around construction equipment
	• Visual tasks associated
	    • equipment
	    • resurfacing

[redacted]	

Common Portable Light Tower Types

Metal Halide

- Widely Used
- Can be aimed
- Offers excellent visibility
- Could cause glare if aimed poorly

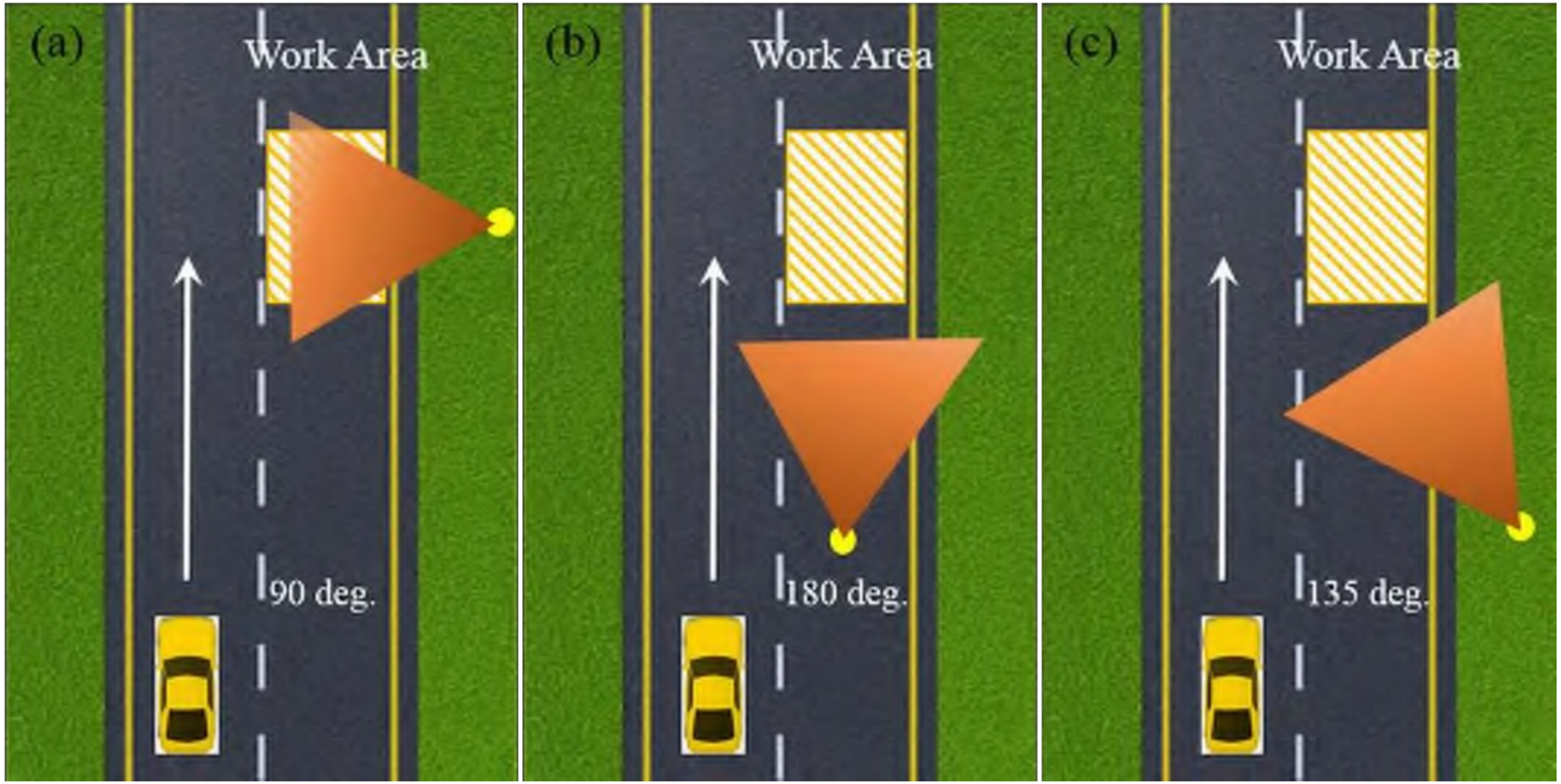
Light Emitting Diode

- New
- Can be aimed
- Potential to dim
- Could illuminate without light trespass
- Lowest glare
- Visibility lower than metal halide and balloon

Balloon

- New
- Aiming is not required
- Potential for lower glare
- Offers excellent visibility
- Could be susceptible to wind

Portable Light Towers Orientation



Mounting Heights

- Light Towers that cannot be aimed – Balloon Light Towers
  - At least 20 ft.
  - At distance of 10 ft. from roadway (in the shoulder or beyond the guardrail)
  - Increase offset distance if light output greater than 440000 lumens
- Light Towers that can be aimed
  - At least 20 ft.
  - Angle between beam axis and vertical is less than 30 degrees