Learning Objectives

- Basic lighting metrics important in the outdoor space.
  - LCS, Photometric Report, Roadway classifications
- Discuss lighting factors that impact human vision.
  - Spectral Power Distribution, CRI, Color
- Understand BUG ratings and prior IES cutoff system.
- Reference IES Recommended Practices covering roadway lighting.
  - RP-8, Required Illuminance, Average/Minimumu recommendations, Veiling Luminance
- Apply key IES lighting calculation factors unique to LED luminaires.
  - Lumen Maintenance, TM-21
- Standards organizations
- Discuss LED street lighting specification considerations
Lighting Fundamentals
Designing for Roadway

Design goal

- Produce quick visibility
- Accurate visibility at night
- Comfortable visibility at night.

- **Quality visible lighting can:**
  - Safeguard, facilitate, and encourage vehicular & pedestrian traffic.
  - Reduce Accidents
  - Facilitate traffic flow, and provide security.

- **Economic/social benefits include...**
  - Reduction in night accidents
  - Aid to police protection
  - Facilitation of traffic flow
  - Promotion of business
Color Temperature

Heating a “black-body”

http://micro.magnet.fsu.edu/optics/lightandcolor/colortemp.html
2007 research proves new type of ganglion cell
ipRGC’s - intrinsically photosensitive retinal ganglion cells

The human eye hasn’t changed.... Just the sources that trigger a response!
Visual Processing

- Photoreceptors of the retina absorb the incident photons of light and convert them into electrical and electro-chemical signals. These signals are processed in the retina and then transmitted to the visual cortex of the brain.
  - 120 Million Rods serve as night retina. (Rod = Scotopic/night vision). High sensitivity to light, but an inability to see detail in color.
  - 8 million cones serve as day retina. (cone = photopic/day vision). Ability to see fine detail and color. (strongly concentrated in the fovea). When cones are operating, visual acuity, contrast sensitivity, color discrimination are at maximum on-axis.
Adaptation

Typical ambient light levels

Photopic luminance (log cd m\(^2\))

Visual function

No colour vision, poor acuity

Good colour vision, good acuity
The human eye can see under full moonlight (0.01 fc) and under bright noon daylight (10,000 fc)

Changes in daylight 1000:1 can be adapted to in less than a second. But adapting from bright sunlight to darkened theater can take as long as 30 minutes.

When cones are operating, visual acuity, contrast sensitivity, color discrimination, etc. are at a maximum on-axis.
Light Source Spectrum

[Graph showing the spectrum of LED and Fluorescent light sources with an integrating sphere image on the right side.]
LED Basics
**Light Emitting Diode**

An LED consists of a single p-n semiconductor junction. Through a process known as **doping**, the n-type material is negatively charged and the p-type material is positively charged. Atoms in n-type material have extra electrons, atoms in p-type material have electron holes. Applying a current to the diode pushes atoms (n-type and p-type) towards the **junction**. N-type atoms donate extra electrons. A negative charge is applied to the n-type side allowing current to flow. When the electrons in the n-type material fall into the holes of the p-type material they release energy in the form of photons (electromagnetic radiation).
Basic structure of Illuminator type LED (surface mount LED)

- Semiconductor chip (die), contacts to apply power, bond wire connecting contacts to die, a heat sync, and lens.

The LED Package provides:

- Protection for the LED die from the outside environment
- Conductive path to carry heat away from the LED die
- Refractive index matching from the LED die to air

Courtesy of Cree
Various phosphors are used to create CCT. Phosphor White Method (remote phosphor).

LED using InGaN (Indium gallium Nitrade) – can handle necessary levels of current, heat, and humidity.
Luminaire Implications
Five key items

- light
- color rendering
- life
- color
- thermal
Photometric Report

**Full Cutoff**

**Medium, Type 2**

**BUG rating**

**LCS values**
Old IES Cutoff System

Increasing concerns from municipalities regarding nuisance light. Increasing need for system which provides more comprehensive data.
Luminaire Classification System

TM-15

- Ten zones / lumen count
# BUG Rating

## Table A-1: Backlight Ratings (maximum zonal lumens)

<table>
<thead>
<tr>
<th>Secondary Solid Angle</th>
<th>B0</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH</td>
<td>110</td>
<td>500</td>
<td>1000</td>
<td>2500</td>
<td>5000</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>BM</td>
<td>220</td>
<td>1000</td>
<td>2500</td>
<td>5000</td>
<td>8500</td>
<td>&gt;8500</td>
</tr>
<tr>
<td>BL</td>
<td>110</td>
<td>500</td>
<td>1000</td>
<td>2500</td>
<td>5000</td>
<td>&gt;5000</td>
</tr>
</tbody>
</table>

## Table A-2: Uplight Ratings (maximum zonal lumens)

<table>
<thead>
<tr>
<th>Secondary Solid Angle</th>
<th>U0</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>U4</th>
<th>U5</th>
</tr>
</thead>
<tbody>
<tr>
<td>UH</td>
<td>0</td>
<td>10</td>
<td>100</td>
<td>500</td>
<td>1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>UL</td>
<td>0</td>
<td>10</td>
<td>100</td>
<td>500</td>
<td>1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>FVH</td>
<td>10</td>
<td>75</td>
<td>150</td>
<td>&gt;150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BVH</td>
<td>10</td>
<td>75</td>
<td>150</td>
<td>&gt;150</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Table A-3: Glare Ratings (maximum zonal lumens)

### Glare Rating for Asymmetrical Luminaire Types (Type I, Type II, Type III, Type IV)

<table>
<thead>
<tr>
<th>Secondary Solid Angle</th>
<th>G0</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVH</td>
<td>10</td>
<td>250</td>
<td>375</td>
<td>500</td>
<td>750</td>
<td>&gt;750</td>
</tr>
<tr>
<td>BVH</td>
<td>10</td>
<td>250</td>
<td>375</td>
<td>500</td>
<td>750</td>
<td>&gt;750</td>
</tr>
<tr>
<td>FH</td>
<td>660</td>
<td>1800</td>
<td>5000</td>
<td>7500</td>
<td>12000</td>
<td>&gt;12000</td>
</tr>
<tr>
<td>BH</td>
<td>110</td>
<td>500</td>
<td>1000</td>
<td>2500</td>
<td>5000</td>
<td>&gt;5000</td>
</tr>
</tbody>
</table>

### Glare Rating for Quadrilateral Symmetrical Luminaire Types (Type V, Type V Square)

<table>
<thead>
<tr>
<th>Secondary Solid Angle</th>
<th>G0</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVH</td>
<td>10</td>
<td>250</td>
<td>375</td>
<td>500</td>
<td>750</td>
<td>&gt;750</td>
</tr>
<tr>
<td>BVH</td>
<td>10</td>
<td>250</td>
<td>375</td>
<td>500</td>
<td>750</td>
<td>&gt;750</td>
</tr>
<tr>
<td>FH</td>
<td>660</td>
<td>1800</td>
<td>5000</td>
<td>7500</td>
<td>12000</td>
<td>&gt;12000</td>
</tr>
<tr>
<td>BH</td>
<td>660</td>
<td>1800</td>
<td>5000</td>
<td>7500</td>
<td>12000</td>
<td>&gt;12000</td>
</tr>
</tbody>
</table>
Roadway Classification

Reference: IES Handbook
Life Implications

- Definition of life
  - **Parametric** vs. catastrophic
  - Designated Lxx
    - L70 normally

- Three “T’s”
  - **Threshold**
  - **Time**
  - **Temperature**
Life Implications

- Ambient and internal operating temperatures and drive currents have significant effect on the lumen maintenance of LED light sources integrated into the fixtures, but so many features of LED lighting fixtures themselves including lensing, quality of components, and thermal design.

- Power surges, static discharge, vibration, and moisture infiltration can also have a significant effect.
LM-79 Photometrics

- Provides Luminaire
  - Lumens
  - Distribution
  - Efficiency
  - CCT / CRI
  - Watts

- Combines lamp & luminaire info!

IESNA LM-79-08
LM-80 Lumen Maintenance

- LM80 provides
  - First 6000 hrs of LED life
  - Measured each 1000hr
    - Lumens, CCT
  - Three temperatures
    - 55C, 85C, Select
  - At specific drive current(s)

- Does not provide
  - Data past 6000hrs
  - Projections of life

- Will be covered in TM21

IESNA LM-80-08
TM-21 Life Estimation

- TM-21 provides
  - Consistent method to predict life
  - Based on LM-80 data
    - At specific temperatures (55, 85, ?)
  - Two numbers to look for...
    - **Reported** - eg L70 (6k) > 36khrs
      - “Capped” at less than 6x test
    - **Projected** – eg L70(6k) = 130khrs
      - No “cap” on hours

IESNA TM-21-11
Recommended Practice
IESNA Recommended Practice

RP-08-00 Roadway Lighting
- Covers Street lighting applications
- **Average** Footcandles and **Av / Mn**
- New edition – luminance preferred
- Varies by pedestrian conflict and interchange size
RP-8 Streets and Roadways

Illuminance

Table 2: Illuminance Method - Recommended Values

<table>
<thead>
<tr>
<th>Road and Pedestrian Conflict Area</th>
<th>Pavement Classification (Minimum Maintained Average Values)</th>
<th>Uniformity Ratio</th>
<th>Veiling Luminance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>Pedestrian Conflict Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeway Class A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeway Class B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expressway</td>
<td>High</td>
<td>10.0/1.0</td>
<td>14.0/1.4</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>8.0/0.8</td>
<td>12.0/1.2</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>6.0/0.6</td>
<td>9.0/0.9</td>
</tr>
<tr>
<td>Major</td>
<td>High</td>
<td>12.0/1.2</td>
<td>17.0/1.7</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>9.0/0.9</td>
<td>13.0/1.3</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>6.0/0.6</td>
<td>9.0/0.9</td>
</tr>
<tr>
<td>Collector</td>
<td>High</td>
<td>8.0/0.8</td>
<td>12.0/1.2</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>6.0/0.6</td>
<td>9.0/0.9</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>4.0/0.4</td>
<td>6.0/0.6</td>
</tr>
<tr>
<td>Local</td>
<td>High</td>
<td>6.0/0.6</td>
<td>9.0/0.9</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>5.0/0.5</td>
<td>7.0/0.7</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>3.0/0.3</td>
<td>4.0/0.4</td>
</tr>
</tbody>
</table>

(Refer to Section 3.6 for Intersection Lighting)
Lighting Calculation

\[ E = \frac{F \times N \times Lm \times LF \times CU}{Area} \]

- \( E \) = Required Footcandles
- \( F \) = Total Number of Fixtures
- \( N \) = Lamps per Fixture
- \( Lm \) = Lumens per Lamp
- \( LF \) = Loss Factors (LAT & LLD)
- \( CU \) = Coefficient of Utilization
- \( Area \) = Area of Space
Computer Simulations
Maintenance Factors

- **Recoverable**
  - Light that can be recovered through lamp changes or properly planned maintenance.
    - LLD: Lamp Lumen Depreciation
    - LDD: Luminaire Dirt Depreciation

- **Unrecoverable**
  - Factors that are inherent to the design of the fixture or the characteristics of the space.
    - LAT: Luminaire Ambient Temperature

- RP-8-00 - Annex A
LED Lumen Maintenance

Lumen Maintenance curves define LED life. And this varies with temperature.
Luminaire Ambient Temperature

All figures on this graph are for illustration purposes only.
Nighttime Temperatures

But average of the nightly minimum is NOT the same as nightly average!

http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl
Overall Lighting Factor

Choose either **Time** or **Threshold** at which maintenance will occur and the **Temperature** of the installation. These will determine both **LLD** and **LAT** for any luminaire.

\[ LF = LLD \times LAT \]
Light Loss Factors

- Required documents
  - NAVLAP or Caliper LM-79 Test Report
  - NAVLAP or Caliper IES photometric file
  - LM-80 (LED manufacturer)
  - Manufacturer’s documented lumen depreciation factor based on expected operating hours at average nighttime ambient operating temperature, utilizing the IESNA TM-21 calculation method
Light Loss Factors

- **Calculation Method**
  - Lamp Lumen Depreciation (LLD) = Manufacturer’s documented lumen depreciation factor at expected system operating hours at ambient operating temperature in degrees centigrade.
  - Luminaire Dirt Depreciation (LDD) = 0.90 (or whatever is deemed appropriate based on your maintenance practices)
  - Calculation: LLD X LDD = LLF
  - Pass/Fail based on compliance with application-specific photometric criteria
Elements of a Good LED Performance Spec

- Clearly defined and stated application space “typicals” by HPS rating
  - Roadway width, number of lanes, median width
  - Pole spacing, position (same side, opposite, staggered), height, setback, and luminaire arm length
Elements of a Good LED Performance Spec

- Clearly defined lighting criteria
  - Roadway classification
  - Pavement type
  - Level of pedestrian conflict
  - Illuminance or luminance criteria and uniformity requirements if other than IESNA RP-08
  - LLF defined based on threshold, time and temp
Elements of a Good LED Performance Spec

- Clearly defined application space & lighting criteria

58' roadway, 4 lane, 35' mounting height, 6' mounting arm, 3' setback, 150' spacing. Minimum average 1.3 fc, minimum average to minimum 3:1 uniformity.

<table>
<thead>
<tr>
<th>Plan View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale 1&quot; = 80&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STATISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
</tr>
<tr>
<td>Symbol</td>
</tr>
<tr>
<td>Avg</td>
</tr>
<tr>
<td>ATB0 30B E10 R2</td>
</tr>
<tr>
<td>ATB2 60B E53 R2</td>
</tr>
</tbody>
</table>
Elements of a Good LED Performance Spec

- Objective photometric analysis
  - AGI32 or Visual modeling of HPS typical application spaces to verify and validate equivalency
  - Utilize actual TM-21 calculated lumen depreciation data at specified operating hours and ambient temperature, rather than an arbitrary “across the board” approach
Elements of a Good LED Performance Spec

- Performance based rather than prescriptive
  - Designed to meet the lighting criteria
  - Designed to achieve maintained performance for the specified system life in operating hours and at the specified ambient temperature
  - Shouldn’t focus on things like driver currents and number of LED’s, or other arbitrary attributes
Economic Highlights
Operational Costs: 400W MH

**Energy Costs**

- **Assumptions**
  - 460W input power
  - $0.15/kWh
  - 365 days/yr @ 12hr/day

- **ENERGY COST per year**
  - 2,015 kWh consumed

**$302/fixture annually**

**Maintenance Costs**

- **Lamps changed 2x in 10yrs**
  - $20 lamp + $150 labor → $340

- **Ballast & Photocell changed 1x in 10yrs**
  - $80 ballast + $20 photocell
    - + $150 labor → $250

**$59/fixture annually**

**$361 Annual Operational Costs Per Fixture**
Operational Costs: LED Equivalent

**Energy Costs**

- **Assumptions**
  - 219W input power
  - $0.15/kWh
  - 365 days/yr @ 12hr/day

- **ENERGY COST per year**
  - 959 kWh consumed

  \[
  \text{ENERGY COST per year} = 959 \times 0.15 = 143.85 \\
  \text{Total Energy Cost} = 143.85 \times 12 = 1726.2 \\
  \text{Energy Cost per year} = 1726.2 / 12 = 144.68
  \]

- **Maintenance Costs**

  - No Lamp changes in 10yrs
  - No Ballast changes in 10yrs
  - Photocell changed 1x in 10yrs
    - $20 Photocell + $150 labor $\rightarrow$ $170

  \[
  \text{Total Maintenance Cost} = 144 + 17 = 161
  \]

**$161 Annual Operational Costs Per Fixture**
# Operational Costs: LED vs. 400W MH

## Annual Costs

<table>
<thead>
<tr>
<th>Annual Costs</th>
<th>400W MH</th>
<th>219W LED</th>
<th>Savings</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$302</td>
<td>$144</td>
<td>($158)</td>
<td>-52%</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$59</td>
<td>$17</td>
<td>($42)</td>
<td>-71%</td>
</tr>
<tr>
<td>Total per Fixture</td>
<td>$361</td>
<td>$161</td>
<td>($200)</td>
<td>-55%</td>
</tr>
</tbody>
</table>

$200 Annual **SAVINGS** Per Fixture
Future of Lighting
LED – Efficacy Plateau

Figure 5.4: White Light LED Package Efficacy Targets, Laboratory and Commercial

Notes:
1. Cool White: CRI 70-80; CCT 4746-7040 K
2. Warm White: CRI 80-90; CCT 2580-3710 K
3. Current density: 35A/cm²
4. These results are at 25°C package temperature, not steady state operating temperature. Thermal sensitivity will reduce efficacies by 24% or so in normal operation, depending on luminaire thermal management.
Figure 3.6: Price-Efficacy tradeoff for LED Packages at 35 A/cm²

Note:
1. Cool white packages assume CCT=4746-7040K and CRI=70-80; warm white packages assume CCT=2580-3710K and CRI=80-90.
2. Ellipses represent the approximate mean and standard deviation of each distribution.
3. The revised MYPP projections have been included to demonstrate anticipated future trends.
Standards Organizations
Standards

- IESNA
  - RP-08
  - LM79, LM80, TM15, TM21, etc.
- DOE
  - Caliper and NAVLAP accredited labs
  - DOE Lighting Facts Program
  - Municipal Solid State Lighting Consortium
- Design Lights Consortium
  - Qualified Products List
  - Required by SCE
GREAT EXPECTATIONS