Evaluating and Comparing LED and Traditional Luminaires: A Technology-Neutral Approach

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sponsored by
ASSIST

www.lrc.rpi.edu/programs/solidstate/assist

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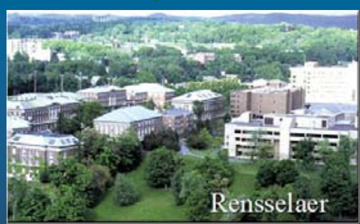
Rensselaer's Lighting Research Center

- Rensselaer is the oldest engineering university in the United States.
- LRC is the largest university-based center for lighting research and education.
- Established in 1988
- **LRC Mission:** Advancing the effective use of light, creating a positive legacy for society and the environment



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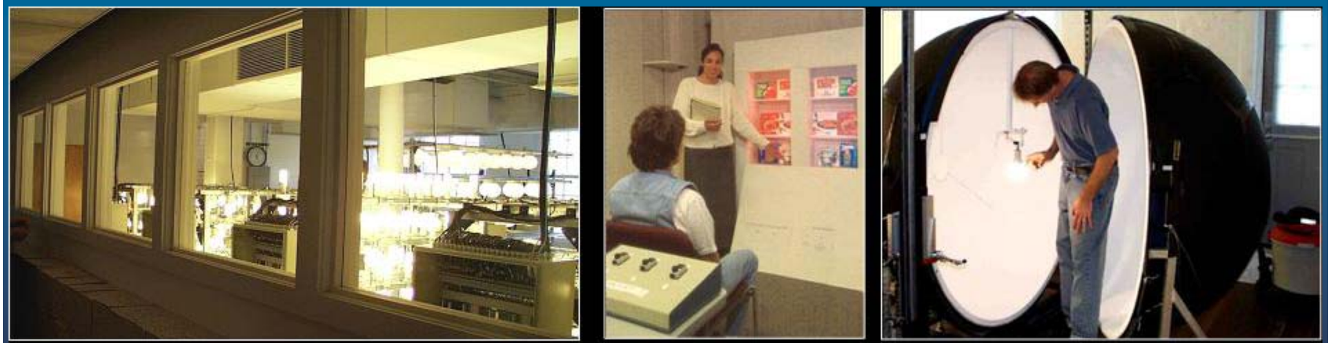
LRC Facilities

- 30,000 square feet of research space
- Well-equipped laboratories
- NVLAP accredited testing facility



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LRC Research Programs

Solid-State Lighting

Light and Health

Transportation Lighting

Lighting Metrics

Education
Ph.D
M.S.
Outreach Education

Daylight Dividends

National Lighting Product Information Program

DELTA

Market Transformation

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Lighting

- Presently, there are many light sources available to cater to lighting needs
  - Incandescent
  - Fluorescent
  - HID
  - LED

- What do end-users care about?
  - Good-quality lighting
  - Reliable technology
  - Cost effective (low energy and maintenance cost)
  - Easy to buy and replace if needed
- Metrics have to be technology-neutral

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LED

- LEDs – Will soon be one of the light source choices for illumination applications.
- The potential for reduced energy use and lower maintenance costs are two key attributes of this rapidly evolving technology that have generated so much interest for its use.
- Rapid improvements and a growing interest in white LEDs have prompted luminaire manufacturers to enter this growing lighting market.
- Several manufacturers are now selling LED-based luminaires for general illumination to compete with traditional lighting, most notably recessed downlights.

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Current Standards

- Performance specifications used in the lighting industry assume the performance of the lamp (or lamp-ballast combination), tested under an ideal environment, as the performance of the luminaire in any environment.
- This assumption is not correct because light sources perform differently inside luminaires; their performance changes depending on the application conditions.
  - Heat affects LED performance in terms of light output and life.

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Need for Metrics

- Applications community interested in using LEDs
- Rapid development of LED technology
- Many commercial products for general illumination
  - Some products have exaggerated claims
  - Insufficient performance data available
- Failed applications can hurt the entire industry
- Many agencies are actively working on standards
  - Insufficient understanding of technology can lead to bad standards

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ASSIST Program History & Background

- Established: In 2002
- Goal: To support the development and widespread application of LEDs for general illumination
  - Identify and reduce the major technical hurdles currently facing solid-state lighting
- Activities: Industry collaboration, research, demonstration, and education
- Sponsors:

- Acuity Brands Lighting
- Bridgelux
- China Solid State Lighting Alliance
- Cree
- Everlight Electronics Co., Ltd.
- Federal Aviation Administration
- GE Lumination
- ITRI, Industrial Technology Research Institute
- Lighting Science Group
- Lite-On
- NeoPac Lighting
- New York State Energy Research and Development Authority
- OSRAM SYLVANIA/OSRAM Opto Semiconductors
- Permlight
- Philips Color Kinetics
- The Lighting Association - UK
- Seoul Semiconductor
- United States Environmental Protection Agency
- USG
- WAC Lighting

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ASSIST recommends

- Standards-setting organizations such as ANSI, IESNA, NEMA, UL, CIE, ... and others have been working on developing standards for the LED industry.
- On behalf of ASSIST, LRC is conducting research to develop information that can be useful for manufacturers, end-users and others involved in developing standards. The results are used to create recommendations for testing and application.
- On behalf of ASSIST, LRC has developed a publication program called ***ASSIST recommends*** to provide a set of formal recommendations to the LED and lighting communities about issues important for the reliable performance of LED lighting and its comparison to other light source technologies.
  - This information is useful for manufacturers, end-users and others involved in developing standards.
- ***ASSIST recommends*** are the basis for some of the industry standards.
  - IESNA LM 80 (LED lumen maintenance) – published 2008
  - IESNA LM XX (LED light Engines) – in progress

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ASSIST recommends

- Recommendations for testing and evaluation
  - LED life for general illumination applications – Published 2005
  - Directional lighting luminaires – Published 2007
  - Under-cabinet lighting luminaires – Published 2007
  - LED light engines – Published 2008
  - Freezer case lighting luminaires – Published 2008
  - Outdoor lighting luminaires – Published 2009
- Can be downloaded from http://www.lrc.rpi.edu/programs/solidstate/assist/recommends.asp

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ASSIST *recommends*

Recommendations for Testing and Evaluating Luminaires Used in Directional Lighting

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Directional Lighting Test Method

- Lighting specifiers use photometric data to select suitable luminaires for a given application
  - Traditionally, photometry is performed at 25°C
  - Selecting LED downlights on the basis of published photometric data could result in considerably lower light levels in the space
    - leading to disappointment
- ASSIST Proposal: Use board temperature instead of ambient temperature and measure luminaire performance in conditions similar to application environment.
- *ASSIST recommends* proposed three environmental conditions to test fixtures:
  - Open air: Here the light source and the driver have plenty of ventilation around them.
  - Semi-ventilated: Here the light source and the driver have limited ventilation around them. (similar to Non-IC)
  - Enclosed: Here the light source and the driver have almost no ventilation around them. (Similar to IC)

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Summary

- Testing lighting luminaires according to ASSIST recommends test methods:
  - Provides more useful information for selecting LED directional lighting luminaires
  - Helps differentiate between good- and poor-performing LED luminaires in terms of light output and life

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Recommendations for Testing and Evaluating LED Light Engines Used in Lighting Luminaires

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LED Industry Trend

- Manufacturers often design families of decorative luminaires.
  - Sconces, pendants, table, and floor lamps
  - These luminaires can provide a coordinated look while serving different functions
- A large number of decorative luminaires can use a common light source (LED light engine).
- Photometric testing of complete fixtures is not a feasible concept for such luminaires.

Figures from: Prescolite

Figures from: Progress Lighting

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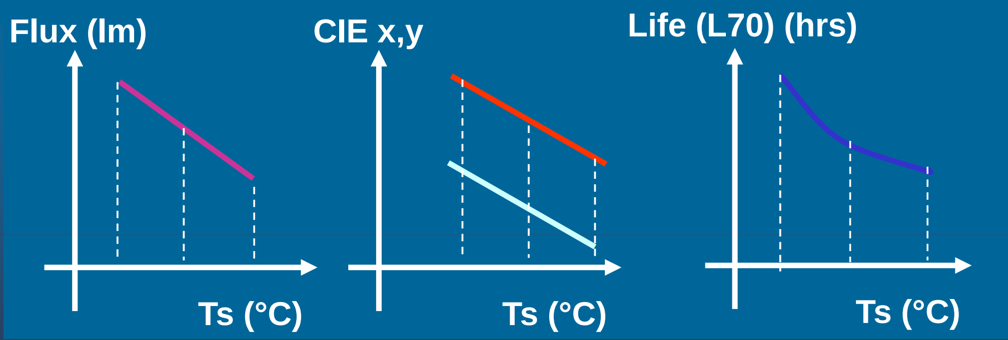
Proposed Method

- First, the LED light engine performance is measured as a function of temperature.
  - LED light engine is placed inside a thermal test chamber.
  - The heater is turned on until Ts reaches 40% (and 60% and 80%) of Tj max (specified by the LED manufacturer)
  - Photometric and electric quantities and life are measured at these three temperatures.



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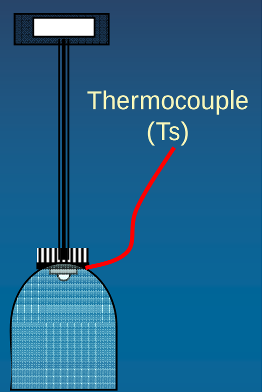
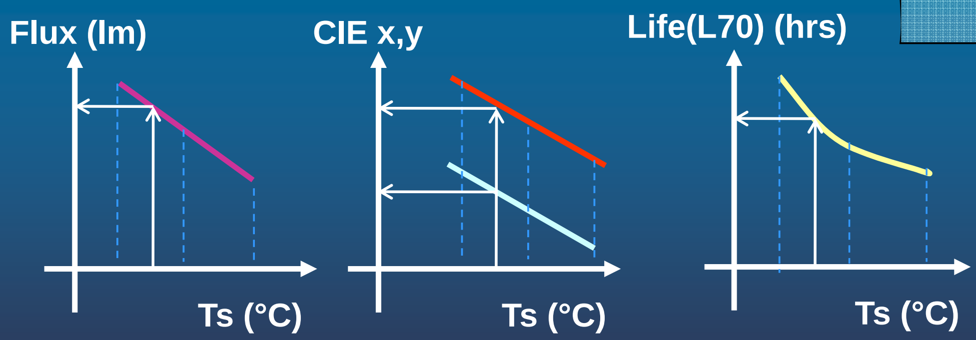
Proposed Method

Estimating light engine performance in a luminaire

- Temperature Ts is measured while the light engine is operating in a luminaire in its operating environment.
- The performance parameter is estimated from the plots generated during the engine's characterization.





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Summary

- Photometric testing of complete fixtures is not a feasible concept for decorative luminaires.
  - Light is significantly altered by the luminaire components (such as the colored cover glass)
- Developing a relationship between LED light engine performance parameters (luminous flux, efficacy, CCT, CIE x,y, and CRI) and the board temperature (Ts) is useful for estimating the performance of an LED light engine in any luminaire.

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Recommendations for Testing and Evaluating Under-cabinet Lighting Luminaires

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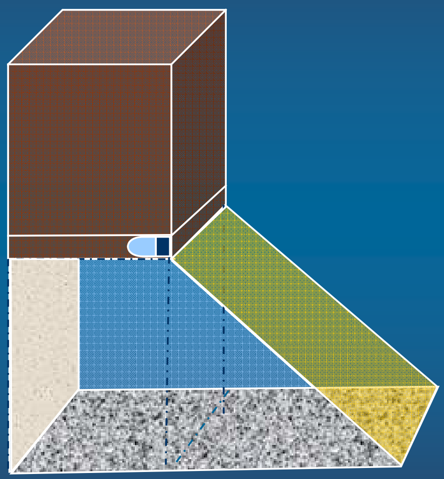
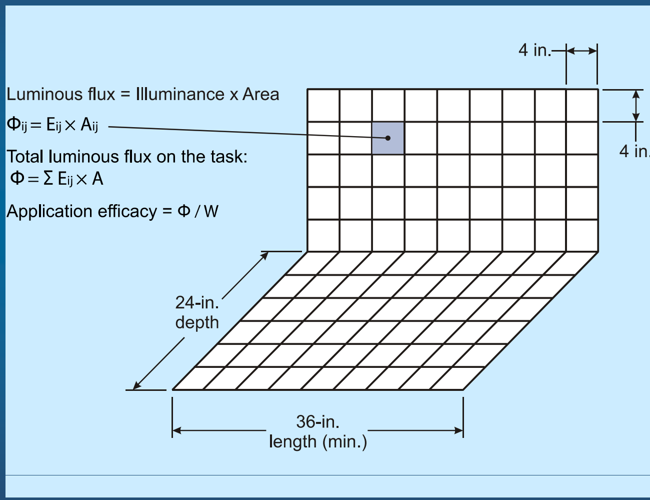
Proposed Test Method

- Light on the task area is what matters





Application efficacy = $\dfrac{\textbf{Total lumens on the task}}{\textbf{Total fixture power}}$

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Summary

- For under-cabinet fixtures
  - Application efficacy is a more meaningful metric for system comparison
  - Counts only the flux in the application area
    - Light where you need it
- Some manufacturers already provide illuminance data on the task

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Recommendations for Testing and Evaluating Outdoor Lighting Luminaires

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Objective

- To develop a method that allows users to analyze the performance of street and parking lot luminaires and select good-quality products.
- Good-quality luminaire:
  - Caters to the application's lighting needs
    - Light level, uniformity, and contrast
    - Good peripheral vision
  - Economical
    - Total cost of ownership
      - Initial material and labor cost
      - Energy cost
      - Maintenance cost
  - Other factors
    - Low glare
    - Low light pollution
    - Low light trespass

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Different Forms of Luminous Efficacy

- **Light source efficacy:** Total lumens out of the light source divided by the total input power
  - › measured in an ideal environment, 25°C ambient temperature
- **Luminaire efficacy**: Total lumens exiting the luminaire divided by the total input power
  - › measured in an ideal environment, 25°C ambient temperature
- **Task efficacy:** Total lumens reaching the task area divided by the total input power
  - › measured in the application environment
- **Application efficacy:** Total lumens reaching a task area and meeting the application lighting requirements divided by the total input power
  - › measured in the application environment

High light source efficacy does not always mean energy savings

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Proposed Method Luminaire Performance Evaluation

- Concept of application efficacy has been proposed by several researchers in the past
  - Mark S. Rea and John D. Bullough. 2001. Application efficacy. *Journal of the Illuminating Engineering Society* 30(2): 73 - 96.
  - Yutao Zhou. 2002. *Lighting Answers: MR16 Lamps*. National Lighting Product Information Program. Troy, NY: Lighting Research Center. Builds on the concept of application efficacy proposed by past researchers
- The proposed method further refined the concept of application efficacy to consider only the lumens within a defined task area that meet the lighting requirements of the application.
- A well-designed luminaire should direct most of the lumens from the light source to the task area and meet the light level requirements of the application.

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Proposed Method Luminaire Performance Evaluation

- Parameters for luminaire performance evaluation
  - Task area
    - Defined based on luminaire type
  - Illuminance on the task area
    - Horizontal pavement illuminance
      - Minimum 0.2 fc, uniformity ratio (Max/Min) smaller than 20:1
      - For enhanced security: Minimum 0.5 fc, uniformity ratio smaller than 15:1
    - Vertical illuminance
  - Total flux on the task area that meets the illuminance requirements
  - Input power to the luminaire
  - Light source spectrum

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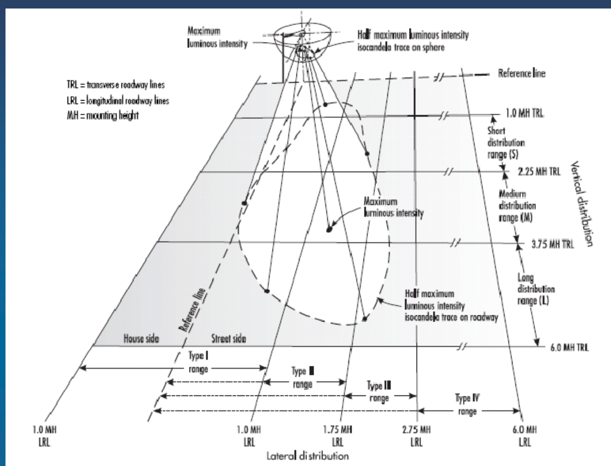
Task Areas

- Street and parking lot luminaires are categorized into several types based on light distribution.
- Typical geometry (task area) for each type of light distribution (Types I to V, and short, medium, and long distribution) on the task plane.



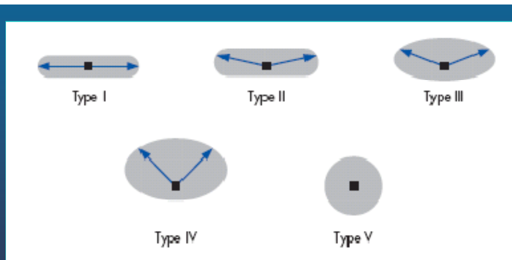


Diagram sources:

IESNA Handbook, 9th Edition

NLPIP Specifier Reports: Parking Lot and Area Luminaires

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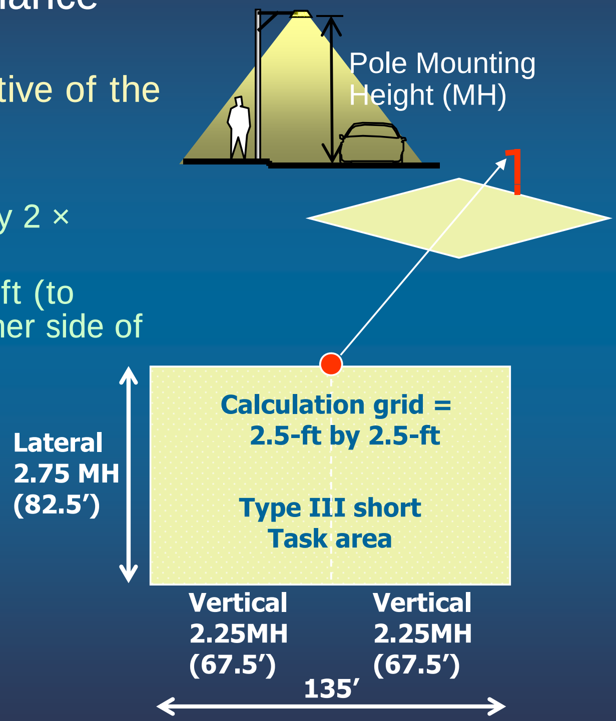
Proposed Method Luminaire Performance Evaluation

- Step 1: Set up and run illuminance calculations
  - The IES file must be representative of the fixtures used
  - Task area/geometry
    - e.g., Type III, Short: 2.75MH by 2 × 2.25MH
    - At a 30-ft MH = 82.5-ft by 135-ft (to account for contributions to either side of luminaire)



Lateral distribution	
Type I	1.0 MH
Type II	1.75 MH
Type III	2.75 MH
Type IV	6.0 MH

Vertical distribution	
Very Short	1.0 MH
Short	2.25 MH
Medium	3.75 MH
Long	6.0 MH

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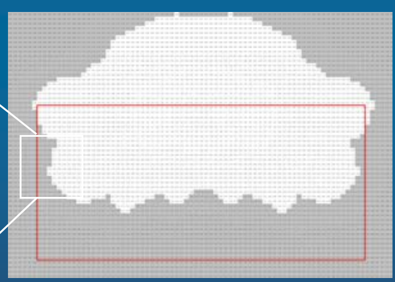
Proposed Method Luminaire Performance Evaluation

- Step 2: Determine which "grid cells" inside the application area meet the target illuminance
  - Cells that are between 0.2 fc and 4 fc (basic)
  - Cells that are between 0.5 fc and 7.5 fc (enhanced security)

5	0.17	0.20	0.22	0.23	0.24	0.26	0.27	0.29	0.31
4	0.16	0.18	0.21	0.22	0.23	0.24	0.25	0.27	0.29
3	0.15	0.17	0.19	0.20	0.21	0.22	0.24	0.25	0.27
2	0.14	0.15	0.17	0.19	0.20	0.21	0.22	0.24	0.26
1	0.12	0.14	0.16	0.17	0.19	0.21	0.23	0.26	0.28
0	0.12	0.14	0.16	0.18	0.20	0.22	0.25	0.28	0.30
1	0.12	0.14	0.17	0.19	0.21	0.24	0.26	0.29	0.32
1	0.13	0.15	0.17	0.20	0.22	0.24	0.27	0.30	0.34
2	0.13	0.15	0.17	0.20	0.23	0.25	0.28	0.31	0.34
2	0.14	0.16	0.18	0.20	0.23	0.26	0.28	0.30	0.32
2	0.14	0.16	0.18	0.20	0.23	0.25	0.27	0.29	0.31



Luminous flux = Illuminance x Area

$\Phi_{ij} = E_{ij} \times A_{ij}$

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Proposed Method Luminaire Performance Evaluation

- Step 3: Derive the lumens meeting the application requirements
  - **Application luminous flux** = Flux meeting the application criteria × percentage of cells that meet criteria
- Step 4: Calculate application efficacy
  - **Application efficacy** = Application luminous flux ÷ luminaire input power

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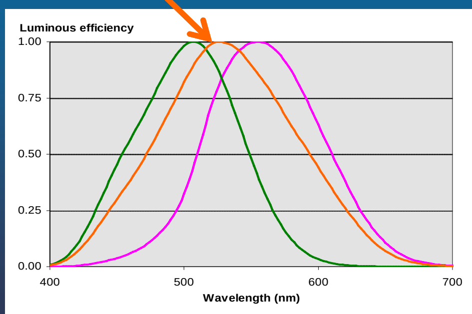
Light for the Visual System

- Visual sensitivity changes with light level and spectrum ($V\lambda$ and $V'\lambda$).
- Characterizing light source efficacy with $V\lambda$ does not account for increased visual sensitivity to short wavelengths during low light level conditions (mesopic).
  - › To address this issue, researchers have developed mathematical models to characterize light sources at any light level.

$V_{mes} = (x)\,V_{10\lambda} + (1\text{-}x)\,V'_{\lambda}$
(mesopic = cones + rods)

- The relative proportion of photopic ($V_{10\lambda}$) and scotopic (V'_{λ}) luminous efficiency for peripheral vision at a given (mesopic) light level (He et al., 1997; 1998)
  - › At high light levels, $x = 1$
  - › At very low levels, $x = 0$
- $V_{mes} = (x)\,V_{10\lambda} + (1 – x)\,V'_{\lambda}$



In this example,
x = 0,40
L = 0,22 cd/m²

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Proposed Method Visual Efficacy

by Mark Rea, John Bullough, Andrew Bierman, and Jean Paul Freyssinier

Table 2. S/P ratio of commercially available light sources.

Low pressure sodium	0.25
High pressure sodium (HPS) 250 W clear	0.63
HPS 400 W clear	0.66
HPS 400 W coated	0.66
Mercury vapor (MV) 175 W coated	1.08
MV 400 W clear	1.33
Incandescent	1.36
Halogen headlamp	1.43
Fluorescent Cool White	1.48
Metal halide (MH) 400 W coated	1.49
MH 175 W clear	1.51
MH 400 W clear	1.57
MH headlamp	1.61
Fluorescent 5000 K	1.97
White LED[1] 4300 K	2.04
Fluorescent 6500 K	2.19

The S/P ratios of phosphor converted white LEDs are bin and manufacturer specific

HPS

MH

LED

Table 3. Values of unified luminance for different base light levels and S/P ratios.

S/P	Base light level (photopic luminance (cd/m^2))										
	0.1	0.12	0.123	0.14	0.151	0.16	0.18	0.2	0.226	0.24	0.26
0.25	0.0355	0.0457	0.0476	0.0573	0.0642	0.0704	0.0849	0.1009	0.1239	0.1373	0.1574
0.35	0.0467	0.0591	0.0614	0.0728	0.0807	0.0877	0.1037	0.1209	0.1448	0.1585	0.1787
0.45	0.0568	0.0711	0.0736	0.0864	0.0950	0.1026	0.1197	0.1377	0.1623	0.1760	0.1963
0.55	0.0661	0.0818	0.0846	0.0983	0.1076	0.1156	0.1335	0.1521	0.1772	0.1911	0.2113
0.65	0.0747	0.0917	0.0946	0.1092	0.1189	0.1273	0.1459	0.1649	0.1903	0.2043	0.2245
0.75	0.0827	0.1007	0.1038	0.1191	0.1292	0.1379	0.1570	0.1764	0.2021	0.2161	0.2363
0.85	0.0902	0.1092	0.1124	0.1283	0.1387	0.1477	0.1672	0.1869	0.2128	0.2268	0.2470
0.95	0.0973	0.1170	0.1203	0.1368	0.1475	0.1566	0.1765	0.1965	0.2225	0.2365	0.2566
1.05	0.1040	0.1244	0.1279	0.1448	0.1557	0.1651	0.1853	0.2054	0.2316	0.2456	0.2656
1.15	0.1104	0.1315	0.1350	0.1523	0.1635	0.1730	0.1935	0.2138	0.2400	0.2540	0.2739
1.25	0.1164	0.1380	0.1417	0.1593	0.1707	0.1803	0.2010	0.2215	0.2477	0.2617	0.2816
1.35	0.1222	0.1444	0.1481	0.1661	0.1776	0.1873	0.2082	0.2288	0.2551	0.2691	0.2888
1.45	0.1277	0.1504	0.1542	0.1724	0.1841	0.1940	0.2150	0.2357	0.2620	0.2759	0.2956
1.55	0.1330	0.1561	0.1600	0.1785	0.1903	0.2003	0.2215	0.2422	0.2685	0.2824	0.3020
1.65	0.1381	0.1616	0.1655	0.1843	0.1963	0.2063	0.2276	0.2484	0.2747	0.2886	0.3081
1.75	0.1430	0.1669	0.1709	0.1899	0.2019	0.2120	0.2335	0.2543	0.2806	0.2944	0.3138
1.85	0.1478	0.1720	0.1760	0.1952	0.2074	0.2175	0.2391	0.2599	0.2862	0.3000	0.3193
1.95	0.1524	0.1769	0.1810	0.2003	0.2126	0.2228	0.2444	0.2653	0.2915	0.3053	0.3244
2.05	0.1568	0.1817	0.1858	0.2053	0.2176	0.2279	0.2496	0.2705	0.2967	0.3103	0.3294
2.15	0.1611	0.1862	0.1903	0.2100	0.2224	0.2327	0.2545	0.2754	0.3015	0.3152	0.3341
2.25	0.1652	0.1906	0.1948	0.2146	0.2270	0.2374	0.2592	0.2801	0.3062	0.3198	0.3387
2.35	0.1693	0.1949	0.1991	0.2190	0.2315	0.2419	0.2637	0.2847	0.3107	0.3242	0.3430
2.45	0.1732	0.1990	0.2032	0.2233	0.2358	0.2463	0.2682	0.2891	0.3150	0.3285	0.3472
2.55	0.1770	0.2030	0.2073	0.2275	0.2401	0.2505	0.2724	0.2933	0.3192	0.3326	0.3512
2.65	0.1807	0.2070	0.2112	0.2315	0.2441	0.2546	0.2765	0.2974	0.3233	0.3366	0.3551
2.75	0.1843	0.2107	0.2150	0.2354	0.2480	0.2585	0.2805	0.3014	0.3271	0.3404	0.3588

High S/P ratio allows for lowering of photopic light levels

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Mesopic Street Lighting

- Several studies have demonstrated the benefits of mesopic street lighting

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Example: Results Spectral Evaluation

Illuminance (photopic) and power requirements for HPS, MH and LED light sources needed to provide an equivalent unified luminance value of 0.190 cd/m²
Reference: 150 W HPS @ 0.66 fc (0.226 cd/m² @ 10% reflectance)

Light source (S/P ratio)	Average photopic illuminance	Avg. photopic luminance	Avg. unified luminance	Luminaire input power	Relative power (%)
150W HPS (0.65)	**0.66 fc**	**0.226 cd/m^2**	**0.190 cd/m^2**	**188 W**	**100%**
150W MH (1.55)	**0.48 fc**	**0.164 cd/m^2**	**0.205 cd/m^2**	**185 W**	**98%**
150W LED (2.15)	**0.46 fc**	**0.158 cd/m^2**	**0.230 cd/m^2**	**146 W**	**78%**

Light source (S/P ratio)	Average photopic illuminance	Avg. photopic luminance	Avg. unified luminance	Luminaire input power	Relative power (%)
150W HPS (0.65)	0.66 fc	0.226 cd/m^2	0.190 cd/m^2	188 W	100%
150W MH (1.55)	**0.44 fc**	**0.151 cd/m^2**	**0.190 cd/m^2**	**170 W**	**90%**
150W LED (2.15)	**0.36 fc**	**0.123 cd/m^2**	**0.190 cd/m^2**	**114 W**	**61%**

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Summary

- Outdoor lighting
  - Application efficacy is the total flux within the task area divided by the effective fixture power
    - Light where you need it
    - Reduced light pollution
  - Visual efficacy can further reduce power use for high S/P ratio light sources.

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Summary

- LED technology has been steadily advancing and is in the process of transforming certain markets.
- LRC's **ASSIST Program** is influencing the solid state lighting industry.

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Thank You!

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