Photometry for Traffic Engineers...

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by

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Many figures borrowed from:
http://www.intl-light.com/handbook/
(An excellent and practical resource!!!)
Basic Light Measurement

- Visible Electromagnetic Radiation (Light)
- Radiometric to Photometric Conversion
- Luminous Flux (Lumens)
- Luminous Intensity (Candela)
- Illuminance (Lux)
- Luminance (cd/m²)
# Taxonomy of Photometric Units

<table>
<thead>
<tr>
<th>Luminous Flux</th>
<th>Lumen</th>
<th>Total “effective” output of a lamp</th>
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</thead>
<tbody>
<tr>
<td><strong>Luminous Intensity</strong></td>
<td>Candela</td>
<td>Light density through space</td>
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<tr>
<td></td>
<td></td>
<td>• Vehicle headlamps</td>
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<td></td>
<td></td>
<td>• Traffic signal lamps/lenses</td>
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<tr>
<td><strong>Illuminance</strong></td>
<td>Lux</td>
<td>Light density falling upon a surface</td>
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<td></td>
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<td>• Roadway illumination</td>
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<td>• Highway sign illumination</td>
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<tr>
<td><strong>Luminance</strong></td>
<td>Candela/m²</td>
<td>Brightness of extended source/surface</td>
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<td></td>
<td></td>
<td>• Highway sign brightness/contrast</td>
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<td>• Proxy for “retroreflectivity”</td>
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</tbody>
</table>
Light Energy

• Light is visible electromagnetic radiation
• Magnitude measured in Watts (1/746 H.P.)
• Wavelength ($\lambda$): 380 to 730 nm
• Frequency: 789 down to 384 THz
CIE Spectral Luminosity Function

- The human eye is more sensitive to some visible wavelengths than others
- Measurements of light must take these effects into account
- CIE $V_\lambda$ curve corrects for the differences across wavelengths
Commission Internationale de l’Eclairage (CIE) $V_\lambda$
Radiometric to Photometric Conversion via CIE $V_\lambda$ and $V'_\lambda$

**Scotopic ($V'_\lambda$)**
- Dark Adapted
- Peak $\lambda = 507$ nm
- $K_m = 1700$ lm/W
- 2.5 X Sensitivity

**Photopic ($V_\lambda$)**
- Light Adapted
- Peak $\lambda = 555$ nm
- $K_m = 683$ lm/W
Luminous Flux
(The Lumen)
Luminous Flux

- Luminous Flux is the photometrically corrected equivalent of the Watt
- 1 Lumen = 1/683 Watts at 555 nm (peak $V_\lambda$)
- Luminous Flux in lumens is calculated as:

$$\Phi_{e,\lambda} V(\lambda) \, d\lambda$$

from 380 to 730 nm
Luminous Flux Equation Revealed

\[
\text{Lumens per Watt Conversion Factor for CIE } V_\lambda \text{ Curve}
\]

\[
\text{Lumens } = 683 \int_{380}^{730} \Phi_{e,\lambda} V(\lambda) \, d\lambda
\]

\[
\text{Integrate over Visible Spectrum}
\]

\[
\text{Radiant Energy in Watts}
\]

\[
\text{Wavelength Sampling Increment}
\]

\[
\text{CIE Spectral Luminosity Function}
\]
Step-by-Step Calculation of Luminous Flux

- Measure radiant energy (Watts) from light source at each $\lambda$ across the visible spectrum (380 - 730 nm)
- Convert Watts to Lumens via the $V_\lambda$ curve and the photopic maximum luminous efficiency constant (683 lm/W at 555 nm)
- Integrate Lumens across visible spectrum
Step 1.
Measure Radiant Energy across $\lambda$ using a Spectroradiometer

(See next slide for sample data)
Sample Data from Spectroradiometer

Radiant Flux (Watts) measured every 10 nm from 380-730 nm
Step 2. Convert Watts to Lumens

(See next slide for results)
Results of $V_\lambda$ Conversion
Step 3.
Integrate Lumens from 380-730 nm

Integration across the visible spectrum yields a Luminous Flux measurement of 2890 Lumens
Luminous Flux Equation Revisited

\[ \text{Lumens per Watt Conversion Factor for CIE } V_\lambda \text{ Curve} \]

\[ \text{Integrate over Visible Spectrum} \]

\[ \text{Radiant Energy in Watts} \]

\[ \Phi_{e,\lambda} V(\lambda) \, d\lambda \]

\[ \text{CIE Spectral Luminosity Function} \]

\[ \text{Wavelength Sampling Increment} \]

\[ \text{Lumens } = 683 \int_{380}^{730} \Phi_{e,\lambda} V(\lambda) \, d\lambda \]
Luminous Intensity
(The Candela)
Luminous Intensity

Luminous Intensity refers to the amount of luminous flux emitted into a solid angle of space in a specified direction (since many sources are not isotropic).

The SI unit of Luminous Intensity is the candela.

The candela is historically linked to “candle power” (ie., 1/683 W/sr at 555 nm).

\[
1 \text{ candela} = \frac{1 \text{ lumen}}{\text{unit solid angle}} \quad \text{steradian}
\]
Solid Angles, Surfaces of Spheres and the Steradian

Imaginary Sphere Surrounding a point source of light

Sphere Area = $4\pi r^2$

Steradian ($\omega$) = \frac{\text{Area}}{r^2}$

1 m² subtends 1 sr at a distance of 1 m…since

$\omega = \frac{A}{r^2} = \frac{1 \text{ m}^2}{1 \text{ m}^2} = 1$

Surface area of a sphere is subtended by $4\pi$ sr

$\omega = \frac{A}{r^2} = \frac{4\pi r^2}{r^2} = 4\pi$

$4\pi = 12.56$
The Candela

An isotropic light source with a luminous intensity of 1 cd is emitting a total luminous flux of approximately $4\pi$ lumens (since an isotropic source emits light into a total volume of $4\pi$ steradians).
Broadband Measurement of Luminous Intensity

- Photometer aperture subtends 0.0004 sr at 50 cm distance
  \( \omega = \text{Area} / r^2 = 1 \text{ cm}^2 / 50 \text{ cm}^2 = 0.0004 \text{ sr} \)
- Light energy in 0.0004 sr is filtered and converted to current
- Current is converted to lumens (per calibration constant)
- Lumens divided by 0.0004 sr = Candelas
  \( \text{e.g., } 0.058932 \text{ lm} / 0.0004 \text{ sr} = 147.330 \text{ lm/sr (candelas)} \)
Illuminance
(Lux)
Illuminance

The photometrically corrected light energy falling upon a given unit of surface area (e.g. lumens/m²)

1 ft² at a distance of 1 ft subtends 1 sr
(ω = 1 ft²/ 1 ft² = 1 steradian)
1 cd source emits 1 lumen into 1 sr
1 lumen per ft² = 1 foot-candle (fc)

1 m² at distance of 1 m subtends 1 steradian
1 lumen per m² = 1 lux

1 ft² = 0.0929 m²
The foot-candle contains 10.76 times more light per unit area than the lux
Inverse-Square Law

Since light from a “point source” expands outward, illuminance available to a surface decreases according to the inverse-square law.

An illuminaire can be treated as a “point source” when the viewing distance is at least 5X greater than the diameter of the light source (5-to-1 rule).
Inverse-Square Law Example

\[ E = \frac{I}{d^2} \cdot \cos(\theta) \]

where:
- \( E \) = illuminance (lux)
- \( d \) = distance (m)
- \( I \) = luminous intensity (candela)

\[ E_1 \cdot d_1^2 = E_2 \cdot d_2^2 \]

Double the distance, 
Quarter the energy

\[ E_2 = E_1 \cdot \frac{d_1^2}{d_2^2} = E_1 \cdot \frac{1}{2^2} = E_1 \cdot \frac{1}{4} \]
Cosine Law

Illuminance also decreases with the angle of incidence, as captured by the cosine law

\[ E_\theta = \cos(\theta) \times E_0 \]

where:
- \( E_\theta \) = Illuminance resulting from light incident at an angle \( \theta \) degrees from the normal
- \( E_0 \) = Illumination resulting from light incident perpendicular (normal) to the surface plane
Cosine Law Example

\[
\begin{align*}
\theta &= 0\text{-deg} \\
E_\theta &= \cos(0) \times E_0 \\
E_\theta &= 1.0 \times E_0
\end{align*}
\]

\[
\begin{align*}
\theta &= 30\text{-deg} \\
E_\theta &= \cos(30) \times E_0 \\
E_\theta &= 0.86 \times E_0
\end{align*}
\]

\[
\begin{align*}
\theta &= 60\text{-deg} \\
E_\theta &= \cos(60) \times E_0 \\
E_\theta &= 0.50 \times E_0
\end{align*}
\]

As the angle of incidence increases from 0-degrees (normal) to 90-degrees, the light density falling upon a surface drops by a factor of \(\cos(\theta)\).
Broadband Photometer
(Illumination Meter)

- Precision Aperture
- Cosine Diffuser
- CIE $V_\lambda$
- Photometric Correction Filter
- Silicon Photodetector
- Current Amplifier
- Display Lux
- Light

147.330 Lux
Cosine Diffuser Head

Precision diffusion "lens" can redirect off-axis light toward the detector while also effectively applying the cosine correction factor.
Luminance
(Candelas/m$^2$)
Luminance

Luminance is a measure of the:

• luminous flux density per beam solid angle

• areal density of luminous intensity emitted from an extended source

• luminous intensity of the projected image of an extended source per unit area of that extended source

• The SI unit of luminance is the candela per $m^2$
Luminance as Projected Luminous Intensity

Luminous intensity (cd = lm/sr)

\[ L_{cd/m^2} = \frac{dI}{dA \cdot \cos(\theta)} \]

Projected Area (m²)

Luminous Surface Area (A)
Luminance is an Abstraction

Luminance is not a source quantity nor a detector quantity; instead, it is a purely geometric quantity that describes the beam of light (areal image) connecting the source and the detector.

An optical system (e.g., eye or photometer) is needed to convert luminance into an illuminance at the detector.

Luminance is useful insofar as it correlates fairly well with the psychophysical dimensions of “brightness” and “contrast”.
Broadband Luminance Meter

- Eyepiece
- Condenser Lens
- CIE $V_\lambda$ Correction Filter
- Silicon Photodetector
- Focusing Lens
- Mirror
- Precision Aperture

- Silicon Photodetector
- Precision Aperture
- Mirror
- Focusing Lens
- CIE $V_\lambda$ Correction Filter
- Condenser Lens
- Eyepiece
Conservation of Luminance Across Viewing Geometry

- Lambert’s Law of Surface Diffusion
- Angle of Observation
- Observation Distance
Lambertian Surface Diffusion
(Another Cosine Law)

Lambertian Reflectance

\[ \cos(0) = 100\% \]
\[ \cos(30) = 87\% \]
\[ \cos(60) = 50\% \]

Lambertian Transmittance
Observation Angle

Surface area sampled through a given aperture size increases as a factor of \( \cos(\theta) \)

However, this increase in surface area is offset by the fact that the emission of light from the area being sampled decreases by the same factor of \( \cos(\theta) \)
Observation Distance

Luminance in independent of viewing distance to an extended source since the sampled area (FOV) increases with distance is a manner that cancels-out concurrent inverse-square losses.

Caveat: The extended source must completely fill the aperture of the measurement device!
Special Problems: LED Symbol Heads

How do you obtain a useful photometric field quantity to characterize LED-based symbol signs?
Light Emitting Diodes (LED’s)

What other problems do LED’s present regarding their photometric characterization?
References


• Photometry for Traffic Engineers Web Page http://www.usd.edu/~schieber/trb2000/