A Multi-Field Analysis of Street Lighting in Grand Rapids, Michigan

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Introduction

This analytical report aims to bridge the gap between peer-reviewed research and those who are making decisions on the regulation, policy and installation of outdoor dusk-to-dawn lighting. A thorough analysis of the existing evidence relevant to outdoor dusk-to-dawn lighting including that of visual performance, human health impacts, ecological impacts and evidence relating to outdoor lighting mechanics is the primary focus of this report. Additionally, commonly referenced factors in outdoor lighting will be given context by a review of their surrounding research.

An evidence-based review of documents and media relating to outdoor lighting in Grand Rapids will be presented in conjunction with a policy recommendation based on a review of the existing evidence relating to outdoor dusk-to-dawn lighting.

Contents

Review of Evidence

Terminology and Metrics

Light source intensity and surface luminance

- Luminance is an important factor in quantifying light as it captures light levels that are perceived by the retina of a viewer's eye. Surface luminance measured in candela per square meters (cd/m^2) has become the preferred metric for standardizing, planning and testing outdoor dusk-to-dawn lighting.[5][6][49][50]
- Luminance of a light source is just as important, as a high-intensity light source within the visual field directly translates to a 'hot spot' of intensity on the retina as seen in the figure below. Note that luminance must be used rather than luminous intensity to capture the output of flat-surface emitters such as LEDs.[63]
- Luminance is used in quantifying visual adaptation and discomfort glare.[7][8][49][50][51][53]

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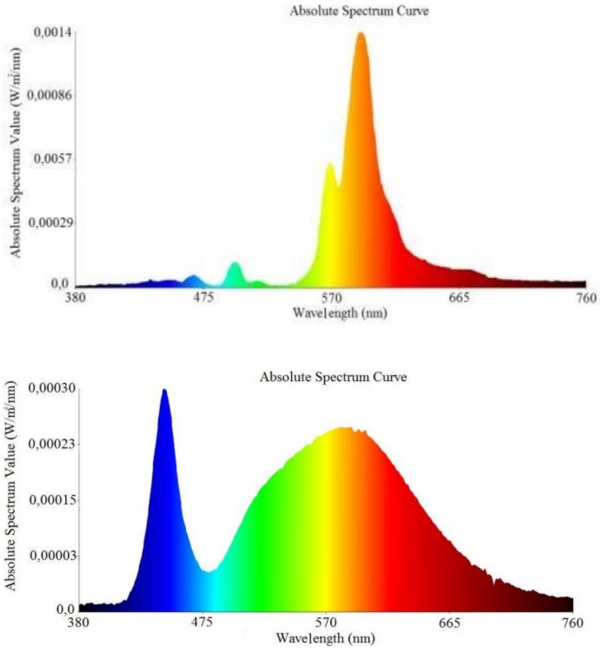
Figure 1

Light source spectral content

- Spectral content is a critical factor in dusk-to-dawn lighting and has been a primary focus of research within fields relating to roadway lighting for several decades.[5][6][50]
- This research greatly accelerated with the introduction of metal-halide and magnetic induction lamps as high efficacy sources of ‘white’ light during the 1990s.[4][50]
- Metal-vapor discharge lamps each have their own respective spectral content; yellow is dominant in sodium-based lighting while mercury-based lighting ranges from greenish-blue to a broader ‘white’ spectrum.[4]
- LED lamps are often advertised as fully customizable, but high-efficacy LEDs are inherently rich in blue light. This is due to their technological basis of blue/violet diode emissions being broadened into a ‘white’ light through the use of phosphors.[38]
- LED dusk-to-dawn lamps lose efficacy as their output is shifted towards a ‘warmer’ spectrum containing less blue light.[9][38][69]



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Figures 2 & 3
Spectrum of light sources;
HPS (top) &
LED (bottom)

Common terms and abbreviations

IES : Illuminating Engineering Society

CIE : International Commision on Illumination

AMA : American Medical Association

Cone cell : Photoreceptor that provides sharp, color vision in the center of our visual field

Rod cell : Photoreceptor that provides blurry, colorless vision beyond the center of our visual field

Photopic vision : Vision used in ‘bright’ adaptation conditions, provided by Cone cells

Scotopic vision : Vision used in ‘dark’ adaptation conditions, provided by Rod cells

Mesopic vision : Vision used in intermediate adaptation conditions, provided by a varying mix of Cone and Rod cell contributions

Dusk-to-dawn lighting : Outdoor lighting that is installed to illuminate outdoor spaces for visibility, security and perceived safety.

Metal-discharge lighting : A high-efficacy type of lighting that produces light by sending an electrical arc through a tube of vaporized metal. Common metals used include sodium and mercury.

Review of Evidence - Visual Performance

The biggest research-based driver behind the transition to LED lighting is that of mesopic vision. Metrics for the output of light sources are based on photopic vision provided by Cone cells. Research in the range of mesopic visions aims to provide adjustment factors for light source metrics by factoring in scotopic vision provided by Rod cells.[43][44]

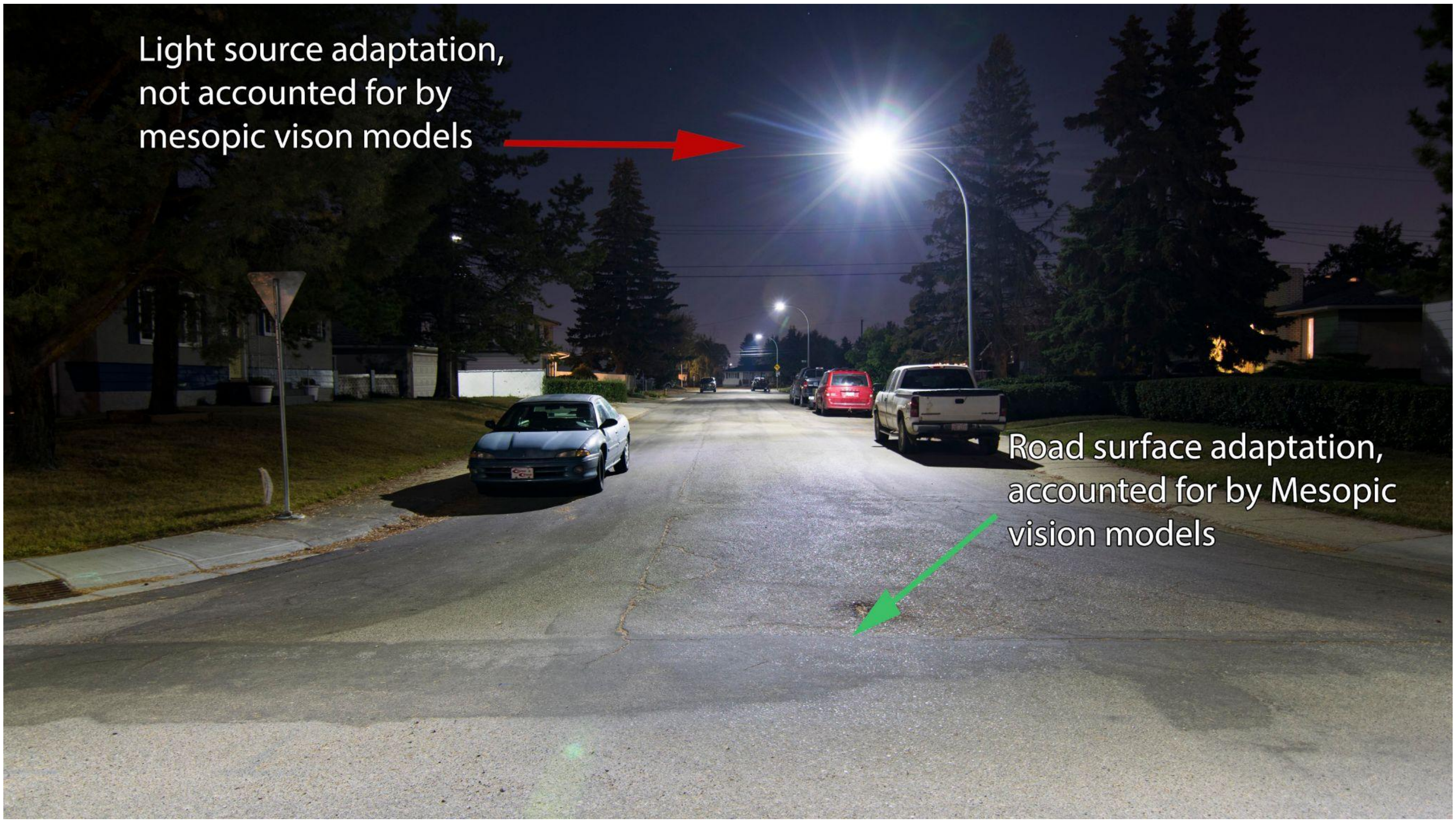
Mechanics of Cone and Rod cells in human vision

- Cone cells provide sharp (high acuity) color vision in the center of our visual field (focal vision).[45][64][65]
- Rod cells provide colorless low acuity vision and are concentrated away from the center of the retina.[45][64][65]
- Cone cells operate in ‘brighter’ conditions, while Rod cells operate in ‘darker’ conditions.[45][64][65]
- The range in which Cone and Rod cells work together is known as ‘Mesopic vision’.[43][44][64][65]
- The sensitivity and time taken to adapt to luminance levels within the visual field differs greatly between Cone cells and Rod cells.[64][65][66]
- Rod cells are taken out of their scotopic adaptation state by bright sources of light within the visual field in a process known as ‘bleaching’.[63][64][65][66]

Mesopic vision testing, modeling and implementation

- 2 Primary models of mesopic visual performance are cited in street lighting standards; The Mesopic Optimization of Visual Efficiency (MOVE) and the Unified System for Photometry.[49][50]
- The MOVE model was developed from 3 visual tasks tested in laboratories at mesopic light levels: reaction time, object detection and object identification.[49]
- The Unified System for Photometry was developed from reaction time studies done within laboratories at mesopic light levels.[50]
- In both the Unified model and the MOVE model subjects were given time to adapt to the luminance level being tested, in some cases as much as 30 minutes.[46]

While these models provide an accurate representation of mesopic visual performance in the vacuum of laboratory conditions, they cannot be applied to the real world on their own. As stated previously, subjects within these laboratory tests were not exposed to luminance levels higher than what was being tested, the highest being 10 cd/m^2. Subjects were additionally given time to adapt to these luminance levels. In the real world there is rarely an illuminated surface without a visible light source, in the case of roadway lighting there are often dozens of visible light sources within the visual field. These roadway light sources, along with other commonly encountered sources such as security lighting and vehicle headlights, significantly impact the adaptation state of human vision. Additionally, Rod cells are impacted to a greater extent and require more time to recover than Cone cells.[49][50][53][64][65][66]



^Figure 4, A representation of visual field adaptation factors. Mesopic vision models such as MOVE and the Unified model only account for the luminance level of illuminated surfaces.

Additionally worth noting is that reflective surfaces such as vehicles, as well as buildings near the streetlight fixture, will often have higher luminance levels than the roadway being illuminated. These further increase the adaptation level of the visual field.

Review of Evidence - Visual Adaptation

Mechanics of adaptation

- Adaptation luminance is the level of luminance that the eye is ‘adjusted’ to.[51]
- A study examining the adaptation effects of a light source within the visual field based on contrast threshold experiments found that a 5.4 Lux light source 7 degrees off of the visual field center was enough to increase peripheral adaptation 10-fold, from ~0.2 cd/m^2 to ~2.0 cd/m^2.[52]
- Data from a CIE study into adaptation luminance suggests a ~25% or more increase to average road surface luminance should be factored into roadway photometry to account for light source adaptation (figure 4b).[51][53]
- This study underestimates adaptation luminance however, as its measurement technique lacks the spatial accuracy to capture the true luminance of LED light sources that are easily 1-2 magnitude higher than the 10,000 cd/m^2 limit of the study’s test measurements.[53][54] (figure 5, 6)

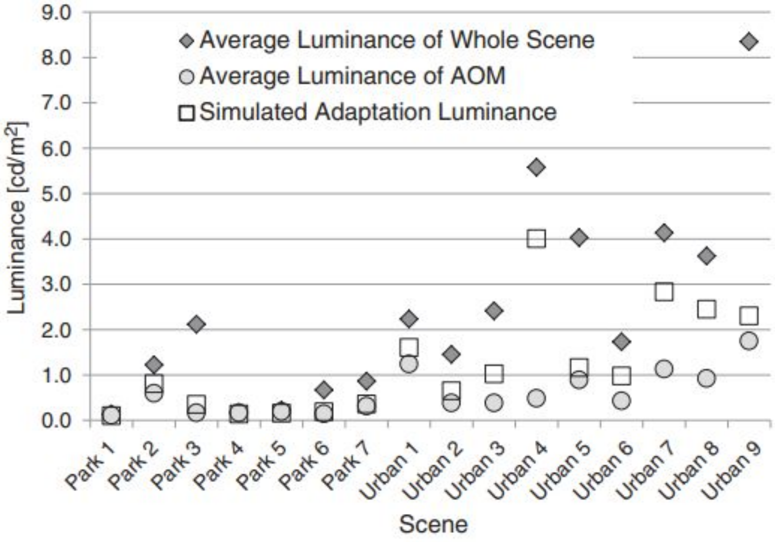


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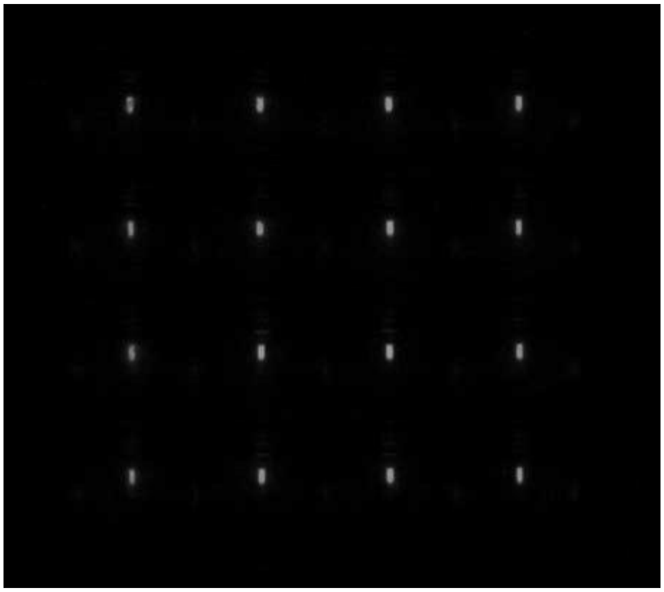
Figure 4b, calculated adaptation luminance values for simulated pedestrians

Figure 2. Luminance distribution examples: Sidewalks in urban area. Areas delineated with dashed lines are AOMs.

^Figure 5



^Figure 6

A comparison of the sample measurement images used in the CIE adaptation luminance simulation taken at a normal-wide angle, compared to a close-up measurement photo of an LED streetlight fixture taken with a telephoto lens. The reduction of the streetlight fixtures to a small pixel resolution in the measurement photos taken at a normal-wide focal length averages out their luminances, missing the true luminance of the small individual LEDs within the fixtures.[53][54]

It is additionally worth noting that the CIE adaptation luminance simulation defines an area of measurement based on the studied eye movement of a driver, with the assumption that the driver will reliably keep their vision focused within this defined area. Any deviation from this area can result in a higher-than-predicted adaptation luminance. Factoring for headlights encountered in the visual field on or near roadways will additionally raise the adaptation luminance significantly.[53]

Importance of adaptation luminance in mesopic photometry

- The basis of mesopic photometry is the Purkinje effect - the shifting of peak spectral sensitivity from yellow in the photopic range to green/blue in the scotopic range.[49][50] (figure 7)
- The theory of blue light efficiency within roadway lighting relies on the assumption that Rod cells, with their peak sensitivity in the blue-green range, are adapted and contributing to visual response in artificially lit nighttime environments.[49][50][51]
- The highest luminance value in which blue light has a spectral efficiency advantage for peripheral vision tasks during laboratory testing for mesopic vision models is 0.6 cd/m^2.[49][50]
- The lowest level of roadway lighting recommended by the IES for vehicle traffic is 0.3 cd/m^2, the highest value is 1.2 cd/m^2.[55]
- Visual adaptation to light sources on a road lit to a 0.3cd/m^2 target luminance will often bring the adaptation luminance close, if not past, the 0.6cd/m^2 threshold of blue light advantages based on Rod contributions.[51][53]

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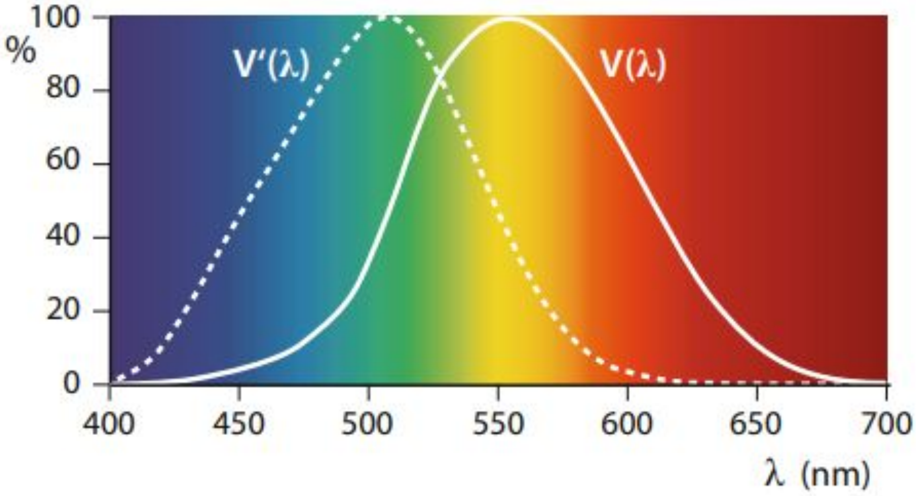
Figure 7, spectral sensitivity of scotopic vision (left curve) and spectral sensitivity of photopic vision (right curve)



Review of Evidence - Light Scattering and Glare

Glare types and definitions

- There are 2 primary types of glare that impact vision:
- Discomfort glare, a subjective sensation measured on the De Boer scale ranging from ‘barely noticeable’ to ‘physical pain’ with a lower rating representing more glare.[51][58]
- Disability glare, an objective metric of lighting that can be calculated for specific lighting scenarios.[51][58]
- Discomfort glare as its name suggests reduces the visual comfort of individuals exposed to it. Higher levels of discomfort glare (lower rating on De Boer scale) can pose a serious safety risk as they trigger glare-aversion responses. These aversion responses lead to drivers and pedestrians looking away from their visual task such as the road ahead of them to avoid glare-induced discomfort.[51][58]
- Disability glare represents the scattering of light particles within the eye, creating a physical wall of light within the eye that obstructs vision. This wall of light is known as ‘veiling luminance’.[51][58][59]

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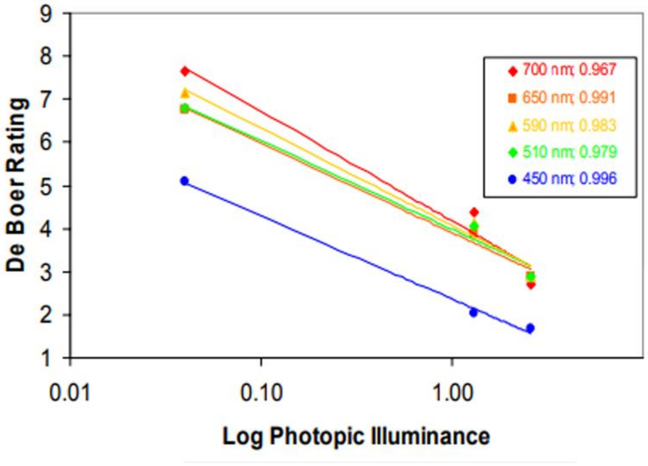
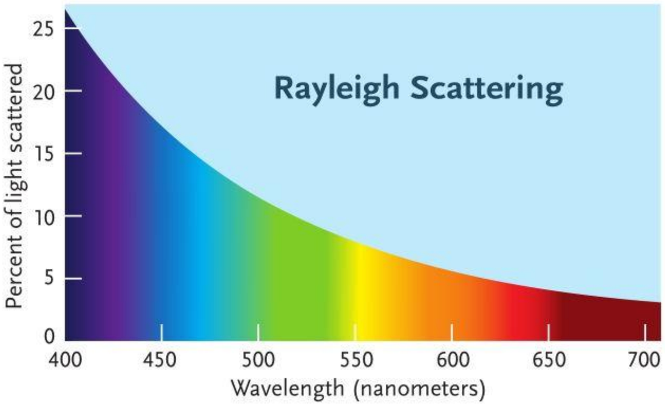
Figure 8, a visual representation of veiling luminance caused by disability glare. Note how the contrast between the pedestrian and background is reduced.

Factors in glare

- In both discomfort and disability glare the spectral content of a glare source is a leading predictor in experienced glare.[56][57] (figure 9)
- Shorter wavelengths of light (cooler sources) produce more glare than longer wavelengths (warmer sources).[56][57]
- A leading factor for this glare is Rayleigh scattering; The increased scattering of light within small particles by shorter wavelengths.[67] (figure 10)
- A leading factor in discomfort glare is the luminance of a light source as well as the luminance contrast of the source to its background.[51][56][58]
- *Glare and its associated visual strain is a probable source of fatigue in nighttime driving*



^Figure 9



^Figure 10

Additional light scattering impacts

^Figure 11, a comparison of environmental light scattering between high-pressure sodium lighting and blue-rich LED lighting. Note how the scattering of blue-rich light becomes visually obstructive at the end of the road.

^Figure 12, another example of environmental scattering. The shorter (cooler) wavelengths within the spectrum of this headlight beam are lost to scattering, while the longer (warmer) wavelengths pass through the fog to illuminate their target.

Adjacent to glare in many ways, the impact of environmental light scattering also needs to be considered in dusk-to-dawn lighting. Similar to glare, shorter (cooler) wavelengths of light result in increased light scattering. This primarily fall under Rayleigh scattering or Mie scattering depending on the size of atmospheric particles. This scattering can turn weather conditions such as rain and fog into blinding walls of light.[67]

Review of Evidence - Fixture uniformity

An important factor in the visual comfort of light sources is fixture uniformity. Fixture uniformity is the ratio between the brightest and darkest parts of a light fixture, such as a light bulb and its housing. Fixture uniformity becomes an important issue with LED fixtures as they are made up of dozens, sometimes hundreds, of tiny individual LEDs as seen in figure 6 previously.

Mechanics of fixture uniformity

- A variety of research has consistently found that a lack of light source uniformity lead to higher levels of discomfort glare.[51][62]
- This problem is made worse for outdoor dusk-to-dawn lighting as the background behind a light source is often the dark nighttime sky, leading to an additional loss of uniformity within the visual field.[51]
- A study on LED lighting fixtures found that subjects are more likely to view an LED light source positively when a diffusing median is used to 'soften' the individual LEDs into a single uniform source of light.[61] (figure 13)

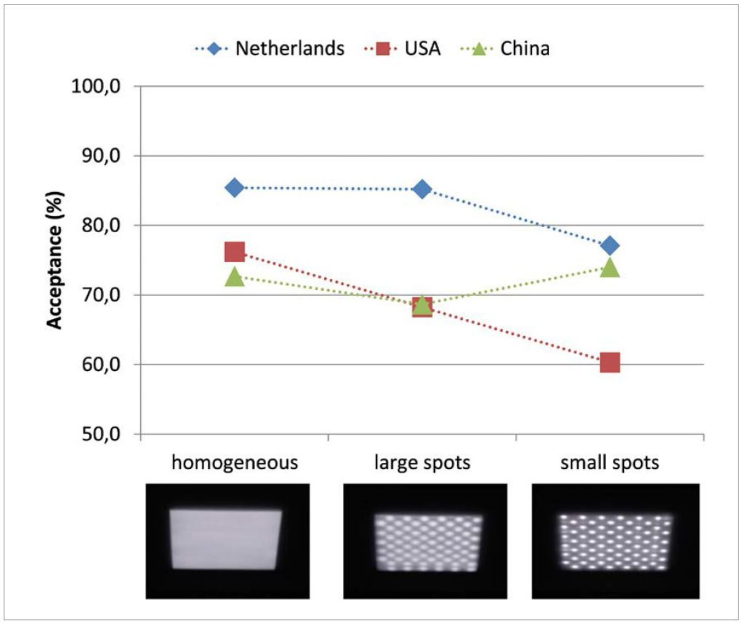


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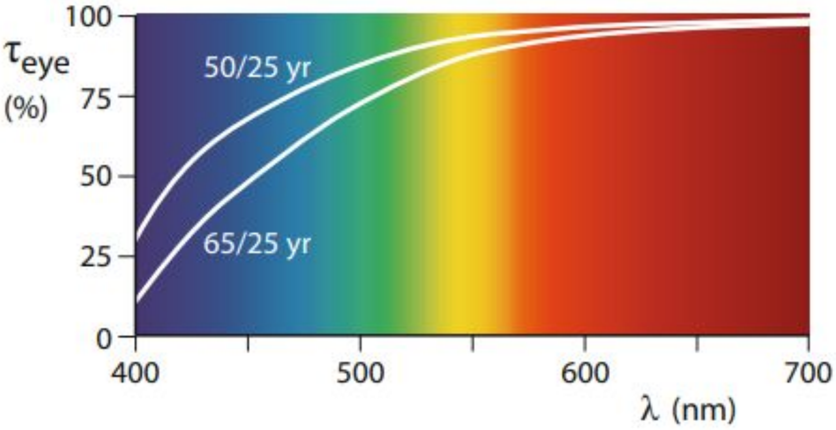
Figure 13

Review of Evidence - Age Considerations

Age plays an important role in spectral sensitivity. As the human eye ages the lens gradually yellows, altering spectral light transmission. By the age of 50 this leads to large losses of light transmission, with losses increasing for shorter (cooler) wavelengths.[51][68]

^Figure 14, examples of the lens yellowing with age



^Figure 15, spectral transmission losses of a 50 and 65 year old eye relative to a 25 year old eye. By 400nm losses can exceed 60%, whereas yellow and amber light is largely unaffected

Review of Evidence - Mechanics of Outdoor Lighting

Perhaps the most overlooked mechanic in lighting transitions is the condition of replaced fixtures. Cities, media and LED advocates are quick to advertise energy savings and roads that appear brighter after transitioning to LED streetlights - In reality the majority of the benefits seen are simply due to old, dirty fixtures being replaced with new fixtures free of dirt and weathering.

- A significant amount of a light fixture's output is lost to the accumulation of dirt, this is referred to as luminaire dirt depreciation (LDD) within the lighting industry.[39][41][42]
- A range of values exist for LDD, both from maintenance guides and field studies[41]
- Transportation Alberta lists a 12-18% loss of light output over a 4 year span after fixture installation for metal-discharge fixtures.[42]
- IES estimates for LDD after 4 years range from 5% to over 40% depending on the environment around the fixture.[39]
- The IES estimates a rate of LDD ranging between 1 and 3.8% per year for outdoor LED light fixtures.[41]
- The extremities of a fixture's illumination pattern are affected by LDD more than the center of its pattern, directly below the light. This contributes to dark spots between light fixtures and reduced levels of luminance uniformity on roadways.[39]
- Many metal-discharge lighting fixtures contain physical piles of dirt when examined.

Figure 16 (left) and figure 17 (right)

Transition to LED Lighting

Beginning around 2009 many municipalities began investigating the use of LEDs for outdoor lighting. This transition rapidly accelerated due to a range of advocacy from energy conservation advocates and LED industry marketing.[34] Initial LED installations for outdoor dusk-to-dawn lighting made use of primitive LED models in the 4000-6000 Kelvin range. These early LED fixtures emitted high levels of blue light with more than 30% of their output falling into the blue range of the visible spectrum.[35] Thanks to advancements in LED technology and early steps in awareness of the relationship between lighting and health, 'warmer' spectrums of light have become available for LED street light installations.[36][37] While there is no shortage of marketing and initiatives, both from private industry, energy advocates and government bodies for blue-rich LED lighting, its benefits for outdoor dusk-to-dawn lighting are often overstated with little to no examination of drawbacks.[36]

Mechanics of LED street lighting transitions

- The majority of installed LED streetlight fixtures are within the efficacy range of high-pressure sodium lighting, many failing to surpass it. Very few, if at all, have surpassed the efficacy of low-pressure sodium lighting.[4][9][38]
- LED street light transitions save energy by lighting a smaller area to a lower level of luminance, a practice justified by the out-of-context use of mesopic vision models reviewed in this report.[49][50]
- Mesopic visual performance models are built around maintaining peripheral visual performance by using a light spectrum within the peak sensitivity range of Rod cells. These models do not account for focal visual performance, which is reduced at lower levels of luminance no matter what spectrum of light is used.[46][47][48][49][40][51][53]

Review of Evidence - Impacts on Human Health

Direct impacts on human health

Humans use a non-image-forming photoreceptor (NIFP) to regulate pineal melatonin secretion. This is understood to be the basis of circadian rhythm for humans and is the link between circadian rhythm and blue light, as the spectral sensitivity of NIFPs peaks at 460-480nm in the blue range of visible light.[10][11]

- Melatonin levels play a leading role in dictating sleep/wake cycles and thermoregulation on a daily basis.[10][11]
- Melatonin is a factor in immune system function.[10][11][22]
- Melatonin is an important antioxidant - it has been repeatedly shown to fight hormonal cancers such as breast and colon cancer in mammals including humans.[10][11][22]
- A 2017 study conducted on the streetlight transition of Los Angeles found that the blue-rich light pollution of LED streetlights increased rates of hormonal cancers when compared to control regions. It was further evaluated that any cost-savings of the LED lights were undone by the economic costs of increased cancer rates.[12]
- Light pollution has been shown to be associated with fetal health, including lower birth weights and increased rates of preterm birth in regions with higher levels of skyglow.[13]
- A study conducted through recording sleep time, sleep quality and sleep behavior on a national scale across the US found that reduced sleep time and quality were associated with higher levels of outdoor lighting.[14]
- Blue-rich light exposure during nighttime has been shown to trigger biological stress responses outside of melatonin disruption.[10]

Further impacts on human health

- Sleep deprivation has significant impacts on daytime alertness and the function of many bodily systems during the day.[15][16][17]
- Sleep deprivation is a contributing factor in a wide variety of health problems and conditions.[17][21][22]
- Sleep deprivation greatly reduces the safety of vehicle operation.[18][19][20]
- *Outdoor light pollution may modify behaviors in a way that increases indoor sources of artificial light, creating a cascading effect of melatonin disruption*

US Department of Energy challenge to AMA report

- The US Department of Energy conducted research to compare different sources of circadian rhythm disrupting light.[75]
- Based on this research the US Department of Energy holds a position that outdoor LED dusk-to-dawn lighting cannot be a significant disrupter of circadian rhythm, challenging the AMA LED streetlight report.[75]
- This research however uses an incorrect metric to determine the perception of light on the retina, Lux. Luminance, measured in candela per square meter (cd/m^2), is required to capture the intensity of light perceived by the retina.[7][8][49][50][51][53][75]
- A streetlight rarely spills a high level of illuminance, measured in lux, into a residence.
- A streetlight is however a high luminance source of light visible from within a residence, resulting in an occupant’s retina perceiving a high level of light.

Review of Evidence - Impacts on Ecological Health

There are many impacts of light pollution on earth’s ecosystems that are worth considering here as human health is often influenced by the health of the surrounding environment. Perhaps most pressing of these concerns are those of food supply impacts caused by the effects of light pollution on insects and their nocturnal pollination activities. Additionally, blue light is the primary spectrum involved in biological and ecological damage.[10][11]

Insect and pollination effects

- A growing body of research is finding that outdoor dusk-to-dawn lighting reduces healthy insect behaviors such as reproduction and pollination.[23][24][27]
- This research additionally finds that outdoor dusk-to-dawn lighting induces harmful behaviors such as light-trapping that sees insects fly to a light source and remain under that light source until death by exhaustion or predation.[26][27]
- A study examining pollination networks found that the losses in nocturnal pollination caused by outdoor dusk-to-dawn lighting were not compensated for by daytime pollination, thus fruit production of the plant was reduced.[23]

Additional ecological impacts

- Many species such as plankton and certain birds rely on lunar cycles to control the timing of important behaviors such as feeding and reproduction, these cycles are easily disrupted by light pollution.[25][28]
- A wide variety of species rely on circannual rhythms to direct critical seasonal behaviors such as thermoregulation, this rhythm is based off of the changing length of days. Light pollution disrupts this rhythm and, for some species, this disruption can be fatal.[29][30][31][32]

Review of Grand Rapids Outdoor Lighting Case

City of Grand Rapids LED color temperature selection process fact sheet

This 9-page LED selection document will be reviewed based on its stated goals; Increasing public safety, quality lighting, energy usage reduction, inventory standardization, consistency with regional partners and community feedback.[74]

Increasing public safety

- The sole source cited for this consideration is a US Department of Transportation pedestrian safety report.[74]
- This report includes testing of reaction times to a simulated child-sized pedestrian under different color temperatures of streetlights on a test track.[73]
- Color temperature was only tested as a variable on the rural highway scenario, it was not tested in the urban scenario.[73]
- The setup of this simulated pedestrian is shown in figure 18 below. Note how the pedestrian is not positioned at the same angle between tests, resulting in a visible difference in illumination of the pedestrian's right edge.[73]
- The potential impacts of this inconsistency on test results cannot be concluded due to the test being described only in brief summarizing details.[73]
- The results of this test disagree with peer-reviewed research on visual performance.[46][47][48][49][50][51][53]

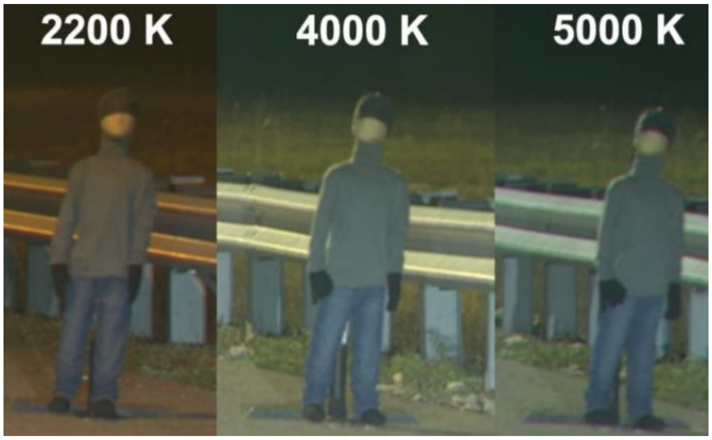


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Figure 18

Energy consumption

- The selection fact sheet correctly identifies that ‘warmer’ LEDs are less efficient than ‘cooler’ LEDs in raw lumens-per-watt efficacy.[9][34][38][69]

Inventory standardization

- The fact sheet states that the combined use of 3000K and 4000K LEDs would increase the number of fixture types being stocked, resulting in increased inventory costs.

Regional partners

- Several nearby cities chose 4000K as their street lighting standard, including Detroit. How this can be used as evidence to support the decision made by the City of Grand Rapids is unclear.

Community feedback

- Several attempts to engage with the public were made, but engagement with 2 feedback surveys was low (14 and 35 participants).
- When 4000K streetlights were compared to 3000K streetlights, 3000K lights were viewed much more positively than their 4000K counterparts.
- 68% of respondents rated the color of the 3000K lights as “excellent or good”, whereas only 38% of respondents gave this rating to the 4000K lights.
- 3000K lights were also more likely to be rated as “excellent or good” for light quality than the 4000K lights (70% vs 45% respectively).
- 75% of respondents agreed or strongly agreed that 3000K fixtures provide the right amount of light for road users, this drops to 64% for 4000K fixtures.
- For sidewalk users 3000K and 4000K lights received similar answers for the same question, 58% vs 60% respectively.

Visibility for senior citizens

- Despite significant impacts of age on the spectral sensitivity of the human eye, the City of Grand Rapids did not consider these effects in their street lighting.[51][68]

Human health concerns

- Through reviewing evidence and reports from the American Medical Association, the US Department of Energy and a variety of lighting industry organizations the City of Grand Rapids determined that “...it doesn’t appear there is a significant difference between 3000K and 4000K street lighting LEDs”.
- The similar weighting of positions taken by lighting industry organizations and peer-reviewed medical research in determining the potential health impacts of light color spectrum in outdoor lighting is highly questionable and concerning.
- Problems with the US Department of Energy’s challenge to the AMA LED streetlight report are described earlier on page 21.

Ecological health concerns

- Despite a well-established, rapidly growing body of peer-reviewed research identifying the negative impacts of blue-rich light pollution on ecosystems the City of Grand Rapids did not consider these impacts in selecting the color temperature of their street lighting.[10][11][22][23][24][25][26][27][29][30][31][32]

Engineering and design case study

- The City of Grand Rapids conducted a case study by simulating the installation of 2700K and 4000K LED streetlights.
- The case study identifies that an installation of 3000K streetlights (the fact sheet is not consistent in stating which 2 color temperatures are being compared) would require tighter spacing than a 4000K installation, resulting in higher costs.

City of Grand Rapids conclusion

The City of Grand Rapids concludes that 4000K is the optimal color temperature for public safety, inventory costs and community feedback. The conclusion additionally states that 4000K LEDs ‘appear crisp’ and that 4000K LEDs ‘appear natural like moonlight’. It further states that the primary goal of street lighting is public safety.

Review of Grand Rapids conclusion

- The evidence on light spectrum, glare and eye adaptation as factors of visual performance, in turn the primary factor of public safety, does not support the choice of 4000K LEDs for public safety. 4000K LEDs produce more glare than their ‘warmer’ counterparts and do not align well with peak visual sensitivity of Cone cells that are the dominant source of vision in an outdoor area illuminated by dusk-to-dawn lighting.[45][49][50][51]{53][56][57][58][60][64][65][67]
- The City of Grand Rapids states that the survey-indicated preference for 3000K LEDs is that of aesthetic choice and completely disregards the survey results.
- The City of Grand Rapids provides their own reasoning on aesthetic choice, making 1 subjective statement that 4000K LEDs ‘appear crisper’ and 1 demonstrably false statement, that 4000K LEDs ‘are very similar to moonlight’ (figure 19).
- The preference of 4000K LEDs over ‘warmer’ LEDs for energy consumption is at odds with public safety based on visual performance.[45][49][50][51]{53][56][57][58][60][64][65][67]

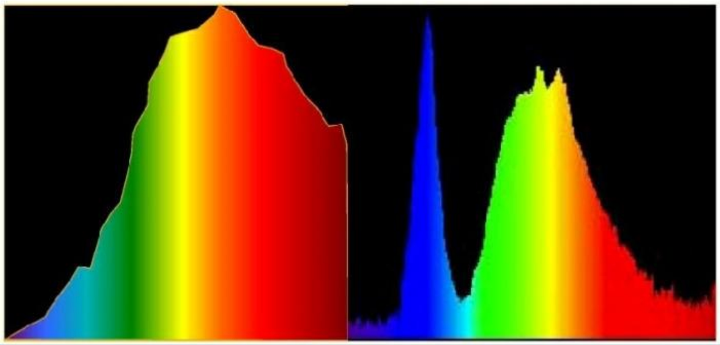

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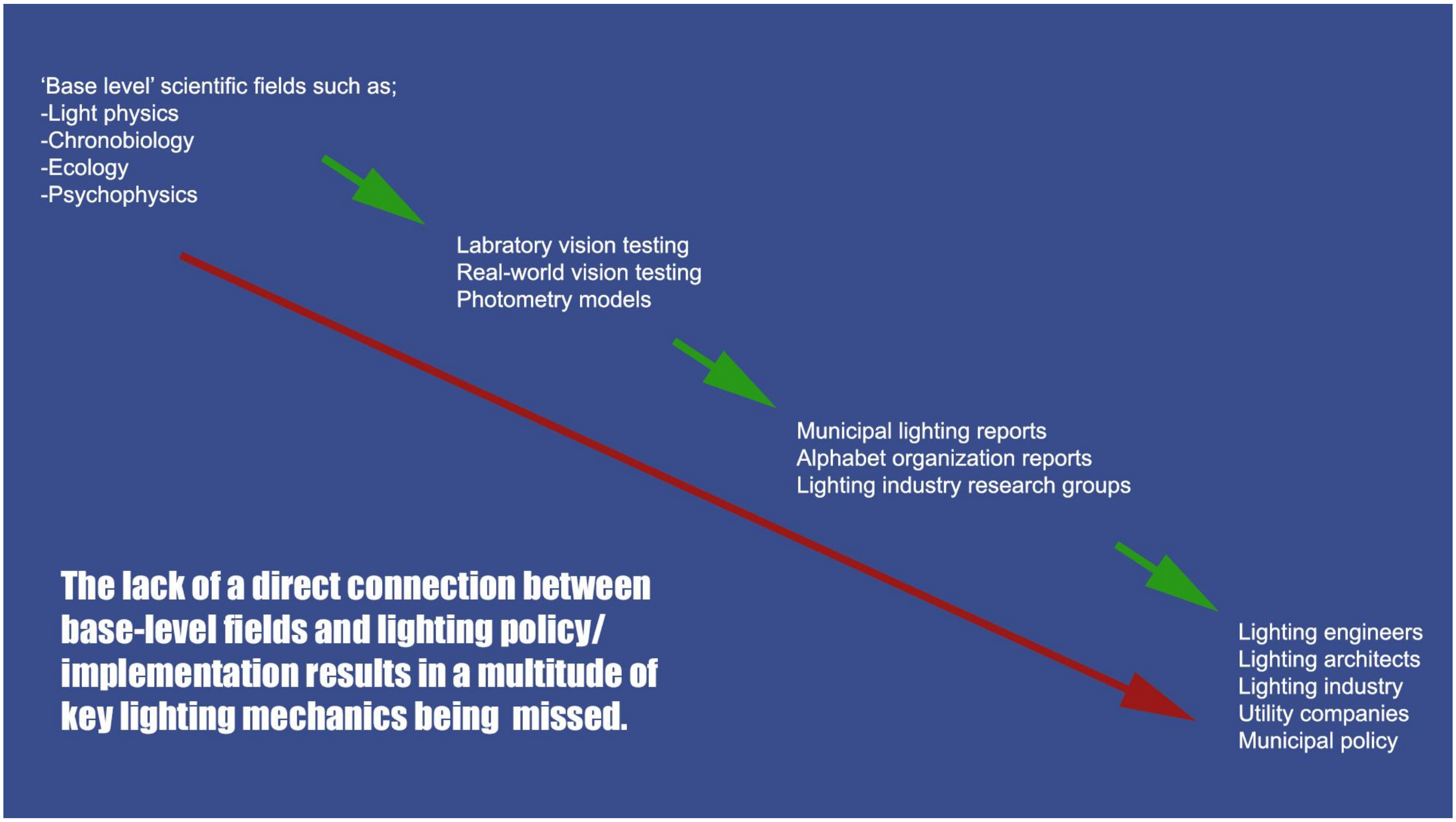
Figure 19, Spectrum of Moonlight (left) and spectrum of a 4000K LED (right)

Policy Recommendations

The goal of this policy recommendation is to provide a direct link between peer-reviewed research and lighting policy, something that is often missing from the implementation of lighting. As was determined in the review of an LED selection document from the City of Grand Rapids, a thorough analysis of peer-reviewed evidence was not done and many crucial pieces of evidence were left unexamined.

All too often, the only information reviewed by those making decisions around the implementation of outdoor dusk-to-dawn lighting is that from government energy efficiency initiatives, industry organizations and even those who are marketing/selling/distributing the lighting. Visualized with figure 20 below.



Policy Recommendations - Wavelength

Spectral content, often limited to but not accurately captured by color temperature measured in kelvin, is perhaps the most critical decision to make in the selection of roadway lighting as it has a large impact on visual performance, visual discomfort, visibility for the aging eye, spread of light pollution and biological impacts of light pollution.

Visual performance

For visual performance, it is recommended to adhere to the photopic luminance efficiency function that captures the contribution of Cone cells for all standard IES roadway lighting targets from 0.3 to 1.2 cd/m^2. For outdoor dusk-to-dawn lighting the contribution of Rod cells needs to be examined very carefully and in-depth due to their sensitivity to light and adaptation mechanics. Due to the potential for Rod cells to be blocked from dark adaptation by sources of light the contribution of Rod cells in artificially illuminated nighttime environments cannot be considered reliable. Exposure to light sources with high luminance intensities can make it impossible for the Rod cells to even begin adapting. Furthermore, the benefit of Rod contributions is limited to the context of peripheral vision at low speeds and low luminance adaptation levels. Faster speeds that result in less use of peripheral vision depend solely on focal vision which is accurately characterized by photopic spectral sensitivity at all roadway lighting levels. If the contribution of Rod cells is to be considered, it should only be considered for low-speed roads at the lowest range of luminance targets. Rod contributions should not be considered for installations with target road luminances of 0.5 cd/m^2 or greater, as the adaptation luminance will exceed the 0.6 cd/m^2 where the advantages of Rod contributions are lost, bleached or not.[45][49][50][51]{53][64][65]

With disability and discomfort glare also being considered factors of visual performance, a similar conclusion is arrived at. Longer (warmer) wavelengths of light should be favored while wavelengths within the blue range of the visual spectrum should be limited, if not completely removed, to limit glare.[51][56][57][58][59][60][67]

Visual discomfort

Visual discomfort due to glare follows the same wavelength recommendations as those for glare-based performance.[51][57][58]

Visibility for the aging eye

By the age of 50 a significant portion of light with wavelengths shorter than 500nm is lost due to the yellowing of the eye's lens with age. For the aging eye it is recommended that the majority of a light source's spectrum is longer than 550nm to prevent loss.[51][68]

Light pollution spread

The increased atmospheric scattering of short wavelengths of light make them a larger contributor to light pollution than longer wavelengths. For limiting light pollution, the longest (warmest) wavelength possible should be considered and wavelengths within the green-blue range and shorter should be eliminated.[67]

Light pollution impacts

For melatonin disruption across much of the species on earth, including humans, as well as other impacts such as light-induced stress and insect light-trapping, blue light is the primary damaging spectrum. Based on the spectral sensitivity of insect vision, light sources with no spectral content shorter than the yellow-amber range can largely eliminate ecological damage to insects. This spectrum can also largely eliminate melatonin disruption in humans and much of the circadian and circannual rhythm disruption experienced by wildlife. It is important to remember that even a fully-shielded light fixture still creates light pollution through ground reflection and atmospheric scattering, therefore the damaging effects of light pollution cannot be mitigated without using a biologically/ecologically friendly spectrum.[10][11][13][14][22][23][24[25]][26][27][28][29][30][31][32]

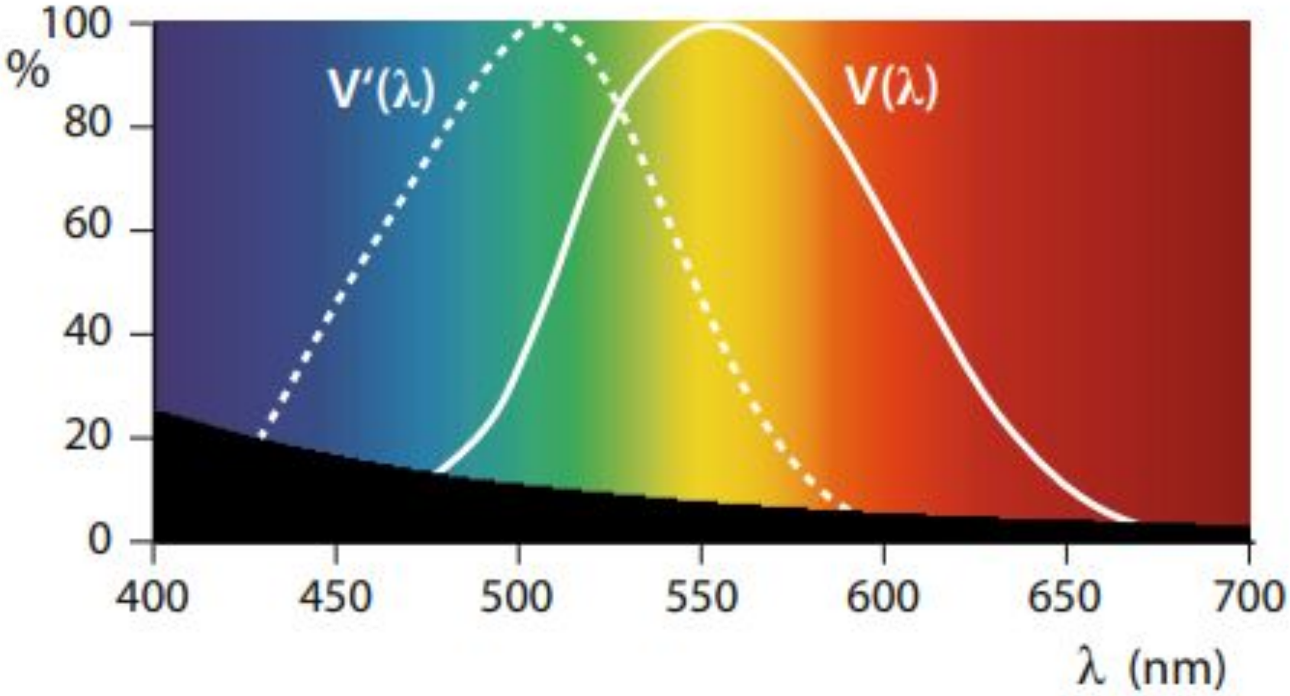
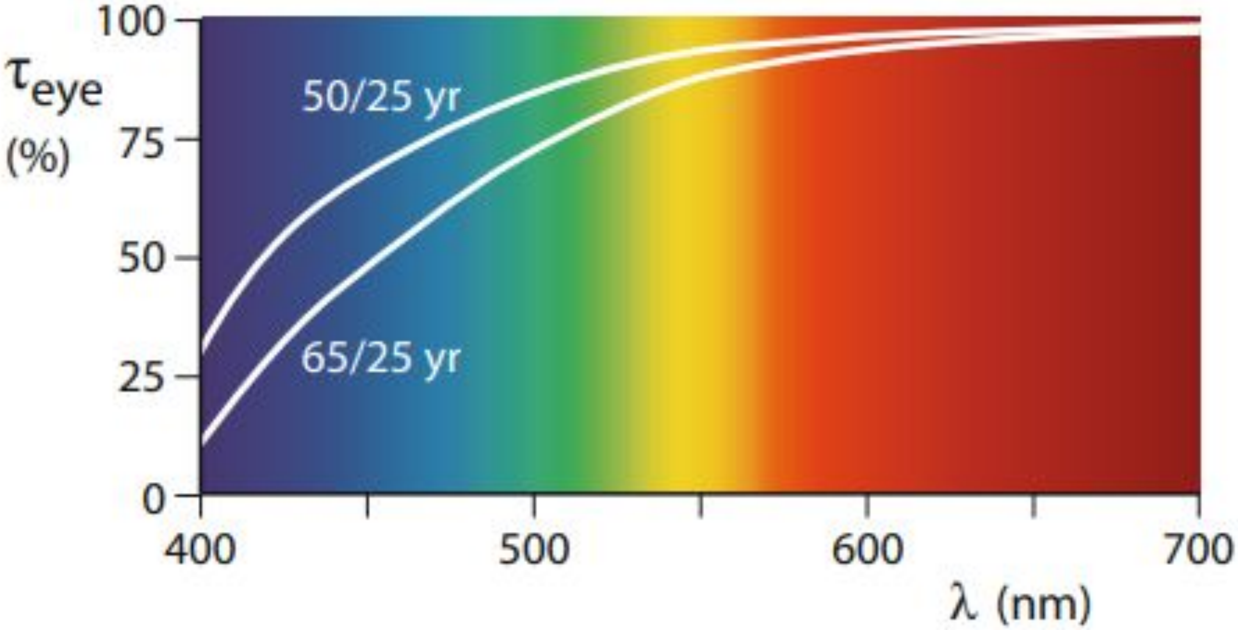


Figure 21 (above) - Photopic sensitivity curve plotted as the solid white line and % of light scattered due to rayleigh scattering plotted as the black infill. The spectral sensitivity peak of photopic vision aligns well with reduced levels of glare and light pollution due to rayleigh scattering. The peak of photopic spectral sensitivity also aligns well with the point at which yellow-lensing light loss is less than 10% for someone who is 50 and less than 20% for someone who is 65.[51][58] (Figure 22, below)



Policy Recommendations - Fixture Design

Fixture design elements that reduce light pollution, discomfort glare and photochemical damage of the retina from high-intensity light sources should be applied to all outdoor dusk-to-dawn lighting installations.

Shielding

Shielding is already a universally sought-after feature of outdoor dusk-to-dawn lighting installations. The lens of the light fixture should be embedded into the fixture in a way that prevents any of is light output from spilling directly into the sky.

Uniformity

An outer lens should be applied to all outdoor dusk-to-dawn light fixtures that 'softens' the individual LEDs into a single uniform light source. Since uncontrolled scattering is a concern with using diffusing lenses, a dual outer lens design may be considered; An initial lens that first diffuses the LED emissions into a single uniform light source and a secondary near-flat refracting lens that directs output. Not only does this design enable both diffusion and precise control of light output, it additionally enables the modification of luminance distribution patterns by simply changing the outer refracting lens.[51][61][62]

Fixture size and intensity

Contrary to the desires of many lighting operators, bigger is better for lighting fixtures. As the metric luminance, defined by candela per square meter (cd/m^2) suggests, the only way to reduce the intensity of a light source is to make it larger. A maximum luminance limit should be set for all outdoor dusk-to-dawn lights, somewhere between the limit for visual comfort and the limit for visual tolerance, below the threshold of photochemical damage to the eye. This limit needs to be measured using high spatial accuracy to prevent inaccurate luminance averaging and carefully controlled temporal accuracy if the light source flickers through its power current or intentional flicker-based dimming.[51][56][58][71]

Policy Recommendations - Light Source Selection

With the above factors considered, there are a few primary candidates for optimal light sources.

Low-pressure sodium

Low-pressure sodium is the original choice of lighting both for dark-sky cities and ecologically sensitive areas. Low-pressure sodium remains the most efficient source of dark-sky and biologically-friendly outdoor dusk-to-dawn lighting on earth, far surpassing the current efficacy of yellow-amber LEDs. If loss of color rendering isn't a major issue for the area being illuminated low-pressure sodium remains a solid choice for its near-perfect wavelength characteristics and efficacy.[4][10]

High-pressure sodium

High-pressure sodium remains a primary lighting candidate for its well-balanced performance. The color-rendering index of High-pressure sodium is low, but it still provides enough color rendering for most if not all tasks performed under outdoor dusk-to-dawn lighting. With efficacies as high as 140 lumens/watt, high pressure sodium is yet to be surpassed by market-ready LEDs with similar spectral content. High-pressure sodium bulbs are economically friendly as well. Old high-pressure sodium fixtures can be replaced with new ones for tighter light distribution patterns and significant energy savings.[4][69][72]

2200K / Yellow / Amber LEDs

It is predicted that the efficacy of LEDs with optimal spectrums, with the majority of their output in the yellow-amber range, will eventually meet and surpass the efficacy of high-pressure sodium lighting. At this point LEDs should be considered as light source candidates, with careful consideration for limiting glare and discomfort easily caused by their small non-uniform nature.[4][34][69]

Policy Recommendations - Additional notes

Inverse efficacy to wattage relationships for metal-discharge lighting and LEDs

Metal-discharge lighting requires a minimum operating temperature for its metal(s) to produce light, whereas LEDs need to remain cool and dissipate the heat produced by their driving circuitry to prevent loss of efficacy and lifespan. Because of these factors, metal-discharge lighting becomes more efficient at higher wattages whereas LEDs generally become less efficient at higher wattages. With these factors considered, a balanced approach of using yellow-amber LEDs for lower wattage fixtures and high-pressure sodium or low-pressure sodium for higher wattage fixtures should be considered.[4][69]

Cleaning

Outdoor dusk-to-dawn lights need to be cleaned on an operator-defined schedule based on the annual rate of light output loss due to dirt accumulation, estimated to be 1-4% per year by the IES for LED fixtures. If a lighting operator claims to bring maintenance savings with long-life LEDs, through avoiding servicing/relamping trips to the light installation, they aren’t doing their job to maintain infrastructure and are losing significant levels of light output.[39][41][42]

Dimming

Dimming may be considered to save energy when the number of people outside is low and the amount of visual tasks needed to be performed is reduced. However, dimming needs to be accomplished through a means other than pulse width modulation. Dimming through pulse width modulation creates sub-sensory flicker and retains the peak luminance of full light output, potentially inhibiting the ability of the eye to adapt to the lower level of luminance.[54][70]

Private lighting

The same wavelength, light pollution and glare-control policies that govern public roadway lighting should be applied as regulations to private outdoor area lighting.

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