LED STREETLIGHTING: ENVIRONMENT & SAFETY IMPACTS

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Abstract

Replacement of High Pressure Sodium (HPS) streetlights with Light Emitting Diode (LED) streetlights has been happening around the world. This has been led by the superior energy efficiency of LED lighting, its greater longevity, its lower need for maintenance and its ability to be dimmed and strengthened according to varying temporal needs. Future choices relate to type of LED rather than whether LED or some other light source is used.

This has led to discussion around the environmental and safety impact of the change, particularly the greater proportion of blue light in the output of LEDs compared with the previous HPS. Environmental discussion has included impacts on wildlife, human health and the visibility of celestial bodies in the night sky. In safety driver fatigue, impacts on central vision, peripheral vision and object detection have featured. Correlated Colour Temperature (CCT) is a rough guide to the percentage of blue light emitted by a source and it is generally agreed that streets should not be lit by lights of colour temperature above 4000K.

This paper looks at the available evidence and seeks to provide practical information to assist practitioners in their choice of LED lighting. It finds that the differences in field performance between 3000K and 4000K street lights are now either small or inconclusive or both. There are potential safety and environmental differences in that range but at present their net size and direction remain murky.

Locally this means that the NZTA’s flexible advice on colour temperature of LEDs as presented in its M30 Specification and Guidelines for Road Lighting Design represents a defensible call, given the evidence available.

Introduction

Replacement of High Pressure Sodium (HPS) streetlights with Light Emitting Diode (LED) streetlights has been happening around the world. This has been led by the superior energy efficiency of LED lighting, its greater longevity, its lower need for maintenance and its ability to be dimmed and strengthened according to varying temporal needs. Future choices relate to type of LED rather than whether LED or some other light source is used. This has led to discussion around the environmental and safety impact of the change, particularly the greater proportion of blue light in the output of LEDs compared with the previous HPS. Environmental discussion has included impacts on wildlife, human health and the visibility of celestial bodies in the night sky. In safety driver fatigue, impacts on central vision, peripheral vision and object detection have featured. Correlated Colour Temperature(CCT)[1] is a rough guide to the percentage of blue light emitted by a source and it is generally agreed that streets should not be lit by lights of colour temperature above 4000K.

This paper looks at the available evidence and seeks to provide practical information to assist practitioners in their choice of LED lighting.

The impact of spectrum on lighting

Light emitted from luminaires is measured in lumens. The unit lumen may appear colour blind, but in reality, each lumen of light is "the product of the emitted energy over the visible wavelength range, factored by the eye sensitivity curve, or the eye's spectral response" (Lewin, et al, 2003 p6). It is well known that the human eye shifts its spectral sensitivity in response to changes in lighting levels. This relates to how the light is received by the eye.

According to Lewin et al, 2003 at around 3 cd/m^2, the dominant light receptors in the retina are the "cones" which are most sensitive to yellow light. These levels are referred to as "photopic." As lighting levels reduce below 3 cd/m^2 the cones progressively lose their dominance and the rods become more important. At extremely low light levels like starlight only the rods are active, and the levels are called "scotopic." Road lighting is almost always in the range 0.1 to 2 cd/m^2, and in that range both rods and cones are active. This middle range is called "mesopic

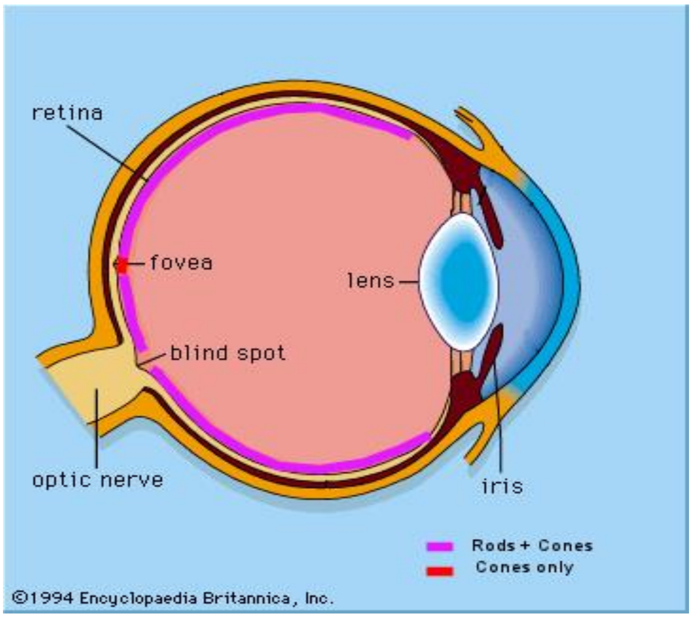

Figure 1: Anatomy of the eye

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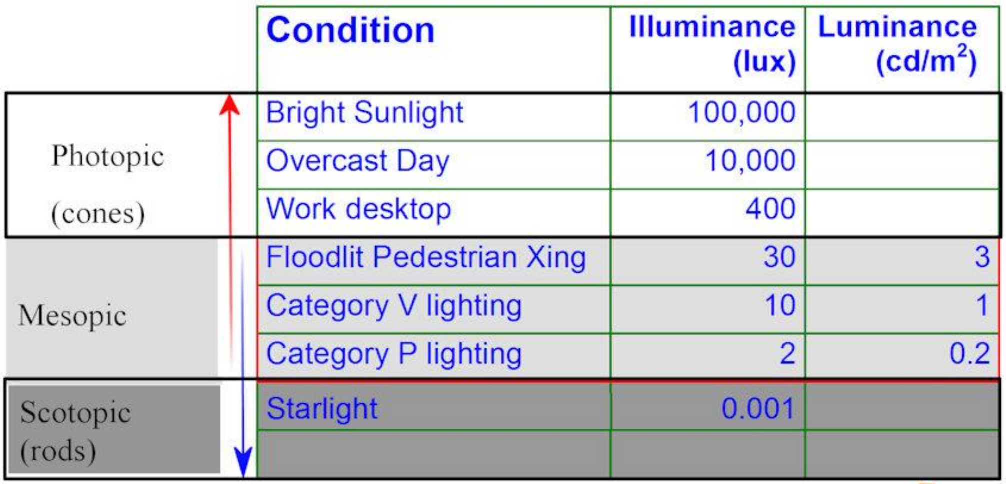
[1] The Correlated Colour Temperature (CCT) of a light source is the temperature of an ideal black-body radiator, radiating light of comparable hue to that source. It is a rough surrogate for the spectrum of the source with lower colour temperature generally meaning less blue light.

The relevant anatomy of the eye is shown in figure 1. Table1 relates this to some practical situations



	Condition	Illuminance (lux)	Luminance (cd/m^2)
Photopic (cones)	Bright Sunlight	100,000	
	Overcast Day	10,000	
	Work desktop	400	
Mesopic	Floodlit Pedestrian Xing	30	3
	Category V lighting	10	1
	Category P lighting	2	0.2
Scotopic (rods)	Starlight	0.001	

Table1: The approximate light intensities associated with various situations (Source: Michael Jackett)

From table1 it is apparent that for Category V lighting we are dealing only with the upper end of the mesopic range. This is important as most of the fairly sparse mesopic research applies to lower down in the mesopic range, Category P in New Zealand parlance. The distribution of cones and rods is not uniform throughout the retina (figure 2). Only cones lie at the exact centre of the field of view, while rods dominate the peripheral field. Thus, a source which makes good use of rods may improve peripheral vision but not improve centre field vision at all. The reverse also applies.

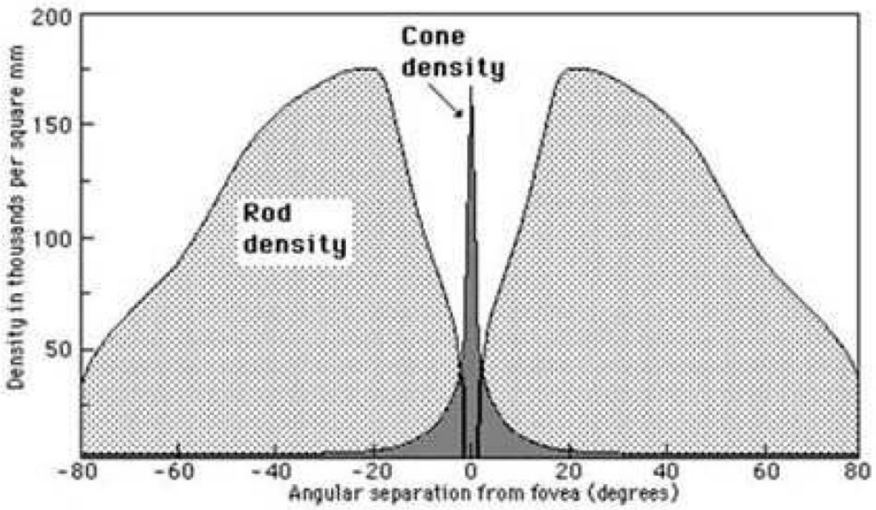


Figure 2: Rod and cone density on retina[2]

In mesopic conditions both rods and cones come into play and light sources which can most optimally utilise them together are to be preferred.

How do LED and HPS light sources differ?

Spectral power distributions (SPDs) for light sources show what percentage of the power output of the source emanates from various wavelengths.

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[2] source www.ledroadwaylighting.com

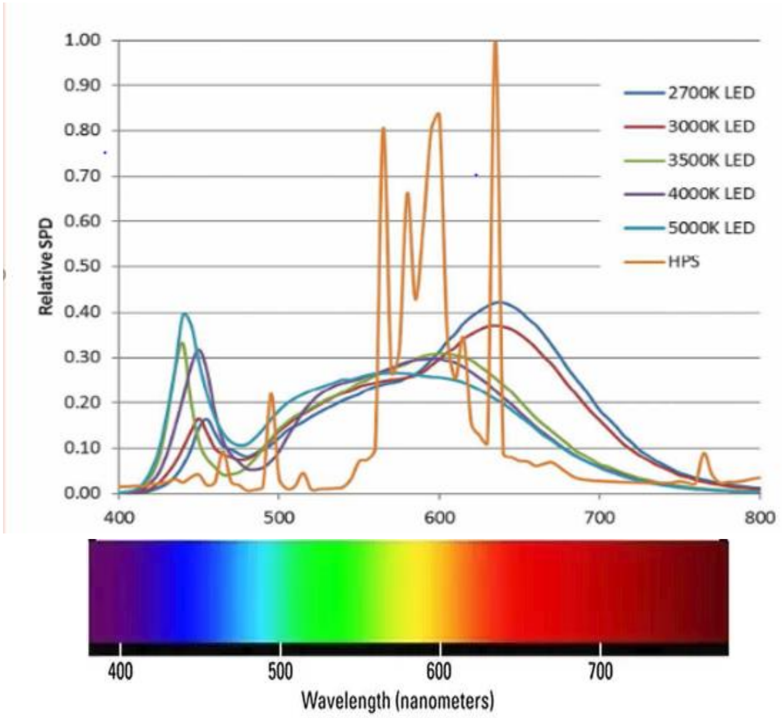

Figure 3: Spectral Power distributions of several light sources of equal lumen output

Figure 3 shows spectral power distribution charts for HPS and several LEDs of different colour temperature and equal light output. It also illustrates the colour of the light associated with the various wavelengths in the spectrum. The LEDs obtain more of their power from the rod sensitive (peripheral vision) part of the spectrum than HPS while still having a generous part of their power in the cone sensitive (central vision) part of the spectrum. They are thus well suited to light roads and may outperform HPS in peripheral vision tasks.

Visibility of objects to drivers

A major objective of road lighting is to improve the visibility of objects to drivers. Visibility has face validity as an intermediate outcome measure for road safety lighting, but directly relating visibility to safety has proved difficult for researchers (Schreuder et al, 1998). This paragraph looks at visibility to drivers of objects both off the road and on the road

To detect off road objects like pedestrians, drivers use peripheral vision (rods). If an object of interest is detected drivers may also use central vision (cones) by moving their heads and eyes.

Frith and Jackett (2014) state that various authors have reported dramatic improvements in the visibility of slightly off-axis small targets under LED versus HPS. Younis (2013) looked at the impact of HPS and LED street lights on visibility to drivers of stationary pedestrian manikins on the footpath at night. The experiment dealt purely with peripheral vision as eye/ head movements were not allowed. The LED street lights' mean detection distance was significantly larger than for HPS. White and yellow clothed pedestrians were also significantly better detected than the black. This indicates that the white light sources assisted peripheral vision more than the HPS.

The impact on central vision, required to detect on-road objects is not so clear as that on peripheral vision. Over the years some researchers have used reaction time as a surrogate for visibility. A laboratory experiment by Zhiyong et al, 2011 found the following (Figure 4) curves of reaction time and luminance for HPS and LED. Measurements were under mesopic conditions using simulated on-road targets. The horizontal axis depicts the background brightness in cd/m² using the increments by which it was varied.

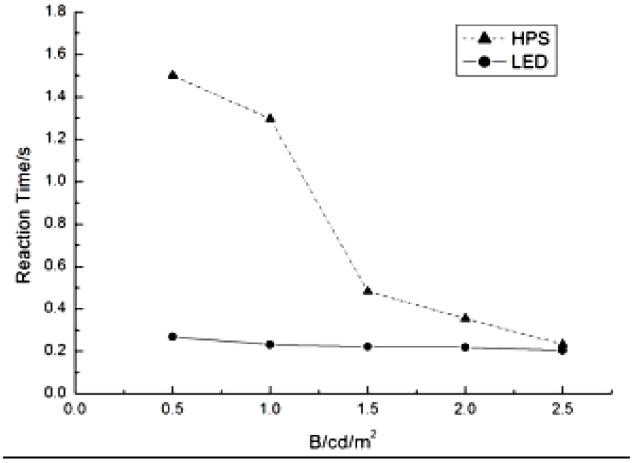

Figure 4: Curve relating reaction time to luminance using HPS and LED

It is obvious from Figure 4 that the LED has lower reaction times throughout the mesopic region and that the two sources' reaction times converge as the photopic region is approached. The colour temperatures of the HPS and LED were not discussed by the researchers.

Trials of several types of LED lighting against HPS were carried out in US cities by consortia led by Nancy Clanton of Clanton Associates[3]. These are reported in Mutmansky (2010a), Mutmansky (2010b), Clanton et al (2014) and Clanton (nd). The trials used the Small Target Visibility (STV) method (IESNA RP-8, 2005) which determines the level of visibility of an array of targets on the road considering factors like the luminance of the targets and the immediate background.

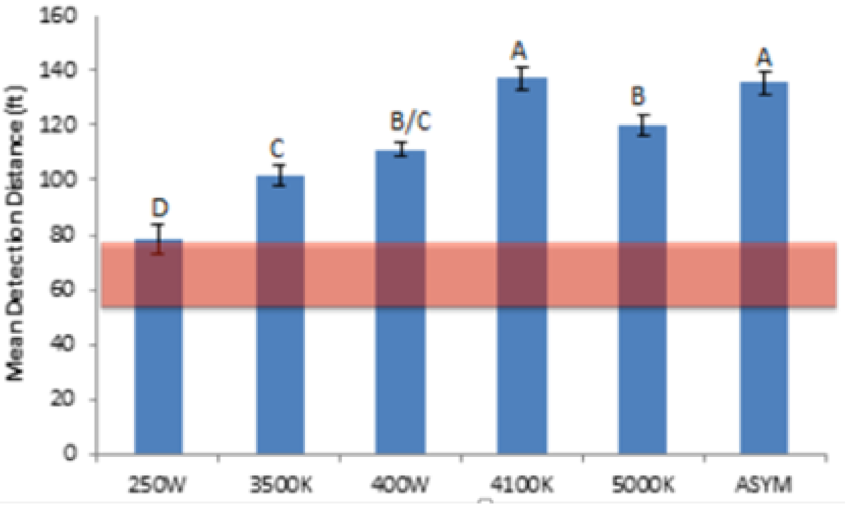

Figure 5: Detection distance comparison of Seattle Luminaries-using wet and dry road data

Clanton (nd) provides the summary results (Figure 5) for the Seattle trial which was the only one specifically designed to compare luminaire performance. The red horizontal bar represents stopping distance in the wet, the columns labelled by wattage are HPS luminaires and those labelled by colour temperature are LED luminaires. This shows that the detection distance of all the luminaires exceeded the wet stopping distance of the surface with the best performance

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[3] http://www.clantonassociates.com/

from the 4100K LED luminaire. These results are from field studies and as such are weather, equipment and site specific. Their interpretation must be tempered by the lack of information available on the relative lumen output of the various light sources, their spectra and their light distribution

Fusheng et al (2012) looked at average visibility ratings and small target visibility (STV) of on road targets using LED (4810K) and HPS (2321K) light sources. The average luminance of the road surface was about 2 cd/m^2, within the range of mesopic vision. Figure 6 illustrates the change in observer ratings for the HPS and the LED sources at different visibility levels. For both LED and HPS as the visibility level increases, the average observer rating of visibility also increases. It is apparent from inspection of the two charts that for any given visibility, the LED obtains a higher rating from the subjects than HPS.

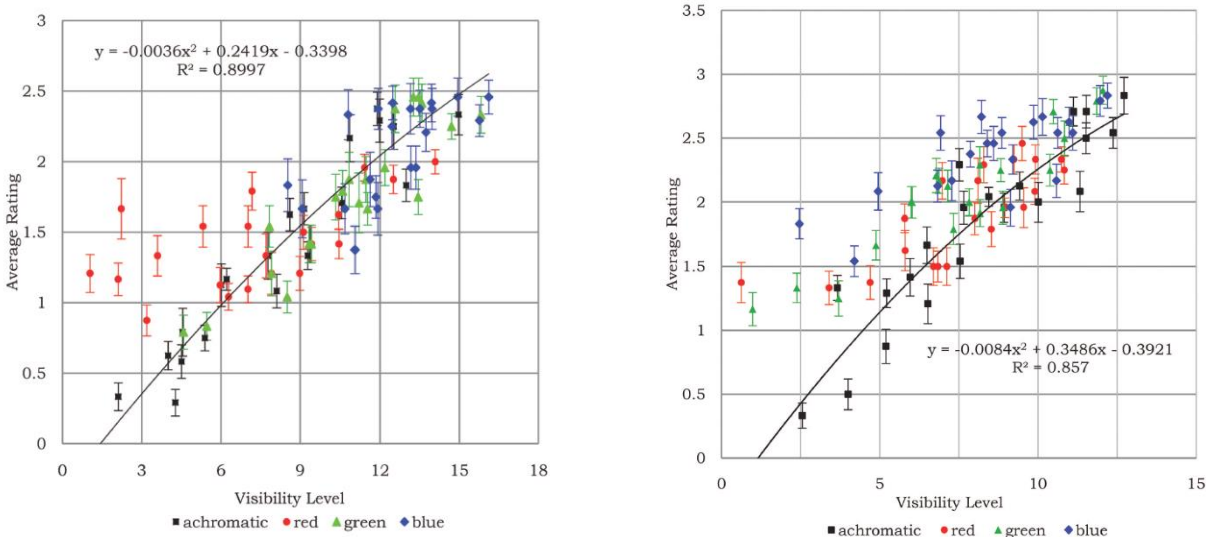

Figure 6: Observer visibility rating of HPS (left) and LED vs calculated visibility level

Jin et al (2015) took a different tack looking at, dark adaption, colour perception, fog penetration, and sky glow related to LED luminaires with different Correlated Colour Temperatures (CCTs). They found that as CCT increases, colour discrimination improves with an optimum around 3000K dark adaption time increases, potential for sky glow increases and transmission through fog and haze decreases. When all those factors were considered the authors concluded that luminaires around 3000K were a reasonable compromise for street lighting.

In conclusion, LEDs appear to be generally superior to HPS for both on road and off-road visibility. There is little information regarding the best colour temperature to use except for the results of Clanton et al (favouring ~ 4000K) and Jin et al. (favouring ~ 3000K) based on different sets of measurements, and much would depend on the individual luminaires being compared

Driver Fatigue

Disability glare is the type of glare which directly reduces visual performance while discomfort glare causes the motorist to feel less comfortable and may distract a driver's attention from the road to the glare source (Van Bommel,2015). These are the main possible contributors to driver fatigue related to road lighting. The main mechanism by which they may induce fatigue is by making the journey less comfortable and as a corollary more tiring to the driver. According to

Van Bommel (2015), the spectrum of a light source has nil or very little impact on disability glare. Thus, the spectrum of an LED used to replace an HPS source should not be an issue.

With discomfort glare research has found that bluer sources are associated with more discomfort glare than less blue sources. Clear guidance as to the differences between lighting with different spectra were not available at the publication date of Van Bommel (2015)

Variation of glare along a route can exacerbate discomfort and is called “pulsating glare”. There are possibilities of restricting this type of glare for LED luminaires which are not available using HPS (Van Bommel, 2015). This is an ongoing area of research (e.g. Zhu et al, 2013).

There is also the possibility that LED luminaires with more blue light may assist in keeping drivers awake by suppression of melatonin production. However, at the illuminance levels of street lighting a driver would need to drive under these conditions for a considerable time (Rea et al, 2012) to be impacted to any useful degree. Work on how often this would happen in practice has not been carried out but unusual congestion conditions at the evening peak in mid-winter would intuitively be the most likely scenario.

Blue light loss by yellowing of the eye’s lens

Blue light is lost by absorption through yellowing of the eye’s lens (Van Bommel, 2015). The yellowing process is well underway by the time an individual reaches age 25. Brainard et al. (1997) found that at 450 nm the transmittance of the lens of a 60-69-year-old is half that of a 20-29-year-old adult. Figure 7 from Van Bommel (2015) illustrates the changes in the lens as it ages.

Figure 7: Changes in the lens of the human eye through ageing (Van Bommel (2015)

A 50-year-old will receive 45% less light to the retina per lumen from a 4000K LED than a 25-year-old and for a 2700K LED the loss will be 34% (Van Bommel (2015).

Blue light loss by absorption by road surfaces

Blue light is absorbed more by road surfaces both asphalt and concrete and thus will result in less luminance for a given amount of illuminance. In Category P lighting the main objective is to illuminate objects directly so loss during reflectance from the surface is not of importance. However, for Category V lighting this loss will be more important as the prime purpose of route lighting is to provide guidance to drivers through light reflected off the road surface. Figure 8 (Van Bommel, 2015) shows the relative surface luminance for an asphaltic surface and various light sources relative to HPS. It is apparent that 2800K LED and 4000k LED differ little from each other and are only about 5% lower than HPS, so the difference from HPS is small.

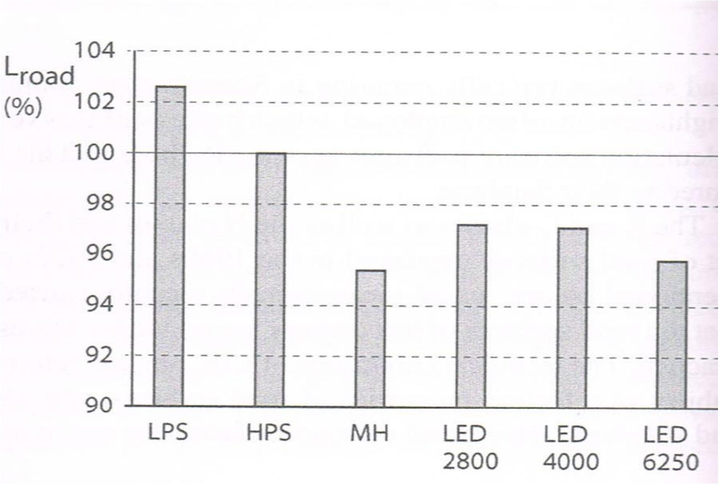

Figure 8: Surface luminance for an asphalt surface and various light sources relative to HPS.

Again, this is a negative impact from the blue light in LEDs and will increase with blue light proportion and thus roughly with CCT but its importance vis-à-vis other impacts is unknown.

Impact on the night sky

Light, particularly bluer light is not conducive to astronomy or indeed simple enjoyment of the night sky (Van Bommel 2015). Street lighting undoubtedly contributes to this impact but its contribution to total sky glow is not well established and will differ from locality to locality as will the totality of the sky glow to which it contributes.

Street lighting is only one of many sources of exterior light at night. Other sources include interior light escaping through exterior windows, architectural and landscape lighting, signage, parking lots and garages, recreational lighting and vehicle lighting[4]. IESNA (nd) states that roadway lighting has been estimated to contribute approximately 30% of sky glow and light trespass but does not give any reference or location type for that estimate.

Concern over possibly damaging the night sky has been part of lighting engineer's ethos for many years. Provisions in the Australia/New Zealand lighting standard have steadily reduced the Upward Waste Light Ratio (UWLR). The International Dark Sky Association has recently revised its previous "fixture seal of approval" for outdoor light sources of 4100K or lower down to 3220K (measured value) and lower. Its previously approved products were given a year to comply. This may result in an increase in market penetration by lower CCT LEDs over time.

The 3 main luminaire characteristics influencing sky glow are spectral power distribution (SPD), total lumen output, and the amount of uplight (Kinsey et al, 2017). Although LEDS have SPDs less dark sky friendly than typical HPS sources, the other 2 variables may be manipulated to provide no overall decrement, Typical US pedestrian conversions to LEDs that reduce lumens 50% and eliminate up light produce less sky glow than the HPS they replace. Table 3 suggests for New Zealand a 50% lumen reduction for pedestrian lighting but without optimized designs perhaps only a 5% lumen reduction would occur with category V lighting[5].

	Cat P HPS	Cat P 4000K LED	Cat V HPS	Cat V 4000K LED
Wattage	70	23	150	123

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[4] https://www.ies.org/lda/led-street-lightings-impact-on-sky-glow/ Viewed 2/8/2017

[5] In addition, the AS/NZS1158 standard has recently updated the r-table used for NZ Category V designs. This may require lights with higher lumen output.

Lamp Lumens	6,600	N/A	17,500	N/A
Luminaire lumens	5,280	2,640	14,000	13,500
Change (luminaire lumens)		50% reduction		5% reduction

Table 3: NZ estimate of the expected lumen reduction when replacing HPS luminaires with LED luminaires[6]

It is difficult to precisely translate the US experience to NZ but the most likely outcome of using 4000K LEDs in place of HPS luminaires is a net reduction in sky glow on Category P roads and a net increase in sky glow for Category V roads. The net impact of this has not yet been considered in detail, but is likely to be small, particularly given that the lighting most likely to be close to human habitation is Category P lighting.

Jackett and Frith (2018), have looked at how sky glow decays with distance from rural LED and HPS lighting installations.

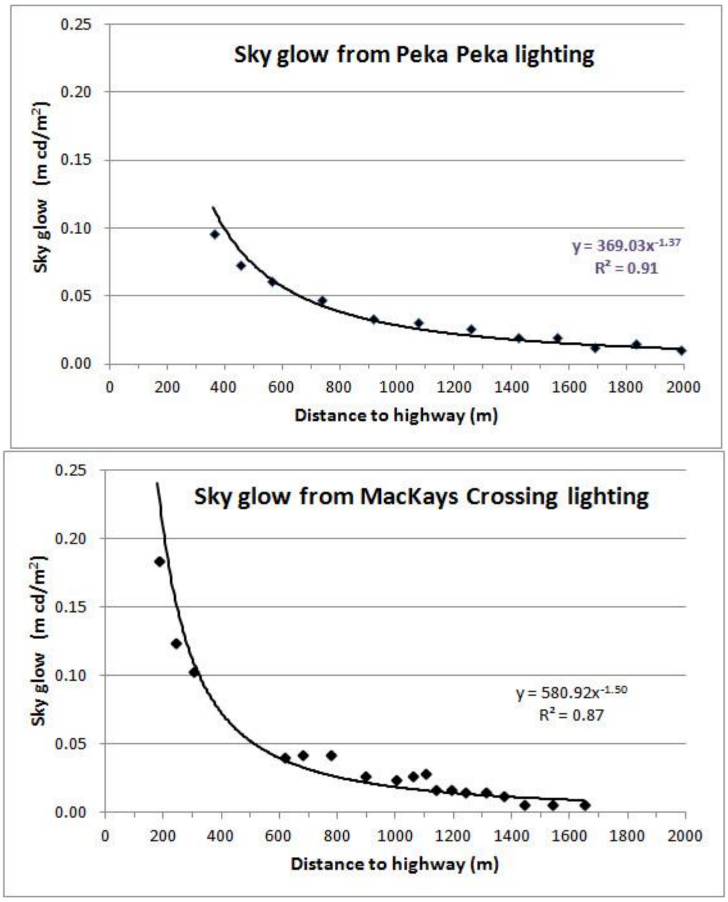

Figure 9: Est. sky glow decay at MacKays Crossing and Peka Peka by distance from the lights

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[6] Note: HPS lamp lumens were reduced 20% to equate with LED luminaire lumens. Greater lumen reductions could be expected if optimized designs were used.

They found, (figure 9) that the sky glow decayed to the background level within 2 km of both the LED installation at Peka Peka and the HPS installation at MacKays crossing, both on SH1 North of Wellington. Although the LEDs at Peka Peka produced less sky glow than the HPS at MacKays no firm comparisons can be made as the installations were not of the same design.

They also looked (figure 10) at the contribution of static lighting (which includes streetlighting, industrial lighting, billboards etc) in Wellington City. Its contribution varied over the night varied from around 70%to 95%. as shown in figure 10.

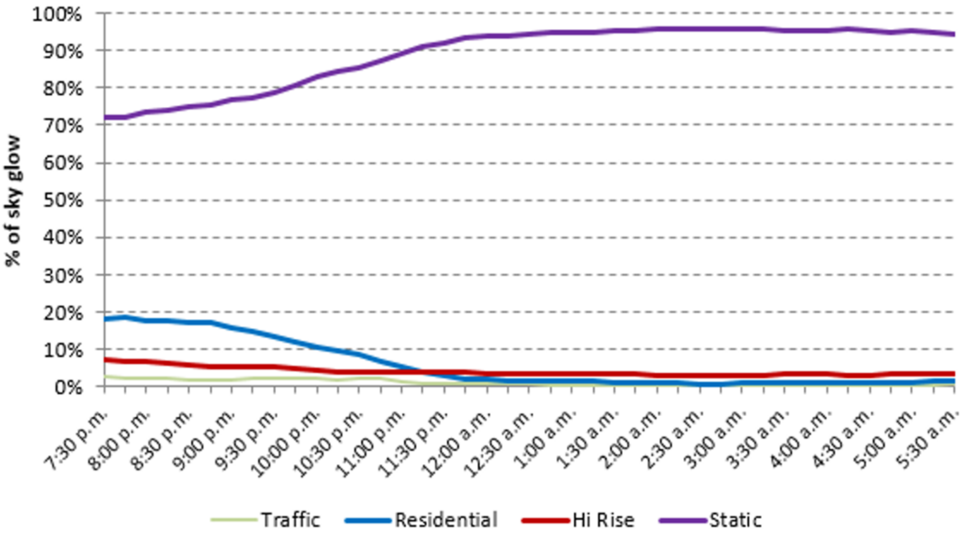

Figure 10: Percentage contribution to overnight Sky Glow by light Source

The contribution of street lights to the totality of static lighting this has not yet been determined and further research in this area is under active consideration by the NZTA.

Impact on wild life

Street lights can interfere with wild life. Examples are interference with moths' ability to avoid predatory bats (LEDs) and the UV radiation from HPS which causes 'flight-to-light' and high mortality (Wakefield et al, 2015).

Rowse et al, 2016 found that a switch from low-pressure sodium (LPS) to LED street lights in southern England did not affect the activity of bat species typically found near street lights. Eisenbeis and Eick, 2011 also found that HPS was more attractive to insects than LED, but with many caveats.

Pawson and Bader (2014) found in rural Hawkes Bay LED lamps at the forest's edge attracted 48% more flying insects on average than HPS lamps. They found little difference in insect attraction between "off-the-shelf" LEDs with colour temperatures between2700 K and 6500 K. The lights used were described as "industrial scale" lights, not street lights and their lumen output was not mentioned in the article. Figure11 depicts some of the industrial LED lights used in their forest edge context.

Figure 11: Industrial scale lights used by Pawson and Bader (2014)

There are variations around the world in the local seriousness of these problems. Europeans are concerned about attracting bats which may cross-infect humans. In New Zealand the survival of native bats is a concern and people may be glad to improve their access to insect food.

Artificial light can impact on many other species including migratory birds CCSAPH (2016). Red beacons on oil rigs can divert them from their courses. However, the difference of impact between HPS and LEDs of various CCTs is not well understood. At this stage the best advice is to design lighting well and do not use more than is necessary to do the job required.

Impact on human health

Blue light hazard

The term "blue-light hazard" describes acute photochemical damage to the retina caused by "staring at an intense light source" like a welding arc or the sun[7]. Methods to evaluate light sources for potential to cause tissue damage are available (IESNA 1996) and the US has standards related to workplace light exposure (ACGIH, 2004). CCSAPH, 2016 has connected these impacts to radiation in the range of 400 to 500 nanometres prompting speculation about the safety of blue-rich light sources used in street illumination. However, the research quoted is animal related. Ian Ashdown (chief scientist, Lighting Analysts) describes it as involving an "exposure time necessary to do damage equivalent to staring at the tropical noonday sun for 15 minutes without blinking." This obviously has no relation to street lighting which is in the mesopic range. A number of these studies are discussed in an internet post (see footnote 7). Regarding human exposure, a Public Health England report[8] states that at a distance of 2 metres reaching the exposure limits for blue light hazard would require steady fixation for over 2.5 hours, based on conservative calculations. The above would indicate that road lighting in the

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[7] http://www.archlighting.com/technology/blue-light-hazard-and-leds-fact-or-fiction_o Viewed 5/6/2017

[8] https://www.researchgate.net/publication/304136116_Human_responses_to_lighting_based_on_LED_lighting_solutions_report_for_CIBSESLL Viewed 20/102018

mesopic region, as used in New Zealand is not a “blue light hazard” with no evidence that LEDs differ from HPS in this regard.

Age related macular degeneration

Blue light exposure has also been implicated by medical researchers in age-related macular degeneration (AMD), a leading cause of vision loss in older people. Often quoted is Taylor et al, 1990 where 838 Chesapeake Bay fishermen were chronically exposed to sunlight. This research found only a marginal association. Again, this obviously has little relation to street lighting which is in the mesopic range

Human sleep patterns and circadian rhythms

The human circadian system is relatively insensitive to light compared to the visual system. (Rea, 2012). It needs several orders of magnitude more light for many minutes to make a measurable response compared to the visual system. This is because the circadian system is biased against false positives in the detection of light. It achieves this by setting high thresholds and by responding only to a narrow subpart of the entire spectrum.

Blue light at night can interfere with human sleep patterns and circadian rhythms by interfering with endogenous melatonin production. Any such impact affects younger people more severely as their eye lenses have not yet yellowed and people who have received cataract operations. This has been a concern in the US since the American Medical Association (AMA) recommended that 3000k or lower CCT lighting be used on roads rather than the more efficacious 4000k. There was no quantification of the health impact or opportunity costs of the difference.

Street lighting is one of many blue light sources. Particularly in residential areas, exposure to street lighting should be generally of brief duration. According to Boyce (2011) citing Figueroa et al (2006) six different studies of melatonin suppression indicate a reasonable threshold for white light to suppress melatonin is a thirty-lux exposure for thirty minutes. A revised threshold (Rea and Figueiro, 2013) of 30 lux for 30 minutes at the cornea is based on 5% melatonin suppression from a 6500K light for 26 minutes. This compares with our values of 10 lux for Category V lighting and 2 lux for pedestrian lighting, using 4000K LEDS. Also, black out curtains can effectively remove extraneous light from a sleeping space (Van Bommel (2015).

General research on the impact of lighting on the circadian system by Zeitzer et al, 2000, Haradar, 2004 and Hashimoto et al, 1996 found night melatonin levels were only suppressed by relatively long periods of lighting at much higher lux levels than New Zealand streetlighting.

There are a small number of relevant studies specific to street lighting. Rea e t al, 2012 looked at the response of 20-year olds after one hour of exposure to outdoor LED lighting (95 lux) of assorted colour temperatures. The results indicated no melatonin suppression except for a 6900K LED source which reduced melatonin by 12% for one scenario and 15% for another.

Conclusions

The conclusions drawn from this work follow.

- There is no evidence to support any health disbenefits from melatonin depletion or blue light hazard or age related macular degeneration from standards compliant road lighting installations in New Zealand, be they HPS or LED.
- Both LED and HPS light sources impact on wildlife but in different ways. There is no evidence to suggest one is better than the other and the evidence for such impacts from streetlighting is mixed.

- There is no hard data from crash studies to show whether white LED light is safer than yellow HPS light but intuitively and from limited visibility and contrast studies white LED light provides a superior visual environment to HPS light. More blue light may help drivers stay alert but no firm evidence yet exists.
- The fine tuning of white light into specific colour temperatures of say 3000K or 4000K is not backed up by strong data. One US field study preferred 4000K while a Chinese laboratory study using different a range of criteria preferred 3000K. A comprehensive and well controlled study is required but even then, the differences are likely to be small.
- Up-to-date information suggests the efficiency gap between 3000K and 4000K has all but closed.
- The International Dark Sky Association is promoting 3000K or lower for street lights but the difference in sky glow between a well-controlled 4000K LED and a 3000K LED is small.
- Experiments at two isolated, rural, state highway lighting installations, one HPS and one LED demonstrated that the sky glow from both installations decayed to near zero within 2 km of the installations.
- Around 70 to 95% of overnight sky glow in the Wellington CBD was estimated to be related to static lighting of which streetlighting is a component. The other components include industrial lighting, waterfront lighting, billboards etc.

Summary of Conclusions

In summary the differences in field performance between 3000K and 4000K street lights are now either small or inconclusive or both. There are potential safety and environmental differences in that range but at present their net size and direction remain murky.

In the local context this means that the NZTA's flexible advice on colour temperature of LEDs as presented in its M30 Specification and Guidelines for Road Lighting Design represents a defensible call, given the evidence available.

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