The safety, health and environmental implications of adopting LED over High Pressure Sodium road lighting

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Date: 30/01/2019

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Executive Summary

Since the 1980s most new road lighting has been of the high-pressure sodium variety. This is yellow in colour. The new LED lighting which is much cheaper to run, easier to maintain and more flexible in its operation is white in colour.

However, LED lighting with its white light has different spectral properties from the yellow HPS light. These differences require investigation to discover any safety advantages or disadvantages.

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. Light reflected off a surface (or luminance) as used in road lighting, is measured in Candelas per square metre (cd/m^2). Above 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". In between levels are referred to as “mesopic”

Road lighting is almost always in the range 0.1 to 2 cd/m^2 towards the top end of the mesopic range where both rods and cones are active. The sharp central vision required for driving primarily uses cones.

Evidence from laboratory trials and some specifically set up on-road scenarios supports the idea that visibility is improved by the wider spectrum achieved by “white” light sources of road lighting like LEDs. This effect is much more pronounced at category P (minor road-emphasis on the pedestrian’s needs) lighting levels than at category V (more major road-emphasis on the driver’s needs) lighting levels. Because of this white light will make pedestrian areas more pleasant and its increased blue component will provide efficiency gains when used at the low light levels found in category P lighting.

The relation between road safety and the colour of light is multifactorial and no on-road studies been carried out to establish a direct linkage between the colour of light and crashes. At category V levels any change may be small and likely to relate to changed colour contrast.

With age, the lens of the human eye yellows meaning that blue light is largely absorbed in the lens, meaning the mesopic impact of blue-rich light is lessened for older drivers.

The British have stated in their lighting standard that there is not enough evidence at this stage to apply S/P ratios to traffic route (category V) lighting based on the greater mesopic luminance associated with white light.

The colour rendition capability of a light source is measured by its Colour Rendition Index (CRI). The colour rendition characteristics of both white light and warm white light as emitted by LEDs exceed by a wide margin that of HPS (LED CRI> 70%, HPS CRI ~24%).There is no evidence of any safety difference between “cool white”, “neutral white” or “warm white” LED lighting.

Owing to the lower power consumption of LEDs yellow high-pressure sodium (HPS) lighting, is quickly being replaced by 4000K “neutral white” LEDs, in New Zealand. This process has moved so fast that there is some degree of controversy about the road safety aspects of the change.

In particular, there have been no fully controlled before and after studies and in existing studies neither the LEDs nor the HPS they replaced may have necessarily been optimised. This means that the results are site and design specific. Thus any comparison must use intermediate measures. These may be on road behavioural measures or lighting related measures. Most studies use visibility of objects to drivers as an intermediate measure. Visibility has good face validity as such a measure, but researchers have struggled to directly relate it to safety.

White light, as emitted by LED sources varies in its spectrum. Correlated Colour Temperature (CCT) is a rough indicator of the spectrum of light delivered by a source. The lower the CCT the greater the percentage of blue light emitted. This review looks at LEDs of various CCTs related to HPS sources..

This report looks at the advantages and disadvantages of lights with more or less blue in their spectra This is because the main difference between HPS light and LED is the lower proportion of blue light in HPS compared to LED. Blue light comes with advantages and disadvantages and little has been done to properly weight the advantages and disadvantages.

In general, with LED technology, in the colour temperature range up to around 4000K, the higher the colour temperature the higher the lumens per watt or efficacy, so all things being equal a 4000K light will be preferred by a designer to a 3000k light. However, the efficacies of LED luminaires in that range are expected to converge between 2020 and 2025 removing that efficacy advantage.

The review covers issues related to:

- Visibility of off the road objects and on the road objects by drivers
- Loss of blue light by yellowing of the eye's lens and by absorption by road surfaces
- The night sky
- Wild Life
- Impact on human health
- Impact on human sleep patterns and circadian rhythms
- Weather conditions

The report concluded that:

- Given the considerable energy savings of LEDs over HPS, there are strong arguments for using LEDs instead of HPS.
- There is no evidence to support any health disbenefits from melatonin depletion or blue light hazard or age related macular degeneration from lighting installations which comply with the current New Zealand Standard.
- There is no direct evidence of any crash related difference between LED and HPS. However, some human behaviour related measurements indicate there may be a yet unquantified safety advantage associated with LEDs. It is unquantified as these intermediate measures have not been linked to crashes when the method of lighting used is LED.
- The above measures include studies of the visibility of small objects on the road by drivers and studies of peripheral vision, which indicate that LEDs may be better than HPS for these measures with a possible optimum around 4000K. Driver fatigue was considered but no firm conclusions were drawn.
- There is currently an efficacy advantage (about 10%) of 4000K LED over 3000K LED however much of this advantage may be offset by the blue light component being preferentially absorbed:
    - by the road surface
    - In the lens of older drivers

- It is expected that the efficacy of 3000k LEDs will reach that of 4000k LEDs within the next 5 years.
- US evidence suggests the blue light component of 4000K LEDs causes more sky glow than HPS light. Present US practice of replacing HPS with LEDs of half the lumen output and the total elimination of upward waste light is claimed to eliminate this increase. In New Zealand a 50% lumen reduction could well be achieved on the Category P network but experience to date suggests it will not be achieved on the category V network. It is not known at present how much of New Zealand's sky glow from street lighting emanates from category V lighting.
- This project has not compared the spectrum of LED light sources in sufficient detail to quantify sky glow effects, but it is noted that;
    - » the spectral plots shows a much-reduced peak for blue light for 3000K as compared to 4000K
    - » 3000K but not 4000K solutions are now eligible for the IDA "seal of approval" something which may be a desirable objective for environment conscious TLAs.

1 Introduction

High Pressure Sodium (HPS) lights have in the last few decades provided most of New Zealand's and the developed world's street lighting. Compared with alternatives they have had the advantages of long life, (hence less maintenance), low cost, energy efficiency and long range optical control1. (Lewin, 2003).

However, now LED lighting which emits white light has been developed to the extent that it has significant advantages over HPS in terms of maintenance, energy efficiency, light control and ease of dimming and brightening to suit changing circumstances via computer control systems.

LED lighting with its white light has different spectral properties from the yellow HPS light. These differences require investigation to discover any safety advantages or disadvantages.

All the safety related work referred to in this document relates either directly or indirectly to visibility. There is nothing here related directly to safety. There is a large body of literature in which visibility is related in different ways to safety (Lewin, 2003). However, in terms of white light vis-vis yellow light safety linkages which can produce direct comparisons are absent. This research has yet to take place.

2 Spectral effects in lighting

2.1 Overview

Light emitted from luminaires is measured in lumens. The unit lumen may appear colour blind, but 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, 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.

Light reflected off a surface (or luminance) as used in road lighting, is measured in Candelas per square metre (cd/m2). According to Lewin, 2003 above around 3 cd/m2, 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/m2 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 lit surfaces are 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". The relevant anatomy of the eye is shown in figure 1.

[1] Optical control refers to the ability to place lumens where the designer want them to be placed.(http://www.cree.com/OCF viewed 2/2/2015

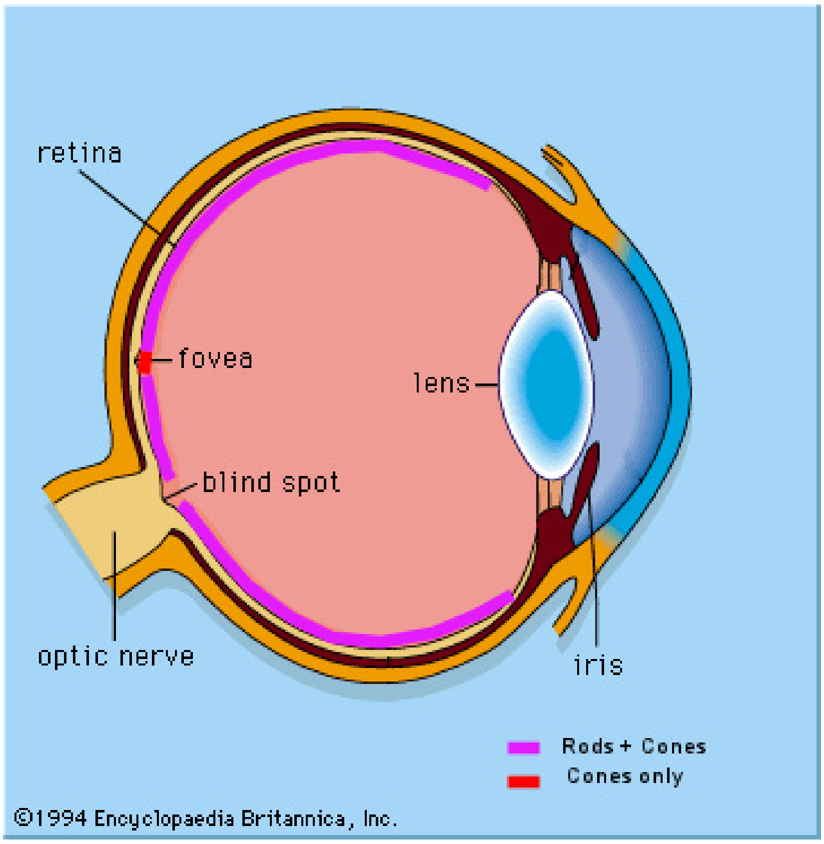

Figure 1: Anatomy of the eye

As shown in figure 1 the eye has a small central area containing only cones called the fovea. The cones in the fovea are responsible for sharp central vision required for activities where visual detail is primarily important like driving and reading.

Figure 2 from Lewin (2003) shows the photopic, mesopic and scotopic ranges and the road lighting levels at that time recommended by CIE and IESNA.

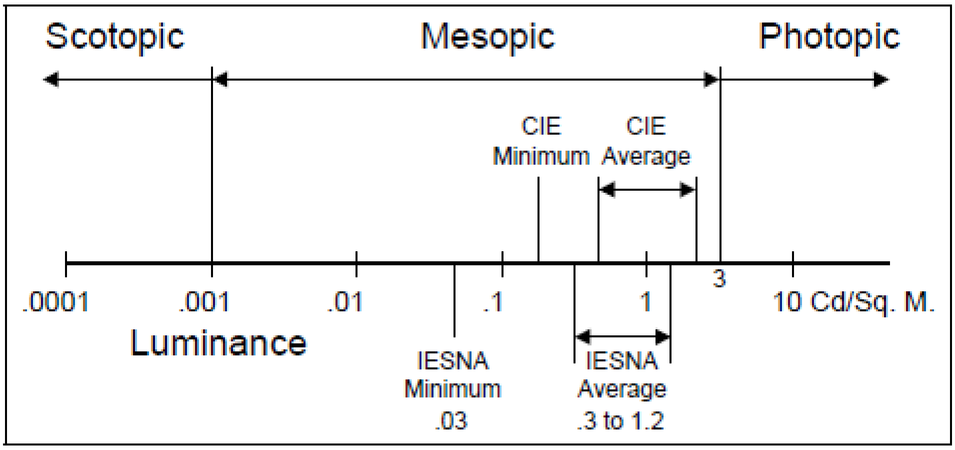

Figure 2: The range of photopic, mesopic and scotopic light levels

Table 1 adapted from Jackett and Culling (2014) relates this to some practical situations. Category V (or route) lighting is that used on motor vehicle routes, where the main objective is to make drivers aware of obstacles that could impact safe driving. Category P lighting is that used for streets lit to pedestrian standard where the main objective is to allow pedestrians to recognise their surroundings and other pedestrians.

Table 1: The different light intensities associated with various 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)	Full moon	0.2	0.02
	Starlight	0.001	

From figure 3 it is apparent that for route 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.

Figure 3 from Institute of Lighting Professionals (2012), illustrates CIE photopic and scotopic luminous efficiency functions V (λ) and V' (λ). The chart illustrates spectral response of the rods and cones. The vertical axis refers to luminous spectral efficiency, a measure of how effectively the rods or cones react to the light of differing wavelengths. V (λ) refers to the response of the cones while V' (λ) refers to the response of the rods.

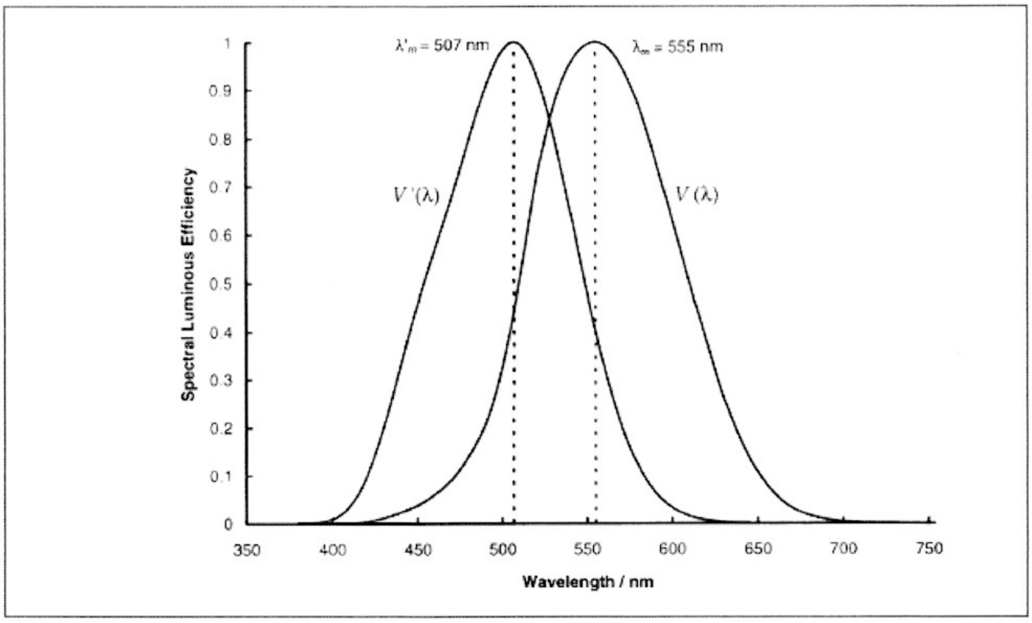

Figure 3: Spectral response of rods and cones

In mesopic conditions both rods and cones come into play and it would seem that light sources which can most optimally utilise them together would be preferred. Given the historic preponderance of sodium light which uses rods inefficiently Lewin, 2003 asks the question "to what extent rod response provides significant visibility of roadway hazards at practical roadway lighting levels "Also, as Lewin (2003) mentions the distribution of cones and rods is not uniform throughout the retina. Only cones lie at the exact centre of the field of view, while rods are significant in the peripheral field. The location of the object to be seen, therefore affects visibility. Thus, a source which makes good use of rods may improve peripheral vision but not improve centre field vision at all. Figure 4 depicts the rod and cone density on the retina

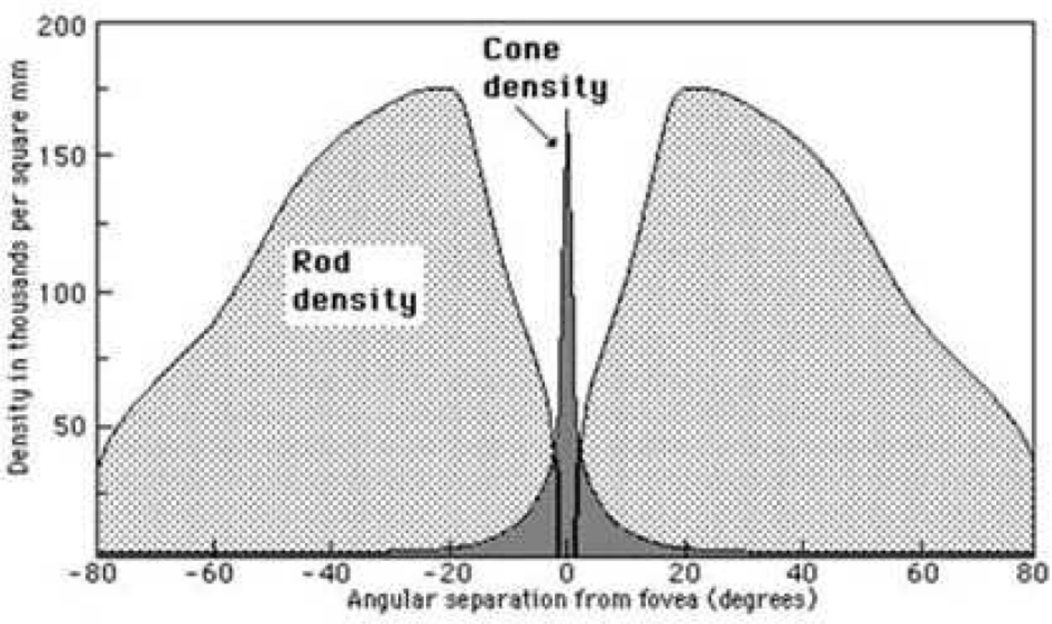

Figure 4: Rod and cone density on retina[2]

2.2 White light (LED) and Yellow light (HPS)

The acronym SPD denotes the Spectral Power Distribution of a light source. The light our eyes can detect is made up of a spectrum of colours ranging from wavelengths of 380nm (violet) to 760nm (red). The SPD is a graph that shows the power of each wavelength of light produced by a particular light source[3].

Compared to sodium sources white sources have much greater output at shorter wavelengths. Figure 5, figure 6 and figure 7 are spectral power distribution charts for HPS, Metal halide and LED respectively.

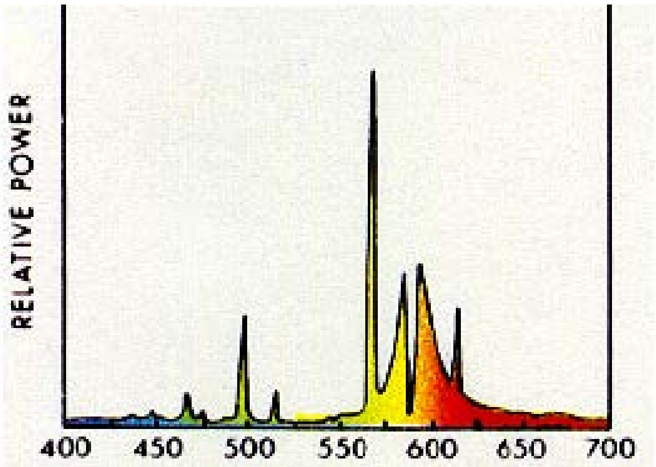

Figure 5: HPS spectral power distribution chart

[2] source www.ledroadwaylighting.com
[3] http://www.lighting.philips.com/main/support/support/faqs/white-light-and-colour/what-is-the-spd-of-a-light-source

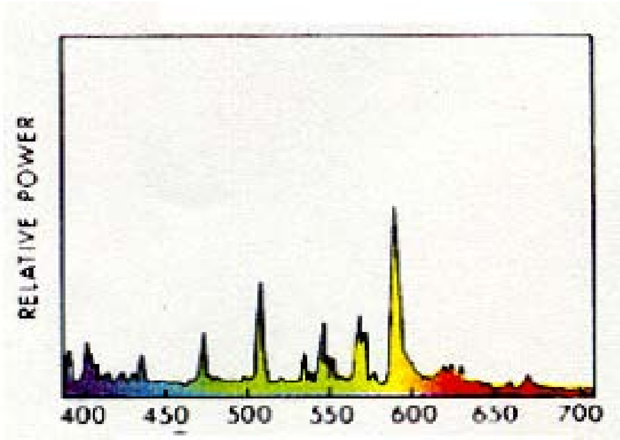

Figure 6: Metal halide spectral power distribution chart

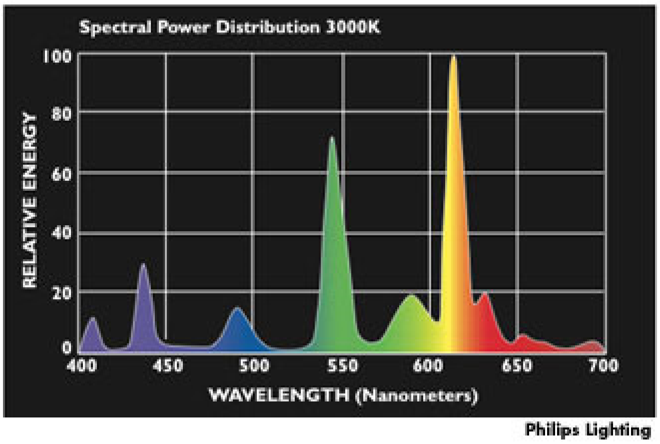

Figure 7: LED spectral power distribution4

It is apparent that the LED and metal halide have broadly similar distributions with both considerably broader than that for HPS. A rough guide to the spectrum emitted by a light source is the colour temperature of the light source. Generally, the higher the colour temperature, the bluer the light emitted. Figure 8 from Van Bommel, 2015 illustrates the spectra of two LEDs. The leftmost one has a colour temperature of 2800K "warm white" and the rightmost one a colour temperature of 4000K "cool or neutral white". It is apparent that the rightmost one has a spike of blue around the 450 nm wavelength and it is this spike which has led to concern about the blue light LEDs put into the environment. The numbers close to the vertical axes (namely 828 and 840) are the colour designations of the two systems

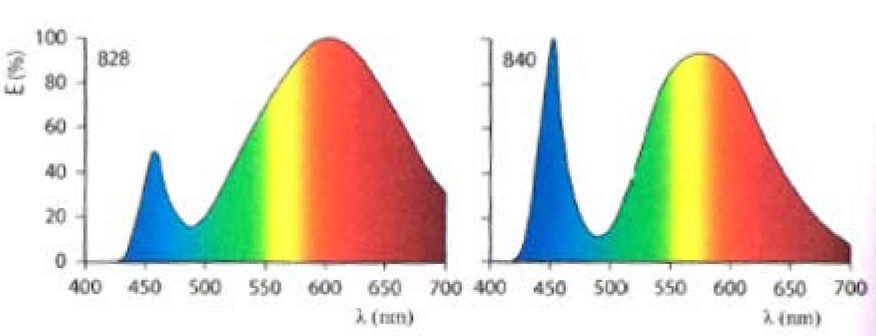

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Figure 8: Spectral Power Distributions of two LED sources: Leftmost 2800K, rightmost 4000K

[4] source http://www.ledaladdin.com/light_guides/led_light_colour_rendering_index_cri.html

Light source manufacturers state the light source's colour properties using an international colour designation consisting of three digits. The first digit represents the light source's colour rendering and the last two digits stem from the colour temperature in degrees Kelvin, being divided by 100.For example a light source with the colour designation 828 has a colour rendering index between 80–89 and a colour temperature of 2800 K. Colour Rendering is the ability of a light source to render colour compared with a standard light source. It is measured by a Colour Rendering Index (CRI) which is a scale from 0 to 100 percent. A CRI of 85 to 90 is considered good colour rendering. Figure 8 tells us that the two light sources, though spectrally different, are similar regards colour rendering as shown by the same first number in the colour designation.

2.3 The efficacy of LEDs with different spectra

With LED technology, the higher the colour temperature in general the higher the lumens per watt so the 4000K light source in the rightmost figure is likely to have greater lumens per watt. This is reflected in both the Transport Agency's M30 Specification and Guidelines for Road Lighting Design (NZ Transport Agency, 2014) and the Australian and New Zealand Road Lighting Standard from which much of the M30 specification is derived. The M30 Specification states that:

"The preferred value of correlated colour temperature for road lighting is 4000°K (p29)"

and the Standard contains a similar statement. All things being equal, street lighting decision makers are more likely to choose the lighting source with the greatest "efficacy". Efficacy is the number of lumens delivered per watt of power. This situation may not persist for more than the end of this decade as the efficacy of cool white and warmer white LED luminaires are expected to converge between 2020 and 2025 (See Figure 9 from Van Bommel, 2015 p138).

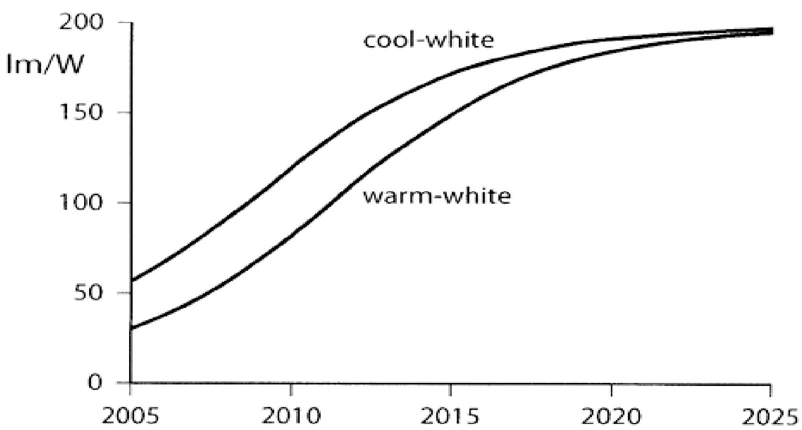

Figure 9: US Department of Energy report DOE 2013 from van Bommel (2015) showing the expected convergence of efficacy for warm white and cool white LEDs

To help establish the current range of efficacies the websites of luminaire suppliers identified in the May 2017 list of "M30 Accepted Luminaires" were examined. Where available the efficacies for 5000K, 4000K and 3000K LED luminaires were noted and the results summarised in Table 2.

Table 2: June 2017 efficacies for NZ market luminaires using 5000K, 4000K and 3000K LEDs

Company	LED manufacturer	Luminaire	Watts	Efficacy 5000K	Efficacy 4000K	Efficacy 3000K	3000K penalty
Orange Tek	Nichia219C	Arialed	54	123	123	115	-7%
Orange Tek	Cree XPL	Arialed	54	142	142	123	-15%
Orange Tek	Cree XPG2	Arialed	55	128	128	120	-7%
Philips	Philips	Iridium Gen3	55	-	125	114	-9%
ADLT	Cree	Cree XSP1	53	112	107	88	-18%
Average			**54.2**	**126**	**125**	**112**	**-10%**
Range (min to max)					33%	40%	

Table 2 implies that:

- The difference in efficacy between 5000K and 4000K no longer exists
- The efficacy penalty for choosing 3000K over 4000K varies between 7% and 18% (average = 10%)
- For 4000K luminaires on the approved list the efficacy varied between 107 and 142 lm/watt (a difference of 33%)
- Van Bommel (2015) estimated the difference in efficacy between cool white and warm white to be around 20%. The figures above suggest that gap may already be starting to reduce.

3 Lighting levels where wider spectrum white light has advantages over HPS

We have seen from the experimental research conducted that the visibility related advantages of white light increase as the lighting level decreases. At some level there must be a point where white light becomes better than HPS.

Historically the illuminating value of lighting has been calculated only under photopic conditions which is obviously going to be inaccurate to some degree under mesopic conditions. The CIE traditionally has used the sensitivity of the retinal cones by wavelength (V-lambda Curve, or V (λ)) to define the lumen value of lighting, ignoring the sensitivity of the retinal rods by wavelength (V-lambda Prime Curve or V' (λ)). This has recently changed with the CIE now recommending a linear combination of the two (CIE, 2010).

The ratio of the luminous output evaluated according to the scotopic V' (λ) to the luminous output evaluated according to the photopic V (λ) is required to make mesopic photometry possible. This ratio is called the S/P ratio. The S/P ratio only gives the ratio of Scotopic to Photopic luminance. It is a scaling factor to reduce or boost photometry made under photopic assumptions to align with the mesopic conditions that apply for the design. The CIE has published a table which relates the differences in effective luminance at various lighting levels between using photopic photometry and mesopic photometry. This as reported in Puolakka and Halonen, 2010 is shown in table 3.

Table 3: percentage differences between mesopic and photopic luminances calculated according to CIE system for a range of S/P

	S/P	Photopic luminance cd·m⁻² 0,01	0,03	0,1	0,3	0,5	1	1,5	2	3	5
LPS ~	0,25	-75 %	-52 %	-29 %	-18 %	-14 %	-9 %	-6 %	-5 %	-2 %	0 %
	0,45	-55 %	-34 %	-21 %	-13 %	-10 %	-6 %	-4 %	-3 %	-2 %	0 %
HPS ~	0,65	-31 %	-20 %	-13 %	-8 %	-6 %	-4 %	-3 %	-2 %	-1 %	0 %
	0,85	-12 %	-8 %	-5 %	-3 %	-3 %	-2 %	-1 %	-1 %	0 %	0 %
	1,05	4 %	3 %	2 %	1 %	1 %	1 %	0 %	0 %	0 %	0 %
MH warm white ~	1,25	18 %	13 %	8 %	5 %	4 %	3 %	2 %	1 %	1 %	0 %
	1,45	32 %	22 %	15 %	9 %	7 %	5 %	3 %	3 %	1 %	0 %
	1,65	45 %	32 %	21 %	13 %	10 %	7 %	5 %	4 %	2 %	0 %
	1,85	57 %	40 %	27 %	17 %	13 %	9 %	6 %	5 %	3 %	0 %
	2,05	69 %	49 %	32 %	21 %	16 %	11 %	8 %	6 %	3 %	0 %
LED cool white ~	2,25	80 %	57 %	38 %	24 %	19 %	12 %	9 %	7 %	4 %	0 %
MH daylight ~	2,45	91 %	65 %	43 %	28 %	22 %	14 %	10 %	8 %	4 %	0 %
	2,65	101 %	73 %	49 %	31 %	24 %	16 %	12 %	9 %	5 %	0 %

The range of normal road lighting levels are shown within the rectangle with a black border and the background coloured for differences of 5% or greater. Concentrating only on HPS and LED, it can be seen that using mesopic photometry changes little for HPS in the road lighting range. LED white light is well suited to Category P level lighting (0.1 and 0.3 cd/m^2) and as can be seen in Table 1 boosts of 10% to 30% above the calculated photopic values are then appropriate.

Note that the British standard does not extend the use of S/P ratios into traffic route lighting (Category V lighting in NZ). As the British Road lighting standard remarks (BSI, 2013 page 53) for traffic route lighting there is insufficient evidence to specify the situations in which the trade-off between light level and S/P can safely be applied. For lower levels the British Standard indicates the trade-off may be carefully applied. Thus, is reflected also in the current standard AS/NZS1158 which requires de-rating the lumens from HPS lights by 25% in minor road (Category P) lighting but not for LED (or MH) white light.

Van Bommel (2015) also points out that the studies leading to the CIE adjustment factors in table 1 were carried out using subjects in the 20-35 age range. With age, the lens of the human eye yellows meaning that blue light is largely absorbed in the lens, meaning the mesopic impact of blue-rich light is lessened for older drivers compared to that shown in table 3.

4 Road Safety aspects

HPS lighting, is quickly being replaced by 4000k LEDs, in New Zealand. This process has moved so fast that there is some degree of controversy about the road safety aspects of the change. In particular, there have been no fully controlled before and after studies and in existing studies neither the LEDs nor the HPS they replaced may have necessarily been optimised. This means that the results are site and design specific. Thus, any comparison must use intermediate measures. These may be on road behavioural measures or lighting related measures. An important behavioural measure related to safety is the visibility of objects at different points in the visual field. A major objective of road lighting is to improve the visibility of objects to drivers. Visibility has considerable face validity as an intermediate outcome measure for road safety lighting, in spite of the fact that directly relating visibility measurements to safety has proved difficult for researchers (Schreuder et al, 1998). Often time taken to observe or reaction time is used as a surrogate for visibility. The next section looks at visibility to drivers of objects both off the road and on the road.

4.1 Visibility of off the road objects to drivers

Lewis (1999) investigated light level, sensitivity to contrast, and reaction time for mercury, metal halide (similar in colour to LED), incandescent, high pressure sodium (HPS) and low-pressure sodium (LPS) light sources. Observers were asked to detect the appearance of a pedestrian standing at the curb and to determine whether the person was a possible hazard (pedestrian facing the roadway) or not (facing away). The time taken for observers to decide was measured and used as a surrogate for visibility. At levels of 3 cd/sq. m. and more, light source type has no effect. As lighting levels decreased the sodium sources require increasingly longer reaction times versus the white MH source. At very low levels, the difference is very significant. Figure 10, from Lewis (1999) reproduced from Lewin (2003) illustrates the time taken by the observers to make this determination versus luminance level, for the various sources.

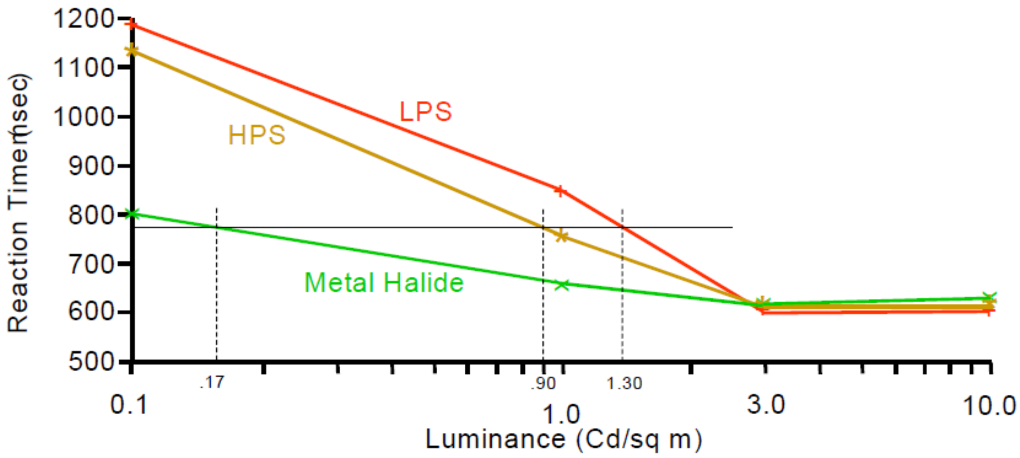

Figure 10: Reaction time versus luminance for HPS, LPS (both yellow) and metal halide (white)

The horizontal line representing 775 msec reaction time intersects all three curves. Dropping vertical lines from each curve to the X-axis provides the luminance level needed to produce that reaction time in this experiment for each source. This reaction time can be produced by a much lower level of MH than HPS. For LPS, a higher lighting level is needed to produce the illustrated reaction time. It can be seen from figure 10 that most of the reaction time divergence between HPS and the white light sources is in the category p or lower range. However, this work is a laboratory experiment and Lewin (2003) warns (p 9) that:

"many factors are involved in determining the extent to which such visibility characteristics apply in real world situations. The nature of the driver's visual task can strongly influence such effects."

Lewin summarised the state of play at the time by indicating that that for roadway visual tasks, the effect of lamp spectral distribution could not be definitively stated. However, he thought that the following (paraphrased) points could be made[5] regarding such tasks.

- No research results indicate lower visibility using metal halide sources, and some report much higher visibility, for equal lighting levels.
- Where a positive impact in using metal halide is indicated, results show a lower lighting level can be used while maintaining equivalent visibility.
- To the extent, however, that foveal tasks are important on roadways at night, cone vision is significant. In such a case, lowering the lighting level is likely to reduce the visibility of such tasks.

[5] Lewin's white light source was metal halide.

- Any visibility benefits to be obtained by converting from sodium to metal halide lighting, and retaining present lighting levels, cannot be quantified.
- For low spatial frequency tasks, substantial visibility increases for such tasks are to be expected, along with commensurate safety improvement.
- For high spatial frequency tasks, there is likely to be no improvement.

His explanation includes the following points:

- In a driving task much information comes from outside of the small central field of view. As an example, a pedestrian stepping off the curb may be initially detected in the peripheral field of view, followed by the driver directing his/her view to more clearly discern the hazard.
- There is debate and much uncertainty on the relative importance of foveal versus peripheral vision for driving tasks, with some authors feeling that foveal vision is of primary importance (Berman and Clear, 1998). However, Owsley and McGwin, 1999 state "Visual acuity is only weakly related to crash involvement, whereas peripheral vision appears to play a more critical role."
- Until recently, it has been assumed that the spectral effects apply only to objects seen in the off-axis field. This is because rods dominate the off-axis portion of the retina, while cones are concentrated in the fovea, or central area of the retina. In fact, exactly in the centre, no rods are present.
- Off-axis tasks are extremely important at night, and are believed to be closely related to issues of safety. Also, there is evidence that rod vision is important for almost *all* visual tasks, even those that are looked at directly.(Lewis, 1998, Lewis 1999)

Since then there have been a small number of research projects in this area. Akashi et al (2007) conducted a field study where subjects drove a vehicle along a lit street while performing a high-order decision-making task. They identified the direction of an off-axis target, toward or away from the street, and braked or accelerated, accordingly. Three light sources were compared, two metal halide, the other HPS. Table 4 shows the target luminances for the three sources. The unified luminance[6] of the HPS and CMH_L were the same while CMH_H had a higher unified luminance. The experiment was also conducted under daytime conditions.

6 Unified luminance is an American measure of lighting which is optimised to the human eye's performance at all levels of lighting through photopic, mesopic to scotopic.

Table 4: Target luminances for three types of lighting[7]

Lighting condition	S/P ratio	Photopic luminance (cd/m²)	Unified luminance (cd/m²)
1. HPS	0.55	**0.057**	**0.035**
2. CMH_H	1.17	**0.057**	0.065
3. CMH_L	1.17	0.030	**0.035**

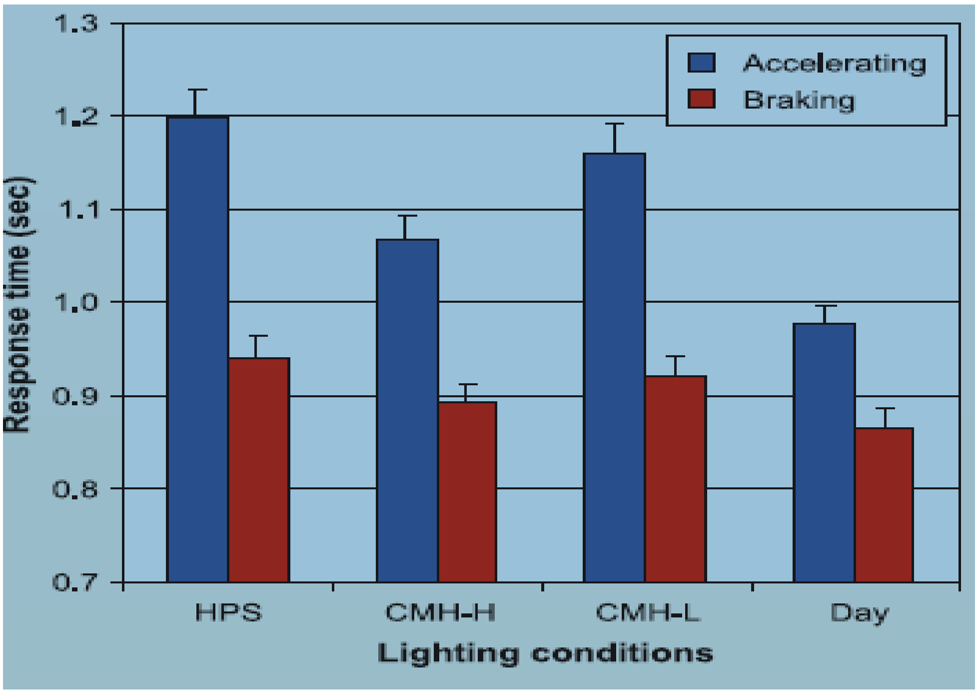

Figure 11: Mean response times for braking and accelerating

The results demonstrated that both braking, and acceleration response times decreased monotonically as unified luminance increased (figure 11). To put these results into perspective, these are all very low lighting levels, an order of magnitude below the design levels for even category p lighting and are thus not relevant to street lighting of any sort in New Zealand.

To detect off road objects like pedestrians typically requires drivers to use peripheral vision. If an object of interest is detected the driver may also seek greater clarity by central (foveal) vision through head/eye

[7] The S/P ratio is the ratio of the luminous output evaluated according to the scotopic V' (λ), to the luminous output evaluated according to the photopic V (λ). This is dealt with in more detail later in the document

movement. Information in peripheral vision comes from both rods and cones but the central foveal portion of the eye contains only cones.

Younis (2012) looked at the impact of HPS, MH (Metal Halide) and LED street lights on pedestrian night time visibility. The pedestrians were simulated by manikins and were in stationary positions on the footpath at the left side of the road. The subjects were 27 male licensed drivers between 18 and 28 who had good visual acuity and were not colour blind. The cars were driven at between 35 and 40 km/hr and kept in the right lane. The drivers were told to focus at the centre of the road directly ahead. This restriction meant that the experiment dealt purely with peripheral vision as eye/ head movements were not allowed. The vehicle used was a Mitsubishi Pajero with xenon-gas discharge (HID) headlamps. The specifications of the lights were given in table 5.

Table 5: Specifications of lights used in Younis (2012)

	Variable	Control Level
Street lighting	Height	Fixed at 10 m
LED	Lamp/Luminaire	LED/Cooper VTS-C04-LED-E1-SL2
	Watt/Lumens	101W/7404 lm
	BUG Rating	B1-U2-G2
Street lighting	Height	Fixed at 10 m
HPS	Lamp/Luminaire	HPS/Cooper VXS-150-HPS-XX-2S
	Watt/Lumens	150W/16000 lm
	BUG Rating	B3-U1-G3
Street lighting	Height	Fixed at 10 m
MH	Lamp/Luminaire	MH/Cooper VXS-150-MP-XX-2S
	Watt/Lumens	185W/14000 lm

The colour temperature of the LEDs were not given but the supplier appears from its literature to provide LEDs at a standard 4000K and 3000K, with, 5000K and 5700K as options.[8] The detection distance was measured in the presence of on-coming car headlamps. Pedestrians wore three different clothing colour; white, yellow and, black. The pedestrian stood on the left footpath. This was done because in LHD countries headlights typically project less light to the left side compared to the right side. The mean detection distances found for the different light sources for pedestrians wearing different colours of clothing are shown in figure 12.

[8] http://www.cooperindustries.com/content/dam/public/lighting/products /documents/mcgraw_edison/spec_sheets/mcgraw-vts-ventus-led-td500008en-sss.pdf Viewed 28/5/2017

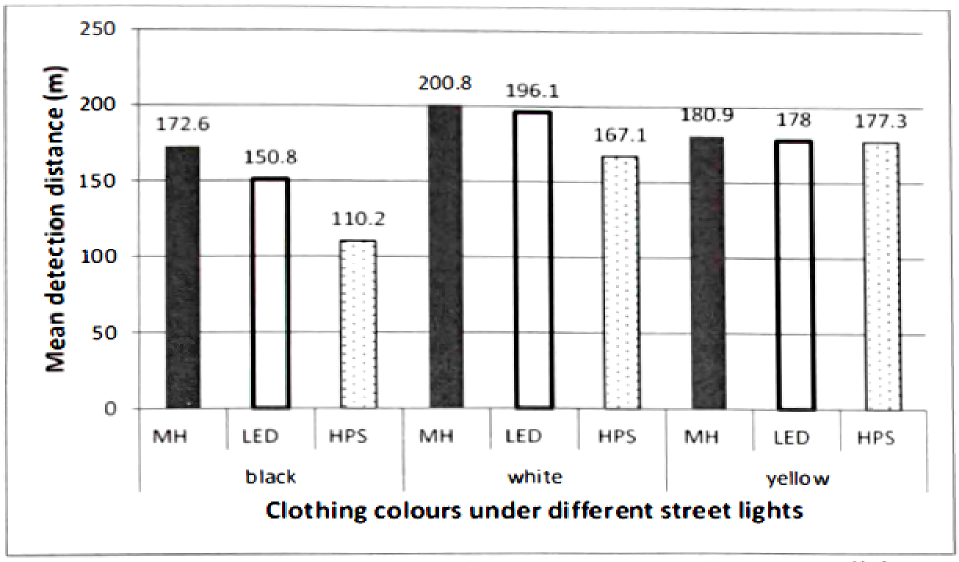

Figure 12: Mean pedestrian detection distances by light source and clothing colour.

Statistically the MH and LED street lights did not differ in mean detection distance which for both was significantly larger than for HPS. The 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.

4.2 Visibility of objects on the road by drivers

It is known that white light such as that from LED or MH sources is better for peripheral vision purposes than the yellow light of HPS and that in LEDs a greater blue component is associated with better peripheral vision. The impact on central vision is not so clear. Various authors[9] have reported dramatic improvements in the visibility of slightly off-axis small objects under white light versus sodium. At the same time no increase in visibility associated with the use of white light versus sodium in cases involving small on axis objects has been reported (Harvard and Janoff (1997)). Lewin's explanation for this is that the fovea, consisting of cones, is used to provide the visibility of such objects, and therefore no benefit would be expected. Lewin also observed that it appears logical that visual tasks exist including those analysed by the Fovea that are best perceived by rods and others that are viewed by some combination of the fovea and peripheral retina.

There have been a number of attempts to look at this and compare the performance of LED and HPS. A confounding factor is the presence of car headlights which tend to lessen the impact of the street lighting regarding visibility of objects on the road. This impact extends up to some 80m from the car depending on the type of headlamp (Van Bommel, 2015). Some studies are in the presence of this confounder others have controlled for it or eliminated it by having car headlights off.

Whiter light results in improved reaction times for Metal Halide vis-a-vis HPS. (Lewin (2004)). A similar result could be expected for LEDs. More recent work involved a team of Chinese researchers, Zhiyong et al, 2011. In a laboratory experiment they found the following (Figure 13) curves of reaction time and luminance for HPS and LED 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.

[9] He et al (1997), He et al (1998) Bullough and Rea (2000), Rea and Boyce(1998)

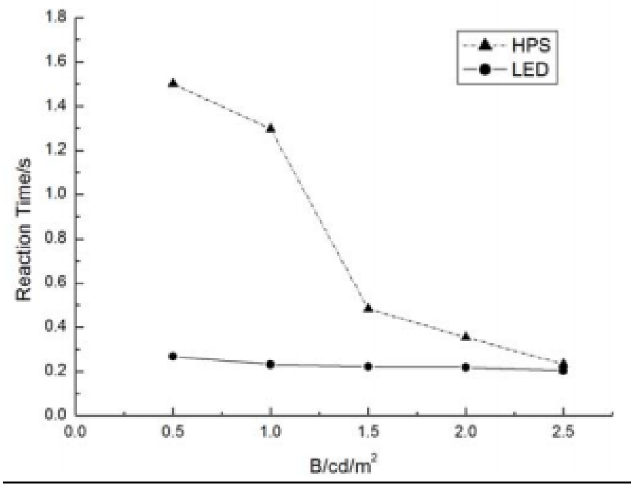

Figure 13: Curve relating reaction time to luminance using HPS and LED

It is obvious from Figure 13 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.

Over the last few years trials of various types of LED lighting against more traditional sources including HPS were carried out in the cities of Anchorage, San Jose, San Diego and Seattle by consortia led by Nancy Clanton of Clanton Associates[10]. The trials in San Jose, San Diego and Seattle are documented in Mutmansky (2010a), Mutmansky (2010b) and Clanton et al (2014), while the Anchorage trial is mentioned and its results reported in Clanton (nd). The Seattle trial was the only one specifically designed to compare light sources although interesting information may be gleaned from the others. In Mutmansky et al (2010a) the impact of different lighting sources in the city of San Jose on the detection of on-road objects was tabulated. The light sources used were as in table 6. The lumen outputs of the luminaires were not harmonised.

Table 6: Table of San Jose Light Sources

Test Area	Technology	Measured CCT	Full Power	Low Power
1	IND	3129 K	112 W	67W*
2	HPS	1894 K	169 W	93W*
3	LED_a	5191 K	98 W	62W*
4	LPS	1742 K	172 W	NA
5	LED_b	3502 K	144 W	75W
6	LED_c	4988 K 4369 K†	96 W	47W

An experiment was carried out to look at the detection distances of small targets of varying colours on the roadway. This was to give a minimum performance measure as it could be expected that larger objects like pedestrians would be detected at larger distances.

The Small Target Visibility (STV) method (IESNA RP-8, 2005) was used. This method 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. The STV targets are flat, vertical, wooden square targets, which measure 7 inches

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

(~18 cm) on each side, with the surface painted. The colours used are grey, blue, green, red and yellow. Figure 14 shows the targets.

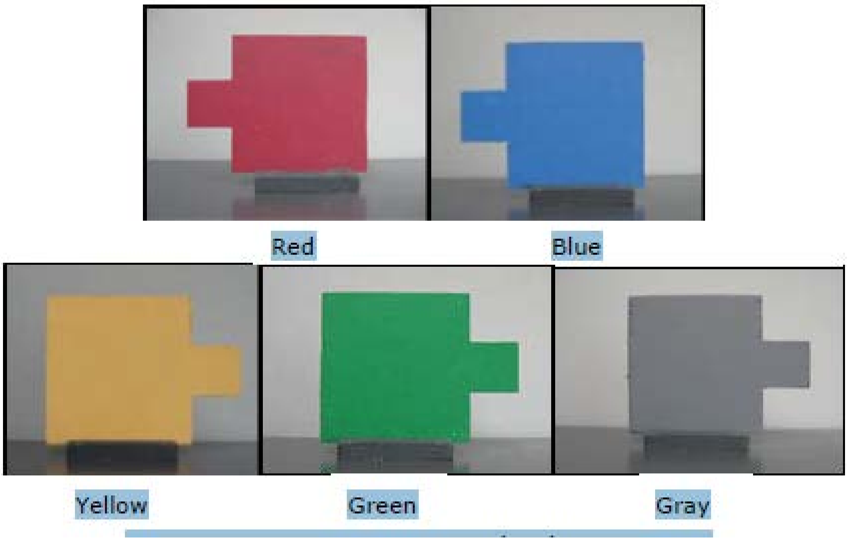

Figure 14: Targets used in visibility experiments by Clanton Associates

All targets were positioned around 60 inches (152.4 cm) from the side of the gutter towards the centre of the roadway (which was median divided) so as not to be struck by the participant vehicle. The participants sat in the vehicle as it moved down the road and pushed a notification button when they detected a target

The results claimed that detection distances for LEDs were similar to or exceeded detection distances under HPS although one of the LEDs (3500K) performed worse than HPS. Figure 15 shows the detection distances of various colours using the different light sources. It can be seen that the only LED which appears markedly different from HPS is LED 3500K which performed worse for all colours. The figures quoted are from the 1st day of the trial when the lights were on at “full power” and the roads were damp from rain.

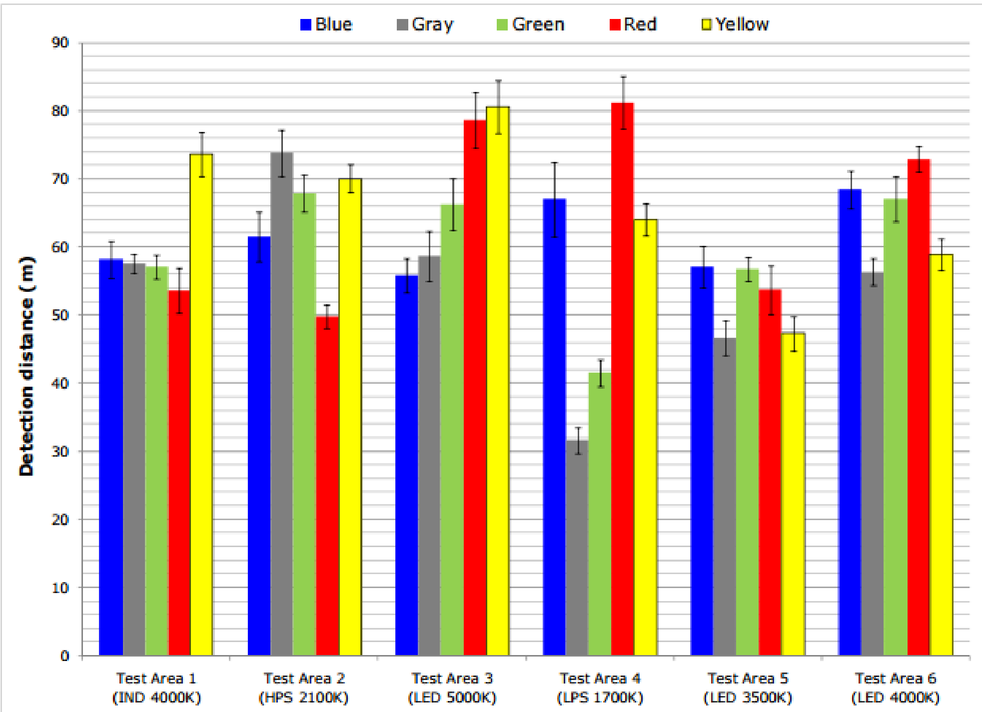

Figure 15: Detection distances by light source and colour-San Jose Wet Surface

The 4000K LED performed better than HPS for blue and red targets, performed the same for green and was inferior for yellow and grey. As an overall comparison using all data from both wet and dry roads the authors produced the following relativity chart (Figure 16).

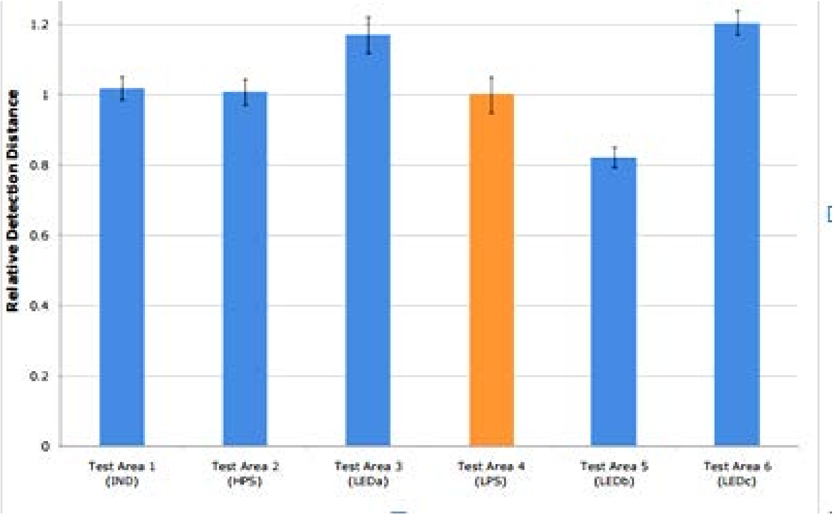

Figure 16: Detection distances all colours –both wet and dry surfaces

It is apparent from the above that the higher CCT LEDs outperformed the HPS by around 20% while the 3500K LED underperformed it by around 20%.

For Seattle (Clanton et al, 2014) a similar experiment with a different set of luminaires was used, again in both wet and dry conditions. The luminaries used are shown along the horizontal axis of figure 17 which shows their comparative detection distances for wet and dry conditions for undimmed luminaires.

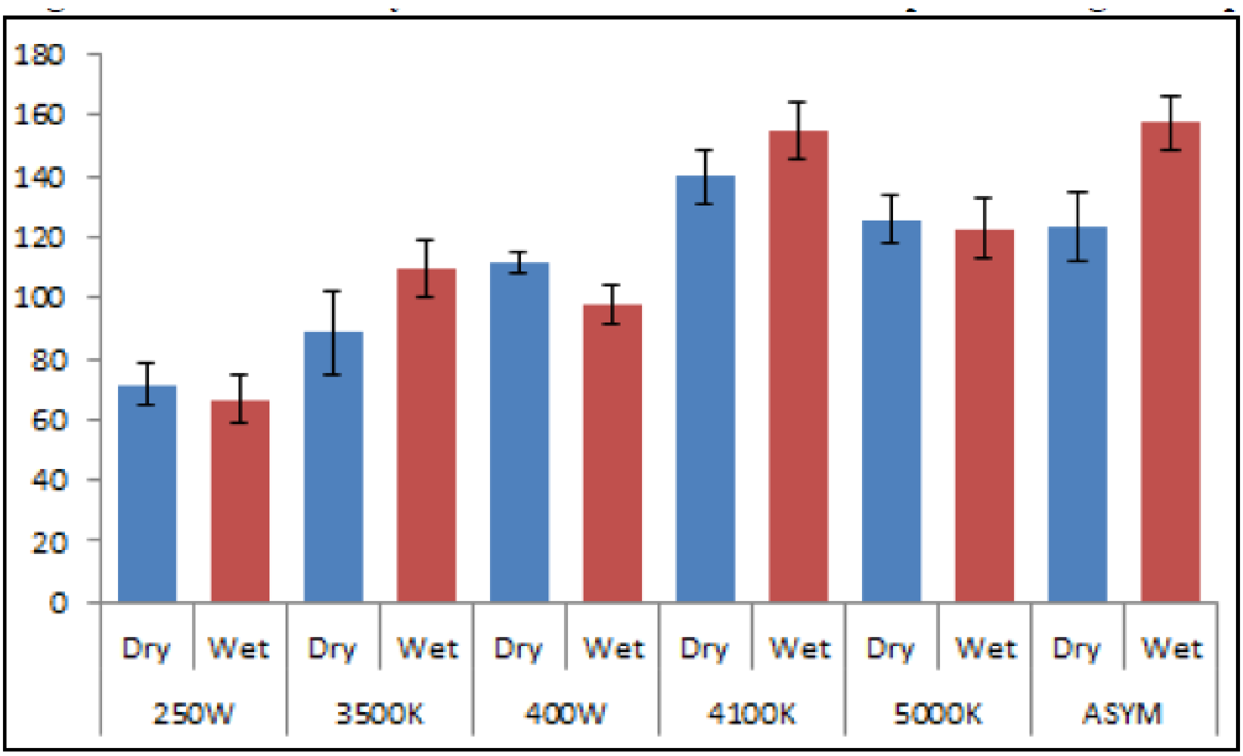

Figure 17: Detection distances for wet and dry conditions for undimmed luminaires -Seattle.

It is clear that the 4100K LED outperforms all luminaires be they LED or HPS, while again the 3500K luminaire appears not as good.

In San Diego (Mutmansky, 2010b) the relevant luminaires shown in table 7 below.

Table 7: Table of San Diego Luminaries

Test Area	Technology	Manuf. Stated Color Temp.	Measured Color Temp.
1	Induction	3000K	2930K
2	Induction	3000K	3250K
3	Induction	4000K	3625K
4	LED	3500K	3475K
5	LED	3500K	3500K
6	LED	3500K	4560K
7	Existing HPS (roadway)	2100K	Not measured
8	Existing HPS (intersection)	2100K	Not measured

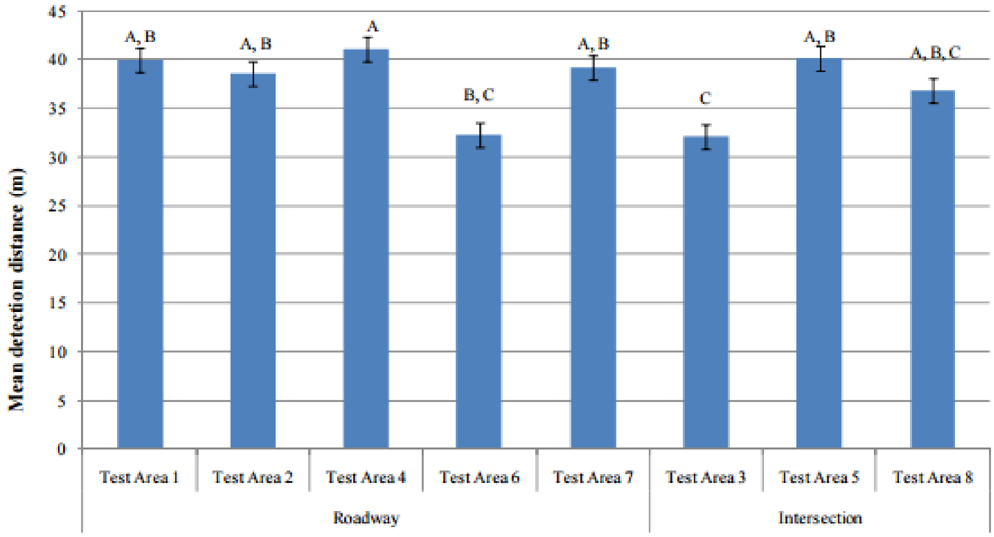

Figure 18: Detection distance of San Diego Luminaires

Figure 18 indicates that the two LEDs which measured at 3500k equalled the two HPS sources but the LED which measured at 4500K was significantly inferior. Clanton provides the following chart (Figure 19) which Clanton states in a personal communication is for the Seattle test which was the only one of the four specifically designed to compare luminaire performance. The red horizontal bar represents stopping distance in the wet.

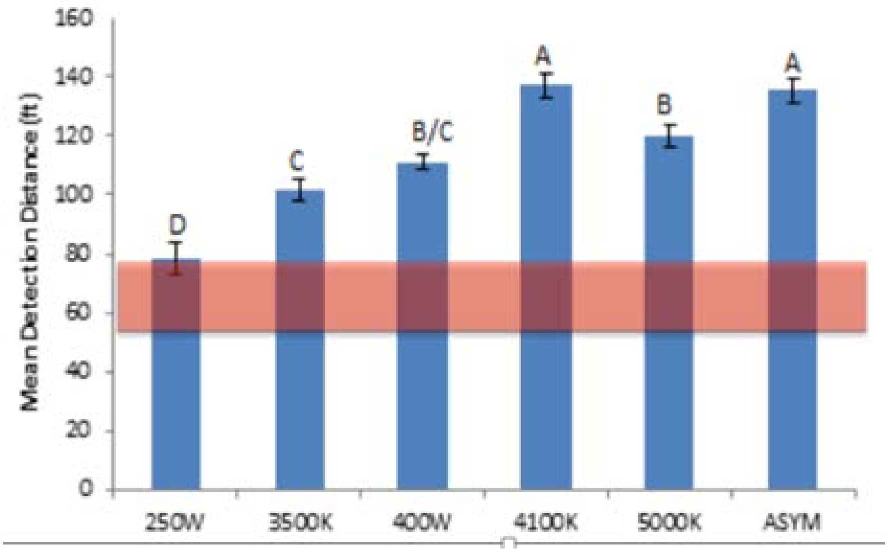

Figure 19: Detection distance comparison of Seattle Luminaires-using wet and dry road data

This shows that the detection distance of all the luminaires complied with the wet stopping distance of the surface and indicated an advantage associated with the 4100K LED luminaire. Also, considering illuminance uniformity the 4100K LED luminaire was the least of all the LED luminaires but also had the greatest detection distance. This indicated that a lower level of uniformity (within reasonable limits) may improve detection distance. The results would indicate for the equipment used in Seattle, the LEDs of around 4100K had the highest visibility distance notwithstanding their lower uniformity. 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) using LED and HPS light sources the spectra of which are shown in figure 20.

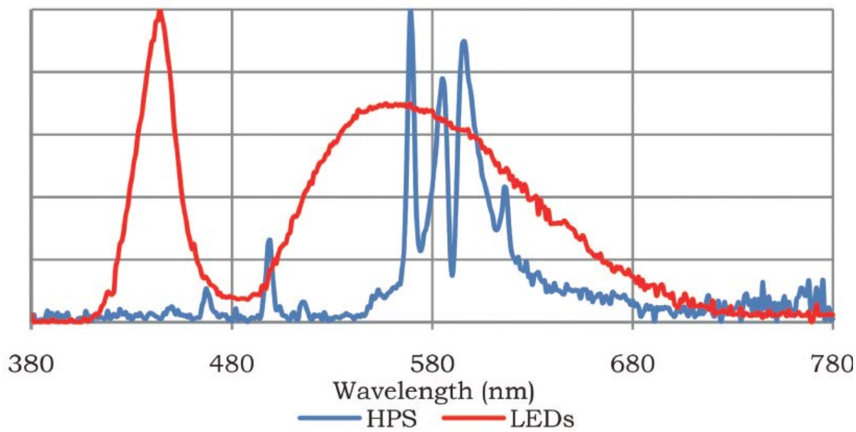

Figure 20: Spectra of the HPS and LED light sources used by Fusheng et al.

The HPS Lamps were 2321K while the LEDs were 4810K. The average luminances of the road surfaces were about 2 cd/m^2, which is within the range of mesopic vision. The subjects were eight university students in their 20s, two females, six males with normal or corrected to normal vision. The targets were on the road rather than the roadside. They assessed the target's visibility for each position and target. Blue, green and red targets plus an achromatic target were used. The subjects' assessments were plotted against calculated visibility level (VL) and good agreement was found suggesting the assessments had an acceptable level of validity. The visibility levels were calculated using the relationship:

$$VL = \frac{\Delta L_{actual}}{\Delta L_{threshold}} = \frac{L_t - L_b}{\Delta L_{threshold}}$$

from Adrian (1989), where L_t is the luminance of target, L_b is the background luminance and $\Delta T_{threshold}$ is the luminance difference needed for minimum visibility between a target and its background. Figures 21 and 22 illustrate the changes in observer ratings for the HPS and the LED sources respectively at different calculated visibility levels.

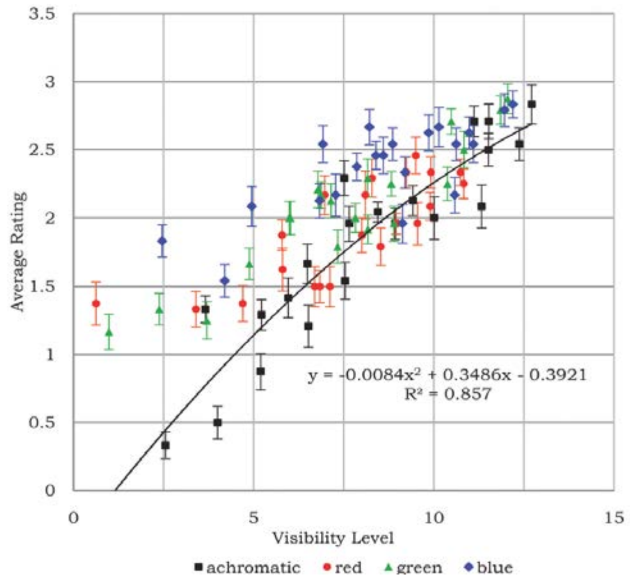

Figure 21: Assessed visibility rating of LED against calculated visibility level

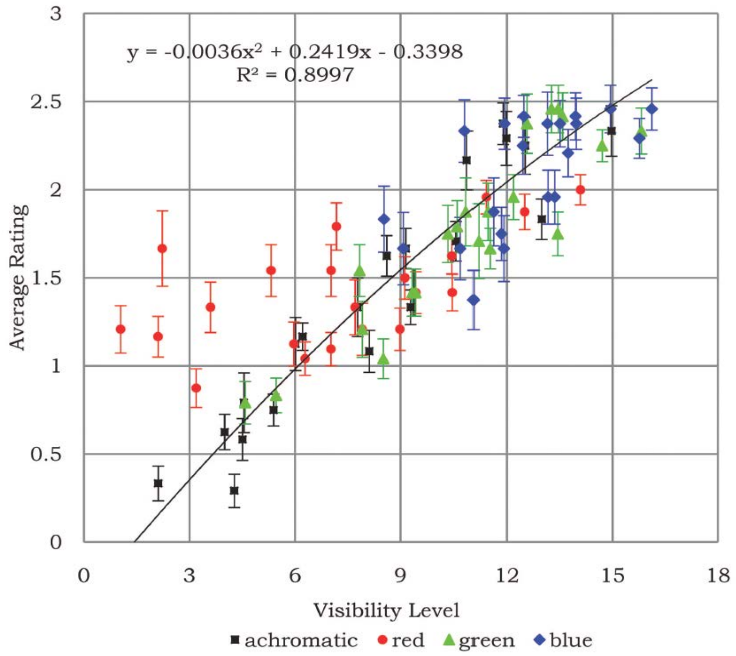

Figure 22: Assessed visibility rating of HPS against calculated visibility level

For both LED and HPS as the visibility level increases, the average rating of visibility also increases. It is apparent from inspection of the two charts that for any given visibility, the 4810K LED obtains a higher rating from the subjects than HPS.

4.3 Conclusions

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

5 Colour rendition and colour contrast

5.1 Colour Rendition

Another aspect mentioned by Lewin (2003) is colour rendition. This refers to the support the lighting provides the eye to distinguish colours as measured by the Colour Rendering Index or CRI. (See Bridger et al, 2012).

Objects like signs, road markings are colour coded and for safety and traffic flow to be optimised it is necessary for these colours to be well discernible at night. Use of a narrow spectrum source like HPS may make colours look different at night vis-a-vis daytime. The extent or impact of colour rendering within the context of roadway lighting is not well understood. It is complicated by the fact that road markings and signs are usually retro reflective thus enhancing their ability to reflect light. This means they are illuminated both by the street lighting and headlamps - a hard to analyse combination.

White light is any light that appears white to the human eye. There are no robust definitions but usually to qualify as “white light” a source needs to have a CRI of 70% or better. This CRI >= 70% has now been incorporated into AS/NZS1158 to define white light from LEDs.

In terms of LED lighting there has been some discussion as to the comparative colour rendition of warm white light (lower CCT) and cold white light (higher CCT) and any possible safety implications. Both warm white light and cold white light LEDs have a CRIs of 70% or better.

Warm white light appears to be more environmentally acceptable in terms of light pollution than cold white light and is thus becoming a preferred option in some quarters. As it is possible to get greater lumen efficiency using cold light there is economic pressure to opt for colder sources (higher CCT) rather than warm sources (lower CCT). There is at present no known safety differential between cold sources and warm sources. A CCT of 4000K is considered “neutral” rather than cold and 3000K is considered “warm”.

5.2 Colour Contrast

In terms of colour contrast Lewin (2003) points out that by adding colour contrast to a visual scene, visibility is increased. A white, wide spectrum light source will add more colour to a coloured scene than a light source which is colour deficient in some parts of the spectrum. He then concludes that that it is reasonable that, if colour is a visibility-producing component in a scene, white light sources will inherently create a greater increase in visibility through colour contrast than more spectrally deficient sodium sources. Lewin (2003) suggests that white light might show up the colours of blue and green objects better than HPS. He also suggests this may be of minor impact given the confounding presence of headlights.

6 Driver Fatigue

The main possible contributors to driver fatigue related to road lighting are disability glare and discomfort glare. The 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 SPD of an LED used to replace an HPS source should not be an issue. However, this is not the case with discomfort glare where research has found that sources with more blue light are associated with more discomfort glare than sources with less blue light. Clear guidance as to the differences between lighting with different spectra were yet to be produced at the 2015 publication date of Van Bommel (2015)

In addition, variation of glare along a route can exacerbate discomfort and is called “pulsating glare”. There are possibilities of restricting this type of glare using 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.

The net result is that driver fatigue would be lower at sites with less blue light, but precise guidelines related to colour temperature are not yet available. In the opposite direction is a small positive impact of blue light on driver alertness due to suppression of melatonin production. This is only likely to happen to an appreciable extent under very congested condition as prolonged exposure to the lights is necessary. LEDs may provide a new opportunity to restrict pulsating glare.

7 Loss of blue light by yellowing of the eye’s lens.

Blue light is lost by absorption through yellowing of the eye’s lens. 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 60-69-year-old people is half that of 20-29-year-old people. At 425 nm it is one third. At 555 nm only a few percentage points are lost while it is equal at 600 nm and above. Another study found that after the age of 20 lenses increasingly absorb light with the absorption increasing with the square of the person’s age. Van de Kraats and Van Norren, 2007 suggest that studies on vision should use a variety of subjects of different ages, to take into account the increasing population of elder drivers. A migration toward bluer lamps, such as LEDs, will exacerbate the difference in vision performance between younger and older drivers. Figure 23 from Van Bommel (2015) illustrates the changes in the lens as it ages.

Figure 23: Illustration of changes in the lens of the human eye through ageing (Van Bommel (2015)

Figure 24, also from Van Bommel, 2015 goes a step further to illustrate the impact of age under 2700K LED and 4000K LED lights. The top left photograph simulates what a 25-year-old would see under LED lighting.

The top right simulates what a 65-year-old with pupil size reduced to 55% of the 25-year old's pupil would see. The bottom left shows what that 65-year-old would see under 2700K LEDs and the bottom right what the 65-year-old would see under 4000K LEDs.

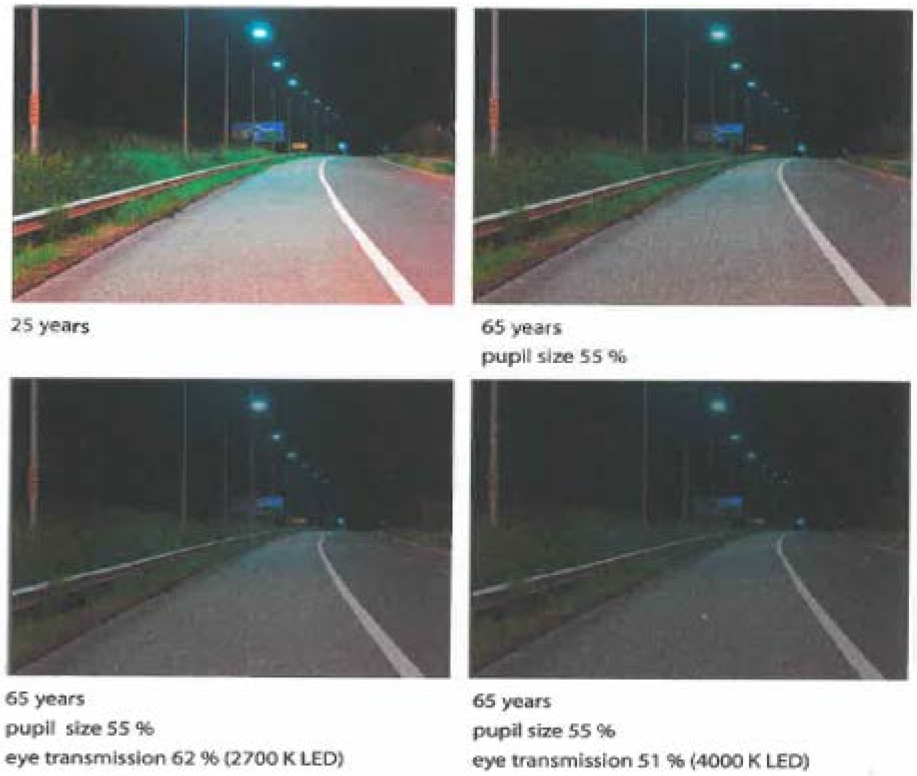

Figure 24: The impact of observer age under 2700K and 4000K road lights

Table 8 also from Van Bommel (2015) quantif1es the above for a 2700 LED and a 4000K LED comparing light transmission of a 25-year-old with that of 50 and 60-year olds.

Table 8: Transmission of warm-white and cool-white LED light through the eye lenses of 50 and 65-year-old people relative to that of a 25-year-old.

Age	Transmission relative to 25 year old (%)	
	Warm-white LED 2700K S/P ratio: 1.28	Cool-white LED 4000K S/P ratio: 1.47
50	66	55
65	62	51

Table 8 shows that on average older people who have not had cataract operations will receive more benefit per lumen from a typical[11] 2700K LED than from a typical 4000K LED. This is related to the bluer spectrum of the 4000K LED. To illustrate, from table 1 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%.

The pertinent question is whether this is an important difference in the great scheme of things? For category V levels S/P ratio becomes of lesser importance. However, for lighting levels below category V (i.e. category P) counterbalancing this loss of light per lumen to the retina is the 4000K LED's higher S/P ratio. This means that the lumens it produces are more visually effective than those of the 2700K luminaire by a ratio of 1.47/1.28 or 15%.

[11] At the time of writing of Van Bommel (2015)

Also, as mentioned earlier, the higher CCT luminaire will produce more lumens per watt of energy although this efficacy advantage is likely to disappear over the next few years. It also must be remembered that the above applies to equal lumens. For pedestrian lighting (Category P lighting in NZ) CIE, (2014} allows lower lighting levels for spectra with higher S/P ratios and colour rendering indexes of at least 0.6. In New Zealand and Australia this is allowed for in the Standard via a 25% allowance on category P roads if a white light source is used. The basis of this is that in the mesopic region lamps with a higher S/P ratio appear brighter and permit better detection of peripheral obstacles than lamps of lower S/P-ratios with the same lumen output.

The net result is that the loss of total light associated with blue light loss from yellowing of the cornea increases with the amount of lower wavelengths in the spectrum of the light and thus roughly corresponds to the light's CCT. However, it is not known how this compares with S/P ratio which works in the other direction at least for pedestrians.

8 Loss of blue light 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. Falchi et al, 2011, estimated that depending on the surface and for an equal lumen package, white LEDs will produce 6-11% less luminance than HPS. Figure 25 from Falchi et al shows the variation in absorption by wavelength of four surfaces, three asphalt and one concrete.

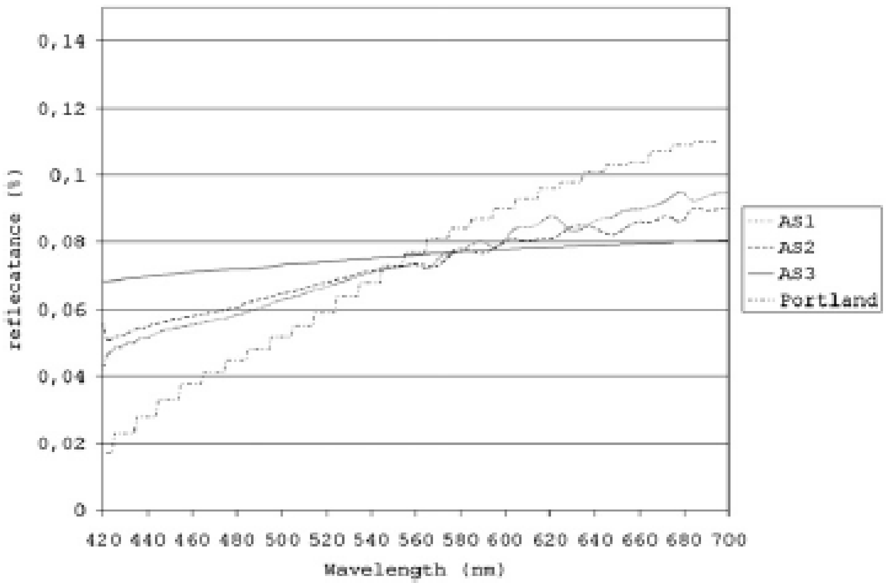

Figure 25: Spectral reflectance of four surfaces from Falchi et al, 2011[12].

[12] Data from NASA/Jet Propulsion Laboratory ASTER Library (Baldridge et al., 2009) and Portland Cement Association (Adrian and Jobanputra, 2005).

Figure 26 (Van Bommel, 2015) shows the relative surface luminance for one of the asphalts in figure 5 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.

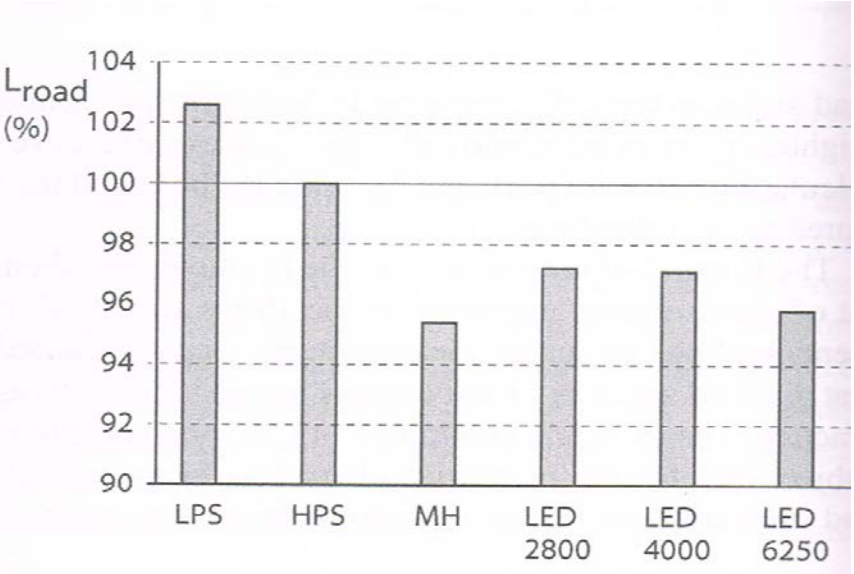

Figure 26: Surface luminance for an asphalt surface and various light sources relative to HPS.

Again, the result is a negative impact from the blue light in LEDs which increases with blue light proportion and thus roughly with CCT. However, its importance vis-à-vis other impacts is unknown.

9 Other more general research

Jin et al (2015) looked at, dark adaption, colour perception, fog penetration, and sky glow related to LED luminaires with different CCTs. They found that as CCT increases, colour discrimination improves with an optimum around 3000K and 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.

10 The night sky

Light, particularly light from the bluer end of the spectrum is not good for astronomy or indeed simple enjoyment of the night sky (Van Bommel 2015). Street lighting undoubtedly contributes to this impact. This is apparent to every city dweller who has gone out into the countryside at night. However, the contribution of street lighting to total sky glow is not well established and will differ from locality to locality. 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 vehicular lighting[13]. IESNA (n.d.) states that roadway lighting has been estimated to contribute to approximately 30% of sky glow and light trespass but does not give any reference or location type for that estimate so knowledge of its contribution is still hazy.

In New Zealand and elsewhere concern over possibly damaging the night sky has been part of lighting engineer's ethos for 20 years. Provisions in the Australia/New Zealand lighting standard have steadily

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

reduced the Upward Waste Light Ratio (UWLR). There is also an astronomy representative on the joint Australian/New Zealand standards committee.

The International Dark Sky Association is concerned about light pollution from LED street lights. It also mentions that this phenomenon is of greater concern in dryer climates than wetter ones as it is dampened by humidity. This may be a factor in the greater concern about this coming from the United States rather than from the British Isles and Europe and may mean that the impact of street lights on the sky may vary between different parts of New Zealand.

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.

Sky glow has been discussed in some detail in a recent report for the US Department of Energy (Kinsey et al, 2017)) which models the impact of several types of lighting on sky glow.

The report points out that although, all other things being equal, light sources with shorter wavelength content increase the potential for sky glow, other characteristics of LED street lighting luminaires can reduce or completely offset these effects. It states that the 3 main luminaire characteristics influencing sky glow are spectral power distribution (SPD), total lumen output, and luminaire light distribution (most importantly the amount of uplight). Although all LEDS have SPDs which make them likely to cause more sky glow than a typical HPS source, the other 2 variables may change in a good design to provide no overall decrement. According to Kinsey et al, 2017, typical US conversions to LEDs that reduce lumens 50% and eliminate uplight will produce less sky glow than the HPS delivering 2% uplight which they replace. The report also counsels that if moving to a 3000K LED from 4000K is being considered, careful checking is necessary to ensure that a more beneficial SPD is being achieved as colour temperature is not a precise measure of the propensity for sky glow

The New Zealand lighting standards and HPS lighting stock are different to the US so the above results may not be directly transferable. Discussions were held with a NZ luminaire supplier / designer (GC) to help ascertain the typical lumen reduction expected when replacing a HPS fitting with LED. The results shown in Table 9 suggest that a 50% lumen reduction is likely with category P lighting but without optimized designs perhaps only a 5% lumen reduction would occur with category V lighting[14].

Table 9: NZ data estimate of the expected lumen reduction when replacing HPS luminaires with a LED luminaire. Note: Greater lumen reductions could be expected if optimized designs were used.

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

Note: HPS lamp lumens were reduced 20% to better equate with luminaire lumens inherent in LED photometry

Overall, 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 for 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.

[14] In addition to these changes Category V designs in future will likely use an amended r-table leading to a possible 28% increase in lumen output.

11 Wild Life

This section should be read in conjunction with section 10 on the night sky which also deals with the pollution impact of lighting. Blue light from LED street lights can interfere with wild life-e.g. interfere with moths' ability to avoid predatory bats (Wakefield et al, 2015). However, other colours of light also interfere with wild life but in a different way so the case against blue light is not clear cut. For instance, Wakefield et al, 2015 intimate that while LED street lights assist the predation of moths by bats they lack UV which in the case of HPS causes 'flight-to-light' and high mortality. Unfortunately, Wakefield et al do not state the SPD of the light they used which comes from the Phillips s Mini Iridium family of luminaires with CCTs of 3000k 4000K and 5700K[15]. However, this may not be a serious issue as Pawson and Bader (2014) found little difference in insect attraction between "off-the-shelf" LEDs with different colour temperatures (2700 K and 6000 K).

Rowse et al, 2016 examined the impact of a switch from low-pressure sodium (LPS) to LED street lights on bat activity at twelve sites across southern England. Neutral and cool LED lights (4000-5700K) were used. They found that the switch over did not affect the activity of bat species typically found near street lights in suburban Britain including the amount of feeding. Results from Dusseldorf in Germany (Eisenbeis and Eick, 2011) also found that HPS was more attractive to insects than LED, but with many caveats.

There are also results in a different direction. Pawson and Bader (2014) found that in rural Hawkes Bay New Zealand (see figure 27) near the edge of a forest which was a source of insects, sampling panes equipped with LED lamps attracted 48% more flying insects on average than HPS lamps. The lights used were industrial lights not street lights so it is not clear how the lights would compare to HPS and LED street lights and the rural situation may differ from the urban situation in terms of insect attraction. Also, the consequences of being attracted may differ for rural New Zealand insects from urban insects in Britain and Germany. There was no discussion of the consequences of attraction in the New Zealand paper.

Figure 27: Light sources on the forest edge in rural Hawkes Bay.

[15] http://download.p4c.philips.com/lfb/3/31b63e5e-1f0b-4959-bd67-a56b001f0fb7/31b63e5e-1f0b-4959-bd67-a56b001f0fb7_pss_en_aa_001.pdf Viewed 11/6/2017

Also, there are variations around the world in the seriousness of these problems in a local context. In Europe there is concern about attracting bats which may be a source of serious cross-species infection to humans. In New Zealand the survival of 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). 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.Again, adverse impacts should be avoided for LEDs of 4000K or lower if designs are carried out well.

12 Impact on human health

12.1 Blue light hazard

The term "Blue-light hazard" "describes acute photochemical damage to the retina caused by "staring at an intense light source", such as a welding arc or the sun according to David Sliney, chairman of the IES (Illuminating Engineering Society) Photobiology Committee[16]. These hazards are controlled in the workplace through occupational safety guidelines limiting the exposure to optical radiation. Methods to evaluate light sources for potential to cause tissue damage are available to use (IESNA 1996) and the US has standards related to workplace light exposure (ACGIH, 2004).

Medical Research from the last 40 years (CCSAPH, 2016) has connected these impacts to radiation in the range of 400 to 500 nanometres—with a peak around 440 nanometres—prompting speculation about the safety of blue-rich light sources used in street illumination. The range 400-500 nanometres is around the area of the blue spike in the 4000K source in figure 1.

However, the research quoted has been animal related and has been described by Ian Ashdown, chief scientist, Lighting Analysts, and president, ByHeart Consultants 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 the internet post of footnote [12].

Recently there has been work done on the impact of chronic exposure of rats to relatively low intensity (750 lux) domestic lighting (Yu-Man, et al, 2014). This intensity is much greater than that of street lighting, to which people are exposed intermittently. The rats were exposed to the light on a 12 hours on, 12 hours off basis for 3, 9 or 28 days. The retinas of the high CCT LED (6500K) rats showed damage. indicating caution in their domestic use.

The above would indicate that road lighting in the mesopic region, as used in New Zealand is not a "blue light hazard" danger with no evidence that LEDs differ from HPS in this regard.

12.2 Age-related macular degeneration

Blue light exposure has also been implicated by medical researchers in age-related macular degeneration (AMD) which is 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, contrary to some beliefs, found only a marginal association. Again, this obviously has little relation to street lighting which is in the

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

mesopic range. It can be safely concluded that street lighting at mesopic levels is most unlikely to be an accelerator of macular degeneration.

12.3 Impact on human sleep patterns and circadian rhythms

Blue light at night can interfere with the sleep patterns and circadian rhythms of humans by interfering with endogenous melatonin production. Any such impact would affect younger people more severely (as their eye lenses have not yet yellowed) and people who have received cataract operations who no longer have yellowing of the lens. Street lighting is also only one of many blue light sources. Also, as one can put a blue light filter on the screen of an electronic device, one can also use black out curtains to remove extraneous light from a sleeping space (Van Bommel (2015) so it is something which can be alleviated by human intervention.

This has become a concern in the US since the American Medical Association (AMA) recommended that 3000k or lower CCT lighting be used on roadways in preference to the usually preferred option of the more efficacious 4000k. This recommendation was based on a review (CCSAPH, 2016) on the human and environmental effects of LED community lighting by the Council on Science and Public Health (CCSAPH) an affiliate of the AMA.

The review basically took the view that 3000K lighting was by its reckoning only 3% less efficacious than 4000k lighting and as it was in the opinion of the authors easier on melatonin, glare, wild life and the night sky, that it should be used. There was no attempt to quantify or cost the differences or to quantify the health impact or any opportunity costs related to the difference. Also, CCT is only a rough guide to a lamp's spectrum and the circadian impact of that spectrum. Modelling the circadian impact of spectra is an active area of present day research. (Boyce, 2011)

All street lighting, whether primarily for drivers or pedestrians lighting is in the mesopic range with illuminance below 100lux and in many cases much lower than that. Also, generally it can be expected that particularly in residential areas, exposure to street lighting should be of brief duration. According to Boyce (2011) citing Figueiro et al (2006) six different studies of melatonin suppression indicate that a reasonable threshold for white light to suppress melatonin is a thirty lux exposure for thirty minutes. The actual recommendation in Figueiro et al (2006) is "about 30 lux of white light at the cornea for a 60-minute exposure" A revised threshold has come out of later work in Rea and Figueiro (2013). This threshold of 30 lux for 30 minutes at the cornea is a conservative criterion based on 5% melatonin suppression from a 6500K light for 26 minutes.

General research on the impact of lighting on the circadian system is worth looking at. Zeitzer et al, 2000 looked at the impact of nocturnal light on circadian phase shift and melatonin suppression. In both cases they found reasonably well-defined dose response relationships. They put human subjects under six and one-half hours of light exposure centred three and one-half hours before the core body temperature minimum[17] is reached. Figure 28 illustrates those relationships. The relationships indicate no evidence for melatonin phase shift or melatonin suppression at the illuminances used in residential road lighting or route road lighting, and on top of that it could be expected that the light exposure to road users or residents would be but a small fraction of 6.5 hours.

[17] Core body temperature normally reaches a minimum around 4am

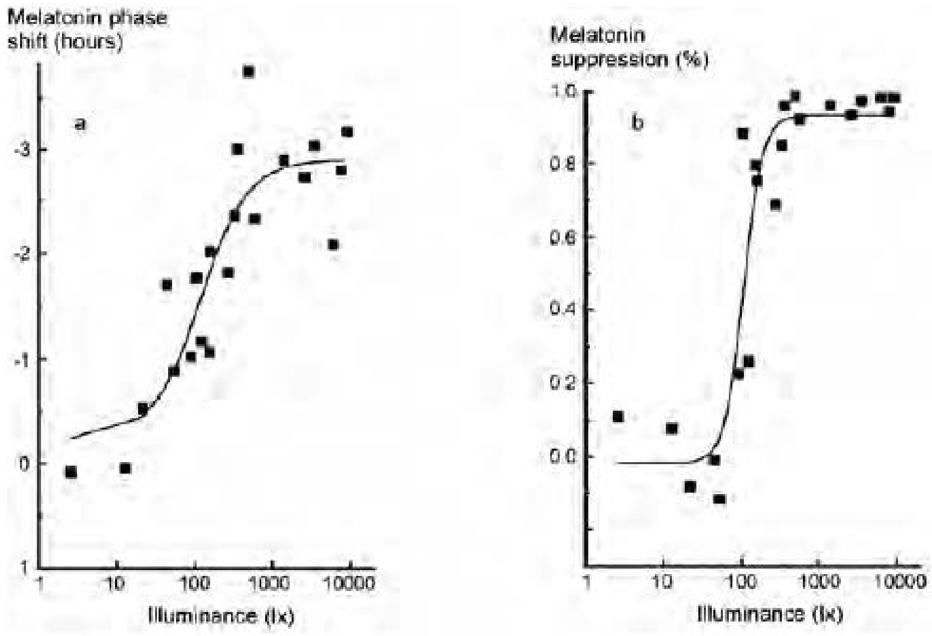

Figure 28: Relationships between melatonin phase shifts and melatonin suppression with illuminance from Zeitzer et al, 2000

Haradar (2004) studied the impact of evening light conditions on salivary melatonin of Japanese junior high school students. A mixed gender group was exposed to bright light (2000 lux) from fluorescent light bulbs for three hours from 19:30 to 22:30 in one evening. A control group was exposed to dim light (60 lux) during for the same period. Both groups consisted of two females and three males aged 14–15 year. Figure 29 illustrates the two groups' salivary melatonin concentration during this time and the day before and after when both groups were under 250 lux lighting. It shows the dim light group's melatonin increasing over time at a much greater rate than the bright light group. The youth of the groups would mean they would not be affected by lens yellowing.

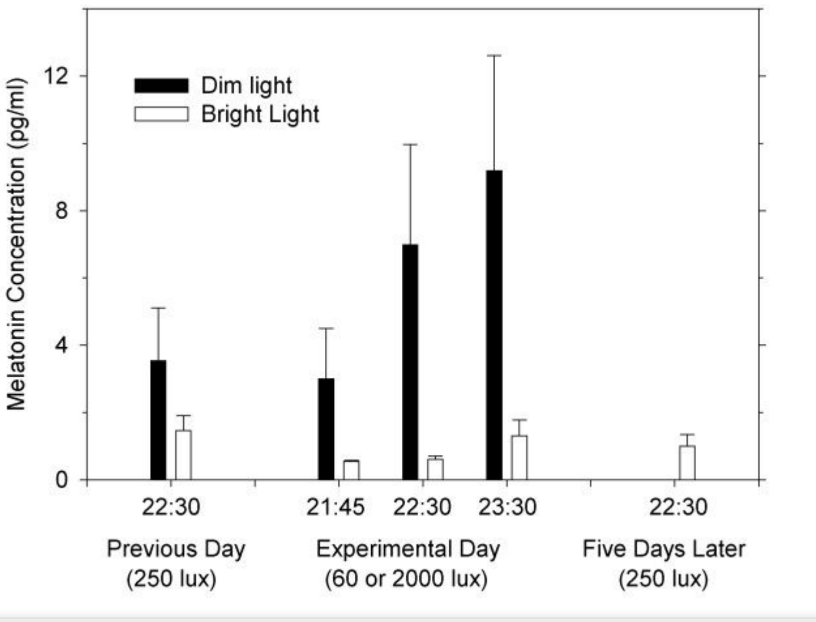

Figure 29: Melatonin concentrations of bright and dim light groups over time (Haradar, 2004)

In another paper out of Japan, which used young adult subjects, broadly similar results were found. Hashimoto et al, 1996 had eight young male subjects spend 3 days in an experimental living facility with lighting below 200 lx. They were exposed to light for 3 hours in the early morning on the 2nd day. The same procedure was repeated five times in each subject with an interval of at least 3 weeks, and five light intensities were trailed. The experiment found that nocturnal melatonin level was not suppressed by light of 200 lx but significantly suppressed by light of intensity > or = 500 lx. The circadian melatonin rhythm was not shifted by any light intensity up to 10,000 lx. It was concluded that the threshold of light intensity for suppressing the melatonin level is between 200 and 500 lx in young Japanese males, and the threshold shifting the circadian melatonin rhythm was much higher. Again, these lux level thresholds are much greater than used in street lighting and the length of exposure was much longer than one would expect to be common for street lighting. The subjects were also too young to have yellowed lenses.

There have been a small number of studies specific to street lighting which have attempted to do assist our understanding of this area. Rea e t al, 2012 looked at the response of the human circadian system after one hour of exposure to outdoor LED lighting of different colour temperatures. The metric used was melatonin suppression. The light sources used were:

- HPS CCT 2050K
- Metal Halide CCT 4000K
- Cool White LED 5200K
- Cool White LED 6900K

at 95 lux.

The subjects were 20 years old. The experiment was carried out under laboratory conditions and then modelling was used to better simulate 4 real road related conditions. The model used was that of Rea et al, 2004 and 2012. The approach was to determine whether sufficient light reached the subject's retina to stimulate the circadian system as measured by melatonin suppression. The pupil area of the subject was estimated using a method from Berman, 1998.

The result of the experiment indicated no melatonin suppression within the 10% uncertainty level for assaying melatonin except for the 6900K LED source which reduced melatonin by 12% for one scenario and 15% for another, both being 1 hour exposures. The authors emphasised that compared to the human visual system, the human circadian system is relatively insensitive to light. Compared to the visual system which responds very quickly the circadian system needs a number of orders of magnitude more light for many minutes for a measurable response to be detected. According to Rea et al, 2012 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.

The authors concluded no meaningful impact on the circadian system for any except the 6900 LED. This experiment would indicate that there is little of concern regarding circadian issues from the common 4000K and lower LEDs in use these days.

Also, as Van Bommel, 2015 remarks, home lighting after dark is much stronger than outdoor street lighting entering a home, so the only time of concern is after the lights go out for bed, when most people will have their curtains drawn.

Falchi, et al (2011) estimated from spectral comparison that a "natural white"[18] LED suppressed Melatonin production 5 times more than an HPS lamp. His estimates are shown in table 10.

Table 10: Suppression of melatonin relative to HPS for various lamp types

440 nm–500 nm energy ratios (second column) and melatonin suppression efficiency (third column) for some common lamps.

Lamp type	Energy relative to HPS, 440–500 nm band	Melatonin suppression effect (relative to HPS)
HPS	1	1
LPS	0.02	0.3
Metal Halide	2.7	3.4
Natural White LED	7.0	5.4
Incandescent 65 W	2.5	2.5

Given the finding of Rea et al, 2012 it is difficult to interpret the meaning in practical terms of this fivefold relative difference, given that there was no evidence found by Rea et al, 2012 that detectable melatonin depletion existed except in a 6900 K lamp which is in the range described as "commercial white". Of course, relative effects are always problematic in terms of the absolute size of the effect. For instance, if the baseline effect is very small, five time the baseline impact is still small and in the case of Falchi no human experiment was involved.

12.4 Conclusions

There is no reason in the literature to suggest that well designed LED or HPS road lighting using CCTs of 4000k or less has any impact on human health.

13 Weather conditions

13.1 Wet conditions

Road lighting is designed for dry conditions and there is very little information on the performance of lighting in wet conditions. Literature discussed in Jackett and Frith, 2012 indicated a worthwhile impact of road lighting on safety under wet conditions and the same authors found a 15% reduction in crashes with lighting on wet roads compared to a 21% reduction on dry roads. The reduction in impact would likely be related to the followings impacts described in Van Bommel, 2015.

- The rain prevents a certain amount of the light directed at the road surface from ever reaching it, thus reducing the quantum of luminance reflected from the surface.
- The rain wets the road surface thus changing its reflective properties so that it may contain large dark and bright patches with potentially large impacts on uniformity. Open structure road surfaces which drain well would have the least impact in the wet.

[18]According to http://www.eaglelight.com/category/lighting_tutorials.color_temperature/ (Viewed 1/5/2017) Natural White LED typically has colour temperatures from 4000 K to 4500. This may also be called "neutral white light"

The second of the above impacts is by far the most important and between the two impacts any of lighting arrangement impacts (like whether HPS or LED is used) are likely to be secondary.

This is confirmed in Mutmansky et al (2010a) where the impact of different lighting sources in the city of San Jose on object detection distances was carried out on two nights, one with dry streets and one when it rained. The results in the wet were described in section 2.2 figure 6 and as previously mentioned the only LED which did not perform well vis-a-vis HPS was the one at 3500K.

13.2 Fog penetration and dark adaption

Jin et al, 2015 analysed the performance of five difference LEDs made to have specific spectra characteristics as in figure 30.

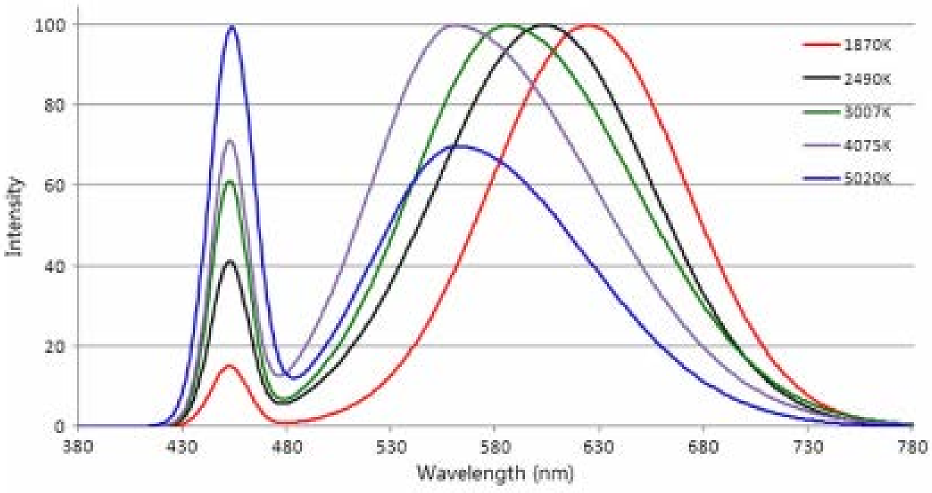

Figure 30: Spectra of LEDs used by Jin et al, 2015

Their performance characteristics were as in table 11.

Table 11: Performance characteristics of LEDs used by Jin et al, 2015

CCT (K)	CRI	LER (lm/W)
1870	65.1	286.8
2490	69.7	333.8
3007	71.9	348.7
4075	67.2	379.7
5020	69.4	345.6

It was found that the dark adaptation times increased with CCT (table 12).

Table 12: Dark adaptation time of LEDs at 30lx and 50 lx used by Jin et al, 2015

CCT(K)	1830	2490	3007	4075	5020
Dark adaption time(s,30lx)	85	102	112	120	126
Dark adaption time(s,50lx)	95	114	124	133	140

Colour discrimination improved (figure 31) so that by 3000k it was nearly 100%. Colour piece number relates to the 15 different colours which were shown to the subjects.

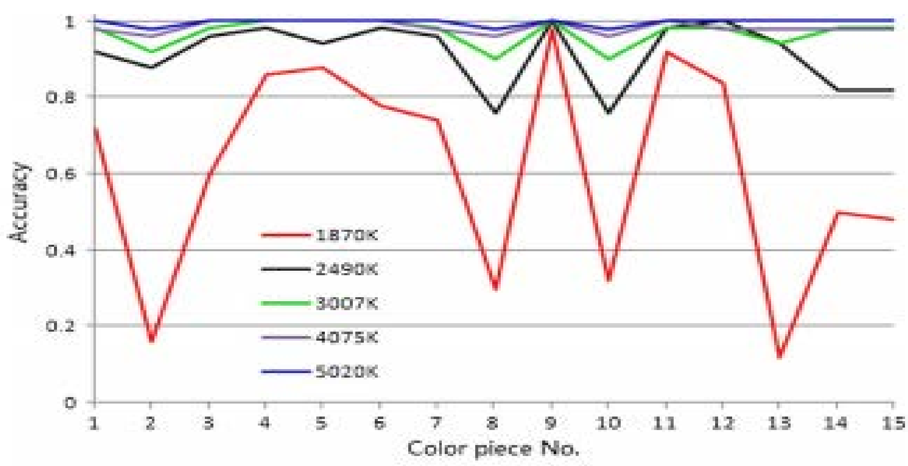

Figure 31: Accuracy in recognizing colours by CCT Jin et al, 2015

Fog transmittance (in a laboratory using an artificial fog) decreased with CCT (Table 13).

Table 13: Fog transmittance by CCT Jin et al, 2015

	1870K	2495K	2985K	4075K	5020K
T (%)	0.479	0.452	0.415	0.372	0.334

The same happened with real street lights at different simulated air quality indices (AQI) related to particulate matter levels. (PM2.5) (Table 14).

Table 14: Transmission level of various LEDs under different fog/haze levels

Air quality			transmission			
Fog/Haze level	AQI	PM2.5	Low CCT LED （1870K）	Warm white LED （2985K）	Pure white LED （5020K）	HPS
1	38.7	18.0	1.000	1.000	1.000	1.000
2	67.3	42.0	0.980	0.966	0.964	0.983
3	97.3	72.0	0.935	0.910	0.908	0.949
4	131.7	100.0	0.913	0.870	0.830	0.928
5	184.3	139.3	0.874	0.837	0.798	0.902

This part of the work included an HPS lamp which performed better than any of the LEDs. However, the differences were not vast between the HPS and the higher CCT LEDs. If one assumes a transmittance of a

4000k LED midway between 2985K and 5020K then the LED is about 10% less penetrative than the HPS used. The colour temperature of the HPS was not divulged by the authors. The authors, based on the results, recommend LEDs of around 3000k because they are similar in colour discrimination to higher CCT LEDs and are better performers in other ways except efficiency which they appear to deem acceptable.

13.3 Conclusions

There are indications that LED luminaires may perform better regarding detection distance in the wet with an optimum around 4100k than HPS and that their fog penetration and dark adaption times may be inferior with the fog detection not being greatly different.

14 Overall Conclusions

14.1 Energy savings

Given the considerable energy savings of LEDs over HPS, there are strong arguments for using LEDs instead of HPS.

14.2 The impact of the colour of street lighting light on safety and environmental pleasantness

- Evidence from laboratory trials and some specifically set up on-road scenarios supports the idea that visibility is improved by the wider spectrum achieved by "white" light sources of road lighting like LEDs. This effect is much more pronounced at category P lighting levels than at category V lighting levels. Because of this white light will make pedestrian areas more pleasant and its increased blue component will provide efficiency gains when used at the low light levels found in minor road (Category P) lighting.
- The relation between road safety and the colour of light is multifactorial and no on-road studies been carried out to establish a direct linkage between the colour of light and crashes. At category V levels any change may be small and likely to relate to changed colour contrast.
- At present there is no evidence of any safety difference between white LED lighting and "warm white" LED lighting or even between LED and HPS lighting
- The British have stated in their lighting standard that there is not enough evidence at this stage to apply S/P ratios to traffic route (category V) lighting based on the greater mesopic luminance associated with white light.
- The colour rendition characteristics of both white light and warm white light as emitted by LEDs exceed by a wide margin that of HPS (LED CRI> 70%, HPS CRI ~24%)
- With age, the lens of the human eye yellows meaning that blue light is largely absorbed in the lens, meaning the mesopic impact of blue-rich light is lessened for older drivers compared to the sample of 20-35-year olds used in producing CIE correction factors.
- Blue light is preferentially absorbed by road surfaces meaning for the same lumens, slightly less light is reflected back to drivers with LED rather than with HPS.
- More blue light may help drivers stay alert but no firm evidence yet exists. Driver fatigue was also studied with no conclusive finding.

- The fine tuning of safety performance into specific colour temperatures of say 3000K or 4000K is not backed up by strong data. One US field study suggesting 4000K has an edge and a Chinese laboratory study using different a range of criteria considered 3000K had an edge. Any differences are multifactorial and a comprehensive, well controlled study is required but even then, the differences may be small.

14.3 The impact of street lighting on people's health

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.

14.4 The impact of street lighting on wildlife

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 street lighting is mixed.

14.5 The impact of street lighting on sky glow

US evidence suggests the blue light component of 4000K LEDs causes more sky glow than HPS light. Present US practice of replacing HPS with LEDs of half the lumen output and the total elimination of upward waste light is claimed to eliminate this increase. In NZ a 50% lumen reduction could well be achieved on the Category P network but experience to date suggests it will not be achieved on the category V network. It is not known at present how much of New Zealand's sky glow from street lighting emanates from category V lighting.

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 reduced to local background levels 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 street lighting is a component. The other components include industrial lighting, waterfront lighting, billboards etc

Spectral plots show a much-reduced peak for blue light at 3000K compared to 4000K. 3000K but not 4000K solutions are now eligible for the IDA "seal of approval" something which may be a desirable objective for environment conscious TLAs.

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