The Road Safety and Environmental Impact of LED Spectra in route lighting

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Executive summary

Route streetlighting's main objective is to allow drivers to see obstacles on the road. A secondary objective is to allow them to see objects on the roadside (like pedestrians and vehicles on driveways) which have the potential to become obstacles on the road. If not carefully controlled streetlighting also can generate unintended consequences. These can include impacts on humans, animals, insects and the beauty of the night sky. It is also a duty of lighting designers to provide the required lighting as efficiently as possible in terms of electricity usage, The has led to a move over the last fifteen years or so to replace High Pressure Sodium (HPS) lights with Light Emitting Diode (LED) lights which use far less energy than the HPS lights and can be relatively easily dimmed or turned up leading to the possibility of lighting designs with more temporal flexibility.

LED lights tend to have a greater proportion of their spectra in the lower wavelength blue region than HPS lights and there is considerable spectra variation between various LED lights. It is not yet clear what impact (if any) this spectral shift has on road safety or its other impacts. The lighting engineer must balance these other impacts against the prime objective of improving safety. This report looks at how the shift from HPS may impact on safety and other possible unintended consequences of the change. A table (shown below) was produced which looked at the pros and cons of moving from HPS lighting to LED with its generally larger proportion of blue light.

Safety Impact of increased blue light proportion		Environmental impact of increased blue light proportion	
Positive	Negative	Positive	Negative
Possible visibility improvement of objects on the road	Increased pavement absorption of light	Increased pavement absorption of light.	The light which is reflected from the pavement will still contain a larger blue component than HPS and will impact on skyglow and wildlife.
Probable visibility improvement of peripheral objects (E.g. pedestrians near the curb.)	Increased human lens absorption with age	Less energy use	
Possible increased vigilance of drivers	Increased pupil constriction with age.	No uplight when LEDs are properly designed-reduces skyglow and wild life disturbance from pavement reflection.	
	More disability glare		
	Possible reduction in driving accuracy		

The safety negatives are all ameliorated by reducing the amount of blue light. The safety positives all involve greater blue light. However, the evidence for the positives is weaker than that of the negatives. At the worst the amelioration, by bringing the SPDs of LEDs in line with that of HPS is unlikely to make the safety impact of LEDs any worse than HPS.

It was concluded that on the balance of probabilities there are safety benefits in reducing the proportion of blue wavelengths in route lighting. Bringing the SPDs of LEDs in line with those typical of HPS is unlikely to make the safety impact of LEDs less than that of HPS. There are also environmental benefits, so this is a win-win policy.

1   Introduction

Route streetlighting's main objective is to allow drivers to see obstacles on the road. A secondary objective is to allow them to see objects on the roadside (like pedestrians and vehicles on driveways) which have the potential to become obstacles on the road. If not carefully controlled streetlighting also can generate unintended consequences. These can include impacts on humans, animals, insects and the beauty of the night sky.

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Correlated Colour Temperature (CCT) is widely used as a rough guide to the proportion of blue light emitted by a luminaire. Generally, the higher the CCT the greater the proportion of blue light and the more efficient the LED, although the gap in efficiency between higher CCT LEDs and lower CCT LEDs is quickly reducing. Also, with modern LED technology it is possible to produce higher CCT LEDs with relatively low proportions of blue light. A better indicator of the contribution of various spectra to the light emitted by a- luminaire is the Spectral Power Distribution (SPD) of the luminaire.

This report looks at how the shift from HPS may impact on safety and other possible unintended consequences of the change.

2   Safety issues

2.1   Visibility of objects by drivers

As mentioned in the introduction a major objective of road lighting is to improve the visibility of objects to drivers. Thus, visibility has some face validity as an intermediate outcome measure for road safety lighting, notwithstanding the fact that directly relating visibility measurements to safety has proved difficult for researchers (Schreuder et al, 1998, Wood et al, 2018). This paragraph looks at visibility to drivers of objects both off the road (but near the road) and on the road.

2.1.1   Visibility of off the road objects by drivers

To detect off road objects like pedestrians preparing to cross the road typically requires drivers to use peripheral vision which is principally provided by the rods. If an object of interest is detected the driver may also seek greater clarity by central (foveal) vision through head/eye movement. Therefore, in reality, Information in peripheral vision comes from both rods and cones and so is influenced by the S/P ratio[1] of the luminaire. However, the central foveal portion of the eye contains only cones so foveal vision is influenced solely by the photopic sensitivity curve, so is not influenced by the S/P ratio.

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[1] The S/P ratio is the ratio of the Scotopic lumens emitted by the luminaire and the photopic lumens emitted by the luminaire. This is discussed in more detail in section 2.31.

Younis (2012) looked at the impact of HPS, Metal Halide (MH) and LED streetlights on the night-time visibility of pedestrians to drivers. 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 1.

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

Table 1: Specifications of lights used in Younis (2012)

The colour temperatures 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.[2] The detection distance was measured in the presence of on-coming car headlamps. Pedestrians wore three different clothing colours: 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 1.

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[2]

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
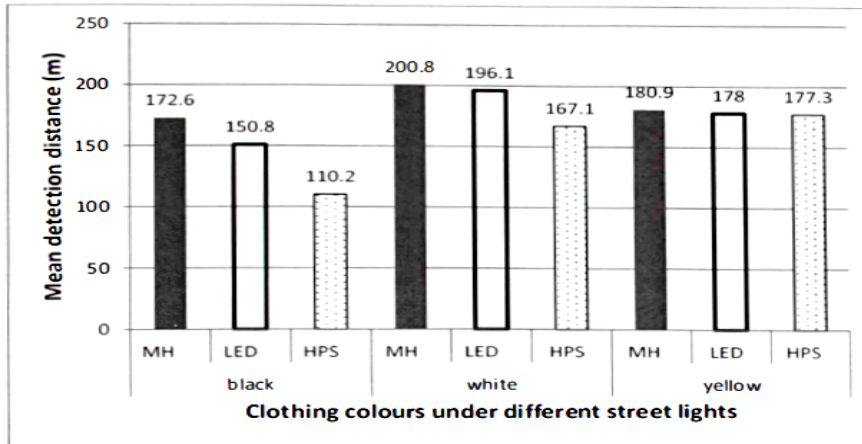
Figure 1: Mean pedestrian detection distances by light source and clothing colour.

Statistically the MH and LED streetlights 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.

2.1.2   Visibility of objects on the road by drivers

It is known that white light such as that from LED or Metal Halide sources is better for peripheral vision purposes than the yellow light of HPS. The impact on central vision is not so clear. There have been several 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.

Over the years some researchers have used reaction time as a surrogate for visibility. Whiter light results in improved reaction times using Metal Halide vis-a-vis HPS. (Lewin (2004)). More recent work involved a team of Chinese researchers, Zhiyong et al, 2011. In a laboratory experiment they found the following (Figure 2) 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/m^2 using the increments by which it was varied.
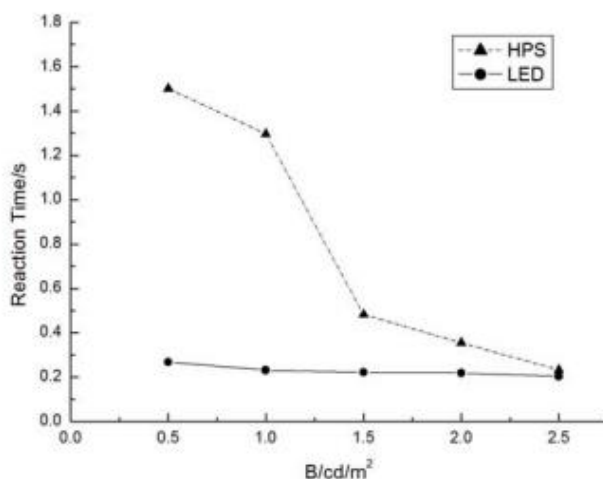

Figure 2: Curve relating reaction time to luminance using HPS and LED

It is obvious from Figure 2 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.

Fisheng 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 3.
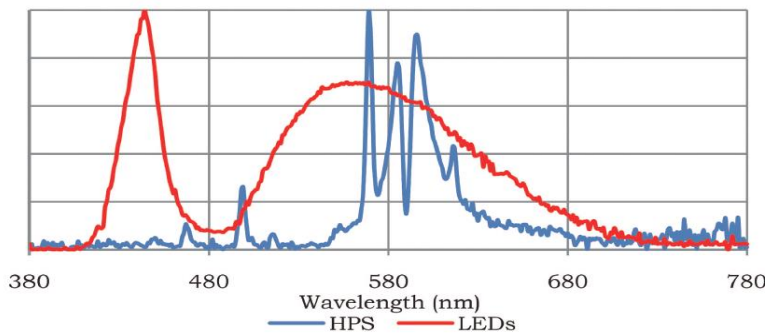

Figure 3: Spectra of the HPS and LED light sources used by Fisheng et al.

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 Lt is the luminance of target, Lb is the background luminance and $\Delta T_{hreshold}$ is the luminance difference needed for minimum visibility between a target and its background. Figures 4 and 5 illustrate the changes in observer ratings for the HPS and the LED sources respectively at different calculated visibility levels.
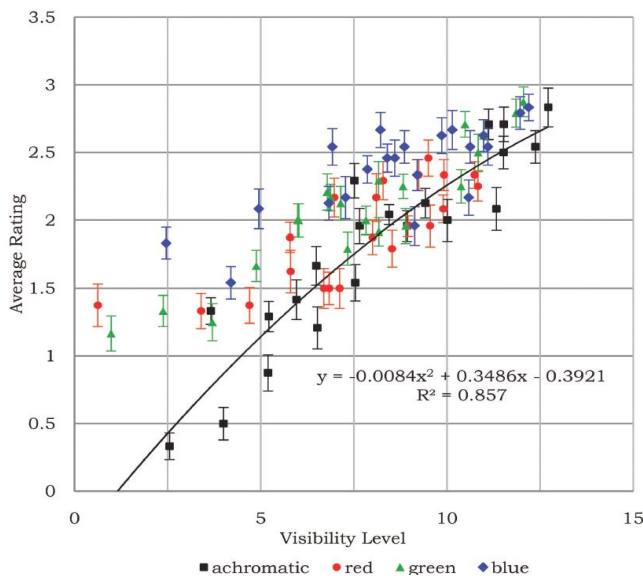

Figure 4: Assessed visibility rating of LED against calculated visibility level
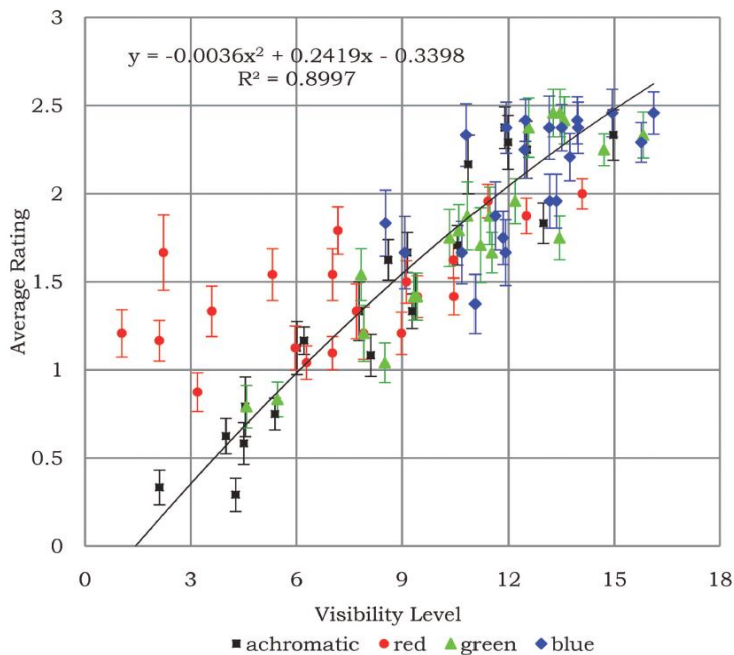
$$y = -0.0036x^2 + 0.2419x - 0.3398$$
$$R^2 = 0.8997$$

Figure 5: 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.

2.1.3   Conclusions

LEDs appear to be superior to HPS for both on road and off road visibility. There is little information regarding the best colour temperature to use to optimise visibility and there is little direct information linking visibility measures to crashes.

2.2   . Driver Fatigue

2.2.1   Discussion

The main possible direct contributors to driver fatigue related to road lighting are disability glare and discomfort glare. Disability glare is the reduction in visibility caused by intense light sources in the field of view, while discomfort glare is the sensation of annoyance or even pain induced by overly bright sources (Rea 2000). Disability glare impairs the vision of objects without necessarily causing discomfort while discomfort glare causes discomfort without necessarily impairing the vision of objects (CIE, 2011). However, discomfort glare may impair vision as it can decrease pupil size and thus limit the amount of light able to reach the retina (Lin et al, 2015). The mechanism by which glare 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 (e.g. Bullough (2009). 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). However, research is continuing and Huang et al(2018) conducted a laboratory experiment to investigate discomfort

glare from white LEDs with different SPDs. They found a significant difference in glare perception between white lights having different CCTs with greater CCT meaning more glare. The CCTs of the lamps used were 3000K, 400k, 5000K 6000K and 7000k. They also looked at a number of 7000K LEDs of different SPDs and found that the SPD differences between the 7000K LEDS did not produce significant discomfort glare differences.

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 e t 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 may intuitively be the most likely scenario.

Very recently, Bhagavathula et al, 2021 l carried out experimental work aimed at determining the impact of LEDs as an indicator of driver alertness and sleep health. Sleep health was measured using saliva melatonin testing. Driver alertness was measured using driver detection and colour recognition distances, the percentage of time a driver's eyelids are closed over three minutes, standard deviation in lane position and the Karolinska Sleepiness Scale (KSS). The study used 10 healthy participants between 18 and 30 years with steady sleep-wake cycles. The luminaire CCTs and lighting conditions used are as laid out in table 2. The exposure time for saliva melatonin was 1 am to 3 am and five saliva samples were collected at 30-minute intervals.

Luminaire CCT	Lighting conditions
2100 K HPS	High (1.5 cd/m2)
4000 K LED	High (1.5 cd/m2)
4000 K LED	Medium (1.0 cd/m2)
4000 K LED	Low (0.7 cd/m2)
No luminaire	(less than 0.05 cd/m2)

Table 2: Luminaire CCT and lighting conditions

The study results indicated that:

- LED roadway lighting at light levels up to a luminance of 1.5cd/m^2 does not significantly suppress saliva melatonin between 1:00 am to 3:00 am in healthy drivers.

- The impact of LED lighting on salivary melatonin suppression was not significantly different from HPS at similar lighting levels (1.5 cd/m^2) or from no lighting.

- No statistically significant differences between any of the roadway lighting conditions for detection distance and colour recognition distance.

- An increase in exposure time to HPS lighting resulted in a statistically significant decrease in detection and colour recognition distances. No such differences ensued for LED or the no roadway lighting conditions.

- No significant differences between the HPS, LED, and no lighting conditions as measured by the KSS.

These findings indicate that up to 1.5 cd/m^2 neither LED lighting nor its spectral content or intensity impacts drivers' saliva melatonin or alertness between 1:00 am to 3:00 am

There have been moves to decrease driver fatigue by providing in vehicle cabin blue light. However, this has been provided at much higher intensities than streetlighting and has had mixed results when looked at scientifically. Rodriguez-Morilla et al (2018) looked at the impact of extra blue light (467 lux) on morning drivers who have trouble staying alert in the morning. They found that the extra blue light improved alertness as measured by reaction time but also decreased simulated lane keeping performance and had no impact on results of a sleepiness assessment.

2.2.2   Conclusion

Other things being equal driver fatigue would be lower where there is less blue light by reason of generally lower glare. In the opposite direction is equivocal evidence of a possible small positive impact of blue light on driver alertness due to suppression of melatonin production but this may also be associated with unwanted results in the area of driving accuracy.

2.3   The impact of driver age and pavement absorption

2.3.1   The performance of LEDs under mesopic conditions

Road lights operate under mesopic conditions. According to Lewin et al, 2003 at 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 lighting is almost always in the range 0.1 to 2 cd/m², and in that range both rods and cones are active. This middle range is called "mesopic" Traditionally, the lumen value of lighting has been calculated only under photopic conditions. This 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 (λ) curve to define the lumen value of lighting required, ignoring the sensitivity of the retinal rods by wavelength (V' (λ) Curve). 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. It is a scaling factor to reduce or boost photometry made under photopic assumptions to align with the mesopic conditions that apply in the case of road lighting. 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

	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 %
LED cool white ~	2,05	69 %	49 %	32 %	21 %	16 %	11 %	8 %	6 %	3 %	0 %
	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 %

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

The range of normal road lighting levels are shown within the rectangle with a black border and the background coloured for differences 5% or greater. For our purposes it is worthwhile to concentrate 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 3, provides boosts of around 30% above the calculated photopic values .This might imply reduced lumens may be considered for pedestrian lighting. 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. These impacts can be counterbalanced by other factors; in particular:

- The wavelength related absorption properties of the human eye's lens as it ages
- The wavelength related narrowing of the pupil with age
- The wavelength related absorption properties of road surfaces.

 In all three cases the absorption is biased towards lower wavelength blue light, which provide more of the lumen output of LEDs than HPS. This means that the light which reaches the retina will have a different S/P ratio from that leaving the luminaire and will also contain fewer lumens than the light leaving the luminaire as some of the lumens will have been absorbed by the pavement and the eye's lens. This impact will be greater for LED than HPS lighting and will increase the percentage of blue light in an LED luminaire's spectrum as it reaches the retina.

2.3.2   The wavelength related absorption properties of the human eye's lens as it ages

 The studies leading to the CIE adjustment factors in table 3 mainly used subjects in the 20-35 age range (Van Bommel, 2015). Preciado and Manzano (2018) provide more detail on the subjects used. The lens of the human eye yellows with age meaning that blue light is absorbed in the lens. This lessens the mesopic impact of blue-rich light for older drivers compared to that shown in table 3. The process is underway by the time an individual reaches age 20. This phenomenon is well documented in the medical literature from study of the lenses of live people in situ, lenses removed by medical procedures and lenses removed post-mortem. Said and Weale, 1959 studied the lenses in situ of British subjects from 4 to 63 years of age. Figure 6 showing a family of curves of optical density against wavelength for various ages[3].

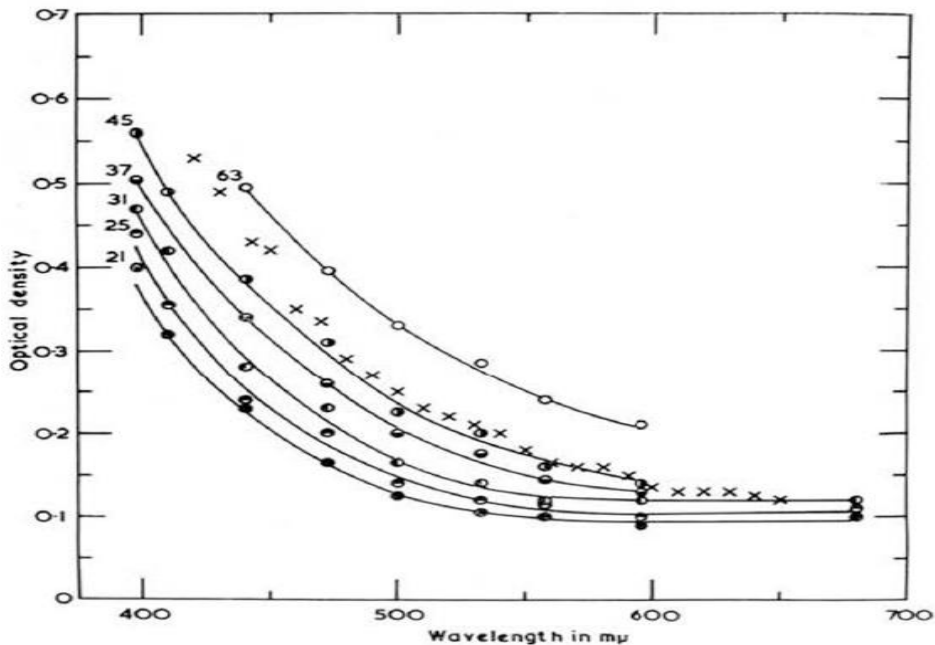[3] The crosses represent earlier data collected by Weale (1954)

Figure 6: Lens optical density of people of various ages by wavelength of light

This shows a well-defined increase in optical density with age at lower wavelengths. There is very little age related change at higher wave lengths. Brainard et al. (1997) looked at post-mortem lenses of 5 new borns, 36 20 to 29 year olds and 40 60-69 year olds. They found that at 450 nm the transmittance of the lens of 60-69 year olds is half that of 20-29 year old adults; 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. In all cases the new born lens transmittance is greater than the others. This was shown in figure 7.
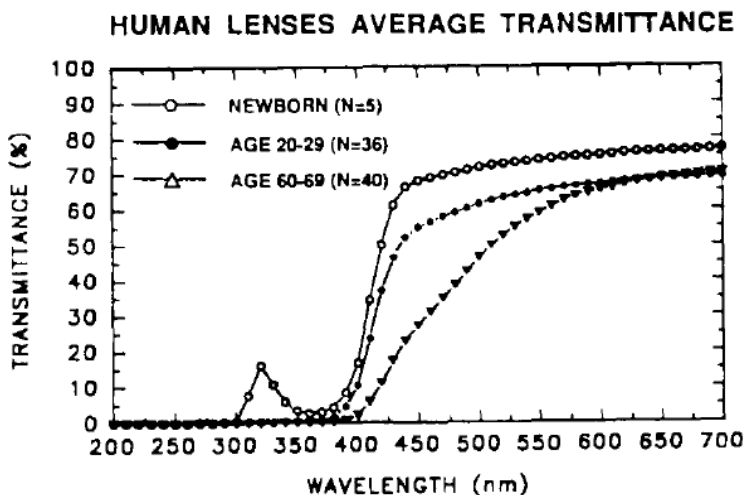

Figure 7: Light transmittance of post-mortem lenses by wavelength for new borns, and people aged 20-29 and 60-69

After a literature review of studies broadly similar to the above Van de Kraats and Van Norren (2007) found that after the age of 20 lenses increasingly absorb light with the absorption increasing with the square of the person's age. They suggest that studies on vision should use a variety of subjects of different ages, to allow for the increasing population of older drivers.

This literature has been augmented by several studies since then. After a literature review the CIE (CIE 203:2012) published values for transmittance of the human lens by wavelengths from 380nm to 780nm for various age brackets. These values have been processed into a set of curves by

Preciado and Manzano (2018) as shown in figure 8. The curves represent the spectral transmission of people aged in the middle of the decade depicted. Preciado and Manzano (2018) point out that these curves indicate that at 500nm the transmittance of a human eye at 60–69 years is 25% less than the transmittance of an eye at 20–29 years and 48% less at 450nm. These results are similar to those of Brainard et al (1997).
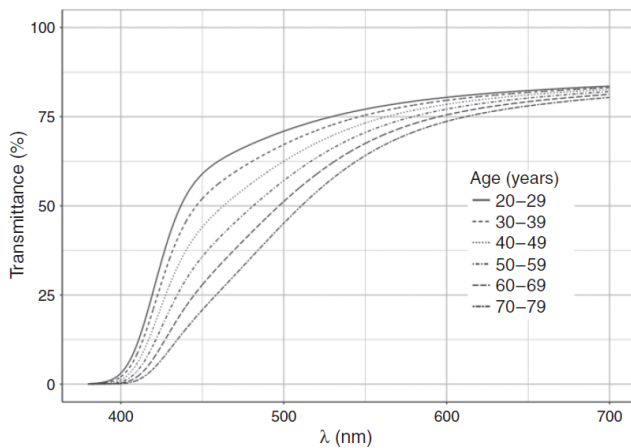

Figure 8: Spectral transmittance of human lens at different ages.

It is apparent, as Preciado and Manzano (2018) point out, that:

 transmittance decreases considerably with ageing, especially between 400nm and 550nm

This means that a migration toward bluer lamps, such as LEDs with a more blue -biased spectral power distribution (SPD), will exacerbate the difference in vision performance between younger and older drivers. Figure 3 from Van Bommel (2015) illustrates the changes in the lens as it ages.

Figure 9: Illustration of changes in the human eye lens through ageing (Van Bommel (2015)

Figure 10, 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 10: The impact of observer age under 2700K and 4000K road lights

Table 4 also from Van Bommel (2015) quantifies 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.

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

Table 4: 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.

Table 4 shows that on average older people will receive more benefit per lumen from a typical[4] 2700K LED than from a typical 4000K LED. This is related to the bluer spectrum of the 4000K LED. To illustrate, from table 3 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%. Preciado and Manzano (2018) went further by plotting the lens transmittance of various age groups against a baseline of 20 -29 year olds (figure 11). This shows the relatively low transmission of the lower wavelengths of the blue light by all age groups particularly those who are older.
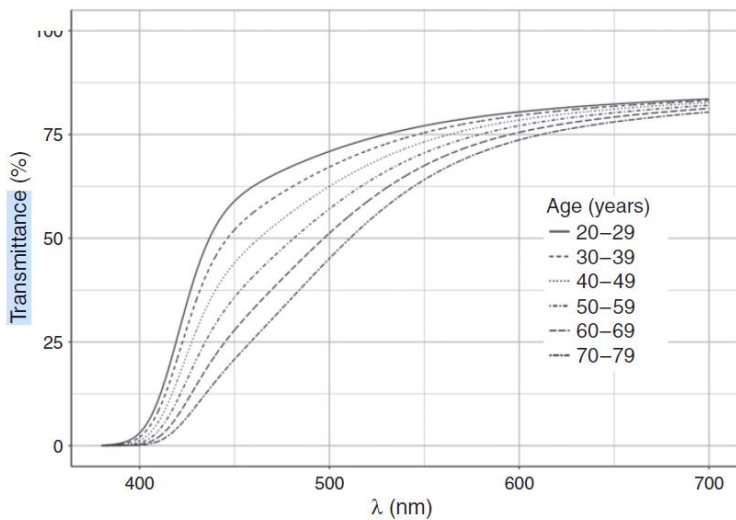
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[4] At the time of writing of Van Bommel (2015)

Figure 11: Human lens transmittance by age-group and wave-length

According to Preciado and Manzano (2018) the CIE derived its V (λ) curve used data from 52 subjects mostly younger people numbering 20 (20–29 years), 21 (30–39 years), 9 (40–49 years) and 2 (50–59 years). Sixty plus were absent. Between 2011 and 2014 inclusive, 60+ contributed 18% of New Zealand's vehicle kilometres of travel. The reference range in figure 11 was 20-29 (mid-point 25) because Sagawa and Takahashi after measuring spectral luminous efficiency functions for 91 subjects of aged from 11 to 78 years, found that the function for age 25 years fitted best to the CIE V (λ) curve. Thus, the V (λ). curve may have differed if it had used a wider age range of subjects.

2.3.3   The wavelength related narrowing of the pupil with age

The pupil of the eye narrows with age owing to weakening of the small muscles which serve to keep it open. Its changes with age are illustrated in figure 12 from Birren et al (1950).
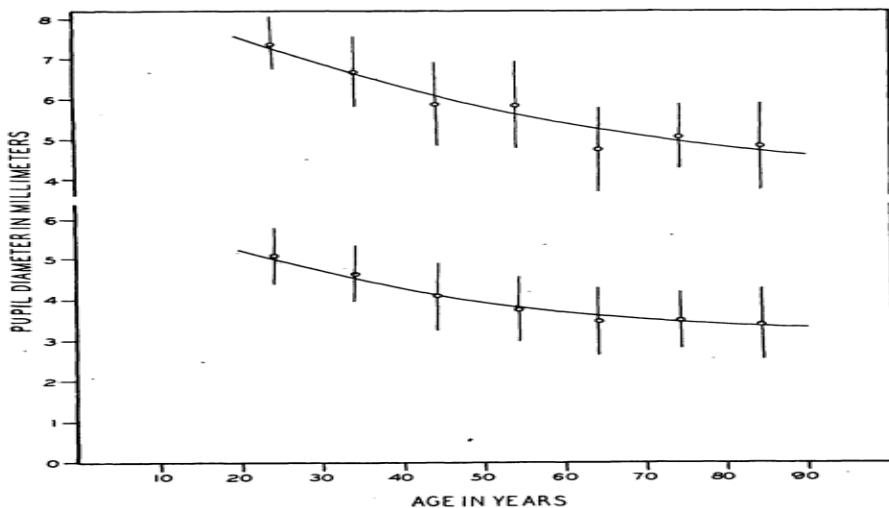

Figure 12: Mean pupil diameter (mm.) by decades of age.

The upper curve relates to pupil size in the dark with the lower relating to pupil size in one lumen of brightness. The lines are least squares regressions and the vertical lines represent ± one standard deviation. This narrowing reduces the amount of light reaching the lens and thus the amount reaching the retina. The pupil size varies with the wavelength of incident light. . Daneault et al, 2012 looked at pupil constriction in 16 young (22.8 ± 4 years) and 14 older (61 ± 4.4 years) subjects with 45s exposures to blue (480 nm) and green (550 nm) monochromatic lights at low, medium, and high irradiance levels. Steady-state pupil constriction was greater under blue than green light in both age groups and increased with increasing irradiance.

2.3.4   The wavelength related absorption properties of road surfaces.

Blue light is absorbed preferentially by road surfaces both asphalt, chip seal and concrete and this will result in less luminance for a given amount of illuminance. In pedestrian lighting the main objective is to illuminate objects directly so loss during reflectance from the surface is not of importance. However, for route 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 13 from Falchi et al shows the variation in absorption by wavelength of four surfaces, three asphalt and one concrete.
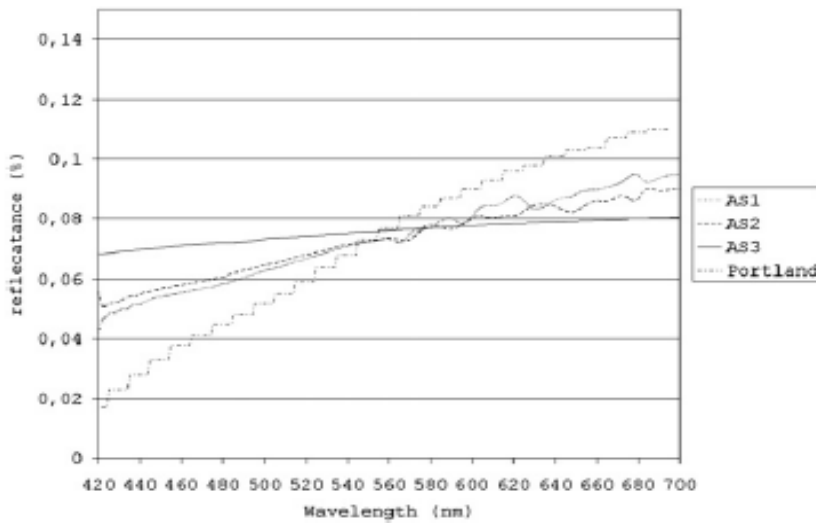

Figure 13: Spectral reflectance of four surfaces from Falchi et al, 2016[5].

Figure 14 (Van Bommel, 2015) shows the relative surface luminance for one of the asphalts in figure 13 under 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 relatively small for that particular surface.

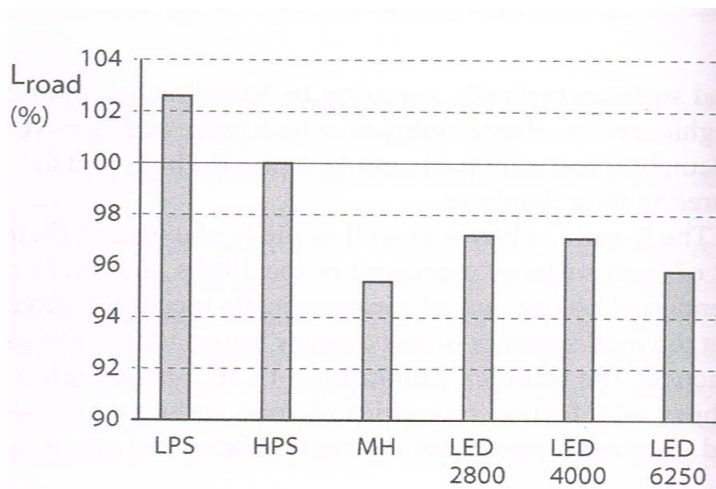*Figure 14: Surface luminance for an asphalt surface and various light sources relative to HPS.*

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

Preciado and Manzano (2018) looked at 22 surfaces compared to the 4 of Falchi et al, 2016. Their reflectances are plotted against wavelength in figure 15.
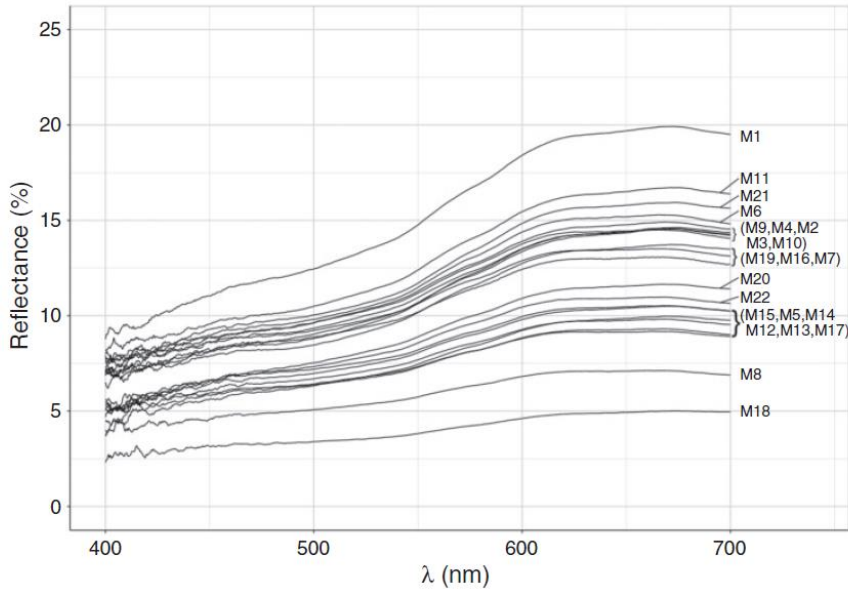

Figure 15: Spectral reflectances of 22 road surface samples from Preciado and Manzano (2018)

It is apparent that all samples reflect more light as wavelength increases. The samples were all asphaltic concrete. Chip seal, a more common pavement in New Zealand, is more reflective than asphaltic concrete as indicated in figure 16 from Herold (2004)[6]. However, at the blue end of the spectrum it is still only around 15% reflective compared to around 20% at 700nm.
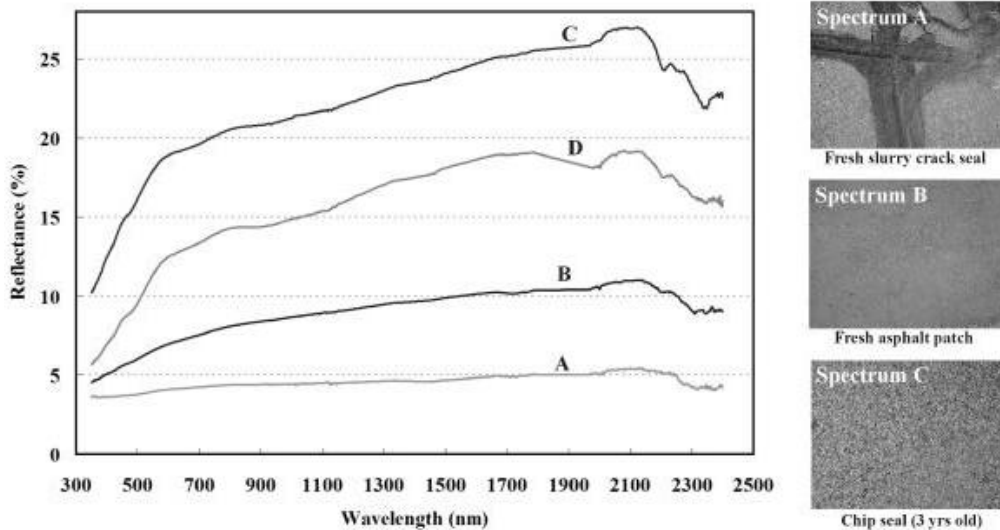

Figure 16: Spectral effects of different road surface treatments from the ASD ground spectral measurements

Spectrum D is a road surface described in the paper as a "normal road surface".

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[6] Ground spectra were acquired with an Analytical Spectral Devices (ASD) Full Range (FR) spectrometer.

Herold (2004) also looked at the reflectivity of white and yellow road marking paint compared with a "normal" road surface (figure 17).
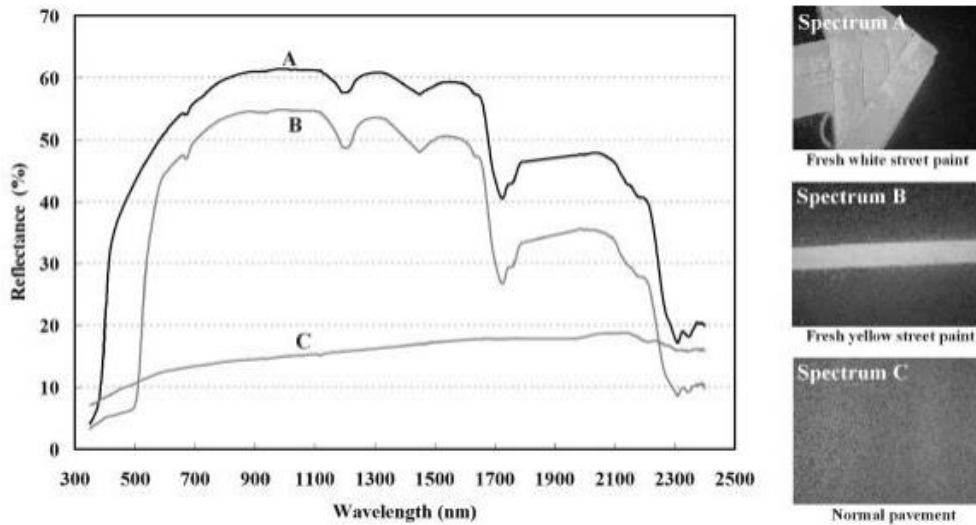

Figure 17: Spectral characteristics of street paint in different colours versus asphalt pavement from the ASD ground spectral measurements

This indicates that yellow paint is less reflective than a normal pavement in the blue wavelengths. This means that drivers on highways with blue rich LED lighting may find no overtaking lines harder to see than with the previous HPS.

2.4   Combined impact of pavement and lens absorption in mesopic conditions

Roads are lit under mesopic conditions, so it is appropriate to look at mesopic impacts rather than photopic or Scotopic impacts. Table 5 from Preciado and Manzano (2018) illustrates the percentage differences between photopic and mesopic illuminance between Metal Halide (MH), LED and HPS with HPS as the reference point.

	S/P	Mesopic luminance (cd/m^2)											
		0.3	0.4	0.5	0.6	0.75	0.8	0.9	1	1.1	1.2	1.5	2
(a) Mesopic vision effect													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	−26.2%	−23.4%	−21.2%	−19.4%	−17.3%	−16.7%	−15.6%	−14.6%	−13.7%	−12.9%	−10.8%	−8.1%
LED	2.41	−30.4%	−27.2%	−24.8%	−22.8%	−20.4%	−19.7%	−18.4%	−17.3%	−16.3%	−15.3%	−12.9%	−9.8%
(b) Road surface effect													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	−15.6%	−12.6%	−10.3%	−8.5%	−6.4%	−5.7%	−4.6%	−3.6%	−2.7%	−1.9%	0.1%	2.7%
LED	2.41	−19.3%	−16.0%	−13.4%	−11.4%	−9.0%	−8.3%	−7.0%	−5.8%	−4.8%	−3.9%	−1.5%	1.5%
(c)Eye transmittance effect (40 years old)													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	−12.9%	−9.9%	−7.7%	−5.9%	−3.8%	−3.2%	−2.1%	−1.1%	−0.3%	0.5%	2.5%	5.0%
LED	2.41	−15.7%	−12.5%	−10.1%	−8.1%	−5.7%	−5.1%	−3.8%	−2.8%	−1.8%	−0.9%	1.4%	4.2%
(d) Eye transmittance effect (60 years old)													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	−8.6%	−5.7%	−3.5%	−1.8%	0.2%	0.8%	1.9%	2.8%	3.6%	4.4%	6.3%	8.6%
LED	2.41	−10.3%	−7.2%	−4.9%	−3.0%	−0.8%	−0.2%	1.0%	2.0%	2.9%	3.7%	5.8%	8.4%

Note: Differences are presented as a function of the mesopic luminance and the S/P ratio of the light source. When the differences become positive the values are shaded.

Table 5: Percentage differences of photopic illuminance between white light sources and HPS, having HPS as a reference

The table is structured cumulatively downward with part b illustrating the impact on mesopic vision of the road surface and part c including the road surface impact and the eye transmittance impact of 40 year old eyes. Similarly, part d shows the combined impact of the road surface and 60 year old eyes compared with the sample of people used by CIE to derive part a of the table.

This shows that at higher values of mesopic luminance around 0.9 CD/m^2 more light is necessary from the LED in order to gain the same impact on the retina as an HPS source, for both 40 year olds and 60 year olds[7]. This will be more so for older people such as 70+ people. According to Ministry of Transport Travel Survey results[8] drivers 70+ travelled on average 1.7 billion kilometres per year in the 4 year period 2011-.2014 out of a total of 30.4 billion.

3   Environmental issues

These relate to the greater presence of blue light in LEDs than in HPS.

3.1   Wildlife

Wildlife is sensitive to light. As an example, birds may have their flight paths disturbed by light. This can have fatal consequences. For instance, they may be misled into landing at places from which they are unable to take off. Broadly similar problems occur to flying insects and bats.

The major impact on wildlife is in the total quantity of light to which they are exposed. Birds, and other wildlife, also vary in their sensitivity to the wavelength of light. However, overall, their sensitivity is predominantly towards the blue end of the spectrum. This is a secondary impact compared to the impact of the total quantum of light on them and it is generally recommended that the total quantum be minimised before the spectrum of the light is adjusted. This sensitivity also varies with the species and type of wildlife. Therefore, spectral adjustment may be more effective in some cases than in others. Streetlights contribute to artificial light at night (ALAN) and thus contribute to any disruption. These considerations feed into the choice of the spectra and light output of streetlighting LEDs where deployed in areas where their impact on wildlife may be important.
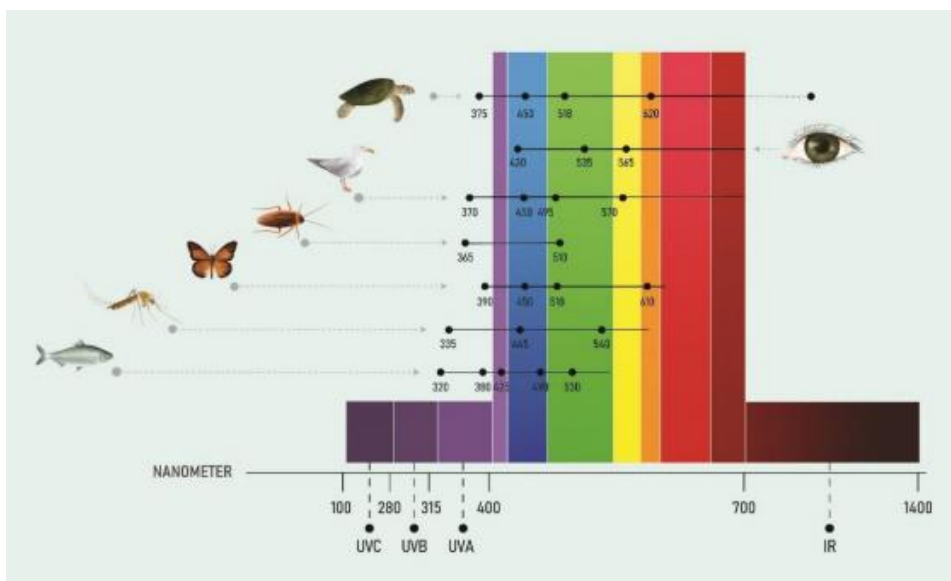

Figure18: Ability to perceive different wavelengths of light in humans and wildlife. © Pendoley Environmental, adapted from Campos (2017).

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[7] These figures may require some discounting when applied to present day LEDS, which may have lower S/P ratios than the 2.41 quoted in the table, implying lower proportions of blue light.
[8] https://www.transport.govt.nz//assets/Uploads/Report/Drivers-Travel-Survey-2015.pdf

Figure18 compares the ability to perceive different wavelengths of light in humans and wildlife. The common sensitivity to ultraviolet, violet, and blue light across all wildlife Is notable. Streetlights potentially have their main impact on birds, insects and bats. 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 streetlights in southern England did not affect the activity of bat species typically found near streetlights. 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 streetlights and their lumen output was not mentioned in the article. Figure 19 depicts some of the industrial LED lights used in their forest edge context.

Figure 19:Industrial Scale Lights used by Pawson and Bader (2014)

One concern is urban impacts. In an urban study (MacNaughton et al, 2021). the authors monitored the timing of dawn and dusk bird song; frequency of owl vocalisations; avian diversity, relative abundance and community composition; small invasive mammal and ground insect activity; and invertebrate relative abundance at 26 residential properties on low volume roads in Auckland. The monitoring happened both in backyards and on the street. These roads were presumably lit with pedestrian standard lighting. The monitoring was done over an 18 months period coinciding with a change from HPS to 4000k LED streetlights. The study observed the following changes over the period:

- Initiation time of dawn song was advanced or delayed for two bird species and backyard avian community composition was altered.

- Avian species richness, relative abundances of three bird species and ground insect activity increased.

No other effects were detected. The authors concluded that direct consequences in the study setting were small and might be mitigated by changes such as dimming.

3.1.1 Seabirds

A specific concern in New Zealand is rural impacts particularly those of rural settlements close to the sea, where the fledging behaviour of seabirds, like petrels may be affected. According to Lukies et al(2019) petrels and shearwaters are disproportionately attracted to ALAN.

Fledgling petrels and shearwaters are particularly vulnerable to land-based artificial lighting on their maiden flight.

The impact of the lighting may make them land prematurely on roads etc and not be able to take off. Unless rescued by human intervention they are vulnerable to traffic, predators etc. As a general rule adult birds differ from fledglings in that they are not attracted to light from a distance, with adult birds only becoming disorientated if flying directly past the source (Imber, 1975). However, for storm petrels the adults are the most vulnerable to light induced groundings.

Seabirds see within the violet-blue spectrum (380nm – 440nm) Nocturnal seabirds have special adaptations that allow them to see in low light levels. This adaption to low light levels makes seabirds sensitive to short wavelength blue light. Therefore, the shift from HPS streetlighting from HPS to LED may adversely affect some seabirds, if the impact of the LED lighting is enough to make an appreciable difference to the total lighting including other forms of lighting.

Two New Zealand sites where there have been concerns have been state highways at Kaikōura and Punakaiki. In a trial at Punakaiki Waka Kotahi NZ Transport Agency turned off streetlights on Sunday, 8 November 2020 and turned them back on in the New Year, RNZ reports[9] indicated that DOC had counted 10 crash landed birds over that period this year compared with 15 -25, which was considered the "usual" number.

Given their sensitivity to blue light , an obvious way to reduce the harm from grounding is to reduce the amount of blue light emitted from the lighting.

This can be done in three ways:

- Reduce the total lumens from the lights (i.e. dimming)
- Reduce the blue light content
- A combination of both

How this squares with safety concerns will depend on the optimal amount of lighting for safety and the impact of blue light on safety.

3.2   Dimming, safety, and the environment

It is obvious that one method of reducing environmental impact of lighting, either on wildlife, particularly birdlife , is to reduce the amount of light emitted. This should be considered along with its possible safety impact. An example of its impact on safety is in Jackett and Frith (2013} where for urban areas, a dose response curve of luminance vis safety was derived (figure 20).

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[9] https://www.rnz.co.nz/news/national/433509/crashing-petrels-moving-south-as-lights-dimmed-in-punakaiki
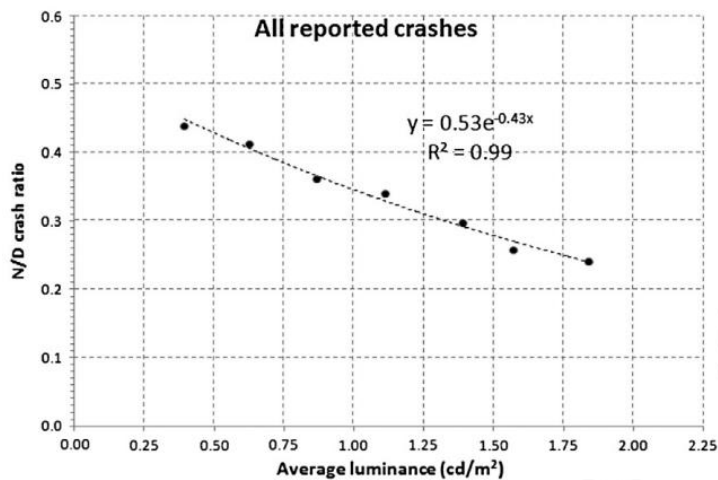
Figure 20: Relationship between urban luminance and safety (Jackett & Frith 2015)

Frith et al (2015) used this curve to study the benefits and costs of adaptive lighting. In the same urban context of Jackett and Frith (2013), Wood et al (2018) investigated the effect of streetlight dimming on night-time driving performance of 14 licensed drivers ages 27-40yrs. They drove an instrumented vehicle around a closed circuit at night. Six 4000K LED streetlights were positioned along a 250 m, straight section and their light output varied between laps. The dimming levels used were 25%, 50%, 75% and 100% of maximum output. At 100% the average road surface luminance was 1.14 cd/m2. The participants were given tasks involving recognition distances and reaction times to a low contrast, moving target and a pedestrian walking at the roadside. Participants drove at an average speed of 55km/hr. The dimming delayed reaction times to the moving target significantly and resulted in significantly shorter pedestrian recognition distances. The changes increased with increased dimming. The authors concluded that the data suggests that streetlight dimming impacts on driver visibility, but it was unclear how these differences impacted on safety.

Lighting mainly impacts multi-vehicle crashes and pedestrian crashes. There is little point in lighting where there are no pedestrians and traffic volumes are such that the probability of vehicles coming into contact with each other is very low (Frith & Lester, 2021). In these cases environmental gains are possible without reducing safety by dimming or turning off road lighting.

3.3   Sky glow

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]. 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). In particular, properly designed LED street lighting should produce no direct uplight meaning that the uplight will all come from reflection from the road's surface. The amount of reflection is discussed in section 2.3.4 but is a relatively small fraction of the light emitted from the luminaire, depending on the particular surface being discussed. Jackett and Frith 2021) found the relation between S/P ratio and skyglow from route lighting streetlights shown in figure 21.
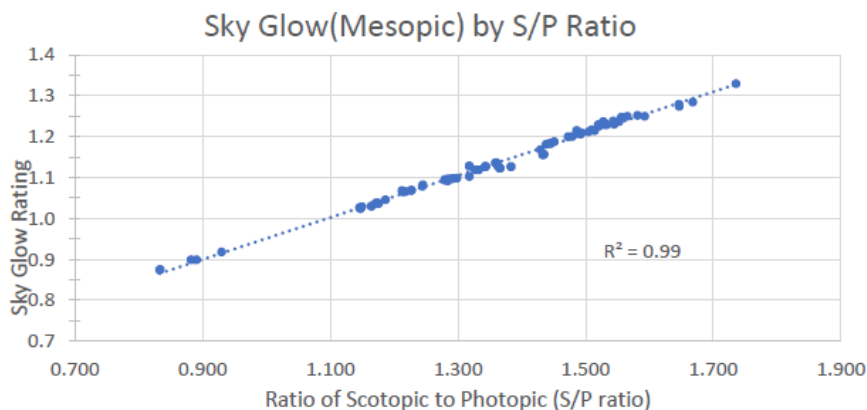
Figure 21: Relationship between skyglow and S/P ratio

This shows that within the range of the sample used mesopic skyglow increases linearly with S/P ratio. As shown earlier, increased S/P ratio is also related to more absorption by pavements and within the eye prior to reaching the retina. Thus, there are synergies between the S/P ratios favourable to skyglow and the S/P ratios favourable to letting more reflected light reach the retinas of older people.

There is a broadly similar synergy between pavement absorption and disturbance to birds. With well set up LEDs the only uplight is that reflected from the pavement. However, some light will be absorbed by the pavement rather than reflected and this absorption will be greater where the blue light proportion of the light emitted is lower.

4   Consequences of a switch from HPS to LED

Table 6 refers to lighting which is installed according to prescribed procedures. It looks at the pros and cons of moving from HPS lighting to LED with its generally larger proportion of blue light.

Safety Impact of increased blue light proportion		Environmental impact of increased blue light proportion	
Positive	Negative	Positive	Negative
Possible visibility improvement of objects on the road	Increased pavement absorption of light	Increased pavement absorption of light- reduces skyglow and wildlife disturbance from pavement reflection.	The light which is reflected from the pavement will still contain a larger blue component than HPS and will impact on skyglow and wildlife.
Probable visibility improvement of peripheral objects (E.g. pedestrians near the curb.)	Increased human lens absorption with age	Less energy use	
Possible increased vigilance of drivers	Increased pupil constriction with age.	No uplight when LEDs are properly designed- reduces skyglow and wildlife disturbance from pavement reflection.	
	More disability glare		
	Possible driving accuracy reduction		

Table 6: The pros and cons of moving from HPS route lighting to LED

The safety negatives are all ameliorated by reducing the amount of blue light. The safety positives all involve greater blue light, however, the evidence for the positives is weaker than that of the negatives. At the worst the amelioration, by bringing the CCT of LEDS in line with that of HPS is unlikely to make the safety impact of LEDs any worse than HPS.

Recent work related to the installation of 4000K LED lighting on SH22 (Frith and Lester, 2021) suggests that the lighting has been associated with improved safety. This, however, does not answer the question as to whether, and in what circumstances there is a safety increment over HPS.

5 Conclusions.

- It would appear that on the balance of probabilities there are safety benefits in reducing the proportion of blue wavelengths in route lighting.

- Bringing the SPDs of LEDs in line with those typical of HPS is unlikely to make the safety impact of LEDs less than that of HPS.

- There are also environmental benefits, so this is a win-win policy.

References

Adrian W. K. (1989). Visibility of targets: model for calculation. Light Res Technol. 21(4):181–188.

Baldridge, A.M., Hook, S.J., Grove, C.I., Rivera G. (2009) The ASTER Spectral Library Version 2.0. Remote Sensing of Environment, Vol 113, pp. 711-715.

Birren, James E . Casperson, Roland C and Botwinick, Jack (1950) Age Changes In Pupil Size Journal of Gerontology, Volume 5, Issue 3, July 1950, Pages 216–221, https://doi.org/10.1093/geronj/5.3.216

Bhagavathula, R., R. Gibbons, J. Hanifin, and G. Brainard. 2021. LED Roadway Lighting: Impact on Driver Sleep Health and Alertness. Pre-publication draft of NCHRP Research Report 968. Transportation Research Board, Washington, D.C.

Bullough JD. 2009. Spectral sensitivity for extrafoveal discomfort glare. Journal of Modern Optics 56(13): 1518-1522

Rukmini, A. V. Milea, Da, Aung, Tin &.Gooley, Joshua J Pupillary responses to short wavelength light are preserved in aging A Nature,ScieNtific Reports | 7:43832 | DOI: 10.1038/srep43832

CIE 115:2010 (2010) Lighting of Roads for Motor and Pedestrian CIE

CIE (2011) International Lighting Vocabulary. Vienna, Austria: International Commission on Illumination; 2011:203.

CIE (2014) Publication 206:2014 The effect of spectral power distribution on lighting for urban and pedestrian areas.

Eisenbeis, Gerhard und Eick, Klaus (2011) Studie zur Anziehung nachtaktiver Insekten an die Straßenbeleuchtung unter Einbeziehung von LEDs Natur und Landschaft 86 (2011): 07 In German https://www.kohlhammer.de/wms/instances/KOB/appDE/Natur-und-Landschaft-fuer-freies-Einkaufen/Studie-zur-Anziehung-nachtaktiver-Insekten-an-die-Strassenbeleuchtung-unter-Einbeziehung-von-LEDs/ Viewed 11/6/2017

Ekrias, Aleksanteri, Eloholma, Marjukka and Halonen, Liisa (2009) The effects of colour contrast and pavement Aggregate type on road lighting performance Light & Engineering Vol. 17, No. 3, pp. 76-91, 2009 No. 3, 2009, pp. 42-53

Frith, W, M Jackett and J Chisnall (2015) The benefits and costs associated with urban road lighting in New Zealand. Presented at IPENZ Transportation Group Conference. Christchurch, 22–24 March 2015.

Frith, Bill and Lester, Tiffany (2021) The safety impact of lighting a previously unlit section of SH22 with LED Luminaires Paper Presented at the NZTA/NZIHT Conference May 2021 Napier

Fusheng, Li, Yuming, Chen, Yang, Liu & Dahua, Chen (2012) Comparative in Situ Study of LEDs and HPS in Road Lighting LEUKOS Vol. 8, Issue 3, 2012

Herold, Martin (2004) Understanding spectral characteristics of asphalt roads http://www.geo-informatie.nl/Projects/Santa_Barbara_Urban_Spectral_Library/urbanspec/understanding_asphaltspectra_web.pdf

Jackett, M. and Frith, W. (2013) Quantifying the impact of road lighting on road safety – A New Zealand study. IATSS Research (International Association of Traffic and Safety Sciences), 36, 139–145. 2.

.Jackett, M. and Frith, B. (2021)   An investigation of the quality of indexes used to estimate the sky glow from LED road lighting luminaires Report prepared for Waka Kotahi NZTA

Jin, Huaizhou, Jin, Shangzhong, Chen, Liang, Cen, Songyuan and Yuan, Kun (2015) Research on the Lighting Performance of LED Street Lights With Different Color Temperatures IEEE Photonics Journal Volume 7, Number 6

Lewin, Ian, Box, Paul and Stark, Richard E (2003) Roadway Lighting: An Investigation and Evaluation of Three Different Light Sources Final Report 522 Prepared for Arizona Department of Transportation

:Lin Y, Fotios S, Wei M, Liu Y, Guo W, Sun Y .(2015) Eye movement and pupil size constriction under discomfort glare. Invest Ophthalmol Vis Sci. 2015;56:1649–1656. DOI:10.1167/ iovs.14-15963
.
Rea MS (editor). 2000. IESNA Lighting Handbook Reference and Application 9th edition New York illuminating Engineering Society

Rodríguez-Morilla, Beatriz, Madrid, Juan A. Molina, Enrique, Pérez-Navarro, José and Correa1, Ángel (2018) Blue-Enriched Light Enhances Alertness but Impairs Accurate Performance in Evening Chronotypes Driving in the Morning Front.
Psychol.,   https://doi.org/10.3389/fpsyg.2018.00688

Schreuder, DA, J Kosterman and A Morris (1998) Road lighting for safety. London: Thomas Telford.
.
Van de Kraats, Jan and Van Norren, Dirk (2007), Dirk Optical density of the aging human ocular media in the visible and the UV Journal of the Optical Society of America A 24 1842-1857

Wood, Joanne M. Isoard, Gillian, Black, Alex Cowling, Ian (2018) Night-time driving visibility associated with LED streetlight dimming Accident Analysis and Prevention 121 (2018) 295–300

Younis, Dana (2013), "Comparative Pedestrian Visibility under Solid State Led Sources" (2013).Theses. Paper 297United Arab Emirates University
http://scholarworks.uaeu.ac.ae/cgi/viewcontent.cgi?article=1299&context=all_theses

Zhiyong , Zhang, Yong, Yang and Lei, Wang (2011) A novel reaction time measurement under road artificial illumination Proceedings of the Third International Conference on Transportation Engineering, Chengdu, China, http://ascelibrary.org/doi/pdf/10.1061/41184%28419%29541 Accessed 17/5/2017

Zhu, X., Deng, S., Zhang, M., Cheng, W., & Heynderickx, I. E. J. (2013). Perception study of discomfort glare from LED road lighting. Light and Engineering, 21(2), 61-68.