Scope

The scope of this document is to show that LED lighting with a broad white spectrum at color temperatures between 4500° and 6500° Kelvin is more efficient and provide better visibility than the often used high pressure sodium (HPS) lamps or PLL lamps with low color temperatures.
In the retina of the human eye (fig 1.) there are photoreceptor cells called cones and rods. The rods are more sensitive to blue/green light during evening and night conditions also considered as scotopic conditions. The sensitivity (quantitatively) of the rods is ~1700 lm/W, compared to the cones that are in the order of magnitude of 680 lm/W. *This is a factor of 2,5*. There are ~20x more rods than cones in the human eye. The peak sensitivity is at ~555 nm.

The document written by Tom Murphy **(a)** describes the (cor)relation between human eye sensitivity and light color linked to Lumen output.

In Murphy's document the following statement is made: at the wavelength of a heliumneon laser at 633 nm, the sensitivity of the eye is only 23,5% of what it is at the peak (leading to 160 lm/W), whereas a green neodymium; YAG lasers at 532 nm come in at 88,5% sensitivity, for 604 lm/W." *This is a factor of 3,8.*

Fig. 1

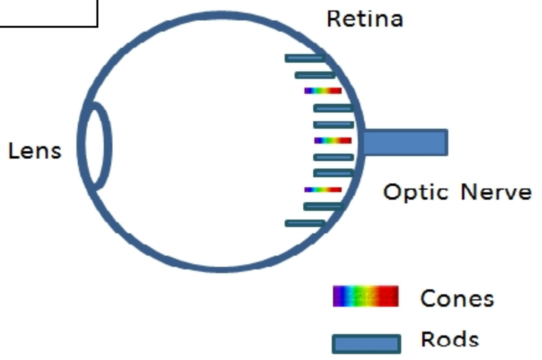
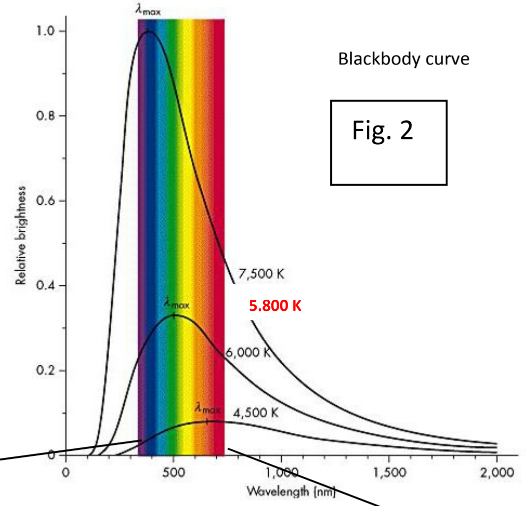
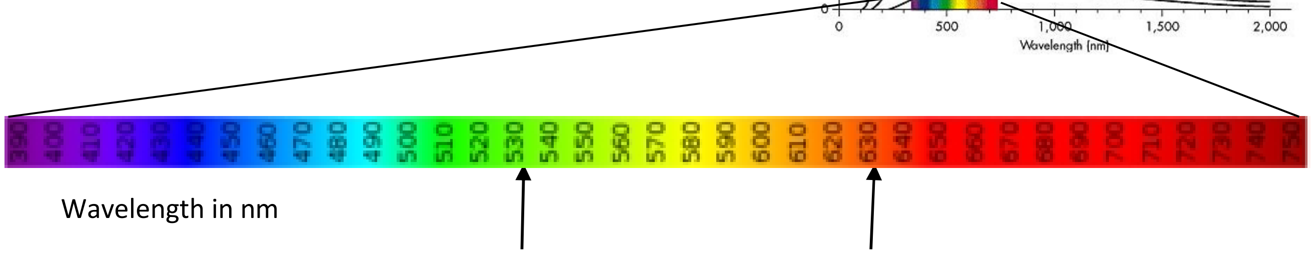


Fig. 2





If we look at the graph at the figure below, we see that the optimum photopic sensitivity is at a color temperature of 5800°K on the blackbody curve (fig. 2). Below 400 nm and above 700 nm the eyes have no photopic response (fig. 3).

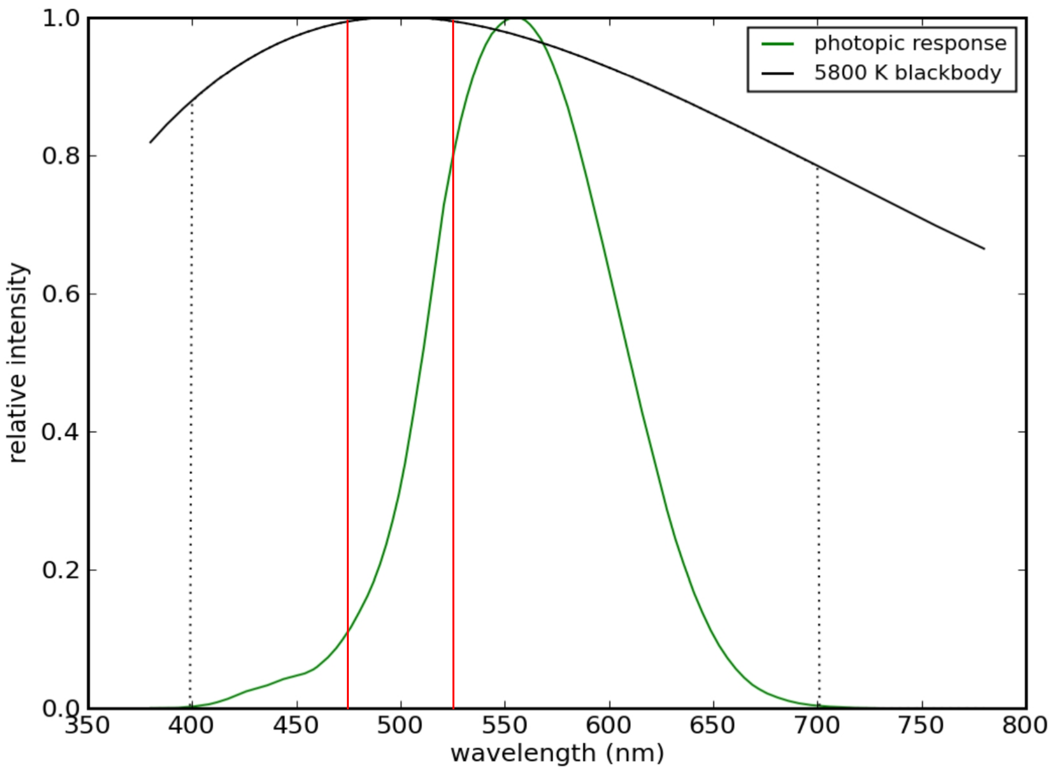


Fig. 3

Looking at the two red lines we see that the optimum is between ~475 and 525 nm, this is in the cool blue to greenish area. Monochrome “white like” LEDs are most efficient the in cool blue area.

Depending on the preference of people in the different parts of the world, cool white (6500K more tending to daylight) or a bit warmer white (4300K close to the color temperature of moonlight) is more desirable.

With all this in mind, and the fact that the human eye functions well in moonlight with a cool white color temperature of ~4100°K (night condition where rods are most efficient), we can safely state that the popular light on Dutch highways with a color temperature of ~2200°K provides less than optimal visibility in dark conditions. If warm color temperatures were optimal, we would all have amber-colored headlights! As indicated, white LEDs are efficient in a range of 4300°K to 6500°K. So the relative power to produce optimal light conditions can be reduced considerably. Looking at the example of the laser, a factor of 2,5 is perhaps a conservative figure.

Moonlight has been the natural light source at night for ages. This might be something we could learn from, i.e. that LED light with this wavelength comes close to the optimal condition. One might conclude that cooler white light (e.g. 6500°K) is better and more efficient, since this is coming closer to the color temperature of daylight, but the difference in eye sensitivity in night conditions is not as large as the difference with amber light at ~2200 K **(b)**

In addition, studies have shown that human beings are more alert at cold white light. This has to do with the Circadian (=24 hour) rhythms. At wavelengths >/principally blue light, around 460 to 480nm, the generation of melatonin is suppressed **(c).**

Melatonin is generated as darkness approaches as this hormone is needed to fall asleep. If we are able to suppress the generation of melatonin with the right light color and intensity, it might help us stay more alert when driving a car.

This section is an overview of several typical luminaires and their specifications.

Main parameters of light source and luminaries											
Light source type	**HP Mercury**			**HP Sodium**			**HFD or HID**		**LED**		
Light source parameters											
Light source power, W	**125**	**250**	**400**	**70**	**150**	**250**	**70**	**150**	**37**	**92**	**148**
Average power of light source, W	131	263	420	74	158	263	70	150	37	92	148
Light output, Lm/W	50	55	60	80	87	95	84	83	91	91	91
Luminous flux, Lm	6250	13750	24000	5600	13050	23750	6200	12000	3511	8778	14045
Lifetime, hour x 1000	15	15	15	25	25	25	60	60	50	50	50
CRI	**50**	**50**	**50**	**20**	**20**	**20**	**>80**	**>80**	**>80**	**>80**	**>80**
Color temperature	>/3000k			2000K-2700K			>/4000		>/4300		
Luminaire parameters	**125**	**250**	**400**	**70**	**150**	**250**	**70**	**150**	**37**	**92**	**148**
Efficiency of the luminaire, %	70	70	70	70	70	70	70	70	100	100	100
Driver/control gear efficiency, %	75	75	75	75	75	75	90	95	90	90	90
Luminaire luminous flux, Lm	3719	8181	14280	3332	7765	14131	3906	7560	3265	8164	13062
Power consumption, W	**175**	**350**	**560**	**98**	**210**	**350**	**78**	**158**	**39**	**97**	**156**
Luminaire light output, Lm/W	**21**	**23**	**26**	**34**	**37**	**40**	**50**	**48**	**84**	**84**	**84**

Light with CRI values >80 give better color recognition. The higher this value the better, however for outdoor applications >80 is sufficient.

Conclusion:

A high pressure sodium luminaire of 260 W can be replaced by LED fixture at 150W if we look only at the lumen output. If we take into account the behavior of the human eye and we estimate that we could divide 260 W by a factor ***2.5***, it is very likely that the visibility of a 100 W Light Engines fixture might give good or even better visibility at a color temperature of >/4300K. Of course, actual tests and trials would be needed to completely prove this theory, but when you search on the internet, searching for "pupil lumen", you will find a lot of information that supports the conclusion of this document. A link to one example is mentioned in (d)

(a) http://physics.ucsd.edu/~tmurphy/papers/lumens-per-watt.pdf.

(b) http://www.schneiderkreuznach.com/knowhow/natuerliche_lichtqeuellen_e.htm

(c) http://en.wikipedia.org/wiki/Melatonin

(d) http://glamox.com/gmo/pupil-lumen