White LED sources for vehicle forward lighting

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ABSTRACT

Considerations for the use of white light emitting diode (LED) sources to produce illumination for automotive forward lighting is presented. Due to their reliability, small size, lower power consumption, and lower heat generation LEDs are a natural source choice for automotive lighting systems. Currently, LEDs are being successfully employed in most vehicle signal lighting applications. In these applications the light levels, distributions, and colors needed are achievable by present LED technologies. However, for vehicle white light illumination applications LEDs are now only being considered for low light level applications, such as back-up lamps. This is due to the relatively low lumen output that has been available up to now in white LEDs.

With the advent of new higher lumen packages, and with the promise of even higher light output in the near future, the use of white LEDs sources for all vehicle forward lighting applications is beginning to be considered. Through computer modeling and photometric evaluation this paper examines the possibilities of using currently available white LED technology for vehicle headlamps. It is apparent that optimal LED sources for vehicle forward lighting applications will be constructed with hereto undeveloped technology and packaging configurations. However, the intent here in exploring currently available products is to begin the discussion on the design possibilities and significant issues surrounding LEDs in order to aid in the design and development of future LED sources and systems. Considerations such as total light output, physical size, optical control, power consumption, color appearance, and the effects of white LED spectra on glare and peripheral vision are explored. Finally, conclusions of the feasibility of current LED technology being used in these applications and recommendations of technology advancements that may need to occur are made.

Keywords: LEDs, automotive forward lighting, illumination, nonimaging optics.

1. INTRODUCTION

Automotive forward lighting systems allow safe and comfortable driving in nighttime or adverse weather conditions. Although only approximately one quarter of the total miles driven in the US are driven at night and twilight the total accident rate for that time period is ~44%.[1] One is roughly twice as likely to get into an accident at night. Although other factors such as alcohol use and fatigue assuredly play a role in the higher likelihood of nighttime accidents, diminished visual performance due to reduced light levels is also a major contributor.[2] Specifications and standards have been developed over the years for vehicle forward lighting systems to ensure that vehicle operators can perform the necessary visual tasks for driving as well as possible.

It is the optical engineer's job to design cost effective and robust headlamp systems that meet the required standards for safety and produce esthetically attractive beams. Headlamps have become styling elements on today's vehicles. Not only must headlamp profiles fit with the aerodynamics and styling of the overall vehicle design, but the headlamps themselves have become brand differentiating elements.

This new emphasis on the styling aspects of headlamps, combined with the need for greater nighttime safety and new lighting technology, has greatly increased the development of innovative forward lighting. New sources have been introduced. In the early seventies halogen bulbs replaced incandescent bulbs and increased the amount of light on the road. In the early nineties high intensity discharge (HID) lamps were developed for automotive use that resulted in greater light output, higher luminous efficacy, and longer life than conventional systems using halogen lamps.[3] HID lamps also result in a different output spectral distributions and new optical design capabilities. In the late nineties coated lamps were developed for aesthetic and efficiency reasons. Blue coated halogen lamps mimic the color appearance of HID lamps.[4] Infra red (IR) coated halogen lamps increase the efficiency of halogen lamps.

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New optical designs for forward lighting systems have also been developed. For styling and beam control reasons design trends have gone away from smooth geometric reflectors and faceted outer lenses to complex shaped (faceted) reflectors and clear outer lenses.[5] Styling aspects and the introduction of HID sources have also driven the development of the projection headlamp systems.[6][7] HID sources have also driven the design and development of remote or fiber coupled headlamps systems.[8] Currently work is being done on new adaptive forward lighting systems. This work was started under the Eureka Project 1403 AFS (Advanced Frontlighting Systems) to comprehensively improve forward lighting technology.[9] To achieve lighting that is adaptable to different driving conditions a variety of optical design solutions, such as multiple additive beams, dynamically moving components, and remote systems, are being considered.

LED vehicle forward lighting systems are a natural progression in this line of source and optical design advances. The development of white LED technology with increased lumen output per device, and the promise of further light output increases in the near future, has led to the consideration of LED sources for use in vehicle forward lighting. LED sources potentially offer several advantages for use in automotive applications. These include longer life, greater robustness, lower power consumption, and design flexibility. This unique flexibility for design makes their application particularly interesting for AFS functionality. LED systems may also offer human factors benefits, such as increased peripheral visual performance, reduced glare, and improved customer preference.

Figure 1 shows two concept vehicles with LED forward lighting systems.[10][11] Figure 1a shows a high flux LED based lighting system on the Fioravanti Yak concept vehicle shown at the Geneva Motor Show. The system is based on individual projector optics for each LED and includes the applications of fog lamps and integrated headlamps with high and low beams. Figure 1b shows an LED forward lighting system on the Mitsubishi SSU (super sports utility) concept vehicle. The system is based on an LED array and is for a driving light application. These LED systems were developed to show the concept and neither one meets the appropriate lighting standards or regulations.

a)

b)

Figure 1. White LED forward lighting on concept vehicles. a) A high flux based LED forward lighting system on Fioravanti Yak concept vehicle. b) A 5 mm array based LED forward lighting system on a Mitsubishi SSU concept vehicle.

The use of white LEDs for vehicle forward lighting is in its infancy. In fact, it is still impractical from a cost and a functionality perspective to use LEDs sources for forward lighting on a production vehicle. However, the promise of what LED technology could bring to vehicle forward lighting in the near future is sufficient enough so that development work is beginning now. For as perspective of how the promise of LED performance can be realized consider colored LEDs as applied to vehicle signal and marking lights. No other lighting technology offers such a rapid possibility of change to the performance and appearance of signal and marking lights as the application of LEDs.[12] Only ten years ago, very few cars had LED center high mounted stop lights (CHMSLs). Now LEDs are standard for this application and most other new signal and marking developments. With further improvement in cost and efficiency of LEDs this trend should only increase.

This paper examines the issues surrounding the use of white LEDs in an effort to begin the discussion of source and system design. This discussion will facilitate future development of LED sources and systems by identifying important issues for manufacturers and specifiers to consider. The issues presented here include; total light output, physical size, optical control, power consumption, color appearance, and the effects of white LED spectra on glare and peripheral vision. To provide a perspective on the development of these sources T 1-3/4 (5 mm), high flux, and the newest very high flux white LEDs will be considered each case. This analysis shows the improving feasibility of using LED sources. Computer simulation analysis will be employed as well, particularly in the discussion of optical control, to examine design issues. Except where noted, this paper only considers phosphor based white LED technology. Color mixing LED technology to produce white light presents another excellent possibility for developing vehicle forward lighting sources. However, color mixing is a lengthy and complicated subject and is out of the scope of this discussion.

2. WHITE LED FORWARD LIGHTING SYSTEM DESIGN CONSIDERATIONS

2.1 Total light output

The biggest and most immediate problem facing the development of LED forward lighting is the amount of light generated per device, or the lumen package, of white LEDs. 5 mm white LEDs have the familiar indictor style shape and produce beams with a half angle of 15^o to 30^o. These LEDs typically produce ~1 lm per device. As a benchmark, a typical 9006 halogen lamp used for US low beam forward lighting nominally produces 1000 lm.[13] Therefore, to reproduce this one would need ~1000 LEDs. This is an impractical solution for cost and other reasons that will be discussed.

In a practical headlamp system not all of the halogen lamp's output lumens are used effectively. This is due to losses within the fixture (efficiencies less than one) and misdirected light in the beam. The actual number of total lumens on the road from a typical halogen complex reflector system is ~400 lm. [8] Although an LED system may be intrinsically more efficient at delivering useful lumens, such a system would still have losses.[14] Here we assume a loss factor of 40%. Therefore, to achieve 400 lm on the road the LEDs would need to produce ~700 lm. This implies that ~700 5 mm LEDs would be needed. Even with the reduced numbers of LEDs needed this is still an impractical solution.

The high flux white LEDs have a new compact shape and produce beams with wide half angles of 100^o to 160^o. These LEDs typically have total output in a range from 20 lm to 40 lm. Therefore, to produce 1000 lm 25 to 50 LEDs would be needed. To produce 400 lm on the road 18 to 35 LEDs would be required. Although the numbers of LEDs required have reduced, due to the increasing light output per device, this is still an impractical solution.

The very high flux LEDs come in the same shape and produce the same general beam angles and the high flux LEDs. However, these LEDs produce 120 lm. Therefore, to produce 1000 lm 8 LEDs would be required. To produce 400 lm on the road 6 LEDs would be required. The numbers of LEDs required have reduced once again due to the increase in output flux per device. This solution is beginning to be feasible from both cost and total light output perspectives. The flux output per LED and the number of LEDs needed to achieve the needed output lumens are summarized in Table 1.

LED Type	Initial Output (lm)	Number to produce 1000 lm	Number to produce 400 lm on road
5 mm	1	1000	700
High Flux	20 - 40	25 - 50	18 - 35
Very High Flux	120	8	6

Table 1. Summary of white LED flux output and number of LEDs required to produce adequate system flux output.

The above analysis only accounts for the initial LED flux output. Like other light sources the amount of output light from LEDs decreases over operating time. Unlike other light sources LEDs rarely fail outright, the lumen depreciation just continues to increase over time. As a benchmark, a typical 9006 halogen lamp used for US low beam forward lighting has a nominal life of 1000 hours.[13] At this point roughly half of the halogen lamps have failed. At this point the flux output of white 5 mm LEDs have reduced to ~90% of their original value when driven at nominal current, 20 mA.[15] This is approximately 5% lower than a typical halogen lamp at the same point in life.[15] Therefore to keep the light output comparable to halogen over the entire life of the forward lighting system the initial light output of the LED system would have to be increased by 5%, or 35 additional LEDs would have to be added.

For the high and very high flux LEDs the lumen depreciation is better than halogen lamps at nominal operating current, 350 mA and 700 mA respectively. At 1000 hours the flux output is at or over 100% of the initial flux output.[15] This raises the interesting possibility of overdriving the high and very high flux LEDs. This would increase light output (decrease the number of LEDs) and correspondingly increase the lumen depreciation rate. The driving current could be adjusted such that the depreciation rate of the LEDs matched that of the halogen lamps. One would have to be careful with this approach, however, since it would cause the LEDs to operate at higher temperatures and increase the thermal management issues.

2.2 Optical control

Possibly one of the greatest advantages that LED sources offer to the design and performance of vehicle forward lighting systems is flexibility in optical design. The types of optical systems that can be used with LED sources to produce the required beam patterns are numerous. These broadly include reflector, refractor, TIR, or combination systems. Like no time before there is currently a host of new optical systems being developed with high flux LEDs for automotive signal lighting applications.[12] There is no reason that vehicle forward lighting will not follow this trend to exploit the design capabilities of LED technology.

Since the number of design possibilities using LED sources is very large it would be impractical to try to investigate them all. Therefore, a reflective nonimaging system will be explored in order to examine some of the issues surrounding optical design. As discussed previously, a number of LED sources can be arrayed together in order to produce the total amount of flux needed. However, this is only part of the story. Forward lighting beam patterns for vehicle are not uniform. The beam must meet standardized and regulated intensity distributions to ensure the safety of the vehicle driver and any oncoming drivers. Standards dictate structure within the beam in terms of intensity levels, gradients, and angular limits. In order to achieve the required intensity distributions traditional forward lighting systems typically use reflective or refractive systems to image elements of the source into the far field. These images are aggregated together to create the desired beam patterns. The low beam hot spot, for example, is typically constructed of overlapping images of a lamp filament.

LEDs can be employed in the same manner. Consider the high flux LED shown in Figure 2. This LED used 50 separate LED die emitters arrayed together in the same packaged and covered with a phosphor to produce a flux output of 42 lm. Both the measured and manufacturer specified output intensity distributions of this LED are shown in Figure 3. This LED was modeled in optical ray tracing software. Since the array of die emitters is covered with a phosphor, which acts like a secondary lambertian source, this LED is reasonable approximated by an angularly appodized rectangular emitter. This is particularly true when considering the source in the far field. Were no phosphor present, an approach of accurately modeling the physical and optical characteristics each element in the source would have been followed. This would have ensured modeling accuracy, particularly if the model were used in the near field. Ray tracing analysis was performed on the source model with 1,000,000 rays traced and collected on a far field receiver. The intensity distribution was calculated from this ray trace analysis and the results are shown in Figure 2. There is good correlation between the measured, specified, and modeled distributions, $r^2 > 0.99$.

By simply aiming the LEDs, without any secondary optics, one could try to generate the required beam pattern. This is impractical however due to the high intensity values need in certain beam pattern locations. Consider the North American low beam standard.[16] It requires a hot spot of between 6,400 cd and 24,000 cd. To meet the minimum requirement, with each LED producing a maximum of ~14 cd in this case, one would need ~457 LEDs. Obviously this is impractical. Therefore, secondary optics are needed for beam shaping.

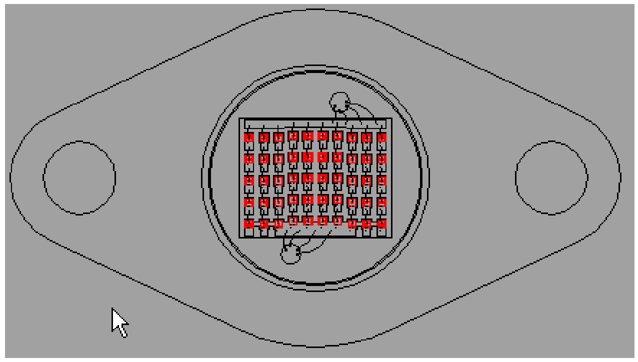

Figure 2. High flux LED source with 50 emitters and a total flux output of 42 lm.

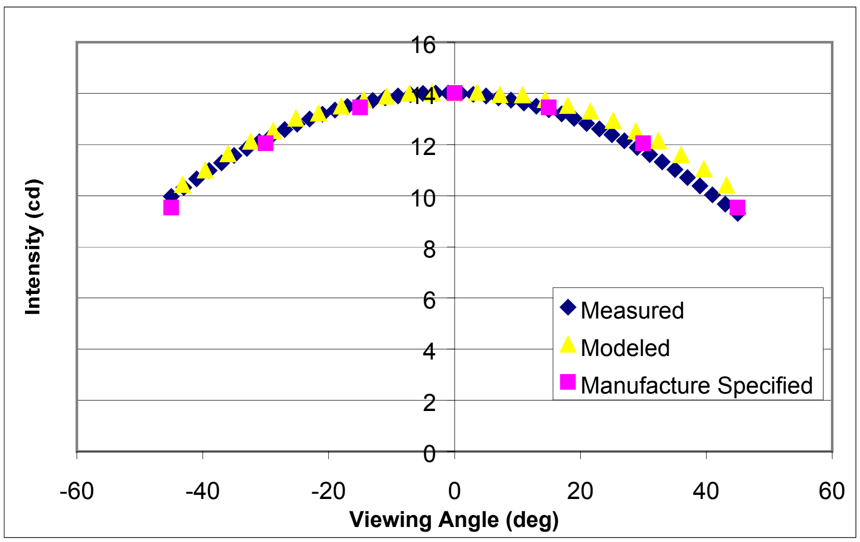

Figure 3. Measured, specified and modeled intensity distribution of the example high flux LED source.

For this example a nonimaging compound parabolic concentrator (CPC) surface was chosen for the reflector shape.[17] This type of reflector is very efficient at transferring all of the flux from the source into the specified beam angle. Note, however, a true CPC reflector is somewhat impractical for actual application since the reflectors tend to get very long for small beam angles. In practice other reflective or hybrid shapes, such as truncated CPCs, freeform surface reflectors, and TIR lenses, would be more functional.[17][18] However, for the purposes of this example, the CPC works well to illustrate design issues.

The surface profile for the CPC was generated using:

$$y(\phi) = \frac{2f \sin(\phi - \theta_{max})}{1 - \cos\phi} - a', \quad z(\phi) = \frac{2f \cos(\phi - \theta_{max})}{1 - \cos\phi} \tag{1}$$

where,

$$f = a'(1 + \sin\theta_{max}) \tag{2}$$

and where θ_m is the CPC acceptance angle (beam angle), a' is the radius of the exit aperture, and ϕ is the parametric variable.[17] In this case the radius of the exit aperture was chosen to fit the dimensions of the example high flux LED, a '= 22 mm. Several different beam angles (30°, 15°, and 7°) were explored to examine the maximum intensity values. The goal is to achieve a high intensity with a relatively wide beam angle. A CPC profile was generated for each beam angle and entered into optical modeling software. The CPC profiles were then rotated about the optical axis to form the reflector shapes. Figure 4 shows the modeled CPC reflector and the high flux LED source for the 30° beam angle case.

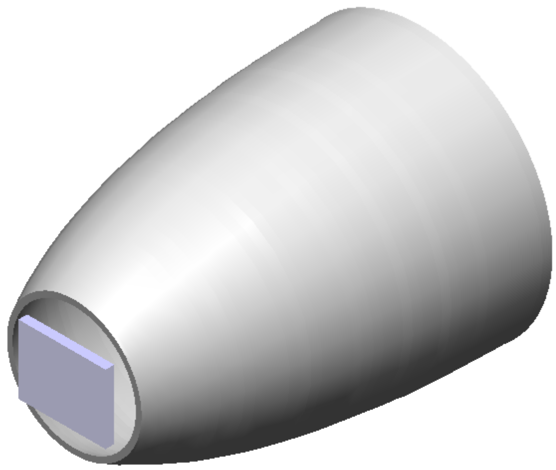

Figure 4. Modeled CPC reflector and LED source for the 30° beam angle case.

Optical simulation was performed through ray tracing. 1,000,000 rays were traced from the source and collected on a far-field surface receiver. From this analysis the system intensity distribution was determined. To verify the accuracy of this simulation the resulting intensity distribution was compared to a measurement of the example high flux LED and a manufacturer supplied 30° CPC. Figure 5 shows both the measured and modeled intensity distributions. Good correlation is seen between the two distributions, r^2=0.98.

From Figure 4 it can be seen that the maximum intensity values achievable with the example high flux LED and the 30° CPC is ~100 cd. To meet the minimum hot spot requirement 64 LEDs and reflectors would be needed. This is still an unacceptable solution. By decreasing the beam angle of the CPC reflector the maximum intensity value can be increased. The 15° CPC reflector produces a maximum intensity of 314 cd and the 7° CPC reflector produces a maximum intensity of 747 cd (Figure 6). Both of these reflector designs would still result in an unacceptable amount of LEDs needed to create the required maximum beam intensity value. By fitting the maximum intensity values, Figure 6, it can be seen that a CPC with an ~1° beam angle would be needed to produce the required intensity from one LED. The resulting very small "pencil" beam would be hard to aim and control, and a great number of them would be needed to fill in the rest of the beam pattern. Therefore, although this example high flux LED produces enough flux such that only 35 LEDs would be needed to generate sufficient light, more than 35 LEDs and associated optics would be needed to create the required intensity distribution. This is an impractical solution and demonstrates that this example high flux LED is not applicable for vehicle forward lighting applications.

This simple design example illustrates how merely adding more and more die emitters to produce the required flux is not a viable approach for designing LEDs for vehicle forward lighting. Although that design strategy produces more flux from the LED package it also increases the source size, particularly when a phosphor coating is placed over the entire die array. Increasing the source size in this manner tends to decrease the source luminance, making optical control and the production of high intensity regions in the far field beam more difficult.

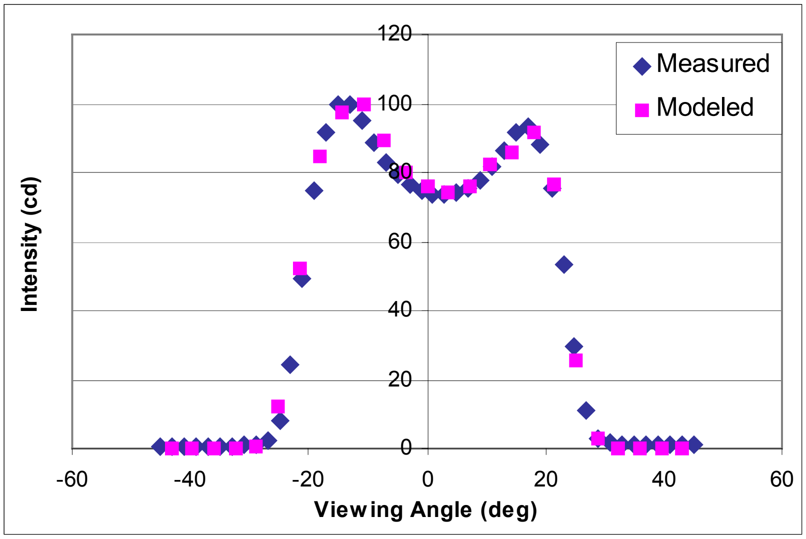

Figure 5. Measured and computer simulated intensity distribution for the example high flux LED with 30° CPC reflector.

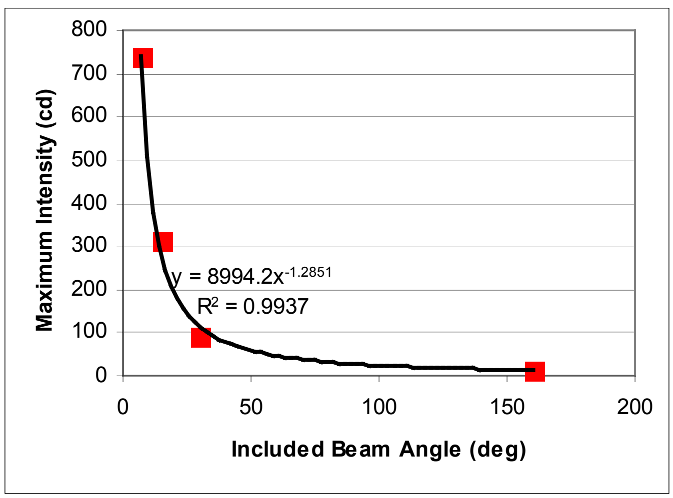

Figure 6. Maximum beam intensity as a function of designed CPC beam angle for the example high flux LED.

2.3 Physical size

The physical size of a LED forward lighting system will depend on how many sources are required, space needed for thermal management, and any packaging or mechanical considerations. The number of sources required will depend on the LED technology employed. Clearly, using the older 5 mm style LEDs will result in a system with a relatively large area extent. Considering only total flux output, 1000 LEDs requires an array of 32 by 32 sources. If arrayed together without any spacing this covers an area of 160 mm by 160 mm or 0.026 m^2. However, arraying LEDs together in this manner is not feasible due to thermal management issues. Adding a 3 mm space between each LED to allow thermal dissipation results in an area of 250 mm by 250 mm or 0.063 m^2. Even if only 700 LEDs are employed this will result in 27 by 27 LED array with an area including spacing of 210 mm by 210 mm or 0.044 m^2. Given that the current trend in automotive forward lighting is growing towards smaller more integrated systems these represent unacceptable system sizes.

For the high and very high flux LEDs the physical size of the system is more promising. One manufacturer supplied high flux LED array source packages 18 LEDs in roughly a 60 mm by 50 mm array.[19] These LEDs produce ~20 lm each.

Therefore, two of these array packages would have to be used together to achieve 400 lm on the road. This results in a 120 mm by 100 mm or 0.012 m^2 area. This is a reasonable sized array for a vehicle forward lighting system. However this analysis does not consider than addition LEDs might have to be added to achieve the required hot spots and cutoffs in the beam as described above. Also, this configuration does not leave much space for secondary optics to provide beam control. This may result in a secondary optical system with significant depth, which also goes against current automotive trends.

For the very high flux LEDs the possibility of a system of small physical size is even greater. Considering only 6 LEDs needed to produce 400 lm on the road, and assuming the spacing can remain similar to the above source array example, results in an array size of approximately 30 mm by 25 mm or .00075 m^2. This is a more than reasonable sized array for a vehicle forward lighting system. As before this analysis does not consider the need for additional LEDs or the depth of the optical system. This analysis also does not consider if the very high flux LEDs, with their higher operating power, might require further spacing between LEDs. Table 2 summarizes the LED array area need to produce 400 lm on the road.

LED Type	Array area to produce 400 lm on road* (m^2)
5 mm	0.0420
High Flux	0.0120
Very High Flux	0.0008

*With space between LEDs for thermal management.

Table 2. Summary of LED array area.

2.4 Power consumption

Power is at a premium in today's vehicles. In fact automobiles are moving towards a 42 V electrical system to try to keep up with demand. Therefore, power consumption is an important consideration. As a benchmark, a typical 9006 halogen lamp used for US low beam forward lighting nominally consumes 55 W.[13] HID systems, which represent a breakthrough in power consumption, use only 35 W to produce 2 – 3 times the flux as halogen systems.[20] Typical 5 mm LEDs use ~0.068 W at a 20 mA drive current. For an array of 1000 LEDs this equates to 68 W of power consumed. For an array of 700 LEDs this equates to 47.6 W of power consumed.

A typical high flux LEDs uses 1 W each at a 350 mA drive current. For an array of 25 to 50 LEDs this equates to 25 W to 50 W of power used. For an array of 18 to 35 LEDs this equates to 18 W to 35 W of power consumed. A typical very high flux LEDs uses 5 W each at a 700 mA drive current. For an array of 8 LEDs this equates to 40 W of power used. For an array of 6 LEDs this equates to 30 W of power consumed. In most cases the power consumption of an LED system could be less than that of a traditional halogen system. In some cases power consumption could be less than that of an HID system, although less light would be produced. A summary of the power consumed for each LED system is given in Table 3. This analysis does not consider that additional LEDs might be needed to achieve the required beam intensity distribution.

Source	Power per LED (W)	Power used to produce 1000 lm (W)	Power used to produce 400 lm on road (W)
5 mm	0.068	68	48
High Flux	1	25 - 50	18 - 35
Very High Flux	5	40	30
Halogen	55	55	55
HID	35	35*	35**

*Produces 2000 lm to 3000 lm. **Produces 700 lm to 1000 lm on the road.

Table 3. Summary of vehicle forward lighting system power consumption.

2.5 Color appearance

Another potentially large obstacle in using white LEDs for vehicle forward lighting applications is the color appearance of the source(s). In general white phosphor based LEDs have a correlated color temperature (CCT) in the range of 4500 K to 8000 K, depending on the production bins sampled. Nominally the high and very high flux LEDs have a CCT of 5500 K.[10] As a benchmark, a typical 9006 halogen lamp used for US low beam forward lighting has a nominal CCT of ~3200 K and a typical D2 HID source has a nominal CCT of ~4200 K.[13][20] LEDs have a higher color temperature than both halogen and HID sources. As is occurring with the introduction of HID technology, this may case an initial acceptance problem with the driving public who are accustomed to the lower CCT of halogen lamps on oncoming vehicles. In time objections should decrease as drivers become used to the new appearance of the headlamp sources, assuming there is no additional glare generated.

A larger obstacle than the high CCT of LED sources is the color consistency between individual LEDs. As discussed, arrays of LEDs will be needed to produce the total light output and beam distribution required for automotive application. However, the color variation between white LED sources can be significant. For the 5 mm LEDs the color variation in chromaticity space between 10 similar white LEDs can be on the order of 10 to 12 step MacAdam ellipses, where a three-step ellipse represents a color difference visible by 99% of observers.[21] Further, the chromaticity of each LED shifts differently over time and as a function of drive current. This difference in color between nominally the same white LEDs over operating time was seen in the high flux LEDs as well.[22]

This large difference in color between LED sources in the same lighting system would result in an unacceptable appearance, particularly to oncoming drivers. The ability of a viewer to notice difference in color appearance between two light sources depends on the application. When viewed directly color differences of light sources are more detectible than when viewed illuminating a scene.[23] Therefore, in any development of LED forward lighting systems care would have to be taken to ensure initial and continuing color consistence between emitters. Current white phosphor based LED technology would have to be further developed to accommodate this. Note, however, this problem may be overcome by using color mixing LED technology in place of phosphor based technology. In color mixing the amount of light produced by each discreet color emitter could be altered to ensure the same output color from each source. However, this adjustment of light output would have to be dynamic to compensate in real time for the effects of different lumen depreciation rates and temperature dependency between each type of colored emitter.[21]

2.6 Spectral effects on peripheral vision and glare

LED sources produce light with different spectra than halogen or HID lamps (Figure 7). While driving at night, off-axis human vision is in the mesopic response range. The mesopic range lies in-between the photopic (high light levels) and scotopic (almost no light) ranges. In this response region the eye's sensitivity shifts from a sensitivity peak at 555 nm to a sensitivity peak at 507 nm. At mesopic light levels off-axis vision is enhanced (faster reaction times, larger detection range) by the use of a lamp more closely matched to the shorter wavelength sensitivity range.[24][25] The S/P ratio is defined as the ratio of a source's light output as per the scotopic luminous efficacy function, to the source's output as per the photopic luminous efficacy function. The absolute value of this ratio is not important, but the relative value when comparing two light sources is useful in determining a light source's efficiency under mesopic and scotopic conditions.

The S/P ratio was calculated for the spectral power distributions shown in Figure 7. The results are given in Table 4. From these results it is evident that there is little difference in mesopic efficiency between the LED and HID sources. However, there is a small difference of 7% between the LED source and the 9006 halogen. Whether this small difference would result in actual visual performance increase for nighttime driving tasks depends on the application and would have to be further researched.

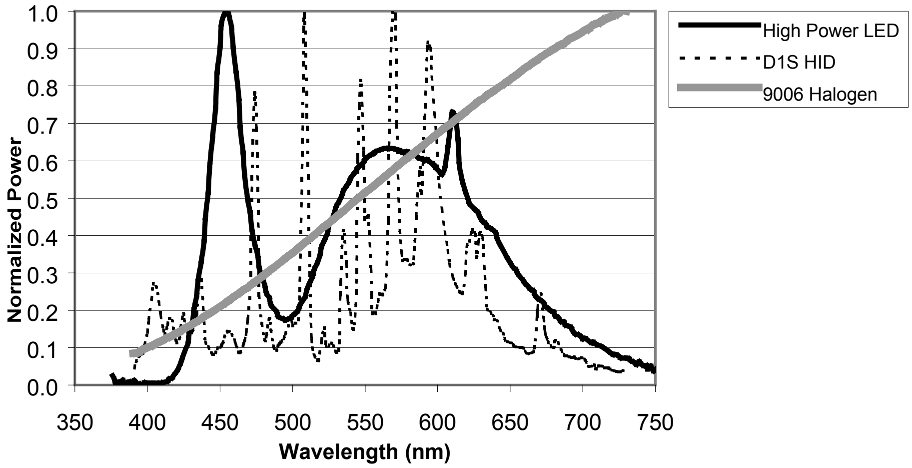

Figure 7. Spectral distributions of a high flux LED compared to that of a 9006 halogen lamp and a D1S HID lamp.

Lamp Type	S/P Ratio
High Flux LED	1.73
D1S HID	1.67
9006 Halogen	1.62

Table 4. Scotopic to photopic ratios of LED, HID and halogen vehicle forward lighting sources.

Two types of glare are recognized: discomfort and disability glare [14]. Discomfort glare is a sensation of caused by high luminances in the field of view [Rea]. Discomfort glare is often measured by means of a subjective rating scale. Discomfort glare does not necessarily impair the visibility of objects. In case of disability glare, visibility is reduced by scattered light in the eye. The glare sources get scattered in the eye that is perceived as a luminous veil over the scene. This veil reduces the contrast of the objects and hence their visibility. There is no spectral dependence for disability glare. It has been shown, however, that there are significant effects of spectrum on discomfort glare.[25] Although the exact relationship between discomfort glare and spectrum is unknown, there is indication that light with a relatively larger amount of short wavelength produces more discomfort glare.[26] Further, there is indication that the short wavelength cone (SWC) photoreceptors, whose response peaks at 440 nm, or another mechanism with a similar sensitivity may be involved in producing discomfort glare.[27] Since the blue peak of the high flux LED's spectral power distribution is located close to the SWC peak response, careful further study should be carried out to ensure that these sources used in forward lighting systems do not produce more discomfort glare for an equal amount of illuminance at the eye.

3. CONCLUSIONS

LED technology is revolutionizing vehicle lighting, particularly in signaling and marking applications. The promise of increasing LED performance will drive this trend into forward lighting applications. While it is presently impractical to develop vehicle forward lighting systems with currently available white LED products, technological advances should enable new and innovative system designs in the near future. As with the introduction of other new lighting technologies, notably the HID source, new design considerations will have to be taken into account. These include: total flux output, optical control, source size, power consumption, color appearance, and spectral effects. These issues were addressed here to help begin the dialog early in the design and development process of LED forward lighting systems. It is the intent that an open discussion of these issues will aid the industry in source and system development.

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