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Spectral Effects of LED Forward Lighting

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Abstract

Light emitting diode (LED) forward lighting systems soon will become a reality on today's roadways. One aspect of LED sources that will differ significantly from tungsten halogen (TH) or high intensity discharge (HID) lamps is their spectral power distribution (SPD).

Lamp SPD can have considerable impacts on a driver's visual performance. Recent studies have shown that headlamp sources that have more energy in the short wavelength region of the visible spectrum provide benefits to the vehicle operator for off-axis target detection. Calculations were performed on a series of LEDs to determine their potential advantage to visual performance. The LEDs chosen for this analysis are in chromaticity bins partially or fully contained within the SAE J578 definition of white. Similar calculations were performed on HID and TH sources for comparison. It was found that most of the LED sources analyzed can theoretically result in increased off-axis visual performance over current headlamp technology. The results of these calculations are compared to field studies of headlamp spectra to determine the magnitude of these effects as potentially seen in practice.

Keywords: ....automotive, LED, headlamp, lamp,
peripheral, illumination, visibility,

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ABSTRACT

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INTRODUCTION

Recent advances in white light LED technology, particularly in the total amount of light output and luminance per device, are allowing for the development of vehicle forward lighting systems.[1] As with any forward lighting technology, LED systems must be developed to reach a balance between providing visibility for the driver and maintaining visibility and comfort for oncoming drivers. Vehicle forward lighting has also become a styling element on today's vehicles. Not only must light system profiles fit with the aerodynamics and styling of the overall vehicle design, but the lights themselves have become brand differentiating elements.

This new emphasis on the styling, combined with the ever-present need for improved nighttime driving safety, has greatly spurred the development of innovative vehicle forward lighting. In the early 1990s HID lamps were developed that resulted in greater light output, higher luminous efficacy, and longer life than conventional halogen systems.[2] The introduction of HID systems, and halogen systems utilizing filters to change the color of their illumination, has also resulted in new SPDs, that have been shown to provide benefits to visual performance.[3,4]

LED vehicle forward lighting systems are a natural progression in this line of advancement. From a styling standpoint, LEDs offer a completely new look for vehicles and a way for brands to distinguish themselves. Additionally, LEDs may offer several other advantages for use in vehicle applications: longer life, less susceptibility to vibration than filament lamps, lower power requirements than halogen systems, and optical design flexibility.[1] Like the introduction of the new headlamp sources before them, LED systems will also expose drivers to new SPDs not currently on today's roadways. The issue then becomes if LED systems can offer a benefit to off-axis visual performance, and if so, how might this benefit vary among LEDs.

A representative sample of phosphor-based, high brightness LEDs, suitable for use in vehicle forward lighting applications, were obtained. The SPDs of these sources were measured and calculations were performed to determine their potential to be of benefit to visual performance. The LEDs chosen for this analysis fall within chromaticity bins partially or fully contained within the SAE J578 definition of white.[5] Similar calculations were performed on HID and TH sources for comparison.

It was found that most of the LED sources analyzed can theoretically result in increased off-axis visual performance. However, the amount of potential benefit varies among the LEDs. The results of these calculations are discussed in terms of SPD and chromaticity binning. It is shown that chromaticity bins are not fully predictive of the effects that LED sources can have on driving-related visual performance. The results of these calculations are further compared to field studies of headlamp spectra to determine the magnitude of these effects as potentially seen in practice.

BACKGROUND

A wealth of research has demonstrated that at low, mesopic light levels, the spectral content of a light source can impact peripheral visual performance above and beyond that predicted by the photopic luminous efficiency function, $V(\lambda)$.[6-12] Identification (an on-axis task) relies on the fovea. However, since objects can also move onto the roadway in front of a car, objects need to be detected by the peripheral retina (off-axis). The faster an object is detected, the faster appropriate evasive action can be taken.

The eye has two types of photoreceptors, cones and rods. Generally, cones alone are used for daytime vision while rods and cones are used at night. Most of the cones are found in the fovea while most rods are found in the peripheral retina. At daytime light levels cones suppress rods and dominate visual performance. As light levels are reduced, the dominance of the cones diminishes and rods begin to play a more dominant role.[6]

Importantly, the shift in photoreceptor workload with light level is also accompanied by a shift in spectral sensitivity in the peripheral retina. The peak spectral sensitivity of the cones is at 555 nm and of the rods is at 507 nm. The luminous efficiency of the peripheral retina gradually shifts toward shorter wavelengths as light levels are reduced.[13]

While driving at night, off-axis vision is in the mesopic response range [14], which lies between 3 cd/m^2 (above which is the photopic range) and 0.001 cd/m^2 (below which is the scotopic range). In the mesopic range, both rods and cones contribute to vision; therefore, at mesopic light levels, off-axis vision is enhanced (shorter reaction times, larger detection range) by the use of a lamp more closely matched to the shorter wavelength sensitivity range.[14]

METHODS

Samples Tested

17 white LEDs, of types currently employed in prototype forward lighting devices, were characterized for this study. The LEDs were 1 W products operated at 350 mA. Samples were chosen such to extend over the portion of the CIE chromaticity space that is readily achievable with this technology, while staying in or near the white box defined by the SAE in J578.[5] Figure 1 shows the chromaticity of the LED samples, along with the SAE white box and the manufacturer's chromaticity bins. For comparison, Figure 2 shows the chromaticity of a representative 9006 halogen (TH) lamp and a D1 HID lamp. It is important to note that although chromaticity was used as criterion for selecting the test LEDs, so that the results of this analysis can be applied to source specification, chromaticity is only very loosely correlated with mesopic performance.

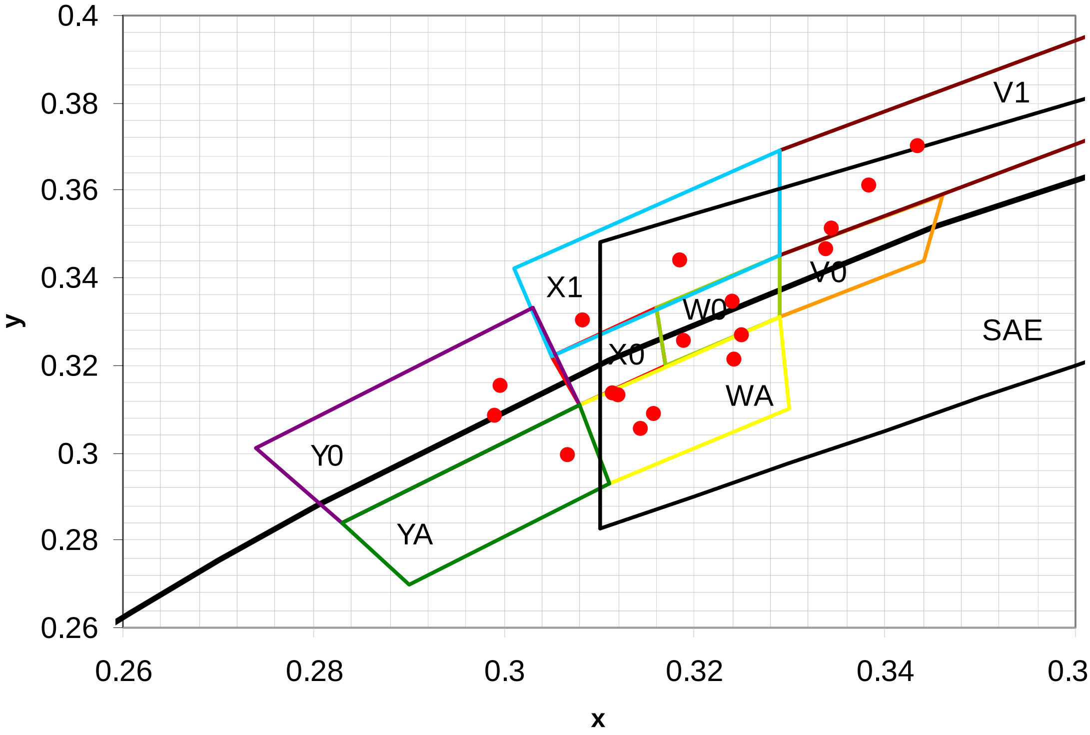

Figure 1. Chromaticity of LED test samples, shown with manufacturer's binning structure and the SAE J578 white box.

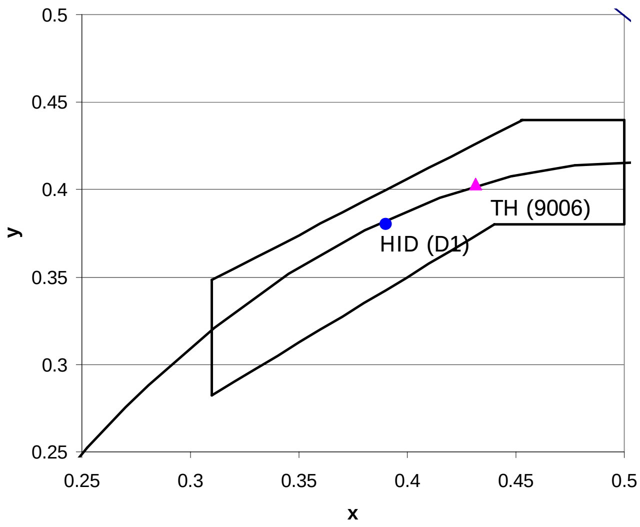

Figure 2. Chromaticity of comparison HID and TH samples

SPD Measurement

To measure the SPDs, each sample (mounted on a heat sink) was operated at 350 mA and used to illuminate a reflectance standard. After a stabilization period of 15 min, the luminance of the reflectance standard was measured using a calibrated Photo Research 705 spectroradiometer. Figure 3 illustrates the measured LED spectral data, showing relative power at each wavelength. Two features can been seen in these data which determine the relative proportion of short wavelength energy; the height and exact location of the "blue" peak near 450 nm and the proportion of the blue peak energy to that in the broader emission from the "yellow" phosphor.

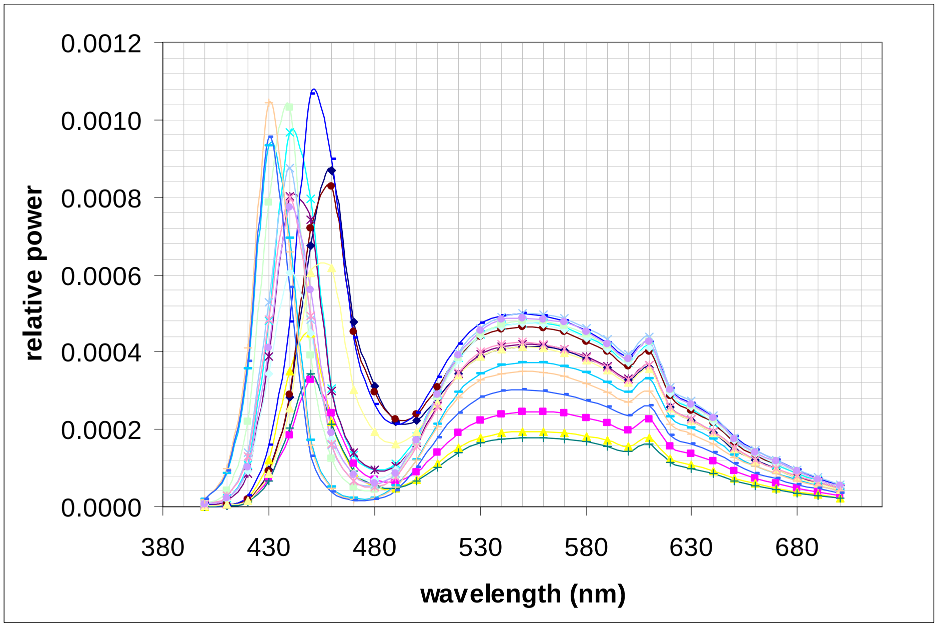

Figure 3. Measured SPDs of the test LED samples.

Mesopic Luminance Calculations

From the measured SPDs the mesopic luminance values were calculated through the methods outlined by Rea et al.[8] The relative photopic and scotopic luminances were determined from the SPDs, weighted by the photopic and scotopic efficacy functions, $V(\lambda)$ and $V'(\lambda)$ respectively. From this, scotopic to photopic (S/P) ratios were ascertained. The S/P ratio is a quantity that indicates how well a source can stimulate the rod photoreceptors. Sources with a higher S/P ratio are stronger stimuli for the rods and therefore, result in higher mesopic luminances as the light level decreases. For the LEDs measured, the highest S/P ratio was 2.31 (x, y = 0.30, 0.32; bin Y_0) the lowest S/P ratio was 1.68 (x, y = 0.35, 0.38; bin V_0). For comparison the S/P ratio for the 9006 TH was 1.57, and for the HID was 1.69. All sources and associated S/P ratios are given in Table 1 and shown in Figure 4. It is interesting to point out again that chromaticity is not a good predictor of S/P ratio or mesopic performance. For example, LEDs in chromaticity bin X_1 have a higher S/P ratio than those in bins Y_A or W_A, even though some LEDs in these bins have chromaticity that is "bluer" (e.g., smaller x chromaticity coordinate value) than those in X_1.

Source	S/P Ratio	Source	S/P Ratio	Source	S/P Ratio	Source	S/P Ratio
LED (Y0)	2.31	LED (W0)	1.96	LED (WA)	1.74	*TH*	1.57
LED (Y0)	2.25	LED (WA)	1.93	LED (V1)	1.72		
LED (X1)	2.19	LED (V1)	1.81	LED (V0)	1.71		
LED (X1)	2.05	LED (W0)	1.79	*HID*	1.69		
LED (YA)	2.04	LED (WA)	1.75	LED (WA)	1.69		
LED (WA)	1.96	LED (WA)	1.74	LED (V1)	1.68		

Table 1. Source S/P ratios (bin designation in parenthesis).

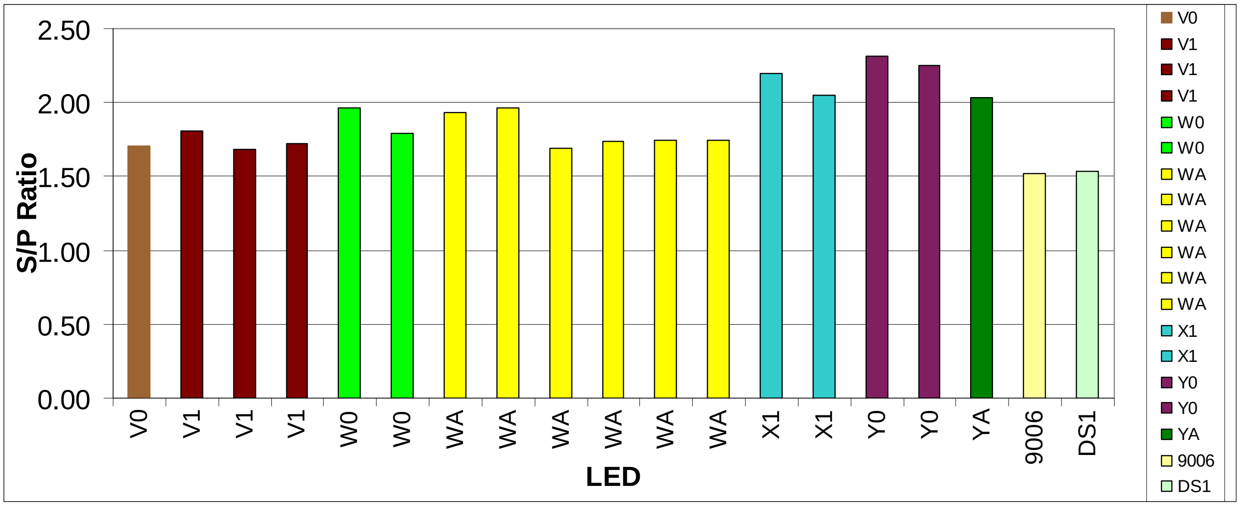

Figure 4. Source S/P ratios, sorted by chromaticity bin.

RESULTS

Once the S/P ratios were determined for each source, the mesopic luminance was calculated as a function of different photopic adaptation luminances (Figure 5). The increase in mesopic luminance between the LED samples and the TH source is shown in Figure 6. As light level decreases, the LEDs offer greater potential increase in off-axis visual performance. In Figure 5, the amount of benefit varies between LEDs and depends on the S/P ratio. At a light level of 0.1 cd/m^2 (not uncommon for nighttime driving conditions) the LED with an S/P ratio of 2.31 (bin Y_0) results in an approximately 30% increase over TH in terms of mesopic luminance. The LED with the lowest S/P ratio of 1.68 (bin V_1) still results in an approximately 10% increase over TH in mesopic luminance at this light level.

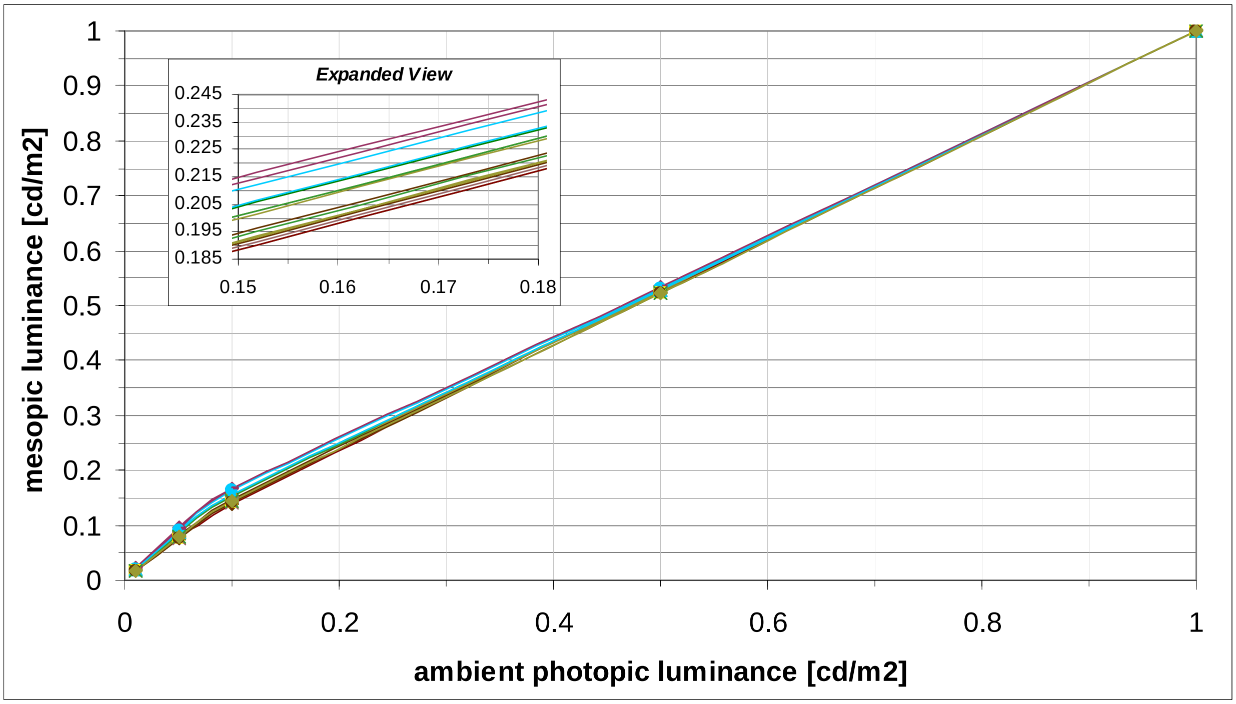

Figure 5. Mesopic luminance of LED samples.

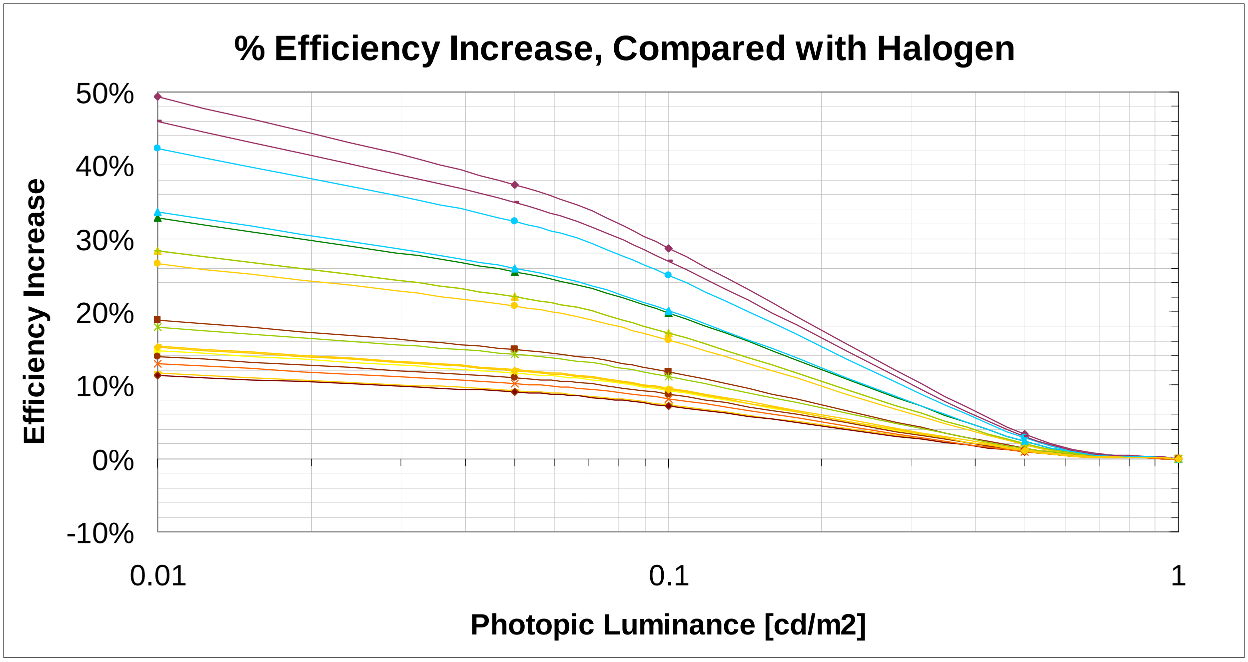

Figure 6. Increase in mesopic luminance of LED samples over TH source.

The percent increase in mesopic luminance between the LED samples and the HID source is shown Figure 7. It can be seen that as the light level decreases, some the LED sources offer greater potential increase in off-axis visual performance (those with an S/P ratio greater than that of the HID, 1.69). For a light level of 0.1 cd/m^2 the LED with an S/P ratio of 2.31 (bin Y_0) results in an approximately 20% increase in calculated mesopic luminance. The LED with the lowest S/P ratio of 1.68 (bin V_1) now results in a decrease of approximately 0.5% in calculated mesopic luminance at this light level.

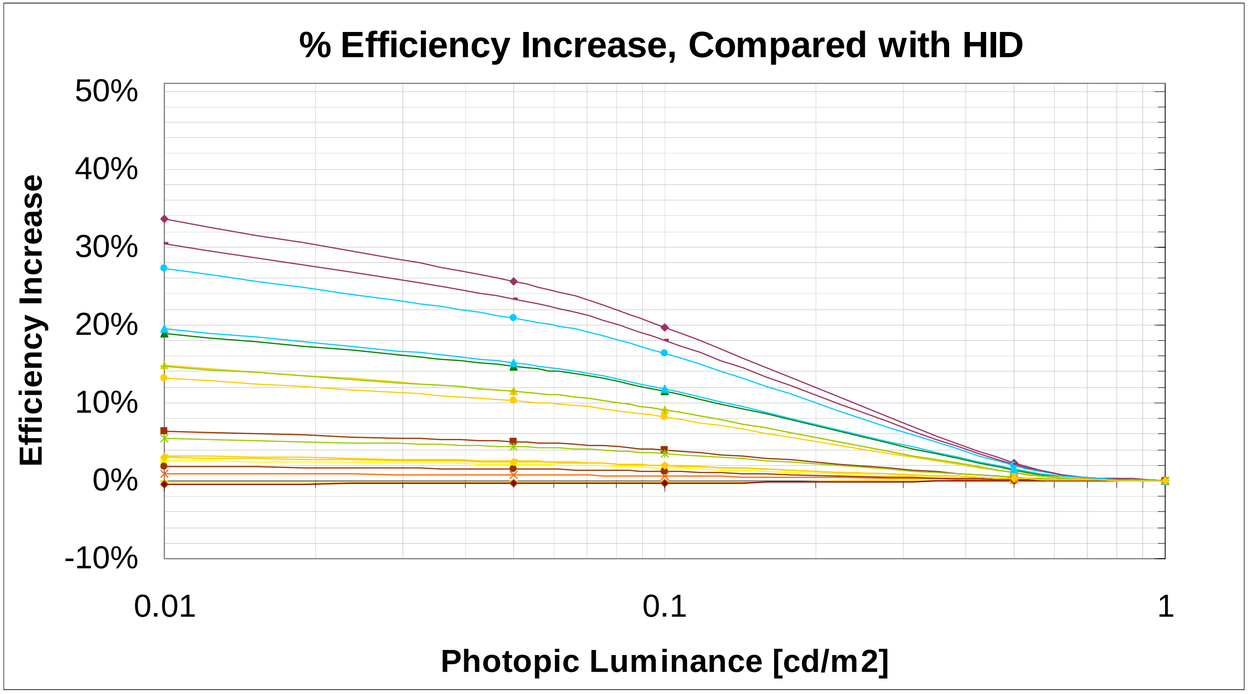

Figure 7. Increase in mesopic luminance of LED samples over HID source.

Two recent studies, one by Lewis and one by Bullough and Rea, show much larger effects of lamp spectra on off-axis visual performance than would be deduced from theory.[8][15] These studies found effects about five times larger than predicted by the model used here. LED forward light sources may result in an even greater benefit compared to TH and HID sources than calculated here depending on stimulus and context.

COMPARISON WITH FIELD STUDIES

Visual performance depends upon various stimulus parameters, such as size, contrast, and characteristics of the target background.[14] Depending on the light level, changes to these parameters can have small or large effects on visual performance. These parameters interact to affect visual performance. It is because of this interaction that field studies must be done under realistic conditions to determine the exact impact of spectrum on visual performance.

Although no direct field studies have been performed to examine the potential mesopic benefits of LED forward lighting, studies have been performed on the spectra of headlamp systems that may offer insight into this issue. Van Derlofske and Bullough performed a study to examine the role that SPD plays in visual performance under realistic nighttime driving conditions.[11] To accomplish this a series of headlamp systems were tested that produced similar (photopic) light output and spatial distributions but varying SPDs. The systems were compared on the basis of S/P ratio. All the SPDs in that study were generated by filtering HID headlamps. Table 2 shows the test lighting conditions. Figure 8 shows the chromaticy coordiniates of the test lighting conditions along with the SAE J578 white box.[5] All conditions created "white" light as defined by SAE J578.

Characteristic	**Filtered Lighting Conditions**			
	Warm	**Halogen simulating**	**HID**	**Cool**
S/P ratio	1.02	1.57	1.69	2.04
Transmission	57%	59%	58%	58%
CCT	2740K	3755K	3884K	5037K
Chromaticity (x,y)	0.47, 0.44	0.40, 0.40	0.39, 0.38	0.35, 0.36

Table 2. Characteristics of the filtered lighting conditions.

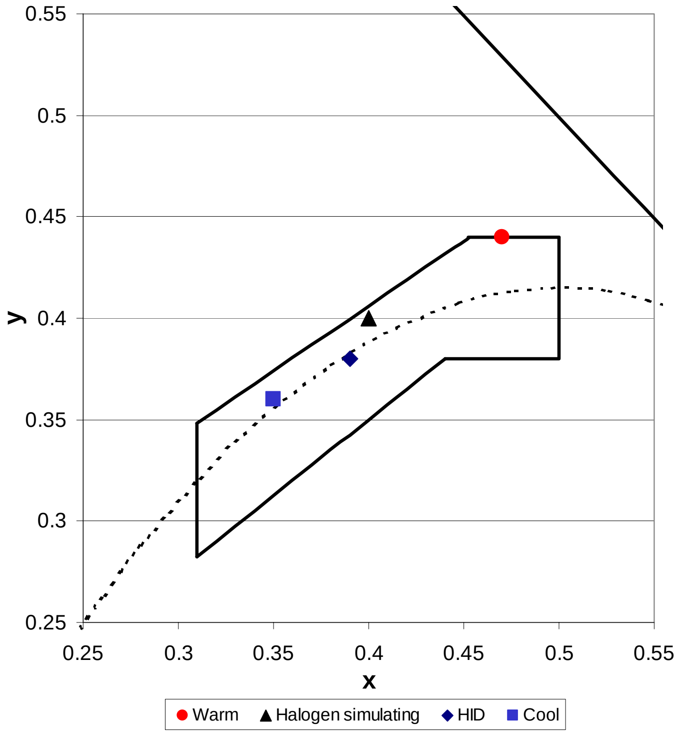

Figure 8. Chromaticity coordinates of the test lighting conditions in Bullough and Van Derlofske.[11]

Subjects performed a visual tracking task, cognitively similar to driving, while seated in a test vehicle. Small targets located from 7.5° to the driver's side to 17.5° to the passenger's side (see Figure 9) were activated and target detection reaction time was recorded. Reaction times greater than 1 second were considered misses. Target illuminances were kept constant between all the lighting conditions, allowing the effects of SPD to be identified and isolated. Figure 10 shows the average reaction time and missed target results for a 20% reflectance target.

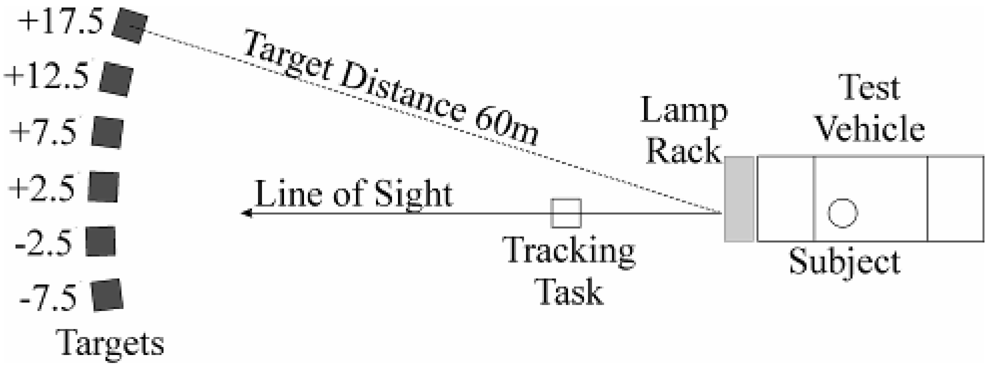

Figure 9. Experimental geometry of Bullough and Van Derlofske.[11]

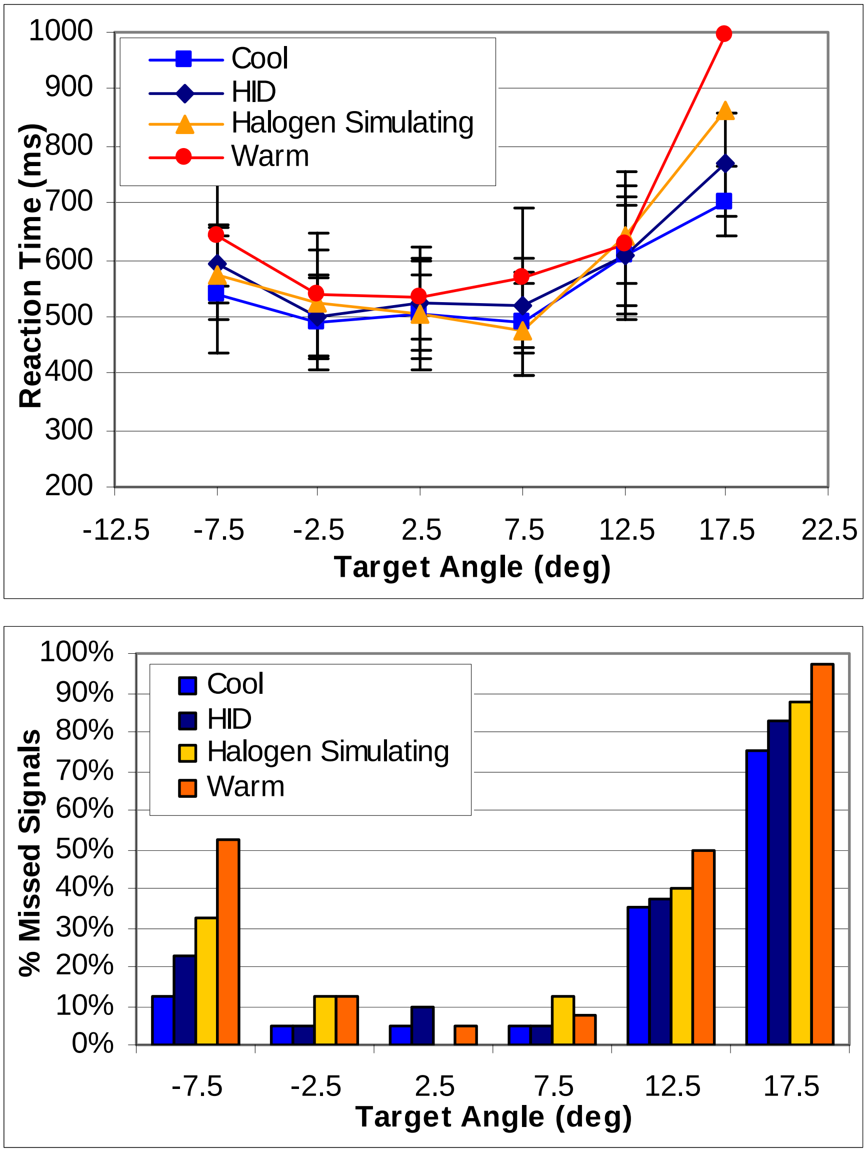

Figure 10. Reaction time and missed signal results of Bullough and Van Derlofske.[11]

By performing an analysis of variance it was found that SPD had a significant effect on both reaction time and number of missed targets. The “cool” headlamps resulted in increased visual performance, shorter reaction times and fewer misses, particularly at the larger angles. It was estimated that ~6 lx from the "warm" source is equivalent in visual performance to ~4 lx from the "cool" source. Illumination from the "cool" source is ~50% more efficacious than illumination from the "warm" source in the region from about 10° to 12.5° off-axis to the right of the driver.

Since the S/P ratio of the X_1, Y_0, Y_A LEDs are similar to, or greater than, the “cool” source, the resulting visual performance of LED headlamps using these sources should also be similar to or greater than the “cool” source (assuming equal photopic illuminance on the targets). The LED forward lighting systems should result in at least a ~150 ms decrease in reaction time over TH at 17.5°, and a ~15% decrease in misses over TH at 17.5°.

Of course, the physical construction of the LEDs and type of optical systems used will be critical in determining what spectral effects will be seen in practice. The SPD of an LED by itself, or an LED through an optical system, can have an angular dependence. That is, for an LED system, the resulting output SPD may vary for different target locations. The spectral distribution of the entire system would have to be considered when assessing mesopic performance in practice.

CONCLUSIONS

Since LED sources contain more relative energy in the short-wavelength region of the visible spectrum (have a higher S/P ratio), it has been shown through calculation that they may provide a benefit to off-axis visual performance over halogen and HID lamps. By comparison with previous studies it has been shown that an LED forward lighting system, using the appropriate LEDs, can result in at least a 150 ms decrease in reaction time over TH systems.

The amount of this visual benefit will depend on the SPD of the LED, which can vary among samples. While chromaticity binning is often used to specify LEDs, it is not necessarily a good predictor of mesopic performance and can be misleading if used as the sole characterization method.

The potential for LED sources in vehicle forward lighting is exciting. Using these insights into the effects of source SPD, and relying on LED systems' inherent characteristics to be modular, it may be possible to develop forward lighting systems that are spectrally "tuned" with high-S/P light at larger angles to increase peripheral vision and light with different spectral properties in other areas of the beam to address such issues as glare.

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