UMTRI-2003-39

LED HEADLAMPS: GLARE AND COLOR RENDERING

Michael Sivak
Brandon Schoettle
Michael J. Flannagan

November 2003

LED HEADLAMPS: GLARE AND COLOR RENDERING

Michael Sivak
Brandon Schoettle
Michael J. Flannagan

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

Report No. UMTRI-2003-39
November 2003

Technical Report Documentation Page

1. Report No.
UMTRI-2003-39

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
LED Headlamps: Glare and Color Rendering

5. Report Date
November 2003

6. Performing Organization Code
302753

7. Author(s)
Sivak, M., Schoettle, B., and Flannagan, M.J.

8. Performing Organization Report No.
UMTRI-2003-39

9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Road
Ann Arbor, Michigan 48109-2150 U.S.A.

10. Work Unit no. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
The University of Michigan
Industry Affiliation Program for
Human Factors in Transportation Safety

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes
The Affiliation Program currently includes AGC America, Autoliv, Automotive Lighting, Avery Dennison, BMW, DaimlerChrysler, DBM Reflex, Denso, Federal-Mogul, Ford, GE, General Motors, Gentex, Guardian Industries, Guide Corporation, Hella, Honda, Ichikoh Industries, Koito Manufacturing, Labsphere division of X-Rite, Lang-Mekra North America, Magna International, Mitsubishi Motors, Muth, Nichia America, North American Lighting, OSRAM Sylvania, Philips Lighting, PPG Industries, Reflec USA, Reflexite, Renault, Samlip, Schefenacker International, Sisecam, Solutia Performance Films, Stanley Electric, TG North America, Toyota Technical Center USA, Valeo, Vidrio Plano, Visteon, 3M Personal Safety Products, and 3M Traffic Control Materials.
Information about the Affiliation Program is available at: http://www.umich.edu/~industry/

16. Abstract
Because of rapid improvements in the light output of light-emitting diodes (LEDs), serious consideration is being given to using LEDs as light sources for headlamps. This study examined the potential effects of LEDs on discomfort glare for oncoming drivers and on color rendering of retroreflective traffic materials. In both cases, the effects of LED light sources were compared to the changes in these properties that occurred when the traditional tungsten-halogen light sources were replaced with high-intensity discharge (HID) light sources. Specifically, the effect on discomfort glare was estimated by comparing the chromaticities of 7 LED light sources (considered for use in headlamps) with the chromaticities of the light sources from 17 actual HID headlamps. Analogously, the effects on color rendering were estimated by comparing the chromaticities of 46 retroreflective materials when illuminated by the LED light sources with the chromaticities of the same materials when illuminated by the HID light sources.

The main findings concerning the range of LEDs that are currently being considered for use in headlamps are as follows: (1) Headlamps using LEDs with the chromaticities examined here are predicted to lead to more discomfort glare than the current HID headlamps, and substantially more discomfort than tungsten-halogen headlamps. Keeping the correlated color temperature as low as practicable is likely to minimize the problem. However, the relationship between spectral power distribution and discomfort glare is not fully understood, and further research on this issue would be valuable. (2) Color rendering with headlamps using the LEDs examined here is likely to be acceptable. (3) The spectral power distributions of headlamps using the LEDs examined here will not have appreciable effects on the relative brightness of colored retroreflective materials.

17. Key Words
headlighting, LED headlamps, tungsten-halogen headlamps, high intensity discharge headlamps, color rendering, glare, retroreflective materials

18. Distribution Statement
Unlimited

19. Security Classification (of this report)
None

20. Security Classification (of this page)
None

21. No. of Pages
22

22. Price

Acknowledgments

Appreciation is extended to the members of the University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research. The current members of the Program are:

AGC America
Autoliv
Automotive Lighting
Avery Dennison
BMW
DaimlerChrysler
DBM Reflex
Denso
Federal-Mogul
Ford
GE
General Motors
Gentex
Guardian Industries
Guide Corporation
Hella
Honda
Ichikoh Industries
Koito Manufacturing
Labsphere division of X-Rite
Lang-Mekra North America
Magna International
Mitsubishi Motors
Muth
Nichia America
North American Lighting
OSRAM Sylvania
Philips Lighting
PPG Industries
Reflec USA
Reflexite
Renault
Samlip
Schefenacker International
Sisecam
Solutia Performance Films
Stanley Electric
TG North America
Toyota Technical Center, USA
Valeo
Vidrio Plano
Visteon
3M Personal Safety Products
3M Traffic Control Materials

Contents

Introduction

During the past few years, manufacturers have made major improvements in the amount of light emitted by individual LEDs. Consequently, there is great interest in exploring LEDs as potential light sources for headlighting. However, LEDs allow a much greater flexibility in spectral power distributions than do tungsten-halogen bulbs—the traditional light sources. Because of this difference, it is important to examine the influence of LEDs on two aspects of headlamp performance that are influenced by the spectral power distribution of the light source: glare and color rendering.

One way to approach the issues of glare and color rendering with any light source is to perform laboratory and/or field studies with observers. However, during the past 15 years or so, we have obtained substantial knowledge about the performance of another recently introduced headlamp light source—high-intensity discharge (HID). This knowledge is based on formal studies as well as on several years of on-the-road experience. Overall, the available evidence suggests that color rendering with HID is acceptable, but that HIDs produce more discomfort glare (but not more disability glare) than do tungsten-halogens. (See Sivak et al., 2003 for a recent comprehensive review.) Consequently, we have a benchmark—HIDs—against which LEDs can be evaluated, and this is the approach taken in this study.

Method

General approach: Discomfort glare

There is strong evidence that the increased blue content of HID headlamps is one of the major reasons for increased discomfort glare from HID headlamps (Flannagan et al., 1989; 1991; 1992a; Flannagan, 1999). There is some concern that because of the substantial blue content of some LED light sources that are being considered for headlamps, such headlamps may also lead to substantial discomfort glare. We evaluated the likely level of discomfort glare from LED headlamps by comparing the locations of the LED light sources in the CIE 1931 diagram to the locations of the two current headlamp light sources—tungsten-halogens and HIDs. The rationale was that should the locations for the LED sources be in between the locations for these two existing light sources, we would conclude that LED headlamps are not likely to lead to more discomfort glare than the current HID lamps. On the other hand, should the LED sources exhibit even more blue content than do HID lamps, we would predict more discomfort than that experienced from the HID lamps.

General approach: Color rendering

The approach used for estimating color rendering with LED headlamps was conceptually analogous to the approach used for estimating discomfort glare. Specifically, we posed the following question: Are the colorimetric changes in traffic control materials when illuminated by LED headlamps greater or smaller than those when they are illuminated by HID headlamps (both in comparison to tungsten-halogens)? We took into account all three colorimetric components: hue and saturation (by examining x, y chromaticities), and brightness (by examining Y). We concentrated on retroreflective materials as the most important color-coded objects in the driving environment, with a special emphasis on red (because of the criticality of red stop signs). (For previous research on color rendering with HID headlamps see Flannagan et al., 1992b; Simmons et al., 1989; Sivak et al., 1991; 1993).

Light sources

Spectral power distributions (SPDs) were obtained for 7 LED light sources produced by 5 manufacturers, 9 tungsten-halogen light sources produced by 5 manufacturers, and 17 HID light sources produced by 2 manufacturers. (The 17 HID light sources came from 17 out of the 19 HID headlamps in Sivak, Flannagan, Schoettle, and Nakata, 2002.) The SPDs for the LED sources (see Figure 1) were obtained from light-source and headlamp manufacturers. The tungsten-halogen and HID SPDs were measured by us using a Photo Research PR-650 spectrophotometer. A summary of the light sources by type and construction is shown in Table 1.

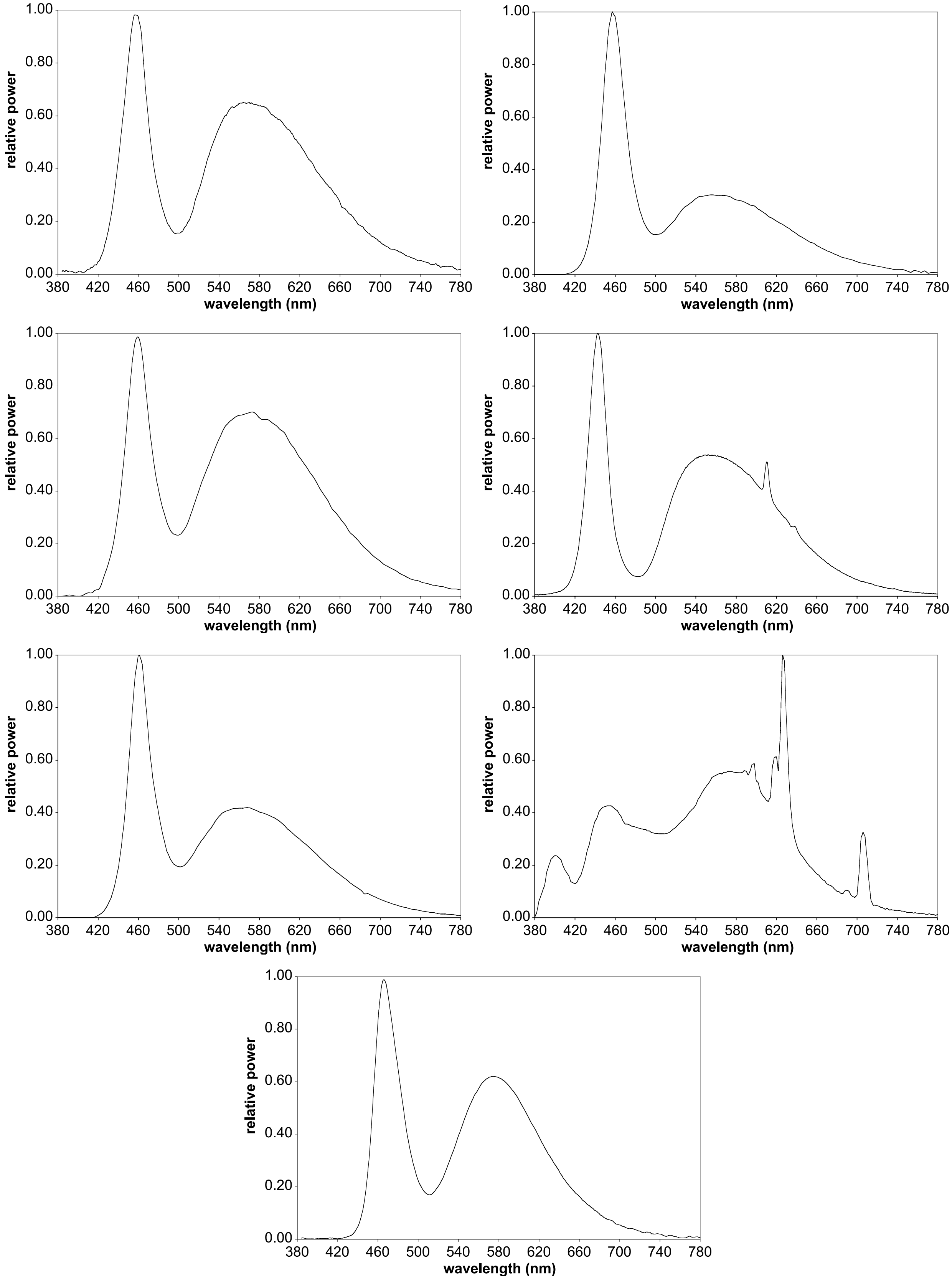

Figure 1. The SPDs of the analyzed LED light sources.

Table 1
Analyzed light sources by type and construction.

Light source type	Construction	Number in sample
LED	Blue LED + phosphor	6
	LED(s) + phosphor	1
Tungsten-halogen	HB2	5
	H7	2
	H1	1
	HB3	1
HID	D2R	9
	D2S	8

Reflective materials

Spectral reflectance data for 7 colors of retroreflective materials were supplied to us by 3 manufacturers. There were 3 types (grades) of material within each color group. The analyzed materials are summarized in Table 2. Sample reflectance data (for one of the two red encapsulated-lens materials) are shown in Figure 2.

Table 2
Analyzed retroreflective materials by color and type.

Color	Material type		
	Enclosed lens	Encapsulated lens	Prismatic
Red	2	2	3
Blue	2	2	3
Brown	2	2	1
Green	2	2	3
Orange	2	2	2
White	2	2	3
Yellow	2	2	3

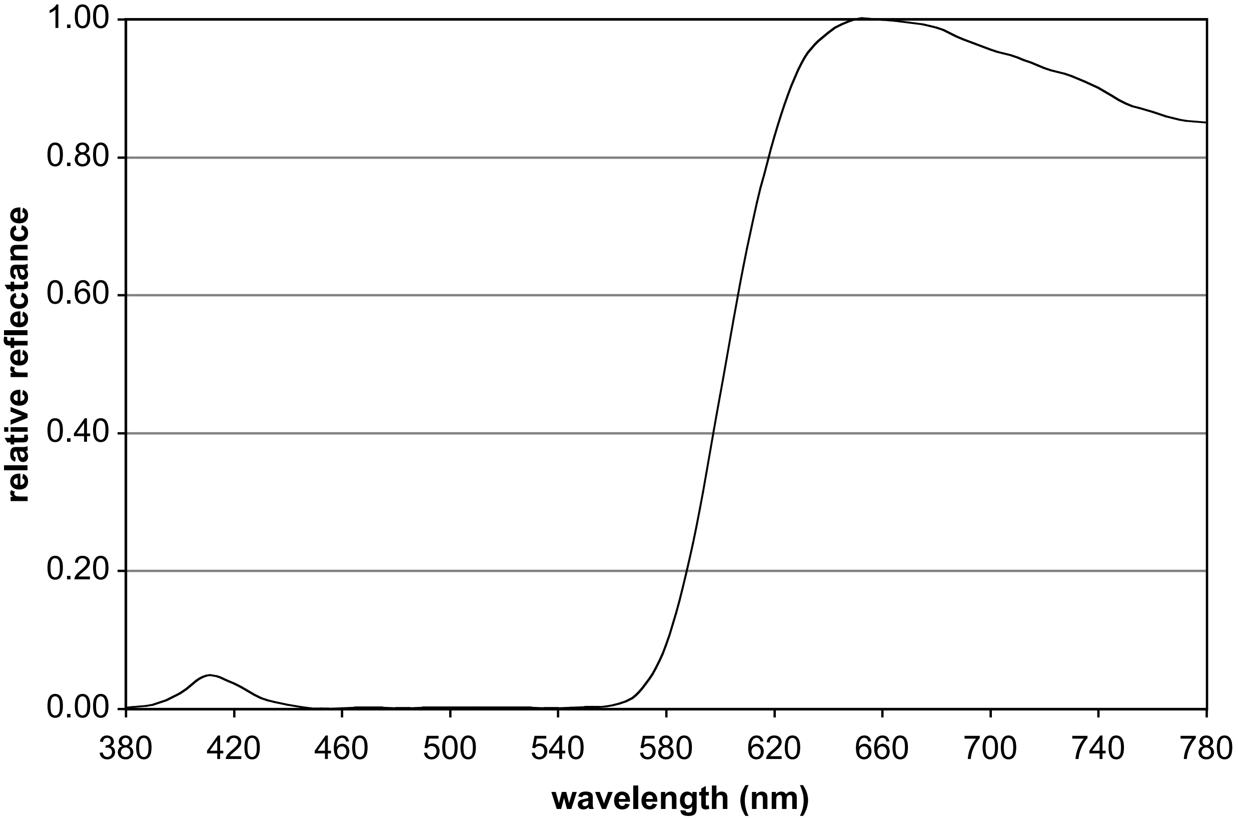

Figure 2. Reflectance data for one of the two red encapsulated-lens materials.

Chromaticity calculations for the light sources for estimating discomfort glare

The calculations that were performed for each light source are shown in Table 3.

Table 3
Calculations for determining light source chromaticity coordinates.

Step	Calculation	Result
1	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\bar{x})_\lambda$	X
2	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\bar{y})_\lambda$	Y
3	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\bar{z})_\lambda$	Z
4	$\frac{X}{X+Y+Z}$	x
5	$\frac{Y}{X+Y+Z}$	y
6	Repeat the calculations listed above for all remaining LED, tungsten-halogen, and HID light sources.	

- $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the CIE color-matching functions.
- The x and y values correspond to the chromaticity coordinates (in the CIE 1931 color space) of the sampled light source.

Chromaticity calculations for the materials/light sources for estimating color rendering

The calculations that were performed for each combination of light source and material color/type are shown in Table 4.

Table 4
Calculations for determining color rendering chromaticity coordinates.

Step	Calculation	Result
1	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\text{material spectral reflectance})_\lambda \times (\bar{x})_\lambda$	X
2	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\text{material spectral reflectance})_\lambda \times (\bar{y})_\lambda$	Y
3	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{light source power})_\lambda \times (\text{material spectral reflectance})_\lambda \times (\bar{z})_\lambda$	Z
4	$\frac{X}{X+Y+Z}$	x
5	$\frac{Y}{X+Y+Z}$	y
6	Repeat the calculations listed above for all remaining LED, tungsten-halogen, and HID light sources in combination with all remaining material colors/types.	

- $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the CIE color-matching functions.
- The x and y values correspond to the chromaticity coordinates (in the CIE 1931 color space) of the sampled light source.
- 33 unique light sources × 46 unique material colors and types = 1518 pairs of x, y chromaticity coordinates.

Relative intensity calculations for estimating relative brightness

The calculations that were performed for each combination of light source and material color/type to derive the relative intensity of the retroreflective materials under each illuminant are shown in Table 5.

Table 5
Calculations for determining relative intensity of the retroreflective materials
when illuminated by each light source.

Step	Calculation	Result
1	The product of each SPD and V(λ) is computed to account for human visual sensitivity.	All light sources corrected to account for human visual sensitivity
2	The sums of the products from Step 1 are computed for each light source. These sums are then equalized across all light sources.	Photopically equalized power for all light sources
3	$\sum_{\lambda=380\text{ nm}}^{780\text{ nm}} (\text{equalized light source power})_\lambda \times (\text{material spectral reflectance})_\lambda \times (\bar{y})_\lambda$	Y

- $\bar{y}$ is one of the CIE color-matching functions.
- 33 unique light sources × 46 unique material colors and types = 1518 intensity values.

The Y value, as computed in Table 5, is an index of the relative intensity of each material under illumination from each sampled light source. This relative intensity calculation applies to a situation in which the incident illumination from the alternative light sources is the same.

Results

Estimated discomfort glare

Figures 3 and 4 plot the locations on the 1931 CIE diagram of the calculated chromaticity coordinates. (Figure 4 is a close-up of the relevant region from Figure 3.) Several facts are evident from these figures:

(1) The three types of light sources form nonoverlapping distributions.

(2) The lowest correlated color temperatures were for the tungsten-halogens (about 3,000 to 3,500° K), followed by the HIDs (about 3,700 to 4,100° K), and the LEDs (about 4,200 to 14,000° K).

(3) Although 6 out of the 7 LEDs were within the SAE white limits (SAE, 1995), they were all more bluish than already "blue" HIDs.

(4) The LEDs showed the largest spread.

Based on the chromaticities of the LEDs relative to the HIDs, we predict that all of the tested LEDs would lead to more discomfort than the HIDs (at a given level of illumination at the eyes of the observer), and substantially more discomfort than the tungsten-halogens. However, based on the wide spread of the chromaticities of the LEDs, there are ways of addressing this potential problem. Specifically, keeping the correlated color temperature as low as practicable is likely to minimize the problem. However, the relationship between spectral power distribution and discomfort glare is not fully understood (Sivak et al., 2003), and further research on this issue would be valuable.

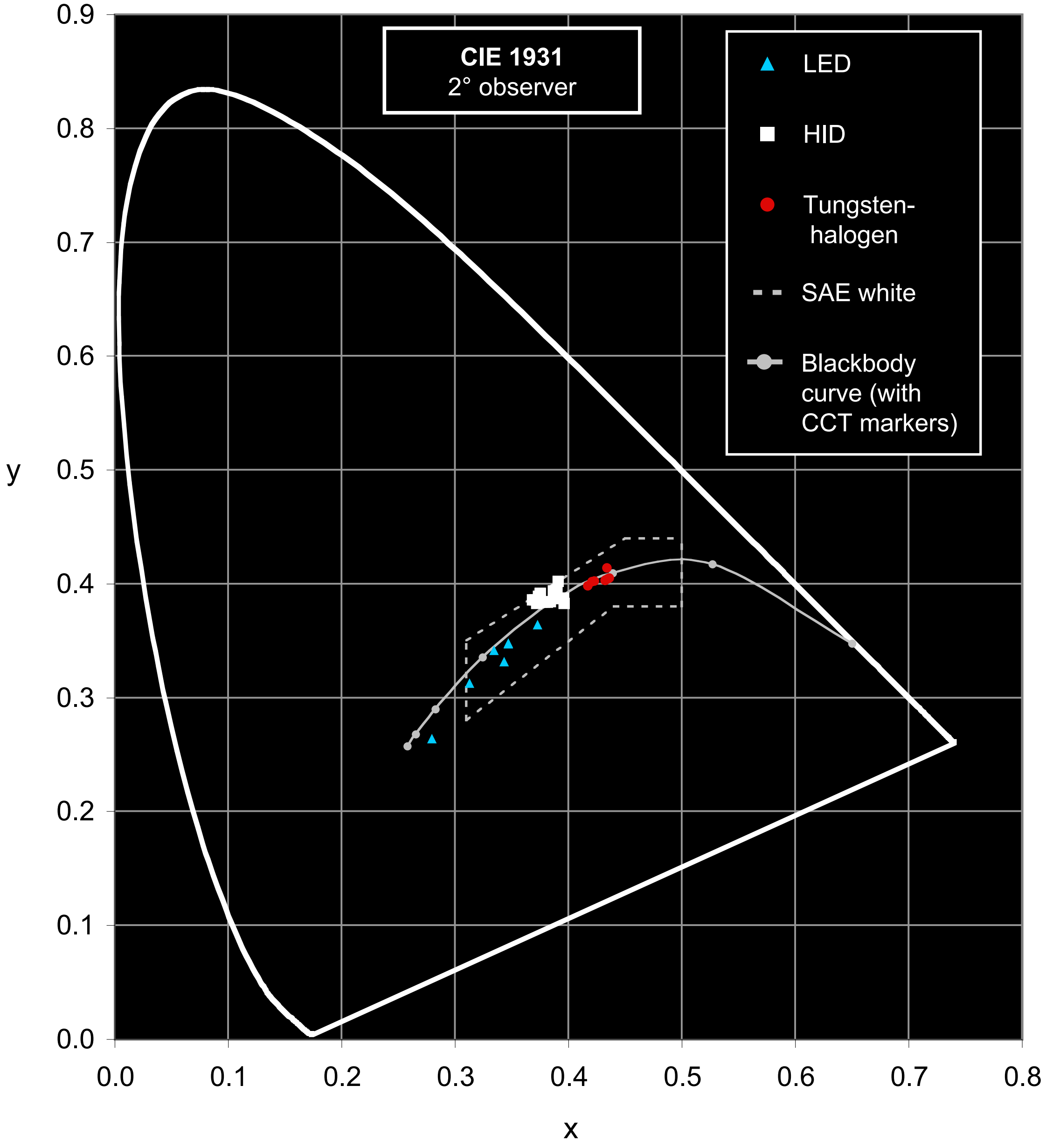

Figure 3. The chromaticity coordinates of the light sources.

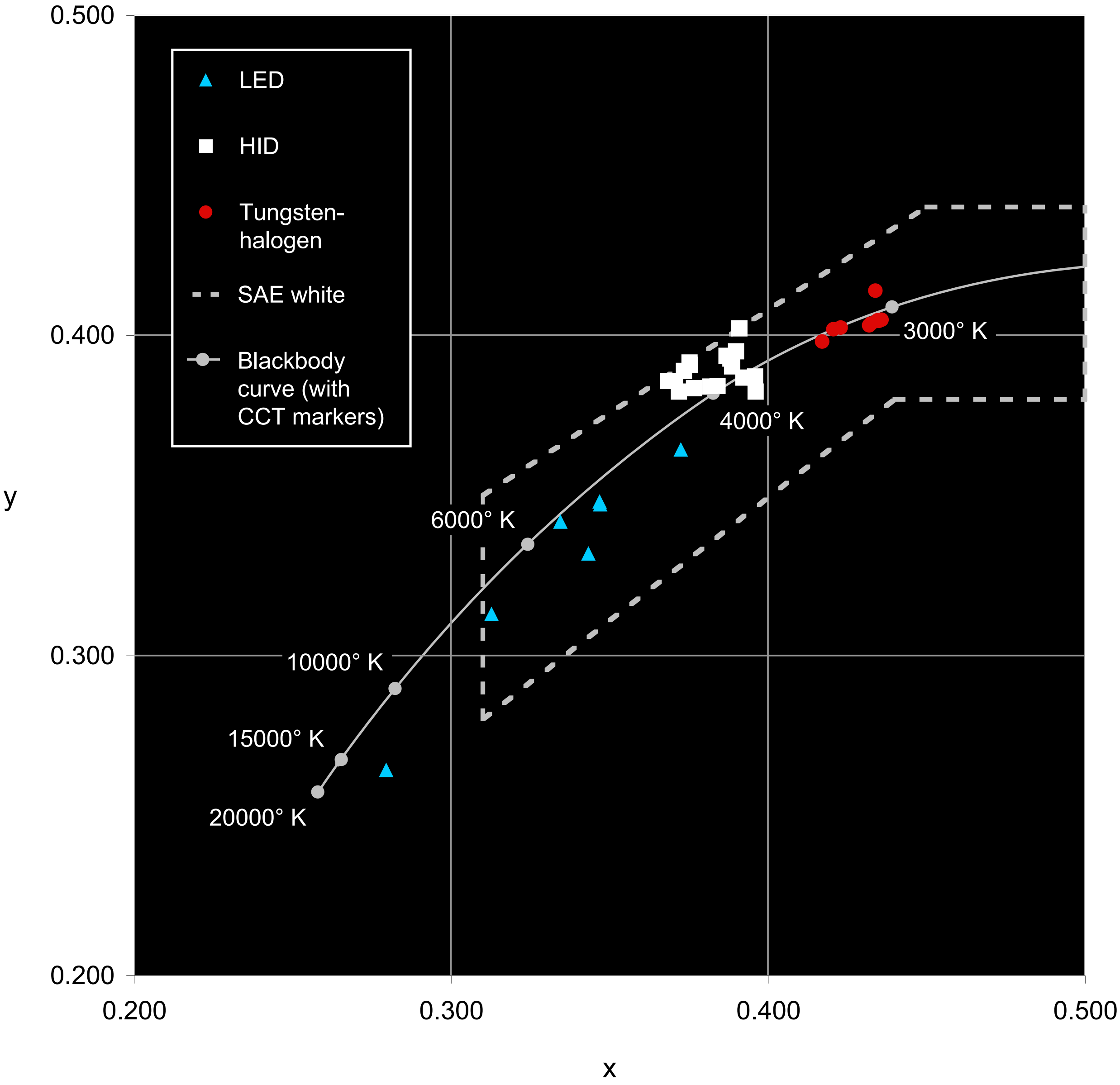

Figure 4. The relevant section of Figure 3, showing the chromaticity coordinates of the light sources.

Estimated color rendering

Red materials

Because of the importance of the red materials (being used for stop signs), the results for the reds will be presented in detail, while the results for the other colors will be presented only in summary. Figures 5, 6, and 7 present the calculated *x, y* chromaticity coordinates for the three types of red retroreflective materials (enclosed lens, encapsulated lens, and prismatic). The main features of the data in these figures are as follows:

(1) For the enclosed-lens and encapsulated-lens materials, the chromaticity coordinates form nonoverlapping regions, while for the prismatic materials the chromaticities partially overlap.

(2) The general tendency is for the locations under the LED light sources to be in between the locations under the tungsten-halogens and the HIDs. This is especially the case for the encapsulated-lens materials.

(3) For the enclosed-lens materials, the resulting locations tend to be less saturated under the LED light sources than under the other two types of the light sources.

(4) The locations tend to cluster by the different manufacturers of the materials. This is especially evident for the enclosed-lens materials.

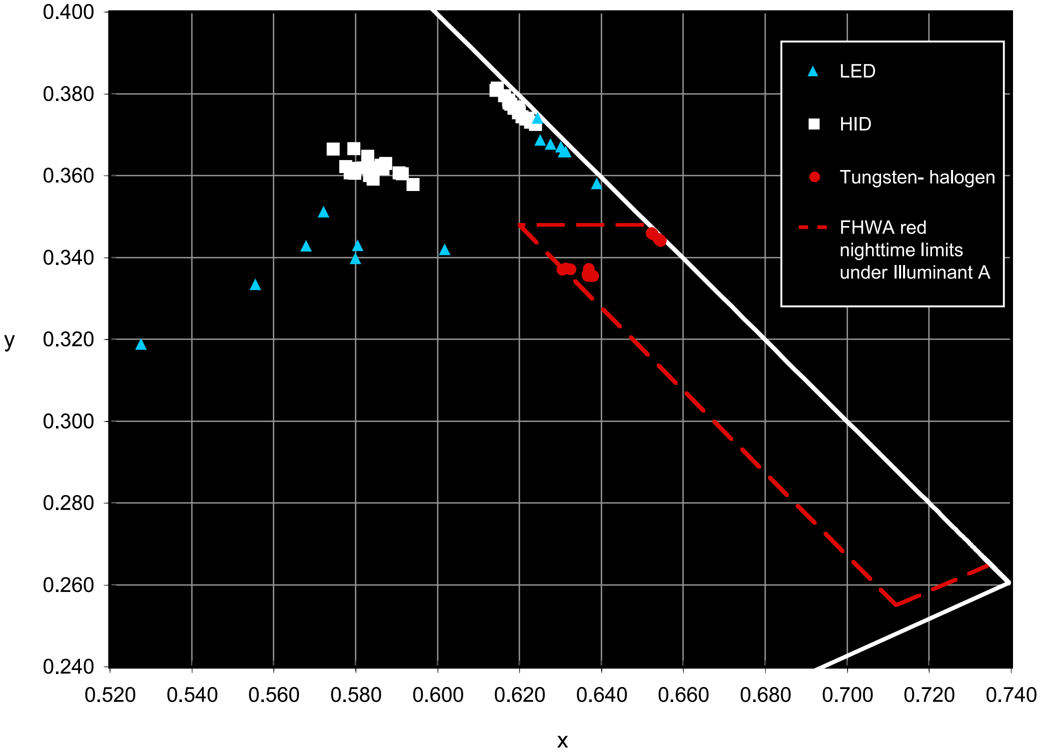

Figure 5. Chromaticity coordinates of the red enclosed-lens materials by light source. The separate clusters within each type of light source correspond to different material manufacturers. The red color limits are from FHWA (2002).

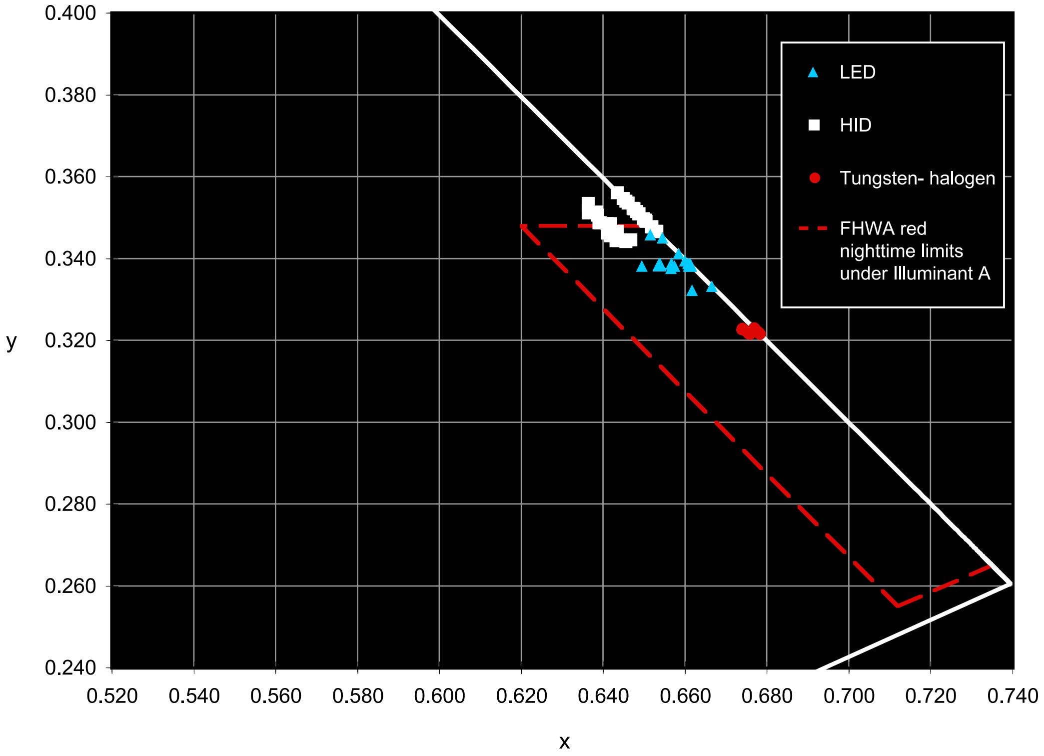

Figure 6. Chromaticity coordinates of the red encapsulated-lens materials by light source.

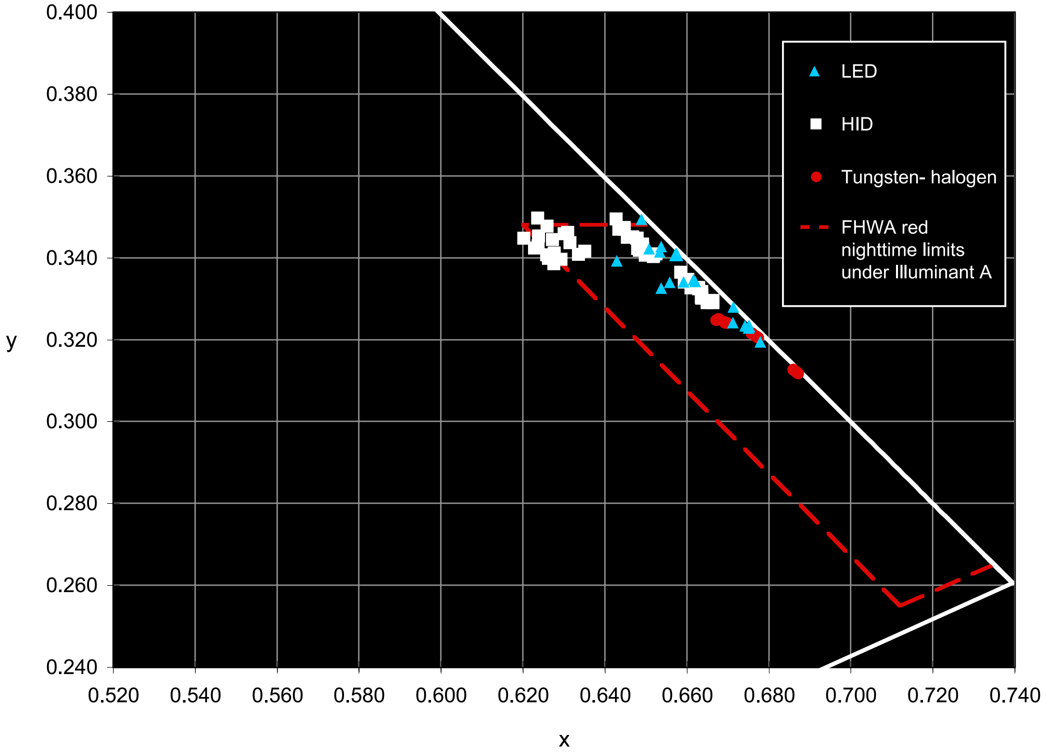

Figure 7. Chromaticity coordinates of the red prismatic materials by light source.

Other materials

The calculated *x, y* chromaticities for the other colors by each type of the light source are summarized in Figure 8. The data in Figure 8 are means across the types and manufacturers of the reflective materials and across the light sources of the same type. (For clarity of exposition, Figure 8 does not include the brown materials.) The main trends of the mean data (including the brown and red materials) are summarized in Table 6.

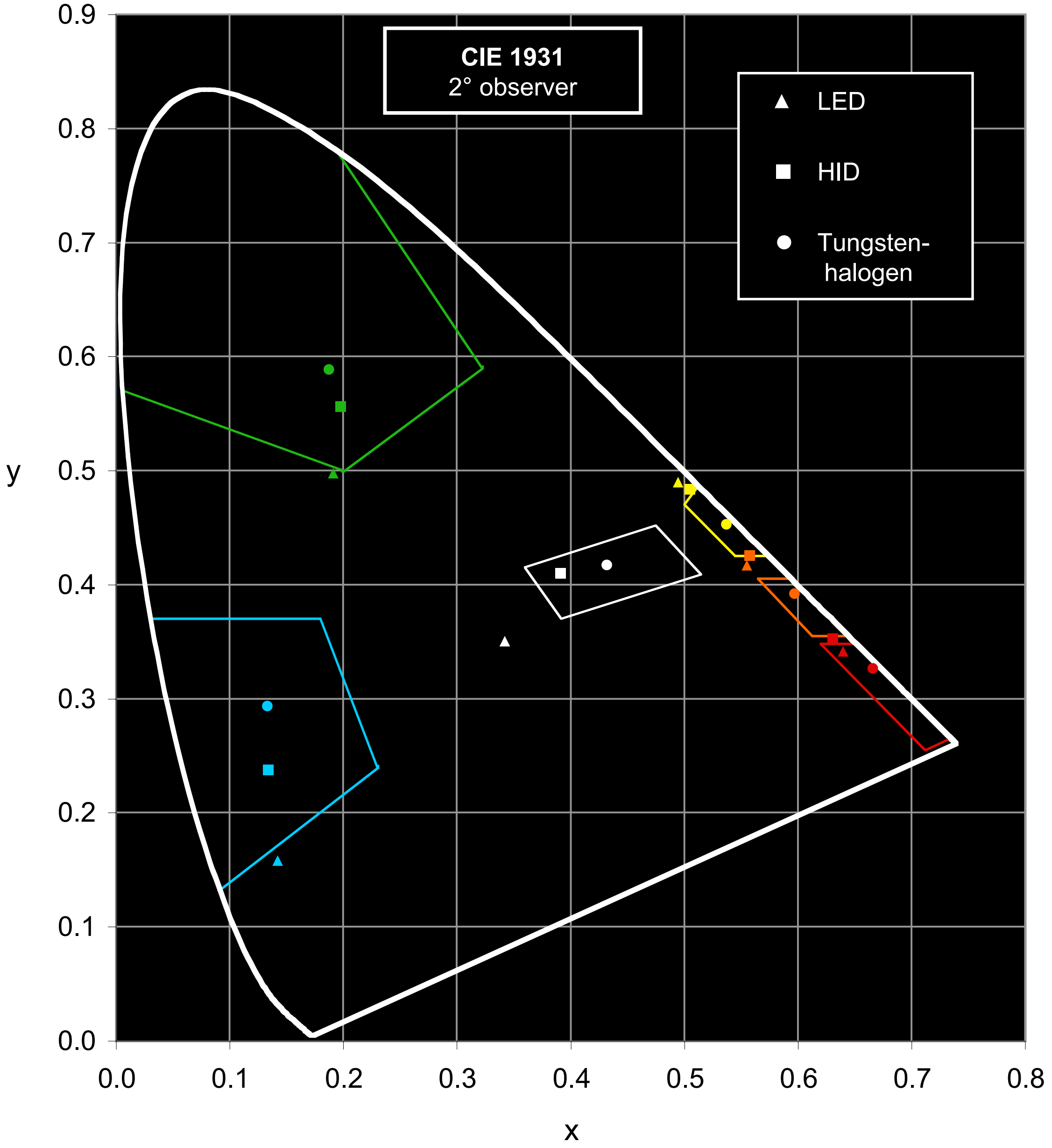

Figure 8. The mean chromaticity coordinates of the retroreflective materials by light source type. The delineated regions are the FHWA nighttime color limits under Illuminant A (FHWA, 2002).

Table 6
The main trends for the different materials when using one of the three light sources.
(T-H: tungsten-halogen light sources)

Color	Main trends
Red	LEDs in between T-H and HIDs
Orange	LEDs in between T-H and HIDs; LEDs (and HIDs) outside of the FHWA limits
Yellow	LEDs beyond HIDs; LEDs (and HIDs) outside of the FHWA limits
White	LEDs beyond HIDs; LEDs (and HIDs) outside of the FHWA limits
Green	LEDs beyond HIDs; LEDs outside of the FHWA limits
Blue	LEDs beyond HIDs; LEDs outside of the FHWA limits
Brown	LEDs near HIDs; LEDs (and HIDs) outside of the FHWA limits

Estimated relative intensity and relative brightness

Table 7 presents the mean relative intensities of the different materials when illuminated by the LED and HID light sources. The entries in Table 7 are the calculated *Y*s, normalized so that the *Y*s under the tungsten-halogen light sources are equal to 1 for each color.

Table 7
Relative intensities of each material type under the LED and HID light sources.
(The entries are *Y*s, normalized so that the *Y*s under the tungsten-halogens are equal to 1.)

Color	Enclosed lens		Encapsulated lens		Prismatic	
	LEDs	HIDs	LEDs	HIDs	LEDs	HIDs
Red	0.88	0.99	0.81	0.92	0.80	0.90
Orange	0.99	1.12	1.01	1.11	1.03	1.11
Yellow	1.07	1.10	1.07	1.11	1.07	1.10
White	1.07	1.08	1.07	1.08	1.06	1.07
Green	1.10	0.96	1.10	0.97	1.11	0.98
Blue	1.01	0.87	1.05	0.93	1.05	0.91
Brown	1.01	1.08	1.03	1.11	0.99	1.11

The data in Table 7 indicate that under the LED light sources (relative to the tungsten-halogen light sources) the red materials tend to provide less intensity, while the other materials tend to provide more intensity. However, it is generally recognized that (1) subjective brightness is approximately a logarithmic function of physical intensity, and (2) 25% is a reasonable benchmark for judging whether a difference is likely to be of practical importance (e.g., Huey, Dekker, and Lyons, 1994). Because all of the intensity differences in Table 7 are less than 25% (the largest difference is 20%), we conclude that there are not likely to be substantial positive or negative effects of the examined LED light sources on the brightness of retroreflective materials.

Conclusions

Discomfort glare

Based on the calculated chromaticity coordinates (see Figure 2), we predict that all of the LEDs considered here would lead to more discomfort than the current HIDs, and substantially more discomfort than the tungsten-halogens. To address this potential problem, we recommend minimizing the blue content by keeping the correlated color temperature as low as practicable.

Color rendering

Our calculations for retroreflective materials that are nominally red (the most important color in the transportation coding system) indicate that the chromaticity changes under LEDs (compared to tungsten-halogens) are generally not as great as the chromaticity changes under HIDs that drivers find acceptable. Although for most of the other colors the chromaticity changes under LEDs tend to be greater than under HIDs, these colors are less important as messengers of meaning. Consequently, we believe that color rendering with LEDs is likely to be acceptable.

Brightness

The calculated differences in the intensity of retroreflective materials under LEDs, HIDs, and tungsten-halogens (see Table 7) are consistent with the fact that the LEDs (and the HIDs) have less red content than do tungsten-halogens. Specifically, the intensity of the red materials under the LEDs (and under the HIDs) is reduced when compared to the intensity under the tungsten-halogens, while the intensity of some other materials (especially green) is increased. However, because none of these differences exceeded the conventional criterion level of 25%, we conclude that the examined LEDs will not have appreciable effects on the brightness of retroreflective materials.

References

FHWA [Federal Highway Administration] (2002). Table 2, Appendix to Part 655, Subpart F – Nighttime color specification limits for retroreflective material with CIE 2° observer and observation angle of 0.33°, entrance angle of +5° and CIE standard illuminant A. In, *Code of Federal Regulations*. Washington D.C.: Office of the Federal Register.

Flannagan, M.J, Sivak, M., Ensign, M., and Simmons, C.J. (1989). *Effect of wavelength on discomfort glare from monochromatic sources* (Report No. UMTRI-89-30). Ann Arbor: The University of Michigan Transportation Research Institute.

Flannagan, M.J., Sivak, M., and Gellatly, A. (1991). *Joint effects of wavelength and ambient luminance on discomfort glare from monochromatic and bichromatic sources* (Report No. UMTRI-91-42). Ann Arbor: The University of Michigan Transportation Research Institute.

Flannagan, M.J., Sivak, M., Gellatly, A., and Luoma, J. (1992a). *A field study of discomfort glare from high-intensity discharge headlamps* (Report No. UMTRI-92-16). Ann Arbor: The University of Michigan Transportation Research Institute.

Flannagan, M.J., Sivak, M., Gellatly, A., and Luoma, J. (1992b). *Ranges of stop sign chromaticity under tungsten-halogen and high-intensity discharge illumination* (Report No. UMTRI-92-17). Ann Arbor: The University of Michigan Transportation Research Institute.

Flannagan, M.J. (1999). *Subjective and objective aspects of headlamp glare: Effects of size and spectral power distribution* (Report No. UMTRI-99-36). Ann Arbor: The University of Michigan Transportation Research Institute.

Huey, R., Dekker, D., and Lyons, R. (1994). *Driver perception of just-noticeable differences of automotive signal lamp intensities* (Report No. DOT HS 808 209). Silver Springs, MD: COMSIS Corporation.

SAE [Society of Automotive Engineers] (1995). *Color specification* (SAE Standard J578). Warrendale, PA: Society of Automotive Engineers.

Simmons, C.J., Sivak, M., and Flannagan, M.J. (1989). *Color of retroreflective traffic sign materials when illuminated by high-intensity discharge headlights* (Report No. UMTRI-89-7). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Gellatly, A., and Luoma, J. (1991). *Subjective preferences for the red color of stop signs: Implications for the design of high-intensity discharge headlamps* (Report No. UMTRI-91-27). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Schoettle, B., and Adachi, G. (2003). *Driving with HID headlamps: A review of research findings* (SAE Technical Paper Series No. 2003-01-0295). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Schoettle, B., and Nakata, Y. (2002). *Performance of the first generation of HID headlamps in the U.S.* (Report No. UMTRI-2002-14). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Traube, E.C., Battle, D.S., and Sato, T. (1993). *In-traffic evaluations of high-intensity discharge headlamps: Overall performance and color appearance of objects* (Report No. UMTRI-93-3). Ann Arbor: The University of Michigan Transportation Research Institute.