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MERCURY-FREE HID HEADLAMPS: GLARE AND COLOR RENDERING

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16. Abstract

This study examined the potential effects of the spectral power distributions of mercury-free high-intensity discharge (HID) headlamps on discomfort glare for oncoming drivers and on color rendering of retroreflective traffic materials. In both cases, the effects of mercury-free HID light sources were compared to the changes in these properties that occurred when the tungsten-halogen light sources were replaced with traditional (mercury containing) HID light sources. Specifically, the effect on discomfort glare was estimated by comparing the chromaticities of 9 mercury-free headlamps with the chromaticities of 17 traditional HID headlamps. Analogously, the effects on color rendering were estimated by comparing the chromaticities of 46 retroreflective materials when illuminated by the mercury-free headlamps with the chromaticities of the same materials when illuminated by the traditional HID headlamps.

The main findings are as follows: (1) The discomfort glare from the mercury-free HIDs is predicted to be comparable to that from the "bluest" of the traditional HIDs. (2) Color rendering with headlamps using the mercury-free HIDs is likely to be acceptable. (3) The use of mercury-free HIDs is unlikely to have appreciable effects on the relative brightness of colored retroreflective materials.

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Contents

Introduction

Mercury has been an important element in the bulbs of high-intensity discharge (HID) headlamps since their introduction. However, because of ecological concerns with headlamps that are damaged or disposed of, lighting suppliers have recently developed HID headlamps in which mercury is replaced by other elements. These changes in the composition of the elements have, in turn, resulted in changes in the spectral power distribution (SPD) of the emitted light. Consequently, it is important to examine the effects of the changed SPDs of mercury-free HIDs on two aspects of headlamp performance that are known to be influenced by the SPDs of the light source: discomfort glare and color rendering.

The approach that we used is analogous to the one in our recent study on discomfort glare and color rendering with LED headlamps (Sivak, Schoettle, and Flannagan, 2003). In that study, the effects of LED light sources were compared to the changes in these properties that occurred when tungsten-halogen light sources were replaced with HID light sources containing mercury. In the present study, the effects of mercury-free HID light sources were compared to the same changes that were used for comparison in the previous study (i.e., the changes that occurred when tungsten-halogen light sources were replaced with HID light sources containing mercury). Specifically, the effect on discomfort glare was estimated by comparing the chromaticities of 9 mercury-free HID light sources with the chromaticities of 17 traditional HID light sources. Analogously, the effects on color rendering were estimated by comparing the chromaticities of 46 retroreflective materials when illuminated by the mercury-free HID light sources with the chromaticities of the same materials when illuminated by the traditional HID light sources.

Method

General approach: Discomfort glare

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

General approach: Color rendering

The approach used for estimating color rendering with mercury-free HID 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 mercury-free HID headlamps greater or smaller than those when they are illuminated by traditional 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 traditional HID headlamps see Flannagan et al., 1992b; Simmons et al., 1989; Sivak et al., 1991; and Sivak et al., 1993.)

Light sources

Spectral power distributions (SPDs) were obtained for 10 mercury-free HID light sources produced by 4 manufacturers,17 traditional HID light sources produced by 2 manufacturers, and

9 tungsten-halogen light sources produced by 5 manufacturers. (The 17 traditional HID light sources came from 17 out of the 19 HID headlamps in Sivak, Flannagan, Schoettle, and Nakata, 2002.)

The resultant *x*, *y* chromaticities of one of the mercury-free light source fell outside of both the SAE and ECE requirements for white light sources (SAE, 2002; ECE, 2001), and thus this light source was not included in the analysis. Consequently, the final set contained 9 mercury-free HID light sources produced by 3 different manufacturers; their SPDs (see Figures 1A and 1B) were obtained directly from the manufacturers. One manufacturer supplied 5 SPDs, while the other two supplied 3 and 1, respectively. In the two instances of more than one SPD per manufacturer, the differences among the SPDs were small, presumably reflecting production variations only.

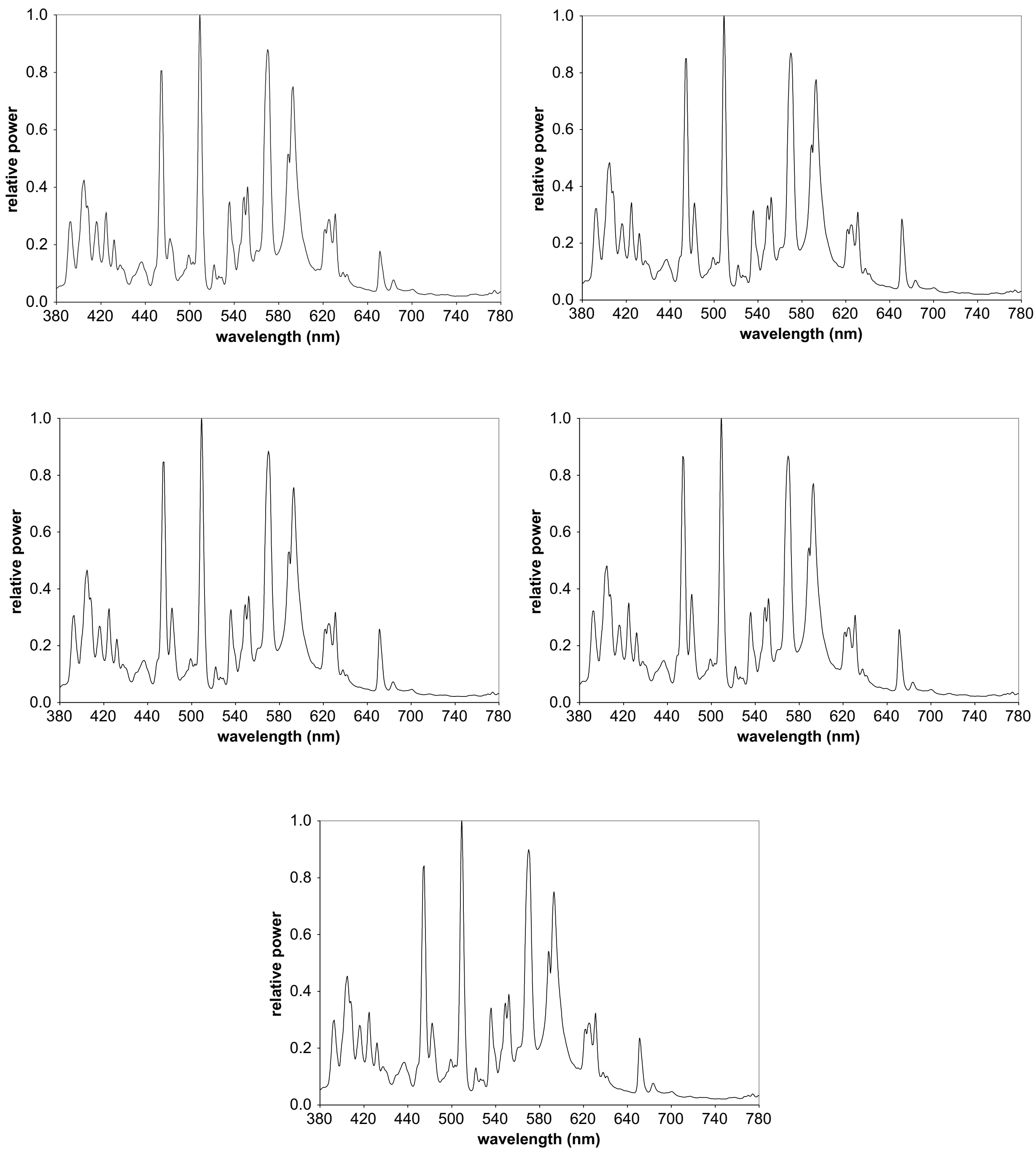

Figure 1A. The SPDs of five of the nine analyzed mercury-free HID light sources. All five light sources are from manufacturer A.

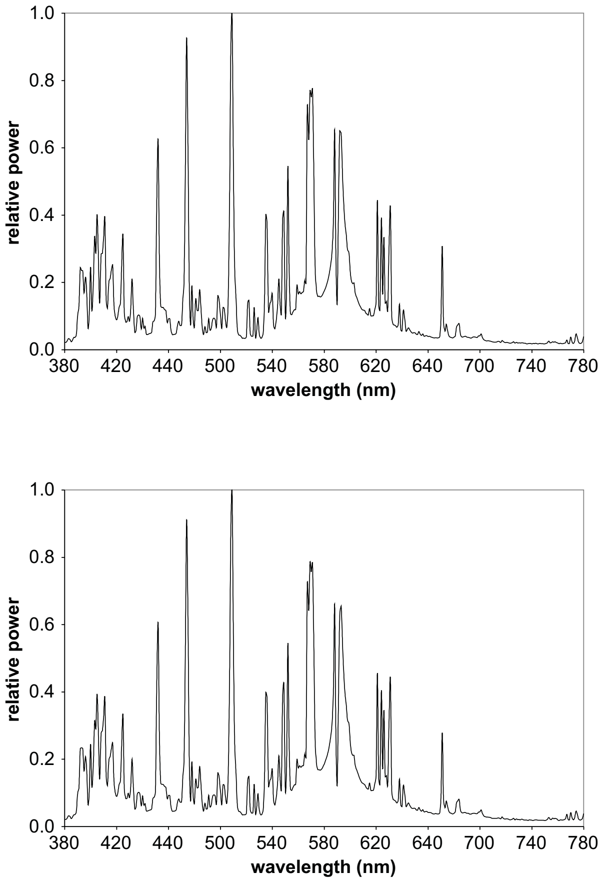

Figure 1B. The SPDs of four of the nine analyzed mercury-free HID light sources. The top two and bottom left light sources are from manufacturer B. The bottom right light source is from manufacturer C.

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 (the same as in Sivak et al., 2003) are summarized in Table 1. Sample reflectance data (for one of the two red encapsulated-lens materials) are shown in Figure 2.

Table 1
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

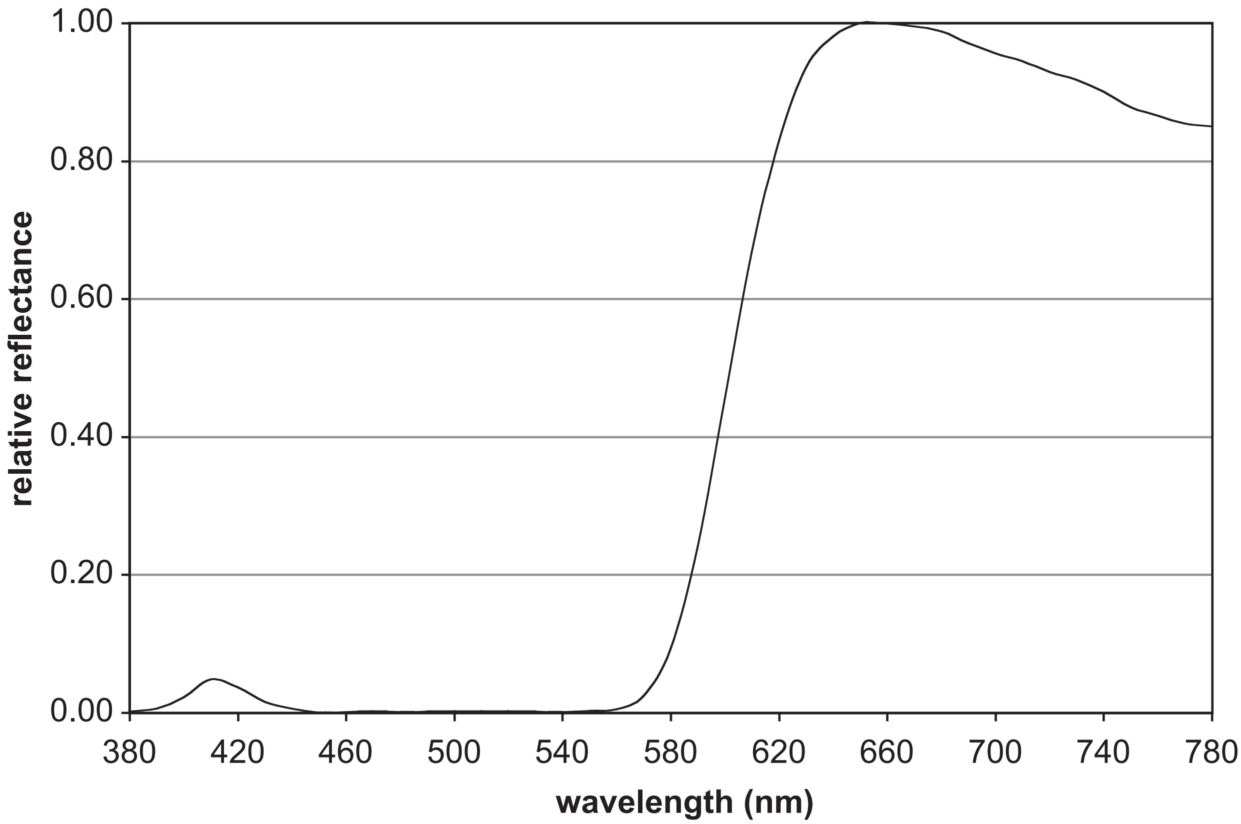

Figure 2. Reflectance data for one of the two red encapsulated-lens materials.

Chromaticity calculations for the light sources for estimating discomfort glare

The calculations that were performed for each light source are shown in Table 2.

Table 2
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 mercury-free HID, traditional HID, and tungsten-halogen 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 3.

Table 3
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 mercury-free HID, traditional HID, and tungsten-halogen 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.
- 35 unique light sources × 46 unique material colors and types = 1610 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 4. The *Y* value, as computed in Table 4, 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 photopically equal.

Table 4
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.
- 35 unique light sources × 46 unique material colors and types = 1610 intensity values.

Results

Estimated discomfort glare

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

(1) The chromaticities of all of the tested mercury-free HIDs fall not only within the current SAE and ECE general limits for white sources (SAE, 2002; ECE, 2001), but also within (or very near) the more restrictive ECE limits for HID sources (ECE, 2001). (Because the SAE and ECE general limits are very similar, for clarity of exposition, Figures 3 and 4 show only the SAE general limits.[1])

(2) The mercury-free HID light sources cluster at the "bluish" end of the distribution of the traditional HID light sources.

(3) The spread of the mercury-free HIDs is relatively small. Furthermore, the spread across the manufacturers (not shown) is small. Indeed, this spread is smaller than the spread within the manufacturer that provided us with 5 samples.

Based on the chromaticities of the mercury-free HIDs relative to the traditional HIDs, we predict that the discomfort glare from the tested mercury-free HIDs would be comparable to that from the "bluest" of the traditional HIDs.

[1] SAE Standard J578 (SAE, 2002) is not internally consistent in the blue limit; the text in the current version was revised from .31 to .30, while the relevant figure was left with the old value of .31. The discrepancy is minor. For consistency with the SAE figure, our Figures 3 and 4 use .31.

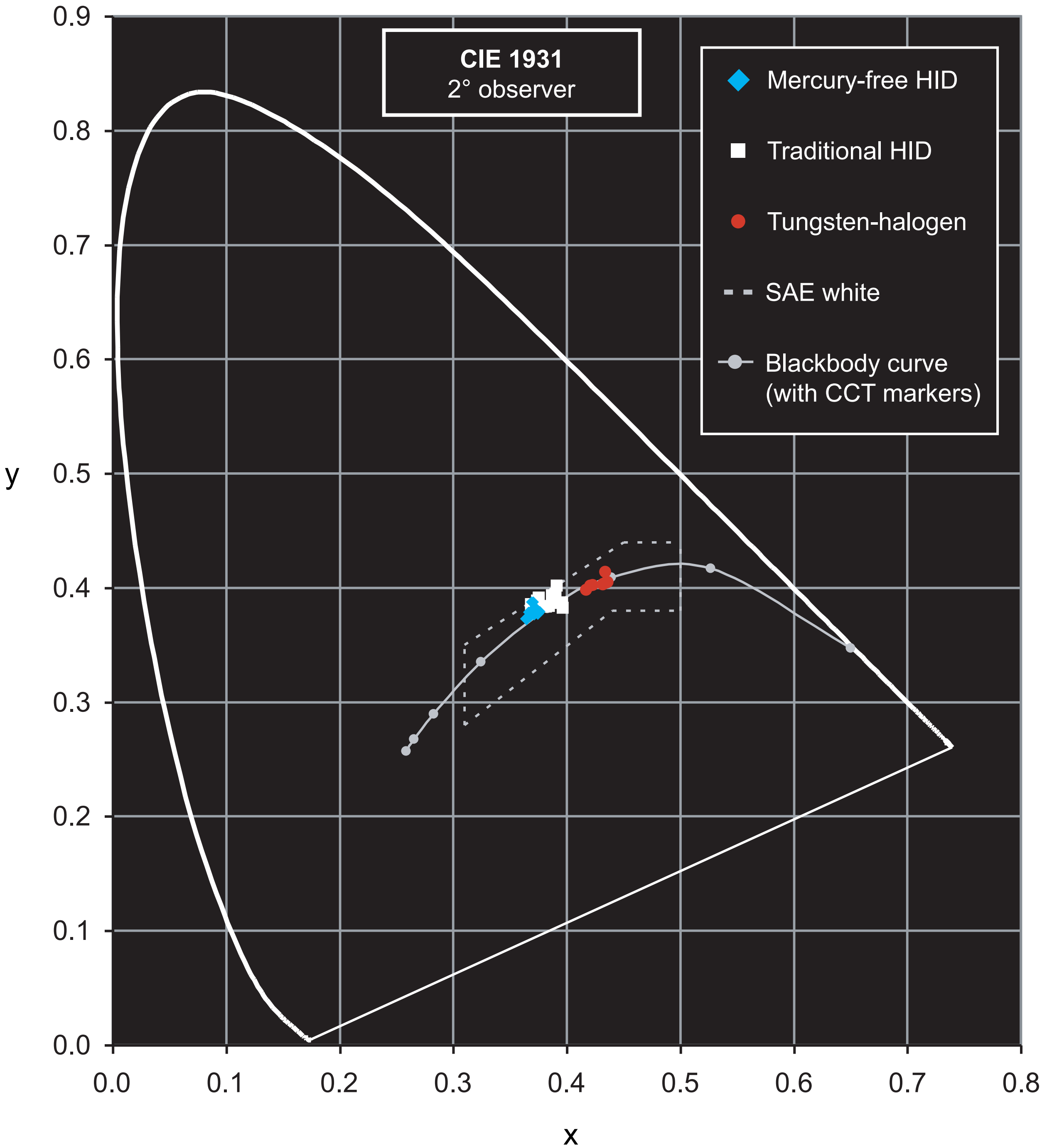

Figure 3. The chromaticity coordinates of the light sources.

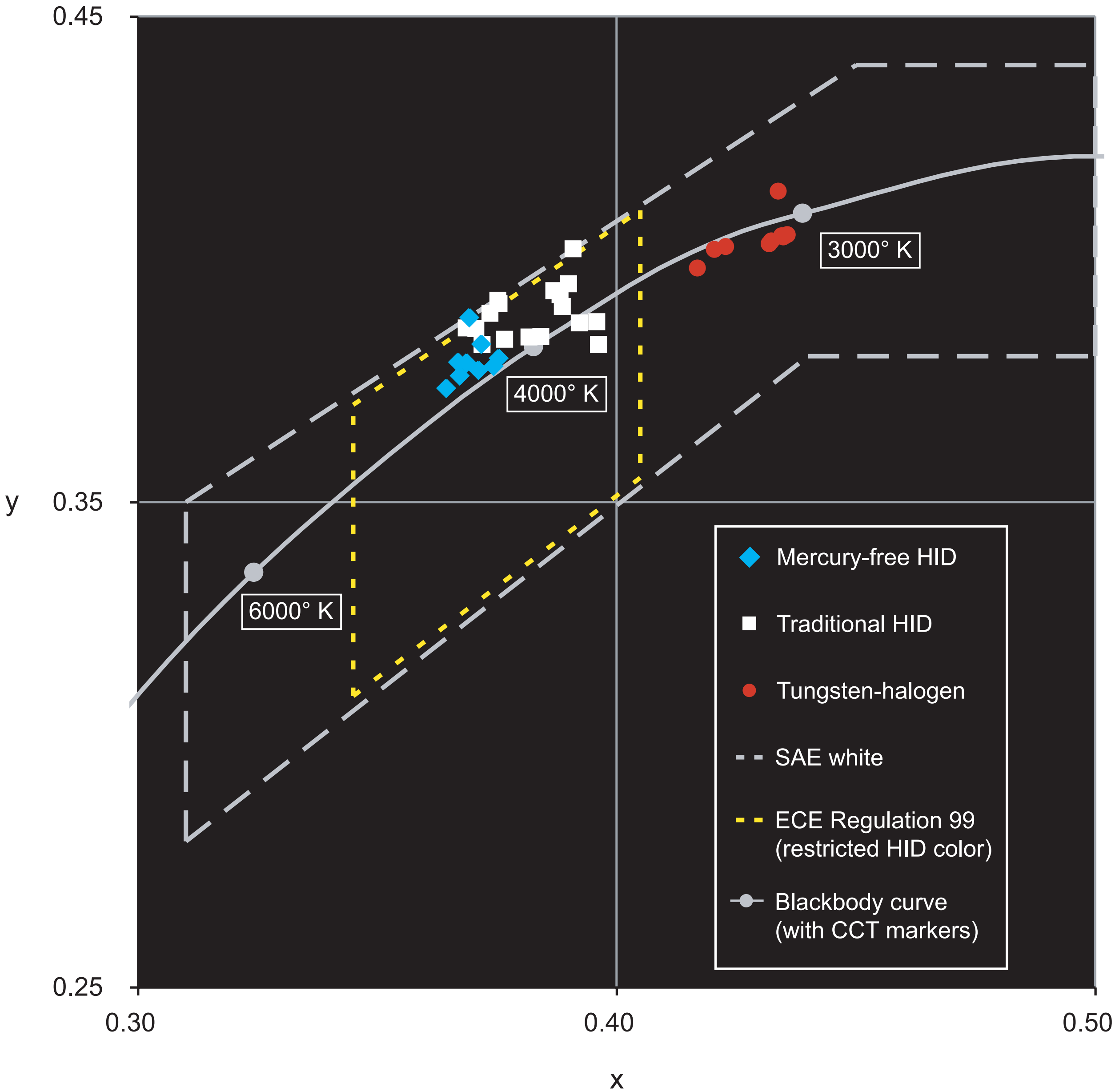

Figure 4. The relevant section of Figure 3, showing the chromaticity coordinates of the light sources.

Estimated color rendering

Red materials

Because of the importance of red traffic control 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) The general tendency is for the locations under the mercury-free HID light sources to be within or near the distributions of the locations under the traditional HID light sources.

(2) For the enclosed-lens and prismatic materials, the resulting locations under the mercury-free HIDs tend to cluster towards the less saturated part of the distributions of the traditional HIDs.

(3) The locations tend to cluster by the different manufacturers of the materials.

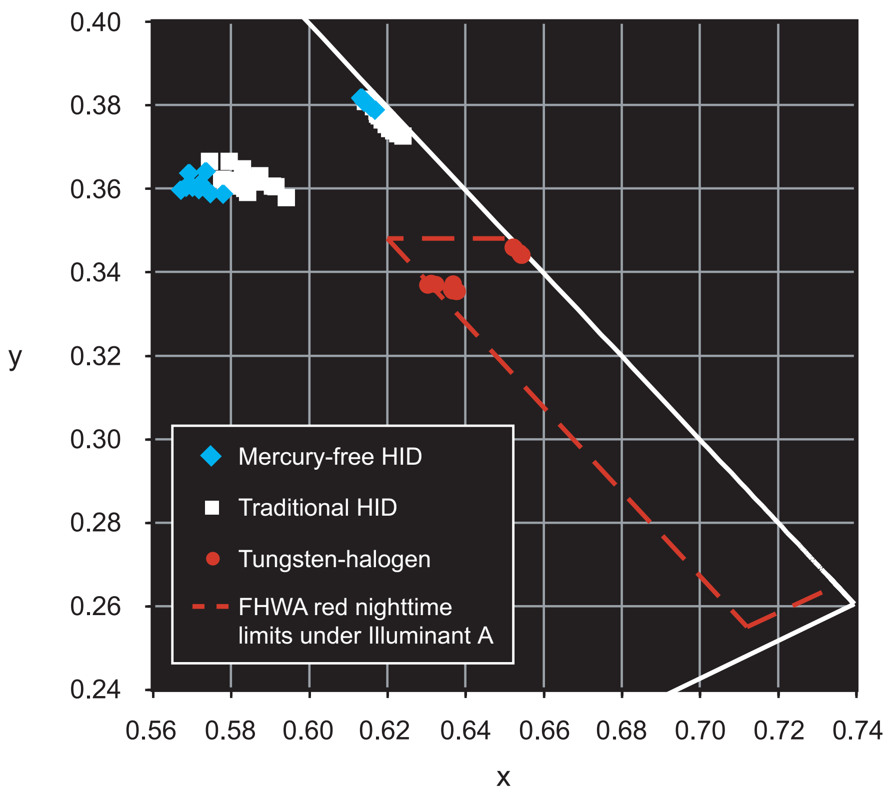

Figure 5. Chromaticity coordinates of the red enclosed-lens materials by light source. The separate clusters within each type of light source correspond to different material manufacturers. The red color limits are from FHWA (2002).

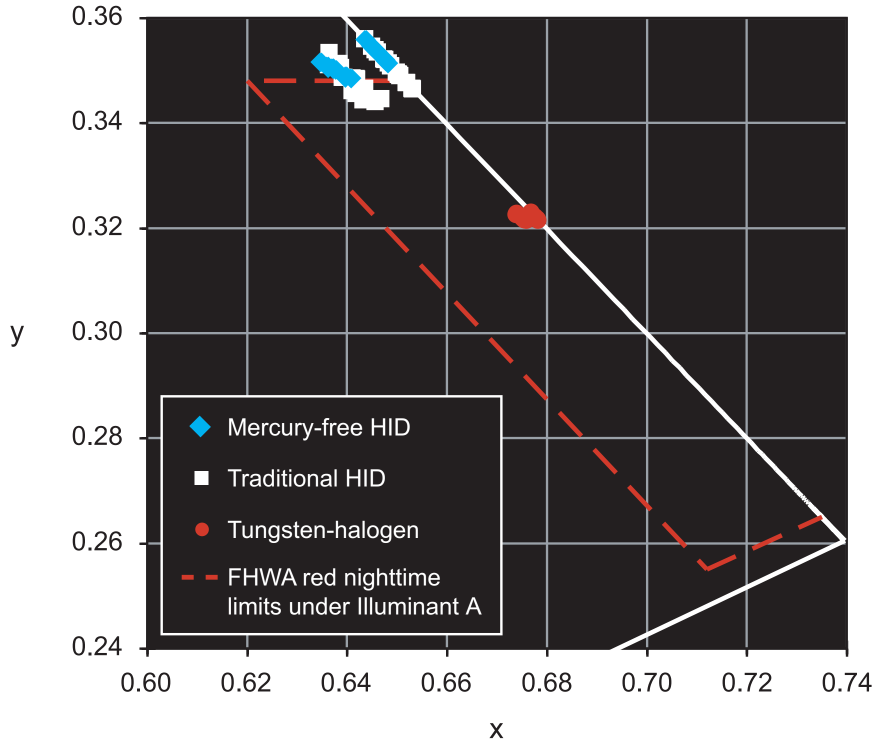

Figure 6. Chromaticity coordinates of the red encapsulated-lens materials by light source.

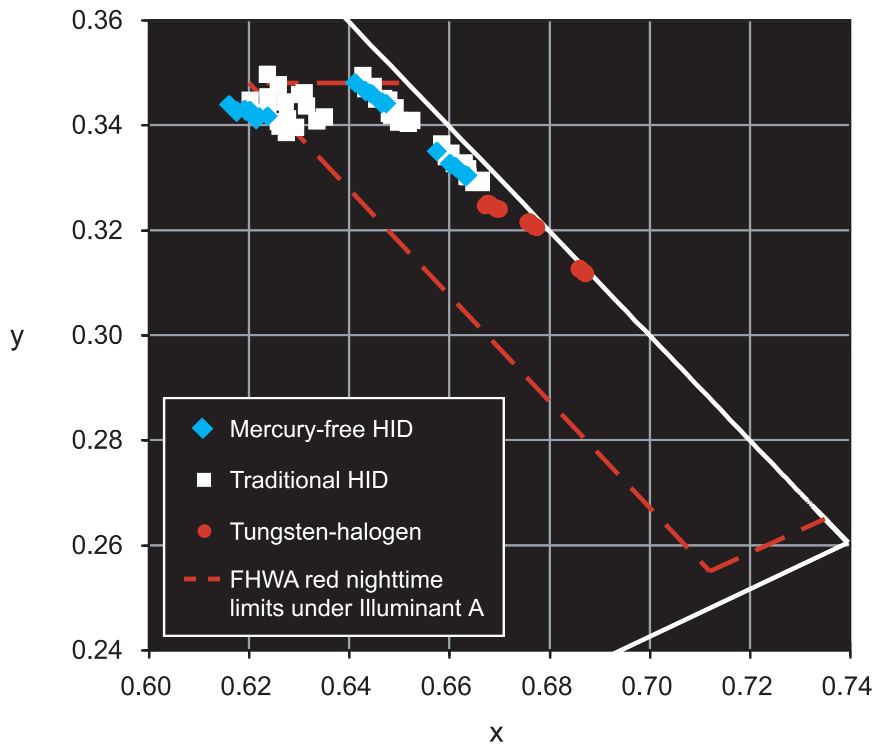

Figure 7. Chromaticity coordinates of the red prismatic materials by light source.

Other materials

The calculated x, y chromaticities for the other colors by each type of light source are summarized in Figure 8. The data in Figure 8 are the means across the types and manufacturers of the reflective materials and across the light sources of the same type. (Each entry for the mercury-free HIDs is a mean of three submeans by lamp manufacturer.) For clarity of exposition, Figure 8 does not include the brown materials. The main trends are as follows:

(1) For the blue, green, and white materials, the mean locations under the mercury-free HIDs are all within the FHWA nighttime color limits under Illuminant A.

(2) For the red, yellow, orange, and brown materials, the mean locations under the mercury-free HIDs are outside the FHWA nighttime color limits, but in each case so are the locations under the traditional HIDs. Furthermore, in each case, the differences between the locations under the two types of HIDs are small.

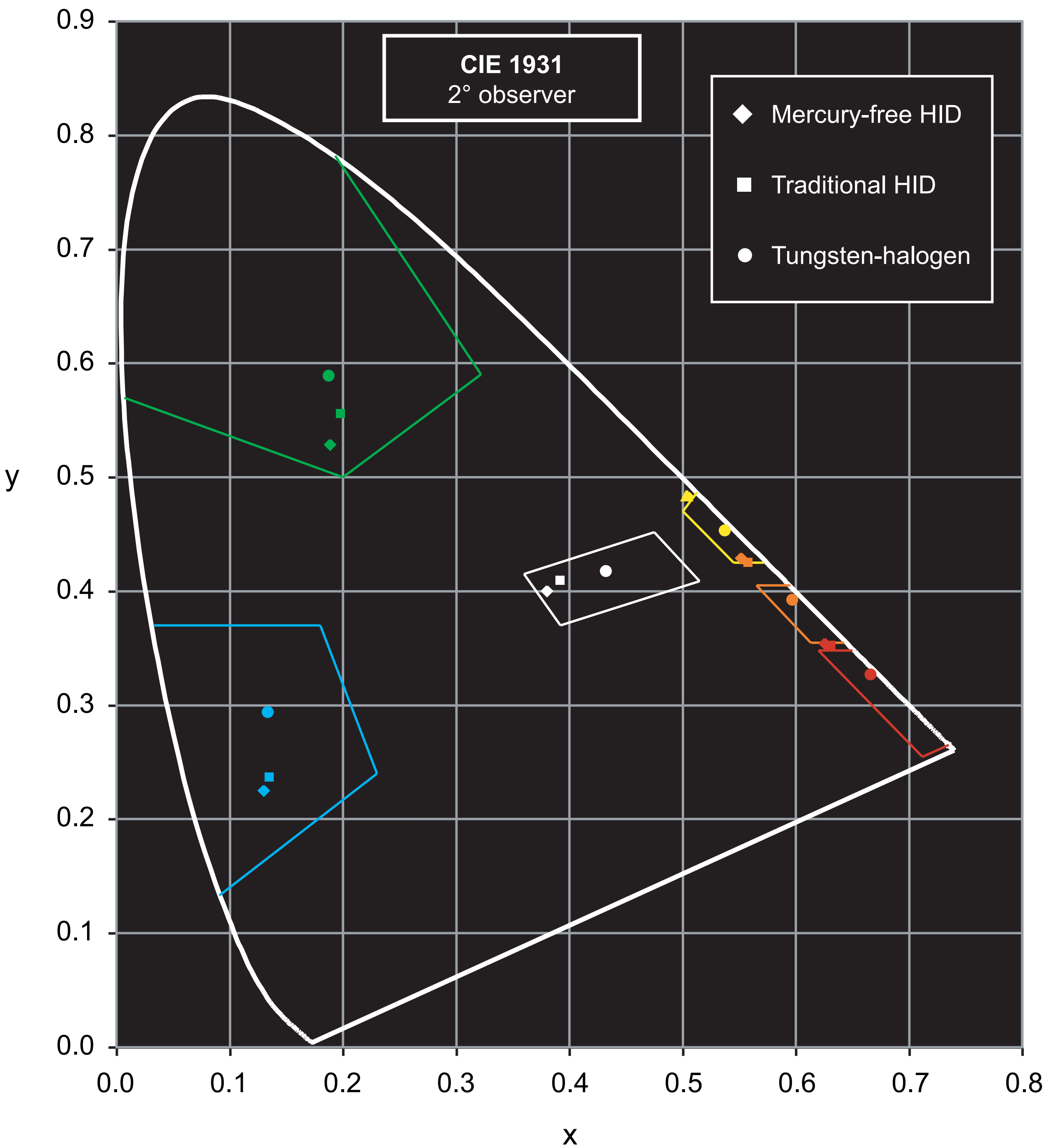

Figure 8. The mean chromaticity coordinates of the retroreflective materials by light source type. The delineated regions are the FHWA nighttime color limits under Illuminant A (FHWA, 2002).

Estimated relative intensity and relative brightness

Table 6 presents the mean relative intensities of the different materials when illuminated by the mercury-free and traditional HID light sources. The entries in Table 6 are the calculated *Y*s, normalized so that the *Y*s under the tungsten-halogen light sources are equal to 1 for each color. (Each entry for the mercury-free HIDs is a mean of three submeans by lamp manufacturer.)

Table 6
Relative intensities of each material type under the mercury-free and traditional 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	
	Mercury-free	Traditional	Mercury-free	Traditional	Mercury-free	Traditional
Red	0.96	0.99	0.88	0.92	0.85	0.90
Orange	1.14	1.12	1.13	1.11	1.13	1.11
Yellow	1.10	1.10	1.12	1.11	1.11	1.10
White	1.08	1.08	1.08	1.08	1.08	1.07
Green	0.94	0.96	0.95	0.97	0.96	0.98
Blue	0.87	0.87	0.93	0.93	0.90	0.91
Brown	1.09	1.08	1.11	1.11	1.12	1.11

The data in Table 6 indicate that under the mercury-free light sources (relative to the tungsten-halogen light sources) the red, green, and blue 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 6 are less than 25% (the largest difference is 15%), we conclude that there are not likely to be substantial positive or negative effects of the examined mercury-free HID light sources on the brightness of retroreflective materials (in relation to either the traditional HID or tungsten-halogen light sources).

Conclusions

Discomfort glare

Based on the chromaticities of the mercury-free HIDs relative to the traditional HIDs, we predict that the discomfort glare from the tested mercury-free HIDs would be comparable to that from the "bluest" of the traditional HIDs.

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 the mercury-free HIDs (compared to tungsten-halogens) are comparable to the chromaticity changes under the traditional HIDs that drivers find acceptable. For the other colors, the chromaticity changes under mercury-free HIDs either do not move the locations outside of the FHWA nighttime color limits under Illuminant A, or the resultant locations are similar to the locations under the traditional HIDs. Consequently, color rendering with mercury-free HIDs is likely to be acceptable.

Brightness

The calculated intensity of the red, green, and blue materials under the mercury-free HIDs (and under the traditional HIDs) is reduced when compared to the intensity under the tungsten-halogens, while the intensity of the orange, yellow, white, and brown materials is increased. However, because all of these differences are well within the conventional criterion level of 25%, we conclude that mercury-free HIDs will not have appreciable effects on the brightness of retroreflective materials.

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