UMTRI-92-17

RANGES OF STOP SIGN CHROMATICITY UNDER TUNGSTEN-HALOGEN AND HIGH-INTENSITY DISCHARGE ILLUMINATION

Michael J. Flannagan
Michael Sivak
Andrew W. Gellatly
Juha Luoma

May 1992

Ranges of Stop Sign Chromaticity under Tungsten-Halogen and High-Intensity Discharge Illumination

Michael J. Flannagan
Michael Sivak
Andrew W. Gellatly
Juha Luoma

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

Report No. UMTRI-92-17
May 1992

Technical Report Documentation Page

1. Report No. UMTRI-92-17	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ranges of Stop Sign Chromaticity under Tungsten-Halogen and High-Intensity Discharge Illumination		5. Report Date May 1992
		6. Performing Organization Code 302753
7. Author(s) Michael J. Flannagan, Michael Sivak, Andrew W. Gellatly, and Juha Luoma		8. Performing Organization Report No. UMTRI-92-17
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 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 affiliate companies supporting this research were Bosch, Carello Lighting, Donnelly, Ford (Plastic and Trim Products Division), GE Lighting, GM (Inland Fisher Guide Division), GTE Products, Ichikoh Industries, Koito Manufacturing, Philips Lighting, Stanley Electric, and 3M.

16. Abstract

The development of high-intensity discharge (HID) sources for automotive headlighting has raised questions about the rendering of colors by those sources, relative to the rendering of colors by tungsten-halogen sources. The rendering of sign colors has been of concern because color is used as an indicator of sign functions. The rendering of the red of stop signs has been particularly of concern because consistent recognition of stop signs is critical for safety.

This study was designed to compare the magnitudes of the shifts in chromaticity of stop signs illuminated by HID and tungsten-halogen headlamps to the range of chromaticities of stop signs under tungsten-halogen. A stratified sample of 25 stop signs was selected in Ann Arbor, Michigan. Stratification was by material (enclosed, encapsulated, microprism), age (more than five years in service, less than one year in service), and compass direction faced by the legend side of the sign (north, south). The chromaticities of these signs were measured in the field under both tungsten-halogen and HID (D1) illumination. The shifts between the chromaticities of the signs when they were illuminated with the tungsten-halogen source and when they were illuminated with the HID light source were moderate relative to the range of chromaticities under tungsten-halogen. We argue that, although the sizes of the shifts should not be interpreted as indicating a problem with color rendering by HID headlamps, they are not small enough to allow us to dismiss the possibility of a problem.

17. Key Words color, chromaticity, high-intensity discharge, HID, headlamps, traffic signs, color rendering	18. Distribution Statement Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price

ACKNOWLEDGEMENTS

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:

Bosch
Carello Lighting
Donnelly
Ford (Plastic and Trim Products Division)
GE Lighting
GM (Inland Fisher Guide Division)
GTE Products
Ichikoh Industries
Koito Manufacturing
Philips Lighting
Stanley Electric
3M

We especially thank Ford Plastic and Trim Products Division for the loan of the HID-equipped automobile used in this study.

CONTENTS

INTRODUCTION

The development of high-intensity discharge (HID) sources for use in automotive headlighting has raised questions about the rendering of colors of objects illuminated by them; particularly colors of traffic signs, for which color is an indicator of function. The spectral power distributions of HIDs differ substantially from those of tungsten-filament lamps, which until now have been the only sources used in headlighting. Tungsten-filament lamps have continuous spectra, and are strongest at long wavelengths. Although no single spectrum has been settled on for HID headlamps, these sources are generally characterized by strong concentrations of energy in spectral lines and by weakness in the long-wavelength range. Because human color perception is not perfectly constant over changes in illumination, these differences in spectral power distributions suggest that the perception of color will be at least somewhat different with HID versus tungsten-filament lamps.

We have conducted two previous studies to evaluate the possible effects of HID lamps on color rendering. One of these was an analytic study in which we quantified the effects of several HID sources on each of a variety of sign colors (Sivak, Simmons, & Flannagan, 1991). We used data on the spectral power distributions of the HIDs and on the reflectance spectra of the sign materials to calculate the expected locations of the resulting chromaticities in a perceptually uniform color space. Our analysis concentrated on two effects: (1) the colorimetric shift of each sign from its appearance under tungsten-halogen lighting to its appearance under various HIDs, and (2) the colorimetric separation of red from its nearest neighbors (yellow, orange, and brown) under tungsten-halogen and the HIDs. The results indicated that, for the seven HID spectra considered, both of these effects were reasonably well predicted from the correlated color temperatures of the HID sources. Both colorimetric shifts and separations increased with increasing correlated color temperature.

In the second study (Sivak, Flannagan, Gellatly, & Luoma, 1991) we asked subjects to indicate their preferences for the red color of stop signs by making judgments of color samples under controlled lighting conditions. The most preferred color was near the center of the FHWA box specifying daytime chromaticity of red retroreflective sign materials. Subjects were differentially sensitive to colorimetric shifts in different directions from this most preferred color. Their preferences declined more with shifts in hue toward orange than with shifts in saturation toward pink.

Although these studies provided some information about the magnitudes of the colorimetric shifts caused by introducing HID headlamps, and about how people may react to them, they did not provide a final answer to the problem of color rendition. For safety, the most important question about color rendition may be: How well do drivers recognize signs (especially red stop signs) under a particular light source? Without extensive data on responses to stop signs by unalerted subjects, it is difficult to know how much color contributes to sign recognition beyond the contributions of the redundant cues of shape and legend, and how much of a colorimetric shift is large enough to reduce whatever effectiveness color has.

We conducted the present study in an attempt to bypass the difficulties of quantifying the effect of color shifts on recognition under actual, unalerted driving conditions. The strategy was to compare the colorimetric shift for stop signs between tungsten-halogen and HID illumination to the existing range of chromaticities of stop signs under tungsten-halogen illumination. The existing range of stop sign chromaticities is a useful benchmark for two reasons: (1) the existing variation in stop sign color is acceptable to the collective wisdom of those who maintain the signs, and (2) whatever the actual consequences of the existing amount of variation, if the shift due to a particular HID source is small relative to that amount, then introducing that source for use in headlamps will not cause a significant increase in the overall variation of chromaticity.

The potential conclusions of this study can be illustrated by reference to two hypothetical outcomes illustrated in Figure 1. The upper example shows a case in which the shift due to an HID source is small relative to the existing range of sign chromaticity. In a case such as that it seems reasonable to conclude that the further variation introduced by the source cannot make recognition significantly harder. In the lower example, the shift due to the HID source is large relative to the existing range. In that case it is possible, although not certain, that the shift caused by the HID source will affect recognition. According to this reasoning, a relatively large chromaticity shift is a necessary, but not sufficient, condition for the existence of a problem with rendering of sign colors.

Our strategy in this study was straightforward: We used a photometer equipped with tristimulus filters to measure the chromaticities of a sample of retroreflective stop signs under both tungsten-halogen and HID illumination. In order to represent the range of existing signs efficiently, we used a sample stratified on three variables: (1) grade of retroreflective material, (2) age (years in service), and (3) compass direction faced by the legend side of the sign (in order to insure differential exposure to sunlight). The HID lamps used D1 bulbs, with the spectral power distribution shown in Figure 2.

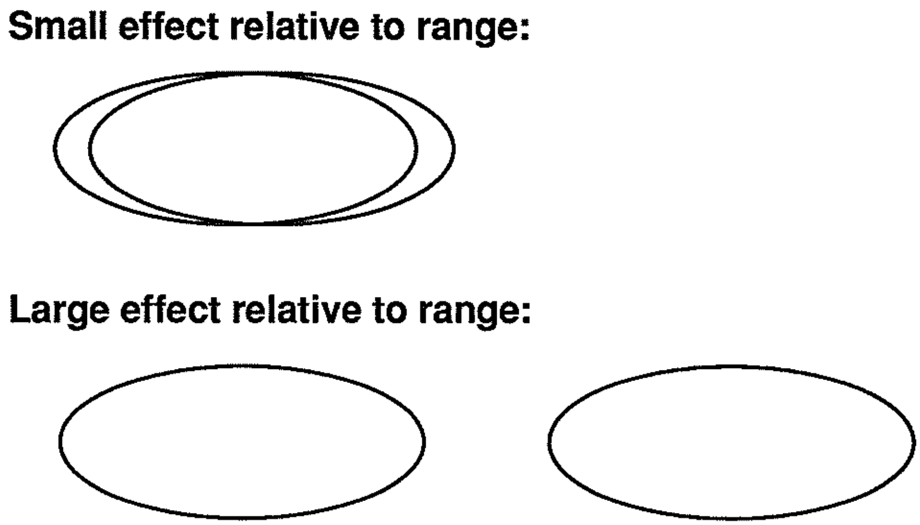

Figure 1. Hypothetical outcomes for the magnitude of chromaticity shifts between tungsten-halogen and HID illumination for a sample of signs. In the upper example the shift due to light source is small relative to the range already existing under tungsten-halogen. In the lower example the shift is large relative to the existing range.

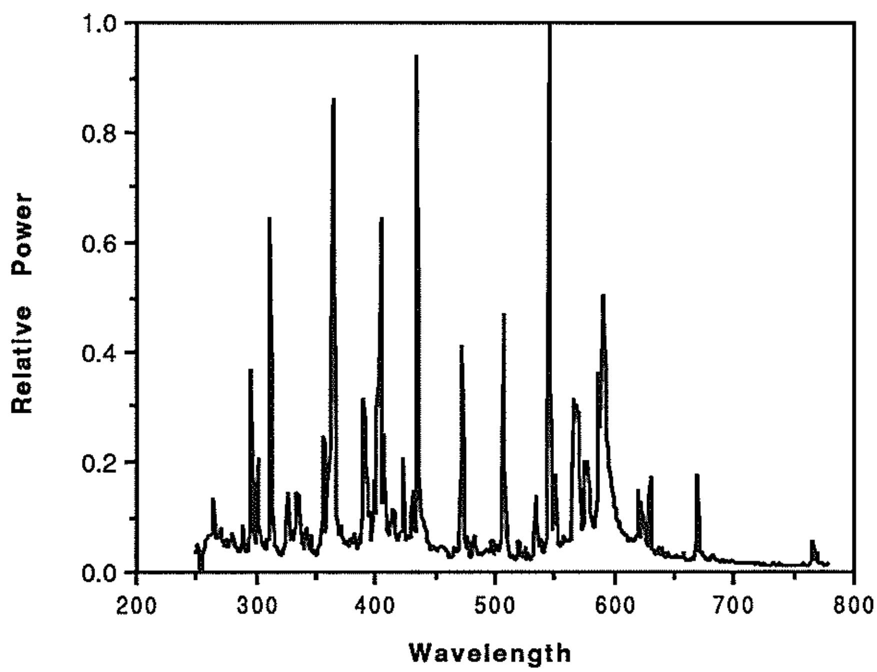

Figure 2. The relative spectral power distribution of the HID bulbs used in this study (D1).

METHOD

Apparatus

Signs were illuminated by the headlamps of an automobile equipped with standard tungsten-halogen headlamps as well as a prototype HID system using D1 bulbs. The lamps were wired so that each system could be turned on alone. The spectral power distribution for the D1 bulbs is shown in Figure 2.

Chromaticity measurements were made using a spot photometer equipped with tristimulus filters (Photo Research Pritchard 1980A with TF-80 tristimulus filters).

Signs

We obtained the maintenance records for all stop signs in the city of Ann Arbor, Michigan and selected from the list a sample of 25 signs stratified by:

(1) grade of material (enclosed, encapsulated, microprism),
(2) age (greater than five years in service, less than one year in service),
(3) compass direction (north facing, south facing).

The combinations of these factors represented in the sample is shown in Table 1. Note that there were no older microprism signs because this material has only recently been used in Ann Arbor.

Procedure

All photometry was done at night with the stop signs illuminated by the headlamps of the test vehicle. The vehicle was driven toward each stop sign as it would be in a normal approach to the intersection, and it was stopped briefly 100 ft (30.48 m) from the sign. Readings were taken while the test vehicle was stationary, with each of the headlamp systems (tungsten-halogen and HID) turned on separately. Photometry was done from the right, front passenger position, through the windshield.

No readings were taken if another vehicle was present. In order to assess the effects of any fixed sources of lighting, readings were taken with the headlamps of the test vehicle turned off. These readings were always at least two orders of magnitude lower than when the headlamps were on. Therefore no source of light other than the headlamps of interest had a substantial effect on the measurements. This is not surprising, because all the signs were retroreflective and light from the headlamps had the advantage of originating close to the photometer.

Table 1

Stratification of stop sign sample (total n = 25).

Age	Direction	Material		
		Enclosed	Encapsulated	Microprism
Old (> 5 yr)	North	2	3	-
	South	3	5	-
New (< 1 yr)	North	2	3	1
	South	3	2	1

RESULTS AND DISCUSSION

Complete results are given in Table 2, which shows CIE chromaticity coordinates for each of the 25 signs illuminated by each of the two sets of lamps. These results are also shown graphically in Figure 3, which shows the chromaticities of the illuminated signs on a portion of the CIE 1931 chromaticity diagram, including the FHWA box for daytime chromaticity of red signs. Note that under tungsten-halogen all but three of the signs fall within the FHWA box, whereas under the HID they are all outside. However, the absolute locations of chromaticities should not be taken too seriously, given that they were measured with tristimulus filters rather than full spectrophotometry (Wyszecki & Stiles, 1982, chap. 3).

The relative locations of the chromaticity points are more reliable and more important for our present purposes. The total variability is about the same under the two light sources. The shift due to changing sources is of moderate size relative to the spread within either source. Quantifying the relative size of the shift more precisely depends on how much weight is given to several outliers. Three signs in the tungsten-halogen condition and one in the HID condition are the most prominent outliers, all lying to the left of the main groups of points. If the boundaries of chromaticities under each condition are defined by all cases, then there is substantial overlap between the boundaries under tungsten-halogen and HID illumination. But if the outliers are eliminated there is no overlap.

The results are thus somewhat ambiguous. The magnitude of the shift between tungsten-halogen and HID illumination relative to the spread under tungsten-halogen is not so small that we can confidently dismiss the possibility of a problem with color rendering by this particular HID source. On the other hand, there is not a clear separation of the two ranges of chromaticity, and in any case, as pointed out in the introduction, even a large shift would be only a necessary, not a sufficient, condition to conclude that a problem with chromaticity exists.

More extensive sampling of existing signs might alter these conclusions. The sample here was stratified to represent the range in the city of Ann Arbor, but other jurisdictions might have a larger (or smaller) range of signs. Including all signs from all jurisdictions might increase our estimate of the range of existing signs. That would tend to reduce the relative size of the shift between light sources.

Table 2

Chromaticity coordinates for the 25 signs under tungsten-halogen and HID illumination.

Sign number	Material	Age (years)	Direction	Tungsten-halogen x	Tungsten-halogen y	HID x	HID y
1	enclosed	> 5	north	.595	.346	.535	.373
2	enclosed	> 5	north	.605	.347	.537	.367
3	enclosed	> 5	south	.588	.353	.495	.373
4	enclosed	> 5	south	.515	.384	.502	.371
5	enclosed	> 5	south	.565	.366	.448	.369
6	enclosed	< 1	north	.625	.339	.566	.357
7	enclosed	< 1	north	.533	.366	.504	.388
8	enclosed	< 1	south	.626	.339	.522	.388
9	enclosed	< 1	south	.587	.357	.553	.362
10	enclosed	< 1	south	.622	.339	.563	.363
11	encapsulated	> 5	north	.602	.350	.504	.364
12	encapsulated	> 5	north	.589	.346	.538	.343
13	encapsulated	> 5	north	.629	.330	.544	.356
14	encapsulated	> 5	south	.604	.347	.511	.359
15	encapsulated	> 5	south	.606	.339	.533	.367
16	encapsulated	> 5	south	.627	.334	.526	.360
17	encapsulated	> 5	south	.594	.346	.564	.370
18	encapsulated	> 5	south	.619	.348	.556	.357
19	encapsulated	< 1	north	.635	.331	.561	.360
20	encapsulated	< 1	north	.639	.329	.564	.365
21	encapsulated	< 1	north	.646	.322	.556	.368
22	encapsulated	< 1	south	.614	.338	.566	.366
23	encapsulated	< 1	south	.634	.338	.537	.364
24	microprism	< 1	north	.610	.343	.545	.351
25	microprism	< 1	south	.634	.311	.537	.349

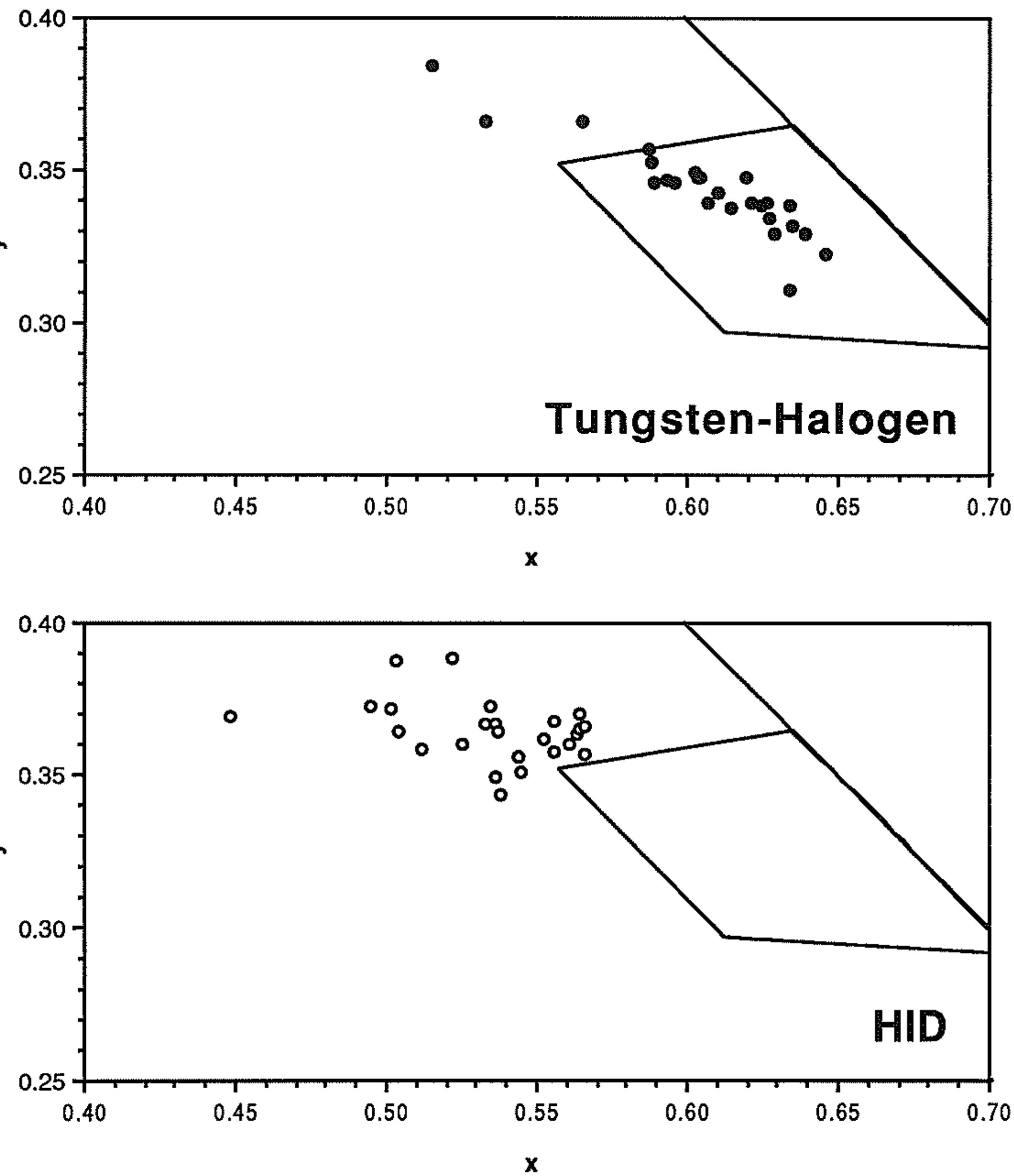

Figure 3. Ranges under tungsten-halogen (upper panel) and under HID (lower panel) shown on a portion of the CIE 1931 chromaticity diagram. The diagonal line at the upper right of each panel is a section of the spectrum locus, and attached to it is the FHWA box for red sign chromaticities in daylight.

Effects of material, age, and direction

For the purposes of this study, the total range of chromaticity for stop signs under tungsten-halogen headlamps is the most important result. Nevertheless, the details of how that variation in chromaticity is related to the stratification variables (grade of material, age, and compass direction) are of some interest. Figures 4, 5, and 6 show the same data as in Figure 3, but distinguished by material, age, and direction, respectively.

Inspection of Figure 4 suggests that there is an effect of material, such that the chromaticities for enclosed-material signs are on average further to the left of and above the encapsulated-material signs, and the encapsulated-material signs are on average above the microprism-material signs. These effects are generally consistent with what would be expected if the enclosed material faded more than the encapsulated, and the encapsulated faded more than the microprism. We performed univariate analyses of variance for the x and y values for each lamp type separately, and also a multivariate analysis of variance, using Wilks' lambda (Pedhazur, 1982, chap. 17, 18), for four variables together: x and y under tungsten-halogen illumination and x and y under HID illumination. The multivariate analysis is appropriate in this case because effects on chromaticity will not generally be reflected in either x or y alone, but rather in a combination of x and y values. In this case the results of the univariate and multivariate analyses are consistent, and both confirm that chromaticities are different for the different materials. When the signs are illuminated by tungsten-halogen lamps, the effects of material type on x and y individually are both significant: $F(2,15) = 4.68$, $p = .026$ for the effect on x, and $F(2,15) = 7.78$, $p = .0048$ for the effect on y. When the signs are illuminated by HID lamps the results are similar, but the effect of material on x alone misses significance, $F(2,15) = 2.13$, $p = .15$. The effect on y alone is significant, $F(2,15) = 5.78$, $p = .014$. The multivariate analysis shows a significant effect of material on the combination of all four variables, $F(8,24) = 2.90$, $p = .021$.

Figure 5 suggests that there is also an effect of age on chromaticity, with the older signs appearing generally to the left of and above the newer signs under tungsten-halogen illumination, and to the left under HID illumination. This is consistent with greater fading for the older signs. The effects on individual variables are not quite significant for the tungsten-halogen data. Individual tests for x and y are marginally nonsignificant: $F(1,15) = 3.40$, $p = .085$, and $F(1,15) = 4.29$, $p = .056$ for x and y, respectively. In the HID data, the individual effect on x is significant, $F(1,15) = 7.51$, $p = .015$, but the individual effect on y is not, $F(1,15) = 0.78$, $p = .39$. The multivariate analysis shows a significant effect of age, $F(4,12) = 3.90$, $p = .030$.

Inspection of Figure 6 indicates that there is not a marked effect of the compass direction in which the legend side of the sign is facing. Although there is a slight tendency for the south-facing signs to be above or to the left of the north-facing signs, there is considerable overlap between the two distributions of chromaticities. Statistical analysis also indicates that there is little evidence for an effect. For the tungsten-halogen data, both of the individual analyses are nonsignificant: $F(1,15) = .005$, $p = .94$, and $F(1,15) = 0.258$, $p = .62$, for x and y, respectively. The same is true for the HID data: $F(1,15) = 1.16$, $p = .30$, and $F(1,15) = 0.099$, $p = .76$, for x and y, respectively. The multivariate analysis also shows no evidence for a main effect of direction, $F(4,12) = 0.995$, $p = .45$.

Figure 7 illustrates that a large portion of the variation in chromaticity seems to be attributable to a particular combination of material, age, and compass direction. For both the tungsten-halogen data and the HID data, most of the chromaticities at the upper left of the distributions are for enclosed-material, older, and south-facing signs. This is consistent with our expectations, because we expected all of those conditions to be conducive to fading. The enclosed material is the lowest of the three grades, and longer time in service as well as facing toward the south should both entail greater exposure to the sun.

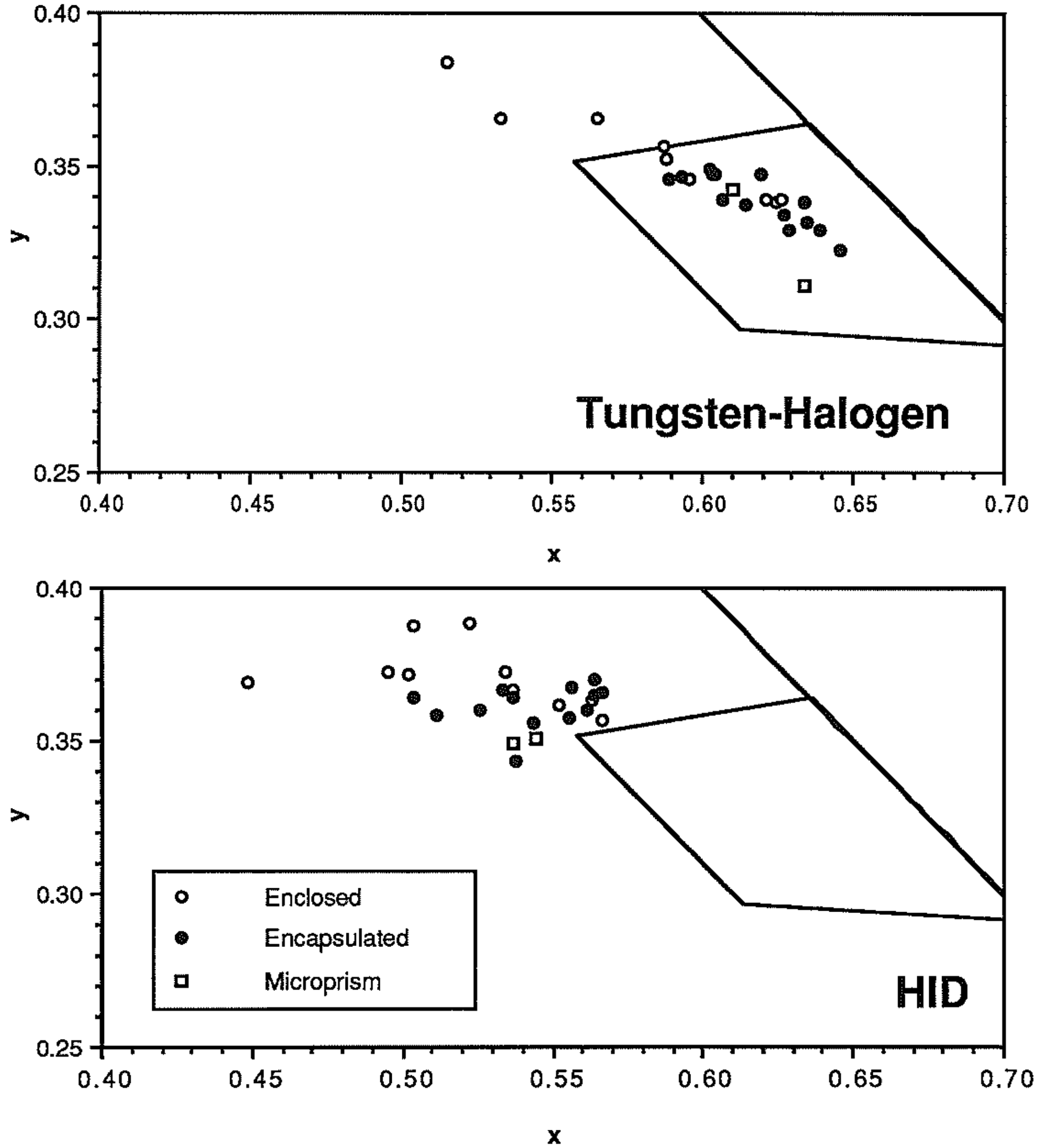

Figure 4. Chromaticities of the 25 signs under tungsten-halogen (upper panel) and HID (lower panel) illumination, stratified by grade of sign material.

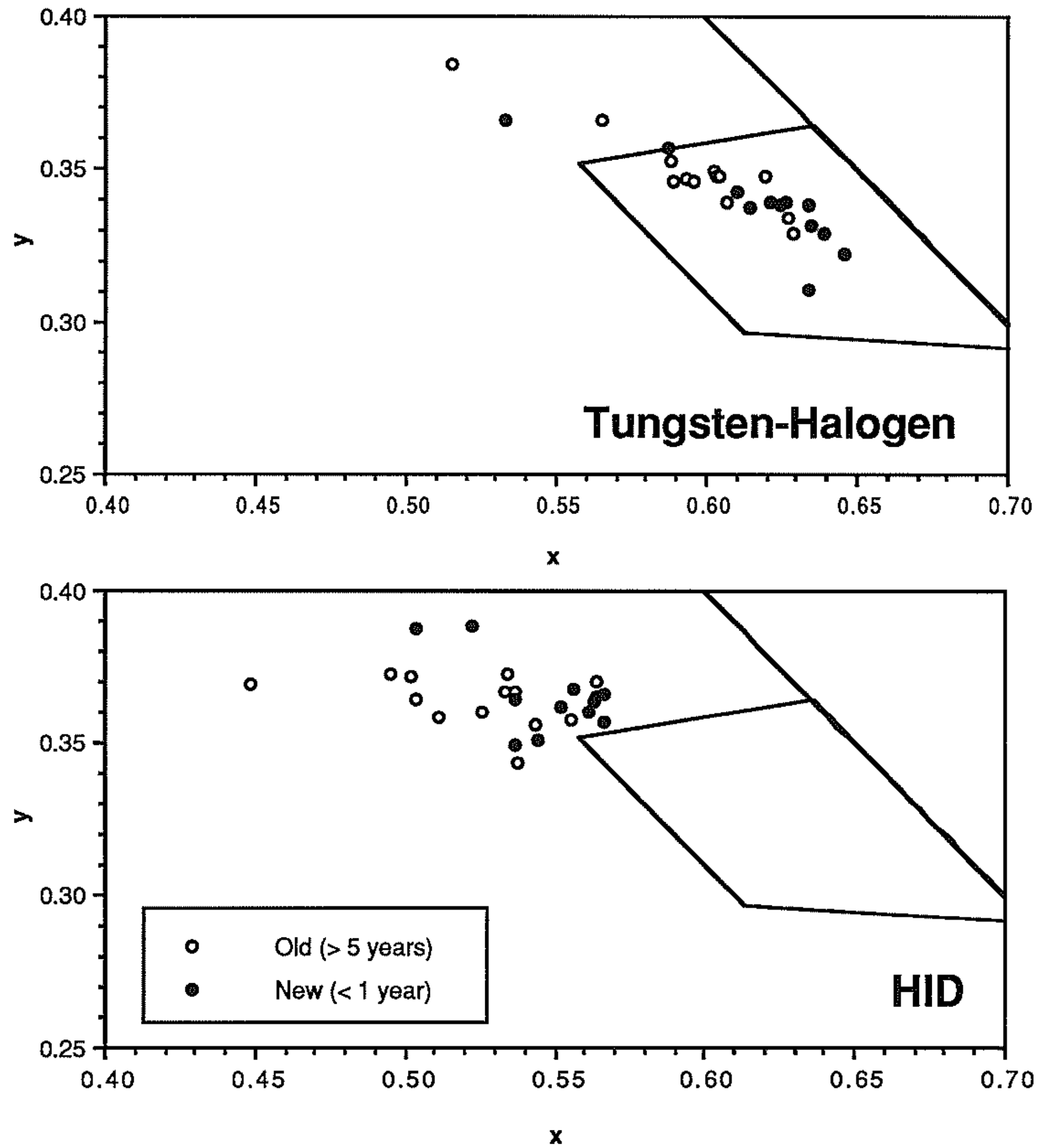

Figure 5. Chromaticities of the 25 signs under tungsten-halogen (upper panel) and HID (lower panel) illumination, stratified by age.

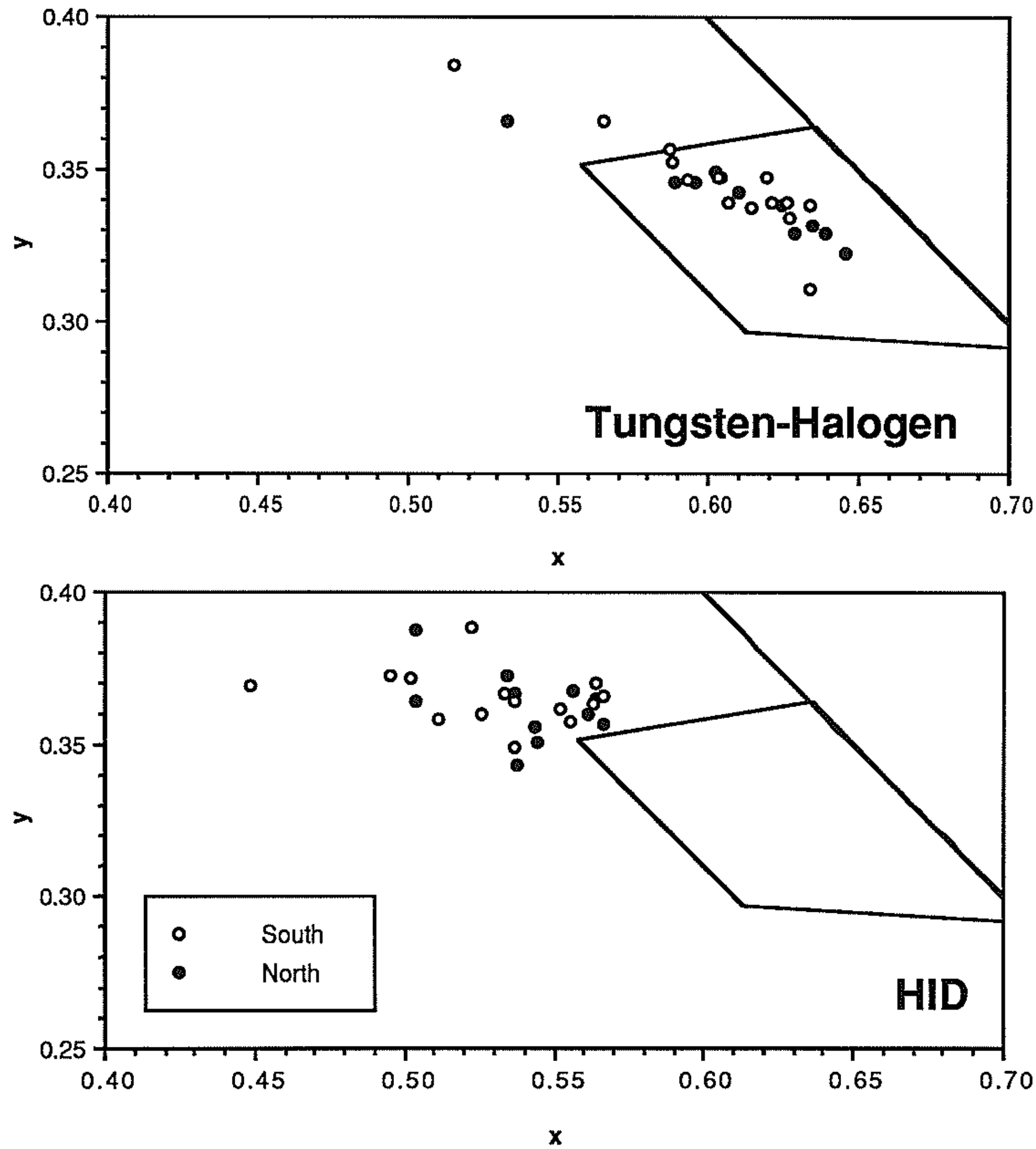

Figure 6. Chromaticities of the 25 signs under tungsten-halogen (upper panel) and HID (lower panel) illumination, stratified by the direction faced by the legend side of the sign.

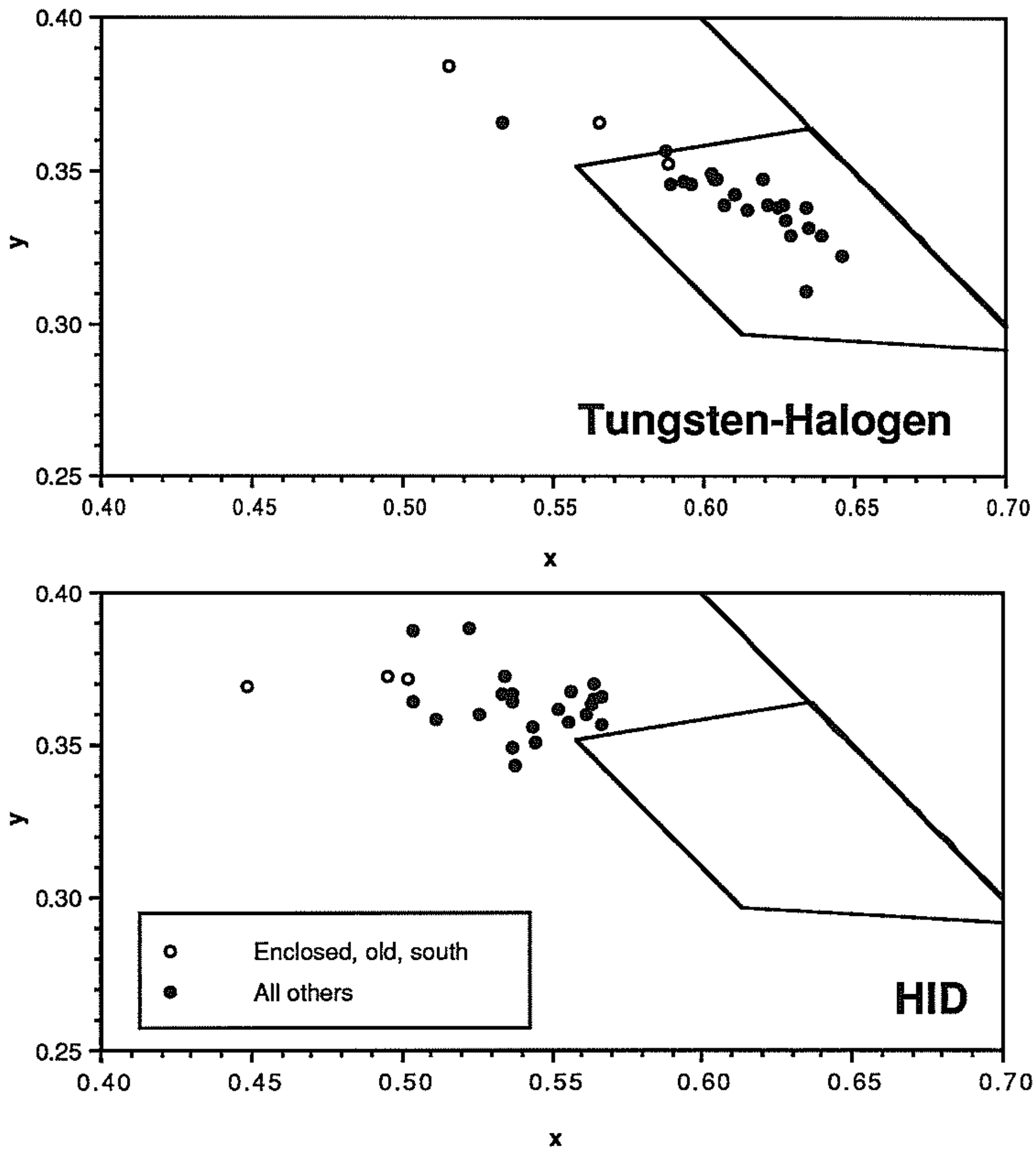

Figure 7. Chromaticities of the 25 signs under tungsten-halogen (upper panel) and HID (lower panel) illumination; distinguishing enclosed, old, south-facing signs from all others.

SUMMARY AND CONCLUSIONS

This study compared the magnitudes of the shifts in chromaticity of stop signs illuminated by HID and tungsten-halogen headlamps to the range of chromaticities of stop signs under tungsten-halogen. If the shifts in chromaticity between the two sources had been small relative to the tungsten-halogen range, we would have felt confident in concluding that there could not be a significant problem with color rendering. However, the shift is actually about equal to the tungsten-halogen range. This outcome does not allow us to make strong conclusions either way about the possibility of a problem with rendering of stop sign color by HID lamps. Although the results do not rule out the possibility of a problem with color rendering, neither are they in themselves evidence that there is a problem. The relative size of the chromaticity shift between tungsten-halogen and HID illumination was moderate, and even if it had been very large, that in itself would only suggest that people would probably notice the shift, not that their ability to recognize stop signs would necessarily be impaired by it.

REFERENCES

Pedhazur, E. J. (1982). *Multiple regression in behavioral research: Explanation and prediction* (2nd ed.). Fort Worth, Texas: Holt, Rinehart and Winston.

Sivak, M., Flannagan, M., Gellatly, A. W., & 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, Michigan: The University of Michigan Transportation Research Institute.

Sivak, M., Simmons, C. J., & Flannagan, M. (1991). Colours of retroreflective sign materials when illuminated by high-intensity-discharge headlamps. *International Journal of Vehicle Design, 12*, 284-295.

Wyszecki, G., & Stiles, W. S. (1982). *Color science: Concepts and methods, quantitative data and formulae* (2nd ed.). New York: Wiley.