Evaluation of light-emitting diodes for signage applications

Jean Paul Freyssinier, Yutao Zhou, Vasudha Ramamurthy, Andrew Bierman, John D. Bullough and Nadarajah Narendran

Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180
www.lrc.rpi.edu

Freyssinier, J.P., Y. Zhou, V. Ramamurthy, A. Bierman, J.D. Bullough, and N. Narendran. 2004. Evaluation of light-emitting diodes for signage applications. *Third International Conference on Solid State Lighting, Proceedings of SPIE* 5187: 309-317.

Evaluation of Light-Emitting Diodes for Signage Applications

Jean Paul Freyssinier, Yutao Zhou, Vasudha Ramamurthy, Andrew Bierman,
John D. Bullough and Nadarajah Narendran
Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180

ABSTRACT

This paper outlines two parts of a study designed to evaluate the use of light-emitting diodes (LEDs) in channel-letter signs. The first part of the study evaluated the system performance of red LED signs and white LED signs against reference neon and cold-cathode signs. The results show a large difference between the actual performance and potential savings from red and white LEDs. Depending on the configuration, a red LED sign could use 20% to 60% less power than a neon sign at the same light output. The light output of the brightest white LED sign tested was 15% lower than the cold-cathode reference, but its power was 53% higher. It appears from this study that the most efficient white LED system is still 40% less efficient than the cold-cathode system tested. One area that offers a great potential for further energy savings is the acrylic diffuser of the signs. The acrylic diffusers measured absorb between 60% and 66% of the light output produced by the sign.

Qualitative factors are also known to play an important role in signage systems. One of the largest issues with any new lighting technology is its acceptance by the end user. Consistency of light output and color among LEDs, even from the same manufacturing batch, and over time, are two of the major issues that also could affect the advantages of LEDs for signage applications. To evaluate different signage products and to identify the suitability of LEDs for this application, it is important to establish a criterion for brightness uniformity. Building upon this information, the second part of the study used human factors evaluations to determine a brightness-uniformity criterion for channel-letter signs. The results show that the contrast modulation between bright and dark areas within a sign seems to elicit the strongest effect on how people perceive uniformity. A strong monotonic relationship between modulation and acceptability was found in this evaluation. The effect of contrast seems to be stronger than that of spatial frequency or background luminance, particularly for contrast modulation values of less than 0.20 or greater than 0.60. A sign with luminance variations of less than 20% would be accepted by at least 80% of the population in any given context.

Keywords: LED, channel letter, sign, fluorescent, neon, cold cathode, backlit, illuminated

1. INTRODUCTION

The size of the electric signage industry was estimated at approximately $2 billion per year in 1997,[1] making it an attractive market for LED manufacturers and energy savings advocates. With the advent of new materials and manufacturing processes in recent years, LEDs have increased in brightness and now have increased efficacy compared with incandescent lamps.[2, 3, 4] Additionally, a greater variety of colors now available, including white, opened a new realm of applications for LEDs such as commercial channel-letter signs. In trying to expedite the penetration of LEDs into the signage market, the lighting industry has extrapolated from some of the very successful applications of colored LEDs – e.g., traffic and exit signs, and high-mounted stop lights in vehicles – to claim similar results for red and white channel-letter systems. Neon and fluorescent lamps are the two most commonly used light sources in this application, but it has been shown that there is a large potential and interest for their replacement by LEDs to attain energy and maintenance savings. However, the literature lacks research comparing the performance of LED systems to that of neon and fluorescent systems.

Although LEDs pose potential benefits for signage applications, their initial benefits need to be maintained over time before a fair comparison to neon or fluorescent lamps can be made. For example, one of the most publicized characteristics of LEDs has been their long life, often claimed to be up to 100,000 hours. However, it has been shown that the light output can diminish rapidly over time, particularly for phosphor-based, indicator-type white LEDs, and that light output is dependent on a series of factors including drive current, temperature, and humidity.[5, 6, 7, 8] As a result, there is a need for a series of metrics to consistently evaluate the life and efficiency of LED systems. Such metrics could develop into a quality- and performance-labeling program for channel-letter signs, e.g., Energy Star®. In addition to these metrics, qualitative factors play a role in signage systems. One of the largest issues with any new lighting technology is its acceptance by the end user. Consistency of light output and color among LEDs, even from the same manufacturing batch, and over time, are two of the major issues that also could affect the advantages of LEDs for signage applications. Presently, there are no brightness uniformity standards for signage. To evaluate different signage products and identify the suitability of LEDs for this application, it is important to establish a criterion for brightness uniformity. The discrete nature of LEDs could potentially create non-uniformities if their number or positioning is not carefully considered. LED arrays operating at different temperatures or having different rates of depreciation could also cause non-uniformities. Depending on the context, a sign with increasing degrees of non-uniformity could be, at some point in time, deemed no longer acceptable. In this sense, the brightness uniformity of a sign could be used, in addition to light output, to define the useful life of a sign.

Based on these needs, the goals of this study was to further the understanding of LEDs as they pertain to channel-letter signage systems and to develop a set of tools to help optimize these signs for efficiency and acceptability. The tasks included a system performance evaluation and a study of brightness uniformity subjective perception.

2. SYSTEM PERFORMANCE EVALUATION

The objective of the system performance evaluation was to compare the electrical, photometric, and thermal characteristics of the LED signs against neon and cold-cathode fluorescent references in order to document potential energy savings. The scope of this task was limited to the measurement and analysis of parameters such as power (P), current (I), voltage (V), power factor (PF), relative light output (LO), temperature (T) inside the signs, and spectral transmittance of the acrylic diffusers.

2.1 Methods

A total of 13 signs were tested in two colors: 7 red (neon plus 6 different manufacturers of LEDs) and 6 white (cold-cathode plus 5 different manufacturers of LEDs) signs. The signs were prepared by an independent neon shop following typical manufacturing practices for the neon signs and manufacturer recommendations for the LED signs. All had the same 24-inch nominal height and represented the same character (uppercase G).

Figure 1 shows a schematic diagram of the measurement equipment setup for the evaluation. The evaluation was conducted inside a 12 ft. by 9 ft., temperature-controlled room. The ambient temperature was set at 25±1 ºC. All major surfaces in the room were covered with a black matte cloth to minimize the effects of stray light and inter-reflection. A data acquisition system formed with two computers collected the data in a systematic and consistent manner. One computer, connected to a spectroradiometer, monitored the spectral power distribution of the signs. The second computer received the data from a power analyzer (P, I, V, PF), a photometrically corrected [$V(\lambda)$] sensor (LO), and nine thermocouples (T). Eight thermocouples were uniformly distributed inside the sign under measurement while the other one monitored the room's ambient temperature. A rack built for this experiment kept the relative geometry among the spectroradiometer, the photosensor, and the sign being measured constant.

All electrical and thermal measurements had a sampling rate of 15 seconds; therefore, 4 measurements were taken per minute. Measurements were taken from the moment the signs were switched on, but only the last five sampled measurements of a 90-minute period were used for the analysis. The rest of the measurements were used to monitor the behavior of the different signs under test and to confirm that they had reached photometric and thermal stabilization.

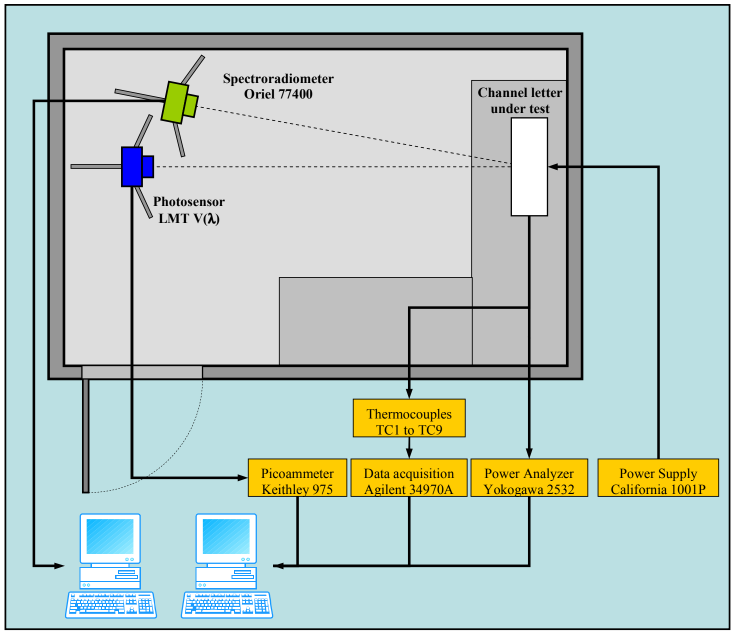
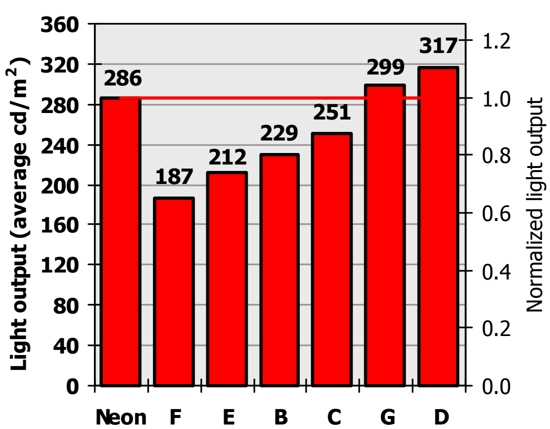


Figure 1. Schematic of the equipment used for the evaluation. Two computers collected the data systematically. The first controlled the spectroradiometer; the second controlled the LMT photosensor, the thermocouples, and the power analyzer.

2.2 Results

2.2.1 Light output and power

The graphs in Figures 2 and 3 show the average light output and power, respectively, for all red and white signs tested. These figures show the large differences in the light output and the power of the signs measured. Therefore, to make the comparison between signs of the same color meaningful, calculations were used to equate the light output of the LED signs to that of their respective reference. It should be noted that light output was defined as the average luminance (cd/m^2) of the sign for reference only. It is not intended to characterize fully, nor to provide further information on the brightness uniformity of the signs, nor their absolute light output (in lumens), nor their absolute brightness (as perceived by people). These calculations assume that the efficacy and power factor remain constant, and that the power of each sign could be increased or decreased linearly to reach the reference light output. The scaled power for equal light output is plotted in Figure 4.



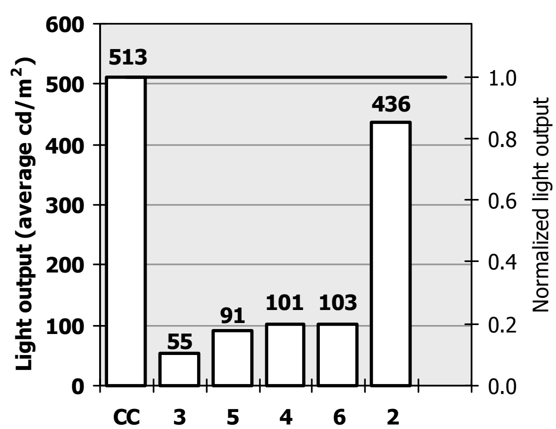


Figure 2. Measured light output of all **RED** (left) and **WHITE** (right) signs tested. Each value is the average of five measurements at the end of the 90-minute stabilization period. The references for normalization (secondary axis) are the neon sign (for **RED**) and the cold-cathode sign (for **WHITE**).

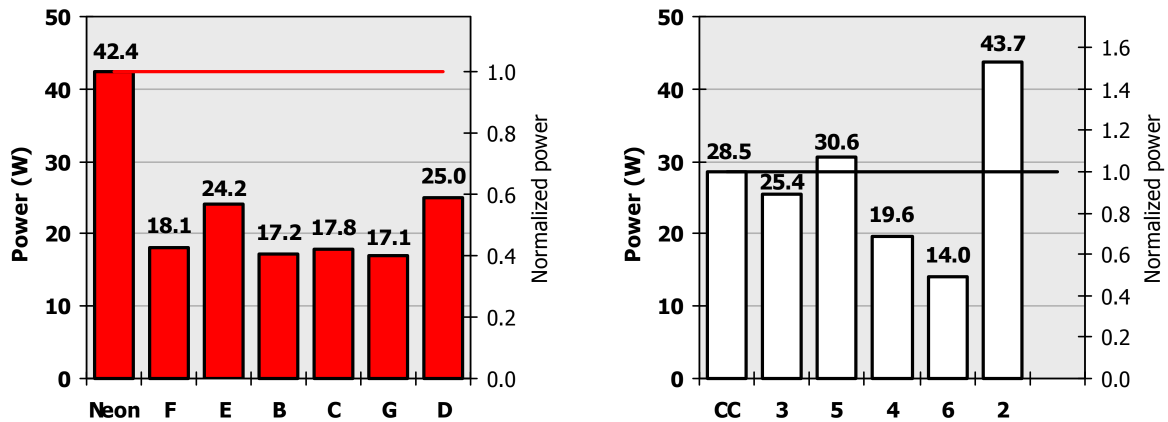


Figure 3. Measured power of all **RED** (left) and **WHITE** (right) signs tested. Each value is the average of five measurements at the end of the 90-minute stabilization period. The references for normalization (secondary axis) are the neon sign (for **RED**) and the cold-cathode sign (for **WHITE**).

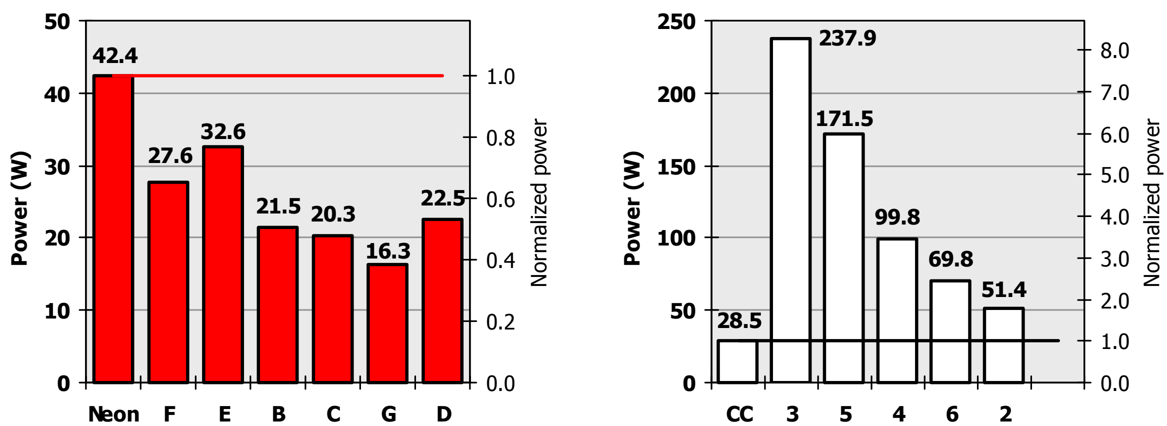


Figure 4. Scaled power of all LED signs for equal light output as the neon (for **RED,** left) and cold-cathode (for **WHITE,** right). The references for normalization (secondary axis) are the neon sign (for **RED**) and the cold-cathode sign (for **WHITE**).

2.2.2 Temperature

At the end of the testing period, the average temperature of the red neon sign had increased by 9.63°C. The increase of the average temperature of the six red LED signs ranged from 0.63°C to 4.61°C. For the white signs, the average temperature of the neon sign increased by 4.27°C, while the increase of the average temperature of the five LED signs ranged from 1.57°C to 6.58°C.

2.2.3 Transmittance of the acrylic diffusers

The measured relative spectral transmittance of the diffusers, the spectral power distribution of the neon and cold-cathode lamps, and the photopic [V(λ)] luminous efficiency function are shown in Figure 5.

As can be seen in Figure 5, the average transmittance of the acrylic diffusers is extremely low. The average reduction in light output due to the diffusers was calculated at 66% for the neon sign and at 59% for the red LED signs. In the case of the white signs, the average reduction in light output was calculated at 60% for both the cold-cathode and the LED signs.

2.2.4 Color variations

An additional issue is the color difference among LED manufacturers. The CIE color chromaticity coordinates of the different red and white LED signs exhibit differences among signs larger than 4-step MacAdam ellipses when compared to their references.

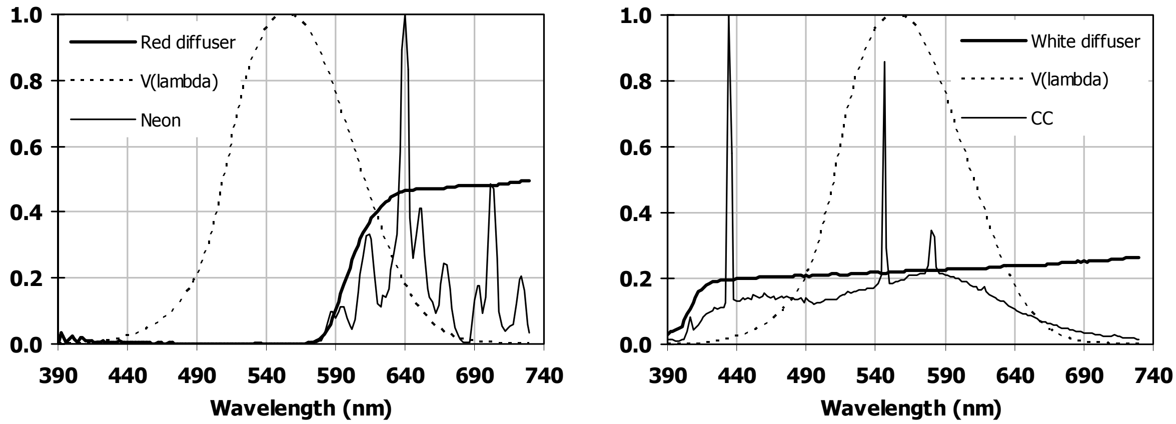


Figure 5. Relative spectral transmittance of the red (left) and white (right) acrylic diffusers, and spectral power distribution of the neon (left) and cold-cathode (right) lamps.

2.3 Discussion

As expected, a large difference exists between the performance and potential savings from red and white LEDs. While only two of the red LED signs had a slightly higher light output than the reference (+5%, +11%), the power consumed by all of them was at least 42% lower. The potential in connected load savings ranges from approximately 42% to 60% (Figure 2). Because there are no current standards for how high the luminance of a sign should be, sign manufacturers may want to equal the light output of the LED signs to that of neon. Therefore, depending on the configuration, a red LED sign could still use 20% to 60% less connected load than a neon sign (Figure 3). The light output of the brightest white LED sign was 15% lower than the cold-cathode reference but its connected load was 53% higher. The other signs produced between 10% and 20% of the cold-cathode light output, while their connected load was only 11% to 51% less, and in one case, 7% higher than neon. The efficacy of the white LED signs was 44% to 88% lower than the reference.

Temperature increase inside the sign was not an issue for any of the red LED configurations, since it was less than 5°C. Because the signs were manufactured according to standard practice or recommendations, some had the power supplies or drivers inside the sign, while others were installed remotely. This fact, along with the difference in the number of LED modules, could explain the variation among systems, although it did not appear to negatively impact the performance of the signs in either case. While the absolute increase in temperature inside the white LED signs may not be objectionable, it was, with the exception of one sign, higher than that of the red signs. In two cases, the average increase inside the sign was higher than the reference. Different configurations or heat sinking may be needed for white LED signs to diminish any potential problem with temperature build-up, especially when trying to equal the light output of cold-cathode signs.

One area that offers significant potential for further energy savings is the acrylic diffuser of the signs. Use of materials with lower transmission losses will result in attractive energy savings. For white LED signs, other issues such as non-uniformities in luminance and color between individual LED modules should be considered [9] before a decision can be made regarding the number and location of the LED modules.

A potential limitation of this study is the small number of samples tested, which might not be representative of the respective technology that each sample uses. Based on information from the manufacturers and with further testing, the variability of a neon system's efficiency could be shown to be greater than 100%. Different types of transformers, the inherent variability of neon tubes that are processed by hand, and other factors yield large differences from sign to sign and from manufacturer to manufacturer. A similar variability can be expected from LED drivers and power supplies, depending on the configuration and number of LEDs operated. Additionally, it is worth mentioning that all these measurements are initial values and that all systems are expected to depreciate at different rates.

The collected data support the conclusion that red LED channel-letters based on current technologies are much more efficacious than conventional neon channel-letters. As seen in this preliminary evaluation, the best product has the potential to save approximately 60% of connected load compared with the neon sign tested. Red LED channel-letter systems could probably be easily optimized to provide more than 80% energy savings in the near future. However, issues that need to be addressed in order to achieve such energy savings include improved drivers for LEDs, a better match between LED emission wavelength and the transmission characteristics of the red acrylic front face, better optics to direct light, dedicated photocells or dimmer controls, and standardized luminous requirements. Conversely, the data collected shows that white LED channel letters are not as efficient as cold-cathode at the present time. It appears from this study that the best white LED system is still 40% less efficient than the cold-cathode system tested. This is not surprising since white LED technology is still under development. However, it is expected that white LED signs can eventually be made more efficient than neon signs. Achieving 50% energy savings with white LED systems is a reasonable goal. To reach this goal some issues need to be addressed. First of all, the white LED systems evaluated use phosphor-based LEDs. The use of RGB white LEDs would likely have shown the LED channel letters to be comparable to white neon in terms of energy use. This is because RGB white LEDs offer twice the efficacy of phosphor-based LEDs. The remaining issues are similar to those relating to the red LED systems.

3. BRIGHTNESS-UNIFORMITY PERCEPTION

Two human factors experiments were conducted for the evaluation of the perception of brightness uniformity. The first one was designed to determine the threshold for just-noticeable differences and is described in detail in Ramamurthy *et al.* (2003).[10] The second experiment was designed to determine a criterion of uniformity that could be used to predict the acceptable brightness uniformity of signs for retail applications.

3.1 Experimental design, setup, and procedure

It was determined that the three most important variables affecting the perception of brightness uniformity were contrast, spatial frequency, and luminance of the background. A channel-letter sign representing the uppercase character G was modified to provide experimental conditions for which the aforementioned variables could be controlled independently. The sign was divided internally into six sections of nominally the same area. The brightness of each section was controlled independently to provide different groupings (spatial frequency) and different degrees of uniformity (contrast). The sign was presented to subjects at background luminance values of 1 cd/m^2 and 100 cd/m^2. The range of spatial frequencies (0.09 to 9.0 cycles per degree) tested was achieved by combining the viewing distance (10', 30', 60' and 340') and the number of independent sections of the apparatus used to create non-uniformities. The six sections of the apparatus were combined into three patterns: SPF1 (six small sections), SPF2 (three large sections), and SPF3 (two larger sections) (Figure 6). See Ramamurthy *et al.* (2003)[10] for a complete description of the apparatus and experimental conditions.

Figure 6. Reference conditions for each pattern: SPF1 (left), SPF2 (middle) and SPF3 (right). The contrast modulation value of these conditions was calculated at 0.70, 0.90 and 1.0, respectively.

Each pattern had ten equally spaced values of contrast modulation measured by the ratio of the difference of average luminance of two adjacent sections to the sum of these two values. For a completely uniform sign, the modulation was equal to zero, while for a sign with alternated sections turned on and off the modulation approached unity. Given the limitations of the apparatus, the maximum achievable non-uniformity for each pattern was different – 0.70, 0.90 and approximately 1.00, for SPF1, SPF2 and SPF3, respectively . However, comparable conditions between patterns were nominally the same. The combination of three patterns and ten modulation values yielded thirty possible conditions. Each one of these conditions was presented three times in random order to each subject to avoid spurious responses. The conditions were presented at four distances and at two different background luminance values (1 cd/m^2 and 100 cd/m^2) for a total of 720 experimental presentations per subject.

The experiments took place inside a dark photometry laboratory (for viewing distances of 10', 30', and 60'), and in a parking lot for the viewing distance of 340'. The main lighting system for the parking lot was turned off during the experimentation to replicate laboratory conditions. Although some of the street lighting could not be controlled, the ambient conditions were similar to those inside the laboratory. Sixteen subjects participated in the experiment and were asked to imagine that while approaching a store, they glanced at the store sign for about 1.5 seconds. After this period of time, the sign was turned off and the subjects were expected to answer whether the overall brightness uniformity of the sign was acceptable or not within that context.

3.2 Results

The subjective responses were used to calculate the percentage of times that each condition was considered acceptable, on a base of 48 independent presentations. Figure 7 shows the results for all patterns and modulation values at all distances.

3.3 Discussion

Contrast modulation seems to elicit the strongest effect on how people perceive uniformity. There is a strong monotonic relationship between modulation and uniformity acceptability. From the two pairs of conditions with the same spatial frequency (SPF1-10' and SPF3-30'; SPF1-30' and SPF2-60'), it could be inferred that as the number of non-uniform segments increases, the acceptability rating decreases. This could also mean that the number of the non-uniformities could be more important than their visual size. This conclusion is consistent with the results described by Ramamurthy *et al.* (2003)[10] for detectability of contrast.

The effect of contrast seems to be stronger than that of spatial frequency or background luminance, particularly for contrast modulation values of less than 0.20 or greater than 0.60. As expected, for the same background luminance, subjective acceptability increased with distance. In other words, the longer the viewing distance, the more uniform the sign appears to be. Also as expected, for the same viewing distance the sensitivity to uniformity increased with background luminance. In other words, the non-uniformities of a sign become more apparent when the background luminance increases. Acceptability ratings are higher for longer viewing distances at the same background luminance, and are lower for the bright background for the same viewing distance.

The results of the acceptability ratings are important because, for all practical purposes, the design of a given sign should be based on this criterion. From these results we can determine the required contrast modulation needed for a sign to be acceptable to a given percentage of the population. For example, a proposed value of 80% would require a sign to be within 0.20 and 0.60, which concurs with the estimated uniformity rating of a neon sign. Additionally, this range could be further refined depending on the estimated viewing distance, background luminance, and type of potential non-uniformities.

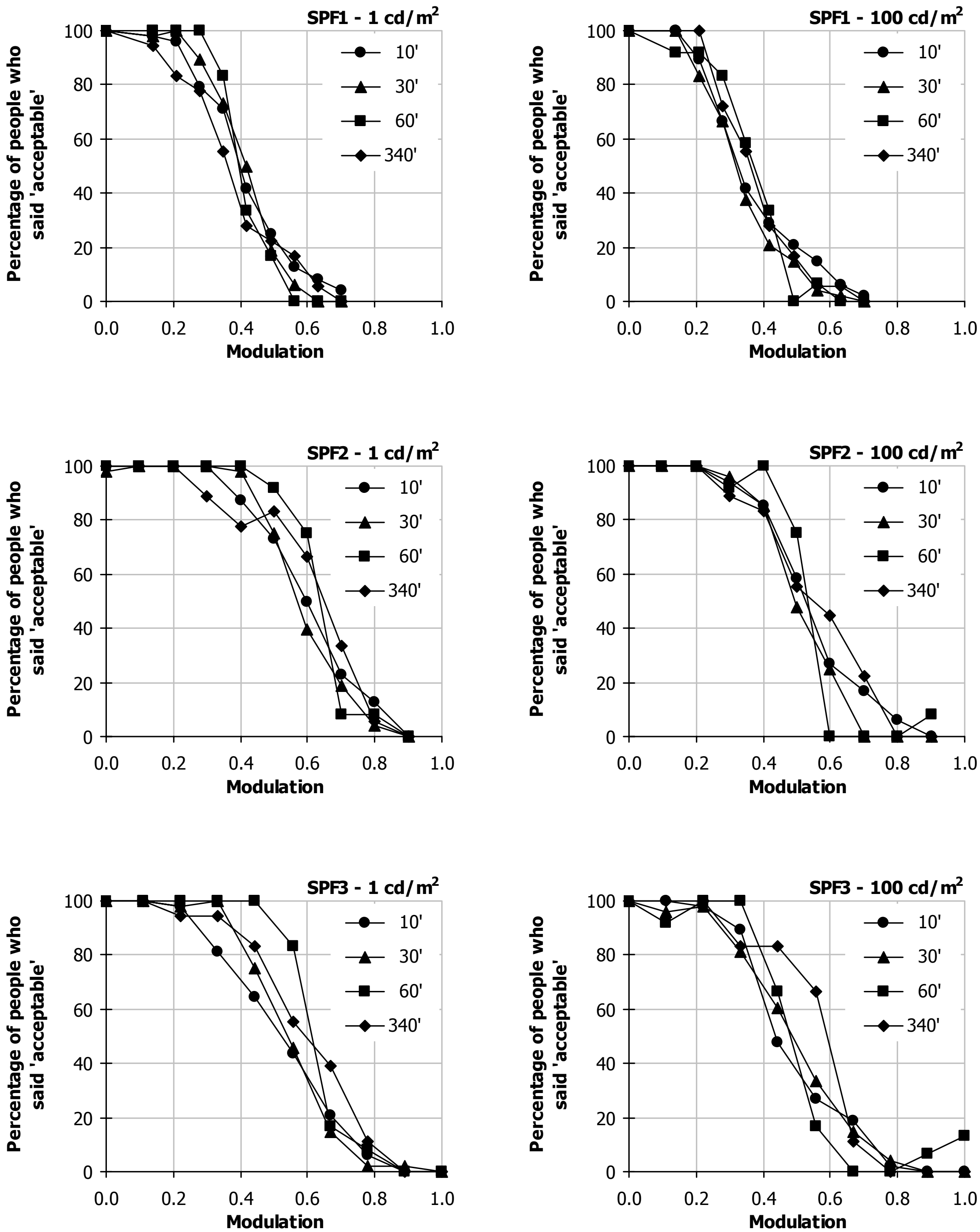


Figure 7. Acceptability rating (percent) for each condition, based on 48 answers from 16 subjects for patterns SPF1 (top), SPF2 (middle) and SPF3 (bottom) at four viewing distances (10’, 30’, 60’, 340’) for background luminances of 1 cd/m^2 (left) and 100 cd/m^2 (right).

4. CONCLUSIONS AND RECOMMENDATIONS

Given the lack of standards for measuring the brightness of signs, the overall average luminance could be used to estimate light output and efficacy of channel-letter systems representing alphanumeric characters. Based on the results of these experiments, it can be concluded that all red LED systems evaluated are more efficacious than red neon. All of the white LED signs evaluated had lower light output and efficacy values than that of the white cold-cathode sign. Only LED systems providing efficacies above 10 $cd/m^2/W$ should be considered for signs if the evaluation criterion is energy efficiency. A sign with luminance variations of less than 20% within the sign would be accepted by at least 80% of the population in any given context.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the sponsor of this project. Richard Pysar, Martin Overington, Terri Ondek, Yimin Gu, Claudia Hunter, and Jennifer Fullam of the LRC are thanked for their valuable input. Jennifer Taylor of the LRC is thanked for her help in preparing this manuscript.

REFERENCES

1. U.S. Census Bureau, 1999. Sign manufacturing. 1997 Economic Census, Manufacturing; Industry Series. U.S. Department of Commerce. Publication EC97M - 3399L.
2. Nakamura, S., 1999. Present status of InGaN-based UV/blue/green LEDs and laser diodes. *Advances in solid state physics* 38: 1-14.
3. Bierman, A., 1998. LEDs: from indicators to illumination? *Lighting Futures*, Vol. 3 Issue 4.
4. Stringfellow, G. B. and M. G. Craford (eds.). 1997. *High brightness light emitting diodes*. San Diego, CA: Academic Press.
5. Bullough, J. D. 2003. *Lighting Answers: Light Emitting Diode Lighting Systems*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.
6. Narendran, N. and J. D. Bullough. 2001. Light emitting diodes as light sources. *Proceedings of the 9th International Symposium on the Science and Technology of Light Sources* (pp. 329-336), Ithaca, NY, August 12-16. Ithaca, NY: Cornell University Press.
7. Narendran, N. and L. Deng, 2002. Performance characteristics of light emitting diodes, *Proceedings IESNA Annual Conference Technical Papers* (2002): 157-164.
8. Narendran, N., Bullough, J. D., Maliyagoda, N., and A. Bierman, 2001. What is the useful life for white light LEDs? *Journal of the Illuminating Engineering Society 30*, no. 1 (2001): 57-67.
9. Rizzo, P., Bierman, A. and M. S. Rea, 2002. Color and brightness discrimination of white LEDs. *Solid State Lighting II. Proceedings of the SPIE*, Volume 4776, pp. 235-246 (2002).
10. Ramamurthy, V., Freyssinier, J. P., Narendran, N., Bierman, A., Raghavan, R., and P. Boyce, 2003. Spatial contrast sensitivity for highly saturated monochromatic gratings. *Third International Conference on Solid State Lighting, Proceedings of SPIE*, Ferguson, I.T., Narendran, N., DenBaars, S.P., Carrano, J.C., editors, Vol. 5187, International Society for Optical Engineering, San Diego, Calif., Aug. 5-7, 2003 (in press).