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Authors
Cohn, Theodore E.
Greenhouse, Daniel
Knowles, Richard

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Theodore E. Cohn, Daniel Greenhouse, Richard Knowles
University of California, Berkeley

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ALTERNATIVE TRAFFIC SIGNAL ILLUMINATION

THEODORE E. COHN, PhD
Professor of Vision Science
DANIEL GREENHOUSE, PhD
Assistant Research Scientist
RICHARD KNOWLES, B.S.
Development Technician

Visual Detection Laborabory
School of Optometry and Institute for Transportation Studies
University of California

April 23, 1998

TRAFFIC SIGNAL HUMAN FACTORS STUDY

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ABSTRACT

New technologies have enabled the production of traffic signals that have significant advantages over standard incandescent signals, including greater energy efficiency and lower maintenance costs. Before the new signals are installed in the field, it is important to assure that they as visible as the older signals. We have developed a quality index we term the usability factor (UF) which can be used to evaluate the visibility of a new device relative to that of a standard reference lamp. We have measured UF's of a variety of new types of lamps by means of heterochromatic flicker photometry. We have found UF's ranging from 0.55 to 1.35 for centrally-viewed targets under standardized viewing conditions. We also report measurements made under conditions of reduced visibility. We attribute the wide range of UF's to spatial factors in the distribution of light among the various sources.

Keywords: Traffic Signals, Energy Efficiency, Usability Factors, Flicker Photometry, LED, Human Factors

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Theodore E. Cohn, PhD
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Richard Knowles, B.S.

EXECUTIVE SUMMARY

The research described in the present report was conducted in order to establish the conditions under which the functional equivalence of alternative traffic signal lamps to standard incandescent lamps can be assured, in order that progress be made toward the goal of replacing incandescent fixtures with energy-efficient, lower-maintenance devices. We have developed the concept of a quality index for such devices that we call the usability factor (UF), which relates the visual effect of a test lamp to that of a standard reference lamp. One reason such a quantity is needed is that unusual spatial configurations of some new devices may either enhance or hinder their visibility. The UF is defined, for lamps with matching area, as the ratio of the luminance, measured photometrically, of the reference signal to the luminance of the test signal when both appear equally bright to a human observer. If the UF of a device is greater than unity, then less actual measured illumination would be required to render it as visible as a standard reference light, while a UF less than unity implies more light is necessary. A UF of unity implies that photometric measures alone would suffice to assess a lamp's visibility. Using a custom-built heterochromatic flicker photometer, we have determined UF's for a variety of alternative technology lamps, including LED, neon, and fiber-optic incandescent devices. We have also considered how the UF may be affected under certain reduced visibility conditions, such as sun glare, sun phantom, fog, or vision anomalies.

Using normally sighted observers, we determined that the UF of a 12" red TsAlInGap LED round device was not significantly different from unity for a directly fixated target, with or without imposed blur (such as one might experience if slightly myopic), or for a target viewed peripherally (when one is looking slightly away from the target). Limited tests with color-defective observers or with aging subjects showed no significant change in the UF. We also could find no significant change of the UF under conditions of glare (such as one might experience when the sun is low in the sky).

With other fixtures we were able to demonstrate UF's different from unity. The orange LED pedestrian head had a UF of 0.92 when fixated directly. The orange neon pedestian head had a UF of 1.35 when viewed directly and even higher with imposed blur or when viewed peripherally, but the actual available illumination from this device was too low to render it a useful alternative to standard pedestrian heads. The orange fiber-optic pedestrian head had a UF of 0.76. The red LED arrow had a UF ranging from 1.09 - 1.15, depending on whether it was viewed directly or peripherally. The red fiber-optic arrow had a very low UF of 0.55. Usability factors that are significantly greater or less than unity can be attributed primarily to various spatial factors in the distribution of light from the various fixtures, such as a punctate appearance in which individual elements are easily discerned.

The measured light output of a new fixture, multiplied by its UF, should meet or exceed minimum acceptance specifications before it is considered a viable alternative to the standard fixture it would replace. The usability factor is a practical quality index which can be used in combination with standard acceptance tests to evaluate the visibility of a new type of traffic signal.

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I. INTRODUCTION

Traffic signals must obey intensity standards as determined by the Institute of Transportation Engineers (ITE). The ITE acceptance standard specifies that the illuminant, when new (and after a brief warm-up period, during which output may change) must satisfy requirements of the "44-point" test. For example, the intensity of a 12” red fixture, as measured 2.5 degrees horizontal and 2.5 degrees vertical (down) from the primary axis, must equal or exceed 399 candelas to achieve acceptance. After acceptance, the output of an illuminant can decline with aging of the lamp and of the fixture housing. The standard incandescent lamp has until recently been the exclusive illuminant for traffic signals. In common practice, these lamps are replaced at regular intervals to assure continued operation of the signal at adequate levels of illumination. The advent of alternative lamp technologies raises the question of whether these new lamps, some of which are designed to serve in the field for many years without maintenance, will provide adequate illumination, both when new and throughout the period of service. The newly proposed ITE warranty standard attempts to address this issue for certain alternative lamps by specifying that the illuminant must equal or exceed 60% of the acceptance level, or 240 candelas, throughout its useful life. The issue of what constitutes an adequate minimum level of illumination is currently being reexamined by research underway elsewhere (NCHRP Project 5-15). This research may lead to a redefinition of acceptance and warranty standards. Meanwhile, there is a need to address the fundmental issue of establishing the conditions under which the functional equivalence of alternative lamps to standard incandescent lamps can be assured. The present project was designed to establish equivalence criteria for a variety of commercially available alternative lamp technologies.

Equivalence could have been determined photometrically, on the assumption that a modern photometer fully emulates human vision and thus suffices to tell when two lamps have equivalent visual effect. Empirical verification of such a prediction, however, is desirable because spectral content and spatial detail differ between different technologies and thus render the assumption untested. The purpose of this study is to ascertain the visibility of various alternative technology traffic signal lamps relative to a standard reference lamp. In making the comparison, we have established a number termed the usability factor (UF), which is defined (for lamps with matching area) as the ratio of the luminance of the reference (incandescent) signal to the luminance of the test (alternative) signal when both appear equally bright ($UF = L_{ref}/L_{test}$, where L_{ref} and L_{test} are the luminances of the reference and test lamps, respectively, at equal brightness). While there is no reason to suppose that the luminances of the reference and test lamps will differ for a normally sighted observer when the subjective brightnesses are equal, and thus that the UF will differ from unity, it is nonetheless important to establish the usability factor empirically to assure that the test lamp provides an acceptable level of illumination.

It must be emphasized that the usability factor compares the visibility of a test lamp to a standard when the luminances are matched. The usability factor does not address the issue of whether the intensity of the test lamp meets ITE minimum specifications. For round signals, the usability factor can be employed in combination with the standard 44-point test of the distribution of luminous intensity to determine whether the test signal meets minimum standards for visibility. For example, if a test lamp is shown to have a UF of 1.03, and the measured intensity (at 2.5 degrees) is 425 candelas, then the equivalent intensity for purposes of comparison to the incandescent standard is 438 candelas. This exceeds the minimum requirement of 399 candelas by 39 candelas, or 9.8%, a quantity we can refer to as the “acceptance margin”. When minimum acceptable levels are later determined by independent research, the UF can be employed to calculate a minimum acceptable level (MAL) of operation, and can thus be used to estimate acceptable degradation.

II
(a). GENERAL METHODS

The method we employed to equate brightnesses of the reference and test lamps is heterochromatic flicker photometry. In this technique, two complete fixtures, containing a reference and a test lamp, respectively, are optically superimposed by use of a beamsplitter, mirrors, and sighting tubes, and then presented to the subject observer in rapid alternation (16 Hz) against a constant surround that adapts the eye to simulated daylight levels. The luminance of each fixture is controlled with neutral density wedges. In all tests the fixtures were placed at a viewing distance of 270 feet, at which distance 12" devices subtend a visual angle of 13 minutes of arc. Lamps were mounted in a standard fixture with backplate present.

In our experiments, the incandescent standard source in the reference channel is set at a fixed luminance, while the luminance of the test lamp is adjusted by the subject until minimum subjective flicker is perceived, at which point a “setting” is achieved. In most of our tests, six subjects are tested, with each subject making seven settings. The median setting for each subject is recorded. The reference channel luminance is then divided by the average of the medians for the six observers to establish the UF of the alternative signal.

Normally, each of our six experienced subjects was asked to make minimum flicker settings under three conditions: (a) fixating a lamp directly, (b) when viewing a lamp peripherally by fixating on a point one degree of visual angle from the center of the lamp, and (c) by central viewing with an imposed +1 diopter blurring lens which degrades the normal observer to an acuity approximating the licensure limit of 20/40. These measurements enable us to estimate usability factors. We also performed measurements to obtain related information on the visual efficacy of the alternative sources. Subjects were also asked to set (d) thresholds for detection (the minimum luminance at which the lamp appears to be on) and (e) color identification (the minimum luminance for which the color of the lamp is distinctly perceived). Exceptions to these procedures for particular lamp evaluations will be noted in the appropriate section.

In our statistical analysis of results, we calculate the standard error of the mean of median settings. The interpretation of this number is as follows: the reported mean plus or minus twice the standard error specifies an interval which would be expected to contain the actual mean 95% of the time that such a determination is made. We then convert the two extreme values of the 95% confidence interval to equivalent usability factors to estimate a UF 95% confidence interval.

(b). ADDITIONAL METHODOLOGICAL CONSIDERATIONS

Line Voltage. All of our tests (except the drive-by field test) were run at a calibrated 117 volt A.C. ±0.1%. Each type of lamp has a characteristic variation with voltage that must be considered in setting acceptance levels and in actual usage. Thus, if the standard specifies one voltage but practice exposes lamps to another, the actual voltage employed (and any variations from it) should be considered when planning to deploy alternative lamps.

Procedure. For each lamp tested, the reference channel was set at a fixed luminance of the highest value that was consistent with the requirments of our experimental procedure. Flicker photometry requires the interposition of a beamsplitter and neutral density filters, and requires that the luminance of the test lamp be adjustable to levels both above and below that of the reference channel. This required that the reference luminance be set below the acceptance standard. This, however, does not diminish the applicability of the results because the UF, or relationship between luminances of the two lamps when they appear equally bright, would be expected to be a constant throughout the photopic range of vision and is thus independent of the level at which it is determined. We have verified this independence in the case of LED lamps with a visual comparison of the incandescent and LED lamps. We set the LED at maximum intensity and the incandescent slightly attenuated to achieve equal brightness (according the calculations based on the maximum intensities and the UF), then viewed them side-by-side through a variable neutral density wedge and confirmed that the brightnesses remain subjectively matched at all luminances throughout the 2 log unit range tested.

<u>Luminance measurements</u> were made with a Photo Research 1980A photometer positioned 2.5 degrees down and 2.5 degrees horizontal from the central axis of the fixture lens, the most central position of the "44-point" test. For round signals, we used an aperture that covered approximately 90% of the surface of the lamp, thus integrating over major spatial inhomogeneities such as the incandescent “hot-spot” and the punctate nature of the matrix in the LED lamp. These luminance measurements were also confirmed by an alternative method, in which we employed a larger aperture that extended beyond the target, and then multiplied the reading by the ratio of the projected aperture area to the area of the source. This latter method was employed to measure the luminance of asymmetrically shaped sources such as arrows and pedestrian signals.

<u>Luminous intensity measurements</u> were made with a Photo Research 1980A photometer equipped with a cosine receptor head. The instrument was placed 25’ from the lamp. We used baffling to reduce contributions from room surface reflections, and compensated for any remaining reflected light by measuring it and then subtracting it from the composite reading. At the request of Caltrans, we conducted all experiments, and hence performed all photometry, with the lamps operating at 117 VAC (rms), using a regulated power supply.

It should be noted that these measurement conditions differ from those specified by the ITE 44-point test ("Vehicle Traffic Control Signal Heads", ITE Technical Council Committee 7S-1, ITE Journal, May, 1984). In the latter, the incandescent lamp is always operated at its rated luminance of 1950 lumens, achieved by adjusting the current. Because the output of an incandescent lamp is known to vary approximately as the fourth power of the voltage, small changes in voltage can result in large changes of intensity. While we were unable to measure lumens directly in our laboratory, we have reason to believe that our lamp was producing significantly less than 1950 lumens while operated at 117 VAC. When a nominally identical fixture was measured by Caltrans, using the conditions specified by the ITE 44-point test, the luminance value was found to be approximately 14,000 candelas per square meter. When our fixture was measured in the same Caltrans facility, using 117 VAC (instead of adjusting the current to obtain the rated output of 1950 lumens), a value of 9700 candelas per square meter was determined. This compares with our laboratory measurement of 8060 candelas per square meter.
This difference in measured luminance at the two facilities is the result of differences in measurement technique such as aperture size or target distance, and/or instrument calibration. For example, the central “hot spot” of the incandescent lamp will result in a higher “average” luminance as less and less of the full area of the signal is included in the measurement. In any case, the difference does not affect the value of the usability factor we determined experimentally. The UF is a ratio between luminances of two lamps measured with the same instrument under identical conditions -- it is the relative luminances of the two lamps, rather than their absolute magnitude, which determine the UF.

Our measured luminous intensity of 528 candelas for the standard incandescent fixture is significantly lower than if the lamp had been operated according to the ITE 44-point test specifications, and underestimates the acceptance margin, but does not affect the usability factor.

<u>Photometer accuracy.</u> In order to assess the accuracy of the photopic filter in the Photo Research 1980A photometer, we used a Photo Research 1980B scanning spectroradiometer to independently determine the luminance values of our sources and compare these to the directly measured values. Small corrections were indicated and applied to the data.

General applicability of results. We have tested one sample of each alternative lamp as presented in this report, and we have employed a single incandescent lamp as a reference standard. It must be borne in mind that our results apply solely to the lamps tested. Planners must ensure that other lamps, or other production samples of the same model lamp, have properties that coincide with the tested lamps, or if the properties are different, that the appropriate compensation in usability factor and/or luminous intensity is applied. Planners must also ascertain the extent to which each type of lamp degrades over its proposed life in field use and make appropriate allowances for this degradation.

III. MEASUREMENTS

a). 12" RED LED LAMP

The unattenuated luminance of our sample of 12" red LED lamp was 6300 candelas per square meter (as measured 2.5 degrees down and 2.5 degrees horizontal to the central axis), and of the reference incandescent signal was approximately 8060 candelas per square meter. The measured values of intensity were 410 candelas (LED) and 528 candelas (incandescent)), corresponding to 3% higher (in the case of the former), and 32 % higher (in the case of the latter) than the minimum accepable value prescribed by the 44-point test. However, it should be noted that our intensity measurements, while performed accurately, were made under conditions different than those specified by the 44-point test (see section IIIb). The attenuated luminance of the reference lamp was set at 900 candelas per square meter, as per the considerations outlined in section IIIb.

For this lamp, we began by conducting a pilot with sixty observers (central viewing condition only) to determine if more than six observers were necessary to obtain valid results. We concluded that there was no statistically significant difference between the results for the groups of six and sixty observers and hence conducted subsequent experiments with six observers only.

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE FOR DETECTION	THRESHOLD LUMINANCE FOR COLOR IDENTIFICA-TION	RATIO OF IDENTIFICATIO N THRESHOLD TO DETECTION THREHOLD
1	1032	1056	1204	10.3	33.8	3.3
2	940	971	1020	3.0	5.9	2.0
3	863	797	742	2.9	6.6	2.3
4	843	663	876	10.2	6.4	0.63
5	926	899	843	2.8	10.2	3.6
6	861	893	966	2.9	10.7	3.7
mean	911	880	942	5.3	12.2	
standard. error of the mean	29	56	66	1.5	4.4	
usability factor	0.99	1.02	0.96			
95% confidence range of usability factor	0.93 - 1.06	0.91 - 1.17	0.84 - 1.11			

Table 1. Median settings for six observers. The luminance of the incandescent reference standard was set to 900 candelas per square meter in this experiment.

The usability factor for the red LED lamp, in the central viewing condition, is 0.99. The 95% confidence interval for the usability factor is 0.93 to 1.06 (see section III), and the UF is not significantly different from unity. A planner has a choice of adopting the mean (0.99), or as a conservative approach, the mean minus k*std error where k is chosen to reflect how conservative the choice is to be.

Peripheral viewing gave a slightly higher value of usability factor, consistent with the notion that the spatial inhomogeneity of the incandescent source, with its prominent central “hot-spot”, has decreasing importance in the peripheral viewing situation where visual acuity is diminished. However, we should point out that although the means differ, there is no statistically significant difference between the central and peripheral viewing conditions. We do believe that the peripheral viewing situation has greater relevance to the real-world environment where drivers are not normally looking directly at a traffic signal but in a lower direction, closer to the horizon. It should also be noted that the increase in UF for peripheral viewing cannot necessarily be generalized to other alternative lamps, which may have spectral or spatial characteristics differing from those of the tested LED lamp.

The blur condition gave a lower usability factor, but, again, there was no statistically significant difference between the blur and non-blur conditions.

As one would predict, the detection threshold is less than the identification threshold by approximately a factor of two, and both thresholds are lower than the maximum luminance available by a factor of two orders of magnitude. The mean threshold for detection for the tested LED lamp was 5.3 candelas per square meter, and the mean threshold for color identification was 12.2 candelas per square meter. These values indicate that observers can detect the lamp and correctly identify its color at levels far below the unattenuated luminances of the lamps.

We have measured the intensities of the two types of fixtures at the most extreme off-axis angle specified by the 44-point test (17.5 degrees down and 27.5 degrees horizontal) to determine how the incandescent and LED lamps are differentially affected by off-axis viewing. The intensity of the incandescent lamp under these conditions is 46 candelas, or 9% of its on-axis value, while the intensity of the LED lamp is 49 candelas, or 12% of its on-axis value. Thus, the intensities of both lamps appear to decline off-axis by similar magnitudes (for the one point tested), and both lamps exceed the minimum standard of 19 candelas specified by the 44-point test. It should be noted that our measurement conditions differ from those specified by the ITE 44-point test (see section IIIb).

b). ORANGE LED PEDESTRIAN HEAD

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE DETECTION	THRESHOLD LUMINANCE IDENTIFICATION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	959	975	728	4.8	8.7	1.8
2	969	1067	1123	25.9	46.9	1.8
3	920	880	886	5.2	14.6	2.8
4	894	964	897	35.2	62.4	1.8
5	1002	912	970	22.7	34.6	1.5
6	843	758	925	4.8	11.3	2.4
mean	931	926	922	16.4	29.8	
standard error of the mean	23.5	42.5	52.4	5.4	8.9	
usability factor	0.92	0.92	0.93			
95% confidence range of usability factor	0.88 - 0.97	0.85 - 1.02	0.83 - 1.05			

Table 2. Median settings for six observers. Reference incandescent pedestrian head was set at luminance of 856 candelas per square meter in this experiment.

The LED pedestrian head usability factor for central viewing is 0.92, with a standard error of 0.03. The 95% confidence range for the usability factor is 0.88 to 0.97, slightly less than unity. Usability factors for peripheral and blurred vision are comparable (0.92 and 0.93, respectively), but the 95% confidence ranges for these conditions include unity due to the larger standard errors. Our interpretation of these results is that, for central viewing, the usability factor is less than unity due to the relatively uneven illumination from the incandescent pedestrian head fixture. The UF is defined in terms of average luminances. When a flicker null is set on the basis of the brighter central portion of the reference incandescent fixture (as is likely the case), a correspondingly greater illumination is required from the LED fixture, thus reducing its value of UF. With peripheral or blurred viewing, the unevenness of illumination becomes less important due to decreased visual acuity, and the usability factor is not significantly different from unity under those conditions. Note the rightmost column in the table, which lists the ratio of identification threshold to detection threshold for each subject. Even though different subjects might have vastly different criteria for setting thresholds, the ratios of the two types of threshold were very similar across subjects.

c). ORANGE NEON PEDESTRIAN HEAD

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE DETECTION	THRESHOLD LUMINANCE IDENTIFICATION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	109	107	87	6.8	7.8	1.1
2	140	109	89	3.7	10.6	2.9
3	113	83	96	1.4	2.2	1.6
4	109	81	85	2.6	4.2	1.6
5	118	104	118	1.5	3.2	2.1
6	87	96	90	7.5	19.7	2.6
mean	113	97	90	3.9	8.0	
standard error of the mean	7.0	5.0	12.4	1.1	2.7	
usability factor	1.35	1.57	1.69			
95% confidence range of usability factor	1.20 - 1.54	1.42 - 1.75	1.32 - 2.34			

Table 3. Median settings for six observers. Reference incandescent pedestrian head was set at luminance of 152 candelas per square meter in this experiment.

Because the luminous intensity of the neon fixture was so low, we had to perform the flicker photometry with the reference set at a much lower value than with other lamps. The usability factor for the orange neon pedestrian head is 1.35, significantly greater than unity. We are unable to suggest an explanation why the neon would be more visually effective than an incandescent source of equal photometric intensity, but because the actual intensity of the neon pedestrian head is so low, compared to that of the incandescent standard, the greater-than-unity usability factor may not lend the neon source any practical advantage.

d). ORANGE FIBER-OPTIC PEDESTRIAN HEAD

SUBJECT	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE DETECTION	THRESHOLD LUMINANCE IDENTIFICATION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	1061	2.7	10.3	3.8
2	1111	13.7	13.4	1.0
3	1061	1.1	4.9	4.5
4	1197	11.5	20.0	1.7
5	1250	2.4	7.4	3.1
6	1415	5.5	11.9	2.2
mean	1183	6.2	11.3	
standard error of the mean	55.8	2.1	2.1	
usability factor	0.76			
95% confidence range of usability factor	0.69 - 0.84			

Table 4. Median settings for six observers. Reference incandescent pedestrian head was set at luminance of 895 candelas per square meter in this experiment.

The fiber-optic pedestrian head produces only an outline of a hand, and this hand is larger than that of the standard incandescent pedestrian head. There is thus no overlap of illuminated areas when the fiber-optic head is optically superimposed with the standard head, and it was therefore neither possible nor meaningful to attempt flicker photometry except in the blur condition, in which an area of overlap results from the expanded (blurred) edges. The result is a usability factor of 0.76, and with the given standard error, significantly less than unity. Note that the fiber-optic pedestrian head uses an incandescent (halogen) source.

e). RED LED ARROW

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE DETECTION	THRESHOLD LUMINANCE IDENTIFICATION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	1248	1190	1187	22.7	49.3	2.2
2	1326	1467	1259	10.4	21.9	2.1
3	1254	1237	1341	20.4	31.4	1.5
4	1358	1234	1054	78.3	90.6	1.2
5	1198	1364	1297	27.0	80.7	3.0
6	1156	1032	992	11.8	23.5	2.0
mean	1257	1254	1188	28.4	49.6	
standard error of the mean	30.9	60.9	56.7	11.6	12.1	
usability factor	1.09	1.09	1.15			
95% confidence range of usability factor	1.04 - 1.15	1.00 - 1.21	1.05 - 1.28			

Table 5. Median settings for six observers. Reference incandescent arrow was set at luminance of 1372 candelas per square meter

The determination of the usability factor for the red LED arrow was particularly difficult because the small area of the targets made it challenging both for the subjects (flicker photometry being easier for larger targets), and for the experimenters (the alignment of the apparatus was even more critical than usual). We determined a usability factor of 1.09 for the direct viewing condition, and a 95% confidence range of 1.04 - 1.15, indicating that the usability factor is slightly greater than unity. This may be due to the punctate nature of the LED source, with subjects adjusting the intensity of the target for minimum flicker while attending to the brighter portions. The usability factor for peripheral viewing is also 1.09, but the greater standard error does not allow us to conclude that the value is statistically different from unity. On the other hand, the increased usability factor for the blur condition is statistically significant, implying that drivers who experience slightly blurred images for distant objects (caused, for example, by improper corrective lenses), may find the LED red arrow more visually effective than an equiluminant incandescent red arrow.

f). RED FIBER-OPTIC ARROW

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION 2 diopters	THRESHOLD LUMINANCE DETECTION	THRESHOLD LUMINANCE IDENTIFICATION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	2276	2199	2527	9.6	27.5	2.9
2	2485	2435	2400	9.4	17.1	1.8
3	2481	2379	2487	21.2	56.9	2.7
4	2781	2627	2781	33.0	35.2	1.1
5	2406	2584	2462	7.1	10.7	1.5
6	2258	2528	2373	5.9	12.7	2.2
mean	2448	2459	2505	14.4	26.7	1.9
standard error of the mean	77.6	64.08	59.8	4.4	7.1	
usability factor	0.55	0.55	0.54			
95% confidence range of usability factor	0.52 - 0.59	0.52 - 0.58	0.51 - 0.57			

Table 6. Results for the red fiber-optic arrow. The incandescent standard arrow was set at a luminance of 1350 candelas per square meter.

We measured a very low usability factor (0.55) for this type of lamp, the lowest of any source tested. This is likely related to the high degree of spatial inhomogenity of the source, which contains only 19 discreet, widely separated emitters. Whereas a small amount of spatial inhomeneity may enhance the UF (as with the red LED arrow), the extreme punctate nature of the red fiber-optic arrow may serve to diminish the UF, as measured by flicker photometry, because there is likely a minimum area (or visual angle) over which the eye integrates to perceive minimum overall flicker in the spatially overlapping signals.

IV. ADDITIONAL MEASUREMENTS WITH THE 12" RED LED SIGNAL

a). DRIVE-BY VERIFICATION

We conducted a drive-by study to assess the relative visibilities of the LED and incandescent lamps under real world conditions. We elected to employ the luminances used in the laboratory experiment in order to assess the visibilities under significantly degraded conditions. We set up fixtures containing the red incandescent and LED lamps side by side at the standard 17 foot height. Neutral density filters were used over each lamp to adjust the luminance to 900 candelas per square meter for the incandescent lamp, and 911 candelas per square meter (the luminance for equivalent brightness) for the LED lamp. These were 11% and 14% of the maximum available (unattenutated) luminances for the incandescent and LED lamps, respectively. The fixtures were placed above a road outside on a sunny day in the early afternoon. Sun direction was generally behind observers during testing. The sun illuminated a uniform white field (the side of a building) beyond the signals to a luminance of approximately 5700 candelas per square meter. Drivers were asked to approach the lamps from a distance of approximately 1000 feet away. Three different pairs of driver and passenger were able to detect, and to identify as red, both traffic signals while approaching the lamps at a speed of 45 miles per hour from a distance of 460 feet from the signals, or even at distances as great as 695 feet (the largest distance for which observers in motion were asked to make such a judgment). Furthermore, the signals appeared to be equally visible at all distances greater than about 100 feet, whether observed from a vehicle or not. They were visible to a standing observer even from as far away as 1500 feet, where they still appeared equally bright, although near threshold. It is certain that when the lamps are operated at their normal intensities (without the neutral density filters) that the signals would be detectable and recognizable from even greater distances.

b). SUN-PHANTOM

While we were set up in the field environment, we conducted a test to ascertain the effects of sun phantom on the incandescent and LED fixtures. Sun phantom occurs when the sun is behind the observer in such a way that the sun, observer, and lamp are on or near the same axis, as may occur when driving away from the sun at or near the time of sunset. The sun's light then reflects off the surface of the lamps, possibly giving the false impression that the lamp is on. The task of the driver is then to determine which of the three color lamps is actually illuminated. We simulated sun phantom during the mid-afternoon by using a large mirror behind the observer to reflect sunlight directly into the fixtures (which also contained unpowered incandescent amber and green lamps). The lamps were operated at their normal intensity. It was easy to distinguish when the red light was on under sun phantom conditions for both incandescent and LED lamps, but the LED actually had a strong advantage because its lens reflects much less of the sun's light back at the observer.

We attempted to quantify this advantage in the laboratory but were unable to illuminate the fixtures with a collimated source at the required brightness to simulate the sun. Under our laboratory conditions, we determined that the light reflected from incandescent fixture was 50% greater than that from the lens of the LED device. We also performed flicker photometry with both fixtures illuminated by reflected light alone, and measured a luminance factor of 1.6 at flicker null, consistent with the photometric determination. We would expect that under actual sun phantom conditions, the factor would be substantially greater.

c). GLARE

We have made measurements of the usability factor of the 12" red LED lamp in the presence of a glare source which simulates the presence of the sun adjacent to the signal. This was achieved by inserting a highly directional incandescent source, of angular dimensions 20 minutes of arc (approximately that of the sun), into one of the optical channels. In addtion, we made measurements in which observers were subjected to the glare through a piece of contaminated glass, intended to simulate a dirty windshield.

SUBJECT	TEST LAMP LUMINANCE NO GLARE	TEST LAMP LUMINANCE WITH GLARE	TEST LAMP LUMINANCE BLURRED VISION NO GLARE	TEST LAMP LUMINANCE BLURRED VISION WITH GLARE	TEST LAMP LUMINANCE WITH GLARE AND CONTAMINATED GLASS
1	980	943	1043	1012	
2	1046	964	994	975	
3	937	1114	937		675
4	1095	992	1090	1070	1081
5	850		884	784	924
mean	982	1003	989	960	893
standard error of the mean	42.5	38.3	36.7	61.9	118.2
usability factor	0.92	0.90	0.91	0.94	1.01
95% confidence range of usability factor	0.84 - 1.00	0.83 - 0.97	0.85 - 0.98	0.83 - 1.08	0.80 - 1.37

Table 7. Results for five subjects in the glare condition. The incandescent reference standard source was set at 900 candelas per square meter.

The 95% confidence range of the usability factor, without glare, includes unity, a result that is consistent with our earlier measurements of UF with the red 12" LED lamp. The UFs with or without glare and/or blur are all approximate equal (from 0.90 to 0.94). With the contaminated glass combined with glare, the UF is slightly larger (1.01) but the 95% confidence range is wider, and the increase compared to the other conditions is not statistically significant. Thus we conclude that the presence of glare does not have a significant effect on usability factor of a 12" red LED signal.

d). FOG

We have performed two separate experiments in which we have attempted to simulate a foggy environment.

First, we endeavored to simulate fog by use of a theatrical smoke machine, conducting the experiment in an outdoor setting. While this produced the visual effect of fog, it proved difficult to control the density of the smoke in order that it remain constant during the course of our experiments.

SUBJECT	TEST LAMP LUMINANCE NO FOG	TEST LAMP LUMINANCE WITH FOG
1	1231	1039
2	1083	2562
3	1019	1115
4	534	749
mean	967	1366
standard error of the mean	151	538
usability factor	0.93	0.66
95% confidence range of usability factor	0.71 - 1.35	0.37 - 3.10

Table 8. Results for four subjects in the fog condition. The incandescent reference standard source was set at 900 candelas per square meter.

The difficulty in maintaining alignment, due to windy conditions, resulted in unusually large variability in the settings made by each subject (standard deviations of medians are not reported in the table). Additionally, the difficulty in maintaining constant fog (smoke) density in the fog condition further increased the already large standard deviations. The usability factor in the no-fog condition was 0.93 and in the fog condition 0.66, but in each case the 95% confidence interval includes unity, and there is no statistical difference between the results for the two conditions. Because of the large variability, however, one should use caution in interpreting these results.

We also simulated fog in the laboratory setting by interposing a glass tank containing a solution of water and Elmer's white glue to produce a diffusing effect. The solution produced an luminance attenuation of 1.94 log units, hence the low values of luminance in the table that follows.

	TEST LAMP LUMINANCE NO FOG	TEST LAMP LUMINANCE WITH FOG
1	2015	27.7
standard error of the mean of settings	76.2	0.39
usability factor	0.99	0.82
95% confidence range of usability factor	0.92 - 1.07	0.80 - 0.85

Table 9. Results for one subject in the fog condition. The incandescent reference standard source was set at 2000 candelas per square meter with no fog, and was reduced to 22.8 candelas per square meter with fog present.

The results with no fog confirm our earlier results with the 12" red LED lamp of a usability factor not significantly different from unity. With fog present, the UF is reduced, although with less magnitude than in the first fog experiment, above.

Because the conditions in either of these experiments may not represent an accurate simulation of fog, it would be worthwhile to conduct the experiment in actual foggy conditions.

e). COLOR VISION ANOMALIES

We can make predictions based on published data for various types of color deficiencies. For a red light, the most serious deficiency is the lack of the red cone system in the eye. A person with this deficiency is termed a protanope, and suffers both from an inability to distinguish red from green, and a reduced sensitivity to red illumination. With the measured spectral distributions of the incandescent and LED lamps, and the known luminous efficiency curves for protanopes, we used numerical integration to predict that the usability factor for the the TsAlInGaP LED would increase approximately 3% from that determined for a normal observer. Other types of LED which peak at a longer wavelength would have result in a significant lower UF (for example, we would predict a 35% decline in UF with a TsAlGaAs LED) . The UFs for a deuteranope, who lacks the green cone system, would not change signifcantly in the case of any type of red LED.

One must keep in mind that because a protanope or protanomalous observer lacks sensitivity at the longer wavelengths, thresholds for any type of red lamp will be higher than with normal observers, and red signals may be difficult to see under some conditions, even if the UF remains near unity.

We have run one color-deficient subject in the flicker photometry experiment, a protanomalous observer whose visual sensitivity at 630 nanometers (the peak of the TsAlInGaP LED spectral emittance curve) is one log unit below normal.

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE FOR DETECTION	THRESHOLD LUMINANCE FOR COLOR IDENTIFICA-TION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	946	984	7.7	8.0	
standard error of the mean of seven settings	47.9	32.9			
usability factor	0.95	0.91			
95% confidence range of usability factor	0.86 - 1.06	0.86 - 0.98			

Table 10. Results for one protanomalous subject. The incandescent reference standard source was set at 900 candelas per square meter.

The usability factor in the central viewing condition is not significantly different from unity and the 95% confidence range includes the predicted UF of several percent higher than unity (see introductory paragraph in this section).

In addition, we ran one subject who was diagnosed as a protanope. Owing to his vision problems, we were unable to train this subject to make meaningful settings in the flicker photometry task, but we did succeed in measuring detection thresholds of 19.3 candelas per square meter for the LED device, and 56.3 candelas per square meter for the incandescent source. These are considerably greater than the detection thresholds for normal observers, as would be expected for one who lacks the red-sensitive cones in the retina.

f). AGING EYE

The aging eye can be affected by decreased acuity or scattering owing to corneal opacities, cataracts, clouding of the media, neurological changes such as degeneration of the retinal, and other causes. In addition, the color perception and sensitivity may change for central viewing owing to yellowing of the lens. We have run one elderly subject, age 68, a retired vision science professor and experienced observer in psychophysical experiments, who has vision that is normal for his age.

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW	TEST LAMP LUMINANCE PERIPHERAL	TEST LAMP LUMINANCE BLURRED VISION	THRESHOLD LUMINANCE FOR DETECTION	THRESHOLD LUMINANCE FOR COLOR IDENTIFICA-TION	RATIO OF IDENTIFICATION THRESHOLD TO DETECTION THREHOLD
1	1013	873	932	5.0	12.6	2.5
standard error of the mean of seven settings	68.4	70.9	49.5			
usability factor	0.89	1.03	0.97			
95% confidence range of usability factor	0.78 - 1.03	0.89 - 1.23	0.87 - 1.08			

Table 11. Results for one elderly subject. The incandescent reference standard source was set at 900 candelas per square meter.

The 95% confidence range of the usability factor includes unity in all three viewing conditions. We conclude that, within the statistical limit imposed by a small subject population, the aging eye does not affect UF.

g). SUNGLASSES

It is known that certain sunglasses have spectral transmission curves that may affect the incandescent and LED lamps unequally. We have obtained a pair of REVO Traveler sunglasses that are designed to have maximum transmission at the red, green, and blue “primary” wavelengths, which the manufacturer claims enhances the appearance of colors. A consequence of the transmission spectrum is that, due to a notch in the yellow region, amber LED lamps are attenuated to approximately 2.5% of the the original luminance, as measured in our laboratory. Red LEDs are also attenuated, although to a lesser degree. With the measured spectral distributions of the incandescent and TsAlInGaP LED lamps, and the measured spectral transmission curve of the sunglasses, we can use numerical integration to predict that the usability factor for the LED, while wearing the sunglasses, would decrease by about eight percent from that determined for a an observer without sunglasses (other types of LED would lead to different predictions).

SUBJECT	TEST LAMP LUMINANCE CENTRAL VIEW NO SUNGLASSES	TEST LAMP LUMINANCE REVO TRAVELER SUNGLASSES
1	940	943
2	861	1044
mean	900	993
standard. error of the mean	39.6	50.5
usability factor	1.00	0.91
95% confidence range of usability factor	0.92 - 1.10	0.82 - 1.01

Table 13. Results for two subjects wearing REVO sunglasses. The incandescent reference standard source was set at 900 candelas per square meter (before attenuation by the sunglasses).

For the two observers tested with the sunglasses, the usability factor of the LED lamp declined to 0.91, consistent with our predictions. However, the 95% confidence range includes unity and this result is therefore not statistically significant.

V. CONCLUSIONS

With normal observers and standardized viewing conditions (central fixation with and without blur, and peripheral fixation), we have determined usability factors for a number of devices, including 12" red TsAlInGap LED round device, three types of orange pedestrian head (LED, neon, fiber-optic), and two types of red arrow (LED and fiber-optic). With the 12" red LED device, we have also determined usability factors under degraded viewing conditions, including fog, glare, sun phantom, and sunglass wear, and with subjects with color vision anomalies or aging eyes.

The UF for the 12" red LED device was not significantly different from unity for any of the standardized conditions. The orange LED pedestrian head had a UF significantly different from unity for the central fixation condition only (0.92, with upper limit of 95% confidence range 0.97). The orange neon pedestian head had a high UF in all viewing conditions (from 1.35 to 1.69) but the actual available illumination from this device was low enough to render it impractical. The orange fiber-optic pedestrian head had a low UF (0.76). The red LED arrow had a UF slightly higher than unity (1.09 - 1.15) for all three standard viewing conditions. The red fiber-optic arrow had a very low UF (0.55).

The presence of sun-phantom had less effect on the 12" red LED device than on a normal incandescent fixture owing to less reflectivity. The presence of glare does not have a significant effect on the UF of the 12" red LED device. Owing to the difficulty of simulating fog in the laboratory, results of tests under this condition were inconclusive, but blur tests have suggested that fog will not have a significant effect of UF. The results of tests of one color defective (protanomalous) observer with the 12" red LED device indicate no significant change in UF for central fixation, but a significant decline (to 0.64) in peripheral fixation. Tests with one elderly observer indicated no significant change in UF for the 12" red LED device. Use of REVO Traveler sunglasses, which have a notch in the yellow region of the transmission spectrum, had no significant effect on UF for the 12" red LED device.

The usability factor represents a useful quality index which can be used in combination with the 44-point test or other appropriate photometry based tests for acceptance, to evaluate the visibility of an alternative technology device in field installations.