The Application of Light Emitting Diodes to Traffic Signals

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Introduction

Incandescent lamps are currently the major illumination source for traffic signals. The incandescent lamps used for traffic signals are, however, inefficient compared to other light sources. Maintenance costs are high for these lamps and the light output degrades as the lamp ages. These problems, plus the ever-increasing cost of energy, justify considering other light sources. One alternative is light emitting diodes (LEDs).

Before existing incandescent lamps are replaced by LEDs, it is necessary to show that LED signals will meet applicable standards for color and intensity, not adversely affect the safety or operation of the roadway, and be economically advantageous. NCHRP Project 5-12 was initiated in response to this need. The objective of the research was to determine the feasibility and implementation potential of LEDs. The project found that red and Portland orange (pedestrian) LED signals are currently feasible.

This paper summarizes the project findings and includes testing results, a discussion of economical analysis, specification guidelines, recommendations for LED use, and suggested future research. It is hoped that the information will be of interest to those involved in designing and specifying traffic signals.

LED technology is rapidly evolving and the research project evaluated the technology available at the time (1992–94). Some of the findings and recommendations will undoubtedly become obsolete as the technology progresses.

Adherence to color standards

The Institute of Transportation Engineers (ITE) standard *Vehicle Traffic Control Signal Heads* is commonly used throughout the US.[1] This standard defines the required color for new traffic signals.

An LED's color is usually referred to by the peak wavelength of the spectral distribution. This can be misleading. The other wavelengths in the distribution cause the dominant wavelength (the apparent color) to differ from the peak wavelength. For this reason, LEDs should be plotted on a CIE chromaticity diagram to verify whether they meet the color requirements. **Figure 1** presents the 1931 CIE Chromaticity Diagram with the boundaries for ITE and CIE/ISO signal colors. Representative incandescent signal colors have been plotted on the diagram.

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Red—At this time, the most common red LEDs comprise gallium aluminum arsenide (known as GaAlAs or AlGaAs) and emit a 660 nm peak wavelength. These fall around a 640 nm dominant wavelength on the CIE diagram. Generally all of the 660 nm LEDs tested will fall within the ITE definition for signal red. However, slight color variations due to manufacturing may result in a batch of 660 nm LEDs that fall just outside of the ITE definition. This is not usually the case.

Orange-Red—Slightly more orange-red LEDs are available. Two of the red prototype signals evaluated use a new indium LED product from Stanley that has a peak wavelength at 630 nm and a dominant wavelength slightly above 620 nm. Hewlett Packard's new aluminum indium gallium phosphide (AlInGaP or InGaAlP) series includes an orange-red LED that is nearly identical in color to the Stanley LED. These LEDs barely meet the ITE red definition.

The inset on **Figure 1** presents the locations of representative 660 and 630 nm red LEDs on the CIE diagram. Note the multiple boundary lines for the CIE/ISO red signal color definition. The ABCD boundary is the general red signal color definition. For greater probability of recognition, the A'B'CD boundaries are recommended. For signals to be used by red-green confusers (those with protan color vision defect), the ABC'D' boundaries are recommended. Similar multiple boundary lines (although not labeled) are also presented for the yellow and green signal colors. Additional information on the CIE/ISO color definitions can be found in the standard.[4]

It may be observed from **Figure 1** that the 660 nm LEDs fall outside of the ABC'D' boundaries for observers with color vision defects. Use of these LEDs in traffic signal applications may be of concern, although safety and operational testing did not indicate any problems.

Yellow—Yellow LEDs are generally either 590 or 594 nm peak wavelength. The dominant wavelengths vary from 584 to 594 nm. However, the ITE defines yellow from 585 to 592 nm. This, coupled with manufacturing variations, results in a larger number of 590 nm LEDs falling outside of the ITE definition than is observed with the 660 nm LEDs.

Green—For several years, green gallium phosphide (GaP) LEDs have been available in colors ranging from

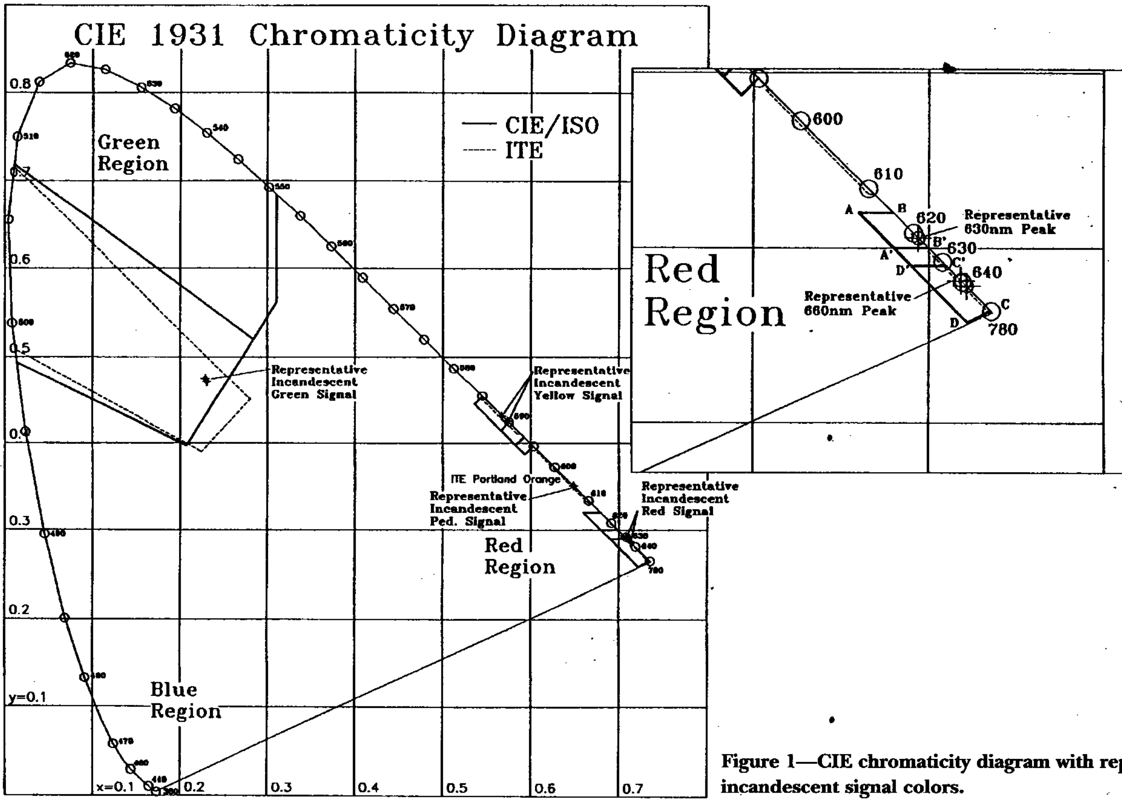

Figure 1—CIE chromaticity diagram with representative incandescent signal colors.

570 to 555 nm. None of these come close to meeting the ITE definitions for green.

The concept of mixing green and blue LEDs has been suggested. This will not, however, produce the required color. Any color produced using two types of LEDs will lie on the straight line connecting their chromaticity coordinates on the CIE diagram. A line of the CIE diagram between a 555 nm green and a 460 nm blue does not intersect the defined area for green. Additionally, mixing discrete LEDs on a circuit board will not achieve a uniform, subjectively pleasing color. The signal would obviously be made of discrete green and blue spots except at very long viewing distances. Using different LED chips within the same package will more effectively mix the color, but the fundamental limitations on achievable color will still apply.

Several LED manufacturers plan to release a deep green LED of approximately 530 nm peak wavelength. These LEDs may not meet the ITE green definition, but they will be a great improvement. Mixing these deep green LEDs with blue LEDs within the same package would most likely result in an acceptable signal green. There are long-term goals to produce LEDs that directly meet the ITE green definition (498–508 nm), but it is not known when this will occur.

Orange—Portland orange for pedestrian signals can be met with existing LEDs. The ITE defines Portland orange from 595 to 610 nm. The orange LEDs typically have a peak wavelength of 620 nm and a dominant wavelength around 610 nm.

White—White LEDs are being produced. These consist of a single package that contains 660 (red), 555 (green), and 470 nm (blue) chips. The idea behind this is to produce a variable LED that, by varying the power to each chip, can produce a wide spectrum of colors. These LED packages can only produce colors inside the triangle produced by connecting their chromaticity plots.

Filters—Filters cannot be used with LEDs to alter the color. Colored filters work on the principle of subtraction; that is, a filter subtracts or absorbs certain wavelengths. A red filter in front of a white light absorbs much of the spectrum except for those wavelengths in the red region. Because LEDs are nearly monochromatic, a filter will only reduce the intensity of the light with minor changes to the color.

Adherence to intensity standards

The ITE Standard also defines the required intensity for new traffic signal heads. **Figure 2** shows the ITE horizontal intensity distribution requirements for 12 inch red ball signals at four vertical angles (–2.5, –7.5, –12.5, and –17.5 degrees). Similar requirements are also specified for the 8 inch red ball and the green and yellow balls in

Table 1—Evaluation of intensity

Size andcolor	Measured intensity (cd)	Required intensity (cd)
8 inch (660 nm)	668	157
12 inch Red (660 nm)	1230	399
8 inch Red (630 nm)	557	157
12 inch Red (630 nm)	993	399
8 inch Yellow (590 nm)	372	726
12 inch Yellow (590 nm)	646	1848
8 inch Green (560 nm)	98	314
12 inch Green (560 nm)	179	798

both sizes.

The optical properties of LEDs utilized within a signal head greatly impact how the light intensity is distributed. Viewing angle is defined as two times the angle from the optical axis to the half intensity point. Most LEDs currently being considered for traffic signals have either narrow (about 7–10 degree) or wide (about 30–35 degree) viewing angles. LEDs with narrow viewing angles are very bright along the axis but quickly grow dim as the observer moves away from the axis. LEDs with wide viewing angles distribute more light away from the axis.

Color also has a tremendous impact on the intensity of the LED. Prototype traffic signals using Stanley LEDs (300 LEDs for 8 inches, 500 for 12 inches) with narrow viewing angles were evaluated for peak intensity (along the optical axis) with the results shown in **Table 1**. Although the peak intensities of both types of red signals far exceed the ITE requirements, the signals fail to meet the intensity distribution requirements. Even with the narrow viewing angles, the yellow and green signal colors cannot meet the peak ITE intensity requirements.

One way to meet the ITE signal intensity distribution requirements is to use narrow viewing angle LEDs with a prismatic lens that alters the distribution. Another common approach is to use a sufficient number of wide viewing angle LEDs to meet the axial intensity requirements. Both approaches can work.

In addition to the ITE requirements, **Figure 2** also shows the intensity distributions for a 12 inch red LED signal utilizing 8 degree viewing angle LEDs with a red prismatic lens and a 12 inch red LED signal utilizing 30 degree viewing angle LEDs. While the 8 degree LED signal nearly meets the peak ITE requirements, its greatest deficiencies occur at the wider horizontal angles. The 30 degree LED signal fails to meet the required intensity near the optical axis while meeting it further out.

Intensity loss due to age—LED intensity degrades over time and this will, most likely, determine the life of the signal. The type of LED, the manufacturing process, and even the encapsulating epoxy can have a significant effect on LED output over time. Some of the external factors that will impact this intensity degradation are ambient temperature, duty cycle, and electrical current. Data on many more LED signals installed in varying environments need to be collected. The limited data found in this study show an estimated usable life between 3 and 6 years. Usable life is defined as when the signal has degraded to half its initial intensity.

Some signal manufacturers are offering 5 year guarantees against signal failure. These guarantees, however, usually only consider LED string failure and do not consider the failure of the signal due to output degradation. Nevertheless, the signal manufacturers have been very responsive in replacing faulty signals.

Intensity loss due to temperature—When the signals were being tested, it was found that the LEDs are so sensitive to temperature that their own heat generation can significantly impact the intensity. **Figure 3** shows how the intensity degraded for a 12 inch red ball signal powered at different duty cycles at an ambient temperature of about 25 °C. When the signals were field tested with ambient temperatures exceeding 80 °F, output loss exceeded 50 percent.

Intensity loss due to power—The intensity of LED signals is very sensitive to input voltage. An LED signal tested at 95 V ac had only 14 percent of the nominal 120 V ac intensity. There are several methods the manufacturers are using to stabilize the input voltage but all decrease the efficiency of signal somewhat.

Safety and operational impacts

Human factors testing was conducted to determine the safety and operational impacts of the use of LED signals as replacement for incandescent signals of the same type. Three tests were performed. The first test assessed the relative visibility of the LED signals in comparison to incandescent signals under ideal viewing conditions. Twenty-eight normal-vision drivers were evaluated using a subjective rating technique.[2]

The second test was designed to evaluate the conspicuity or "attention getting" powers of the signals found to perform best in the first test. It required test subjects to identify the type, color, and location of the types of LED signals (and equivalent incandescent ones), based only on a brief glance at the signal. Seventeen subjects were individually tested while seated in a stationary test vehicle and any one of the signals could appear (i.e., be energized) at any one of three different eccentricities (locations). Drivers with both normal vision and with color deficiencies were tested. This experiment is more fully described elsewhere.[3]

The third test was a field observation of the LED signals found to perform best in the first two tests in comparison to their incandescent counterparts: round red, red arrow, and Portland orange pedestrian. A single approach on each of three different intersections was evaluated separately for incandescent signals and LED signals. The number of vehicle and pedestrian violations,

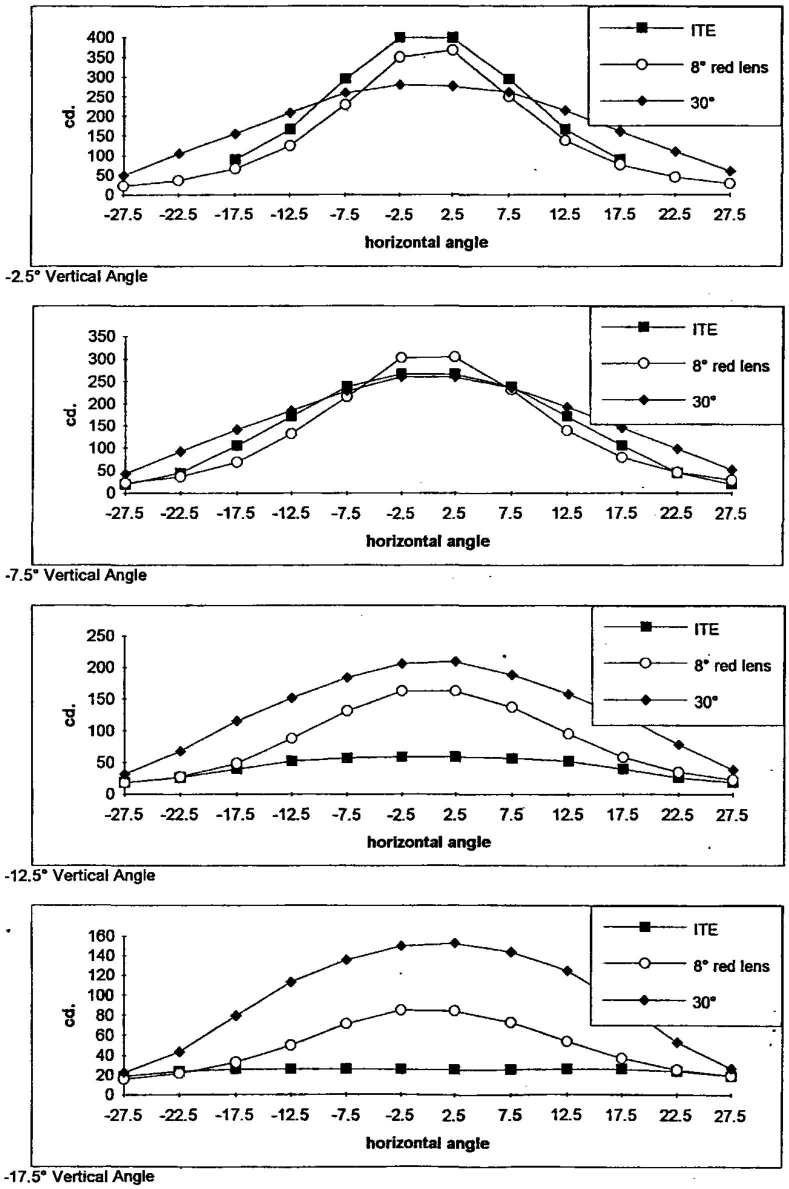

Figure 2—Comparison of ITE intensity requirements and 12 inch red LED signals using 8 and 30 degree LEDs.

e.g., stopline, entering of pedestrians, and erratic maneuvers (such as horns, squealing brakes, standing in intersection) were recorded.[3]

The major result of the three tests was that red round, red arrow, and Portland orange pedestrian LED signals perform as well as or better than their incandescent counterparts.

Specific conclusions of the safety and operational tests included

- The green LED signals, both ball and arrow, performed poorly, both absolutely and in comparison to incandescent signals. This is attributed to both the low intensity of the green LED signals and their almost yellow color.
- The yellow LED signals, both ball and arrow, normally were inferior to the incandescent signals. This is attributed to the lower intensity of the yellow LED signals.
- The red LED signals, both ball and arrow, normally performed as well or better than the incandescent signals, in both 8 or 12 inch sizes.
- Pedestrian LED signals normally performed as well as the incandescent signals. Pedestrian signals of both types seem to perform better when seen directly ahead rather than at wide eccentricities. This is not considered to be a problem since these signals are normally viewed straight-on.
- The use of visors on LED signals normally decreases their visibility while the opposite is true for incandescent signals.
- Visibility and conspicuity are directly related to the signal intensity. The required intensity for a red ball LED signal seems to be in the range of 300–500 cd. Red arrows appear to require about 44 additional candelas of intensity. Yellow ball LED signals probably require about twice the intensity as a red ball LED signal, and green ball LED signals require about 2-1/2 times the red intensity.
- Improving the light distribution of an LED signal can significantly reduce the intensity requirements. The intensity required for red ball LED signals can be reduced by about 26–52 percent if the distribution is doubled (from 7 to 15 degree viewing angles). Yellow and green LED signals do not show as dramatic an improvement.
- The results for red signals are believed to be much more accurate and valid than for the other two colors. Similarly, the results for ball signals are believed to be more accurate and more valid than for the arrow signals. This is partly attributed to the larger amount of data available for the red ball signals.
- Color-vision-deficient drivers and normal-vision drivers seem to have similar error patterns and times to react, but the small number of color-vision-deficient drivers makes generalizations somewhat tenuous.
- Performance at night appears to be similar to daytime performance, except for the effects of visors. Overall, nighttime performance was better than daytime performance.
- The red ball, red arrow, and Portland orange pedes-

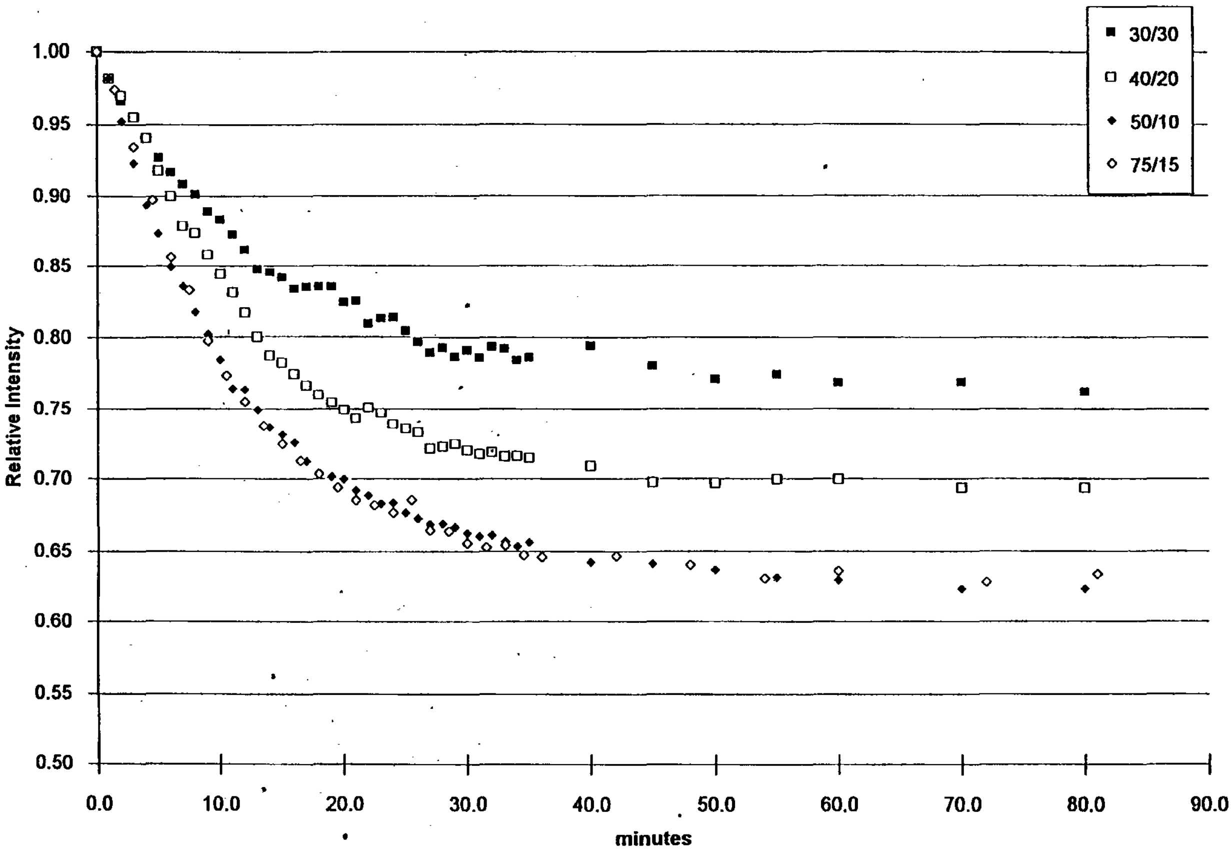

Figure 3—Output vs time for 12 inch red signal—three duty cycles at ambient temperature of 25 °C

trian signals appear to perform as well as incandescent signals, both during the day and at night.

Economic analysis

Justification for use of LED signals must depend on an economic analysis that demonstrates a cost savings. This analysis should consider the following factors.

Initial cost—LED signals are very expensive relative to incandescent signals. The cost of a single signal can range from $115 for an arrow to $430 for an orange pedestrian hand symbol. Typical costs for some types of heads are: 12 inch red ball $230; 8 inch red ball $190; 12 inch red arrow $115; and orange pedestrian hand symbol $250. An incandescent krypton lamp, on the other hand, costs about $2. As a market is established for LED signals, the initial cost will undoubtedly decrease.

Power savings—LED signals consume much less power than incandescent signals. The reduced cost of power can be estimated using the following equation:

$$A = 8760 * D * (PI - PL) * C$$

where A is the annual power cost savings ($/yr)
8760 is the hours in a year (hr/yr)
D is the duty cycle (percent time on)
PI is the incandescent power consumed (kW)
PL is the LED power consumed (kW)
C is the cost per kilowatt-hour ($/kWhr)

Some typical examples of annual power savings are shown in **Table 2**.

Life—LED signals will last longer than incandescent signals, though good estimates of the expected life are not yet available. Incandescent lamps are replaced every 6 mos to a year. The life of the LED signal is a critical factor because calculations using a 5 year life can justify LED signals not justified when using a 3 year life.

If an entire intersection could be converted to LED signals, there would be significant savings because semiannual relampings would not be needed. This would reduce the amount of preventive maintenance required and the number of trips. The lack of a satisfactory green LED makes this unlikely in the near future.

Analysis—One method of analysis is to determine the payback period. This is the amount of time over which the savings in operating costs will equal the increased initial cost. **Figure 4** shows a payback period analysis for the four most promising LED applications.

Though the payback period analysis method is useful,

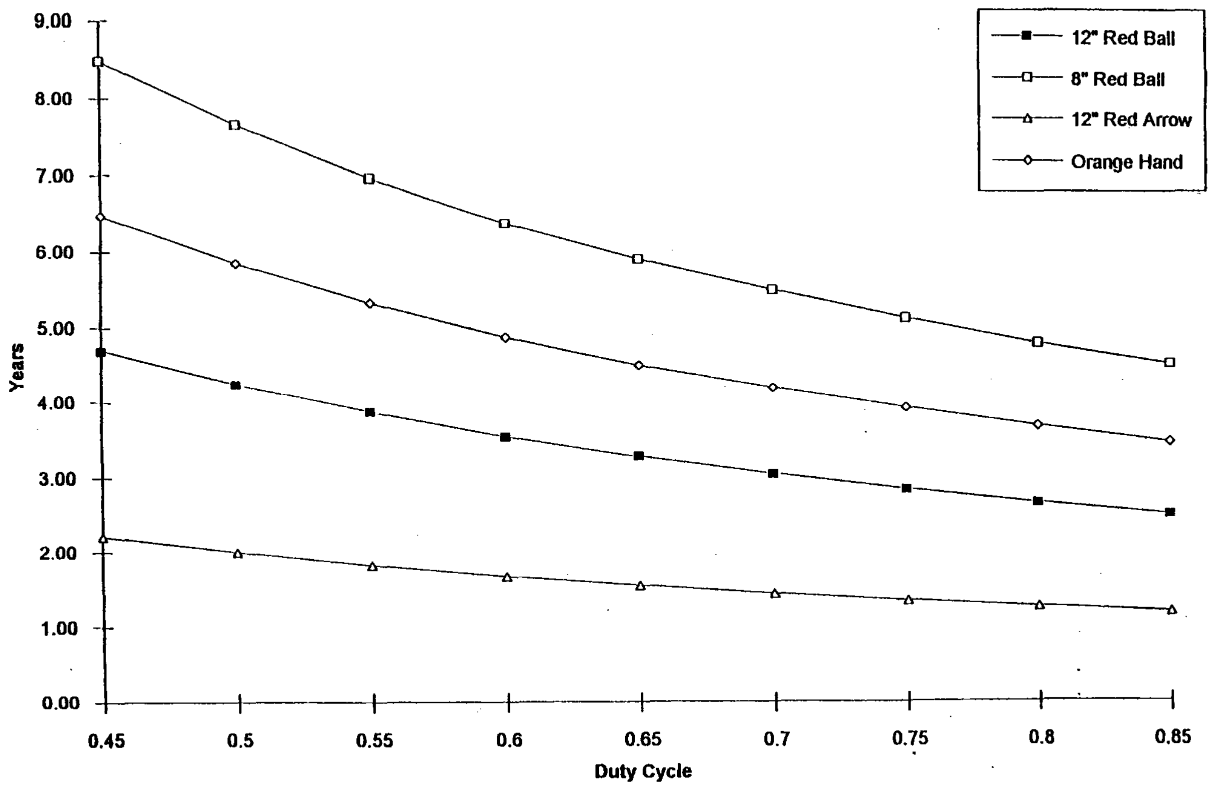

Figure 4—Payback period for representative LED signals.

it fails to consider the time value of money. Another approach is to convert the annual cost savings over the life of the signal into present-day dollars and then compare that to the initial cost.

Specification guidelines

If a jurisdiction chooses to use LED signals, they should consider several points in developing specifications.

Minimum intensity requirements over a range of horizontal and vertical angles should be specified. Stating a particular quantity or type of LED should be avoided. The specification should clearly state the conditions under which the signal must meet the requirements (e.g., "initial intensity of new signal at room temperature conditions (24 °C)"). In addition, due to the sensitivity of the signals to their environment, instructions should be included regarding how the signal is to be aligned and whether any multiplying factor will be used to increase signal output tested at steady-state operating conditions to initial conditions.

The minimum level of performance over the operating voltage range should be defined (e.g., "new signal output at room temperature conditions shall not fall below 85 percent of intensity requirements over the operating voltage range"). To require a signal to meet 100 percent of the intensity requirements over the operating voltage range is unrealistic. The amount of loss allowed may (within reason) be based on what the signal manufacturers can achieve with regulatory circuitry.

The minimum level of performance over the operating temperature range should be defined (e.g., "new signal output at nominal voltage conditions shall not fall below 70 percent of intensity requirements over the operating temperature range"). Also, it should be stated what the operating temperature refers to: ambient, printed circuit board, or perhaps, internal signal head temperature. It is unrealistic to require a signal's intensity to remain unchanged above room temperature. The amount of loss allowed may be based on environmental testing of a variety of discrete LEDs that may be used in signal applications, or a number of available signals could be tested. Instructions on how a signal's temperature response will be verified may also be included in the specification.

A maximum signal output loss (as percentage of intensity requirements) due to a single LED failure should be specified. Stating a specific number of LED strings should be avoided.

When some level of output degradation over time is specified, the conditions under which the amount of degradation would be measured should be specified

Table 2— Annual power cost savings of LED signals

Duty cycle(percent)	12 inch red ball	8 inch red ball	12 inch red arrow	Orange red signal.
50	$54.3	$24.8	$57.5	$42.8
60	$65.1	$29.8	$69.0	$51.3
70	$76.0	$34.8	$80.5	$59.9
80	$86.8	$39.7	$92.0	$68.4
LED Power Consumption (W)	17W	15W	10W	23W
Incandescent power consumption (W)	135W	69W	135W	116W

Power is assumed to cost $0.105/kWhr.

(e.g., "signal output at nominal voltage and room temperature conditions shall not fall below 80 percent of intensity requirements before 1000 hrs of field operation"). It is reasonable to define signal end of life as the point when the signal reaches some percentage of the stated intensity requirements.

Recommendations

Based on the research performed, the following recommendations are made.

1. Round ball LED signals can be used under the same conditions as incandescent signals. The intensity of the red LED signal should be in the range of 300–500 cd with a narrow distribution (7 degree viewing angle). If a wider distribution is used, then intensity can be reduced significantly. Color can be either 660 or 630 nm, but the 630 nm signal is recommended because its color is more similar to the incandescent signal and will pose fewer detection problems for many color-vision-deficient drivers.

2. Red arrow LED signals can be used under the same conditions as incandescent signals. The intensity of the red arrow LED should be about 40–50 cd more than the red ball LED.

3. Portland orange pedestrian LED signals can be used under the same conditions as incandescent signals. The intensity of the pedestrian LED signal should be at least 20–25 cd.

4. Present yellow ball LED signals could probably be used if the intensity of the signals were increased. It is difficult to justify their use, however, because of the short duty cycle. Yellow arrow LED signals did not perform well and are not recommended.

5. Present green LED signals should not be used because of their poor color and very low intensity.

6. Present red LED lane control signals were found to perform well in visibility but poorly in conspicuity. They are not recommended for use.

Suggested research

Large scale field testing in a variety of environments needs to be performed. Red signals of different types using different LEDs and different duty cycles should be included in a multistate cooperative study. Long-term testing should be done for at least 3 yrs. Signal output as a function of time, environment, and duty cycle is needed for the different LEDs.

Research into possible methods to reduce the temperature sensitivity of LED traffic signals is needed. The solutions should not significantly increase the power consumption or total signal price. Complex retrofit work on the signal heads should be avoided. The effect of stabilizing the temperature of the LEDs on the usable signal life should also be investigated.

The LED manufacturers should investigate the development of an asymmetric LED package that would direct most of the LED output to the areas defined by the traffic signal intensity standards. A more efficient use of the light would result in a lower signal cost with reduced power consumption.

The human factors and safety performance experiments, especially the field test, only addressed a limited number of intersection types and only for a very brief period. A fuller evaluation would necessarily include a broader range of types of intersections over a much longer period. Intersections in more complex visual environments with higher approach speeds and higher traffic densities should also be evaluated.

A larger installation base of LED signals will allow a better analysis of the safety impacts of LED signals.

As new types of LEDs become available, they should be evaluated in comparison to incandescent signals.

Acknowledgments

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Discussion

This paper seems to adequately address the intensity and color concerns for an LED based traffic signal although limited data is presented. Since the life and operating characteristics of an LED (and LED system) are different from an incandescent lamp, a discussion on the appropriateness of the definition of LED "usable life" would be useful as it plays an important role in payback and maintenance studies. The eighth conclusion in the safety and operational tests does not appear logical. Also, why does the use of the visor affect the subjective results for LEDs differently? The statements in the recommendation section seem preliminary because strenuous studies have not been performed. Could I trust any of the LED signals after 2 years of operation in Sacramento, CA? Would the light output meet ITE standards in midsummer after 2 years?

M. Packer
Lawrence Berkeley Laboratory

As a general note, I suggest that we replace the word ball (i.e., red ball, yellow ball, etc.) with the word "indications." Indications is predominantly utilized by the signal manufacturers and also by the various governmental agencies. I think that the word indications is also used in various technical magazines such as *ITE* and *MUTCD*.

Life—Usually the traffic signal lamps are replaced through a routine maintenance program on a yearly basis. It is not uncommon to have a 2 year lamp replacement program.

Regarding the specification guidelines on signal output degradation, I would suggest that the signal output at nominal voltage should not fall below 90 percent of intensity before 3000 hrs of operation. I feel that output degradation occurring at 1000 hrs of service is a little too uncommon.

Overall this paper does point out the pitfalls as well as the good points of LEDs. As a point for discussion, I suggest that we have an intensity table for both incandescent and LEDs. I feel strongly that this table should be in English units (i.e., fc) since most governmental agencies do have traffic signal engineers who are mostly nonelectrical. Having the intensity in English units, would probably be more meaningful to them when they read this paper.

B. Ananthanarayanan
Wisconsin Department of Transportation

As a municipal utility, the City of Palo Alto is always looking for ways to increase efficiency of our traffic signal system. We look forward to advances that will make the safe and economic application of this technology possible. LED traffic signals may offer greater public safety in the future, especially if intersection loads can be reduced enough to allow battery backup during power outages.

A combination of technology and cost issues will have to be addressed before this technology can become a fiscally sound choice for utilities in areas with lower utility rates (ours averages $0.07/kW). Would the authors gather some good information on maintenance costs for adequate lifecycle costing? I believe one of the most attractive aspects of this technology is its longer life.

One notes the precipitous drop in intensity and the authors' comments regarding the impact of temperature on the LED performance over time. It would be useful if the author included a line on the graph indicating the present standard that these new LED lamps are held to. By including the line, it would be easy for the reader to determine the point in time in which the intensity level exceeded, met, or fell below the standard.

An opportunity may exist to improve these test results. I understand from comments made by our utilities personnel that the circuits within the LED heads are fairly simple at this juncture. Perhaps the application of current controls within the circuit for the purposes of adjusting LED intensity would allow the standards to be met while providing a longer useful life. The concept would be to adjust the intensity down whenever logically possible. It would have to be limited so that the LEDs would not fail prematurely. Future tests will have to be performed to confirm whether this option is viable.

V. Waik
City of Palo Alto

As a member of the NCHRP panel that overviewed NCHRP Project 5–12, from which this paper was extracted, I appreciate the opportunity to comment.

In view of the current interest in the use of LED traffic signal heads, this paper is both timely and appropriate. The paper's main value lies in its countering some of the rather robust claims being made about LEDs and LED signals by their respective manufacturers. Lewin assigns considerably more realistic values of service life to LED signals, values that take into account the very important factor of lumen depreciation over life for LEDs. His values contrast sharply with those advertised by the manufacturers of both LEDs and LED signals.

In its introduction the paper properly points out one possible weakness: research on a product, such as LEDs, with rapidly evolving technology often results in findings and recommendations that are obsolesced by improvements in the product that are developed as research progresses. This strongly suggests that the research described must be of a continuing nature so that newly developed versions of LED signals can be evaluated.

A prime example of this is the three-color LED signal. I assume that the three colors in this signal face are those discussed under the **Adherence to color standards** section. If so, the reader should be advised that at the 1994 convention of the Institute of Transportation Engineers, a prototype three-color LED signal was demonstrated that had yellow and green displays that were very close to the ITE chromaticity requirements and each lens used only one type of LED. Chromaticity, intensity, and price improvements have yet to be made, but the manufacturer predicted that a marketable product could be available in 2–3 years. Could the authors suggest a more timely means of evaluating a new product?

Although the paper introduces the important factor of intensity loss due to age, it provides no concrete figures as to the lumen depreciation of LED signals. It does state that "usable life" is defined as the period that it takes for the light output of the signal to drop to one-half of its initial value and this is stated as being from 3 to 6 years. However, it further suggests that "long-term testing should be done for at least 3 years," which indicates that such testing was not done on this project. So what is the basis for the 3–6 years"?

Another problem I see is that the final report on NCHRP Project 5-12 will not be published, although interested parties may, once they know of the report, borrow a copy for study from the NCHRP. I would therefore urge that this paper or versions thereof be made available to the traffic engineering community in order that its members may make more intelligent decisions regarding the use of LED signals.

V.H. Waight

Authors' response

To M. Packer

The choice of the definition of usable life of an LED signal (time at which output is 50 percent of initial) was based on similar definitions within the LED manufacturing industry. It is difficult to apply the typical definition of "time at which 50 percent have failed" to a lamp that does not generally experience catastrophic failure modes. Output will continue to degrade indefinitely, however, some quantity of light may still be emitted from the LED. For this reason, a usable life based on the relative intensity of the lamp seems more appropriate.

The recommendations made in the paper reflect that under initial operating conditions, the red LED signals are comparable to the incandescent signals. It is accepted that definitive conclusions about the long-term operation of the signals must be made only after the appropriate testing has been performed. Additionally, some of these tests must be performed under environmental extremes so that operational limit may be deduced.

To B. Ananthanarayanan

Regarding the reviewer's comment on signal output degradation, the statement in the paper, "signal output at nominal voltage and room temperature conditions shall not fall below 80 percent of intensity requirements before 1000 hrs of field operation," was intended as only an example of how the subject of output degradation should be addressed in the development of LED signal standards. The statement was not intended as a technical recommendation.

To V. Waik

Regarding maintenance costs, the greatest advantage of currently available red LED signals is the elimination of emergency or unscheduled replacement of red signal lamps. The magnitude of this cost savings is difficult to quantify due to the lack of records available from transportation agencies. However, until LEDs can be applied to all three signal colors, regular maintenance of the yellow and green signals will still be necessary.

Regarding the inclusion of a plotted "standard threshold" line on the graph of LED signal Output vs Time, no accepted standards for LED signals currently exists. Therefore, plotting a threshold line is not possible. It is important to note that the output vs time graph in the paper is intended to demonstrate the short-term, reversible effects of duty cycle and internal heat generation on the relative output of the red LED signal. These results will change depending on the ambient temperature of the test.

Electrical current controls to adjust signal output during times of high temperature or to compensate for normal output losses are being considered by signal manufacturers. However, when current is increased, the rate of output loss of the LEDs is accelerated. This might be offset if current could also be reduced during night operation. Until a manufacturer produces a signal of this kind, the results would be difficult to predict.

To V.H. Waight

During the close of NCHRP Project 5-12, it was found that several LED manufacturers were working on deep green LEDs that would be a significant improvement over the existing product. These new green LEDs were still in their development stage, therefore samples could not be obtained. It is not surprising that a signal manufacturer has now put together a prototype signal using this new generation of LEDs. The cost of such a signal must have been significant because the LED manufacturers were quoting prices of around $10 per LED at the time of our investigation. Whether or not the signal cost decreases enough to be economically feasible will depend on the availability of large quantities of these LEDs.

Sample testing of these new LEDs (direct from the LED manufacturer) can provide information about how well the future signals will meet the color standards. Also, an upper limit estimate of the intensity of the signals may be calculated. However, how well the new signals meet the intensity standards will depend on how the LEDs are powered within the signals. This is impossible to predict.

The stated 3–6 years of usable life for the red LED signals was based on life data from LED manufacturers. This data was recorded for discrete LEDs under a variety of conditions. Also, some short-term output data (approximately 1 year) on installed signals were available. The latter data were superimposed over the long-term discrete LED data to determine what possible trends might be occurring. It is believed that reasonably good predictions for usable life could be obtained in this manner. However, actual long-term testing of the LED signals in a variety of environments will yield much more conclusive data.