PHOTOMETRIC REQUIREMENTS FOR SIGNAL LAMPS USING INNOVATIVE LIGHT SOURCES: UPDATING REQUIREMENTS BASED ON LIGHTED SECTIONS

Michael J. Flannagan
Michael Sivak
Eric C. Traube

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

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Michael J. Flannagan, Michael Sivak, and Eric C. Traube

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16. Abstract

Current photometric requirements for some signal lamps in the U.S. are based on the number of "lighted sections" that comprise the lamp. Intensity requirements are somewhat higher for lamps with more sections, partially adjusting for the presumably larger lighted area of a lamp with more sections, and thereby establishing some control of luminance. The number of sections is used as a proxy for area, based on the assumption that lamps will be constructed with optical units of a certain approximate size, each with a single incandescent bulb of relatively high candle power. However, recently there has been growing interest in, and in some cases use of, a greater variety of sources for signal lamps, including LEDs, neon tubes, miniature halogen bulbs, and distributive light sources. The relationship between number of lighted sections and surface area that could be assumed for lamps with relatively large incandescent bulbs cannot be extended to the new sources. Therefore the way in which photometric standards address the areas or luminances of signal lamps must be reassessed. This document reviews the existing research that is relevant to the roles of lighted sections and area in signal-lamp performance, presents the findings from a new experiment, and offers tentative recommendations about how to update the lighted-section photometric requirements for new light sources.

The available evidence suggests that, although references to lighted sections should be replaced by something more broadly applicable to a variety of sources, something similar to the spirit of the current requirements should be retained (i.e., primary emphasis on control of intensity but with some recognition of area and luminance). One major alternative would be to abandon control of area and luminance entirely, regulating lamps only in terms of intensity. This would be an extremely flexible approach that would allow maximum innovation in the use of new technologies, and it would continue to insure control of the most important aspect of signal lamps (intensity). However, the current evidence does not support a complete elimination of area and luminance control. We recommend that the concept of a lighted section in the current regulations be replaced by a standard area, with a tentative value being 225 cm^2.

17. Key Words
photometry, signal lamps, stop lamps, tail lamps, turn signals, luminance, intensity, area, aspect ratio, reaction time, brightness

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Contents

1.0 Introduction

The current photometric requirements in Federal Motor Vehicle Safety Standard (FMVSS) 108 (1998) for certain signaling and marking lamps are based on the number of lighted sections that make up the lamps. Three classes of lamps are distinguished on that basis—those having one, two, and three or more sections. The intensity requirements, both minima and maxima, are somewhat greater for lamps with more sections (although the increases in the requirements are less than proportional to the number of sections). The lamps regulated in this way are the front and rear turn signals, the tail lamps, and the stop lamps (but not the center high-mounted stop lamp, or CHMSL).

For lamps of traditional construction, the meaning of "lighted section" is reasonably obvious: each lighted section is the light emitting surface illuminated by a single bulb. Because of the optical constraints of reflector cavities and lenses, and assuming that the bulbs involved all have about the same candle power, the lighted sections can all be expected to have about the same area. Knowing the number of lighted sections that make up a lamp therefore tells one something about its total area, and the number of lighted sections can be used as a proxy for total area. Adjusting the intensity requirements on the basis of the number of sections achieves some level of constraint on the overall average luminance (total intensity divided by total area) of the lamp. There will also be some constraints on the shape of each section. The ratio of height to width (the aspect ratio) for a single lighted section will not normally be extremely high or low, given that the light must all come from a single location (a single bulb).

However, for lamps that use various innovative light sources—or may use them in the near future—the value of the number of sections as an indicator of area and shape breaks down. In the case of LEDs or miniature halogen bulbs, the candle power of each element is normally so much smaller than that of conventional signal-lamp bulbs that virtually all lamps will be composed of more than three lighted sections, even though many of those lamps may have small total areas. Because there are many elements, the overall shapes of the lamps are less constrained than those of lamps using only a few, more powerful sources. Neon tubes and various forms of distributive lighting (including fiber optics as well as other forms of light guides, all of which are less constrained than conventional cavities and lenses) complicate the situation further. In those cases, a single source may be relatively powerful, so that a lamp with only one source (and therefore only one lighted section if number of sections is determined by number of sources) may be very large and of virtually any shape.

It seems likely that the use of sources other than conventional filament bulbs in signaling and marking lamps will grow, and therefore the practice of specifying intensity requirements in terms of number of lighted sections needs to be reassessed. (Although, interestingly, the largest use of innovative sources so far is the use of LEDs in CHMSLs, which are not regulated in terms of number of lighted sections.) The references to lighted sections in FMVSS 108, and in several documents of the Society of Automotive Engineers (SAE), are strongly tied to a specific type of light source (incandescent bulbs of a certain approximate candle power). However, given the current circumstances, the National Highway Traffic Safety Administration (NHTSA) has had no clear alternative to applying the concept of lighted sections to innovative sources in a straightforward way, such that a stop lamp using three or more LEDs would have to meet the intensity values for a three-section lamp even though it might have a smaller area than many conventional one-section lamps ("Notice of proposed rulemaking," 1994).

There is a clear need for some way of specifying lamp characteristics that is more flexible—and more closely tied to the parameters that presumably really matter in determining the visual effectiveness of lamps; such as intensity, area, luminance, and shape. One way of adapting the lighted-section concept to LEDs is incorporated into SAE J1889 (SAE, 1993). In that document, lamps are nominally assigned to one of the three lighted-section classifications based on their maximum linear dimensions, with no consideration of how many lighted sections (i.e., LEDs) they actually have. If the maximum linear dimension is less than or equal to 150 mm, the lamp is considered to have one section; if it is from 151 to 300 mm, the lamp is considered to have two sections; and if it is 301 mm or more, the lamp is considered to have three sections. Various other proposals have been made for reinterpreting the lighted-section requirements to make them more broadly applicable, although none have been accorded as much formal status as SAE J1889.

The purposes of this document are (1) to review the research that bears on the current lighted-section photometric requirements, as well as research related more generally to the roles of intensity, area, luminance, and shape in determining the visual effectiveness of lamps, (2) to present a new set of results that addresses a discrepancy in the previous results concerning lamp area, (3) to review the alternatives for adapting, or simply dispensing with, the lighted-section requirements (including SAE J1889), (4) to make tentative recommendations about the alternatives best supported by the evidence, and (5) to identify remaining issues that could be addressed by future research.

A large number of sources of relevant evidence are available, ranging from studies that specifically addressed the issue of the number of lighted sections in automotive signal lamps, to more basic studies of the roles of stimulus luminance and intensity in visual performance. Our overall assessment is that, in spite of some uncertainties and some apparent discrepancies that we discuss and try to resolve, the available evidence is sufficient to support a practical solution to the question of how the lighted-section requirements should be changed to accommodate new signal-lamp source technologies.

2.0 Previous Research

There are several differences between conventional incandescent bulbs and various innovative light sources that may affect the visual appearance and effectiveness of signal lamps. In this section we consider five of these differences and review the evidence from past studies of visual performance that bears on the issues that they raise. The first two of these differences raise questions with the current strategy of basing photometric requirements on the number of lighted sections, and therefore are most important for the question of how the current standards should be modified:

1. *Area, Intensity, and Luminance.* The rough proportionality between number of lighted sections and total area that can be expected with conventional incandescent bulbs no longer applies when a greater variety of sources is considered. For some sources, the unit that can reasonably be construed as a single lighted section may be very small (e.g., LEDs) whereas for others it may be very large (e.g., neon). Because the number of lighted sections can no longer serve as a proxy measure for total area, it is necessary to find an alternative. It is also an occasion to reexamine more generally the relative roles of intensity, area, and luminance in determining lamp effectiveness.
2. *Aspect Ratio.* Lamp shape is less constrained with some of the new light sources. There are few limits to the variety of shapes that designers might consider for lamps based on LEDs, neon, or fiber optics. However, much of that variety may be captured in a relatively manageable way by a simple shape parameter—the aspect ratio (height to width, or vice versa). Aspect ratio is a full description of shape only for rectangular lamps, but it may be that even many exotic shapes can be modeled satisfactorily by using the smallest rectangles that could enclose them.

The other three differences have no direct effects on the meaning or usefulness of the number of lighted sections, but we discuss them in this section because they are potentially important for a comprehensive understanding of the visual effectiveness of lamps that use innovative sources:

3. *Spectral Power Distribution.* Some sources, even when they are matched with incandescent-bulb lamps in chromaticity, will be substantially different in spectral power distribution. Do such differences affect visual performance?
4. *Luminance Uniformity.* The type of light source used may affect the distribution of luminance within the nominal face of a lamp. Many LED lamps appear as arrays of very bright dots against a dark background, neon lamps tend to have very even luminance distributions, and a typical lamp made with an incandescent bulb behind a lens is probably somewhere in between. Do these differences affect the appearance or

performance of a lamp, or is average luminance (total intensity divided by total area) all that matters?

5. *Rise Time.* Certain light sources are inherently faster than incandescent bulbs. Considering the strong practical importance of reaction time, at least for stop lamps, should this difference be taken into account in some way in determining photometric standards for signal lamps using such sources?

2.1 Area, Intensity, and Luminance

There has been a considerable amount of discussion of the roles of intensity, area, and luminance in determining the visual effectiveness of lamps (e.g., Henderson, Sivak, Olson, & Elliott 1983; Sivak, Flannagan, & Olson, 1987). Conventional thinking has been that, under most practical conditions for signal lamps, intensity is the most important of the three; but that either area or luminance should also be taken into account to a lesser extent. That view is consistent with the current U.S. regulations for signal lamps, which primarily control intensity but also make relatively minor adjustments in intensity based on area (using number of lighted sections as a proxy for area). As an example, the current U.S. photometric requirements for stop lamps (not including CHMSLs) are shown in Figure 1.

Figure 1 is intended to summarize and illustrate how limits on intensity, area, and luminance are interrelated. Any lamp can be assigned to a point in Figure 1 based on its intensity and area. Because luminance is intensity (the y-axis variable) divided by area (the x-axis variable), the luminance of the lamp is then indicated by where it falls on a set of straight isoluminance lines radiating from the origin (lines having the form y/x = a constant). Figure 1 thus illustrates that, although each of the three variables being discussed (intensity, area, and luminance) may be useful for some purposes, they do not refer to three independent aspects of signal lamps. They are three ways of describing a set of possible lamps that is in a more fundamental sense two dimensional. As soon as any two of the three variables are specified, the location of a lamp in a diagram like Figure 1 is determined, and the value of the third variable can be calculated.

In Figure 1, pure limits on intensity can be illustrated as horizontal boundaries, pure limits on area can be illustrated as vertical boundaries, and pure limits on luminance can be illustrated as diagonal boundaries radiating from the origin. As shown in the figure, the current actual limits are not any one of these pure types, but something of a mixture. The intensity limits in Figure 1 are all from FMVSS 108, but only the lowest of the area limits (50 cm^2) is explicitly in the standard. FMVSS 108 is written in terms of number of lighted sections, and the areas in

Figure 1 are translations from those terms to implicit areas, based on SAE J1889. That document suggests that a maximum horizontal or vertical linear dimension of "150 mm per lighted section represents a typical large lighted section in present incandescent lighting device designs" (SAE, 1993, rationale section 4.1.5.1). (Note that the claim made in SAE J1889 is that 150 mm represents a "typical large" lamp rather than a lamp that is typical or average in general, as is probably appropriate for establishing a maximum limit.) The areas used in Figure 1 are the square of that value (225 cm^2) for the maximum area of a single lighted section, and twice that area (450 cm^2) for the maximum area of two sections. The intensity values from FMVSS 108 that are used to define the upper and lower boundaries of the shaded areas in Figure 1 are (for one, two, and three or more lighted sections, respectively) 80 to 300, 95 to 360, and 110 to 420 cd.

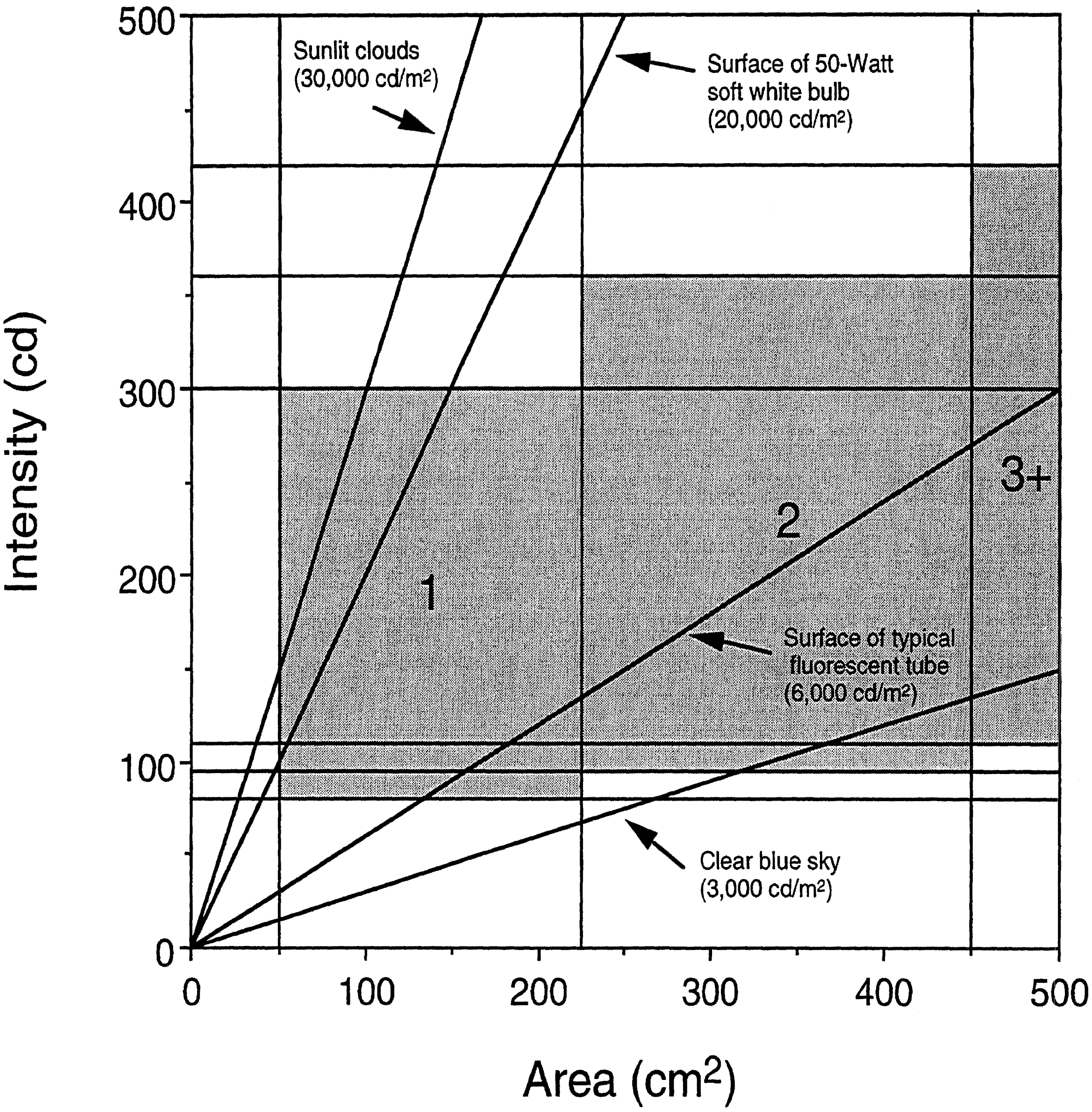

Figure 1. An illustration of the current intensity and area limits in FMVSS 108 for stop lamps (not including CHMSLs). The shaded areas represent the range of legal lamps with one, two, or three or more lighted sections. The higher area limits (225 and 450 cm^2) are not explicitly in FMVSS 108, and are based on SAE J1889 (see text for details). The intensity limits are (for one, two, and three or more lighted sections, respectively) 80 to 300, 95 to 360, and 110 to 420 cd. The diagonal lines radiating from the origin are isoluminance lines of several common stimuli that are near the approximate luminance limits implicit in FMVSS 108.

2.1.1 Basic Research.

A number of formal studies, specifically oriented to signal lamps, have been done to investigate the effects of area, intensity, and luminance. However, before turning to those applied studies we will summarize some useful results from more basic work on the effects of those stimulus variables on human vision. Although the basic research results cannot easily be extended to give specific answers about the effectiveness of real lamps under practical conditions, they may be useful in suggesting the general form of the results that can be expected. The basic work suggests that, for the conditions that are of practical importance for signal lighting, no one of the three variables alone (area, intensity, or luminance) is likely to be sufficient to predict signal effectiveness. As we discuss below, the basic vision work suggests that the critical value is the product of area raised to a variable power (ranging from 0 to 1 for various conditions) and luminance. This will turn out to be consistent with most of the applied work discussed below as well.

A considerable amount of basic work has been concerned with the extent to which area and luminance trade off in determining the threshold for detecting a visual stimulus (e.g., Brown & Mueller, 1965; Thomas, 1975). Although threshold detection is not directly relevant to signal-lamp effectiveness (practical lamps presumably have to be well above threshold to be effective), there is evidence that similar relationships hold above threshold, for example in determining minimal reaction time to visual stimuli (Ueno, 1979). When stimuli are relatively small there is a complete tradeoff between area and luminance, such that the visual threshold is determined simply by their product. This is often referred to as Ricco's law, which states that at threshold the product of area, A, and luminance, L, is a constant:

$$AL = k$$

Note that area can be canceled out of the expression AL (because luminance is intensity divided by area) and Ricco's law therefore implies that visual performance is constant for constant intensity. This suggests that visual performance is based on complete spatial summation of light energy over the area in question, and in that sense the stimulus can be considered a point source.

It is not possible to specify a single value for the maximum area at which Ricco's law applies because the value depends on other circumstances—including background luminance, location in the visual field, and stimulus duration. However, an approximate limit for a broad range of conditions is 10 minutes of arc (Geldard, 1972). Although this value cannot be applied with certainty to make inferences about lamp performance, note that this would be the angle subtended by a lamp 15 cm in diameter viewed at a distance of 52 m. If the approximation of 10 minutes is accurate, and if threshold detection is the performance measure of concern (probably some form of conspicuity is of more practical importance for signal lamps), then such a lamp can only be considered a point source if it is more than about 50 m away.

For somewhat larger stimuli, the relationship changes such that differences in area are less effective in compensating for differences in luminance, as characterized by the formulation known as Piper's law:

$$A^{0.5}L = k$$

And as stimuli become even larger, differences in area no longer matter and the threshold is eventually determined solely by luminance:

$$L = k$$

Note that these relationships are special cases of a more general formulation in which the exponent on area is a variable, n:

$$A^{n}L = k$$

This general formulation offers a way to describe a range of outcomes for the roles of area and luminance in determining visual threshold. Note that if viewing distance is constant, so that area can be measured in terms of absolute size rather than in terms of subtended angle, then when $n = 1$ performance is determined purely by intensity (absolute area times luminance), and when $n = 0$ performance is determined purely by luminance. Often the value of n will not be 1 or 0 but somewhere in between (for example, when Piper's law holds, $n = 0.5$). Thus, only in certain limiting circumstances will performance be determined purely by intensity or luminance.

Figure 2 shows functions based on various values of the exponent. All of the functions originate at a point corresponding to a lamp with an intensity of 80 cd and an area of 50 cm^2 (currently the minimum intensity and area for a stop lamp in the U.S.). Each of the functions is a candidate isoperformance curve, joining points representing lamps that would have performance equal to each other if each of the various values of the exponent were valid. The horizontal line (triangles) corresponds to Ricco's law and an exponent of 1.0. If Ricco's law applies, then each point along that line represents a lamp that should be equal in performance to the 80-cd, 50-cm^2 lamp. Because Ricco's law states that area times luminance (i.e., intensity) is a constant at visual threshold, then intensity is all that matters in determining performance. Likewise, the uppermost function (squares) corresponds to constant luminance and an exponent of 0.0. The next-to-highest function (open circles) corresponds to Piper's law.

The function with filled circles is meant to represent, in an approximate way, the lower limits of the region permitted by current regulations. We derived it by fitting the general form of the area/luminance law to the one-, two-, and three-section lamps with the minimum intensities and areas (80 cd and 50 cm^2, 95 cd and 225 cm^2, 110 cd and 450 cm^2). We used linear regression of log intensity on log area to fit the three points, yielding a value of 0.86 for the exponent n. This value provides one way to compare the limits implicit in FMVSS 108 to the equal-luminance ($n = 0.0$) and equal-intensity ($n = 1.0$) limits. Both graphically, and in terms of values of n, the current limits are much more similar to the equal-intensity limit. There are several aspects of this curve fitting that could be done differently. Perhaps most prominently, the area limits between one and two sections (225 cm^2) and between two and three sections (450 cm^2) could be lowered. But even if each section is considered to be 50 cm^2, so that the upper area limits are 100 and 150 cm^2, the resulting value of n is lowered only to 0.71, still much closer to equal intensity than equal luminance.

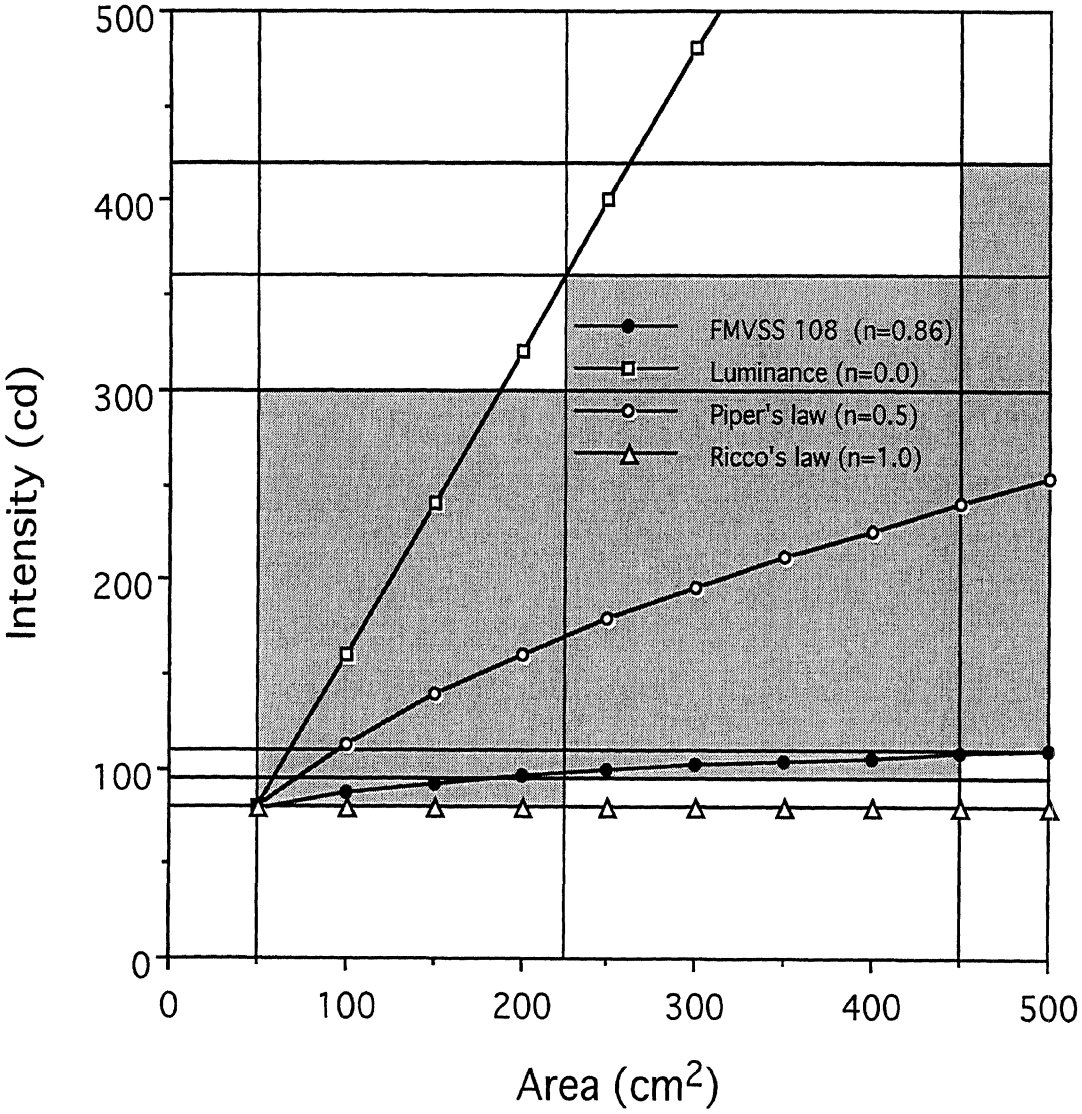

Figure 2. The best fitting function for the lower limits of the intensity and area regions currently permitted by FMVSS 108 for stop lamps. See text for details. Also, for comparison, illustrations of isoperformance curves passing through 80 cd and 50 cm^2 (minimum intensity and area for a stop lamp) based on Ricco's law, Piper's law, and constant luminance.

2.1.2 Applied Research

We now turn to information that bears directly on signal-lamp effectiveness. We will concentrate the discussion on studies that were concerned with the minimum intensities for stop lamps. There are two reasons for this. First, it is the issue that has motivated by far the most work, and, second, it is the issue of most practical importance for current purposes concerning use of LEDs in stop lamps. The studies to be reviewed have come to different conclusions on the crucial question of whether intensity values should be adjusted for lamps of different area. We will review first the studies that concluded that there should be some adjustment, and then the ones that concluded that intensity alone was sufficient to determine performance. Interestingly, the two groups differ markedly in their methods. The studies in the latter group were all based on reaction time methods, while those in the former group primarily used subjective methods, such as expert judgment.

These two broad classes of methods should probably be considered complementary, and it is not simple to resolve a discrepancy between them. Subjective methods may capture more aspects of lamp performance that are important for real world functioning, but they may be subject to various prejudices. Reaction time methods are free from such prejudices, but they may not capture all aspects of lamp performance that are important in actual traffic. Speed of response is not the only criterion for true effectiveness. A quality that might be described as salience, or the ability to get a distracted driver's attention, is probably also an important part of a lamp's overall effectiveness. If reaction time is measured in the proper context—perhaps with multiple possible lamp locations, or a concurrent loading task similar to driving—it may be possible to capture that aspect of lamp performance, but it is difficult in any experimental setting to match the cognitive and perceptual task loads that may be typical in critical traffic situations. Even when an experiment is performed in actual traffic, the subjects are probably more attentive than actual drivers in routine driving, simply because they know their performance is being monitored in some way.

The idea that lamp intensity should be adjusted for area is an old one in automotive lighting. Mortimer (1970, p. 232) suggests that, even prior to the explicit distinctions among lamps with different numbers of lighted sections, which were introduced in SAE J575d (SAE, 1967), concern for area was implicit in the treatment of class A and B turn signals in SAE J575c (SAE, 1966). In that older document, the limits for class A signals, which were meant to be used on larger vehicles such as heavy trucks, included a minimum area of 12 in^2 (77.4 cm^2), and a minimum intensity of 80 cd. In contrast, the corresponding minimum requirements for class B signals, which were meant to be used on smaller vehicles such as passenger cars, were only 3.5 in^2 (22.6 cm^2) and 40 cd. The increase in minimum area between class B and class A, a factor of 3.4, is less than the increase in intensity, a factor of 2. Because of this, the luminance corresponding to these minima is lower for class A signals (10,300 cd/m^2) than for class B signals (17,700 cd/m^2). This is illustrated in Figure 3. As was shown in Figure 1, isoluminance lines in such a figure are straight lines passing through the origin. A line from the origin to the lower point in Figure 3 derived from SAE J575c (corresponding to the class-B minima) would have a higher slope (indicating a higher luminance) than a line from the origin to the upper point (corresponding to the class-A minima). It can therefore be argued that the thinking behind SAE J575c was that intensity limits alone were not adequate to insure signal performance, that intensity should be adjusted for area, and that the change in intensity should be less than proportional to the change in area.

Intensity requirements that were adjusted for the number of lighted sections in a lamp were introduced by a change in Table 2 of SAE J575 between versions J575c (SAE, 1966) and J575d (SAE, 1967). The section-based intensity requirements applied to tail lamps, stop lamps, and class B turn signals (those used on smaller vehicles). For example, the minimum intensities for stop lamps at HV (on the optic axis) were 40, 70, and 100 cd for one-, two-, and three-section lamps, respectively. Previously, in SAE J575c, the required value at HV was 40 cd, with no reference to number of lighted sections. The section-based requirements introduced in 1967 were not applied to class A turn signals (those used on larger vehicles), a fact that is consistent with a general pattern in SAE documents over the years of applying the section-based requirements only for smaller vehicles. This was also the case, for example, when separate standards for stop lamps on smaller vehicles (SAE, 1984) and larger vehicles (SAE, 1985) were established. Presumably this is because of the large difference in styling concerns between smaller vehicles such as passenger cars and larger, typically more utilitarian vehicles such as trucks. Because of styling concerns, the signal lamps used on passenger cars are much more varied in size and shape than those used on trucks. With the relatively uniform sizes of lamps used on trucks, luminance and intensity are highly correlated, and it is less important to consider whether they might have separate effects.

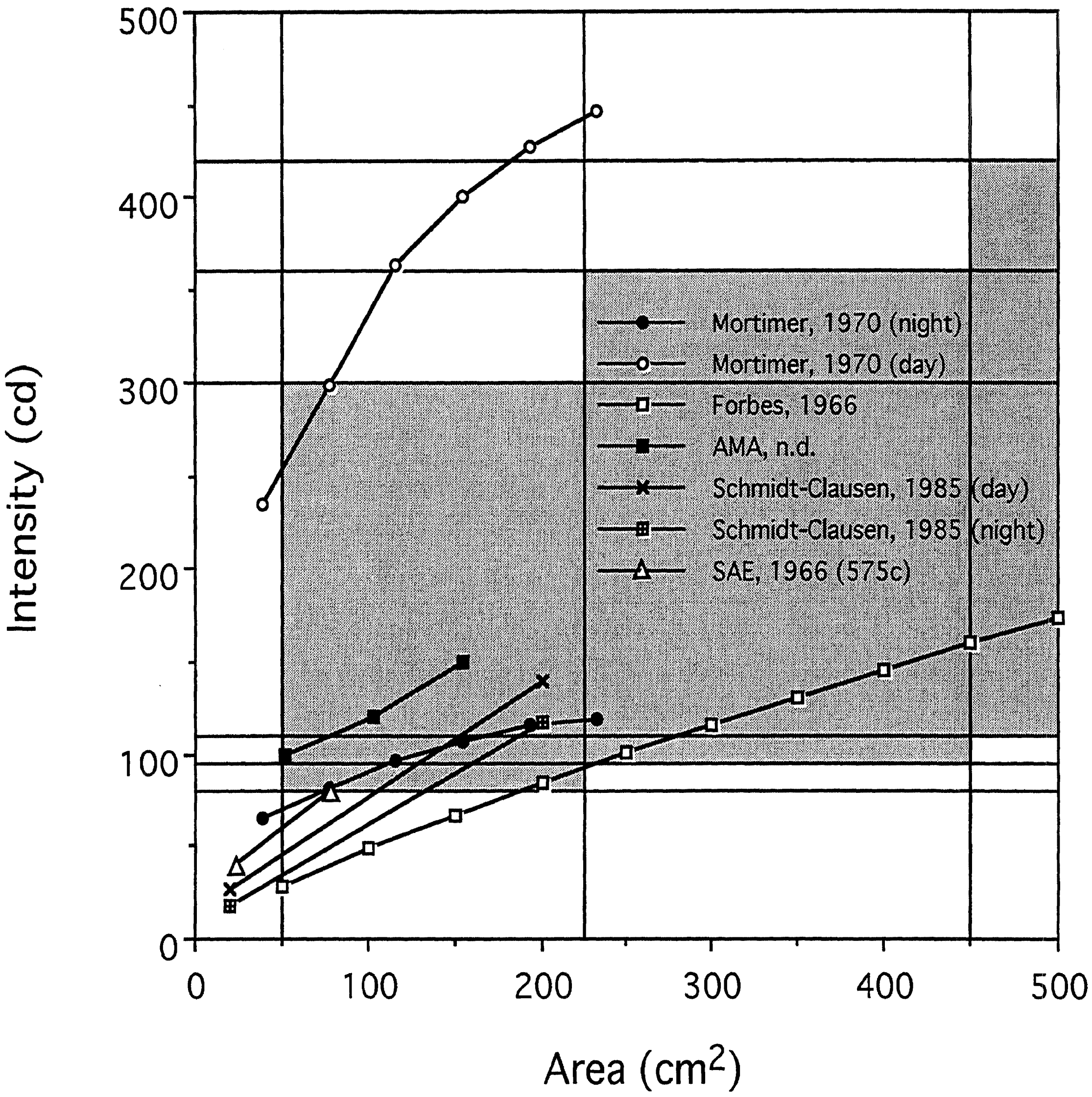

Figure 3. Summary of results on required minimum intensity as a function of area for stop lamps (not including CHMSLs), from several sources using a variety of subjective-rating methods. The shaded area is a representation of the combinations of area and intensity currently allowed by FMVSS 108 (see the caption for Figure 1 and the text for explanation of the higher area limits). Each group of points joined by a line represents a set of lamps that can be claimed to have equal effectiveness (see text for details).

Formal research on the joint effects of intensity and area on lamp effectiveness can be traced at least as far back as a series of demonstrations involving multiple-section lamps, performed in the 1960s under the auspices of the Vehicle Lighting Committee of the Automobile Manufacturers Association (AMA; currently the American Automobile Manufacturers Association, AAMA), and the Lighting Committee of the SAE. The documentation for these studies is minimal (AMA vehicle lighting tests, n.d.), but the methods involved can apparently all be characterized as subjective judgments by expert juries, primarily lighting engineers with substantial experience in automotive lighting. Typically, a group of experts would assemble at an outdoor test site, view a formally prepared series of lamps at realistic distances, and systematically record their subjective judgments about the visual effectiveness of the lamps. In the documentation of the demonstrations, the ambient lighting conditions are typically described as day or night, without further detail. The age, sex, and visual characteristics of the jury members are not described, but it is likely that they were neither very young nor very old (probably few, if any, above 65), and primarily male. The task of the jury members was to make ratings of each of the various lamps presented, usually using straightforward terms such as "acceptable" and "unacceptable," or "too bright" and "acceptable bright." The tests covered minima and maxima for several types of lamps. For example, a study conducted in Anderson, Indiana, on November 10 and 11, 1964, resulted in the following maximum intensities, at night, for tail lamps with one, two, or three lighted sections, respectively: 19, 25, 30 cd (i.e., 19, 12.5, or 10 cd per section) (AMA vehicle lighting tests, n.d., pp. 55-55A). Note that the increases in intensity are less than proportional to the increases in area, so that luminance decreases with increasing area. (These values were averaged over three sets of results for different section sizes; but, within each set, area was simply proportional to number of sections. The effect of area was about the same whether area was varied by changing the size of a single section or by combining sections of the same unit size.) A study conducted at General Motors Desert Proving Ground in Mesa, Arizona from April 6-10, 1964 provided the following minimum intensities, in the daytime, for stop lamps with one, two, or three sections, respectively: 100, 120, 150 cd (i.e., 100, 60, or 50 cd per section) (AMA vehicle lighting tests, n.d., pp. 61-61A). Note that, as above, the increases in intensity are less than proportional to the increases in area (each section was rectangular, 2 by 4 inches [5 by 10 cm]), so that luminance decreases with increasing area. The results for stop lamp minima are shown in Figure 3, for comparison with the values from SAE J575c (SAE, 1966) and with additional results to be discussed below.

In the late 1960s, Mortimer (1970) performed an extensive series of studies on rear signaling for the U.S. Department of Transportation. The roles of intensity, area, and luminance were among the many issues covered by that work. Mortimer's methods were considerably more formal than the demonstrations reviewed above; in some ways they were complementary to those demonstrations, but in other ways they were probably more valid. He used typical drivers as subjects rather than lighting experts. Although lighting experts may have insights from their technical knowledge of lighting, and simply from having paid more careful attention to lighting than most people, they may also have prejudices that—right or wrong—are of uncertain validity. For that reason, it is important to investigate the opinions and performance of typical drivers. Mortimer ran subjects individually rather than in groups, allowing for more careful photometry. The documentation of Mortimer's work is more complete than that of the demonstrations.

The results of most importance for current purposes are in his Figure 2.6 (Mortimer, 1970, p. 84). That figure shows desirable maximum and minimum intensity levels for red lamps as a function of their area, both during the day and at night. The minimum intensities for both day and night are reproduced here in Figure 3. Intensity values are higher for larger areas, but differences in intensity are less than proportional to differences in area, especially for the nighttime values. The values are primarily based on a study in which subjects viewed lamps of different area in a static field setup. The lamps were varied in intensity, and subjects made judgments about when the light levels were high enough to "certainly attract your attention" or so uncomfortable to view that they were "definitely too bright." As reflected in the recommended values reproduced in Figure 3, the findings were that the intensity limits depended on area.

Forbes (1966) undertook an analysis of the effects of intensity, area, and luminance that involved basic modeling of human vision and some new data collection with actual lamps. Although he was not explicit about how it was derived, a key element in his discussion of desirable lamp photometrics was the daytime threshold for lamp luminance as a function of area, shown in his Figure 6 (p. 14). That function is reproduced here in Figure 3 (translated into intensity, rather than luminance, as a function of area). Recommended intensity increases with area. The recommended changes in intensity are almost—but not quite—proportional to area, as indicated by the fact that a straight line fit to the data would intersect the y axis above zero (at 18 cd).

Schmidt-Clausen (1985) collected data concerning the intensity, area, and luminance of rear signal lamps from European drivers. He used a field setup with both fully static (lamps and subjects static) and semidynamic (lamps static, subjects in a moving vehicle) conditions. Subjects viewed lamps that varied in area and intensity, and rated each lamp on a scale from "too dark" through "optimal" to "too bright." A key set of results for present purposes are from his Table 5 (p. 223), which shows optimal light intensities, for both day and night, for lamps with areas of 20 and 200 cm^2. Those results are reproduced here in Figure 3. As with the previously reviewed studies, recommended intensity increases with area. The differences in intensity are slightly less than proportional to the changes in area. Interestingly, Schmidt-Clausen finds a smaller difference in desired intensity values for day and night conditions than was seen in Mortimer's results.

The data summarized in Figure 3 consistently show an increase in required intensity with increasing area. The results are also consistent in suggesting that the increases in required intensity are at least somewhat less than proportional to the corresponding changes in area. Comparison to the boundaries of the current U.S. stop lamp limits suggests that the consensus of the results shown in Figure 3 is that intensity should be increased by more than the values currently specified for one-, two-, and three-section lamps (for the minima, currently 80, 95, and

110 cd). However, it could be argued that the area values used to define the boundaries between one and two sections (225 cm^2), and between two and three sections (225 cm^2) are too large. If smaller values were used, the current requirements would be closer to the consensus of the data in Figure 3. However, those data are not the whole story. We now turn to a set of studies that provided evidence for a different conclusion—that intensity alone is sufficient to determine the visual effectiveness of signal lamps, and that intensity therefore does not need to be adjusted for lamps with different areas. These studies were all based on a relatively objective measure—reaction time.

The first of these studies was part of a comprehensive study of motor vehicle signal lamps (Cole, Dain, & Fisher, 1977). Citing results from a previous study of reaction time to stimuli that varied in area and intensity (Cole & Brown, 1968), Cole and his colleagues suggested limits for both area and intensity of signal lamps. Their recommendations for stop lamps are shown in their Figure 5.11 (Cole et al., 1977), and are partly reproduced in Figure 4 of the present report. They recommended minimum intensities of 100 cd at night and 200 cd in the day, with no adjustment for area up to a maximum area of 177 cm^2.

Sivak and colleagues performed a series of studies on stop lamp photometric requirements for the U.S. National Highway Traffic Safety Administration (NHTSA) in the mid 1980s (Sivak, Flannagan, Olson, Bender, & Conn, 1986). As part of that work they measured subjects' reaction times to red stop lamps that varied in area (78, 83, and 157 cm^2) and intensity (40, 60, 80, and 100 cd). The 12 stimuli resulting from the combination of the 3 areas and 4 intensities are represented by the open circles in Figure 4 of the present report. Only intensity had an effect on reaction time. Reaction times to the lamps at each level of intensity, but differing in area, were the same. In Figure 4 we have therefore joined the points for each of the four intensities, indicating that the lamps within those groups can be considered equally effective by the reaction time criterion.

Sayer, Flannagan, and Sivak (1995) also used reaction time to evaluate the effectiveness of lamps with areas of 50 and 150 cm^2, and intensities of 35 and 150 cd. The four stimuli resulting from the combination of these areas and intensities are represented by the filled circles in Figure 4 of the present report. Once again, only intensity affected subjects' reaction times, and we have joined the points for each of the intensities in Figure 4, just as for the results from Sivak et al. (1986).

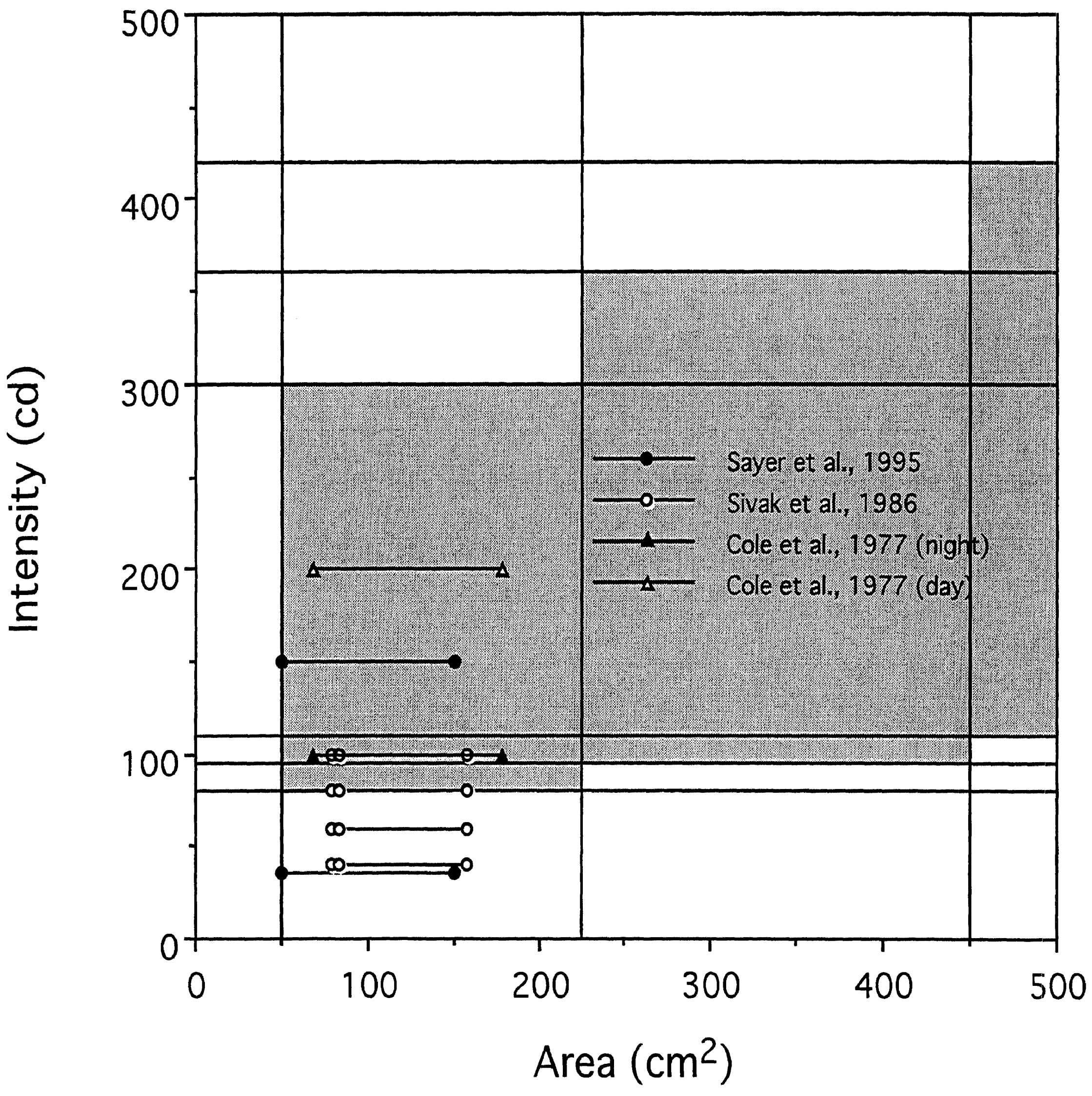

Figure 4. Summary of results on required minimum intensity as a function of area for stop lamps (not including CHMSLs), from several sources using reaction time as the primary criterion. The shaded area is a representation of the combinations of area and intensity currently allowed by FMVSS 108 (see the caption for Figure 1 and the text for explanation of the higher area limits). Each group of points joined by a line represents a set of lamps that yielded equal reaction times, and on that basis can be claimed to have equal effectiveness.

All of the results in Figure 4 indicate that, at least for the ranges of area investigated, intensity alone determines reaction time, and therefore—it can be argued—determines overall visual effectiveness. Comparison of Figures 3 and 4 thus reveals a consistent discrepancy between the studies that used reaction time and those that used alternative methods (primarily subjective judgments of lamp effectiveness, either by lighting experts or by typical drivers). It is not immediately obvious how to resolve this discrepancy. As we argued earlier, neither method can simply be rejected as invalid.

In spite of the fact that both experts and typical drivers consistently indicate that, in order to be equally effective, lamps with larger areas should be somewhat more intense, the reaction time studies fail to indicate this. Is there some aspect of lamp effectiveness that expert judgment captures, but reaction time does not? Certainly that is possible. But at least one obvious possibility—some sort of salience or ability to attract attention—may not be a very good candidate. In all three reaction time studies (Cole & Brown, 1968; Sayer et al, 1995; Sivak et al., 1986) subjects were required to perform a tracking task concurrently with reacting to the lamp onsets. The tracking tasks were meant to at least approximate the perceptual demands of driving, and therefore there should have been at least some opportunity to observe effects of any special attention-getting properties of the lamps. On the other hand, it could be argued—as we suggested earlier—that subjects in an experiment are always substantially more alert than the average driver on the road.

Given that two sets of data, both of which have a reasonable amount of face validity, seem to give different answers about the roles of intensity, area, and luminance in determining signal-lamp effectiveness, it is difficult to argue for a change in the status quo. By this reasoning, the default approach to the practical question of how to set photometric limits for signal lamps would be to continue the spirit of the current requirements, simply adopting a more broadly meaningful definition of area than the current reference to number of lighted sections. The new alternative would still put primary emphasis on intensity, but continue to make relatively minor (far less than proportional) adjustments in intensity on the basis of area.

Given the current state of knowledge, what new data—if any—would help to resolve the situation? Because it is the reaction time data that seem to challenge the status quo (by suggesting that intensity limits alone are sufficient) we reasoned that it would be useful to see how strong a case could be made from reaction time data. In Section 3 of this report we describe an experiment in which we used a particularly strong manipulation of lamp area. If even a very strong manipulation of area fails to cause a difference in reaction time, it might be worth more seriously considering the possibility of regulating only intensity (rather than just primarily intensity, with some consideration of area, as is presently the case). On the other hand, if area can be shown to have an effect, and if the effect is relatively large, then the status quo is even more strongly supported.

2.2 Aspect Ratio

The various new technologies that are becoming available for signal lamps allow more flexibility in lamp shape than has been possible previously. In this section we summarize the information available concerning how lamp performance is affected by lamp shape—specifically aspect ratio, the ratio of height to width or vice versa. Aspect ratio does not capture all of the differences in lamp shape that may be contemplated. For example, consider a lamp with a lighted area that is 1 cm wide and curved to form a circle 20 cm in diameter at the outer edge, so that it appears as a thin ring of light around a large, dark center. Such a lamp would have a lighted area of about 60 cm^2. Would it have the same effectiveness as a more conventional round lamp of the same area (which would appear as a filled circle of light about 9 cm in diameter)? Present research results cannot be extended to answer questions about such relatively exotic shapes with much confidence. However, a number of results are available for the effect of aspect ratio, and, to the extent that many shapes may be adequately approximated by the smallest rectangle that can enclose them, these results may be extendible to the great majority of practical lamps.

The basic vision research that is most relevant to the issue of aspect ratio is that of Lamar, Hecht, Hendley, and Shlaer (1948; Lamar, Hecht, Shlaer, & Hendley, 1947). Their work was concerned with the effects of area and aspect ratio on the luminance threshold for detecting a visual stimulus. As we mentioned earlier, simple detection may not be the best criterion for effectiveness of a signal lamp. Nevertheless, work on basic detection may reveal fundamental aspects of how the visual system operates—specifically, how it integrates over space—that may help in understanding signal effectiveness. Lamar and his colleagues measured visual threshold for a range of stimulus sizes (defined in terms of square minutes of angle subtended at the eye of the observer) and aspect ratios. Their findings suggest that for larger stimulus sizes (above about 100 square minutes—equivalent to a 150-cm^2 lamp viewed at about 42 m or closer) aspect ratio makes little difference in detectability. (If anything, their findings suggest that for areas above 100 square minutes stimuli with higher aspect ratios may be somewhat more detectable than square stimuli—opposite what is probably the most common expectation, that lamps with high aspect ratios may be less effective.) For stimulus sizes smaller than about 100 square minutes, higher aspect ratios are less detectable, but only for ratios above about 7:1. Thus, their data suggest that relatively high aspect ratios may reduce the detectability (and perhaps the general effectiveness) of signal lamps that are small or viewed at a long distance. Given the gaps that drivers typically allow in traffic, rear signal lamps will often be larger in angular size from the point of view of a following driver than the 100-square-minute level that Lamar and his colleagues identified as the maximum size at which larger aspect ratios seemed to have negative effects on detection.

Several relatively applied studies, specifically concerned with motor vehicle signal lamps, have examined the possible effects of aspect ratio. Olson (1987) investigated a set of signal lamps that included two LED lamps, one that was square (i.e., with an aspect ratio of 1:1) and one that was an elongated rectangle with an aspect ratio of about 100:1. The lamps were matched in total area and in intensity; they, in fact, had the same number of LEDs, simply arranged differently. Olson had a set of typical drivers observe the lamps in a road test and then make subjective evaluations of the visibility and overall effectiveness of the lamps. The high-aspect-ratio lamp was consistently ranked as less effective than the square lamp. However, Olson also measured reaction time to the lamps and found no difference between the two lamps.

In two studies in which they measured reaction time to simulated stop lamps, Sayer and colleagues (Sayer et al., 1995; Sayer, Mefford, Flannagan, & Sivak, 1996) found that aspect ratio had little effect on reaction time unless aspect ratio was relatively high (greater than about 6:1) and lamp intensity was relatively low (less than about 25 cd)—values that might be encountered in a CHMSL, but not in other stop lamps, which must have minimum intensities of 80 cd.

A demonstration designed to explore the effect of aspect ratio on the perceived effectiveness of LED and neon signal lamps was performed at a meeting of the SAE Lighting Committee in September of 1996 (Bhise, Jack, & O'Day, 1997). The observers were members of the Lighting Committee and can be regarded as vehicle lighting experts, but they may not be typical of the driving public. Of the sample of 53 observers, only one was older than 65 and only one was female. During the study, the observers were shown red signal lamps with either LED or neon light sources, and aspect ratios of 2:1, 8:1, or 32:1. They were asked to make a variety of subjective evaluations about the "attention getting" qualities of the lamps. Aspect ratio was found to have an effect on those ratings that was very consistent across subjects. For example, when asked to indicate which of a set of 100-cd LED lamps was most attention getting, 72% of the observers chose the lamp with an aspect ratio of 2:1, 22% chose the lamp with an aspect ratio of 8:1, and only 6% chose the lamp with an aspect ratio of 32:1. However, although the effect was consistent across subjects, the data cannot be used to estimate how strong the difference in perceived effectiveness was in terms of how much of a change in intensity might compensate for the perceived differences.

Interestingly, the results that are available concerning the effect of aspect ratio on signal effectiveness are similar to the results on the effect of area in that studies that collected subjective ratings of effectiveness suggest that the variable in question does change signal effectiveness, whereas the studies that used reaction time suggest that it does not. In the case of the Olson (1987) results, this contrast exists within the same study. As before, it is difficult to resolve this discrepancy. However, in this case, the evidence in favor of an effect is weaker in the sense that neither the subjective ratings reported by Olson (1987) or Bhise et al. (1997) were collected in a way that allows estimation of how big an adjustment in intensity would be needed to compensate for the differences in aspect ratio. Therefore, even accepting the subjective data as definitive, the differences among aspect ratios, in terms of intensity adjustments, have not been shown to be substantial.

2.3 Spectral Power Distribution

The colors of signal lamps must meet limits defined in terms of the 1931 CIE chromaticity coordinates (SAE, 1995). However, lamps that are similar or even identical in terms of those coordinates may have substantially different spectral power distributions. For example, LEDs typically have narrow bands of power concentrated at their peak wavelength, whereas filtered incandescent bulbs typically have relatively broad bands. These differences raise the possibility that human visual responses to such lamps may be different. Several studies of signal lamps have addressed this possibility.

A demonstration of red signal lamps, made with filtered incandescent bulbs and LEDs, was conducted by the SAE Lighting Committee in September 1986 (McKinney, 1986). A group of vehicle lighting experts were shown a series of pairs of lamps, each with one incandescent lamp and one LED lamp, and asked to judge the relative "conspicuity" or "attention getting quality" of the pair. Across pairs, the incandescent lamps were at constant intensity while the LED lamps varied. This allowed an estimate to be made of the relative photometric intensities of the lamps at which they were perceived to be equally conspicuous. The incandescent and LED lamps were not significantly different, suggesting that lamps that are matched in chromaticity will not differ in visual effectiveness, even if their spectral power distributions are different.

Although many subjects in Olson's (1987) study reported that an LED lamp looked brighter than a photometrically matched incandescent lamp, when he formally investigated these reports by having subjects adjust the lamps to be subjectively equal in brightness, there was no difference between the light sources.

Sivak, Flannagan, Sato, Traube, and Aoki (1994) investigated reaction time to red lamps with incandescent, LED, and neon sources. The main focus of that study was differences in reaction time that could be attributed to differences in the rise times of the various lamps, but the results can also be used to make inferences about the possible effects of the difference in spectral power distribution between the LED and neon lamps. Those two lamps did not differ substantially in rise time, but they did differ in spectral power distribution. Reaction times to the lamps were not significantly different, indicating that the differences in the spectral power distributions of the two lamps had no consequences for human reaction time.

Existing research therefore has not found that differences in spectral power distribution among filtered incandescent bulbs, LEDs, and neon sources have important consequences for signal-lamp effectiveness. The studies cited above all described the stimuli in terms of photometry based on photopic (daytime) visual efficiency, suggesting that photopic photometry is adequate to predict the visual effectiveness of the various red signal lamps that were involved.

2.4 Luminance Uniformity

In many lamps made up of LEDs, the individual LEDs appear as discrete bright dots against a dark background. The luminance across the face of the lamp is thus much less uniform than for neon lamps, which tend to have very evenly spread luminance, and for incandescent lamps, which vary in how even they appear depending on optical design. Although there has been speculation about how these differences might affect signal-lamp performance, there has been little research on the issue. Sivak et al. (1986) had subjects match the subjective brightness of actual red signal lamps (which used incandescent bulbs and varied in luminance uniformity) and variable stimuli that had the same area and shape as the actual lamps, but which had very uniform luminance. When the lamps were equally bright subjectively, the luminances of the uniform stimuli were consistently higher than the average luminances of the corresponding actual lamps. These results suggest that observers respond to the local luminance of the relatively bright parts of the lamps, rather than to the true average luminance of the entire face of the lamp, including the darker parts. As would be expected, this effect was weaker when the viewing distance was greater, as if the lamps were closer to being point sources at greater distance. Although this experiment does not clearly define how differences in the distribution of luminance affect lamp performance, it does indicate that average luminance (total intensity divided by total area) is not enough to capture all that matters for lamp effectiveness.

However, even if differences among lamps in uniformity of luminance were demonstrated to have substantial effects on lamp performance, it would probably not be a good idea to assume that the type of source used in a lamp (incandescent, LED, neon) reliably determines the degree of uniformity on the face of the lamp. For example, as individual LEDs become more powerful the optics that are used with them may become more similar to those used with incandescent bulbs, so that the face of a lamp made with LEDs would not necessarily show the discrete spots of light that are now often regarded as typical of LED lamps. If uniformity does emerge as a significant issue, it may be necessary to decide on a way of quantifying uniformity itself, independent of references to source type.

2.5 Rise Time

Several light sources—including LEDs, neon, and fast-rise incandescent bulbs (Sivak et al. 1994)—are inherently faster than conventional incandescent sources. Lamps using these sources may provide substantial savings in reaction time (Olson, 1987; Sivak et al., 1994). However, benefits in reaction time may or may not indicate benefits in conspicuity.

Reductions in reaction time are clearly good, but reaction time is not the only quality that is important for an effective signal. Reaction time is used in some studies as the main dependent variable to evaluate lamps, but it is not normally interpreted as simply a measure of response time. It is used to make inferences about more general properties of the stimuli, like conspicuity or the ability to attract attention. The differences in reaction time between fast-rise sources and standard incandescent bulbs should not necessarily be interpreted as demonstrating greater salience or greater general effectiveness of the fast-rise sources. For that comparison, the difference in reaction time should perhaps be interpreted more simply—as if the stimuli just appeared sooner rather than with greater conspicuity. If the reaction time advantage for fast-rise stimuli indicates simply earlier effective stimulus onset, rather than greater general stimulus effectiveness, then it is not clear how to trade off this benefit with other stimulus qualities.

For example, should LED lamps be held to lower photometric standards because they produce faster responses? This might be reasonable, but it would have to be based on a rather complex assessment of overall system effectiveness. Thus, two signal lamps—one based on LEDs and one based on incandescent bulbs—might be considered equivalent when the LED lamp had lower intensity. Under many circumstances the LED lamp would produce faster reactions, but under some circumstances (e.g., a following driver who is not paying attention, fog dense enough to make detection distance critical) the greater intensity of the incandescent lamp might make it more effective. However the effects of such tradeoffs on overall safety are not easy to quantify. Without a definitive solution to that issue, the improved response time to LEDs (or other fast-rise sources) should be viewed as a real benefit, but a benefit that is independent of other photometric aspects of the lamps.

2.6 *Summary*

Previous research suggests the following concerning the five issues introduced at the beginning of this section:

1. *Area, Intensity, and Luminance.* The evidence is inconsistent. Reaction time studies indicate that intensity alone may be sufficient to ensure adequate signal quality, but other studies, using more subjective data, suggest that some adjustments in intensity need to be made for lamps with different areas. (Although even much of the subjective evidence indicates that performance is more closely related to intensity than luminance.) Given that the evidence is equivocal, it is difficult to recommend a change from the status quo, in which the primary emphasis is on intensity, but in which the influence of area is recognized by increasing intensity levels (less than proportionately) as area increases. In the next section of this report we present a new experiment, using reaction time, to try to provide a somewhat better resolution for this situation.
2. *Aspect Ratio.* The evidence about the importance of aspect ratio is mixed as well: subjective evidence indicates that there is an effect of aspect ratio, but reaction time evidence is more negative. If there is a substantial effect of aspect ratio, it is probably that relatively high aspect ratios make lamps somewhat less effective when the lamps are relatively low intensity. Following the same logic used above—that equivocal evidence should not be used to recommend a change from the status quo—and considering that aspect ratio has not previously been used to modify intensity requirements, the conclusion would be to continue not to recognize aspect ratio. However, it may be worth examining the issue more thoroughly, at least in the case of low intensity lamps (e.g., tail lamps).
3. *Spectral Power Distribution.* The evidence that exists on differences in spectral power distribution (at least among red lamps) does not seem to show much of an effect.
4. *Luminance Uniformity.* Luminance uniformity has not been thoroughly studied. It may have a slight effect, but in any case it should probably not be assumed to be linked to source types. If it does emerge as an important issue, a way of defining and quantifying luminance uniformity independent of references to sources would be useful.
5. *Rise Time.* Rise time shows big advantages for certain sources, but it isn't clear how this time advantage should be traded off against other qualities that are part of the general performance of signal lamps, such as conspicuity or maximum detection distance.

Although it is tangential to the purposes of this report, it is worth noting the differences concerning desirable photometry for signal lamps in the day and at night that appear in several of the reviewed sources. In Figures 3 and 4, the results from Mortimer (1970), Schmidt-Clausen

(1985), and Cole et al. (1977) all suggest that stop lamps should be more intense in the day than at night. In the case of Mortimer's study, the difference is particularly strong. Schmidt-Clausen's optimal intensities are relatively low (probably at least partly due to the fact that the study involved European drivers who were accustomed to less intense signal lamps than those used in the U.S.) but the ratios between night and day are still substantial. The possible practical benefits of different day and night intensity levels deserve further consideration.

3.0 Reaction Time with Large-Area Lamps

The purpose of this experiment was to make a particularly strong manipulation of the area of signal lamps and see whether reaction time would be affected. The evidence concerning the effects of area reviewed in the previous section was equivocal. Reaction time studies consistently led to the conclusion that area had no effect, and that intensity limits alone were adequate to insure lamp effectiveness. In contrast, studies using more subjective methods generally suggested that differences in area did matter, and that greater area had to be compensated for with at least somewhat greater intensity. (However, none of the results support limits strictly in terms of luminance.) What are the consequences of these results for the question of how standards that refer to "lighted sections" of signal lamps should be changed? This mixed set of results cannot be used to argue convincingly for a clear change from the status quo, such as simply dropping all reference to lighted sections (or area) and setting standards in terms of intensity alone. The logical consequence would seem to be that the spirit of the existing standards should be preserved (i.e., continue to recognize area, simply in a more generally applicable way than by reference to lighted sections). Our reasoning in devising the present new experiment was that it was the only type of study that might yield evidence for a more substantial change in standards, specifically, strong evidence that area was not of importance. If even a strong manipulation of area shows no effect, then there would be reason to change from current practice. Alternatively, if a strong manipulation of area results in an effect on reaction time then at least there would be one study using the relatively objective method of reaction time that supports the recognition of area in devising standards.

We measured reaction time to red signal lamps of different areas that were matched in intensity. The difference in area was strengthened in several ways. First, we used a larger difference in nominal area than had been used in previous studies: 50 cm^2 versus 500 cm^2. Second, we were careful to make sure that the luminance on the faces of the lamps was uniform. It could be argued that nonuniformity makes the effective size of a lamp smaller than its nominal size, and the effective luminance higher than the average luminance over the entire nominal face of the lamp. For example, when an observer looks at the face of a lamp made with an incandescent bulb, there is typically a bright spot near the center of the lamp. If the observer is sensitive to that area of high luminance, he or she will be responding, in effect, to a smaller, higher-luminance lamp than that represented by the total intensity and area of the lamp. Third, we used a relatively short observation distance (15 m). The angle subtended by lamps presumably has an influence on whether or not the area matters. At extreme distances, that angle would be very small and the lamp would be a point source for all purposes, so that area could not have an effect on any aspect of how the observer perceives it.

3.1 Method

Participants. Twelve paid subjects participated in this study. There were six younger subjects (ranging from 19 to 33 years old, with an average age of 25.7), and six older subjects (ranging from 64 to 77 years old, with an average age of 71.5). Each age group had three males and three females. All subjects were licensed drivers.

Experimental setup. The experiment was conducted outdoors, in the daytime. Figure 5 shows the field setup used. The subject was seated in a car, facing directly north. The lamps were 15 m from the subject's eyes, to the left and right of a table that held power supplies and other equipment. The center table was hidden from the subject by a large white board that also had a visual fixation mark on it. The centers of the lamps were 1.31 m to either side of the fixation mark (so that, from the subject's point of view, they were 5 degrees of visual angle from the mark). Figure 6 shows the subject's view of the lamps. There were two lamps on either side of the fixation mark, one large and one small, one above the other. The visual fixation mark, as well as the midpoint of the vertical line between the centers of the two lamps on each side, were at the approximate seated eye height of the subject (1.1 m).

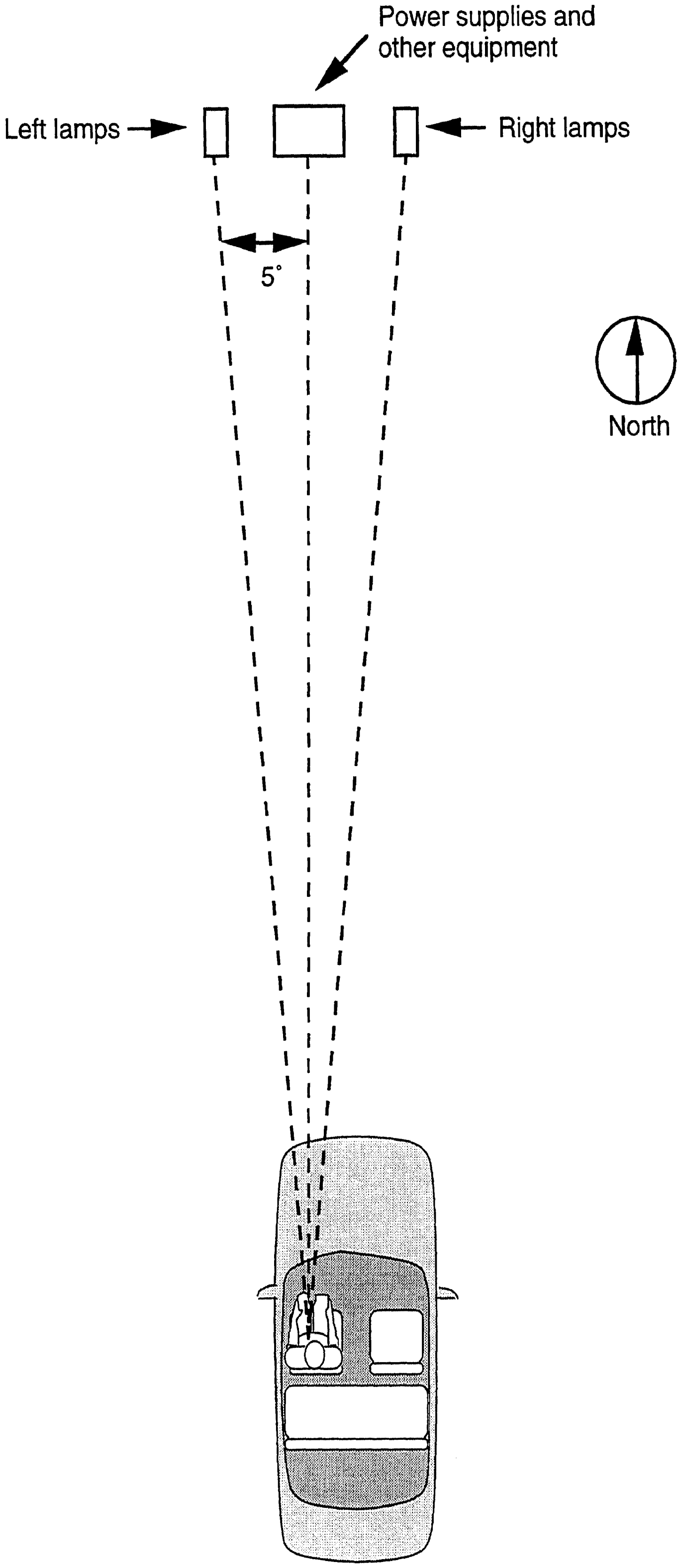

Figure 5. An overhead view of the field setup. The subject's vehicle faced directly north. The lamps were 15 m from the subject's eyes.

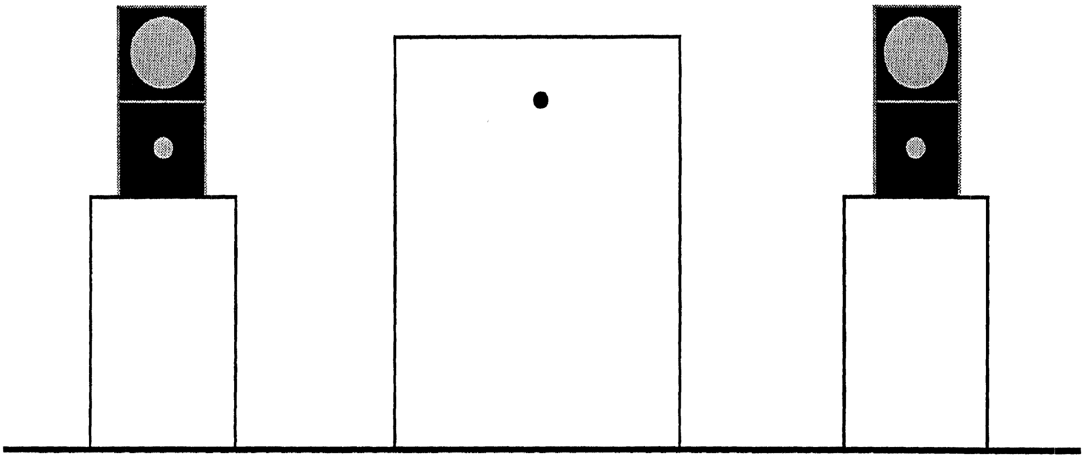

Figure 6. The subject's view of the stimuli. The white rectangle in the middle of the setup was a board that served to hide power supplies and various other pieces of equipment. The small black dot on that rectangle was the visual fixation point. In this view the large lamps are mounted above the small lamps. Half of the subjects saw these vertical positions reversed (small above large).

Experimental lamps. Four round lamps were constructed for the experiment. The face of each lamp consisted of a round, red lens centered in a square frame that was 30 cm on each side and flat black in color. Two of the lamps had large lenses (500 cm^2) and two had small lenses (50 cm^2), as detailed in Table 1. The lamps were designed to have relatively constant luminance within their illuminated areas. The construction of one of the 500-cm^2 lamps is shown schematically in Figure 7. Each lamp consisted of a large, nonreflective enclosure, at one end of which was a round aperture, a collimating Fresnel lens, and a red spreading lens consisting of an array of square elements. The enclosures were sealed, but relatively large (54,000 cm^3) so as not to concentrate heat. (During the experiment each lamp was on only intermittently, for periods of 3 seconds or less, at average intervals of about 50 seconds.) The source for each lamp was a single 100 W, 12.8 V tungsten-halogen bulb, located at the focal point of the Fresnel lens. No reflectors were used within the lamps. In order to make the illumination of the lamp face relatively uniform from the center to the edge, the Fresnel lenses were selected to have relatively long focal lengths (7 cm for the 50-cm^2 lamp and 20 cm^2 for the 500-cm^2 lamp). The square elements in the spreading lens were 6.35 mm on each side. The faces of the lamps thus appeared as arrays of bright images evenly spaced, 6.35 mm apart vertically and horizontally. Because the subjects viewed the lamps at 15 m, the spacing between the bright images was only 1.45 minutes of visual angle and the individual images were difficult to resolve. From the subject's position, the lighting of the faces of the lamps appeared virtually continuous.

Table 1
Dimensions of the experimental lamps. There were two large lamps and two small lamps. The visual angles subtended by the diameters of the lamps are given for the distance at which the subjects observed them during the experiment (15 m).

Nominal size	Area (cm^2)	Diameter (cm)	Visual angle at 15 m (degrees)
Small	50	8.0	0.30
Large	500	25.2	0.96

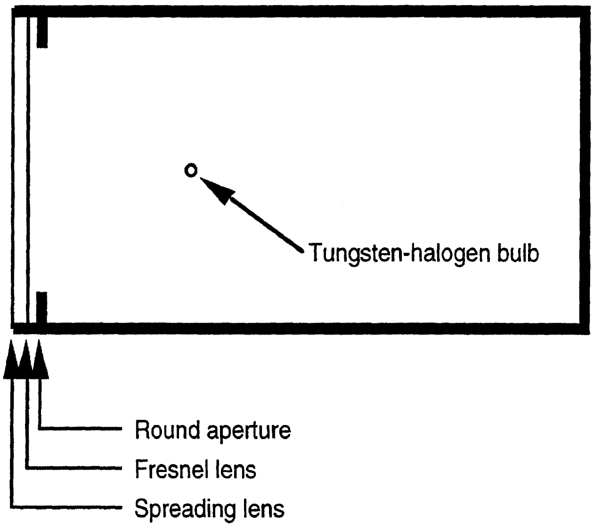

Figure 7. A schematic diagram of the construction of one of the 500-cm^2 lamps. The 50-cm^2 lamps were the same except that the round apertures were smaller and the bulbs were located closer to the Fresnel lenses (because of their shorter focal length).

A Photo Research 1980A Pritchard Photometer was used to measure the luminance at various points within the faces of the lamps (the center, the outer edge, and halfway between the center and the outer edge) from the subject's point of view. The field of view for the photometer was set at 20 minutes of angle for the 500-cm^2 lamps and 6 minutes of angle for the 50-cm^2 lamps. Several meridians across the faces of the lamps were measured. The results are shown in Figure 8. (Figure 8 also shows the falloff in brightness that would be expected from the cosines of the incident angles for rays from the bulbs to the centers and edges of the illuminated lamp faces. The falloff is roughly consistent with that expectation, with some further losses due to other mechanisms.)

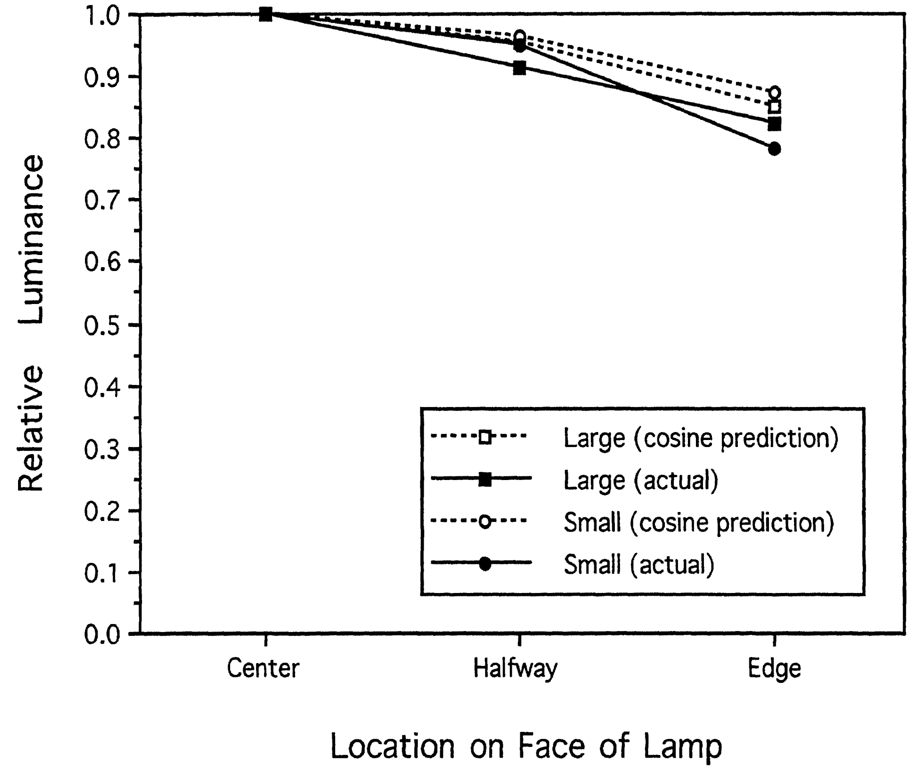

Figure 8. Falloff in luminance with distance from the centers of the faces of the lamps. Locations are at the center, halfway from the center to the edge, and at the edge. See text for details concerning the predicted and actual values.

Because perceived brightness is a nonlinear function of luminance, corresponding approximately to the log of luminance, the perceived falloff in brightness is even more subtle than suggested by Figure 8. To casual inspection, the faces of the lamps appeared to be evenly bright, an observation consistent with the fact that the falloffs in luminance from the center to the edge (18% for the large lamps and 21% for the small lamps) were less than the 25% criterion that Huey, Dekker, and Lyons (1994) found to be a reasonable estimate of the minimum detectable difference in intensity between signal lamps that are viewed simultaneously.

In order to produce a range of intensities with the same lamps, neutral density filters were used. These filters, which could be quickly attached or detached from the fronts of the lamps, had densities of 0.15 and 0.30. The lamps had varying numbers of lower-density neutral filters permanently attached to adjust the intensities of each of the lamps to 130 cd when no detachable neutral density filters were in place. The three intensities produced by the lamps are shown in Table 2. The CIE 1931 chromaticity values for all combinations of lamps and filters were $x = .66$ and $y = .33$.

Table 2.
The three intensities produced by each of the lamps alone, or in combination with the detachable neutral density filters.

Filter	Intensity (cd)
None	130
0.15 ND	92
0.30 ND	65

The power supply for the lamps was set at 12.8 V and had a continuous current capacity of 36 A. The same power supply was used for all of the lamps (switched so that only one lamp was ever used at one time). The rise time for the 100-W bulbs was 375 ms from when they were energized to 90% of asymptotic intensity. The rise time was the same for all four lamps. (Because of the high wattage bulbs, this is somewhat slower than for a typical stop lamp. For example, the brake filament of an 1157 bulb operated at 12.8 V takes 250 ms to reach 90% of its asymptotic intensity.)

Ambient light. All sessions were run on two days, between the hours of 10:00 AM and 4:00 PM. The sky was virtually cloudless throughout the periods of data collection, but there was usually a light, high haze. Over the course of each day, the position of the sun (from the point of view of the lamps) varied from 47 degrees left (east) to 53 degrees right (west), and from 22 to 38 degrees up. Vertical and horizontal lux measurements were taken before and after the data collection for each subject. The vertical measurement was made at the visual fixation point, between the two sets of lamps; the horizontal measurement was made at ground level, halfway between the subject's location and the visual fixation point. The means and standard deviations of those values are given in Table 3.

Table 3.
Ambient illuminance measured before and after data collection for each subject.

	Illuminance (lx)	
Orientation	Mean	Standard Deviation
Vertical	64,500	20,900
Horizontal	51,000	14,100

Procedure. Subjects were run individually. Data collection for each subject took about 30 minutes, and each session took about an hour altogether, including instructions and debriefing. The presentation of stimuli and collection of responses was controlled by a computer. The subject was seated in a car throughout the experiment (see Figure 5). He or she was instructed to look at the fixation point between the right and left lamp positions (see Figure 6). Their compliance with this instruction was not closely monitored, but because the potential stimuli were symmetrically arrayed around the fixation point it is not likely that there would be a net advantage in looking anywhere but at the fixation point. The subjects' task was to respond as quickly as possible whenever any of the four lamps came on. They responded by pressing one of two buttons on a small box that they held in their hands. If either of the two lamps on the left came on they were to push the left button, and if either of the two lamps on the right came on they were to push the right button.

For each subject, 6 blocks of 16 trials were run. The filters that controlled the intensity of the lamps were changed between blocks. The same filter density was used for all four lamps within each block. The order of the filters was balanced across subjects. The 16 trials within each block corresponded to combinations of the 4 lamps and 4 intertrial intervals (the period from a response to the onset of the next stimulus). The intertrial intervals were 5, 10, 15, and 20 seconds. The order of the 16 trials within each block was randomized.

Reaction time for each trial was measured from the onset of voltage to the lamp until the subject pressed one of the two buttons. The lamp was turned off when the subject pushed a button. If the subject pressed the wrong button the trial was coded as an error. If a subject did not respond within three seconds of the onset of voltage, the lamp was turned off and the trial was considered a miss. Any missed trials and error trials were repeated, randomly mixed with the remaining trials in a block.

3.2 Results and Discussion

The rate of trails without a correct response (misses and errors combined) was acceptably low at 2.75%. The range across subjects was 1% to 6%; the average for older subjects was 2.7% and the average for younger subjects was 2.8%.

We performed an analysis of variance on reaction times for correct trials. (For this analysis, intensity was used as a three-level categorical variable, rather than a continuous variable.) There was a significant effect of age, with younger subjects responding faster overall (518 ms) than older subjects (631 ms), $F(1,10) = 11.19$, $p = .0074$. The effects of sex, side (left or right), and vertical position (top or bottom) were not significant. Area had a significant effect, $F(1,10) = 114.91$, $p < .0001$, with reaction times to the large lamps being longer (601 ms) than to the small lamps (547 ms). The main effect of intensity as a categorical variable was not significant, $F(2,20) = 0.63$, $p = .54$, but the interaction of area and intensity was highly significant, $F(2,20) = 6.40$, $p = .0082$, using the Greenhouse-Geisser correction. That interaction is shown in Figure 9. The nature of the interaction appears to be that intensity variation within this range has little or no effect on reaction time to the small lamps, but that increasing intensity causes faster reactions to the large lamps.

The data in Figure 9 can be used to generate a prediction about the intensity that the large lamps would have to have to yield reaction times as low as the small lamps. Assume that the reaction times for the three intensities of the small lamps are actually equal at the mean reaction time for small lamps, 547 ms. (The data in Figure 9 for the small lamps actually show a slight increase in reaction time for higher intensities, but it is statistically nonsignificant and not theoretically plausible.) Then fit a regression line to the reaction time data for the large lamps and extrapolate that line to higher intensities (rightward in Figure 9) until it reaches 547 ms. The equation of the regression line for large area is

$$y = 649 - 0.491x \quad (r^2 = .999)$$

Setting $y = 547$ ms:

$$547 = 649 - 0.491x$$

$$x = 208 \text{ cd}$$

Thus, a simple linear model for reaction time as a function of intensity for the large lamps suggests that one of the large lamps would have to have an intensity of 208 cd to yield reaction times as short as one of the small lamps with any of the intensities used (from 65 to 130 cd). Using a linear extrapolation is likely to underestimate the intensity required, because the function relating reaction time to intensity for large lamps is likely to flatten out at higher intensities. Therefore 208 should be considered a minimum estimate of the intensity required to equate performance for the large and small lamps. This result is shown in Figure 10, in the same format as used earlier in this report to summarize the results of previous studies (Figures 3 and 4). In Figure 10 the small lamp is assumed to have an intensity of 80 cd (the legal minimum, and within the experimental range of 65 to 130 in which reaction time to the small lamp appears constant).

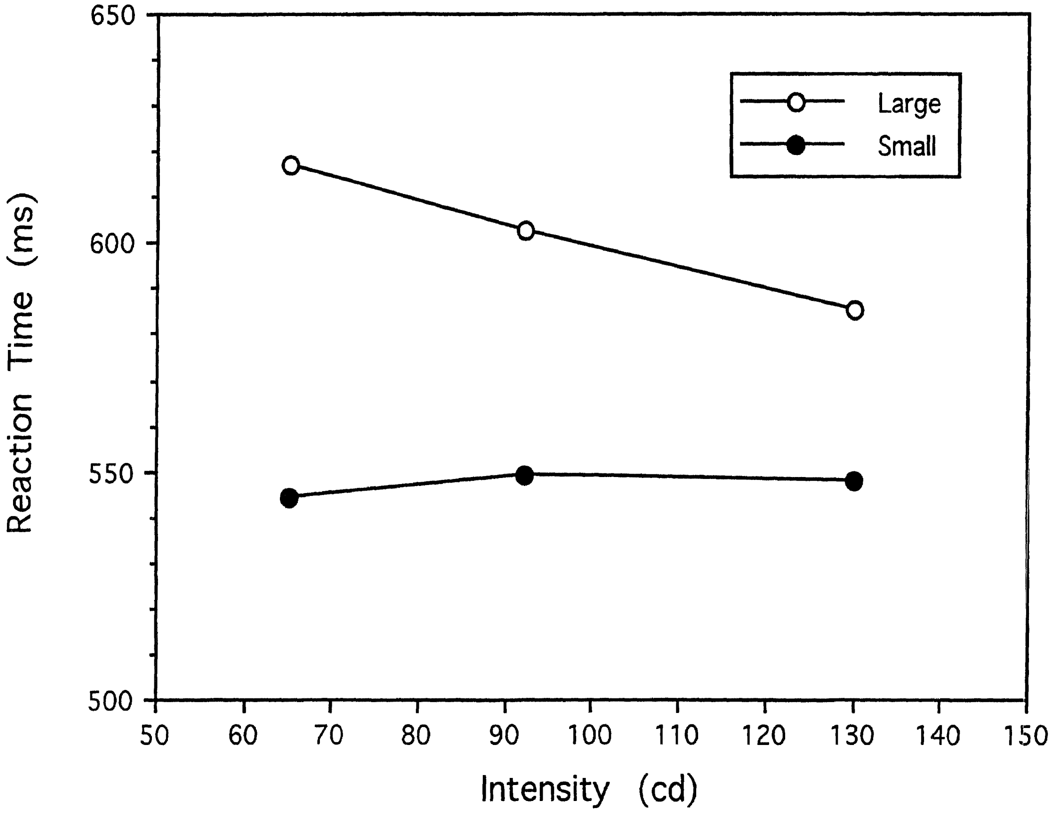

Figure 9. Reaction time as a function of intensity for the large and small lamps.

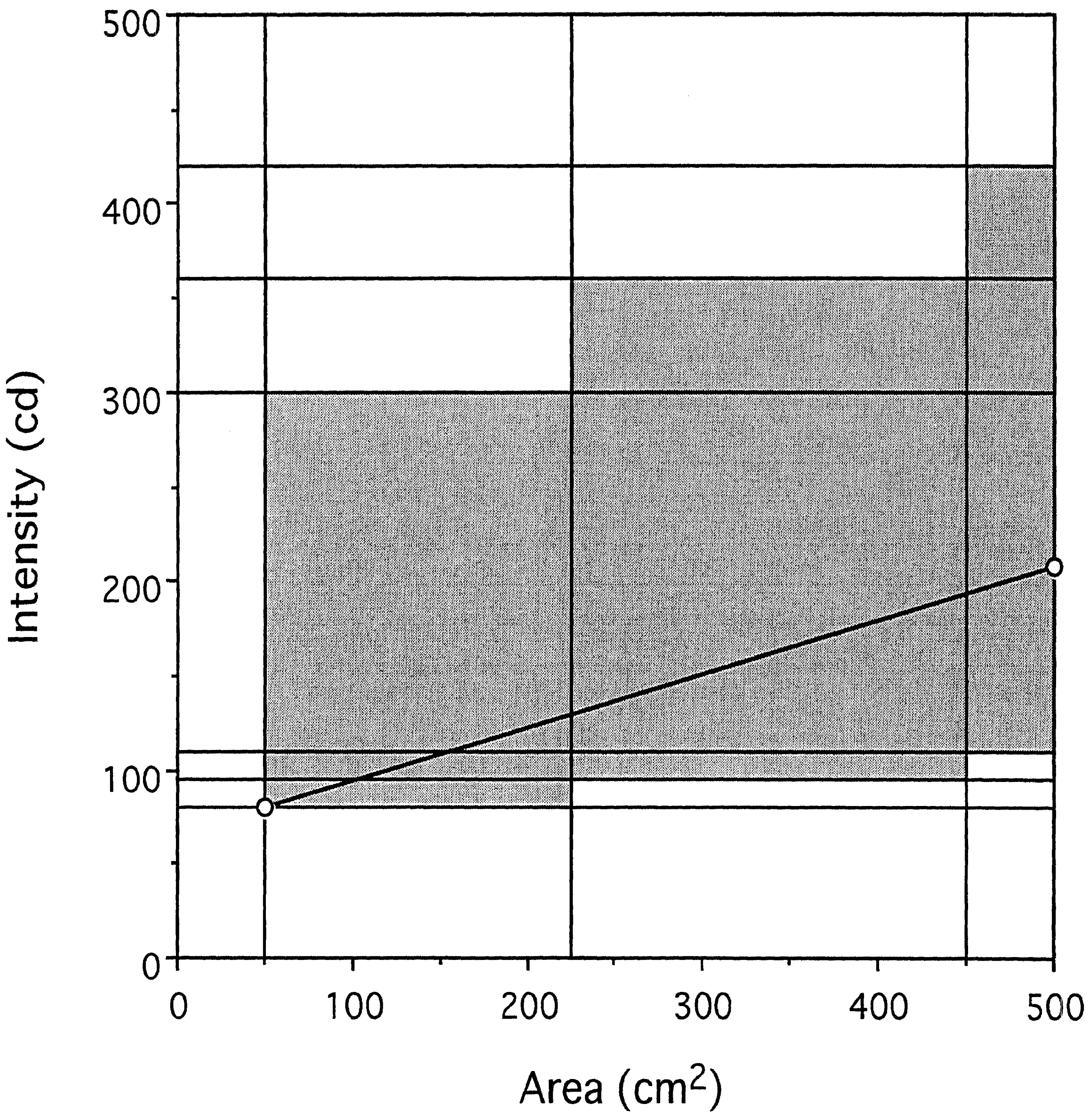

Figure 10. Results derived from the new reaction time data, shown in the same format as the previous results displayed in Figures 3 and 4. The new data suggest that reaction time would be the same for a lamp with minimum area and intensity (50-cm^2 and 80 cd) and a 500-cm^2 lamp with an intensity of 208 cd. See text for details.

3.3 Summary

These results indicate that area does affect reaction time, at least when the manipulation of area is strong enough. Although the manipulation of area used here was very strong, it was not entirely beyond plausible limits for real signal lamps. Also, the effect obtained here was surprisingly large, given the consistent negative findings in past studies. (In this study the large lamp would have to have an intensity of 208 cd to match the small lamp at an intensity as low as 65 cd.) It is not clear how to explain the discrepancy between these reaction time results. There is a large gap between the areas for which there are results from previous reaction time studies (see Figure 4) and the large area used here (500 cm^2). It also may be important that the stimuli here had unusually uniform luminance, so that the light was spread as evenly as possible across the entire nominal area of the lamps. If some lamps with nominally large areas in previous studies had local bright spots, they may have functioned as smaller, higher-luminance lamps.

The results of this experiment do not fully resolve the inconsistencies in experimental effects of intensity, area, and luminance that were described in Section 2 of this report, but they add weight to the argument that standards should in some way continue to recognize the role of area in determining the effectiveness of lamps.

4.0 Conclusions

In light of what is known from previous studies and from the new data reported here, how should the photometric requirements that are currently based on number of lighted sections be updated to be compatible with new light sources? In this section we consider a number of alternatives and make a tentative recommendation.

4.1 Alternatives for Photometry

Lighted sections. The current use of lighted sections in SAE documents and in FMVSS 108 was decided upon at a time when the only light sources being used for signal lamps were incandescent bulbs of a certain range of candlepower. It cannot be applied to the variety of light sources that may be used in signal lamps in the future in a way that is meaningful for the visual appearance of the lamps. For example, a lamp made with a large number of LEDs may have the same visual appearance as a lamp made with a single incandescent bulb, but currently the incandescent lamp would be considered to have a single lighted section whereas the LED lamp would be considered to have "three or more" lighted sections.

Point source (intensity alone). Intensity is clearly the most important single characteristic of signal lamps, and the idea of setting standards in terms of intensity alone has great appeal. It would be simple and flexible. However, a variety of results from previous studies, as well as the new reaction time data reported here, suggest that intensity alone is not enough to determine signal-lamp performance. It seems likely that some control of area, or some adjustment of intensity requirements for different areas, is needed.

Spacing. Lighted sections could be defined in terms of spacing of more basic units, with spacing defined either as separation between the centers of light sources or between the adjacent edges of light-emitting surfaces. Without regard to how many light sources are involved, a lamp could be considered to consist of only one lighted section if the spacing between all of its adjacent elements was within some limit (e.g., 2 cm between the centers of light sources). The main problem with such a proposal is that it would allow lamps with very large areas to be considered one-section lamps. And, as mentioned above, the available evidence suggests that area does affect the perception of signal lamps to some extent.

Luminous flux. Because each lighted section was expected to have a single incandescent bulb, the old lighted-section limits could be made more flexible by translating them into luminous flux limits that correspond approximately to single bulbs. Suppose that each lighted section is expected to have a single bulb with a luminous flux of about 400 lumens. Lamps with total source flux of up to 400 lumens would be considered one-section lamps; lamps with total flux of 410 to 800 would be considered two-section lamps; and lamps with total flux over 800 lumens would be considered three-section lamps. Thus, a lamp might have a large number of LEDs, but if their total flux was within the 400 lumens considered typical of a single bulb, the lamp would only have to meet the intensity requirements for a one-section lamp. One technical issue that this raises is that the important value is not total flux from the source itself, but the light that would be expected to pass through a colored filter. In order to be functionally equivalent, the flux value for LEDs would have to be adjusted downward because they do not necessarily have to be filtered to produce a colored signal. In addition to this difference in what might be called intentional light loss due to filtering, there might be characteristic differences between sources in unintentional losses within the lamp. The amount of light that can be usefully directed to the eyes of an observer, given reasonable assumptions about lamp optics, is the critical value for vision; therefore it would make sense to adjust the flux values for any characteristic differences between sources in the proportion of the total flux that is likely to contribute to useful signal light. These issues could be dealt with, but perhaps the main argument against the use of total luminous flux to substitute for the older reference to lighted sections is that luminous flux is not directly connected to human visual considerations.

Maximum linear extent. SAE J1889 currently applies the lighted-section requirements to LED signal lamps by assigning to such lamps an equivalent number of lighted sections in terms of their maximum horizontal or vertical linear extent. If that value is less than or equal to 150 mm the lamp is considered to have one lighted section, if it is from 151 to 300 mm it is considered to have two lighted sections, and if it is 301 mm or more the lamp is considered to have three lighted sections. The rationale for this is that "150 mm per lighted section represents a typical large lighted section in present incandescent lighting device designs" (SAE, 1993, rationale section 4.1.5.1). Although it is not explicit in the rationale, the use of a maximum linear extent—rather than an equivalent area—means that some limitation is placed on aspect ratio as well as area. A very long, thin lamp might not exceed an area limit chosen to correspond to a single lighted section even if its maximum linear dimension was much greater than the 150 mm maximum linear dimension. However, the existing evidence does not seem to justify limits on aspect ratio, at least for higher intensity lamps such as stop lamps. Also, the use of maximum linear dimension does not directly address area, which seems to be more important than aspect ratio. For example, a square lamp 29 cm on each side would have an area of 841 cm^2, but would be considered only a two-section lamp. Alternatively, a long, thin lamp 31 cm wide and 1.6 cm high would have an area of only 50 cm^2, but would be considered a three-section lamp.

Area. References to lighted sections could be translated into equivalent areas by adopting an area corresponding to a single lighted section. Such a solution would recognize the role of area in signal effectiveness, but could be applied to any source technology. It would not limit aspect ratio, but current evidence indicates that, within broad limits, aspect ratio is not a major influence on lamp performance.

4.2 Recommendations

We suggest that the current references to lighted sections in specifying photometric limits for signal lamps be translated to area-based limits by adopting an area that corresponds to a single lighted section. Several ways of selecting such an area could be proposed. We would argue that the value should be somewhere toward the high end of the range of areas for single sections, since it is meant to represent the border between one and two sections rather than a typical or average value for one section. One candidate is the square of the value adopted in SAE J1889 for the maximum linear extent of a single section: 15 cm squared, or 225 cm^2. In SAE J1889 15 cm is claimed to represent the maximum linear extent of a "typical large lighted section." However, it could be argued that it is not appropriate to square 15 cm, since that value is meant to represent the maximum horizontal or vertical dimension of a lamp that is not necessarily square. For most lamps, it could be argued, the other dimension would be substantially less than 15 cm. However, squaring 15 cm is in keeping with the philosophy of adopting a limit toward the high end of the one-section range. Additionally, some support for using an area of 225 cm^2 comes from a survey of 40 stop lamps (Sivak et al., 1986). That study found that the average area of single sections was 137 cm^2, with a standard deviation of 73 cm^2. As shown in Table 4, 225 cm^2 falls between the 85th and 90th percentiles of that distribution. Although any exact choice of percentile would be somewhat arbitrary, this is at least in a reasonable range. The Sivak et al. sample is not necessarily definitive. It covered passenger cars from model years 1974 to 1984, and may not be representative of more recent vehicles. However, it could be argued that in order to best preserve the intent of the existing lighted-section requirements, a representative area should be based on vehicles that were typical at the time those requirements were developed (the 1960s), and that the Sivak et al. sample is at least close to that era.

Whatever value might be selected to represent the area of a single lighted section, the existing research suggests that it should be used to simply translate the existing lighted-section-based photometric limits. Thus (assuming the 225 cm^2 value), a signal lamp with an area of 225 cm^2 or less would be considered a one-section lamp, a lamp with an area of 226 to 450 cm^2 would be considered a two-section lamp, and a lamp with an area of 451 cm^2 or greater would be considered a three-section lamp.

Table 4
Areas corresponding to various percentiles of the distribution of stop lamp single sections in the study by Sivak et al. (1986).

Percentile	Area (cm^2)
85	213
90	231
95	258

Several related topics are deserving of further research. There is some evidence that high aspect ratios may decrease the effectiveness of low-intensity signals, such as tail lamps. Although the current evidence is not strong enough to recommend adjusting intensity levels on the basis of aspect ratio, it suggests that the situation should be evaluated further.

The nominal area of a lamp may often be larger than the true effective area of the lamp if the luminance across the face of the lamp is markedly uneven. This discrepancy is one possible explanation for the difference between the new findings described in this report concerning the effects of area on reaction time and previous reaction time findings. Further research should be done to clarify the importance of luminance uniformity.

Several of the studies reported here have suggested that it might be beneficial to use different signal-lamp intensities for day and night (Mortimer, 1970; Schmidt-Clausen, 1985; Cole et al., 1977). Considering the innovative light sources that are becoming available for signal lamps, this may be a good time to reexamine the feasibility and possible benefits of this relatively old proposal.

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