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Changeable Message Sign Visibility

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FOREWORD

This report presents research aimed at providing guidance for ensuring the adequate visibility of changeable message signs (CMS's) - i.e., matrix-type signs capable of variable message displays. Both permanent and trailer-mounted CMS's have been used increasingly in the United States over the last two decades. However, unlike other traffic control devices, there are no nationally recognized specifications regarding the appearance of CMS's. Accordingly, a myriad of CMS designs has developed, with differing sizes, fonts, spacings, and colors. This lack of design uniformity has resulted in some CMS's having inadequately legible CMS messages. Inadequate maintenance and operational practices have also at times contributed to this poor legibility of CMS's.

The present research effort included: (1) a review of published and unpublished information on CMS's, (2) photometric measurements of selected in-service CMS's, (3) laboratory experiments on legibility of computer-simulated CMS's, (4) static testing of a full-size CMS mock-up display, and (5) dynamic field tests of commercially available CMS's. Based on data from these tasks, draft design guidelines and operational recommendations for CMS's are presented (Appendix A).

This report will be of interest to anyone involved in the design, specification, use, or maintenance of changeable message signs.

Samuel C. Tignor, Acting Director
Office of Safety and Traffic Operations, Research and Development

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16. Abstract

The object of this contract was to identify problems with the visibility of CMS's, particularly for older drivers, and to develop design guidelines and operational recommendations to ensure adequate conspicuity and legibility of in-service CMS's. This project was divided into three main sections: a field survey of in-use CMS's, a series of laboratory experiments and static field studies, and a partially controlled dynamic field study. The research was designed to optimize CMS components, including the character variables (font, width-to-height ratio, color, and contrast orientation) and the message variables (inter-letter, inter-word, and inter-line spacing).

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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PROBLEM STATEMENT

Changeable message signs have been used on State and Federal highways in the United States since the 1970's. However, unlike any other traffic control device (TCD), there are no nationally recognized specifications regarding the appearance of changeable message signs. The term *changeable message sign*, or CMS, as used in this document, includes all matrix-type signs capable of variable message displays, and excludes any sign with fixed message components such as rotating-drum signs. This absence of guidelines has resulted in CMS's that display a myriad of colors, shapes, sizes, fonts, borders, and spacings. One of the main goals of this research project was to address this issue and to provide guidance with regard to both the uniformity and to the increased visibility of CMS's.

INTRODUCTION

This research began with a detailed critical review of the literature to determine the factors that most affect CMS visibility. Those variables determined to have the greatest impact on visibility were selected for a three-level analysis. Level One consisted of a laboratory study using a computer simulation of a CMS. During this stage, 11 variables were assessed regarding their effects on minimum observable letter size. These variables were: character width-to-height ratio (W:H), stroke-width-to-height ratio (SW:H), matrix density, font, color, contrast orientation, character luminance, word-length, inter-word spacing, inter-letter spacing, and inter-line spacing. Level Two was a static field study in which a mock-up CMS, an actual CMS, and the observers were stationary. This second level of analysis measured the effects of time of day, sun position, character height, inter-letter spacing, font, and distance from the observer on minimum character luminance required for CMS legibility. Level Three involved a dynamic field study using actual trailer-mounted CMS's on public roadways. An assessment was made on the effects of seven variables on the distance at which the signs could be found and read. These variables were: sun position, sign type, character luminance, contrast orientation, inter-letter spacing, character height, and character W:H.

SCOPE

Several features of CMS's that may contribute to CMS visibility are not included in this document. Message content issues, such as scrolling copy and use of symbols, were determined to be outside the scope of this report. Similarly, treatments specifically designed to improve conspicuity were not assessed. These treatments include the use of flashing lamps, flashing messages, or borders. A formal cost-effectiveness analysis was also outside the scope of this research although the project was conducted with a sensitivity to cost issues. This project also considered the capabilities of old and young drivers.

LITERATURE REVIEW

Character Components

This evaluation focused on the aspects of a CMS face that contribute to its visibility. The review included here resulted in a set of important CMS design parameters that when optimized, will improve the visibility of all CMS's, regardless of technology.

These components fall into two major classes: character and message. Character components consist of element and character variables. Element variables include the shape, size, number, spacing, luminance, and color of each individual element (or pixel) that make up the characters on a CMS. Character variables include the height, width, font, mean luminance, contrast, and contrast orientation of alphanumeric characters. Message components are associated with the overall impression made by the sign copy and address spacing issues, such as inter-letter, inter-word, inter-line, and copy-to-border spacing.

Of the two component classes, character components present the CMS researcher with the greatest challenge. There is an inherent problem in assessing the effects on legibility of any single CMS character component: the inevitable confounding that occurs when manipulating any one variable. It is impossible to manipulate a specific component of a character matrix without affecting others. For example, if the number of elements is increased, character height, width, and/or stroke width must also change (figure 1). This also may result in changes in character luminance. Another example of this confounding occurs specifically in light-emitting signs. When element luminance is increased, there is an apparent increase in the size of the elements and the character, as well as a concurrent decrease in inter-element spacing (figure 2). The problem of confounding variables makes it difficult to attribute any improvement in performance to the nominally manipulated variables. This type of problem was found within many of the CMS studies reviewed.

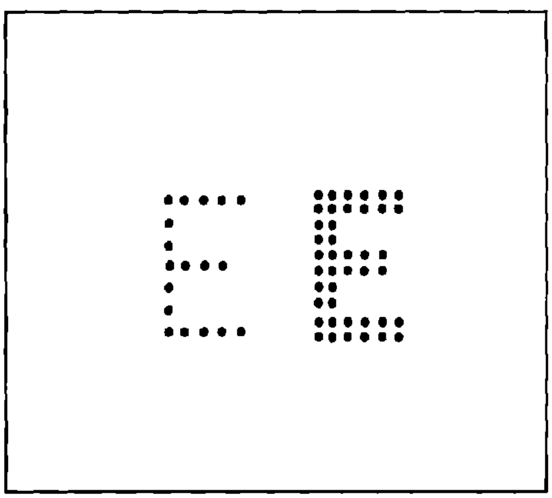


Figure 1. Confounding number of matrix points with letter height and stroke width.

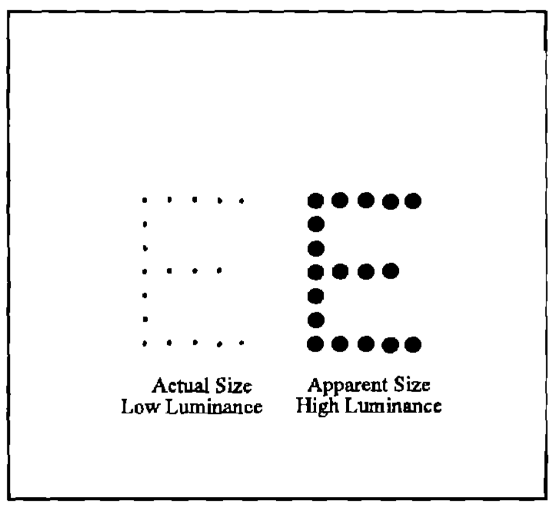


Figure 2. Confounding matrix-point luminance with size.

In addition to the *within*-study problems just discussed, the abundant differences *between* the various studies reviewed make it even more difficult to summarize this field of research effectively. The inevitable differences in procedure and measures of effectiveness found in any line of research are often accompanied by the unique problem of stimulus representation. Of the four laboratory-based studies reviewed, two used computer simulations, one displayed the signs as slides, and one used metal masks with holes punched out. The reviewed field research consists of four studies employing a light-emitting diode (LED) mock-up; a fiber-optic (FO) mock-up; a lamp mock-up; and an actual flip-disc sign, respectively. To further complicate matters, each study used different definitions of luminance and luminance contrast.

A summary of the CMS literature requires consideration of all of the above-mentioned problems and complications. The following summary is based on both the direct results of the reviewed individual studies and general conclusions drawn from this entire line of research.

Element Variables

A series of experiments were conducted for the U.K. Department of Transportation to study the factors affecting the perception of light-emitting CMS's.[1] In one experiment, the researchers assessed the effects of element size and element spacing under daytime and nighttime conditions. They concluded that while both old and young benefit from increased element spacing at high-contrast ratios (nighttime), only old people benefit from increased element size. At 300 m (984 ft), the researchers recommended element spacing of 8 cm (3.1 in) and element diameter of 2 cm (0.78 in).[1] In assessing the effects of element color, it was found that no significant difference in response time or error rate occurred between white and yellow elements under any contrast condition for either uppercase or lowercase characters. However, another study found that yellow and white elements provided greater legibility distance than retroreflective white, red, or orange.[2,3]

Only one study was found that addressed the issue of element shape, the effect of rectangular and circular flip discs on legibility distance was compared.[2,3] The researchers concluded that the performance of the two shapes did not differ significantly. They did not state that rectangular and circular discs produced the same legibility distance, but that the two shapes are similarly affected by W:H. It has yet to be determined whether the three-dimensional "cube corner" technology, which represents one additional shape, provides any increase in legibility.

In 1988, a research group published a study designed to optimize the photometric features of CMS's.[4] Using hard-wired, FO mock-ups, the researchers measured the subjective visibility of the number "5" at various levels of element spacing and luminance under a range of ambient light levels. The results of this procedure led these researchers to conclude that dim sources spaced close together work as well as bright sources spaced widely apart.[4] In 1991, Jenkins reached this same conclusion.[5] In essence, the results of these studies indicated that for a single character, the importance of spacing, number, and intensity of individual elements is superseded by that of average character luminance.

In 1987, another study used a CMS computer simulation to determine the best combination of element size and luminous intensity under three levels of ambient adaptation.[6] Only nighttime conditions could be simulated due to the restrictive luminance of computer monitors. Alphanumeric characters of five different element sizes and seven luminance levels from 1 to 230 cd/m^2 were evaluated. The percentage of correct responses was the measure of effectiveness.

This same study examined a range of character luminances within each element condition, allowing researchers to determine the effects of luminance across and within the element size conditions.[6] The researchers' conclusions mirrored those of the 1988 research group.[4] Mazoyer and Colomb stated that the best performance resulted from "...practically constant luminous intensity, which is the product of the luminance and area of the dots."[6] In this case, the element size and luminance was found to be less important than the average character luminance.

In a follow-up to the above study, Colomb and Hubert conducted a controlled field study to determine the effects of element size and luminance/contrast on letter legibility under both daytime and nighttime conditions.[7] Using LED, single-character mock-up CMS's, they varied the luminance of the letters from 9 to 730 cd/m^2 at night and 280 to 4090 cd/m^2 during the day. The contrast was varied from 1.5 to 20 in daylight. All the letters of the alphabet were viewed from a distance of 200 m under 6 luminance conditions and 6 element sizes ranging from 1 to 36 LED's per element. The dependent measure was the percent of correct responses.

This research exemplifies the problem of variable confounding previously discussed.[7] The luminance as well as the contrast of the stimulus characters are determined by the number of LED's per element. Colomb and Hubert's data showed that neither contrast nor luminance was varied to any great extent within an element size condition.[7] The conclusion that increased contrast had a positive effect on daytime legibility cannot be legitimately made without noting that the low-contrast letters had only 1 LED/element, while the high-contrast letters had 36 LED's/element which resulted in a larger element size and an increase on some of the character variables discussed below.

A similar problem occurred in the nighttime portion of the study. Colomb and Hubert found "no significant change in the percentage of correct answers with increasing luminance" and no effect of element size.[7] The absence of improvement in visual performance with a nearly two-log unit increase in luminance is a finding that should be addressed. The brightly lit elements consisted of 25 and 36 LED's each and were closely spaced, whereas the dimly lit elements had 1, 4, and 9 LED's each and were widely spaced. As discussed previously, Padmos et al. found that a large number of closely spaced, dimly lit elements performed as well as a small number of widely spaced bright ones. However, closely spaced bright elements and widely spaced dim ones produced poorer performance due to irradiation and sub-threshold brightness, respectively. Interestingly, in her own paper, Colomb stated that "highly luminous large dots yield only moderate performance because they become dazzling and interfere with reading...."[6]

Of the reviewed studies, those with the cleanest methodologies resulted in the conclusion that, with the exception of color, the design of the element variables can be flexible as long as the character variables of average luminance and contrast are within acceptable ranges. The issue of acceptable luminance and contrast ranges will be addressed in the next section.

Character Variables

In addition to those characteristics discussed above, other, more holistic variables affect the legibility of CMS characters. These variables are font, height, SW:H, W:H, and contrast. No character feature is structurally independent of the element variables previously discussed. For example, to increase stroke width, either the diameter or luminance of the element must be increased or a multiple-element stroke must be used (figures 1 and 2). However, it is important to note that the perception of the character at highway distances is one of increased stroke width only; the method used to structurally achieve this is irrelevant to the observer.

To optimize visibility, the literature suggests a luminance contrast between 5 and 10 and a mean luminance requirement of about 50 cd/m^2 at night. Under "normal" daylight, 500 to 1000 cd/m^2 is suggested and 2000 to 4000 cd/m^2 is recommended for backlit, daytime conditions.[1, 5, 6, 7] Of the studies that assessed various character matrix densities, most found a 7-by-9 element matrix to be necessary when using lowercase letters due to the descenders and ascenders. The Vartabedian font was found to be the best 7-by-9 font available.[1, 2, 3, 8] An 18-by-14 double-stroke matrix design was also evaluated, but no significant difference in response time (RT) or error rates over the standard 7-by-9 matrix was found. However, the effects on legibility distance were not assessed.[1] A 5-by-7 font is generally deemed acceptable with uppercase-only lettering. One research group found the Tiled font to work best with uppercase letters.[2,3] Another variable assessed was the effect of increasing W:H.[2] The researchers varied the vertical and horizontal spacing between elements to increase the W:H from 0.4 to 1.0 and found legibility distance improved; however, these researchers also found that smaller W:H resulted in reduced reading times.[2,3]

Message Components

Message variables are sign characteristics that affect the legibility of the sign copy without regard to the internal characteristics of the character modules. Message variables concern the spacing between letters, words, lines of text, and copy and border. Less than optimal spacing will, in effect, reduce letter legibility.

Surprisingly, very little experimental research has been conducted to evaluate the message components of CMS's. This may be due to the assumption that the spacing standards used for static traffic signs may be applied to CMS's. Two studies that addressed message components produced conflicting results possibly due to their use of different dependent variables. One study found no significant difference in reaction time between inter-letter spacings of one, three, and five elements.[1] Another study replicated these reading time results; however, it found significantly longer *legibility* distance with two-element, as compared to one-element spacing.[2,3] Dudek cites studies by Lotens (1987) and Bomier (undated) that found a space equal to approximately one letter height was sufficient between copy and border.[9] No empirical research into the effects of inter-word or inter-line spacing was found. Table 1 provides a summary of literature addressing character and message components.

Table 1. Summary of results across component studies.

Independent Variables	Recommendations
Element Variables:	
Element Size Element Shape Number of Elements Element Spacing Element Luminance	Design of element variables can be flexible as long as the average character luminance and contrast are within an acceptable range.
Element Color	Inconclusive
Character Variables:	
Contrast (TL-BL/TL)	Between 5 and 10
Luminance (cd/m^2)	Night, 50; Day, 500; Overbright, 4000
Font	7-by-9 Vartabedian; 5-by-7 Tiled
W:H	0.75-1.0
Matrix Density	UC & LC, 7-by-9; UC only, 5-by-7
Message Components:	
Inter-character Spacing	Inconclusive
Inter-word Spacing	Minimum of twice stroke width
Word-to-border Spacing	Inconclusive

CMS Technology Comparison Studies

A recent study conducted for the Australian Road Research Board (ARRB) contains the following disclaimer:

> The results of these experiments pertain to the particular samples tested, the formats of the symbols and characters used, the mounting assemblies they were in, and the lighting systems that were used for illumination.... The conclusions found should not be generalized to other configurations.(5)

This statement sums up the basic problem with studies that attempt to assess the relative effectiveness of different CMS technologies.

Two studies reviewed compared CMS's that used LED's, FO bundles, and fluorescent discs as elements.(5,10) Both studies found that the FO and LED signs performed comparably well under both daytime and nighttime conditions. Also, both studies reported that the performance of the flip-disc signs was worse at night than for the other two technologies. However, in both studies the nighttime performance of the flip-disc signs might well have been improved via better illumination systems. While one study found that the flip-disc signs provided good legibility during normal daylight conditions, another study reported "...legibility distances that are barely adequate...." for the flip-disc CMS's.[10,5] The first study reported poor legibility of all signs tested under backlit and washout conditions.[10]

A recent study conducted for the British Columbia Ministry of Transport and Highways compared the photometric performance and observer preference of a LED sign, a FO sign, and a fiber-optic/reflective disc (FO/RD) sign.[11] They concluded from the photometric measurements that the FO sign and the FO/RD sign were "optimal for such communication designs." However, the observer sign-preference data for daytime visibility at 300 m (984 ft) ranked the FO/RD sign first, the LED sign second, and the FO sign third. The exact dimensions of the characters tested are not provided by the authors of this study. However, the photographs in the report clearly show that the FO/RD characters had greater height, width, and stroke width than either of the other two signs, and that overall, the FO characters were the smallest.

Finally, another study compared a flip-disc sign with a lamp matrix sign.[12] The study found that the flip-disc sign provided greater subjective daytime legibility distance than the lamp matrix sign. This finding was reversed at night, with the flip-disc sign resulting in a 198-m (650-ft) legibility distance and the lamp matrix sign resulting in a 229-m (750-ft) legibility distance. It was stated that reduced contrast and uneven lighting produced by the fluorescent "black-light" tubes might have been responsible for the loss in legibility distance with the flip-disc signs.[12]

VISUAL COMPLEXITY

The messages on CMS's are often both timely and critical. The traffic engineer must be certain that the messages are seen far enough in advance to provide adequate visibility distance so that all of the information on the sign can be recognized and understood. One research group provided one of the most succinct operational definitions of conspicuity: a conspicuous object is one that will, for a given background, be seen with a greater than 90 percent probability of detection, within a short observation time (250 ms), regardless of its location relative to eye fixation.[13]

Two research groups that have studied sign conspicuity call attention to the importance of background complexity:

> No object is conspicuous per se. It can only be conspicuous in a certain background; if the background changes, then the object may or may not remain conspicuous.[14]

> Conspicuity ... is not an observable characteristic of a sign, but a construct which relates measures of perceptual performance with measures of background, motivation, and driver uncertainty. [15]

One of these studies added motivation and uncertainty to the definition of conspicuity and recommended that threshold perception paradigms not be used for the measurement of traffic sign conspicuity.[15] Instructions such as "tell me when, or where, you see something" may overload the subject because of the amount of distractions along the highway.

For similar reasons, another study suggested that the conspicuity of a target depends on the instruction given to the observer.[16] Yet another study stated that "the likelihood of an object being noticed depends very much on the observation strategy adopted–on the way attention is directed–and this will, in turn, depend on the observer's need for information and on the explicit or implicit instruction given to the observer."[17]

A 1984 study dichotomized conspicuity into attention and search.[16] This is helpful in understanding the role of motivation and driver uncertainty in conspicuity. Attention conspicuity is the capacity of the target to attract attention when the driver's motivation is low and he/she has little need for the information, or the driver's uncertainty is high and the information is not expected. Search conspicuity was defined as a measure of an object's accessibility when the observer was specifically directed to search for it. In search conspicuity, the driver's motivation is high and the level of uncertainty is relatively low.

While these descriptions of two types of conspicuity are helpful, they should not obscure the fact that driver motivation and uncertainty result in a continuum of conspicuity needs that range from getting the unsuspecting driver's attention to helping the driver find the information for which he or she is already looking. Collapsing conspicuity into these two classes also masks the independence of motivation and uncertainty. For example, drivers expect stop signs to appear on the right near intersections whether or not they are looking for a stop sign. Also, a CMS has a wide range of possible locations whether or not drivers have a need for the information contained on the CMS.

A 1986 study conceptualized the process of noticing an object in the following way:

> The visual environment contains information which is transferred to the retina of the eye where the information is transformed to a neural code and transferred to iconic memory. There is probably little loss of information in this process: the loss that does occur is the result of the threshold limits of the eye and visual pathways for spatial resolution and contrast discrimination. The iconic memory decays rapidly and information is lost from this short-term store in about 300 ms (Sperling, 1960). However, the iconic memory can be "read" during this time by some form of central processor and the information "read" is then transferred to short-term memory where it is available for recall or for decision-making. Short-term memory decays over a period of several seconds, but its contents tend to be obliterated by new incoming information. The information in short-term memory is what is noticed.[17]

Some experiments were conducted to describe "how a driver distributes attention and what classes of object attract attention."[17] The methodology relied upon the drivers' verbalization of what they noticed without further instruction that might direct their cognitive processes. To determine whether driving imposes a significant cognitive load that interferes with reporting or whether the automatic processes of driving cause inattention to some elements of information, the experiment was repeated with two groups: one that drove and one that watched a film. The driving task did not have a substantial effect on what was reported by the subjects. Laboratory observers behaved like drivers, reporting slightly more driving-related events. Attention patterns in residential, arterial, and shopping areas suggested that although more attention was directed toward advertising in shopping and arterial areas, this was offset by reduced attention being given to other non-driving-related objects. The authors suggested that the removal of advertising might only result in greater attention to trivial objects.(17)

Methods of Improving Conspicuity

Hughes and Cole noted that spare capacity of a driver's attention is likely to be devoted to objects unrelated to driving, not road signs.(17) To ensure that road signs are noticed, they suggest increased size, improved contrast with background, and a reduction in background clutter. The signs can be given bolder graphics and can be located close to the expected direction of a driver's gaze. The information content of a sign may also determine its conspicuity. It was suggested that signs with familiar, expected, or redundant information may be filtered from entering short-term memory and may be part of the clutter that determines the sensory conspicuity of more important signs.(17)

Increasing the size of the sign and/or its contrast with its background are obvious steps to be taken to increase sign conspicuity. Other studies have observed that visual clutter is equally important for daytime conspicuity. With regard to nighttime conspicuity, one group of researchers concluded:

> When visual complexity of the scene was high, complexity is a more significant determinant of sign detection than contrast of a sign to its surroundings. When visual complexity is low, conspicuity is not an issue and target contrast and size would determine detection.
>
> Black-on-white regulatory signs have poorer conspicuity than other signs, even at close distances.
>
> Yellow-diamond warning signs have greater conspicuity than other signs at long distances even though they are not as bright as white signs.
>
> Increasing the brightness of signs (except black on white) can offset the decrease in conspicuity from increased visual complexity.(18)

Methods of Classifying Background Surroundings

There are two methods of classifying visual surrounds with regard to traffic sign conspicuity: digitization and subjective ranking. Numerous studies have described visual noise in laboratory studies of target detection and have digitized highway scenes for the purpose of describing their visual complexity.(19,20) Others have suggested practical scaling techniques for describing the visual surrounds of traffic signs for daytime and nighttime conspicuity.(14,20)

One study asked people to rank postcard-sized color prints of scenes with regard to the degree of clutter they saw in the scene.[20] This subjective ranking was found to correlate with another ranking (r=.54) based upon visual performance. The correlation increased to 0.73 when one specific scene was removed from the 20-scene scale.

A different study found that at night, visual clutter was not a unidimensional attribute of the visual complexity of sign backgrounds.[21] This study described a four-factor scale for quantifying nighttime visual complexity. The multiple correlation of these four scales with the detection of yellow-diamond warning signs was 0.78 among 19 night-traffic scenes. These scales were recently cross-validated, resulting in a multiple correlation of 0.61.[22]

The greatest limitation of the subjective ranking procedure is that it is not a scale and therefore provides a relative assessment of each scene in a group of scenes and not an absolute scale value. Therefore, this type of ranking scale cannot be applied to any single new scene.[21] The greatest limitation of the four-factor scale is that it was developed for black-on-yellow warning signs and may not predict the detection of other colored signs.[20]

For now, the subjective ranking method during daytime and the four-factor procedure at night are the only methods for scaling visual complexity.[21,20] Since neither of these studies used detection of CMS's as the visual performance measure, the validity of these scales for measuring CMS conspicuity is questionable. One study used the detection of disk targets and the other used the recognition of yellow traffic signs as the measure of visual performance in estimating the validity of the visual complexity scale.[21,20] The detection or recognition of a CMS might provide different results.

FIELD SURVEY OF IN-SERVICE CMS

OBJECTIVES

The field survey had two objectives: (1) to assess the visibility characteristics of various CMS technologies across a range of geographical and climatic locations, and (2) to develop an understanding of current problems associated with the different sign types. The purpose was to gain an increased knowledge of CMS usage and range of performance through an evaluation of these signs in real-world situations. This knowledge was then used in conjunction with the literature review to develop the range of conditions and sign parameters used in the laboratory and field experiments.

PROCEDURE

Sign Location Selection

Data were collected from signs in seven locations (table 2). The sites selected for this field survey represented various geographic and climatic areas in the United States and depended on several factors. First, the location had to have at least two different CMS technologies/manufacturers currently in place. Second, locations with a relatively long history of CMS use were targeted in order to assess a range of CMS ages. Next, all of the chosen locations had several signs positioned in an east-west orientation, thereby permitting an assessment of the signs at the sun angles most detrimental to sign legibility. Finally, and most importantly, the sites had to be accessible to the field data collection procedure described below.

Descriptive Data and Personal Reports

The descriptive data included the type of CMS technology; manufacturer and model number; date of installation; date of last element replacement; cleaning and any other maintenance; sign size; exact location and placement; and detailed specifications concerning character size, font, stroke width, spacing, and color. Most of these data were obtained through telephone interviews with the relevant highway personnel and manufacturers. These reports included information related by the local highway agencies regarding their experience with the signs. Again, most of these data were already collected before the field survey crew traveled to the sign sites.

Subjective Evaluation

Two types of subjective evaluations were obtained by the individuals conducting the field surveys. First, where possible, the legibility distance for each sign was estimated. The agency in charge of sign control was contacted and asked to activate a neutral message on the sign. When the field crew was in sight of the sign, they pulled onto the roadway shoulder and drove toward the sign until they could just read it. At this point, one of the crew got out of the car and measured the distance to the sign with the aid of a distance measuring wheel. In addition, the crew member wrote down the distance at which all letters in the message were just clearly legible.

Table 2. Task B data collection locations and sign information.

Number of signs tested	Location	Date Installed	Manufacturer (nighttime lighting for flip-disc signs)
Flip disc			
2	Phoenix, AZ	1990	Tele-Spot (black-light tubes)
3	Hartford, CT	1990	Daktronix (black-light tubes)
3	Long Island, NY	1985	Tele-Spot (high-pressure sodium)
6	Northern Virginia Washington, D.C.	1983 & 1990	Lake Technologies (high-pressure sodium)
5	Seattle, WA	1977, 1987, & 1989	Tele-Spot (black-light tubes)
FO			
3	Phoenix, AZ	1991	FDS
3	Cumberland, MD	1989	FDS
1	Toronto, Canada	1990	FDS
LED			
2	Phoenix, AZ	1991	LED STAR
1	Long Island, NY	1991	Centaure
3	Toronto, Canada	1990	Seattle, WA
1	Seattle, WA	1992	Tele-Spot

The second group of subjective measures assessed general qualities that relate to sign legibility and conspicuity. The level of glare on the sign face, shadowing of characters by the sign frame, and letter brightness/contrast were each judged on a five-point scale. Photographs and videotapes of the sites were taken during daylight in order to scale them on visual complexity. These subjective measures took place at the same distance as the photometric readings.

Photometric Data

Rationale

A standardized procedure for photometric measurement of CMS signs has yet to be established. As pointed out by one research study, one of the principal issues is whether the unit of measurement should be the light emitted by individual elements or whether the luminance should be measured across an entire character matrix, including both lighted and unlighted areas when all elements are lit.[5] The latter is similar to the technique currently being developed by Great Britain Department of Transport and is consistent with the 1990 Illumination Engineering Society (IES) guide for photometric measurements of standard "button copy" signs.[23] Theoretically, this method may provide a more realistic picture of what the driver observes. At most distances, CMS characters appear to be a coherent whole with the lighted elements "blending in" with the inter-element spacings.

The practical limitations involved in a photometric field study of CMS's were of even greater importance to the present task. Light-emitting technologies are simply not amenable to field evaluation of individual elements without the use of a bucket truck or "catwalk." Even the Pritchard photometer, with its smallest aperture of 2 minutes of arc, would need to be less than 6 m (20 ft) from the surface of both FO and non-clustered LED signs, and approximately 61 m (200 ft) from the clustered LED's. The angles required for roadside measurements at these distances would result in luminance levels far below those encountered by highway users at normal observation distances. The Lambertian nature of flip-disc signs *would* allow measurement at these large angles, since they reflect equal amounts of light in all direction. However, to achieve consistency across all technologies and to best represent the observed phenomena, a measurement summing the element and background luminances was deemed preferable.

Procedure

A series of luminance measurements was taken with a Pritchard photometer at each sign location. Due to the considerations discussed earlier, the procedure included luminance measurements of a representative number of character matrices "on" (a fully lit CMS character module), and several character matrices "off" (a fully blanked-out CMS character module) (figure 3). The former represents a weighted average of the character elements and their background, while the latter provided a luminance value used in contrast calculations.

Additional luminance measurements of the sign's immediate surroundings were taken and used to evaluate external contrast (figure 4). As stated above, the literature suggests that it may be necessary to vary character luminance based on sign illuminance. Therefore, in addition to the luminance measurements, the vertical illuminance at the general sign location was determined with a Minolta T1 hand-held illuminance meter to ascertain the level of sunlight hitting the sign face. Vertical illuminance and horizontal illuminance were measured at the position of observation to obtain a rough measure of driver adaptation level.

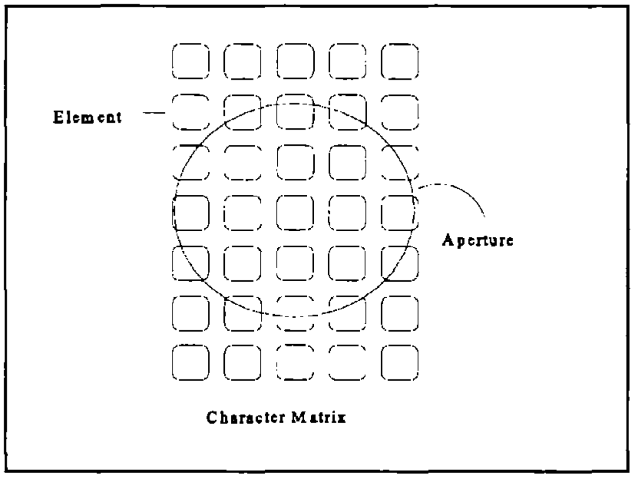


Figure 3. CMS character matrix and photometer aperture.

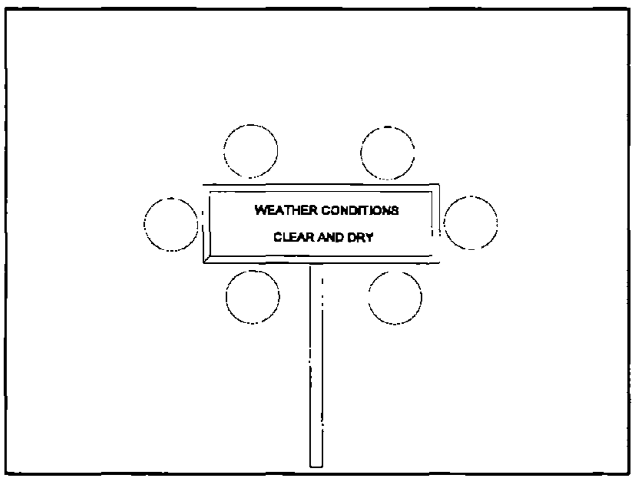


Figure 4. Background luminance sampling conditions.

All measurements took place from either the shoulder or median, depending on access. Except for some early trial tests, signs with 46-cm-(18-in-) high matrices were evaluated at a distance of approximately 168 m (550 ft) using the Pritchard's 6-minutes-of-arc aperture. This distance was chosen for two reasons. First, to measure the signs at approximately the minimum suggested legibility distance for a CMS, which is 4.3 m/cm (36 ft/in). This distance ensured that for light-emitting signs, the angle of measurement would be comparable to that incurred on the roadway. Second, it was desirable to include as much of a single-character matrix in the photometer's aperture without the aperture exceeding the width of the character matrix. The aperture available on the Pritchard photometer, which most closely matches the legibility distance, is 6 minutes of arc in diameter. This corresponds to 30.5 cm (12 in)–the average width of a 46-cm-(18-in-) high overhead-mounted CMS character.

RESULTS

All conclusions regarding CMS performance were restricted to the specific signs examined (table 2). The installation date of the CMS and variables, such as sun angle and height, ambient light level, and sign orientation, were also taken into consideration.

Photometric Data

Light-emitting and light-reflecting signs will be addressed separately. The discussion of light-emitting signs will discriminate between normal and overbright modes, while light-reflecting signs will be discussed with regard to vertical sign illuminance.

Sign contrast can be calculated in a number of different ways. For the purposes of this study, target luminance minus background divided by background luminance (Lt-Lb/Lb) was selected . This is the standard formula used for determining the contrast of light targets on dark backgrounds.

Light-Emitting Signs

The luminance of light-emitting signs is user-controlled and restricted only by the limits of the technology. The objective measure of light-emitting sign luminance is functionally independent of ambient lighting conditions and sun position. The luminance levels obtained for the LED and FO signs are, therefore, discussed with regard to the three most common user-defined modes: normal daytime, overbright, and normal nighttime (figure 5). Overbright is a term that refers to increasing the character luminance to improve visibility during adverse sun conditions, such as backlit and frontlit.

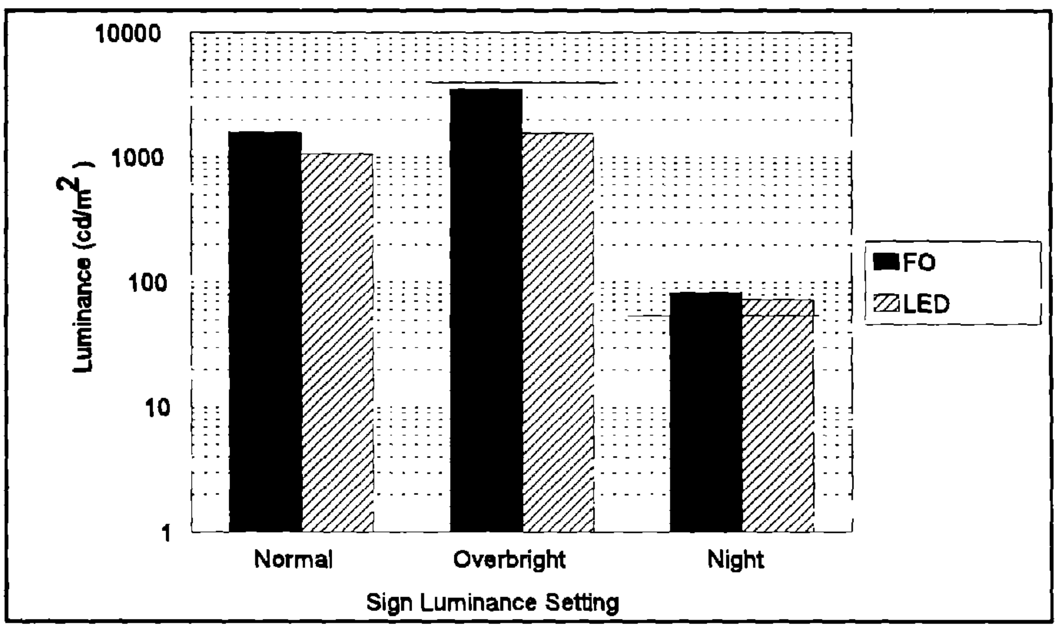


Figure 5. Light-emitting CMS luminance.
(Solid horizontal line indicates literature recommendations.)

In all three modes, the FO signs had higher luminance levels than the LED signs. The difference is minimal at night, with both technologies measuring at about 100 cd/m^2. Under the normal daylight mode, both technologies produced nearly twice the 500 cd/m^2 recommended in the literature. The range of 2000 to 4000 cd/m^2 suggested for use with challenging sun positions was achieved by the FO signs, but not by the LED's in the overbright mode.[1,6,7] Two instances of overbright LED's were encountered and the LED manufacturers indicated that these signs were at least two generations removed from the current models. Finally, it is not yet known whether the differences in luminance between these two sign types are predictive of performance.

Unlike the FO signs, the LED signs did not yield levels of contrast recommended in the literature in either the normal or overbright modes (figure 6). Since both sign types had similar character luminance, the lower contrast of the LED signs was produced by an overly bright background. There are two likely causes for this: dirty or scratched glare screens, and/or ambient light reflecting from the "off" elements on the sign face.

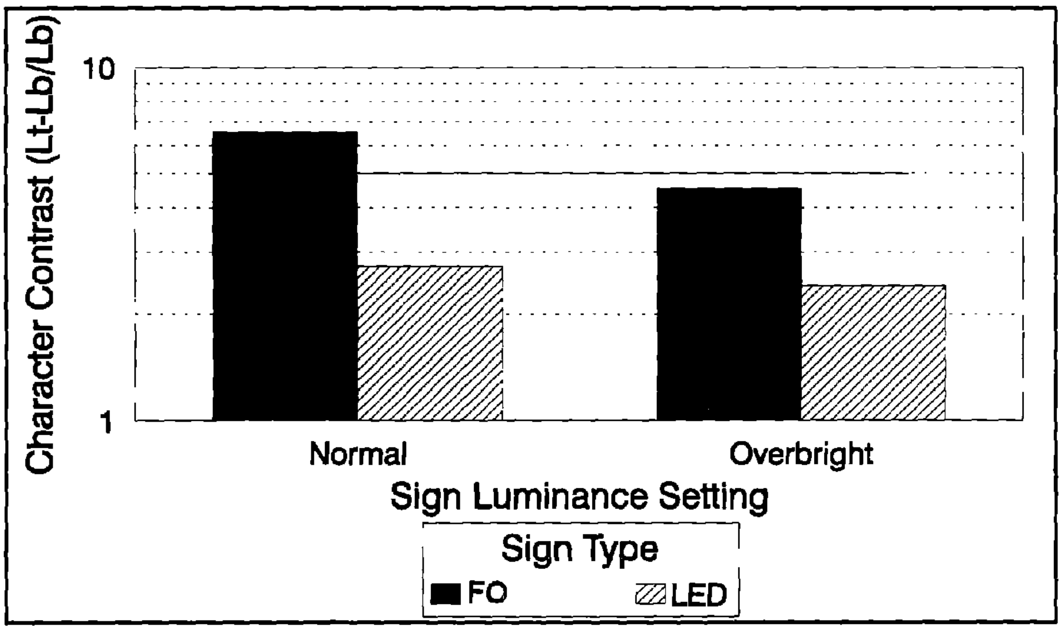


Figure 6. Light-emitting CMS contrast.
(Solid horizontal line indicates literature recommendations.)

Light-Reflecting Signs

The luminance of a light-reflecting sign is dependent on the reflectivity of the material used and the level of illumination. The luminance of these signs will, therefore, be discussed with regard to the vertical illuminance on the signs (figure 7). Vertical illuminance is divided into low (≤10,000 lx), intermediate (10,000 to 25,000 lx), high (>25,000 lx), and nighttime conditions.

As figure 7 shows, character luminance increased with the level of sign illuminance. The greatest increase found in a single sign was from 800 to 7000 cd/m^2. Based on the luminance recommendations in the literature, all the tested signs would appear adequate for normal daytime use (500 cd/m^2, see table 1). A problem lies, however, in the sun angle conditions that produced the measured luminances. The highest luminances occurred under the most friendly viewing conditions with the sun above or behind the observer. None of the reflective disc (RD) signs studied would produce high enough levels of luminance to overcome backlighting by the sun. If a sign is backlit, the vertical illuminance at the sign face will fall into the "low" category, producing luminance levels that fall far short of the 4000-cd/m^2 recommendation. For these signs, a range of 600 to 800 cd/m^2 was found. Based solely on luminance data, all other sun angles, as well as overcast days, would be adequately handled by RD signs. None of the light-reflecting signs tested produced luminance levels that approached those recommended in the literature for nighttime legibility (50 cd/m^2).

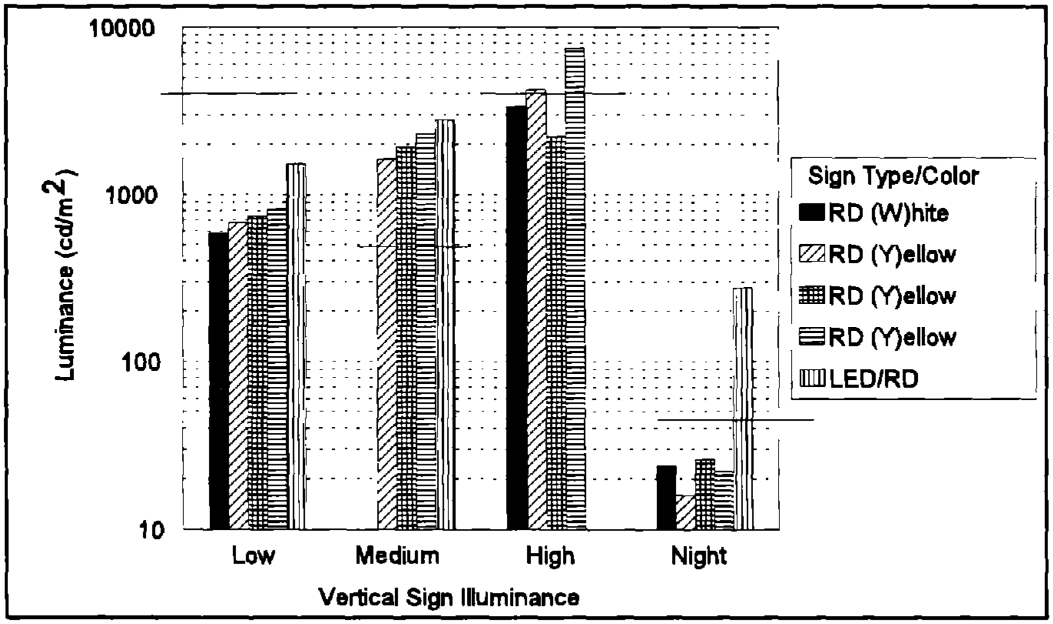


Figure 7. Light-reflecting CMS luminance, day and night.
(Solid horizontal lines indicate literature recommendations.)

Although light-reflecting signs generally provided adequate luminance during most daytime conditions, their performance with regard to contrast was suspect. Of all the RD signs measured, only one sign under the high illuminance conditions came close to providing the daytime contrast levels recommended in the literature (figure 8). While contrast is seldom used as a measure of a CMS's nighttime legibility, it is interesting to note how low the night contrast is for all of these RD signs.

Subjective Data

Conspicuity

The data collection procedure guaranteed a purely subjective rating of sign conspicuity. The field crew had to know the location of signs in order to collect the data. However, photographs and videotape recordings were taken for all sites under several lighting conditions and the locations were assessed for visual complexity. Figures 9 and 10 are indicative of the situations in which permanently mounted CMS's are used. As is apparent from these photographs, the visual clutter in the scene is minimal and, therefore, unlikely to distract the driver from the sign. However, we found that signs mounted on overpasses (figure 11 [N-VA #3]) were more difficult to locate. This is probably due to the minimal external contrast between the overpass and the signs. The visual surroundings for all of the measured signs fell into the low end of the visual complexity scale.

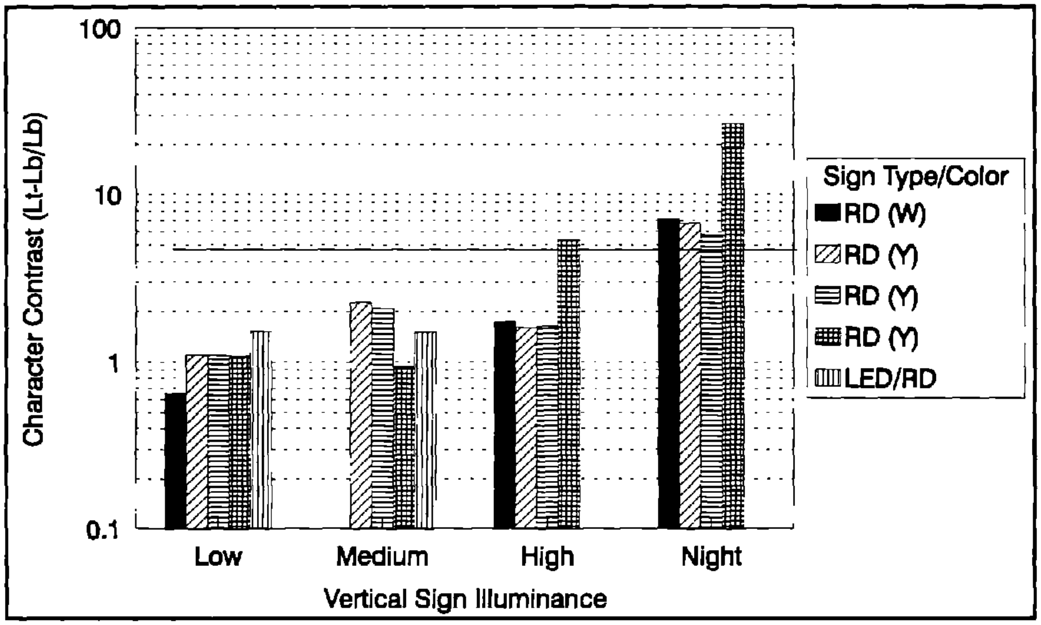


Figure 8. Light-reflecting CMS contrast, day and night.
(Solid horizontal line indicates literature recommendations.)

Legibility and General Sign Quality

Legibility distances were measured for all signs. The results depicted in figure 12 show the relative word legibility of FO, LED, LED/RD, and RD signs. About 90 percent of the observations were conducted by the same crew member. The observer was 30 years old with visual acuity corrected to 20/18. Legibility distance dropped from day to night for all but the LED signs. The low contrast of LED signs in daylight may have contributed to their lower daytime legibility distance.

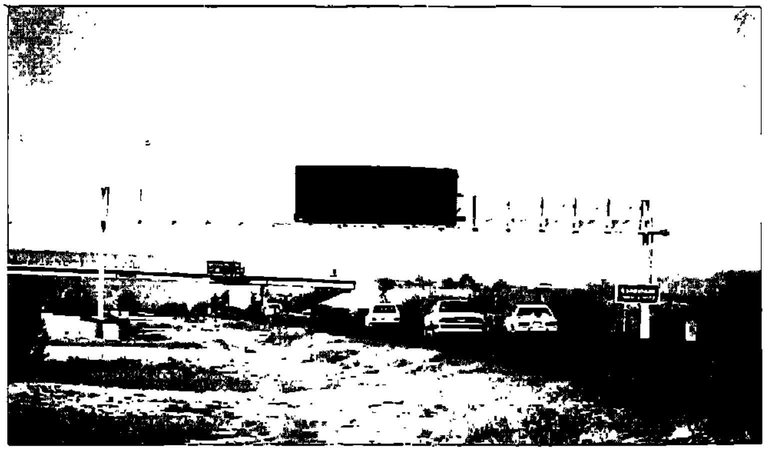


Figure 9. Permanently mounted CMS.

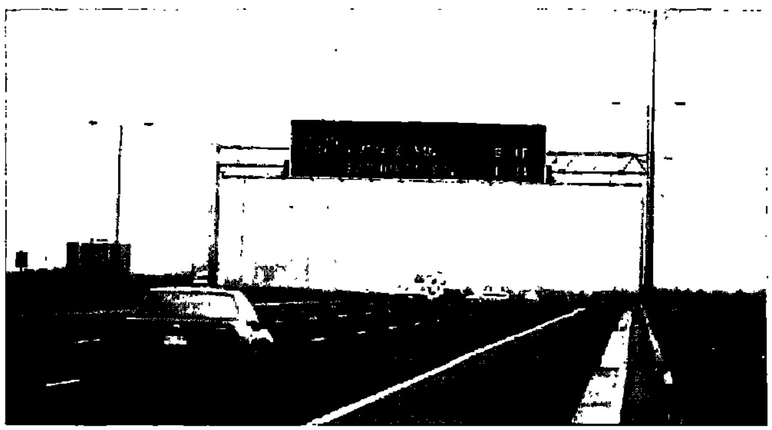


Figure 10. Permanently mounted CMS in Toronto, Canada.

Figure 11. Overpass-mounted CMS.

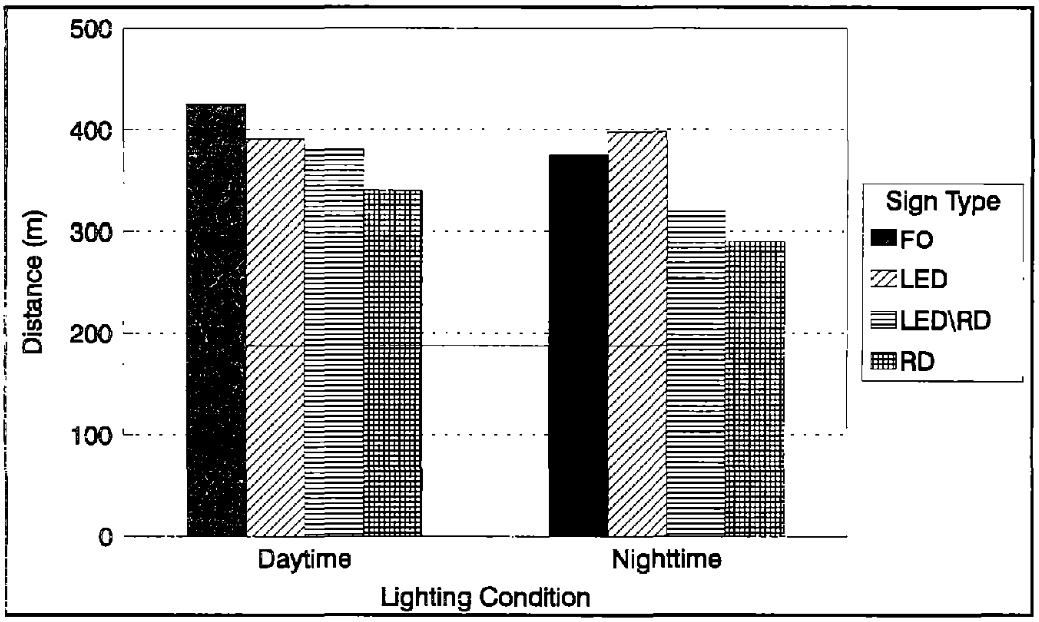


Figure 12. Legibility distance of field CMS during day and night.
(Solid horizontal line indicates literature recommendations.)

Three indices of general sign quality were assessed by the field crews: glare, clarity, and shadowing. Glare from headlights was detected only occasionally on the sign faces. This was typically observed when the sign was in the off position; when the sign was turned on, glare was not a problem. Glare was not observed from the sun on the sign face. The FO and LED/RD signs resulted in the highest average score for day and night clarity with a mean of about four on a five-point scale. The white RD signs had the lowest average clarity, with a score of two for both night and day. However, some of the yellow RD signs scored as low as one for clarity at night due to poor lighting design.

The third measure of sign quality was the assessment of shadowing or shading of the characters by either the sign border or uneven light distribution. Detrimental effects of shadowing by the border were not observed; however, as just noted, many of the RD signs were unevenly lit at night. In some cases, the three incandescent lamps mounted below the sign produced only three very bright spots of light, leaving much of the sign in the dark. In instances where fluorescent tubes were used, only the top or bottom half of a letter row was illuminated.

DISCUSSION

RD Signs

Of the tested RD signs, the Connecticut signs performed the best overall with regard to luminance and contrast. These disc signs were, in fact, the only ones that ever reached the daytime contrast levels recommended in the literature. One reason for their good contrast performance in the bright sun and at night is that the responsible highway agency maintained a regular cleaning schedule. The plastic sign covers were cleaned three to four times a year. Sunlight and internal sign lighting on a dirty or scratched sign cover, reduces contrast by creating a veil of light over the sign.

Sign performance varied greatly between locations. The white disc CMS's exhibited the worst overall performance. However, these signs were about 10 years old. When the white discs were replaced with new yellow ones, the performance improved. The Northern Virginia signs were judged to be the least conspicuous because they were relatively small and often placed on overpasses. The 7-year-old signs mounted at Long Island, NY, performed very poorly in nighttime, daytime, and foggy conditions. The probable reason for their poor performance was lack of maintenance. The sign covers were visibly scratched and very dirty. The sunlight that penetrated the covers was yellowed, producing poor color contrast and luminance contrast between the "on" and "off" elements. New York's INFORM system was considering retrofitting their 80+ signs with either LED/RD's or FO/RD's and has installed these signs in a few test locations since our data collection trip. The newer reflective signs in Seattle, Washington, performed better than those in New York on all subjective and photometric measures. However, there were still major problems with the nighttime lighting, as mentioned above.

LED/RD Signs

Only one hybrid sign was examined during this task. Its daytime photometric and subjective performance was improved by the new reflective material and the nighttime and fog performance was greatly enhanced by activating the LED clusters embedded in the discs. These signs were rated subjectively by the field crew as having clarity equal to the FO signs.

FO Signs

Of all the signs examined, the FO CMS's had the best and most consistent overall visual performance, including the greatest daytime legibility distances and highest clarity rating by the field observers. Their excellent performance was most likely due to their large size and high contrast and luminance levels. All subjective reports from the highway agencies using these signs were also positive.

LED Signs

All of the permanently mounted LED signs that were evaluated reached the recommended levels of luminance under normal daytime and nighttime conditions. The overbright mode might not be sufficient to overcome the effects of backlighting, and the contrast for both normal daytime and overbright was low (less than 3). The characters produced by these signs also appeared less sharply defined than the FO signs. However, because of their large size, they are quite conspicuous and their legibility is good, particularly at night.

Luminance and contrast were the only measurements taken on a trailer-mounted continuous-matrix red LED sign. This sign differed from the permanently mounted LED signs in two major ways: the permanently mounted signs had clusters of LED's, while the trailer-mounted sign was a matrix of individual LED's with 16 LED's in a square typically making up a character matrix element. The trailer sign used only red LED's, while the permanently mounted signs tested combined red and green LED's in an attempt to produce yellow. The trailer-mounted sign was photometered in the shade, producing a luminance of 2181 cd/m^2 and a contrast of 6.5. This type of sign provides a great deal of flexibility with regard to character style, spacing, and size, and also allows the use of symbols. Because the trailer-mounted sign was still in the warehouse, we were not able to assess its nighttime performance.

CMS DESIGN PARAMETERS

The purpose of this subtask was to identify characteristics of CMS's that influence their legibility. This was accomplished through a literature review, personal communication with sign manufacturers and highway agencies, and a field survey. The key design parameters deduced from these resources included character luminance and contrast; character height and width; font; color; contrast orientation; and inter-letter, inter-word, and inter-line spacing.

EMPIRICAL STUDIES

Regardless of whether a sign is light-emitting or light-reflecting, certain fundamental properties exist. The research reported below was intended to assess these technologically independent properties of CMS's.

The first laboratory experiment assessed character legibility while manipulating letter width, stroke width, matrix density, contrast orientation, font, and color. Another laboratory experiment assessed variables associated with message legibility and addressed the issues of word length, spacing between letters within a word, word-to-word spacing, and line-to-line spacing. Due to the luminance limitations of computer monitors, both laboratory studies were conducted under simulated nighttime viewing conditions.

In addition to these laboratory-based studies, two static field studies were conducted. The static field experiments were used to assess the effects of sign luminance in daytime settings. The experimental stimuli for field studies were actual CMS's obtained from manufacturers and mock-up CMS's developed by the contractor. Finally, a dynamic field study was conducted using trailer-mounted CMS's on an in-use highway.

SUBJECT RECRUITMENT AND SCREENING

A battery of cognitive, perceptual, and motor tests was conducted to ensure that the subject sample had the same performance characteristics as the population of interest. The major weakness in this approach is the lack of normative data on the U.S. driving population for any measure other than static visual acuity. For this reason, static visual acuity, as measured with a Bausch & Lomb Master Orthorater and Snellen Chart, was the only measure used for the actual screening of study participants. Persons with high-luminance binocular-far acuity worse than 20/40 were excluded from participation.

LABORATORY STUDIES

Apparatus

Both laboratory studies employed a CMS simulator programmed to run on a PC-compatible computer with graphics capabilities. The simulator displayed images having the same appearance as existing, and possible future, CMS's. The full-color monitor was 33 cm (13 in) diagonally and contained 1024 by 768 elements. At a 7-m (23-ft) observation distance, the limits of resolution for a 20/15 subject are approximately 1.25 mm (0.04 in) and the limits of the above-mentioned graphics system is 0.27 mm (0.01 in).

Procedure

The subjects were tested individually and they adapted to ambient light levels simulating normal nighttime CMS viewing conditions. Size threshold legibility was measured for all levels and combinations of the independent variables. Subjects were tested at one of three distances from the monitor, depending on their static acuity. Subjects with 20/20 vision or better were tested at

10.67 m (35 ft); 20/22 to 20/25 acuity were tested at 7.62 m (25 ft); and 20/29 acuity or worse were tested at 6.1 m (20 ft). Three younger subjects with acuities better than 20/18 were tested at 12.2 m (40 ft).

All signs were shown one at a time, beginning with the smallest size for each condition. Each sign size was stored in the computer's memory. The size increments and the range in sizes varied with matrix density. This was unavoidable given the constraints of the graphics system used. Differences also occurred in range and step size among the three distances used. The smallest steps were in the middle-to-large end of each range, where most of our subjects reached threshold. A detailed description of the tested sizes, converted into both visual angle subtended and legibility index (LI), appears in table 3.

Study 1 was run in a single 45-min session with 5-min breaks between its three parts. The subjects responded by reading the letters aloud. Subjects were instructed *not* to wait until they were absolutely certain of a letter before responding, but to take a "reasonable guess" if they had one.

The experimenter was seated close to the display monitor. As the subject read each letter, the experimenter pressed labeled keys, registering correct or incorrect responses. The experimenter corrected key-press errors with a switch key that reversed the last response, from correct to incorrect. When the subject completed the response to a sign, the experimenter pressed an "end-of-sign" key and the next sign was automatically shown on the monitor. If the subject indicated that he/she could not read any of the letters, the experimenter pressed a single "bail-out" key and moved to the next sign. When 80 percent of the letters on a particular sign were correctly identified at two consecutive sizes, that condition was automatically removed from the stimulus set and the threshold size was recorded for analysis.

STUDY 1: THE EFFECTS OF CHARACTER VARIABLES AND COLOR ON CMS LETTER LEGIBILITY

Objective

Study 1 had numerous objectives, which focused on improving character legibility. The Matrix Study was designed to determine the W:H and SW:H combinations that produced the best letter legibility. The objective of the Font Study was to identify a single CMS font that produced the smallest size legibility thresholds. The goal of the Color Study was to assess the effect of color on legibility. All of these objectives were accomplished under simulated nighttime viewing conditions for older and younger subjects.

Table 3. Target sizes for studies 1 and 2.

Character Description		Height (mm)	Distance (m) 6.1		7.62		10.67	
			(visual angle <)	(m/cm)	(vis. <)	(m/cm)	(vis. <)	(m/cm)
Size 1	5-by-7	7.0	3.95	8.7	3.16	10.9	2.26	15.2
	7-by-9	8.5	4.79	7.2	3.84	9.0	2.74	12.6
Size 2	5-by-7, 12 & 15-by-15	10.0	5.64	6.1	4.51	7.6	3.22	10.7
	7-by-9	11.0	6.2	5.6	4.96	6.9	3.54	9.7
Size 3	5-by-7	13.0	7.33	4.7	5.86	5.9	4.19	8.2
	12 & 15-by-15	15.0	7.61	4.1	6.09	5.1	4.35	7.1
Size 4	7-by-9	15.0	8.45	4.1	6.77	5.1	4.83	7.1
	5-by-7	16.0	9.02	3.8	7.22	4.8	5.16	6.7
	12 & 15-by-15	17.0	9.58	3.6	7.67	4.5	5.48	6.3
Size 5	5-by-7	19.0	10.71	3.2	8.57	4.0	6.12	5.6
	12 & 15-by-15	20.5	11.55	3.0	9.25	3.7	6.6	5.2
	7-by-9	21.0	11.83	2.9	9.47	3.6	6.77	5.1
Size 6	5-by-7	22.5	12.68	2.7	10.15	3.4	7.25	4.7
	12 & 15-by-15	24.0	13.53	2.5	10.83	3.2	7.73	4.5

Methodology

Subjects

A total of 70 subjects representing three age groups participated in study 1. Descriptive statistics for this sample are presented in table 4.

Table 4. Study 1 subject description.

Age Group	Sample Size	Age Range	Mean Age (S.D.)	Mode Age	Visual Acuity Range (20/x)	Mean Acuity (S.D.)
Young	24	16-40	26.6 (6.2)	25	16-40	20.3 (5.4)
Old	25	62-73	67.9 (3.0)	65	18-40	25.9 (5.8)
Old-Old	21	74+	77.2 (4.0)	75	18-40	28.5 (5.4)

Variables

The dependent variable was the threshold size at which a character became legible. The smallest size at which a subject was able to correctly discern a character was the threshold for that subject and that letter. These threshold sizes were then converted into a generic LI expressed in m/cm (ft/in) of letter height in order to facilitate comparison with real-world highway conditions.

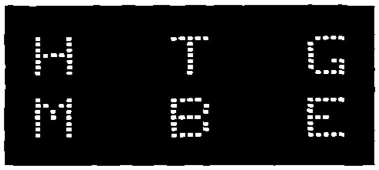
The independent variables for the Matrix Study were W:H, SW:H, and matrix density. For the Font Study, the independent variables were font and matrix density. Color was the independent variable for the Color Study.

MATRIX STUDY

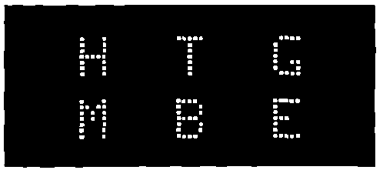
Stimuli

Seven experimental conditions using three matrix densities, three levels of W:H, and two levels of SW:H were tested (figure 13). Three conditions used a 5-by-7 matrix. The maximum SW:H for a 5-by-7 matrix, single-stroke character is approximately 0.13 with minimal vertical spacing between matrix elements. This SW:H was tested at three W:H's: 0.7, 0.8, and 1.0. A 12-by-15 matrix with a W:H equal to 0.8 and a 15-by-15 matrix with a W:H equal to 1.0 were both tested at SW:H's of 0.13 and 0.20. The font used in the 5-by-7 size was developed by the authors based on current usage and will be called Typical CMS. The fonts used in the 12-by-15 and 15-by-15 matrices approximated the Typical CMS in these matrix densities.

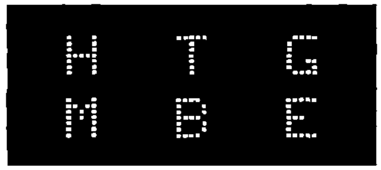
Each of the seven conditions was tested using a combination of curved alphabet letters B, C, G, S; straight letters E, F, H, T; and angular letters K, M, X, Z. These characters were chosen to ensure that a response was based on more than global letter form alone. There were two signs per experimental condition. Each sign had six randomly selected letters, arranged in two rows of three letters each. In all, 14 signs were tested. Inter-letter spacing was at least equal to letter height, and inter-line spacing was at least 75 percent of letter height. Figure 13 shows one sign from each experimental condition.



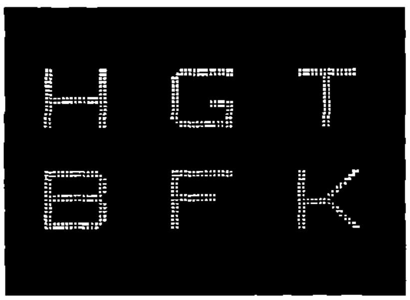
a) 5x7 W:H=1.0, SW:H=0.13



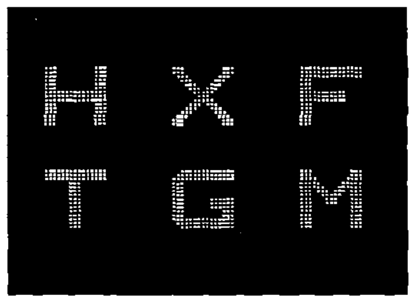
b) 5x7 W:H=0.8, SW:H=0.13



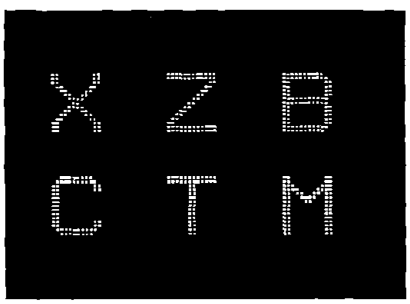
c) 5x7 W:H=0.7, SW:H=0.13



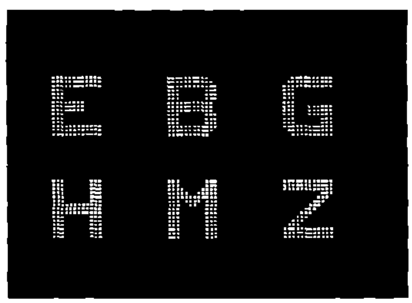
d) 15x15 W:H=1.0, SW:H=0.13



e) 15x15 W:H=1.0, SW:H=0.2



f) 12x15 W:H=0.8, SW:H=0.13



g) 12x15 W:H=0.8, SW:H=0.2

Figure 13. Stimuli tested in the Matrix Study.

As previously discussed, it is impossible to manipulate CMS letter characteristics without changing some fundamental matrix components. In order to increase letter width while keeping letter height and SW constant, either the number of horizontal elements or the horizontal spacing must be increased. To increase SW, either the elements must be made larger or more elements must be used and the inter-element spacing must be made smaller. However, the number of matrix elements and the spacing between those elements have been shown to be of less importance than the W:H and the SW:H. Therefore, the element characteristics were allowed to vary as necessary.

Luminance

The selection of character luminance was based on what was found to be optimum in the literature and on our own field measurements and pilot tests. The procedure for the photometric measurements was identical to that previously discussed. Average character luminance "on" was approximately 30 cd/m^2 (9 fL). The exact measures varied slightly across matrix density and W:H (table 5).

Table 5. Character luminance for the Matrix and Font studies.

Description	Luminance (cd/m^2)
5-by-7:	
W:H=1	24
W:H=0.8	32.9
W:H=0.7	39
DOUBLE	21
7-by-9	32.5
12-by-15	24.7
15-by-15	25

Experimental Design

The Matrix Study used an incomplete factorial repeated measures design that consisted of three matrix densities, three W:H's, and two SW:H's (figure 13).

Results

Age Group

The analysis of variance (ANOVA) procedures that were conducted uncovered the main effects of age. Under all of the conditions discussed above, the young group performed best, followed by the old group, and then the old-old group. Mean age effects resulted in an approximately 1.2-m/cm (10-ft/in) drop in LI from the young to the old group, and an approximately 0.6-to 1.2-m/cm (5-to 10-ft/in) drop from the old to the old-old group (figure 14).

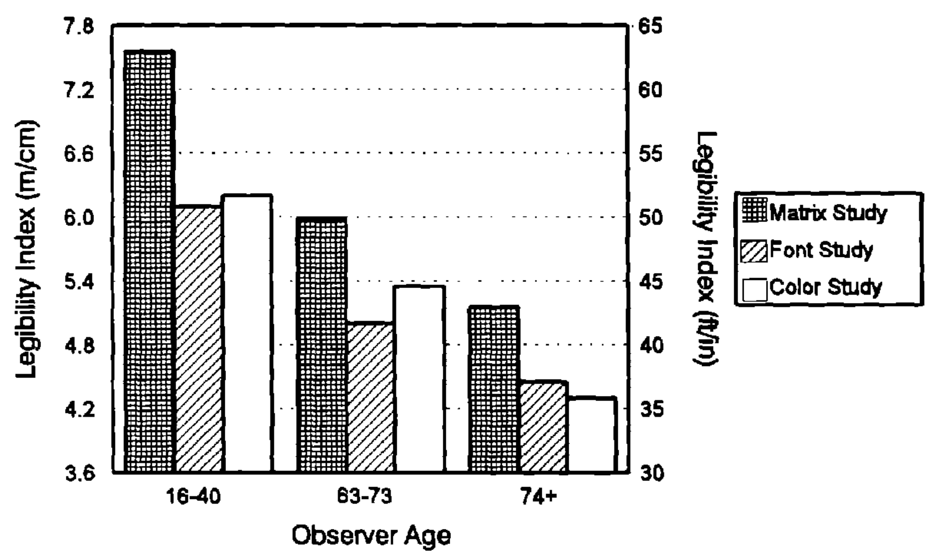


Figure 14. Mean age effects on legibility.

In general, the variables examined in Study 1 and, for practical purposes, in the Font and Color studies showed that factors that worked well for one age group worked for all ages. For this reason, the remainder of the Study 1 results section will be devoted to a discussion of the data analysis without regard to age. LI by age and the percentile observer for selected conditions will be included.

W:H

A significant main effect of W:H was found through an ANOVA (figure 15). Within a given matrix density and font, increasing the W:H from 0.7 (figure 13[c]) to 1.0 (figure 13[a]) increased the LI 0.84 m/cm (7 ft/in). This is equivalent to a theoretical 38-m (126-ft) advantage for the wider letter when using a 46-cm (18-in) letter height, or approximately 1.5 s at 89 km/h (55 mi/h).

Other research, however, suggests that the actual advantage might be less, since the LI decreases with larger letter sizes.

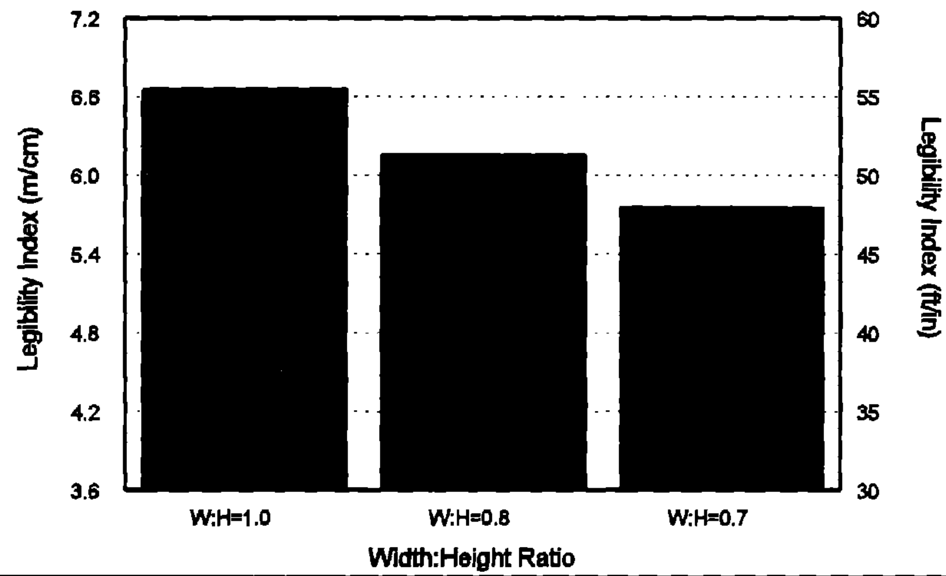


Figure 15. Significant effect of W:H.

SW:H

An ANOVA indicated that for relatively narrow letters (W:H=0.8), a significant SW:H main effect occurred. The thinner stroke was found to perform better than the wider stroke by 0.48 m/cm (5 ft/in), although this effect was not significant with a wider letter (figure 13[d] vs. 13[e]). Only positive-contrast letters were tested. Because of the influence of irradiation effects, the reverse might be expected if negative-contrast was used; however, current research indicates that this is not likely to be the case.[22]

Matrix Density

No significant effects of matrix density were found in the Matrix Study. Increasing the number of elements and thereby increasing their definition did not improve legibility for uppercase letters.

FONT STUDY

Stimuli

Four fonts were selected for analysis in the Font Study: The Optimum Composite font (figure 16[a]) and the Double Composite font (figure 16[b]) were tested in a 5-by-7 matrix. Vartabedian (figure 16[d]) was displayed on a 7-by-9 matrix. The Typical CMS font, developed for the Matrix Study, was tested under both 5-by-7 and 7-by-9 matrices (figure 16[c] and [e]).

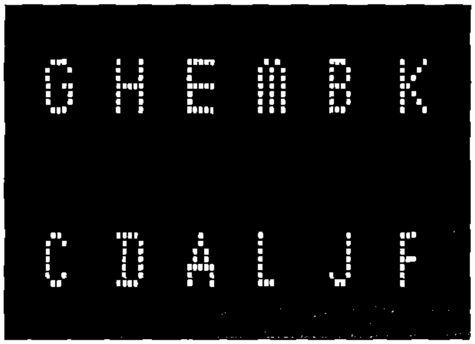
Again, as in the Matrix Study, the letters tested consisted of 12 characters that represent curved (D,O,P,Q,U), straight (I,J,L), and angular (A,R,W,Y) forms. Inter-letter spacing was at least 80 percent of letter height and inter-line spacing was at least 150 percent of letter height. The differences in spacing and number of letters per sign between the Matrix and Font studies were due to our desire to present as many letters per sign as possible under a wide range of letter heights while maintaining spacings of at least standard highway levels. For example, since the letters in the Font Study had a smaller W:H than in the Matrix Study, we were able to test rows of six letters instead of three. However, in doing so, we had to decrease the inter-letter spacing from equal to letter height to 80 percent of letter height.

Luminance

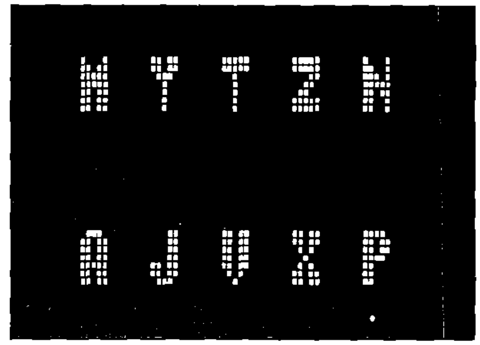
The luminance measurements for the Font Study were conducted in an identical manner as those in the Matrix Study. The results of these measurements are depicted in table 4.

Experimental Design

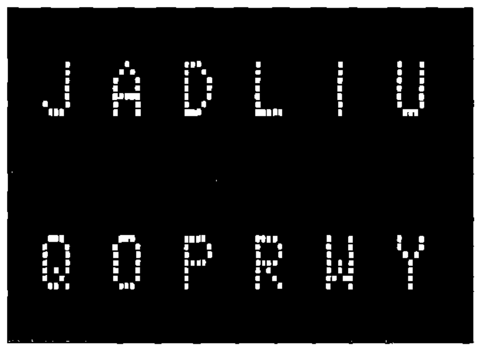
The Font Study used a two-factor repeated measures design with five levels of variable font and two levels of matrix density.



a) Optimum Composite.

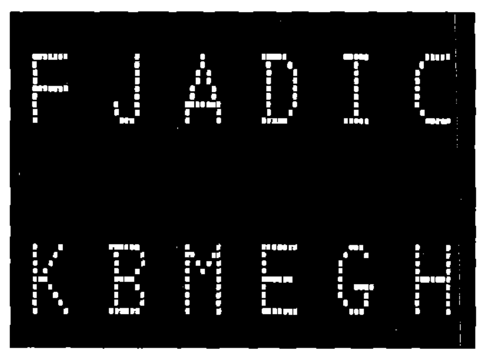


b) Double Composite.



c) Typical 5x7 CMS.

d) Vartabedian.



e) Typical 7x9 CMS.

Figure 16. Stimuli tested in the Font Study.

Results

Age Group

In the Font Study, an interaction effect occurred between age and font. However, there were no differences between age groups in rank order of the conditions (figure 17).

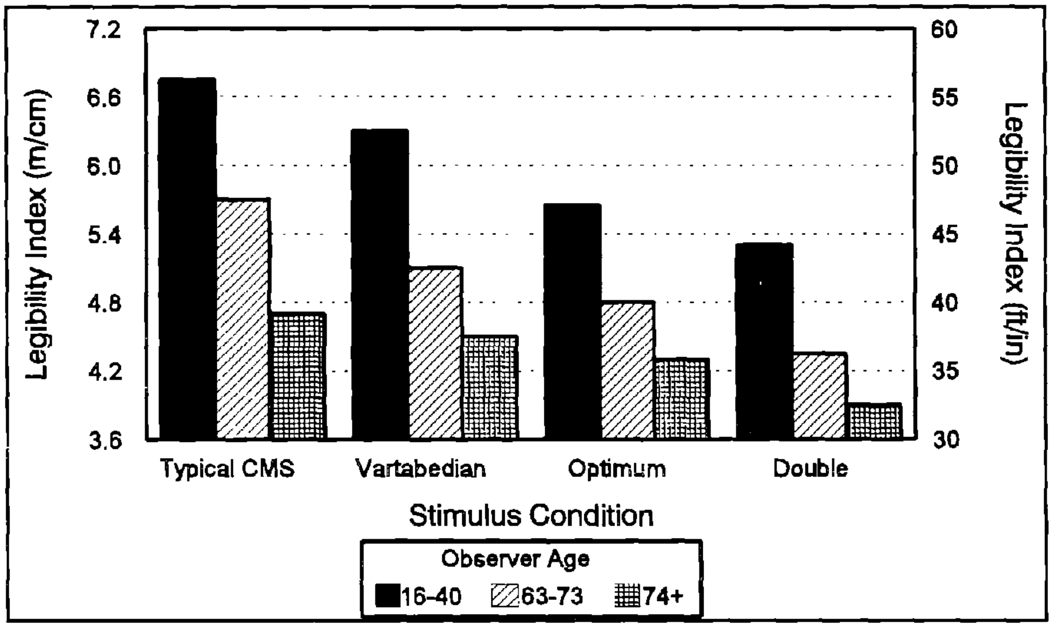


Figure 17. Interaction effect of age and stimulus condition.

Font

Figure 18 depicts the LI for each of five fonts tested in the Font Study. An ANOVA showed the Typical CMS fonts, 5-by-7 and 7-by-9 matrices, performed significantly better than the other three tested. In the interpretation of our results, a 0.6-m/cm (5-ft/in) change in LI was the criterion for an important difference between conditions. A 0.72-m/cm (6-ft/in) difference occurred in LI between the Typical CMS 5-by-7 and the Optimum Composite 5-by-7 fonts, which was deemed important. Double Composite was the worst font by far with over 1.2-m/cm (10-ft/in) decrement.

Matrix Density

No significant effects of matrix density (5-by-7 vs. 7-by-9) were found in the Font Study. Increasing the number of elements and thereby increasing the definition, again, did not improve legibility.

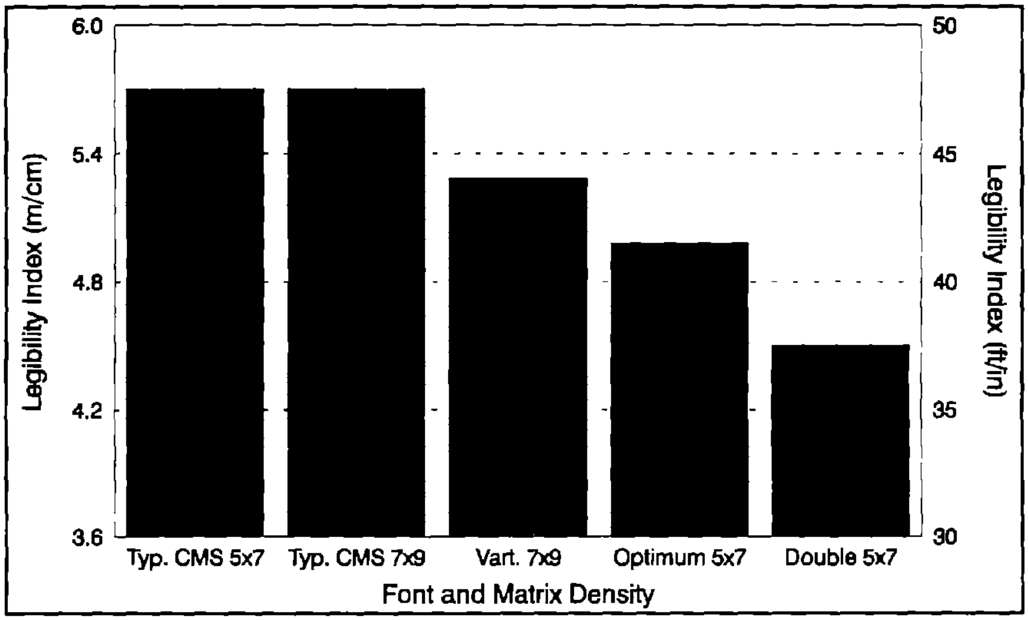


Figure 18. Comparison of sign fonts.

COLOR STUDY

Stimuli

Six color combinations were examined. Four of these combinations replicated standard highway usage: white-on-green (W/G), black-on-orange (B/O), black-on-white (B/W), and black-on-yellow (B/Y). The remaining two color combinations were representative of current and possible future CMS's: yellow-on-black (Y/B) and red-on-black (R/B). The choice of stimulus letters was the same as in the Matrix Study, and spacings were identical to those used in the Font Study. The font was the Typical CMS 5-by-7 used in both the Matrix and Font studies.

Luminance

Each of the color combinations were paired with a black-and-white control of matched luminance and the same contrast orientation. The average character matrix luminance, on and off, for all stimuli can be found in table 6. The "off" for the positive-contrast, black background stimuli approached zero.

The purpose of matching the color targets with black-and-white controls was to establish direct comparisons between color and B/W signs without confounding the results with luminance or changing sign chromaticity. The effects of contrast orientation and luminance were examined by comparing the B/W sign 1(b) to B/W sign 3(b) and to W/B sign 2(b).

Experimental Design

The Color Study used a two-factor repeated measures design with color/contrast orientation and matched color pairs as described previously.

Table 6. Color Study, luminance with cell on and off (cd/m^2).

Sign #	Color	Luminance On	Luminance Off	Sign #	Black-and-White Control	Luminance On	Luminance Off
1(a)	R/B	4.5	--	1(b)	W/B	5.5	--
2(a)	Y/B	35.6	--	2(b)	W/B	39.0	--
3(a)	B/O	9.6	19.5	3(b)	B/W	8.2	17.5
4(a)	B/Y	24.0	50.4	4(b)	B/W	26.0	58
5(a)	W/G	45	4.1	5(b)	N/A	N/A	N/A

Results

Age Group

The results resembled those of the Font Study with a statistically significant, yet practically non-important, interaction between the age groups.

Color

There were no significant effects of color that could not be explained by changes in character luminance or contrast orientation. Color was inexorably confounded with luminance as a function of the apparatus used in the laboratory studies. When characters of color were matched on luminance with black-and-white characters, no differences occurred in letter legibility. This was found to be the case with letters of high luminance, low luminance, and both positive and negative contrast (figure 19).

Contrast Orientation

An ANOVA showed a very strong significant effect of contrast orientation on letter legibility. Positive-contrast stimuli were, on average, over 1.2 m/cm (10 ft/in) superior to negative-contrast stimuli. This was the case regardless of whether the positive-contrast targets had higher or lower character luminance than the negative-contrast targets (figure 20).

Luminance

The luminance results from the Color Study are a byproduct of the attempt to match the different colors with a black-and-white sign of equal luminance. This technique produced white-on-black and black-on-white signs of varying contrast. A significant luminance effect was found in both contrast orientations (figure 20). The black-and-white stimuli tested in this experiment showed a small decrease in the LI with relatively large reductions in character luminance.

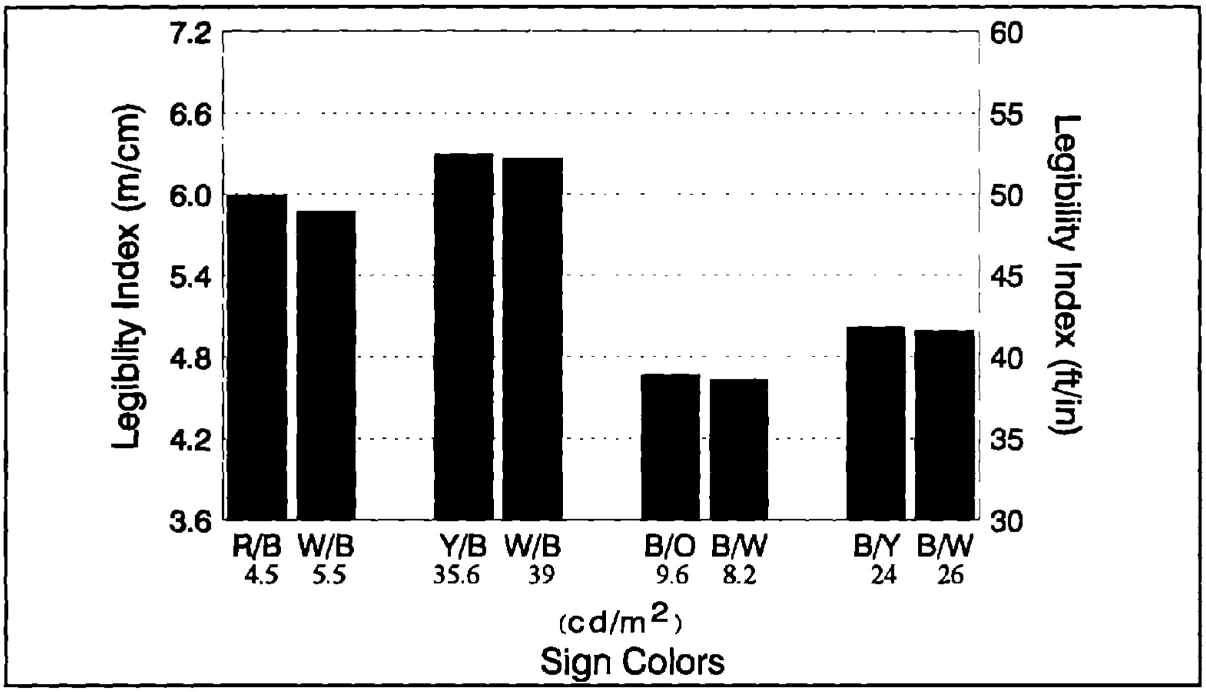


Figure 19. Legibility of B/W characters vs. colored characters.

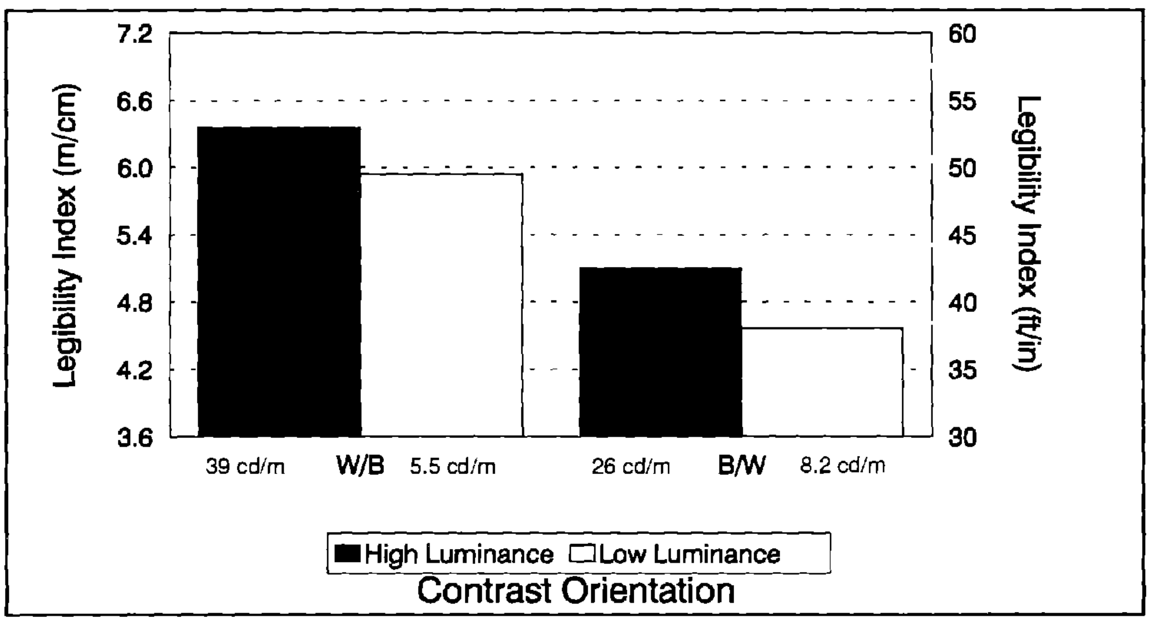


Figure 20. LI of positive-contrast signs vs. negative-contrast targets.

Discussion

Best-Case Character

The purpose of the previous discussion of Study 1 results was to delineate the effects of the manipulated variables, and not the effects of age for each condition. However, at some point, the results must be discussed in the context of observer age. The most efficacious time to do this is with the "best case," or recommended, conditions.

With regard to character shape in a CMS format, the results of the Matrix and Font studies indicate that of the studied combinations, the Typical CMS font with a W:H of 1.0 and a SW:H of 0.13 (figure 21[a]) was optimal. Figure 21(b) shows the legibility index of this optimal CMS for the three age groups from median to 95th percentile observer. Even the 85th percentile old-old observer was capable of reading these letters at the LI typically expected of CMS's (i.e., 4.2 m/cm [35 ft/in]).

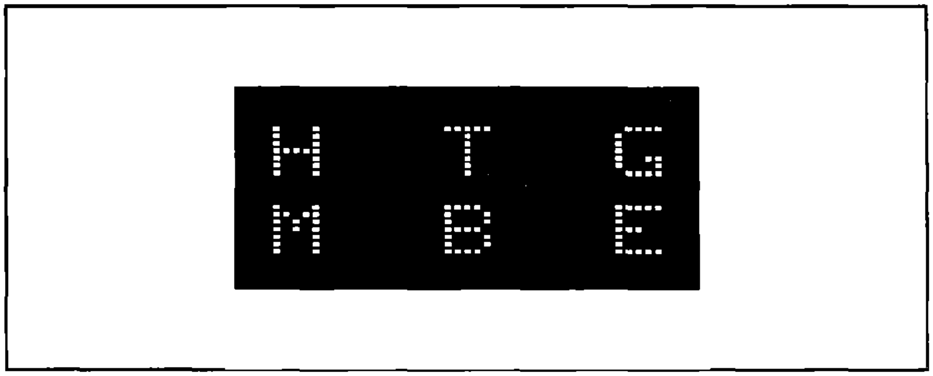


Figure 21(a). Best character shape.

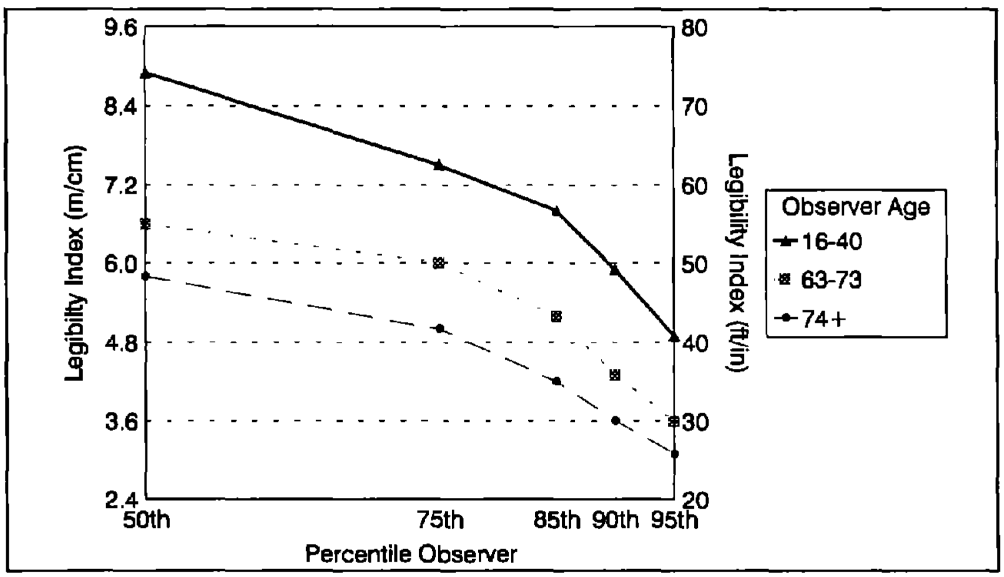


Figure 21(b). Performance of optimal CMS conditions by age and percentile observer.

Best Case Spectral

The LI for the CMS with optimal color, contrast orientation, and luminance are depicted by age and percentile observer in figure 22 (a)-(c). This figure shows the similarity of the results for the luminance-matched W/B and Y/B signs. Except for the highest percentile in the old-old group (figure 22[a]), these two colors performed equally well and produced the highest legibility of those tested.

As people get older, they become more sensitive to changes in target luminance. The R/B signs performed as well as the other two colors for young subjects (figure 22[a]); however, the two older groups found the R/B signs to be less legible. This discrepancy between the old and young observers lends credence to the conclusion that the reduced performance of the color red is due mainly to its lower luminance.

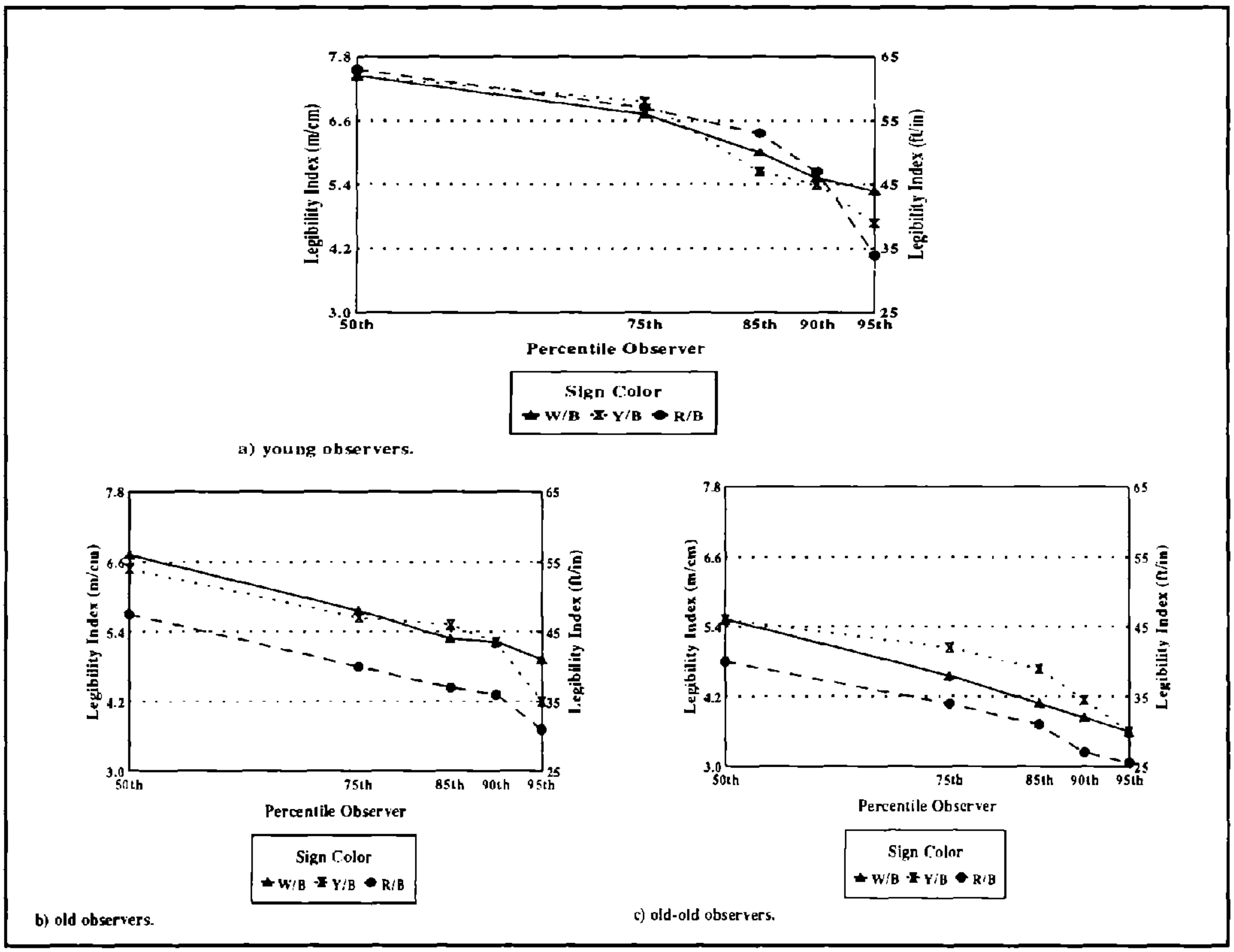


Figure 22. Best performance of lighting characteristics by age and percentile observer.

Ineffective Variables

Matrix density, color, luminance (within a restricted range), SW:H, and W:H had little or no effect on the legibility threshold of CMS's for any tested age group. Matrix density and color were completely ineffective in producing any change in legibility. The effects of matrix density were not surprising. As stated previously, no improvement in either response time (RT) or error rates was found between the 14-by-18 and 7-by-9 matrices. If only uppercase letters are used, our studies augment those of Kerr et al. in showing that the increased resolution provided by greater matrix density does not improve legibility over a standard 5-by-7 matrix.(1)

The literature's treatment of the effects of color on CMS's was less clear-cut than it was for the effects of matrix density. Our results conform most with Kerr et al., who found no difference in RT or error rate between white and yellow elements.(1) Our study extends these findings to threshold size for legibility and red elements, as well as to negative-contrast CMS's.

Luminance, SW:H, and W:H had limited effects on CMS legibility. The literature supports a 50-cd/m^2 optimum luminance for nighttime legibility of CMS's. Our study, however, showed only minimal improvement in legibility with a luminance increase from 5 to 40 cd/m^2. One problem with resorting to past studies for appropriate CMS luminance is the lack of a standard for the photometric measurement of these signs.

Contrary to the results of Kerr et al., we found improvement with increased SW:H at night using positive-contrast letters, but only for older observers. Other studies found that SW:H was less important than luminance in affecting CMS legibility. The effects observed in Study 1 showed minor improvement with a decrease in SW:H for positive-contrast signs and only with the narrower letters. The effects of SW:H in the literature are typically discussed as increased element size. Our reduction of SW:H was unique in that we reduced the stroke only on the inside of the characters (figure 13[d] vs. 13[e] and figure 13[f] vs. 13[g]). This manipulation only affected the "tighter" 12-by-15 (W:H=0.8 vs. 1.0) letters, indicating that this method reduces the blurring effect of irradiation produced by positive-contrast luminous characters. This effect, albeit statistically significant, was not substantially important.

Effective Variables

Subject age and visual acuity were shown to have a great effect on the legibility of CMS's. Neither of these variables, however, are amenable to manipulation to any meaningful extent.

Numerous CMS studies, as well as research on permanent message traffic signs, have indicated that an increase in W:H up to 1.0 leads to an improvement in legibility. We also found this to be the case. However, the increase in cost associated with increasing W:H may not justify the benefits of improving legibility distance.

Surprisingly, font was a fairly powerful tool for improving CMS legibility. While minor "tweaks" to a font (Typical CMS vs. Vartabedian vs. Optimum Composite) produced minimal results, the Double Composite font produced substantially poorer legibility. Interestingly, this font is sometimes touted by manufacturers as a method of improving sign "punch." The reason for the poor performance of the Double Composite font was the mixing of double and single strokes necessitated by the 5-by-7 character matrix (figure 16[b]). While this technique might be attractive and would produce short response times at close distances, it proved difficult to decipher at simulated longer viewing distances.

Of the independent variables tested in Study 1, contrast orientation had the greatest effect on CMS legibility. In some instances, more than 1.4 m/cm (12 ft/in) of letter height was gained with positive-contrast signs. This improvement is equivalent to an additional 67 m (220 ft) of legibility distance for a 46-cm (18-in) letter height, or 2.75 s at 89 km/h (55 mi/h). The effect was robust enough to cut across color and character luminance. The results of a study of retroreflective materials suggest that it is not likely that the legibility of negative-contrast CMS can be improved by manipulating SW:H, although this should be examined.[22] W:H and character height seemed to be the only character variables that might improve the legibility of negative-contrast characters.

Table 7. Summary of Study 1: results and conclusions.

Independent Variables	Results	Conclusions
Subject Age	Up to 2.4-m/cm (20-ft/in) decrement from young to old-old group. Limited interaction with other variables.	Improvements for one age group benefit all groups.
W:H	Statistically significant, yet small (0.72 to 0.84 m/cm [6 to 7 ft/in]), improvement from 0.7 to 1.0.	As wider letters have a higher cost (larger signs), this level of improvement may not be cost-effective.
SW:H	Statistically significant, yet small (0.48 m/cm [4 ft/in]), improvement with positive-contrast letters with a decrease in SW:H from 0.2 to 0.13.	Although the legibility increase is small, no increase in expense is necessary to achieve it.
Matrix Density	No significant differences between the densities tested (5-by-7, 7-by-9, 12-by-15, 15-by-15). Testing was conducted with all uppercase letters.	Increasing the density or definition of a character does not improve legibility for uppercase characters. A 5-by-7 matrix is as legible as a 15-by-15 matrix. 5-by-7 will not, however, accommodate lowercase letters.
Font	The Typical CMS font (derived from that found most in the field) performed the best overall. The Double Composite font (derived from the 5-by-7 double stroke found most in the field) performed the worst (1.2 m/cm [10 ft/in] less than the Typical CMS).	The fonts currently used by manufacturers are probably sufficient. Any attempt to "double stroke" a sign within a 5-by-7 character module should be strongly discouraged.
Color	No difference between a color sign and a B/W sign of the same luminance. Differences in performance between colors could best be explained by differences in luminance and contrast orientation. Although significantly different, an R/B sign was only 0.36 m/cm (3 ft/in) of letter height lower than a Y/B, even with a large luminance difference.	At least under the conditions tested, and as long as appropriate luminance levels and contrast orientation are maintained, the color of a sign is not a factor in letter legibility.
Contrast Orientation	Aside from age, contrast orientation had the largest effect on legibility of all tested variables. More than 1.4 m/cm (12 ft/in) of letter height was lost from positive to negative contrast. This occurred with B/W as well as color signs, and high as well as low luminance.	Care needs to be taken if negative-contrast CMS's are to be used in the field. For example, it may not be possible to significantly improve the legibility of these signs through changes in character variables such as SW:H.
Luminance	Luminance had a very small, but statistically significant, effect (less than 0.48 m/cm [4 ft/in]) and only at the most extreme levels tested. Small changes in luminance (less than twofold or threefold) produced no change in letter legibility.	Under nighttime conditions, a W/B sign with a luminance level of 5.5 cd/m^2 (1.6 fL) performed as well as a sign with a luminance level of 39 cd/m^2 (11 fL). If this lower luminance level would be appreciably less expensive to produce, it might be recommended as a cost-effectiveness measure, unless the higher luminance was shown to improve conspicuity.

STUDY 2: THE EFFECTS OF SPACING VARIABLES ON CMS WORD LEGIBILITY

Letter spacing and spacing between words are known to be important factors in the legibility of all road sign types, including CMS's. In current CMS usage, inter-letter spacing ranges from a single column of elements (one SW) to about one-half of the character width. However, the CMS literature does not provide adequate data on either appropriate or minimum spacing between letters, words, or lines of text.

Word length was included in Study 2 so that its interaction with inter-letter spacing could be examined as suggested in the literature. Berger found that to maintain legibility, the spacings between strings of numbers must increase as the length of the string increases.[24]

Objectives

Study 2 had numerous objectives which focused on improving word and message legibility. The objectives of Study 2 were to select the optimum and minimum acceptable spacing between letters, words (Word Length Study), and lines of text (Message Study). This was accomplished under simulated nighttime, positive and negative contrast viewing conditions for old and young observers.

Methodology

A total of 82 subjects participated in the Word Length Study and 73 subjects in the Message Study. The same age group categories were used as in Study 1. The descriptive statistics are presented in table 8.

Table 8. Word Length and Message studies subject description.

Study	Age Group	Sample Size	Age Range	Mean Age (S.D.)	Modal Age	Visual Acuity Range (20/x)	Mean Acuity (S.D.)
Word Length	Young	36	16-40	26.3 (6.4)	21	15-40	20.3 (4.8)
	Old	25	62-73	67.9 (3.0)	65	18-40	25.9 (5.8)
	Old-Old	21	74+	77.2 (4.0)	75	18-40	28.5 (5.4)
Message	Young	27	16-40	26.8 (6.6)	25	16-40	20.1 (5.2)
	Old	25	62-73	67.9 (3.0)	65	18-40	25.9 (5.8)
	Old-Old	21	74+	77.2 (4.0)	75	18-40	28.5 (5.4)

Variables

The independent variables were word length, inter-letter spacing, and contrast orientation in the Word Length Study and inter-word and inter-line spacing in the Message Study. Again, the dependent variable was size-threshold legibility, which was subsequently converted into LI.

Procedure

Size-threshold legibility was determined for all levels and combinations of the independent variables. The procedure was identical to that used in Study 1; except instead of reading letters, the subjects were required to read aloud the words on the signs.

In brief, the two experiments were run as part of the 2- to 3-h session that included Study 1. Each of the Study 2 experiments lasted approximately 15 min, with a 5-min inter-experiment break. The experimenter was seated close to the display monitor. The subjects responded by reading aloud to the experimenter the words on each of the signs. As the subject read each word, the experimenter pressed keys to indicate correct or incorrect. The experimenter could correct any typing errors with a switch key that reversed the last entry. When the subject completed the response, the experimenter pressed an end-of-sign key and the next sign was automatically brought onto the monitor. If the subject indicated that he/she could not read any of the words, the experimenter pressed a single bail-out key and moved on to the next sign. When 100 percent of the words on a particular sign were correctly identified at two consecutive sizes, that condition was removed automatically from the stimulus set and the threshold size was recorded for analysis.

WORD LENGTH STUDY

Stimuli

The stimuli consisted of actual words arrayed in three lines of text (one word per line) with inter-line spacing always equal to letter height (figure 23). Three word lengths were examined on each sign (three-, five-, and seven-letter words). Each of the words used the Typical CMS font in a 5-by-7 matrix depicted in figures 13(c) and 14(c). Two-thirds of the signs were shown in positive contrast W/B and the rest in B/W. The inter-letter spacings consisted of four levels. Three of these were: The *Manual on Uniform Traffic Control Devices (MUTCD)* standard for series E; 75 percent of standard; and 125 percent of standard.[25] The fourth spacing was equal to the SW of the tested characters. This last spacing was included because it is often used on in-service CMS's, and it represents the minimum producible spacing.

A total of 18 words (6 words per word length) were used. All words were selected through pilot testing on the basis of equivalent legibility distance from a list of preprogrammed CMS messages. Since this precaution may not be sufficient to counteract all word-difficulty effects, the subjects were divided into four groups. The words were balanced so that each word was tested under each spacing condition, thus eliminating the possibility of confounding the treatment effects with word difficulty (table 9).

a) Letter spacing equal to SW.

b) Letter spacing equals 75% of Standard Highway.

c) Letter spacing equal to Standard Highway.

d) Letter spacing equals 125% of Standard Highway.

Figure 23. Stimuli tested in the Word Length Study.

Two of the six signs were shown in negative contrast (B/W) to assess the possibility of an interaction between letter spacing and contrast orientation. These negative-contrast signs were tested under the two extreme spacing conditions, single stroke and 125 percent of standard.

Experimental Design

All subjects were tested under all conditions in both portions of Study 2. The Word Length Study consisted of an incomplete 4 (inter-letter spacing) by 3 (word length) by 2 (contrast orientation) design (table 9). The positive-contrast signs were tested with all combinations of the other two variables; while the negative-contrast signs were tested with all word lengths, but only the two extreme spacings.

Table 9. Word Length Study experimental design.

Letter Spacing / Stroke Width	Highway Standard	75% of Standard	125% of Standard
Subject Group 1			
Positive Contrast	FOG LANES FREEWAY	CAR ALERT WORKERS	OFF SPEED CONTROL	TWO DELAY STOPPED
Negative Contrast	FOR LOCAL ROADWAY			ONE AHEAD PREPARE
Subject Group 2			
Positive Contrast	STOPPED TWO DELAY	FREEWAY FOG LANES	WORKERS CAR ALERT	CONTROL OFF SPEED
Negative Contrast	PREPARE ONE AHEAD			ROADWAY FOR LOCAL
Subject Group 3			
Positive Contrast	SPEED CONTROL OFF	DELAY STOPPED TWO	LANES FREEWAY FOG	ALERT WORKERS CAR
Negative Contrast	LOCAL ROADWAY FOR			AHEAD PREPARE ONE
Subject Group 4			
Positive Contrast	CAR ALERT WORKER	OFF SPEED CONTROL	TWO DELAY STOPPED	FOG LANES FREEWAY
Negative Contrast	ONE AHEAD PREPARE			FOR LOCAL ROADWAY

Results and Discussion

Subject Age

As in Study 1, ANOVA's revealed significant main effects of age in the Word Length and Message studies. A significant decline in LI was found between the young and old group and between the old and old-old groups (figures 24[a] and 24[b]). The Word Length Study contained the only significant interaction between age and any other variable. This occurred between age and contrast orientation. The interaction is discussed below.

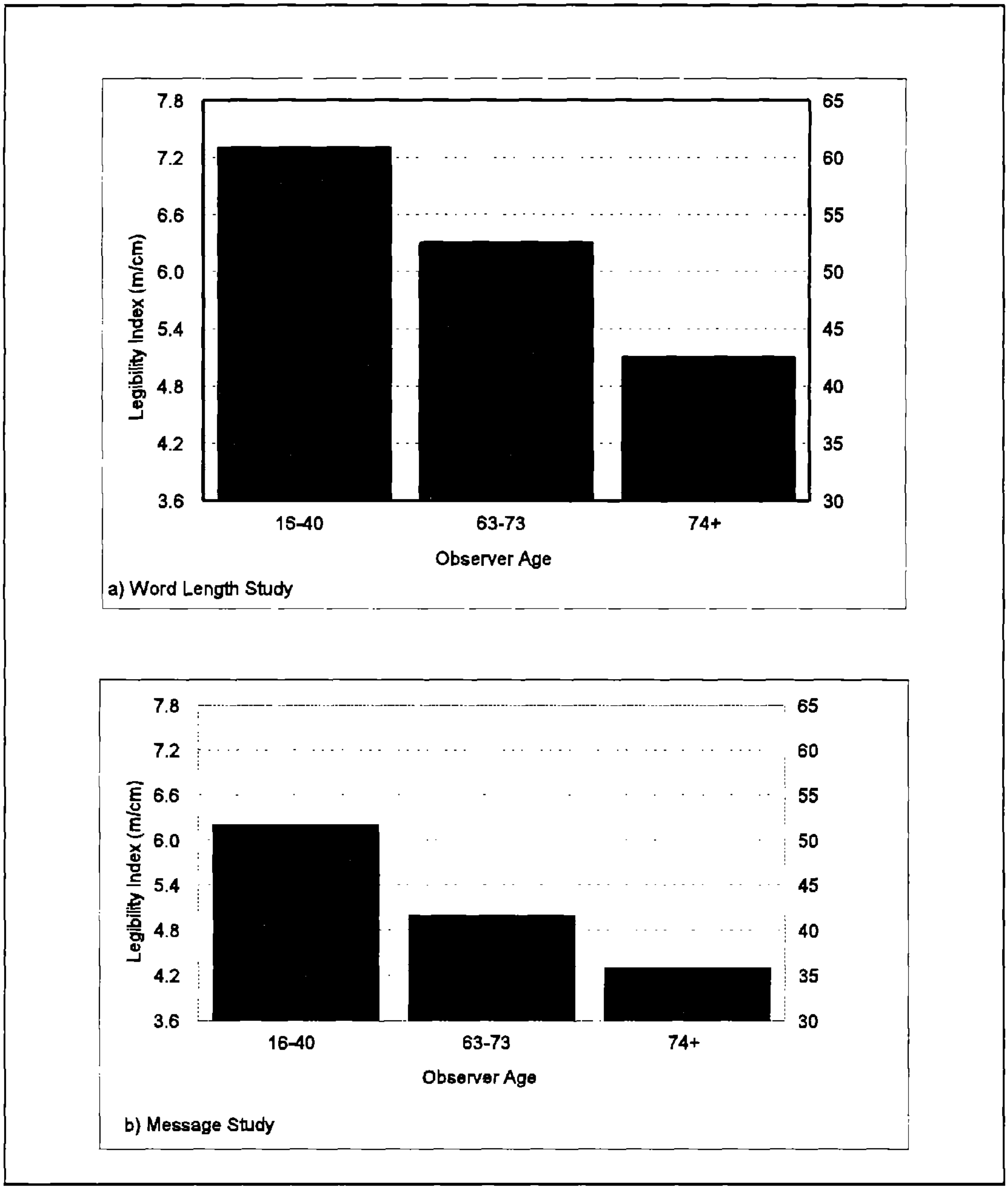


Figure 24. Word Length and Message studies: main effects of age group on legibility.

Word Length

An ANOVA showed a significant, but not substantial, effect of word length. Wherein, seven-letter words resulted in a maximum 0.31-m/cm (2.6-ft/in) reduction in legibility over three- and five-letter words. No interactions were found between word length and any other variable.

Inter-Letter Spacing

An ANOVA indicated a significant main effect of inter-letter spacing, but no interaction with contrast orientation. Inter-letter spacing equal to SW produced the poorest legibility. Spacing equal to 125 percent of the standard resulted in the best performance. Approximately, a 1.2-m/cm (10-ft/in) difference in letter height was found between the two spacings. Further probing into the significant main effect of inter-letter spacing indicated that 75 percent of standard spacing performed as well as the standard highway spacing (figure 25).

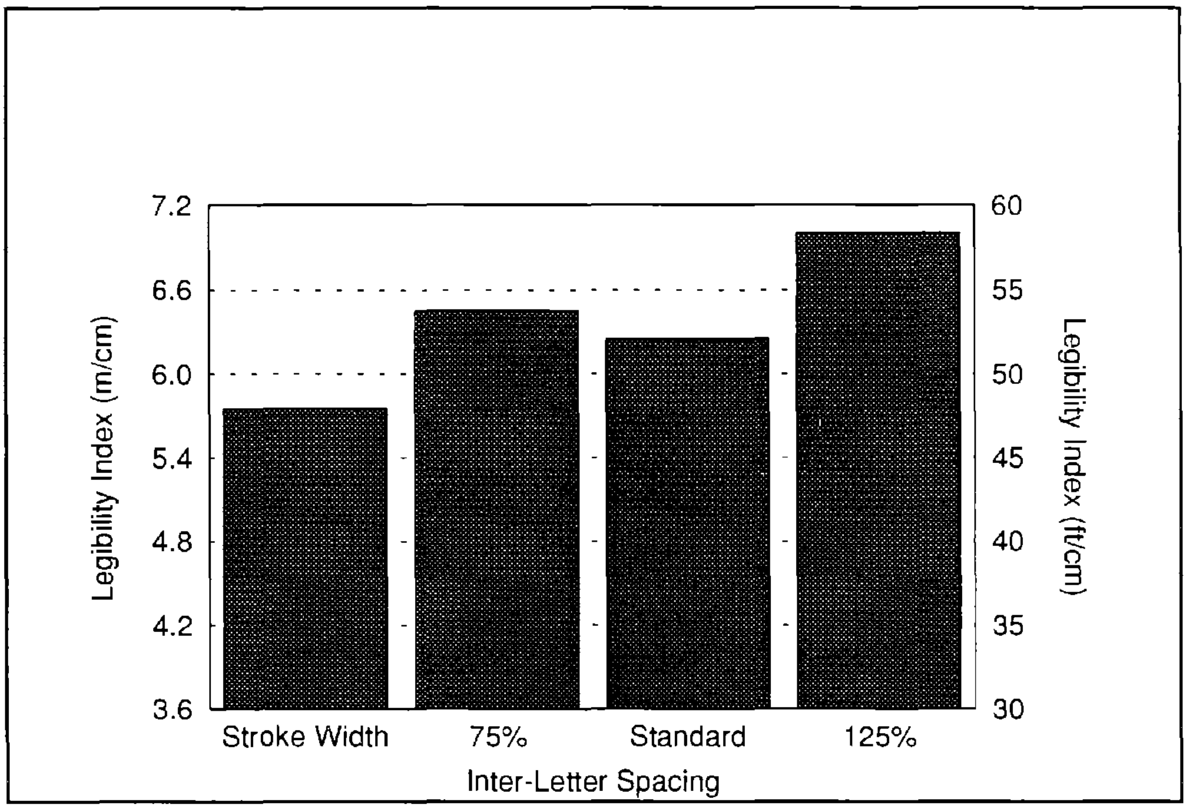


Figure 25. Main effects of inter-letter spacing.

The inter-letter data are presented for various percentile observers by age group in figure 26(a) and (b). This graphic representation reveals several interesting findings. Inter-letter spacing equal to SW provided a LI of 4.2 m/cm (35 ft/in) of letter height for up to the 90th percentile young and old groups, and up to the 50th percentile old-old group. Increasing inter-letter spacing to 125 percent of the standard provided the minimum 4.2-m/cm (35-ft/in) LI for the 80th percentile old-old group and even higher LI's for the other age groups.

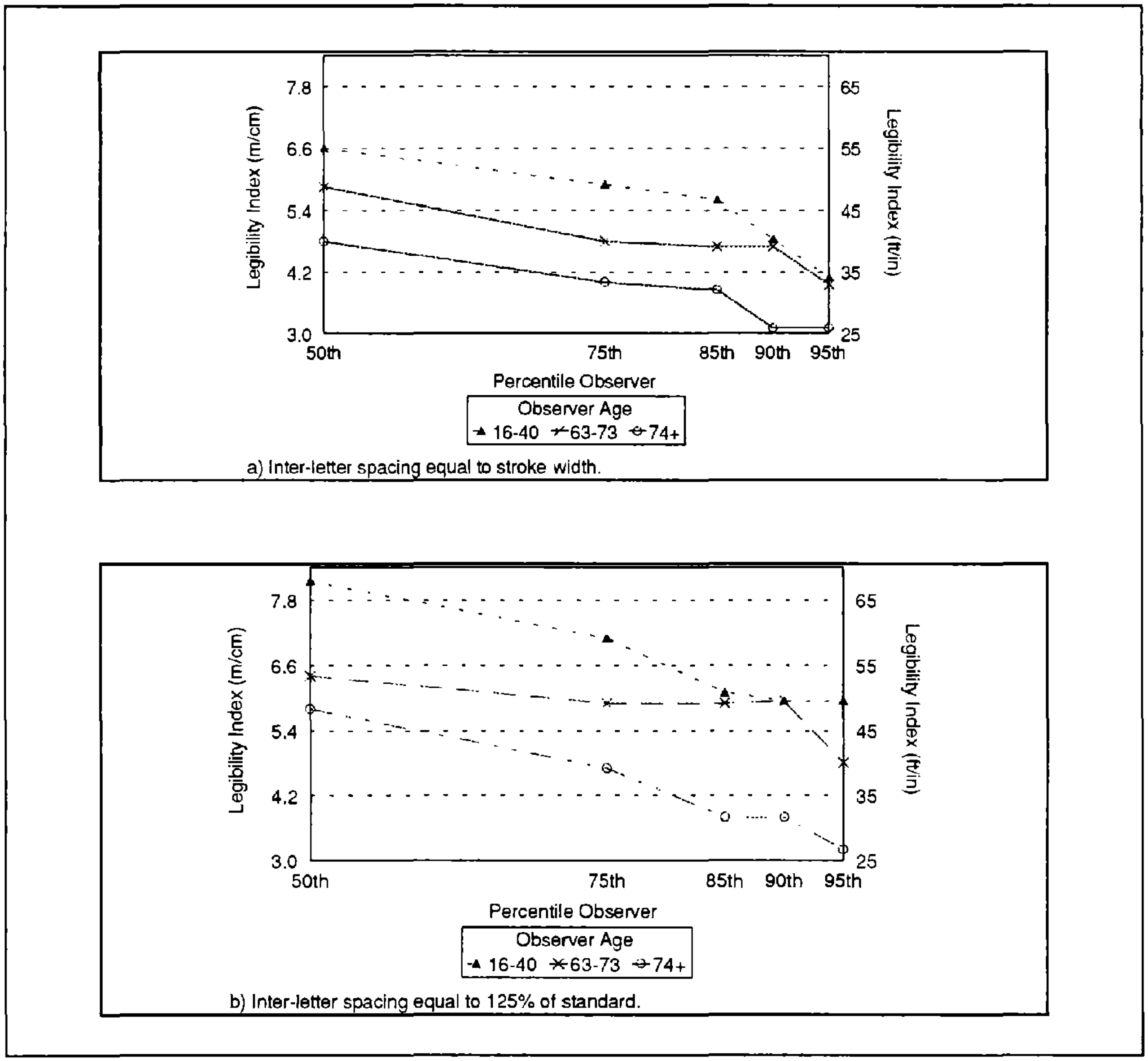


Figure 26. Various percentile observers and two inter-letter spacings.

Contrast Orientation

As in the Color Study, contrast orientation produced statistically significant and functionally important results. A 1.2-m/cm (9-ft/in) improvement in LI, from 4.8 to 5.9 m/cm (40 to 49 ft/in), occurred with the positive-contrast words. As previously stated, there was an interaction between age and contrast orientation. This interaction resulted from a quantitative effect. That is, negative contrast produced significantly lower legibility in all age groups, but had a significantly greater effect on the old group. The difference between the age groups is quite small. Negative-contrast signs were, at most, about 0.24 m/cm (2 ft/in) worse for the old group than the other two age groups.

MESSAGE STUDY

Stimuli

Inter-word spacings were equal to letter width, the static highway standard letter height, and 150 percent of highway standard. Two inter-row spacings were tested with each of the inter-word spacings (figure 27). Row spacing equal to 20 percent of letter height was used because it was found on many CMS's, particularly those trailer-mounted. Spacing equal to 75 percent of letter height represented the static highway standard as well as many permanently mounted FO and LED CMS's.

The sign copy consisted of three sets of three-letter words, selected in the same manner and using the Typical CMS font as in the Word Length Study. Single-element, inter-letter spacing and positive-contrast W/B letters were used for all stimuli. Each sign consisted of three lines of text with three words on each line. Each word set consisted of nine words.

Experimental Design

The Message Study consisted of a complete 3 (inter-word spacing) by 2 (inter-line spacing) design (table 10). The subjects were divided into three groups of eight subjects per age group. The same nine words were used for each word spacing and both row spacings for each subject group. The word sets were counterbalanced across word spacing such that each set was tested under a different condition in each of the three subject groups (table 10).

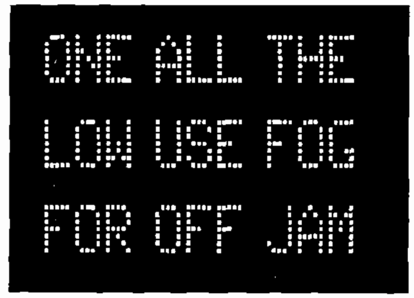
Results and Discussion

Inter-Line Spacing

An ANOVA showed that changing inter-line spacing from 20 to 75 percent of letter height significantly improved the LI. The effect was about 0.6 m/cm (5 ft/in) of letter height for the middle word, middle column, and outside corner words (figure 27). Analyses of the middle row revealed an almost doubling of this effect.

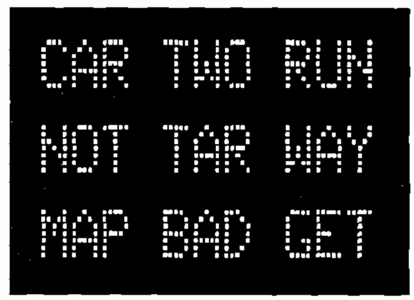
The analyses of middle-row-only data are further examined by age and percentile observer in figure 28. Again, if 4.2 m/cm (35 ft/in) can be taken as a minimum LI, inter-line spacing equal to 20 percent of letter height would accommodate the 95th percentile young observer, but just barely satisfy the 50th percentile old and old-old groups. An increase in inter-line spacing to 75 percent of letter height would satisfy all of the young observers, the 90th percentile old observer, and marginally the 75th percentile old-old observer.

a) Row spacing=20% of letter height.
Word spacing=letter width.

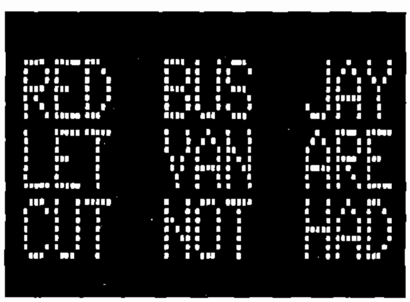


b) Row spacing=75% of letter height.
Word spacing=letter width.

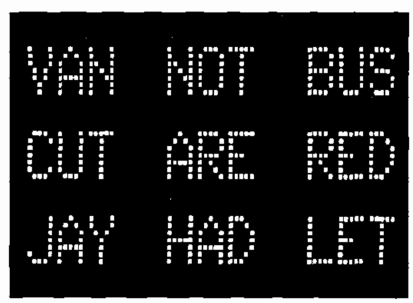
c) Row spacing=20% of letter height.
Word spacing=letter height.



d) Row spacing=75% of letter height.
Word spacing=letter height.



e) Row spacing=20% of letter height.
Word spacing=150% of letter height.



f) Row spacing=75% of letter height.
Word spacing=150% of letter height.

Figure 27. Stimuli tested in the Message Study.

Table 10. Counterbalancing of word sets across subjects and conditions for the Message Study.

	Row Spacing = 20% Letter Height	Row Spacing = 75% Letter Height
Subject Group 1		
Word Spacing = Letter Width	USE ALL ONE JAM OFF FOR THE FOG LOW	ONE ALL THE LOW USE FOG FOR OFF JAM
Word Spacing = Letter Height	TAR NOW GET MAP BAD RUN TWO WAY CAR	CAR TWO RUN NOT TAR WAY MAP BAD GET
Word Spacing = 150% Letter Height	RED BUS JAY LET VAN ARE CUT NOT HAD	VAN NOT BUS CUT ARE RED JAY HAD LET
Subject Group 2		
Word Spacing = Letter Width	RED BUS JAY LET VAN ARE CUT NOT HAD	VAN NOT BUS CUT ARE RED JAY HAD LET
Word Spacing = Letter Height	USE ALL ONE JAM OFF FOR THE FOG LOW	ONE ALL THE LOW USE FOG FOR OFF JAM
Word Spacing = 150% Letter Height	TAR NOW GET MAP BAD RUN TWO WAY CAR	CAR TWO RUN NOT TAR WAY MAP BAD GET
Subject Group 3		
Word Spacing = Letter Width	TAR NOW GET MAP BAD RUN TWO WAY CAR	CAR TWO RUN NOT TAR WAY MAP BAD GET
Word Spacing = Letter Height	RED BUS JAY LET VAN ARE CUT NOT HAD	VAN NOT BUS CUT ARE RED JAY HAD LET
Word Spacing = 150% Letter Height	USE ALL ONE JAM OFF FOR THE FOG LOW	ONE ALL THE LOW USE FOG FOR OFF JAM

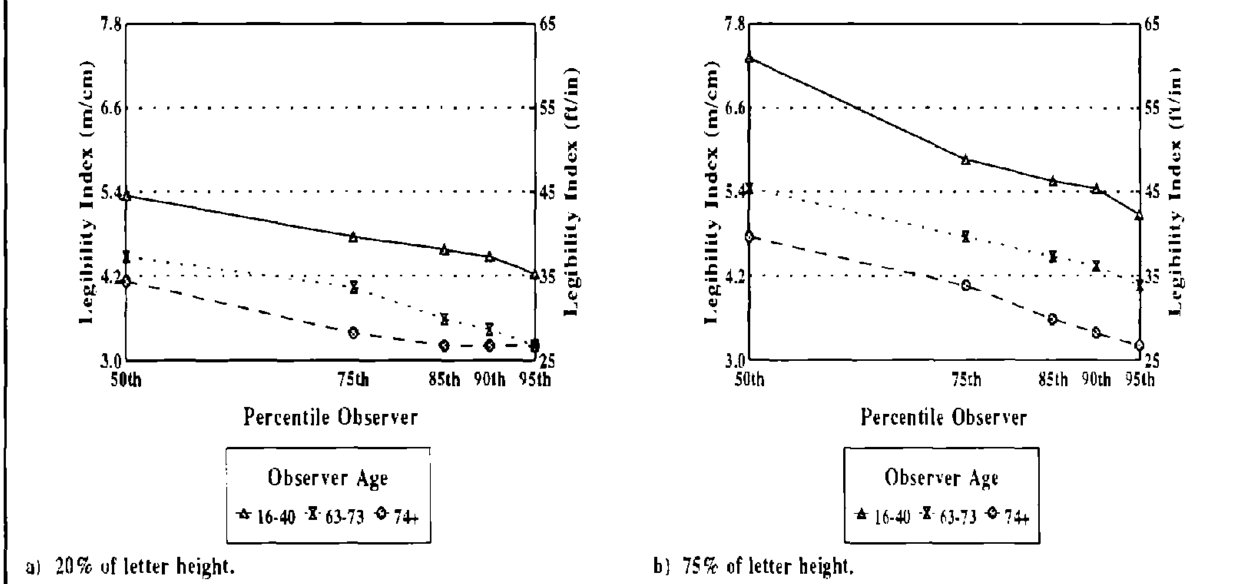


Figure 28. Various percentile observers for middle-row, inter-line spacing.

Inter-Word Spacing

No significant main effect of word spacing was found. No interactions occurred between this variable and any other variables tested.

Ineffective Variables

At the tested levels, neither word length nor inter-word spacing had any substantial effect on word legibility. The results indicate that there is no need to increase inter-letter spacing with longer words on CMS's.

As previously discussed, there were no empirically based recommendations for inter-word spacing on CMS's. The two levels of this variable selected for study were based on common usage in CMS's and the highway standard. One unexamined factor in this study was the possibility of an interaction between inter-letter spacing and inter-word spacing. While no significant differences were found for the two examined inter-word spacings, some other letter and word spacings combination not tested, may maximize legibility.

Effective Variables

As in Study 1, age and contrast orientation had a strong effect on legibility. Not finding interactions between age and any other independent variable leads to the conclusion that factors that work well for one age group worked for all. The decision then centers on selecting the age group, and percentile observer within that age group, for which CMS's should be designed, and the costs/benefits involved. Since these decisions are beyond the scope of the current project, the results are displayed in figures 26 and 28 to allow for flexibility in criteria selection and to provide information regarding the benefit or cost of CMS improvements.

Over the range of tested variables, inter-letter and inter-line spacing were both shown to contribute a great deal to the legibility of CMS words. Increased inter-letter spacing was shown to significantly improve legibility regardless of contrast orientation. Furthermore, replacing the often-used SW inter-letter spacing with 125 percent of the standard highway proportional spacing increased word length by an average of only 10 percent, while improving word legibility by almost 20 percent.

An increase in inter-line spacing from 20 to 75 percent of letter height produces significant increases in legibility for all words on the tested signs. This improvement was understandably the most dramatic (1.2 m/cm [10 ft/in]) with the middle row of words. A consideration in determining whether to use the larger and costlier spacing might be the number of text lines on a particular sign. If a sign is to contain only two lines of text, the smaller spacing might provide sufficient legibility.

A summary of the results is provided in table 11.

Table 11. Summary of Study 2: results and conclusions.

Independent Variables	Results	Conclusions
Subject Age	Up to 2.4 m/cm (20 ft/in) loss in legibility from the young to old-old groups. No interactions between age and any other variable.	Improvements for one age group benefit all groups.
Word Length	A statistically significant, but functionally unimportant, effect of word length from 3- to 7-letter words was found. No interaction between word length and other variables.	It is not necessary to provide different spacing for different lengths of words. This is true for positive- and negative-contrast words.
Inter-Word Spacing	No significant effect of inter-word spacing from equal to letter height to 150% of letter height. No significant interaction between this and other tested variables.	No need for costly increases in inter-word spacing. It is possible that with reduced inter-letter spacing, inter-word spacing could be even less than equal to letter height without a loss in legibility.
Inter-Letter Spacing	125% of highway standard spacing outperformed highway standard and CMS standard (SW spacing) by 1.2 m/cm (10 ft/in) of letter height. 75% of standard performed as well as standard.	An increase in inter-letter spacing that produces only a 10% increase in word length (from SW to 125% of standard) can produce substantial (1.2 m/cm [10 ft/in]) improvement in legibility. Positive- and negative-contrast words are equally improved by increased inter-letter spacing.
Inter-Line Spacing	75% of letter-height, inter-line spacing was significantly more legible (1.2 m/cm [10 ft/in] greater) than 20% of letter-height spacing for the middle row. Middle column and outside words were less affected.	When constructing a CMS with three or more lines of text, inter-line spacing becomes very important. Signs with two lines of text may maintain spacing between 20% and 75% of letter height without appreciable loss in legibility.
Contrast Orientation	Positive-contrast words were more legible than negative-contrast words.	Negative-contrast signs reduce legibility, which quite likely outweighs the possible benefits of greater target value.

FIELD-BASED STUDIES

Three limited outdoor studies were necessary to supplement the laboratory-based experiments described earlier. As mentioned previously, there are several limitations to computer CMS simulation. First, neither daytime sign luminance nor ambient light conditions were readily amenable to replication in the laboratory. Second, it is unclear whether computer simulation can supply information on more than the relative performance of the manipulated variables. That is, legibility distances calculated from visual angles subtended at short distances in the laboratory might not predict absolute performance at long distances in the field. Before proceeding to the field studies, preliminary analyses of the laboratory studies were conducted. The results of the laboratory studies were used to select several field variable levels.

STUDY 3: STATIC FIELD STUDY OF MINIMUM LUMINANCE FOR CMS LEGIBILITY–RED LED SIGN

Luminance and luminance contrast are widely recognized for their effects on sign legibility. In addition, these photometric values are related to the costs involved in CMS use and maintenance. For these reasons, it is important to establish the minimum luminance necessary to accommodate various levels of the driving population.

Objectives

The objectives of Study 3 were to determine the optimum, minimum, and maximum luminance for daytime and nighttime legibility of CMS's at several viewing distances and letter heights for old and young observers.

Subject Characteristics

Participants in Study 3 totaled 89, ranging in age from 17 to 88 years old. Seventy-nine subjects participated in the daytime administration of Study 3. A total of 43 subjects participated in the nighttime sessions. Since there was lower nighttime participation by older subjects, the old and old-old age groups were combined into one age group for analysis. Means and standard deviations for age and acuity for both studies are presented in tables 12 and 13.

Methodology

Variables

The independent variables were age group, sign distance, and letter height. The dependent measures were luminance threshold legibility and subjective measures of optimal and glaring luminance levels.

Table 12. Daytime subjects in Study 3.

	Age	Acuity
Young 17-40 yrs. (n=21)	X = 25.5 s.d.= 6.9	X = 20.1 s.d.= 9
Old 65-74 yrs. (n=38)	X = 69.6 s.d.= 2.8	X = 26.6 s.d.= 6.0
Old-Old 75+ yrs. (n=20)	X = 77.8 s.d.= 9	X = 31.1 s.d.= 8.7

Table 13. Nighttime subjects in Study 3.

	Age	Acuity
Young 17-40 yrs. (n=22)	X = 26.3 s.d.= 7.6	X = 19.9 s.d.= 4.1
Old 65+ yrs. (n=21)	X = 71.1 s.d.= 5.1	X = 24.9 s.d.= 5.3

Stimuli

Sign copy consisted of a subset of the 12 characters used in the Matrix Study (B, C, G, S; E, F, H, T; K, M, X, Z). All stimuli were presented on a Red Centaure continuous-matrix, discrete LED sign 51 cm (20 in) tall by 2.4 m (8 ft) long, using the Typical CMS font. The sign displayed two characters during each exposure.

Procedure

The procedure was a modified version of that used in a 1988 study.[4] The sign was mounted on top of a mini-van at 2.4 m (8 ft) measured from the bottom of the sign to the pavement. A maximum of eight subjects were tested simultaneously. These observers viewed the signs for approximately 5 s at three distances: 131, 198, and 275 m (430, 650, and 900 ft). These distances, in combination with the two letter heights of 30.5 and 46 cm (12 and 18 in), resulted in LI's ranging from 2.9 to 9 m/cm (24 to 75 ft/in). The subjects were divided between two vehicles. An experimenter was in each of the vehicles, while a third experimenter controlled sign luminance and stimulus presentation from the van. The sign was in the off position at the start of each session and the luminance was then increased in discrete steps. The subjects were asked to write down on an answer sheet the characters that appeared on the sign as soon as the characters became legible. The experimenters indicated the step number, and the subject recorded the response next to that number on the sheet (table 14).

Table 14. Study 3 sample subject response sheet.

	275 m (900 ft)		198 m (650 ft)		131 m (430 ft)	
Luminance (cd/m^2)	**Sign 1**	**Sign 2**	**Sign 3**	**Sign 4**	**Sign 5**	**Sign 6**
50	1	1	1	1	1	1
75	2	2	2	2	2	2
90	3	3	3	3	3	3
120	4	4	4	4	4	4
140	5	5	5	5	5	5
180	6	6	6	6	6	6
340	7	7	7	7	7	7
650	8	8	8	8	8	8
925	9	9	9	9	9	9
1270	10	10	10	10	10	10

The subjects also were instructed to indicate when the characters reached very good visibility and when the letters become glaring or irradiated. When all subjects reached the final level, or when the highest luminance level possible was reached, the sign was extinguished and testing on another one began. When both letter heights had been tested at the first distance, the sign was driven to the next distance and the process was repeated. This entire sequence of events was repeated until all subjects viewed both letter heights at all three distances. The order of sign presentation and the choice of letters shown on the signs at each distance was balanced across conditions and was not known beforehand by the observers.

Before, after, and between sessions, one of the experimenters monitored horizon luminance per recommendations by Padmos et al., using a Pritchard 1980A photometer. Vertical illuminance was measured at both the sign face and at the observers' position using a Minolta handheld illuminance meter. Sun position also was measured at these times.

Three daytime and three nighttime sessions were scheduled for each day of the study. The daytime sessions were conducted shortly after sunrise, midday, and shortly before sunset. The purpose of the dawn and dusk sessions was to show the signs under backlit and washout conditions. The midday session was run to assess the effects of overhead sun conditions. Attempts were made to obtain equal numbers of backlit, washout, and overhead sessions. Unfortunately, only 1 day exhibited partial sunshine, while the remainder had diffuse gray cloud cover.

The procedure took approximately 10 min at each distance–a total of 45 min for the entire session, including instruction and sign moving. This same procedure was used during nighttime data collection. The only differences between the daytime and nighttime sessions were the use of headlamps, overall reduction in the tested sign luminances at night, and ambient photometric measurements during the daytime. The daytime study was followed by a 15- to 20-min break while the experimenters set up for Study 4.

Experimental Design

A 3-by-2 repeated measures experimental design was used in which each subject was tested on all levels of each distance and letter height (table 15).

Table 15. Study 3 experimental design.

Distance	275 m		198 m		131 m	
Character Height	30 cm	46 cm	30 cm	46 cm	30 cm	46 cm
LI	9.1 m/cm	6.0 m/cm	6.5 m/cm	4.3 m/cm	4.3 m/cm	2.9 m/cm
Sign Copy	G H	C X	S E	K S	K X	H C

Results and Discussion

Two of the dependent variables–clear threshold and glare threshold–were not reported with enough frequency to perform analyses on them. During daytime conditions, it was not possible to increase the sign luminance to glare levels. At night, if the subjects were going to reach threshold, they did so at the lowest luminance available. It was not possible to determine whether a lower luminance level would have produced a clear or a glare response from the observers; therefore, those nighttime subjective data were not analyzed. Frequently, individuals indicated that the letters were clear before reaching legibility threshold.

The third dependent variable used in Study 3 was the minimum required luminance for legibility threshold. One of this study's objectives was to determine minimum required luminance at three distances and two letter heights. In order to accomplish this, it was necessary to push the observers' vision to its limits. As a result, many subjects never reached legibility threshold at any luminance level under several experimental conditions (table 16).

Table 16. Percent of observers reaching threshold under daytime and nighttime conditions.

Condition		30-cm Letters			46-cm Letters		
LI		4.3 m/cm	6.5 m/cm	9.1 m/cm	2.9 m/cm	4.3 m/cm	6.0 cm/m
Daytime	Observer Age	131 m	198 m	275 m	131 m	198 m	275 m
	16-40	100	57	38	100	98	100
	62-73	87	47	13	100	97	66
	74+	70	10	0	80	70	55
Nighttime	16-40	100	52	17	100	100	96
	62+	91	17	13	100	96	91

Under both daytime and nighttime conditions more than 90 percent of the young group was able to discern the letters in all but the two most difficult conditions. Similarly, about 90 percent of the old group was able to reach threshold in all reasonable conditions. Reasonable is defined as letters with LI's at or below 4 m/cm [36 ft/in]. The old-old group was only able to achieve 80 percent threshold in the easiest (2.9 m/cm [24 ft/in]) condition and performed very poorly with the 30.5-cm (12-in) letters at distances greater than 131 m (430 ft). Study 3 results indicated that it is possible to establish minimum luminance levels below 1300 cd/m^2 (349 fL) for over 65 percent of the old-old drivers and for almost all drivers under 75 years of age, using 46-cm (18-in) letters at or closer than 198 m (650 ft), and 30.5-cm (12-in) letters at or closer than 131 m (430 ft).

In the nighttime tests, almost all of the observers who reached threshold on any of the tested signs and distances did so at the lowest luminance of about 50 cd/m^2 (15 fL). If the subjects could not read the letters at the lowest luminance level, increases in luminance did not improve their performance. Therefore, the statistical analyses reported no significant effects of letter size, distance, or age on luminance threshold legibility. The strong effects of size and distance are evident in table 16. The remaining discussion of Study 3 results will include daytime data only. Additional testing in Study 3(a) examined nighttime luminance levels below 50 cd/m^2.

Effects of Subject Characteristics

Age. The increased need for luminance as a function of observer age was clear for those conditions having sufficient data for analysis. Because of the paucity of data for the older groups with the smaller letters at the longer distances, the effects of age group by letter height are shown for the 131-m (430-ft) distance only.

The effects of age group by distance only include data from the larger letter size because the older groups performed poorly with the smaller letters. An ANOVA showed that age had a significant effect of about 0.3 log units in the expected direction on the minimum luminance required to read the letters tested (figure 29[a]). Mild interactions of age group by height and age group by distance are demonstrated in figure 29(a) and (b).

Acuity. Analyses revealed a small, but significant, negative correlation between acuity and the minimum luminance necessary to reach threshold. As static visual acuity decreased, the need for higher sign luminance increased. Figure 30 depicts this relationship for the entire sample of subjects averaged across age. The relationship holds true for each age group. As with the earlier discussion of subject age, only those conditions that provided legibility for a reasonable percentage of the subjects are presented in figure 30.

Effects of Stimulus Characteristics

Letter Height. An ANOVA revealed main effects of letter height, wherein a higher minimum luminance level was required for the observers to reach threshold for the 30.5-cm (12-in) letters than for the 46-cm (18-in) letters (figure 29[a]). The significant interaction between letter height and age is mostly evidenced by the performance of the young observers. These individuals, unlike their older counterparts, needed very little additional character luminance to read the 30.5-cm (12-in) letters.

Observation Distance. A significant effect of observation distance can be seen in figure 29(b). The farther away the sign, the more luminance necessary to discern the letters. While this was true for all age groups, a significant age-by-distance interaction was found. The analyses indicate that the old-old subjects did not need as much additional luminance between 198 and 275 m (650 to 900 ft), as did the old and young groups.

Summary

Ineffective Variables. Under nighttime conditions, the dependent variable of luminance threshold was found to be ineffective at the luminances tested. The lowest luminance level capable of being produced on the Centaure LED sign was 50 cd/m^2. This luminance proved to be sufficient to elicit nighttime legibility for most subjects under most experimental conditions. Because this was the lowest possible luminance, it cannot be determined if a lower level of luminance would have been sufficient. Furthermore, standard analyses using means to determine potential effects of manipulated variables are useless if the mean scores are the same in each cell. Therefore, it was decided to examine the effects using the percentage of subjects reaching threshold as the measure of effectiveness.

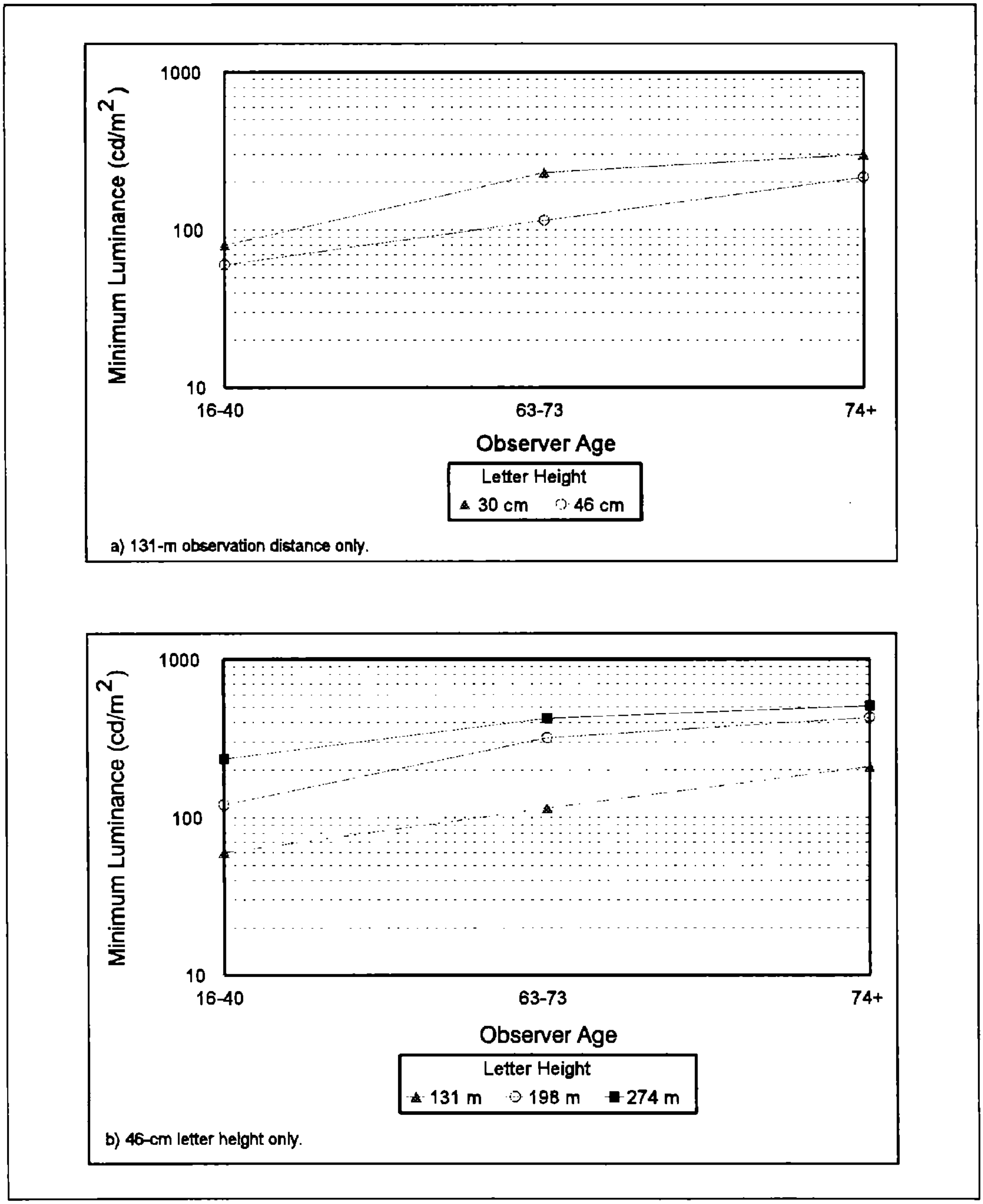


Figure 29. Age group interactions with letter height and distance.

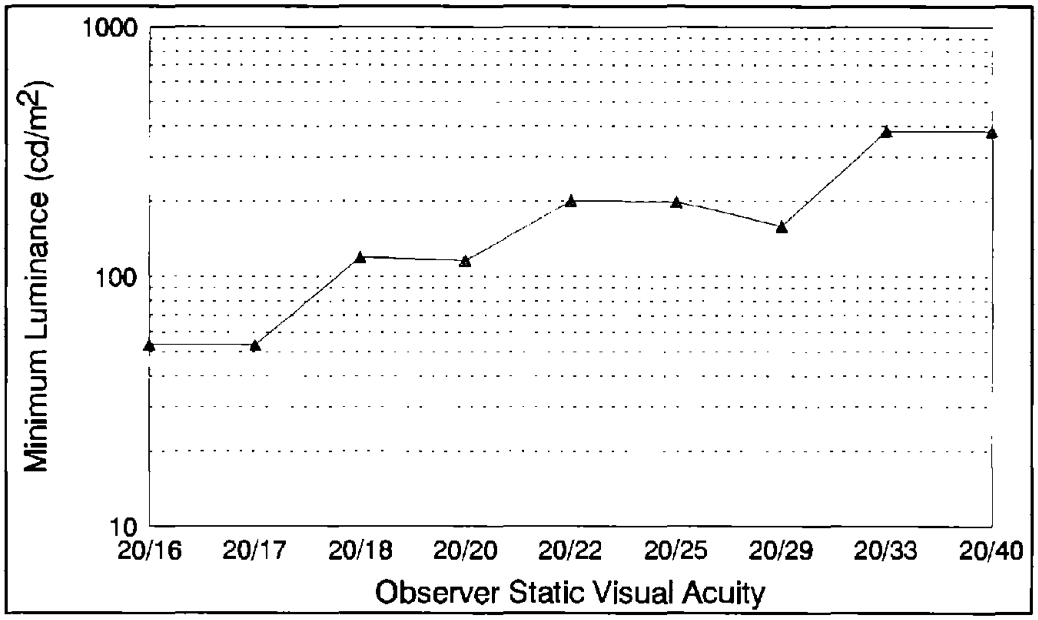


Figure 30. Effect of acuity on minimum luminance.
(30- and 46-cm letters at 131 m, and 46-cm letters at 198 m only.)

For 30-cm (12-in) letters at observation distances greater than 131 m (430 ft), the highest luminance level was not capable of invoking threshold legibility for an acceptable percentage of subjects in any age group. If the daytime conditions had been more challenging (i.e., backlit and frontlit), it might be argued that a luminance of 1270 cd/m^2 would be insufficient to produce legibility. As stated above, however, the ambient lighting was produced by a diffuse gray sky on all but 1 day of data collection. The literature previously discussed supports the contention that 1270 cd/m^2 is more than sufficient for that lighting condition. Therefore, under the tested conditions, the use of 30.5-cm (12-in) letters with a legibility distance of 198 m (650 ft) or greater is not recommended, regardless of the sign's brightness. On the other hand, this study indicates that if a sign needs to be read at 131 m (430 ft) or less, a sufficiently luminous (400 cd/m^2 or more) 30.5-cm (12-in) letter would be adequate for at least 70 percent of all age groups under both nighttime and daytime conditions (figure 31[c]).

Effective Variables. Only three combinations of the variables of age, letter height, and distance resulted in an acceptable percentage of subjects reaching threshold. These three conditions were further analyzed to determine the minimum required luminances necessary to elicit threshold response by various percentile observers in each age group (figure 31 [a]-[c]). Even in the best of these situations, only 80 percent of the old-old group was capable of reaching threshold. Figure 31 (a)-(c) represents those subjects able to read the letters at some luminance level; therefore, the estimate might not be considered conservative. However, as previously mentioned, neither the data nor the literature suggest that increasing the luminance above the tested levels would bring those observers to threshold. Thus, the luminance levels presented in figure 31 (a)-(c) are appropriate, and measures other than increased luminance would be necessary to accommodate those individuals not represented.

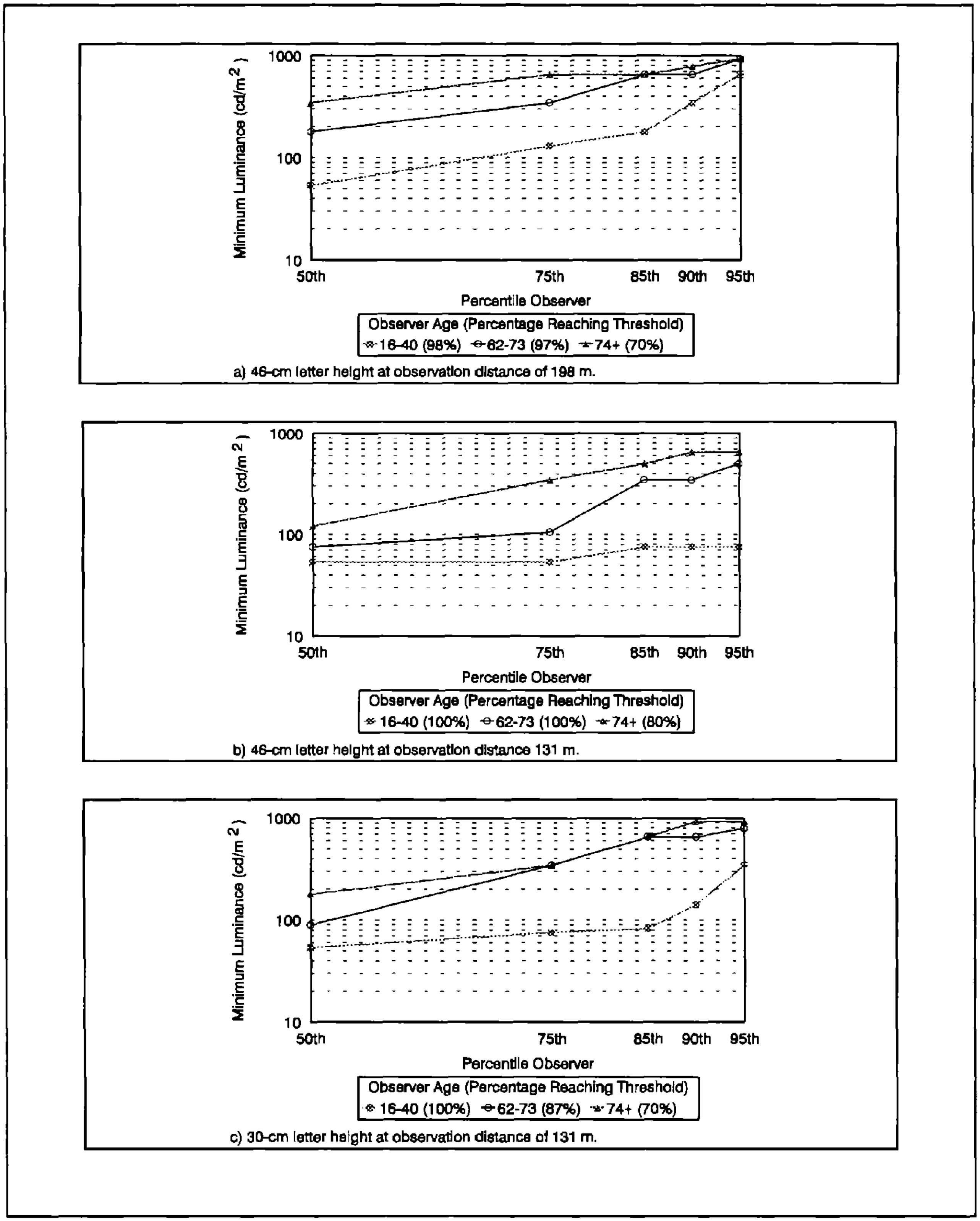


Figure 31. Minimum luminance requirements for various percentile observers.

STUDY 3(a): STATIC FIELD STUDY OF MINIMUM LUMINANCE FOR CMS LEGIBILITY–AMBER MOCK-UP SIGN

Rationale and Justification

There were three reasons for conducting this study. First, Study 3 used only red LED stimuli; therefore, comparing the results to other CMS's was questionable. Second, one of the main goals of Study 3 was to assess appropriate daytime luminance levels for different ambient conditions (i.e., backlit, frontlit, and overhead). Because Study 3 was conducted in November and December in central Pennsylvania with mostly diffuse gray skies, these analyses were not possible. Third, the LED sign for Study 3 was not capable of producing luminances below 50 cd/m^2, a level more than sufficient to produce nighttime legibility for above size-threshold letters at all of the tested distances. The design of Study 3(a) included levels from 0.02 to 50 cd/m^2.

Objectives

The objectives were to determine the optimum, minimum, and maximum luminance for CMS legibility at several viewing distances, letter heights, and ambient lighting conditions for old and young observers.

Methodology

Subject Characteristics

All subjects participated in both daytime and nighttime studies and, as much as possible, in all three daytime conditions. This resulted in subject participation in two to four, 1-h sessions over a 2-week period. The paid participants were all screened on site for visual acuity deficits. All subjects who participated in the study had visual acuity of 20/40 or better in at least one eye, which is the cut-off for driver licensure in the Commonwealth of Pennsylvania.

The sample sizes used in this study (table 17) were based on the results of Study 3. Fifteen young subjects participated in the sun-overhead and backlit daytime sessions and 16 participated under frontlit conditions. Sixteen old subjects took part in the overhead sessions and 17 participated under the backlit and frontlit conditions. Twenty-two young and nineteen old subjects participated at night.

Variables

The independent variables were subject age; sign distance; letter height; and for the daytime sessions only, sun position. The objective dependent measure was luminance threshold for legibility, defined as the lowest of two consecutive luminances at which two-thirds of the letters in a condition were correctly identified. As in previous studies of letter legibility, we found that some letters were more legible than others. In a recent FHWA study, the letters K and E were legible at much greater distances then the letter B.[22] Similarly, in our study, some letters were legible at a lower luminance than others. The two-thirds criterion avoided the overly conservative letter recognition estimates that would have resulted with a criterion of 100 percent. In most cases, two-thirds letter recognition would be sufficient for word or message recognition. Two subjective measures also were obtained: optimal or "clear," and irradiated or "glaring" luminance levels.

Table 17. Subject age statistics for three daytime studies and one nighttime study.

	Mean	Std. Dev.	Range
Night:			
Young (n=22)	27.6	7.7	16-41
Old (n=19)	72.7	4.4	66-84
Day-Overhead:			
Young (n=15)	25.7	6.7	19-40
Old (n=16)	71.1	4.2	66-77
Day-Backlit:			
Young (n=15)	26.0	5.3	22-40
Old (n=17)	72.4	4.3	66-84
Day-Frontlit:			
Young (n=16)	30.2	6.0	23-40
Old (n=17)	72.8	4.9	66-84

Stimuli

All stimuli were presented on a mock-up CMS created in the contractor's woodworking and electronics shop. Sign copy consisted of the 12 uppercase characters used in studies 1(a) and 1(b): B, C, G, S; E, F, H, T; K, M, X, and Z. The character font was Typical CMS 5-by-7 with a W:H of 0.7 and a SW:H of 0.11. For the 46-cm (18-in) letters, the elements were 5-cm-(2-in-) diameter circles, with inter-element spacing of 6.78 cm (2.67 in) from center to center, creating a 32.18-cm- (12.67-in-) wide character matrix. The dimensions for the 30-cm (12-in) letters were proportionally reduced. Three characters were displayed during each exposure, with inter-letter spacing equal to one-third of letter height. Letter-to-border spacings on the left and right sides of the box were equal to one letter width, and the top and bottom borders were 30 cm and 22.86 cm (12 in and 9 in) for the 46-cm and 30-cm (18-in and 12-in) letters, respectively.

Apparatus

Two large panels containing three sets of 35 holes arrayed in 5-by-7 matrices made up the 2 faces of the mock-up CMS (figure 32). One of these face panels was used to present the 30-cm (12-in) letters and one was used to present the 46-cm (18-in) letters. Twenty-four occluders were made out of wood panels. One-half of the occluders were used to create the 30-cm (12-in) characters and one-half were used for the 46-cm (18-in) characters. These occluders slid into place behind the face panels' 5-by-7 matrices, and occluded or blocked all holes in a particular matrix that were not part of the matrix for that letter.

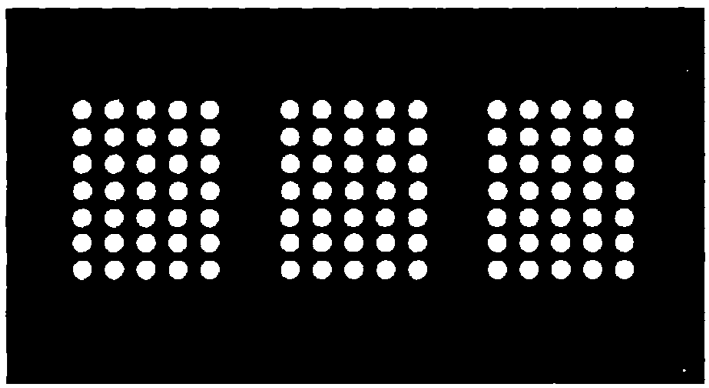


Figure 32. CMS 5-by-7 matrix mock-up.

A light box was behind each of the three matrices in the face panels. Each of the three light boxes contained a set of eight lamps for daytime operation and a set of four lamps for nighttime operation. The nighttime lamps were used in pairs. The computer turned the nighttime lamps on and off many times per second. The ratio of "on" time to"off" time varied the luminous intensity of the nighttime lamps. The daytime lamps were controlled individually, and were either fully on or fully off. Both the daytime and nighttime sessions used different combinations of lamps to achieve the necessary luminance levels. A piece of amber plexiglass was mounted within each light box to produce the desired color.

Procedure

The experimental procedure was very similar to that used in Study 3. In brief, the sign box was mounted on top of a mini-van at a height of 2.4 m (8 ft), measured from the bottom of the sign to the pavement. A maximum of 12 subjects were tested simultaneously.

All subjects observed 30-cm (12-in) signs at 131 and 198 m (430 and 650 ft). The same subjects viewed the 46-cm (18-in) signs at 131, 198, and 274 m (430, 650, and 900 ft). The LI for each of these distance/height combinations is shown in table 17. For the sake of convenience, from this point on, the stimuli will be referred to as signs A through E as on table 18.

Table 18. Study 3(a) experimental design.

Distance	131 m				198 m				274 m	
Character Height	30 cm		46 cm		30 cm		46 cm		46 cm	
LI	4.3 m/cm		2.9 m/cm		6.5 m/cm		4.3 m/cm		6.0 m/cm	
Sign ID	A	A	B	B	C	C	D	D	E	E
Sign Copy	HZT	SKC	EMG	XBF	FGM	TBX	ZCE	KHS	CHK	STZ

1 m=3.28 ft; 1 cm=0.039 in; 1 m/cm=8.4 ft/in

The subjects were seated in lawn chairs on a closed section of roadway. Two experimenters were with the subjects, while a third experimenter controlled sign luminance and stimulus presentation from the van. For the daytime sessions, the sign was in the off position at the start of testing for each of the 10 signs, and the luminance was increased in discrete steps. Five of the ten signs tested in the nighttime sessions were tested in the same manner as in the daytime sessions, while the other five were first tested at the brightest level and were then dimmed.

At each luminance step, the subjects were asked to transcribe the sign copy that appeared discernable on the sign. The subjects also were instructed to indicate whether the characters were at optimal legibility and, at night, whether the letters were irradiated. This was repeated for one sign under all luminance levels until threshold values were achieved for both the objective and subjective measures. At that point, the next sign was introduced at the same distance and the procedure was repeated.

Testing began with signs A and B at a distance of 131 m (430 ft). The van was then driven to the 198-m (650-ft) distance and the process was repeated for signs C and D. This entire sequence of events was then repeated for sign E at 274 m. The order of sign presentation and the choice of letters shown on the signs at each distance was balanced across conditions. The procedure took approximately 20 min at each distance–a total of 1.5 h for the entire session, including instructions and moving the sign.

During each daytime session, one of the experimenters recorded horizontal illuminance, sun position, and vertical illuminance on both the sign face and the observers' eyes. Eleven levels of sign luminance were used during the daytime and 24 were used at night (table 19). Luminance was measured with a single aperture setting of 20 minutes of arc at 45.7 m (150 ft) that spanned the width of the character cell. The character cell used for luminance measurement was the 5-by-7 matrix in the face panels without any occlusions; this resulted in a character cell that was fully on. Spot checks of luminance levels were randomly conducted to ensure stability in the dependant measure.

Table 19. Luminance levels used in Study 3(a) (cd/m²).

Daytime		Nighttime			
1)	0.04	1)	0.02	13)	27.00
2)	15.00	2)	0.39	14)	37.00
3)	28.00	3)	0.45	15)	47.00
4)	47.00	4)	0.70	16)	54.00
5)	65.00	5)	1.50	17)	63.00
6)	85.00	6)	3.75	18)	73.00
7)	119.00	7)	4.95	19)	83.00
8)	200.00	8)	5.25	20)	91.00
9)	265.00	9)	7.70	21)	250.00
10)	338.00	10)	10.45	22)	425.00
11)	418.00	11)	14.40	23)	485.00
---	--------	12)	19.00	24)	530.00

The daytime sessions were conducted shortly after sunrise, midday, and shortly before sunset. The purpose of the dusk and dawn sessions was to show the signs under backlit and washout conditions, and the midday session was run to assess the effects of overhead sun conditions. The mean level of incident sunlight falling on both the observers' eyes and the sign during the three daytime lighting conditions is depicted in table 20.

Table 20. Mean vertical illuminance (lux) on sign face and the observer.

	Sun Overhead (Overhead)	Sun Behind Sign (Backlit)	Sun On Sign (Washout)
Sign Face Illuminance	18,740	7,170	43,920
Observer Illuminance	21,120	35,330	10,307

Experimental Design

Each subject saw the two letter heights (30 and 46 cm [12 and 18 in]) at the two closer distances (131 and 274 m [430 and 900 ft]) (table 17). Each subject also saw the 46-cm (18-in) letter height at 274 m (900 ft). During daytime testing, three levels of a third variable–ambient lighting–were introduced. This variable was treated as a between-subjects variable with a different group of subjects being tested in each lighting condition (table 17).

Analyses

The data from this study underwent three separate analyses: percent reaching threshold, analysis of variance, and threshold percentiles. A percentage of subjects in both age groups were unable to reach either legibility or clear thresholds within the range of tested character luminances. The first analysis describes the percentage of each age group that reached threshold for each sign condition and ambient illumination. ANOVA's were then conducted on the conditions that elicited a correct response from at least 80 percent of the subject sample. These analyses examined the effect on threshold luminance of the independent variables of age, letter height, observation distance, and ambient lighting. Finally, the threshold luminance values for the 50th, 75th, 85th, 90th, and 95th percentile old and young subjects were plotted for those conditions that provided sufficient data.

Results and Discussion

Percentage Reaching Threshold

Tables 21 and 22 provide an overview of subject performance under daytime and nighttime conditions. These tables depict a scenario wherein almost all of the young subjects were capable of reaching legibility threshold under all conditions. These young observers also reached clear threshold under all but the most difficult daytime ambient lighting conditions and the most difficult size/distance combinations (signs C and E) at night.

Threshold legibility for 80 to 90 percent of the old subjects was attained in all but the two most difficult sun conditions and letter height/distance combinations. However, only under the most benign circumstances (signs A and B) did the old subjects consistently reach clear threshold during daytime testing. Given the range of luminances tested, obtaining either legibility or clear thresholds on a reasonable percentage of old subjects was not possible with signs C and E under backlit, washout, and nighttime lighting conditions. Therefore, the remainder of the discussion of the results will concentrate on signs A, B, and D, where the LI was 4.3 m/cm (36 ft/in) or less.

Analysis of Variance

Age Effects. Figure 33 shows the mean legibility threshold scores for each age group under the three daytime conditions and at night. The ANOVA indicated that under all ambient lighting conditions, age had a significant effect on performance. Old observers needed higher character luminance than did their younger counterparts to reach legibility threshold. Two significant, but small, interactions between age and the variables of height and distance are discussed below. At night, age did not have a significant effect on glare threshold. Mean glare threshold for both old and young observers was approximately 320 cd/m^2.

Table 21. Percent of observers reaching legibility threshold and clear threshold under three daytime conditions.

Young Observers	30-cm Letters			46-cm Letters		
Threshold	**Sun Position**	**131 m**	**198 m**	**131 m**	**198 m**	**274 m**
Legibility	Overhead	100	100	100	100	100
	Backlit	100	100	100	100	100
	Frontlit	100	94	100	100	100
Clear	Overhead	100	87	100	100	80
	Backlit	100	68	100	94	87
	Frontlit	100	69	100	100	69
Old Observers						
Threshold	**Sun Position**	**131 m**	**198 m**	**131 m**	**198 m**	**274 m**
Legibility	Overhead	94	78	100	94	94
	Backlit	95	59	100	95	59
	Frontlit	95	18	100	95	36
Clear	Overhead	94	43	94	76	43
	Backlit	58	6	94	58	36
	Frontlit	58	7	89	70	12

Table 22. Percent of observers reaching clear threshold, legibility threshold, and glare threshold at night.

	30-cm Letters			46-cm Letters		
	Threshold	**131 m**	**198 m**	**131 m**	**198 m**	**274 m**
Young Observers	Legibility	100	100	100	100	100
	Clear	69	38	100	82	73
	Glare	92	100	78	97	100
Old Observers	Legibility	95	79	100	95	95
	Clear	82	0	82	82	52
	Glare	85	100	62	62	90

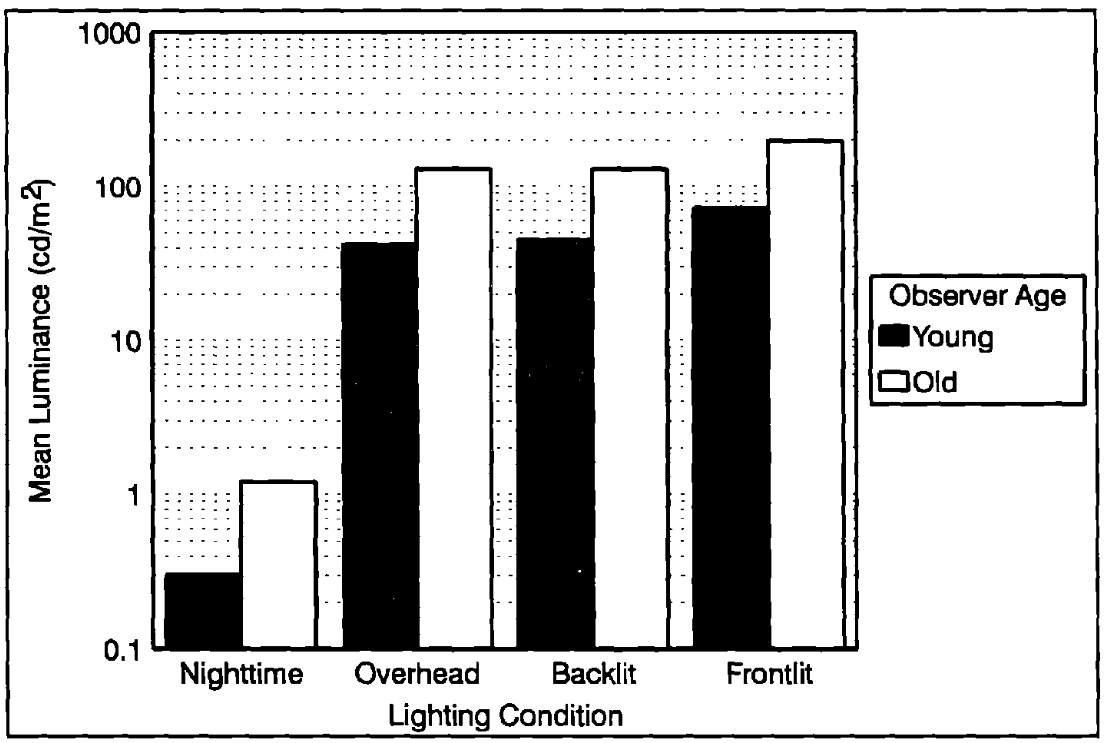
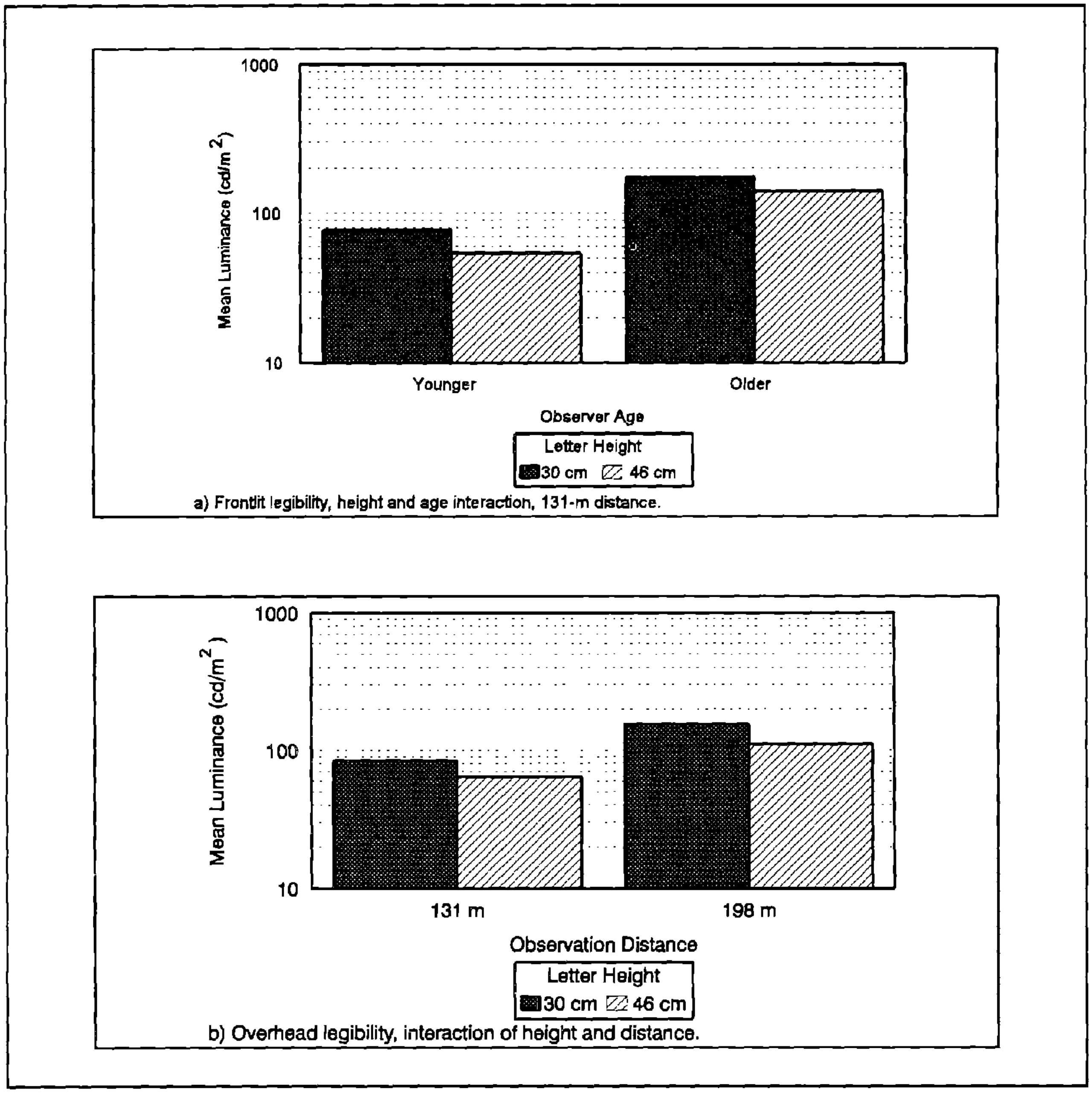


Figure 33. Age effects on minimum luminance required to reach legibility threshold for four light conditions–daytime.
(Signs, heights, and distances used: A, 30 cm, 131 m; B, 46 cm, 131 m; D, 46 cm, 198 m)

Letter Height. During daytime testing, increasing letter height from 30 to 46 cm (12 to 18 in) had a minimal effect on the character luminance necessary to reach legibility threshold. ANOVA's revealed a significant effect of letter height only under the overhead ambient conditions. A significant distance-by-height interaction in the overhead condition indicated that the increase in luminance necessary for small letters to reach threshold was greater at the further distances. The age-by-height interaction found in the frontlit condition shows young observers to be more affected by a change in character height than their older counterparts (figure 34[a]). Young observers do not need as much luminance with large letters, while older drivers need almost as much luminance with large letters as with small.



a) Frontlit legibility, height and age interaction, 131-m distance.

b) Overhead legibility, interaction of height and distance.

Figure 34. Interaction of character height and observer age/distance on minimum luminance for daylight legibility.

ANOVA's on the data from nighttime testing mirrored those for daytime testing, with changes in letter height producing a greater change in luminance threshold for legibility at the farther distances. A significant letter-height effect was found with clear thresholds for old observers; however, this effect was on the order of a 0.5-cd/m^2 increase that was necessary with the smaller letters.

Observation Distance. ANOVA's conducted on all three daytime conditions and one nighttime ambient lighting condition revealed that increasing observation distance had the effect of significantly increasing the character luminance necessary to reach legibility threshold (figure 35). This finding held true for both the 30-and 46-cm (12-and 18-in) character heights. A significant interaction between age and distance was found in the backlit conditions, wherein the legibility thresholds of the old subjects increased more at greater distances than their younger counterparts (figure 36).

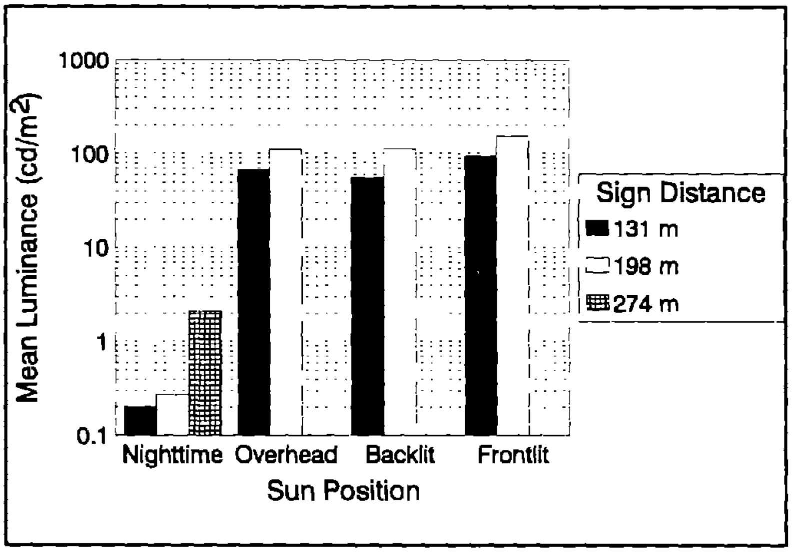


Figure 35. The effect of observation distance and sun position on minimum luminance required—46-cm letters.

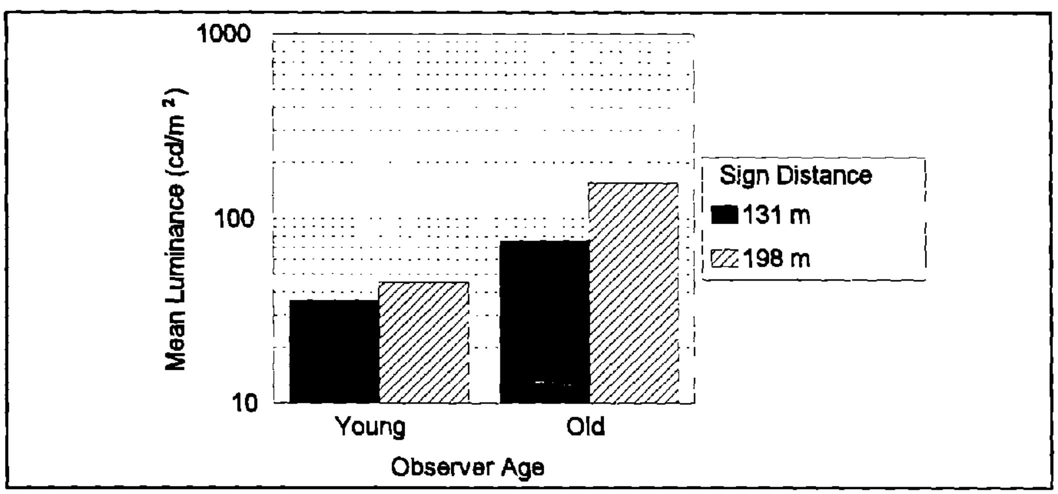


Figure 36. Interaction between observation distance and age on minimum luminance backlit, day, 46-cm letters.

LI. Two conditions were tested that allowed us to examine the effectiveness of using LI as a surrogate for distance/height combinations in determining CMS luminance levels. Signs A and D both resulted in LI's of 4.3 m/cm (36 ft/in). Figure 37 shows the mean scores for these two signs under the four ambient conditions used in this study. There were no appreciable differences between the luminance threshold of signs A and D under any of the lighting conditions. Essentially the same luminance was required whether a larger letter was viewed at a greater distance or a smaller letter was viewed at a closer distance.

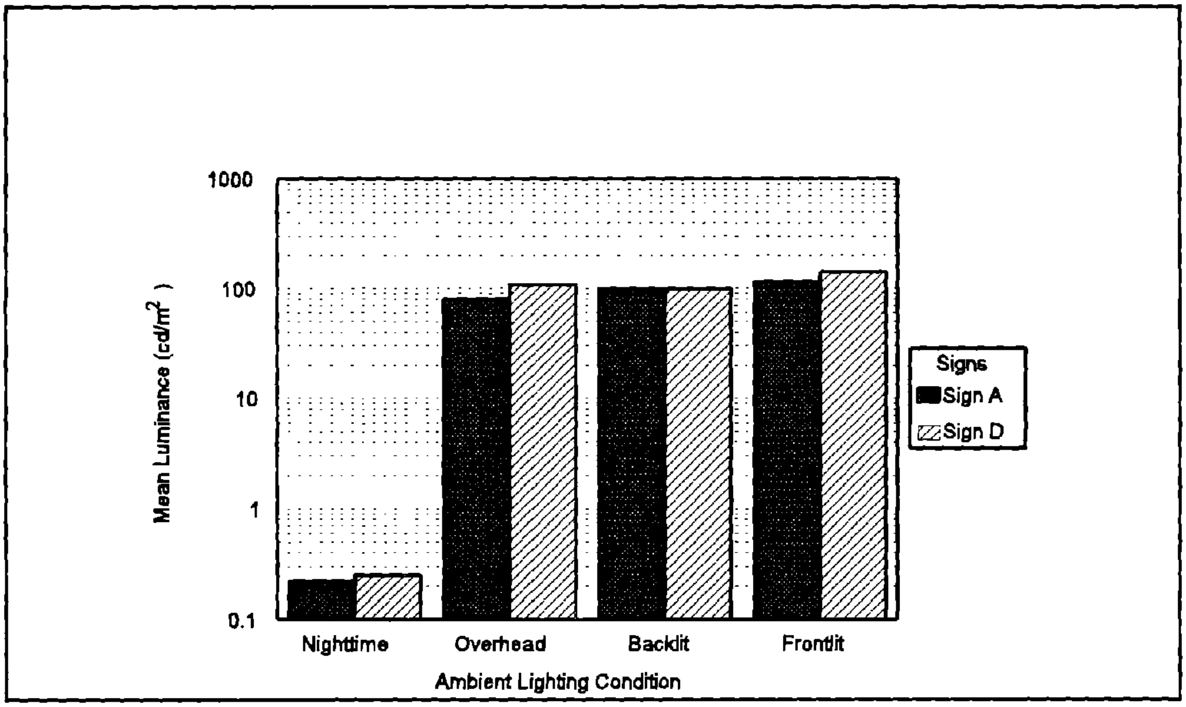


Figure 37. Mean luminance threshold for two signs under four ambient conditions.

Daytime Ambient Lighting. The position of the sun had little effect on the percentage of young drivers who reached legibility threshold (table 21), and only a moderate effect on the most difficult stimuli for clear threshold. Sun position had a marked effect on the number of old drivers who were able to read the characters. This performance decrement with backlit and frontlit lighting was again found only under the two most difficult stimulus conditions requiring LI's greater than or equal to 6 m/cm (50 ft/in). The deleterious effects of backlit and frontlit lighting were distributed more evenly across character height/distance conditions with the clear thresholds (table 21).

ANOVA's revealed no significant differences in legibility threshold between overhead and backlit sun positions for either old or young observers. However, analyses showed a statistically significant increase in minimum luminance necessary for legibility of frontlit characters compared to performance under the other two daytime lighting conditions. This finding was restricted to old observers.

Percentiles

Only three combinations of letter height and distance resulted in an acceptable percentage of both old and young subjects reaching threshold under all ambient lighting conditions; these were signs A, B, and D. The LI's of these three signs were equal to or less than 4.3 m/cm (36 ft/in). All three of these conditions resulted in over 90 percent of all observers reaching legibility threshold under all lighting conditions (table 21). As in Study 3, these three conditions were further analyzed to determine the minimum required luminances necessary to elicit threshold legibility by various percentile observers in each age group (figures 38 [a]-[c]).

The percentiles for old observers at clear threshold are excluded for all ambient lighting conditions, since even under the most benign circumstances, the percentage of these observers reaching clear threshold was too low to analyze in this manner.

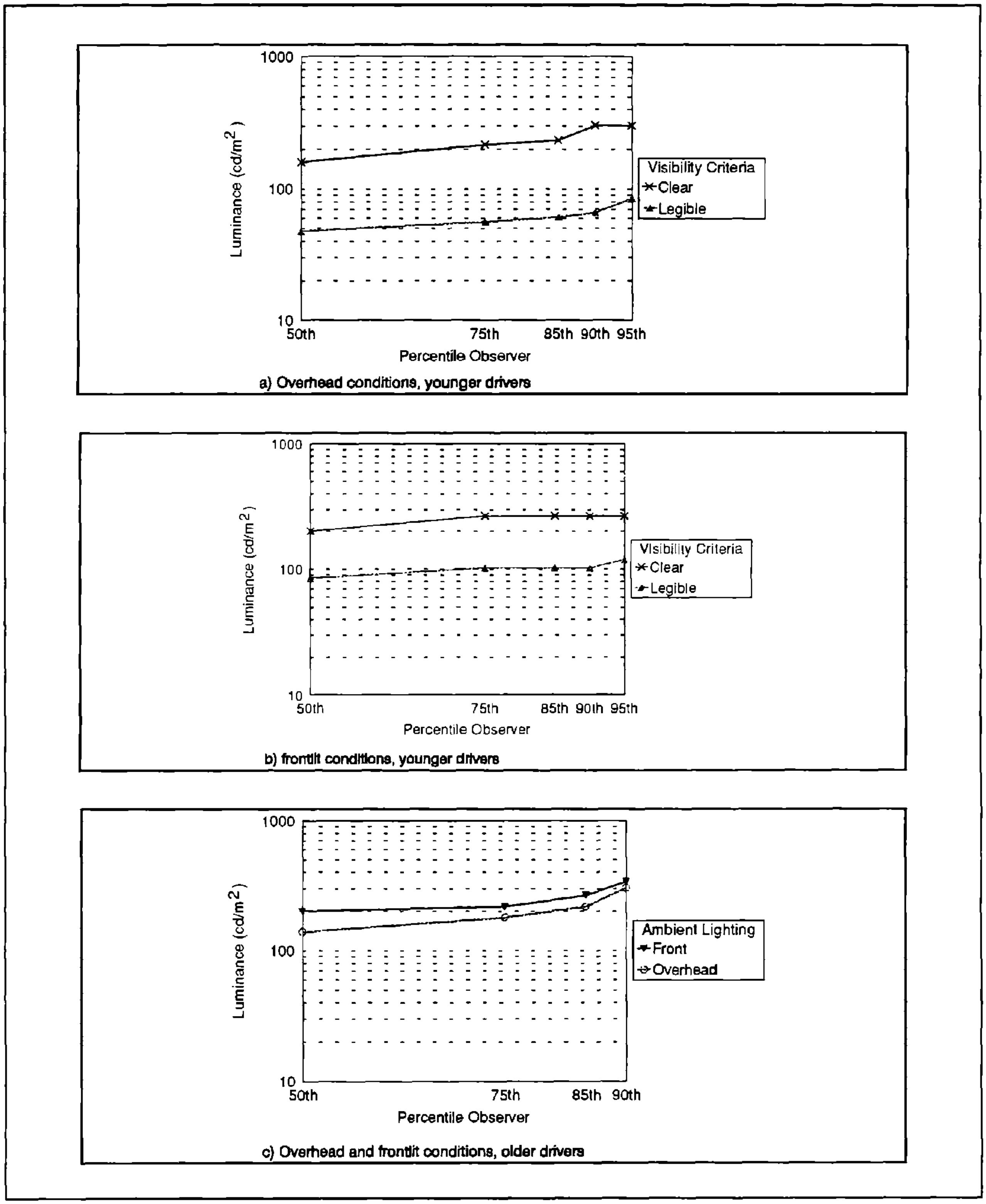
Conclusions

As in Study 3, age, character height, and observation distance had statistically significant effects on the level of luminance necessary to reach legibility, clear, and glare thresholds. However, in this study, the effect of height was not of practical significance. With letters having LI's of 4.3 m/cm (36 ft/in) or less (signs A, B, and D), sun position had an effect on threshold luminance for legibility for old observers only under the frontlit condition.

Signs C and E caused problems for both old and young drivers. While close to 90 percent of the young drivers were able to reach legibility threshold on all of the stimulus conditions tested, the characters with LI's greater than 4.3 m/cm (36 ft/in) were less likely to elicit a clear response. The data reflect the idea put forth by Mace and supported by recent FHWA research–that is, to provide adequate visibility, the traffic engineer should install signs based on size and maintain luminance.[28,23] The old drivers had difficulties with both legibility and clear thresholds for these smaller letters. The effect of the higher LI's on legibility threshold is most pronounced with the backlit and frontlit daytime conditions, in which less than 60 and 40 percent, respectively, of the old and old-old drivers were able to correctly identify the letters. The percentage of old drivers who indicated that these characters were clear was 50 percent or lower for all ambient conditions.

In summary, the character luminance (clear or threshold) found to be necessary to accommodate 90 percent of the observers under the conditions tested is 350 cd/m^2 during daytime testing. This would provide legible letters under overhead, backlit, and frontlit conditions for signs A, B, and D for both young and old observers. To provide glare-free legibility for 90 percent of the old and young observers at night for signs A, B, and D, the luminance values would need to be between 12 and 60 cd/m^2.

The highest daytime luminance level capable of being produced by the CMS mock-up was 418 cd/m^2. Based on the high percentage of old drivers reaching legibility threshold at night and under the overhead sun position, it seems possible that with higher luminance levels a greater percentage of these observers could reach threshold under the backlit and frontlit conditions. The mock-up, however, did not include a protective cover for the sign's face. If the sign is not clean and scratch-free, the legibility of a front-lit CMS is greatly reduced. This "screen-free" viewing increased the available character luminance and luminance contrast. Further study of the effects of maintenance levels and various types of protective coverage on minimum luminance requirements for legibility seems warranted.



Figures 38. Daytime thresholds for various percentile drivers for signs A and D.

STUDY 4: STATIC FIELD STUDY OF THE EFFECTS OF CHARACTER VARIABLES ON CMS LEGIBILITY–RED LED SIGN

Objectives

Daytime sign luminance, daytime ambient light conditions, and letter height are not readily amenable to laboratory investigation. Field Study 4 was conducted to address these issues. The objectives of this study were to assess the effects of manipulating font, letter height, inter-letter spacing, and luminance on the legibility distance of CMS's.

Methodology

Variables

The independent variables were age, inter-letter spacing, font, luminance, and letter height. The dependent variable was distance threshold legibility or "pure legibility."

Stimuli

Characters were selected using the same methods employed in Study 3. The Centaure LED sign was again used to present the stimuli. This sign was selected because it enabled us to readily manipulate the variables of interest.

Procedure

Distance threshold legibility was assessed in a manner similar to that used by Forbes and Holmes, and in the contractor's recent FHWA contract "Relative Visibility of Increased Legend Size vs. Brighter Materials."[26, 22] The sign was placed in the center of an unused portion of a University Park Airport taxi-way at a height of 2.1 m (7 ft). From within two vehicles, a maximum of eight subjects simultaneously began viewing the sign at a distance of 354 m (1160 ft). At that distance, subjects recorded the letters they saw on the sign onto an answer form. The sign was then moved to the next closer viewing distance where the messages were shown exactly as at the previous distance. This procedure was repeated at each distance. The steps between distances represented a reduction in LI of 0.6 m/cm (5 ft/in) for the 46-cm (18-in) characters and 0.9 m/cm (7.5 ft/in) for the 30.5-cm (12-in) characters.

Experimental Design

An incomplete 3-by-2-by-3-by-2 repeated measures experimental design (table 23) was used. This entailed testing each subject on all levels of the four independent variables of font, letter height, inter-letter spacing, and luminance.

Each message was shown at a luminance level that was selected through the literature review and pilot tests. A second luminance level (L2) was added to assess the effects of varying luminance on legibility distance. In the daytime portion, the first luminance level (L1) was equal to 925 cd/m^2 and L2 was equal to 340 cd/m^2. At night, L1 was equal to 50 cd/m^2 and L2 was equal to

140 cd/m². Horizontal illuminance, vertical illuminance at the observers' eyes, and character luminance were monitored before, during, and after each daytime session. As mentioned in Study 3, the time of year prevented performance assessment under varying ambient lighting conditions.

Table 23. Study 4 experimental design: table cells show sign copy for 17 treatments.

Font	Vartabedian		Typical CMS 5-by-7 Matrix			Double Composite	
Letter Height	30.5 cm	46 cm	30.5 cm	46 cm		30.5 cm	46 cm
Luminance in cd/m² (day/night)	925/50	925/50	925/50	925/50	340/140	925/50	925/50
Inter-letter Spacing = Letter Width	S K E	G Z C	X S Z	S H G	S H G	K E Z	CGK
Inter-letter Spacing = 2/5 Letter Width	G Z H	C S X	Z G K	E K X	E K X	N/A	N/A
Inter-letter Spacing = 1/5 Letter Width	C X E	S X H	H G C	C E H	C E H	N/A	N/A

The threshold for each letter was recorded as the greater of the first two consecutive distances at which correct responses were made. At each distance, the subjects made 17 observations (table 23). The character fonts Vartabedian and Typical CMS represented the two best fonts in laboratory Study 1. These fonts were shown using three inter-letter spacings and two letter heights (figure 39). The Typical CMS 46-cm (18-in) characters were shown at the two luminances discussed earlier. A third font representing Double Composite was tested in both 30.5-cm and 46-cm (12-in and 18-in) character heights, but only with the widest inter-letter spacing.

Although an attempt was made to create characters to match those used in the laboratory studies, a comparison of figures 39 and 16 indicate that this was not wholly successful. The general forms of the Vartabedian and Typical CMS fonts are close to those of the lab studies; however, the Double Composite font used in the field study is much more "open." This is particularly true with the 46-cm (18-in) Double Composite.

Results and Conclusions

Three daytime and three night ANOVA's were conducted on the data collected in this static field study. Analysis 1 compared Vartabedian with Typical CMS at 30.5-cm and 46-cm (12-in and 18-in) character heights and at the three letter spacings, but only at L1. This analysis corresponds to columns 1 through 4 of table 23. Analysis 2 looked only at the Typical CMS font at a 46-cm (18-in) character height to assess the effects of luminance and letter spacing. The stimuli in this analysis are represented in columns 4 and 5 of table 23. Analysis 3 evaluated the effects on legibility distance of three fonts: Vartabedian; Typical CMS; and Double Composite. These were shown at the two letter heights and one spacing (columns 1 through 4, 6, and 7). The stimuli used in this analysis are depicted in the "Inter-letter Spacing = Letter Width" row of table 23, but again, only using L1. Throughout this report, analyses 1 through 3 will be referred to as "font/height/spacing," "luminance/spacing," and "font/height," respectively.

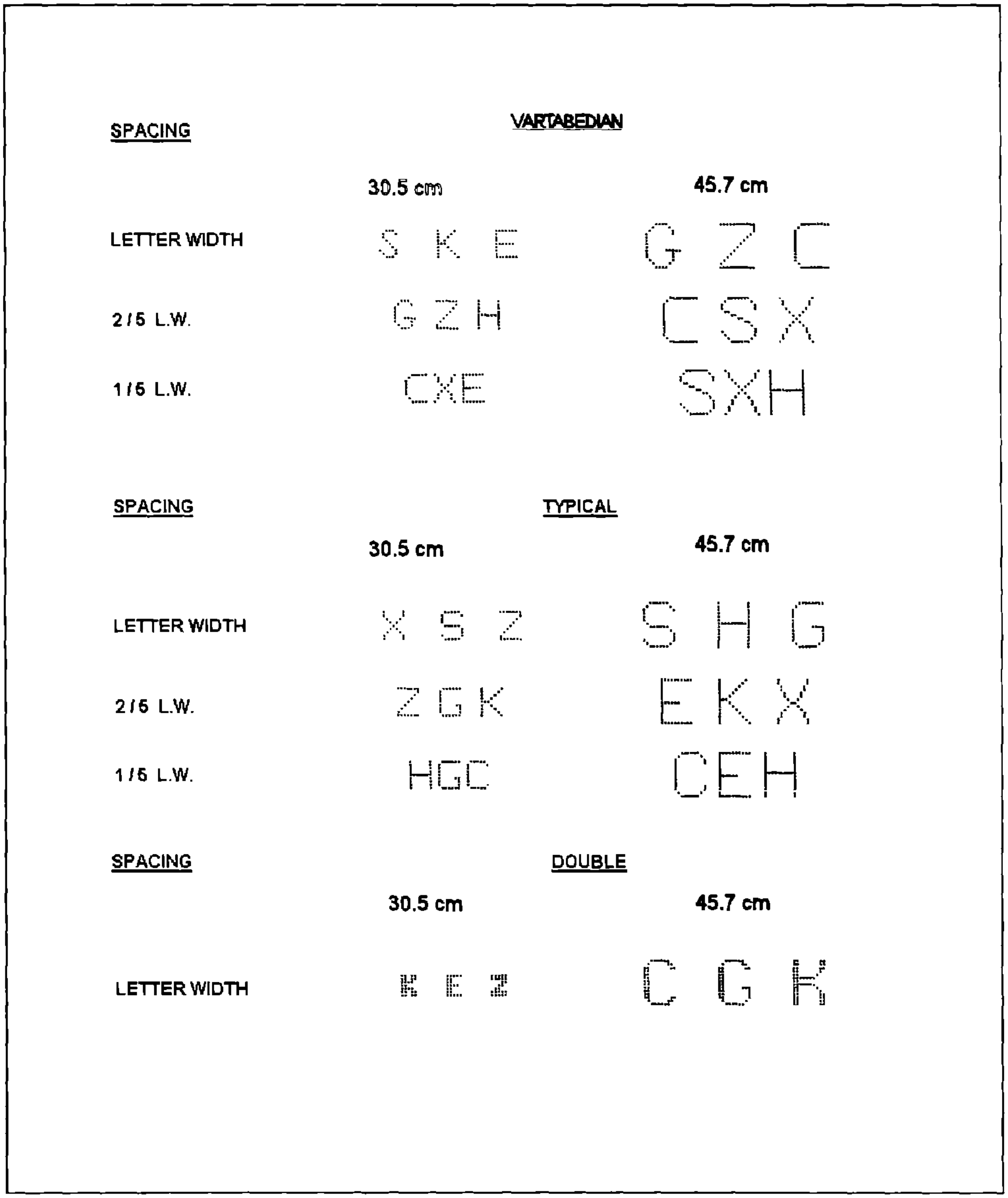


Figure 39. Stimuli tested in Study 4.

Subject Age

Daytime. All ANOVA's of daytime data revealed significant effects for age (figures 40 and 41). A decrease of 2.4 m/cm (20 ft/in) in letter height was found between the young group and the old-old group in the font/height analysis. The only interaction between age and any other variable was found in font/height/spacing analysis. This ANOVA showed a significant age-group-by-height interaction. As can be seen in figure 41, this interaction is at best marginal, with 46-cm (18-in) letters resulting in a decrease in LI of less than 0.6 m/cm (5 ft/in) for the young and old-old groups. The lack of any practical interaction in the font/height/spacing analysis supports the findings in the luminance/spacing analysis that old and young respond proportionally to changes in CMS copy.

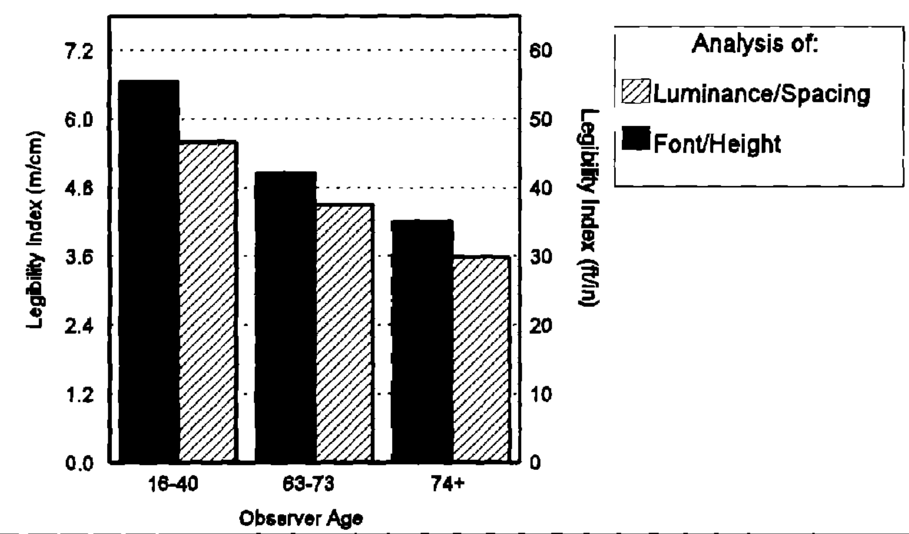


Figure 40. Age effects on legibility for two analyses during daytime.

Nighttime. None of the nighttime analyses showed any age effect on legibility distance, nor any interaction between age and any other variable. While the mean performance of the young group remained fairly stable from day to night across all analyses, the performance of the old group improved an average of over 1.2 m/cm (10 ft/in). The probable reason for this discrepancy was subject attrition from daytime to nighttime. It was necessary to combine our old and old-old groups into one old group for nighttime analysis because it was difficult to obtain participants from these age groups on winter nights. A comparison between tables 12 and 13 indicates that the old subjects who did participate at night had a mean age closer to the 65-to-74-year-old group, and an acuity distribution falling somewhere between the young and the old groups. These changes in subject characteristics were apparently enough to reduce the differences between old and young to non-significant levels.

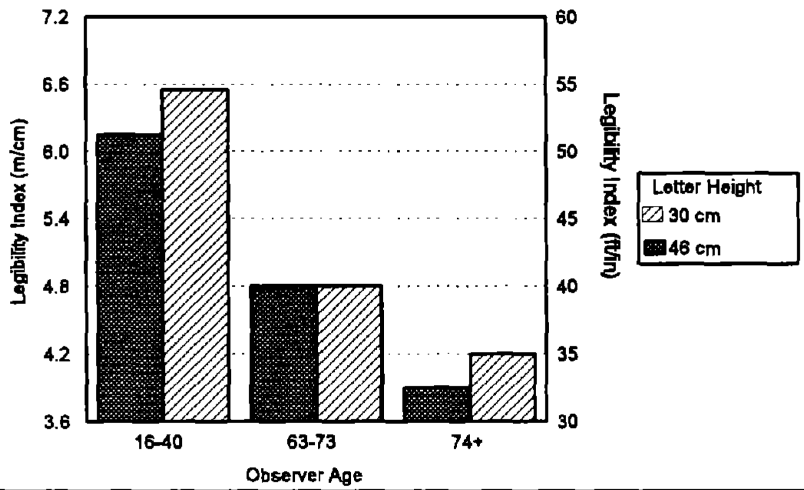


Figure 41. Age effects on daytime legibility for two letter heights: font/height/spacing analysis.

Acuity

Daytime/Nighttime. As in the laboratory studies, a significant correlation between static, high-contrast, high-luminance acuity, and daytime LI was found. LI decreased as visual acuity worsened (figure 42[a]). Analysis of the nighttime data showed a significant correlation in the same direction. The relatively small sample size in the 20/20 acuity group (n=3) produced the dip in the curve depicted in figure 42(b).

Letter Height

Daytime. For the daytime condition, both of the analyses that looked at letter height found it to significantly affect legibility distance. The results of the font/height analysis show a strong letter-height main effect with the 30.5-cm (12-in) letters holding a greater than 0.8-m/cm (7-ft/in) advantage in LI over the 46-cm (18-in) letters. The font/height analysis also demonstrated an interaction between font and letter height (figure 43). In this analysis, letter height had no effect on the Typical CMS font's LI, but there was a difference of over 1.2 m/cm (10 ft/in) on the other two fonts.

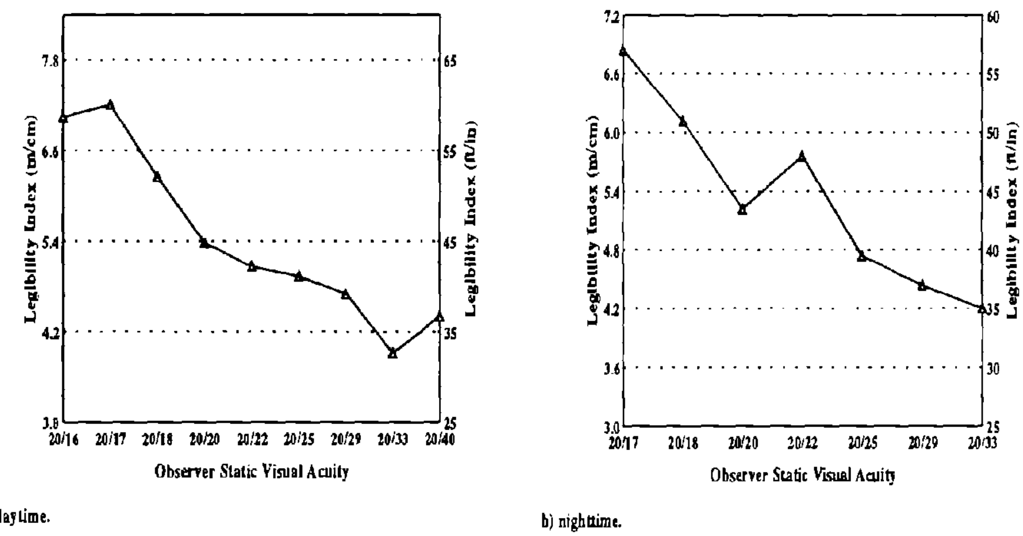
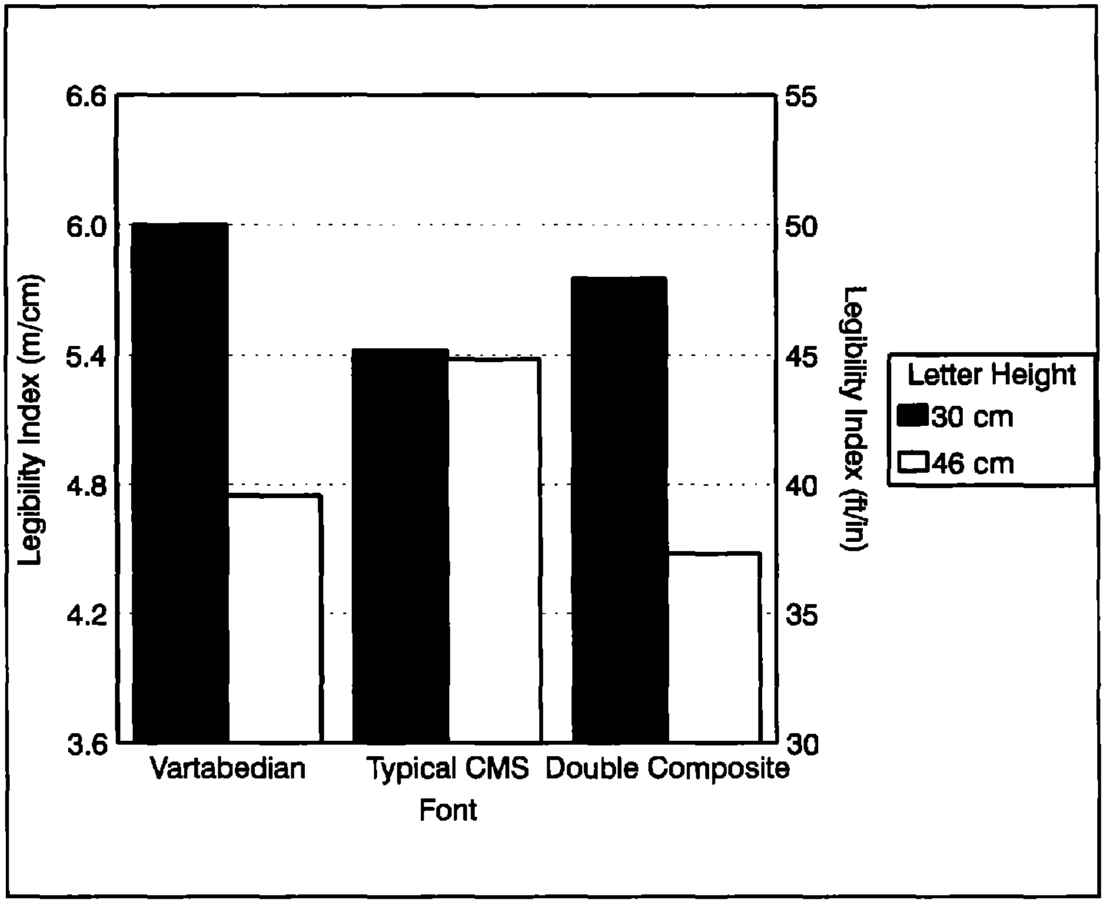


Figure 42. Effects of visual acuity on legibility.

The letter height results of the font/height/spacing and the font/height analyses are represented in figure 43 and figure 44 (a) and (b). As previously discussed, a small letter height interaction with age group was found. The two analyses indicated that the letter height effect also interacts significantly with font and letter spacing. For example, the 1.2-m/cm (10-ft/in) difference shown with the Vartabedian font and the inter-letter spacing equal to letter width is reduced to almost nothing with the smaller inter-letter spacings (figure 44 [b]). The true picture of the letter height effect is reflected in the significant three-way interaction found in the font/height/spacing analysis among font, height, and spacing (figure 44 [a] and [b]). Overall, the data indicated a loss in LI with increased letter height (figures 41, 43, and 44[a] and [b]). However, the effect is highly dependent on the level of the other factors. These interactions made a blanket statement concerning LI and letter height impossible.

Nighttime. For nighttime data, a statistically significant, but negligible, effect of letter height was found in the font/height analysis. This analysis also uncovered an interaction between letter height and font. The font/height/spacing analysis revealed no significant effect of letter height, although letter height was found to interact significantly with font and spacing in this analysis. If one accepts a 0.6-m/cm (5-ft/in) letter height rule of thumb for importance in the real-world, then, although statistically significant, these nighttime interactions and main effects are negligible.



(Data for largest inter-letter spacing only.)

Figure 43. Effect of font/height interaction on daytime legibility.

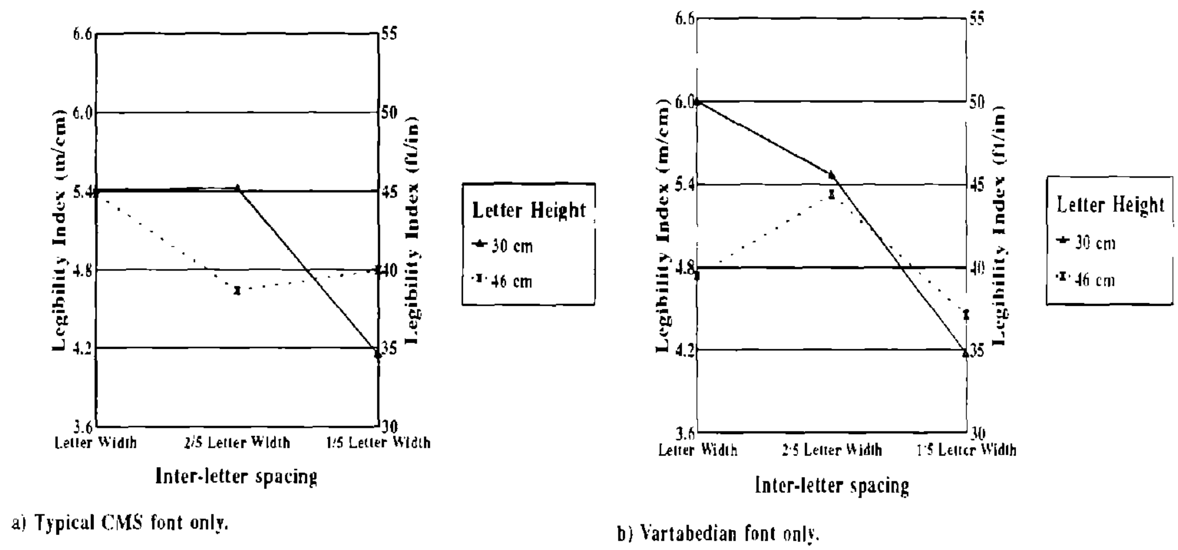


Figure 44. Spacing and letter-height interaction for daytime legibility.

Inter-Letter Spacing

Daytime. The font/height/spacing and the luminance/spacing analyses revealed significant effects of inter-letter spacing (figure 45). As previously mentioned, a significant spacing-by-letter-height interaction was found in the font/height/spacing analysis, wherein spacing had mixed results for the 46-cm (18-in) letters (figure 44 [a] and [b]). The significant effect of letter spacing in the luminance/spacing analysis shows that spacing equal to letter width was significantly better than either 2/5 or 1/5 letter-width spacing. The ANOVA indicated that there was no statistically significant difference in the performance of the latter two. There also was no significant interaction between inter-letter spacing and luminance.

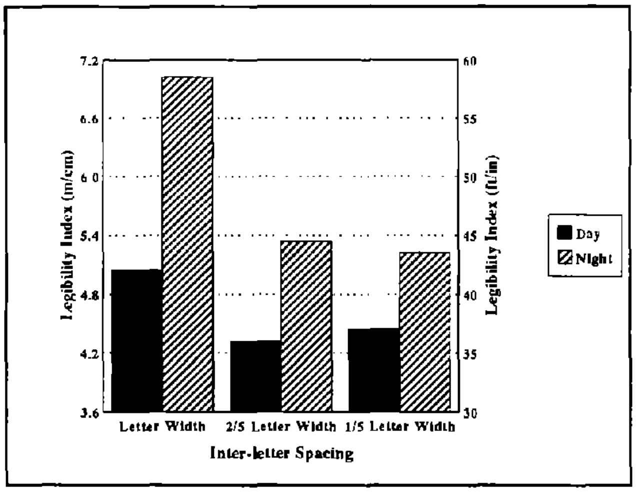


Figure 45. Effect of inter-letter spacing on day and night legibility for Typical CMS 46-cm (18-in) font.

Nighttime. Again, the font/height/spacing and luminance/spacing analyses found significant effects of inter-letter spacing. Although the font/height/spacing analysis still found an interaction among font, height, and spacing, the spacing effect was more consistent across conditions at night than during the day. The effect at night was also larger than during the day, with a decrement in LI of almost 1.8 m/cm (15 ft/in) between a spacing equal to letter width and one equal to SW (1/5 letter width) (figure 45). As in the daytime luminance/spacing analysis, the nighttime analysis found a significant effect of spacing and no interaction with sign luminance.

Font

Daytime. The font/height analysis found a significant effect of font, wherein the Double Composite performed worse overall than the other two fonts. This difference was only 0.24 m/cm (2 ft/in) of letter height and was further mitigated by the interaction with letter height (figure 43). As in the laboratory studies, neither the font/height/spacing analysis nor the font/height analysis found significant differences between the Vartabedian and Typical CMS fonts.

Nighttime. As in the daytime analyses, the font/height/spacing and luminance/spacing analyses revealed no significant difference between the Vartabedian and Typical CMS fonts. However, the font/height analysis did uncover a significant effect of font reflected in an almost 1.2-m/cm (10-ft/in) loss in legibility with the 46-cm (18-in) Double Composite letters.

Luminance

Daytime. The luminance/spacing analysis evaluated the only situation in which the effects of luminance were tested. This analysis uncovered a statistically significant main effect of luminance, wherein the higher luminance signs (925 cd/m^2) were read more than 31 m (100 ft) farther away

(0.67 m/cm [5.6 ft/in] LI) than those of lower luminance (340 cd/m^2). No interaction was found between luminance and either age group or inter-letter spacing.

Nighttime. The luminance/spacing analysis found a marginally, statistically significant effect of luminance (p=0.044), placing the lower luminance (50 cd/m^2) above the higher luminance (140 cd/m^2). While significant, the less than 0.6-m/cm (2-ft/in) increase in LI failed to meet the criterion for importance. The lack of any functional difference between performance with the two luminance levels was reflected in the findings of both the lab study of color effects and the static field study of luminance effects.

Table 24. Summary of Study 4: results and conclusions.

Independent Variables	Results	Conclusions
Subject Age	Significant effect of age in daytime–as much as 2.4-m/cm (20-ft/in) loss from the young group to the old-old group. No significant age effect in the nighttime studies. No appreciable interactions with any other variable in either daytime or nighttime testing.	Lack of interaction with other variables indicate again that improvements for one age group benefit all.
Subject Acuity	Acuity significantly correlated with LI in both daytime and nighttime studies.	Acuity should be used along with age to predict drivers' sign-reading ability.
Font	Minimal daytime effects, but significant (about 1.2 m/cm [10 ft/in]) nighttime effects of font.	Some fonts (e.g., Double Composite) are more affected by irradiation than others.
Letter Height	Minimal effect on LI in daytime or nighttime studies.	For the two sizes tested, a stable LI may be assumed. (Applies only under fairly clear atmospheric conditions.)
Inter-Letter Spacing	Significant effect in both daytime and nighttime; however, the reduced spacing had a greater effect (over 1.8-m/cm [15-ft/in] loss compared to the largest spacing) at nighttime.	During daytime hours, a 2/5 letter-width (two-element) inter-letter spacing is sufficient; however, at night when irradiation is more likely to occur, an increase in this spacing is recommended.
Character Luminance	Significant and moderately large (7 ft/in) improvement with increased luminance (340 and 925 cd/m^2 [99 and 270 fL]) in the daytime study, no appreciable effect at night with luminances of 50 and 140 cd/m^2 (15 and 41 fL).	Increases in nighttime luminance above 50 cd/m^2 (15 fL) are not necessary, although increases up to 140 cd/m^2 (41 fL) do not detract from performance.

STUDY 5: DYNAMIC FIELD STUDY

Objectives

The purpose of this study was to analyze CMS's under real-world conditions. The objectives were to assess the generalizability of the results from the laboratory and static field tests and to evaluate the effectiveness of various CMS technologies with regard to detection and legibility distance.

Subject Characteristics

A total of 81 subjects were tested under both daytime and nighttime conditions. Table 25 provides an age breakdown for daytime and nighttime subjects. Table 26 provides subject performance characteristics for various measures of visual ability and cognitive functioning. Vistech contrast sensitivity was tested for a small number of subjects (46 [a] and [b]). Any subject with worse than 20/40 visual acuity in both eyes, as tested by either the Snellen Chart or the Bausch & Lomb Master Orthorator, was excluded from participation in the study. Due to the absence of normative values on the other measures, the subject performance characteristics were not used for screening, but only for descriptive purposes.

Table 25. Study 5 subject age statistics.

	Mean	Standard Deviation	Range
Daytime			
Young (n=33)	25.2	6.68	19-40
Old (n=24)	67.8	3.58	60-72
Old-Old (n=24)	76.2	2.40	73-82
Nighttime			
Young (n=30)	24.7	6.23	19-38
Old (n=25)	67.4	3.84	59-72
Old-Old (n=26)	76.1	2.35	73-82

Table 26. Subject performance characteristics.

	Young	Old	Old-Old
Daytime			
Snellen (Acuity)	20/15	20/19	20/24
Orthorator (Acuity)	20/20	20/25	20/27
Pelli-Robson (Contrast Sensitivity)	1.95	1.81	1.68
Stroop C (Cognitive)	43.12	61.64	66.66
Dvorine (Color)	1 Failure	1 Failure	All Pass
Nighttime			
Snellen (Acuity)	20/16	20/18	20/24
Orthorator (Acuity)	20/21	20/24	20/27
Pelli-Robson (Contrast Sensitivity)	1.91	1.81	1.69
Stroop C (Cognitive)	43.83	63.72	65.79
Dvorine (Color)	1 Failure	2 Failures	All Pass

Methodology

Variables

The two dependent variables of legibility distance and detection distance were measured for the following independent variables:

Age Group (3)------------------------------ Young, Old, Old-Old
Contrast Orientation (2)-------------------- Positive, Negative
Character Height (2)------------------------ 46 cm, 107 cm (18 in, 42 in)
Lighting Condition–Day (4)---------------- Backlit, Frontlit, Overcast, Rain
Character Luminance–Day (4)------------ 350, 570, 850, 1200 cd/m^2
Character Luminance–Night (6)----------- 30, 80, 130, 200, 570, 1200 cd/m^2
Inter-letter Spacing–Night (2)------------ Single, Double
Sign Lighting–Night (4)-------------------- Internal vs. External and Blacklight vs. LED

The parenthesized number associated with each independent variable represents the number for levels of each variable. Literature recommendations for daytime luminance levels in excess of 1200 cd/m^2 were not assessed due to limitations in the luminance capabilities of the signs used in this study.

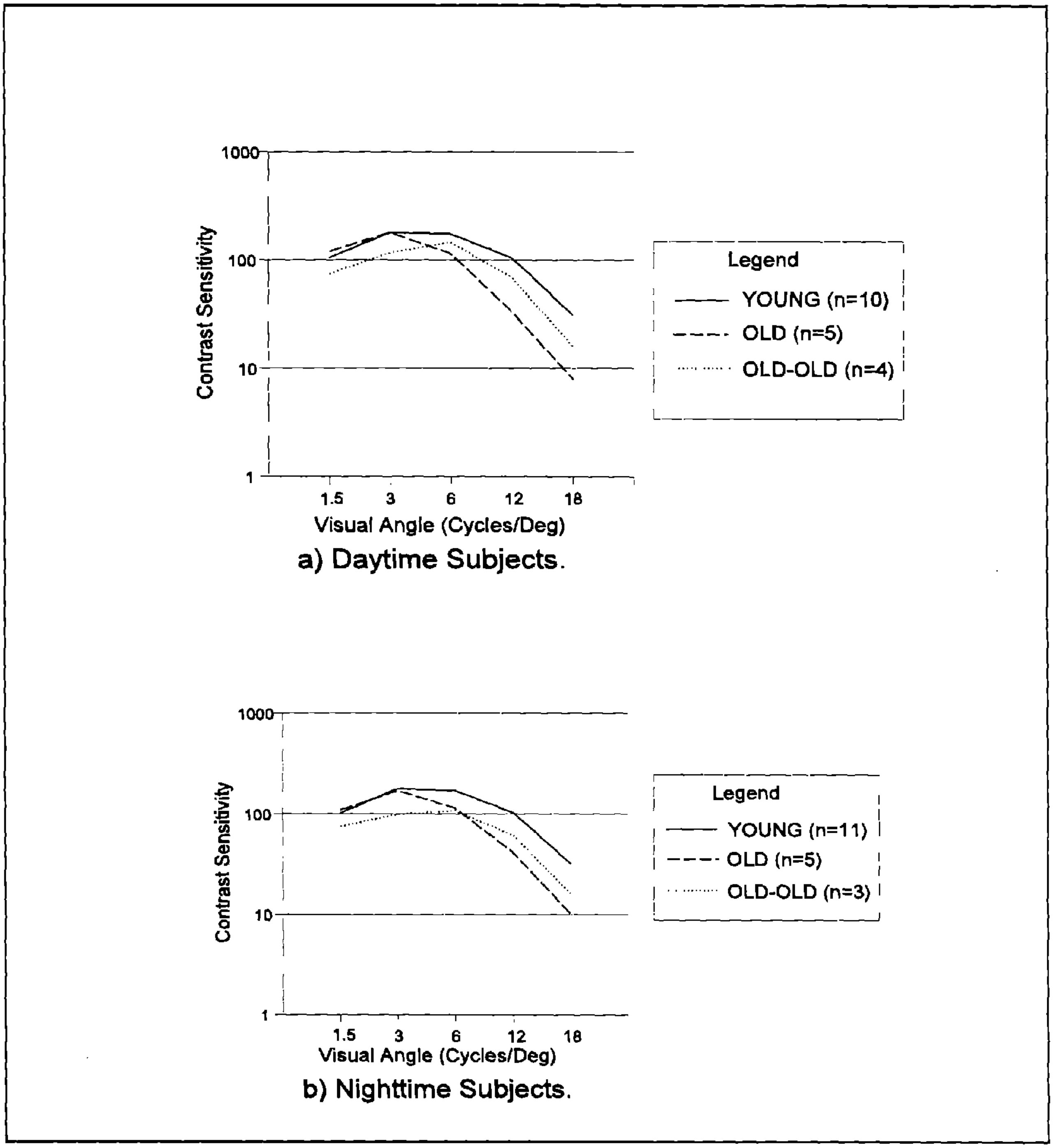


Figure 46. Vistech contrast sensitivity for a small sample of daytime and nighttime subjects.

Stimuli

The stimuli were actual words arrayed either in three lines of text with one word per line, or a single word centered on the sign (table 27). The character variables and characteristics of the message components differed from sign to sign. Table 28 describes the important characteristics to CMS legibility for each sign. Cells with "Var." in table 28 indicate a characteristic that was intentionally varied during testing; the question mark for sign 4 stroke-width-to-height ratio indicates the inability to determine the perceived diameter of an all-LED element.

Table 27. Study 5 message content.

DONT DRIVE DRUNK	TRAFFIC CONTROL TEST	PLEASE DRIVE SAFELY	TRAFFIC SAFETY STUDY	SIGN STUDY ZONE	LOCAL EXITS AHEAD	55 MPH SPEED LIMIT	TEST
WEST (EAST) BOUND TRAFFIC	OBSERVE SPEED LIMIT	ARRIVE HOME SAFELY	USE EITHER LANE	PLEASE DONT LITTER	DRIVE WITH CARE	FASTEN SAFETY BELTS	SIGN

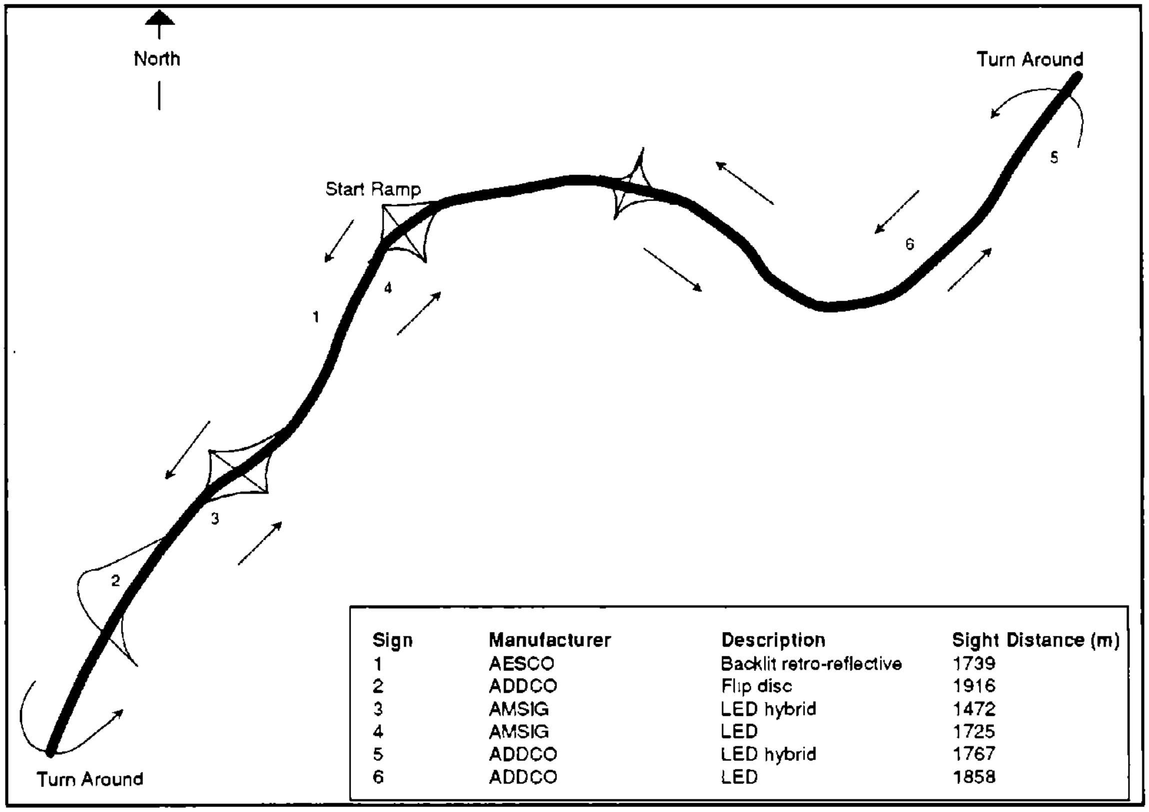
Table 28. CMS characteristics.

Sign	Manufacturer	Description	Color	W:H	SW:H	Matrix Format	Letter Height (cm)	Inter-letter Spacing (cm)	Inter-line Spacing (cm)
1	AESCO	Backlit retro-RD material	Yellow	Var.	Var.	Var.	Var.	Var.	Var.
2	ADDCO	Fluorescent flip-disc matrix	Yellow	0.50	0.09	5x7	46	11.4	17.2
3	AMSIG	LED/RD hybrid	Yellow	0.69	0.125	5x7	46	7.6	15.2
4	AMSIG	LED	Amber	0.55	?	5x7	53	12.7	15.2
5	ADDCO	LED/RD hybrid	Yellow	0.50	0.09	5x7	46	11.4	17.2
6	ADDCO	LED	Red	0.57	0.143	8x14	46	Var.	17.2

1 cm = 0.3937 in

Apparatus and Facilities

Six portable CMS signs were evaluated (table 28). The study was conducted on an 89-km/h (55-mi/h) section of the Route 322 business bypass located in the State College, PA, area. The bypass is a 32-km (20-mi) rural section of four-lane divided highway (figure 47). All signs had an unobstructed viewing distance of at least 1.3 km (0.8 mi). The signs were viewed against the tree line. Signs 1, 2, and 6 were on the westbound portion of the roadway; and signs 3, 4, and 5 were viewed with the test vehicle traveling east. From hereon, signs 1 through 6 will be referred to as "BRD" (backlit RD), "RD," "LED/RD-1," "amber-LED," "LED/RD-2," and "red-LED," respectively.



Sign	Manufacturer	Description	Sight Distance (m)
1	AESCO	Backlit retro-reflective	1739
2	ADDCO	Flip disc	1916
3	AMSIG	LED hybrid	1472
4	AMSIG	LED	1725
5	ADDCO	LED hybrid	1767
6	ADDCO	LED	1858

Figure 47. Schematic of Route 322 bypass.

Photometric Measurements

In order to characterize the viewing conditions for each experimental session, several observations were made. During the daytime sessions, an experimenter recorded the location of the sun in the sky, vertical illuminance on BRD and amber-LED, horizontal illuminance, and the general weather. These observations were used in the analyses to determine the levels of the ambient lighting condition variable.

Procedure

Each session lasted approximately 45 min. A single subject was tested per session. The subjects were seated in the front passenger seat with an experimenter as the driver. The subjects were shown photographic examples of CMS's prior to testing, to familiarize them with the signs. They were told to report when they could see a CMS, and to read the sign when they were able. By pushing a button connected to a distance measuring computer (DMC), the experimenter marked the moment the subject detected the CMS, the moment the subject began to read the sign, and when the subject completed reading the sign correctly. The experimenter also pressed the button when the vehicle passed the sign, thereby providing a DMC reading from which the response distances were computed.

The subjects were divided into two groups: A and B. Each subject was tested during the day and at night. Group A participated in the daytime session first and the nighttime session second; the order was reversed for group B. All of the subjects in both groups were tested in the first 1.5 weeks of data collection. The message content was then changed and all subjects were tested a second time over the last 1.5 weeks of the study. The second run was used to assess legibility only. Data on detection could be collected only on the first run for each subject, since the subjects then knew the signs' locations.

During detection runs, a subsidiary task was required to elicit eye movements akin to those of a vehicle operator. Subjects were instructed to look for orange "X's" on the left and right side of the road. The 25.4-cm (10-in) X's were made of 3M's diamond-grade fluorescent sheeting and were affixed to 1.2-m (4-ft) stakes that were placed on the shoulder and median of the roadway throughout the test route. Detection of the X's was used for task loading only and their detection distances were not recorded or scored.

During daytime sessions, each subject saw seven separate messages on the six CMS's. At night, the subjects saw either 8 or 10 CMS messages during a single session. The messages in excess of six were tested by routing subjects through part of the test route a second time. An example of daytime and nighttime sign presentation is given in table 29. The order of presentation of the manipulated variables was counterbalanced across subjects.

Experimental Design. Because of the reduction in experimental control inherent in large field studies, the experimental designs often become fairly complicated; this study is no exception. In order to facilitate understanding, table 30 provides a breakdown of the variables and the signs used to test them. Table 30 also provides the number of subjects tested on those variables. The following discussion is meant to explain design elements not amenable to tabulation.

The only manipulation of RD and LED/RD-1 was the message content; the same is true for LED/RD-2 during daytime. The counterbalancing of message content was designed to assuage potential confounding of the independent variables if the selected messages did not have equal legibility or detectibility. Since RD and LED/RD-2 were identical, with the exception of nighttime lighting, we were afforded an excellent opportunity to examine the relative effectiveness of using fluorescent blacklight tubes versus LED's for nighttime CMS illumination.

BRD was used to test three independent variables: contrast orientation; letter height; and, at night, sign lighting (internal vs. headlights). Contrast orientation and letter height were between-subject variables and sign lighting was a within-subject variable.

Character luminance was manipulated for amber-LED. Four luminance levels were tested during daytime and six were tested at night. This variable was of a mixed design, with some levels tested within-subject and some between-subject. Two levels of character luminance were tested at night on LED/RD-2. Character luminance was a between-subject variable. Red-LED was only tested at night where inter-letter spacing was manipulated as a between-subject variable.

Table 29. Sample stimulus presentation.

	Daytime	Nighttime
Message 1	* BRD: 46-cm letters, three lines of text, negative contrast.	* BRD: 46-cm letters, three lines of text, positive contrast.
Message 2	RD: 46-cm letters, three lines of text, positive contrast.	RD: 46-cm letters, three lines of text, positive contrast.
Message 3	LED/RD-1: 46-cm letters, three lines of text, positive contrast	LED/RD-1: 46-cm letters, three lines of text, positive contrast.
Message 4	* Amber-LED: 53-cm letters, three lines of text, positive contrast, luminance = 850 cd/m².	* Amber-LED: 53-cm letters, three lines of text, positive contrast, luminance = 30 cd/m².
Message 5	LED/RD-2: 46-cm letters, three lines of text, positive contrast.	* LED/RD-2: 46-cm letters, three lines of text, positive contrast, luminance = 25 cd/m².
Message 6	------------	* Red-LED: 46-cm letters, three lines of text, positive contrast, double inter-letter spacing.
Message 7	* BRD: 46-cm letters, one line of text, positive contrast.	* BRD: 107-cm letters, one line of text, positive contrast.
Message 8	* Amber-LED: 53-cm letters, three lines of text, positive contrast, luminance = 80 cd/m².	* Amber-LED: 53-cm letters, three lines of text, positive contrast, luminance = 1200 cd/m².
Message 9	------------	* BRD: 46-cm letters, three lines of text, positive contrast, sign lighting turned off.
Message 10	------------	* Amber-LED: 53-cm letters, three lines of text, positive contrast, luminance = 200 cd/m².

* Messages that varied throughout the study; 1 cm = 0.3937 in

Analyses and Results

Daytime Ambient Lighting Conditions

Legibility and Detection. There were two reasons to analyze the effects of daytime ambient lighting conditions on CMS legibility and detection. First, according to both our literature review and anecdotal observations, the position of the sun and ambient daytime adaptation have an effect on CMS visibility. The second reason was to determine whether the variables manipulated in this field study needed to be analyzed with respect to lighting conditions, or if the analyses could be limited to nighttime versus daytime.

Table 30. Quasi-experimental design for dynamic study showing sample sizes for each condition by group (A and B).

		Daytime						Nighttime					
		Young n = 30		Old n = 25		Old-Old n = 26		Young n = 33		Old n = 24		Old-Old n = 24	
		A	B	A	B	A	B	A	B	A	B	A	B
BRD	Pos. Contrast	7	7	6	0	7	7	7	8	4	4	8	7
	Neg. Contrast	9	6	6	12	5	7	8	9	7	9	3	4
	46 cm	3	5	5	12	5	7	7	10	7	9	4	5
	107 cm	11	7	7	0	7	7	6	8	2	4	7	7
	Sign Lighting (Headlights only)	Nighttime Only						N/A	18	N/A	13	N/A	11
RD		16	11	12	12	10	14	15	18	11	12	11	12
LED/ RD-1		16	14	13	12	12	14	15	18	11	13	12	12
Amber-LED	30 cd/m^2	Nighttime Only						8	10	7	9	4	5
	80 cd/m^2							7	10	7	9	4	5
	130 cd/m^2							N/A	10	N/A	9	N/A	5
	200 cd/m^2							5	8	4	4	7	6
	350 cd/m^2	5	6	8	9	5	6	Daytime Only					
	570 cd/m^2	6	5	8	9	5	6	7	8	4	4	8	7
	850 cd/m^2	8	8	5	0	7	7	Daytime Only					
	1200 cd/m^2	8	8	5	0	7	7	N/A	8	N/A	4	N/A	7
LED/ RD-2	Flip disc	16	14	13	12	12	14	Daytime Only					
	25 cd/m^2	Nighttime Only						10	10	9	9	6	5
	125 cd/m^2							4	8	2	4	6	5
Red-LED	Single-spacing	Nighttime Only						N/A	4	N/A	7	N/A	4
	Double-spacing							N/A	2	N/A	3	N/A	4

1 cm = 0.3937 in

A total of 81 daytime sessions were run, but only 25 of these sessions took place under sunny skies. Overcast conditions accounted for 43 sessions and 13 were run in the rain. The 25 sunny day sessions were further broken down into frontlit and backlit cases, resulting in 13 frontlit and 11 backlit cases (one case had insufficient lighting data). The frontlit/backlit breakdown was based on the vertical illuminance on the sign face. Observations with vertical lux greater than 20,000 were considered frontlit, and those under 20,000 lx were labeled as backlit. The analysis of ambient lighting conditions was restricted to RD, LED/RD-1, and amber-LED as these signs were on a stretch of the test route that produced the most extreme sun angles. The mean vertical illuminance for RD frontlit was 38,000 lx and backlit was 11,000 lx. The mean vertical illuminance for LED/RD-1 and amber-LED frontlit was 53,000 lx and backlit was 9000 lx.

Only six young subjects were tested under sunny day conditions. Most of the remaining 27 were tested under overcast conditions. Therefore, ambient analyses were restricted to the two old groups, which presented a more even distribution between lighting conditions. The old and old-old groups were combined to maximize the number of subjects in each lighting condition. Table 31 shows the sample sizes tested for each lighting condition for the three signs.

Table 31. Sample sizes for lighting condition analysis.

	RD		LED/RD-1		Amber-LED	
	Legibility	Detection	Legibility	Detection	Legibility	Detection
Frontlit	7	2	12	5	12	5
Backlit	12	5	9	4	9	4
Overcast	19	4	20	6	16	6
Rain	9	9	9	8	9	9

Separate between-subject ANOVA's were conducted on the detection and legibility data. There was no significant effect of lighting condition on detection distance for any of the three tested signs. Between-subject ANOVA's on RD and LED/RD-1 revealed no significant effect of lighting condition on legibility distance. A between-subject ANOVA on amber-LED indicated a significant main effect of lighting condition. A post hoc Tukey- Honestly Significant Difference (HSD) analysis showed that the rain condition produced significantly longer legibility distances than the frontlit condition. None of the other conditions differed significantly (figure 48).

Daytime lighting condition and sun position had no statistically significant effect on detection and, with the exception of amber-LED in the rain, no significant effect on legibility distance. In general, it was believed that RD signs work particularly well when the sun is directly on the sign, but experience major problems with "backlit" and overcast conditions. FO, lamp matrix, and LED signs can, to some extent, overcome the problem of backlighting; however, they have much more difficulty with "washout" when the sun is directly on the sign face. The results of the dynamic study (figure 48), although for the most part not significant, are consistent with these expectations.

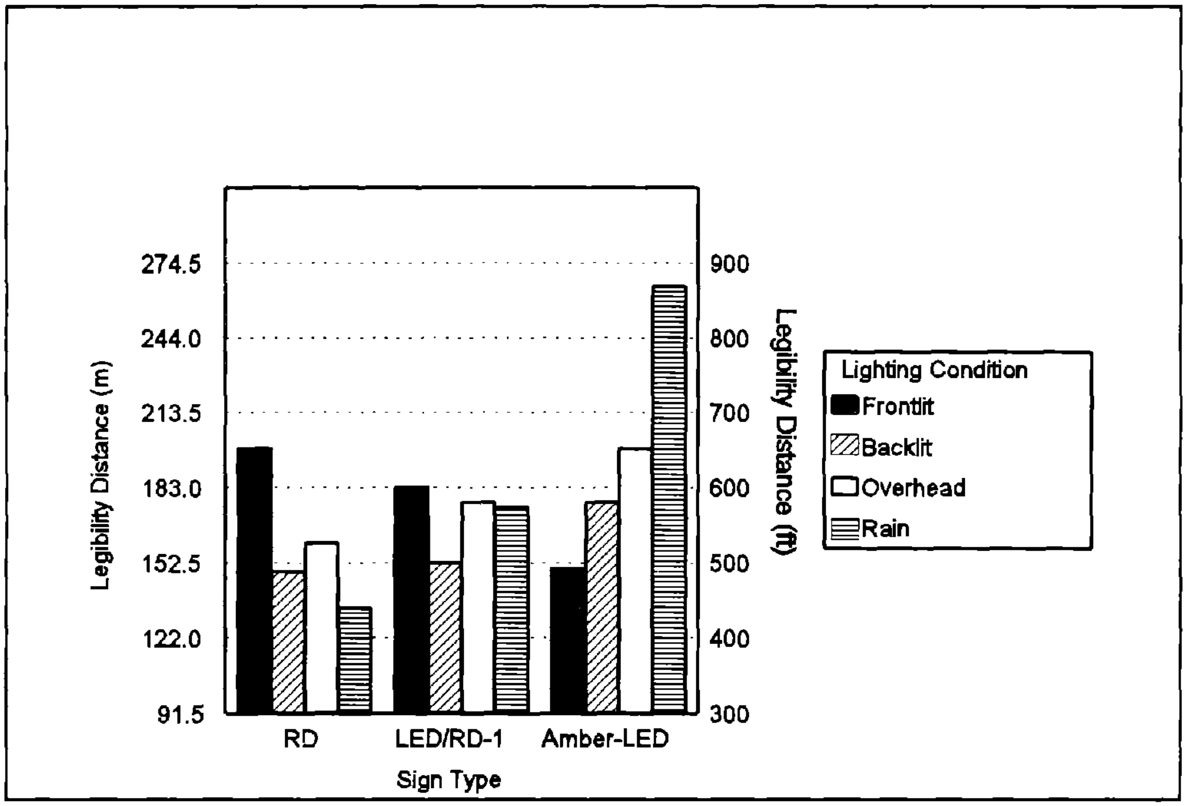


Figure 48. Comparison of legibility distance for three signs under four lighting conditions.

There are several possible explanations for the discrepancy between the results reported here and the generally accepted belief that CMS visibility is significantly affected by daytime lighting conditions. The first explanation has to do with the sample, which was small and limited to observers age 60 and older. The large between-subject variances found with such a sample are evident in figure 48, where it can be seen that mean differences in excess of 30 m (100 ft) between lighting conditions resulted in nonsignificant findings. It is possible that the results would have been different if a larger sample was used or if young observers were included in the analysis. Furthermore, the signs were new or recently cleaned and shoulder-mounted. Sun effects are exacerbated by dirty or scratched protection screens as well as by overhead mounting. Whatever the reasons, the analyses indicated that with the one exception of amber-LED in the rain (representing nine subject observations), there were no significant differences between mean legibility and detection distances due to daytime ambient lighting.

ANOVA's alone cannot answer the question of whether a control for the effects of lighting condition should be placed on the remaining daytime analyses. Equal between-treatment means do not necessarily indicate that the variable did not affect performance. In order to fully describe the samples' performance, we conducted separate Levene tests for homogeneity of variances for RD, LED/RD-1, and amber-LED detection and legibility. The results of these tests were all negative. No significant differences in variances were found between treatments for any of the three signs and either of the dependent variables. On the basis of the results of the ANOVA's and Levene tests, we determined that the daytime data could be treated in analysis as a study conducted under homogeneous ambient lighting conditions without jeopardizing the validity of our results.

Age Group. Age group analyses were conducted within each of the separate independent-variable analyses. Wherever there was an interaction between age group and another variable, the age group effect was included in that section. However, to avoid redundancy and to provide a clear picture of age effects on CMS visibility, the results of the analyses of age group are presented in table 32. Where differences in row shading indicate significant differences in mean performance, the lighter shading indicates greater visibility distances.

Table 32. Age group effect on CMS visibility.

	Age Group		
Independent Variable:	Young	Old	Old-Old
Contrast Orientation			
Letter Height (Day)			
Letter Height (Night)			
Character Luminance (Day)			
Character Luminance (Night)			
Nighttime Lighting			
Overall Sign Legibility (Night)			
Overall Sign Detection (Night)			

Note: Lighter shading indicates greater visibility distances.

Contrast Orientation

Daytime Legibility and Detection. Analyses of the computer simulation studies reported earlier as the Color and Message studies indicated a significant effect of contrast orientation. Positive-contrast light-on-dark signs produced legibility indices as much as 1.4 m/cm (12 ft/in) greater than negative-contrast dark-on-light signs. This would translate into a 61-m (200-ft) legibility distance improvement with positive-contrast signs employing the standard 46-cm (18-in) character height.

BRD was tested using both positive- and negative-contrast messages. Between-subject ANOVA's on age group and contrast orientation for legibility failed to reach significance on the main effect of contrast orientation. The mean legibility distance for positive contrast was 212 m (696 ft) and for negative contrast was 200 m (657 ft). There were too few subjects in the detection cells to conduct a meaningful ANOVA with age group. Therefore, a single-factor ANOVA was performed on the effects of contrast orientation on detection. Although mean detection distances were 792 m (2600 ft) for the positive-contrast signs and 975 m (3200 ft) for the negative-contrast signs, the difference between the two distances was not significant. The sample sizes for the contrast orientation analyses for both daytime and nighttime analyses are given in table 33.

Table 33. Sample sizes for contrast orientation analysis.

Contrast Orientation	Legibility			Detection
	Young	Old	Old-Old	All Age Groups
Daytime				
Positive	14	6	14	10
Negative	15	18	12	9
Nighttime				
Positive	15	8	15	6
Negative	17	16	7	7

Nighttime Legibility and Detection. Unlike the daytime portion of this study, an ANOVA on the nighttime data found a significant effect of contrast orientation on legibility distance. The contrast-orientation effect was in the same direction and of the same magnitude as that found in the laboratory computer simulations. Positive-contrast signs produced a mean legibility distance of 152 m (497 ft) and negative-contrast signs produced a mean legibility distance of 118 m (386 ft). This represented a 29-percent improvement in legibility distance with positive-contrast messages.

Again, there were too few subjects in the detection cells to conduct a meaningful age group analysis on the data. As in daytime, the results of a single-factor ANOVA with data collapsed across age groups were in the expected direction; the more luminous negative-contrast signs had a longer mean detection distance. The positive-contrast signs had a mean detection distance of 751 m (2646 ft) and the negative-contrast signs had a mean detection distance of 1105 m (3625 ft). However, a single-factor ANOVA on contrast orientation for detection was not significant.

Character Height

Daytime Legibility and Detection. One of the variables that we were unable to manipulate effectively in the computer simulation studies was character height. The image on the retina of a 23-cm (9-in) letter, at 30 m (100 ft) away is the same as a 46-cm (18-in) letter at 60 m (200 ft). However, some research indicates that increases in letter height might not produce proportional increases in legibility distance. A recent FHWA-sponsored study on static highway signs showed an increase in legibility distance to be around 80 to 85 percent of what would be expected from the increased retinal image size.[22]

We manipulated character height on BRD. We compared the legibility and detection distance for a single word (either SIGN or TEST) at character heights of 46 and 107 cm (18 and 42 in). A between-subject ANOVA on legibility resulted in the finding of significant effects of character height and age group, but no significant interaction between the two variables. As for the character height effect, the 107-cm (42-in) letters resulted in an overall mean of 411 m (1348 ft) of legibility distance compared to 244 m (802 ft) for the 46-cm (18-in) characters. While this represents a significant increase in legibility distance, the increase was less than proportional to the increase in character height. If the 244 m (802 ft) for the 46-cm (18-in) letters were to be taken as a standard, increasing the character height to 107 cm (42 in) should have produced a legibility distance of 568 m (1864 ft), or a 233-percent increase. The observed increase was 168 percent, or 72 percent of the expected proportional increase (figure 49). Put another way, the 107-cm (42-in) letters had an LI of 3.8 m/cm (32 ft/in), while the 46-cm (18-in) letters had an LI of 5.4 m/cm (45 ft/in).

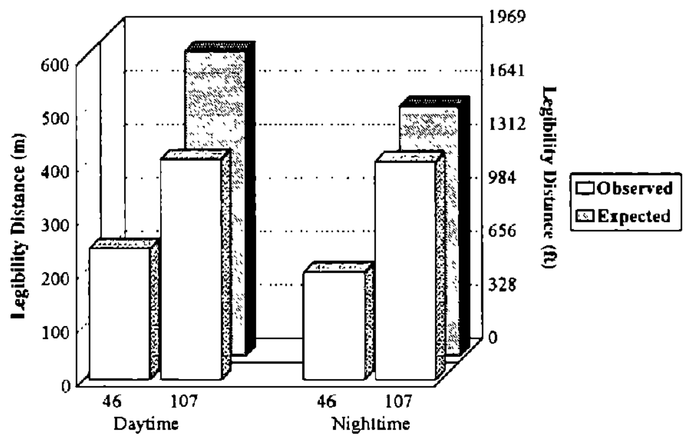


Figure 49. Effect of character height on legibility.

The sample size was insufficient to conduct a meaningful age group analysis on the detection data (table 34). A single-factor ANOVA with data collapsed across age groups indicated a significant difference between detection distance for the smaller and larger character heights. The overall means for character height were in the predicted direction: 922 m (3027 ft) for the 107-cm (42-in) letters and 560 m (1838 ft) for the 46-cm (18-in) letters.

Nighttime Legibility and Detection. A two-factor between-subject ANOVA was conducted to assess the effects of character height and age group on legibility distance. The effects of both variables were found to be significant. Like the daytime data, the effect on legibility distance of increasing character height at night was less than proportional to the increase in letter height. The 46-cm (18-in) characters had a mean legibility distance of 200 m (656 ft) compared to the 407 m (1335 ft) for the 107-cm (42-in) letters. Using the logic discussed in the daytime section, a legibility distance of 465 m (1531 ft) would have been expected with the 107-cm (42-in) letters. This represents an 18-percent loss in the expected legibility distance (figure 49), or an LI drop of 0.6 m/cm (5 ft/in).

Table 34. Sample sizes for character height analysis.

Character Height	Young		Old		Old-Old	
	Legibility	Detection	Legibility	Detection	Legibility	Detection
Daytime						
46 cm (18 in)	8	1	17	3	12	2
107 cm (42 in)	18	7	7	3	14	4
Nighttime						
46 cm (18 in)	17	5	16	1	9	3
107 cm (42 in)	14	6	6	2	14	4

The detection data was collapsed across age groups to increase the sample size for analysis. Although the means were again in the predicted direction (46 cm [18 in] at 959 m [3148 ft] and 107 cm [42 in] at 1093 m [3587 ft]), no significant effect of character height was found in this single-factor ANOVA.

Character Luminance

Daytime Legibility and Detection. Daytime character luminance was another variable that was not amenable to manipulation in the laboratory computer simulations. Threshold and clear luminance levels were established for several key distances in the static field studies discussed previously. The inclusion of the character luminance variable in the dynamic study was aimed at verifying the results of the static study under more natural driving conditions.

The effect of increasing amber-LED character luminance from 350 to 570 cd/m^2 was analyzed using a within-subject ANOVA, as was the effect of going from 850 to 1200 cd/m^2. A significant main effect of luminance was found in the lower luminance analysis; however, the two higher levels were not found to differ significantly from each other.

The within-subject data from the 850- and 1200-cd/m^2 conditions were combined and compared to the 350-cd/m^2 luminance level using a between-subject ANOVA; an identical analysis was conducted comparing the combined mean of the two higher levels with the 570-cd/m^2 data. Both of these analyses resulted in a significant main effect for character luminance. In summary, the luminance level with the shortest legibility distance was the 350-cd/m^2 condition, the next longest was 570 cd/m^2. The increase in legibility distance peaked with the 850-cd/m^2 signs, and the increase in luminance to 1200 cd/m^2 did not produce a significant increase in this distance (figure 50).

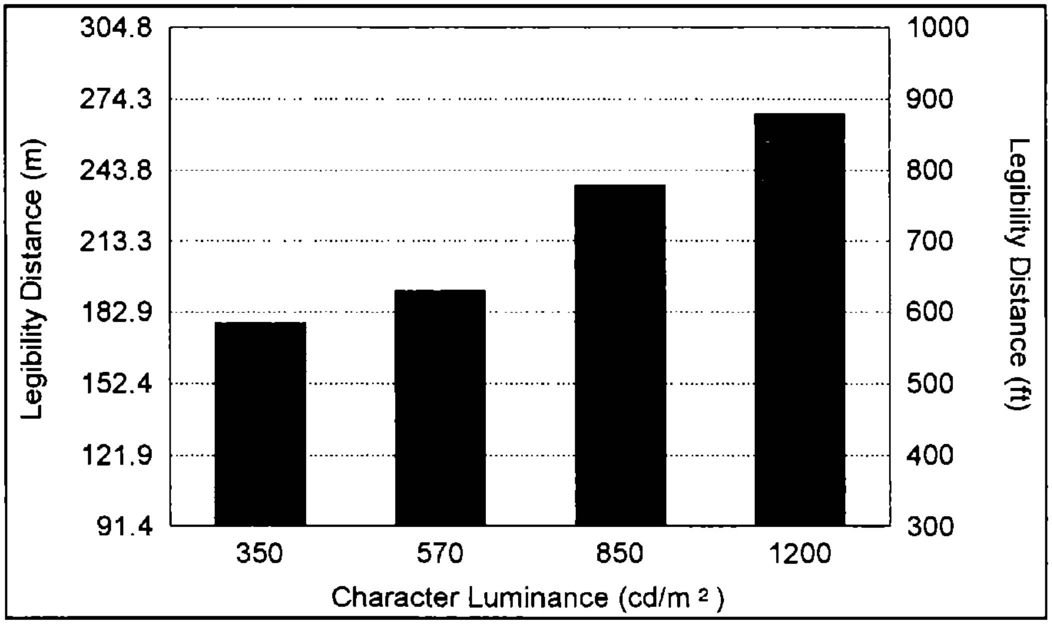


Figure 50. Effect of character luminance on daytime legibility distance—amber-LED.

Within-subject ANOVA's for detection distance were conducted in the same manner as described earlier, even though the sample sizes were fairly small (table 35). No significant differences were found between the two lowest or the two highest luminance levels. The means of the two lowest and two highest luminance levels were then compared using a between-subject ANOVA. Again, no significant effects of luminance were found. The detection means for the four lighting conditions reflect this lack of effect. In order of character luminance, detection distances were 1114, 1016, 1018, and 1199 m (3656, 3333, 3339, and 3934 ft).

Nighttime Legibility and Detection. The effect of character luminance on legibility and detection distance at night was examined on amber-LED and LED/RD-2. The levels tested on these two signs and the sample sizes used are enumerated in table 36. Character luminancewas analyzed separately for each of the signs.

Table 35. Sample sizes for daytime character luminance analysis–amber-LED.

Character Luminance	Young		Old		Old-Old	
	Legibility	Detection	Legibility	Detection	Legibility	Detection
350 cd/m^2	11	7	17	8	11	5
570 cd/m^2	11	7	17	8	11	5
850 cd/m^2	16	9	5	5	14	7
1200 cd/m^2	16	9	5	5	14	7

Table 36. Sample sizes for nighttime character luminance analysis–amber-LED and LED/RD-2.

Character Luminance	Young		Old		Old-Old	
	Legibility	Detection	Legibility	Detection	Legibility	Detection
LED/RD-2						
25 cd/m²	20	10	18	9	11	6
125 cd/m²	12	4	6	2	11	6
	All Age Groups					
Amber-LED	Legibility			Detection		
(1) 30 cd/m²	43			19		
(2) 80 cd/m²	42			17		
(3) 130 cd/m²	24			---------		
(4) 200 cd/m²	34			16		
(5) 570 cd/m²	38			19		
(6) 1200 cd/m²	19			---------		

LED/RD-2. A two-factor between-subject ANOVA for age group and character luminance effects was conducted for legibility distance. The ANOVA's on LED/RD-2 legibility failed to find significance on either character luminance or an interaction between character luminance and age group. The 25-and 125-cd/m^2 conditions produced average legibility distances of 159 and 176 m (521 and 577 ft), respectively. The detection ANOVA collapsed across age groups was also non-significant.

Amber-LED. Within this section, the six luminance levels used on amber-LED will be referred to by the numbers found on table 36. During the first half of the data collection, character luminance levels of 30, 80, 200, and 570 cd/m^2 were tested exclusively. This is reflected in table 36, amber-LED detection, as detection data were only collected during the first half of the study. In this portion of the study, 30 and 80 cd/m^2 were tested within-subject as were 200 and 570 cd/m^2. The second half of the data collection examined luminance levels of 30, 80, and 130 cd/m^2 within-subject. Levels with 200, 570, and 1200 cd/m^2 were also tested within-subject.

Initial analyses of the data, using both between- and within-subject ANOVA's, both with and without age group as a second variable, uncovered several instances of significant differences between legibility means. For example, 570 cd/m^2 produced greater legibility distance than 200 cd/m^2, while 30 and 80 cd/m^2 were found not to differ significantly. Although this type of sporadic effect of character luminance occurred, there was no consistent effect. Increasing luminance neither improved nor deteriorated legibility distance; on the contrary, its effects appeared random (figure 51). The lowest and highest luminance levels both resulted in legibility distances of approximately 245 m (800 ft) and the remaining four levels tested were all within about 30 m (100 ft) of the low and high luminance levels. Since the legibility distance obtained with the lowest luminance level (30 cd/m^2) was not significantly lower than the distance obtained with the highest luminance level (130 cd/m^2), the 30 cd/m^2 appears to be asymptotic. The detection ANOVA's for detection distance revealed no significant effect of character luminance.

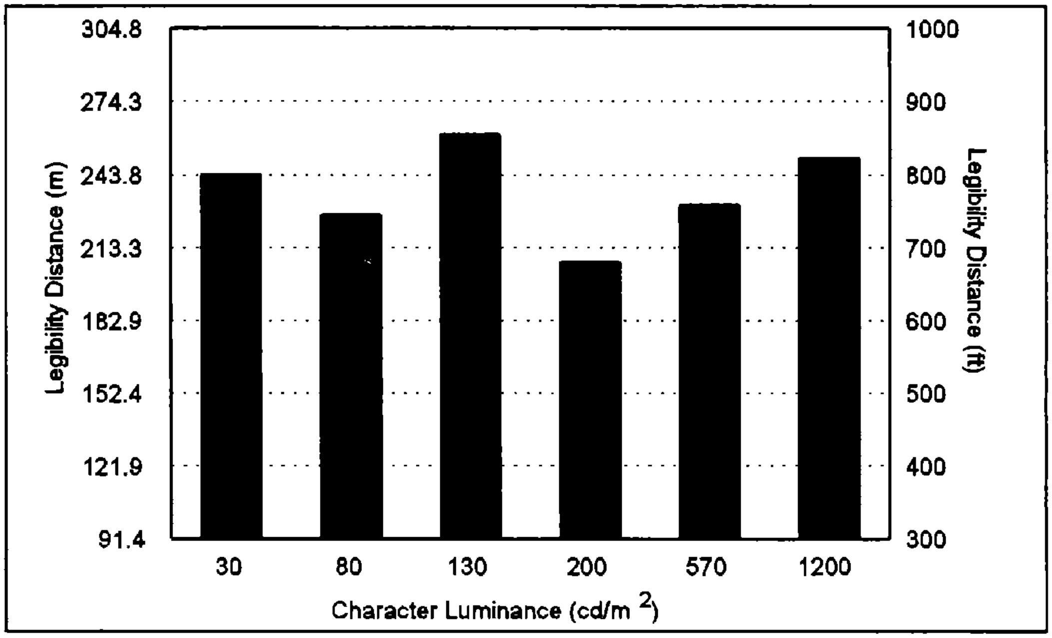


Figure 51. Mean nighttime legibility distance for six levels of character luminance–amber-LED.

Inter-Letter Spacing

Nighttime Legibility. Our literature review and laboratory and static field studies indicated that increasing inter-letter spacing would result in greater nighttime legibility distances. Red-LED was used to determine the effects of inter-letter spacing in a real-world setting. Two levels of inter-letter spacing were examined: single-stroke width and double-stroke width. Because of electrical difficulties with the sign, we were only able to collect data during the nighttime portion of the last 4 days of the study. Only legibility data were obtained for this variable.

Since the sample was small (n=15 single space, n=9 double space), a single-factor ANOVA collapsed across age groups was used to assess this variable's effectiveness. The analysis found no significant difference between the two means. Mean legibility distance was 186.4 m (611 ft) for the single-space condition and 186.6 m (612 ft) for the double-space condition.

Sign Lighting

Nighttime Legibility. BRD afforded the unique opportunity to examine the effectiveness of a new CMS technology. At night, this sign is backlit via a series of vertically mounted white-light fluorescent lamps. The light passes through translucent retroreflective CMS elements and is blocked by opaque elements, thereby forming the characters. If the lights are inactivated for any reason, the retroreflective elements are supposed to work as a backup lighting system. The variable tested here was sign lighting; the two levels tested were internally illuminated and retroreflective.

A two-factor between-subject ANOVA was run on sign lighting and age group. There was no significant difference between the two lighting conditions. With the lighting on, the mean legibility distance was 152 m (497 ft); with headlights as the only source of illumination, it was 158 m (517 ft).

RD and LED/RD-2 enabled us to examine two additional methods of nighttime lighting. RD used ultraviolet ("blacklight") lamps to illuminate the message, while LED/RD-2 had LED bundles placed behind the elements for this purpose. As expected, daytime legibility was not significantly different between these two signs (figure 52). However, at night LED/RD-2 had significantly greater legibility distance (figure 55). This finding is consistent with the hypothesis that reduced contrast produced by illuminating both the elements and the background would result in reduced legibility distances.

Overall Sign Effect

Daytime Legibility. These analyses were aimed at examining the effectiveness of each of the signs in comparison to the others, for all three age groups. Since no daytime effect was found for the contrast-orientation variable, the between-subject positive-contrast and negative-contrast data were pooled to form one BRD data set. Although there were differences between the luminance conditions, to increase the sample size, amber-LED was analyzed with data pooled from the two luminance levels that produced the greatest legibility distance for that sign. The data from RD, LED/RD-1, and LED/RD-2 were included in their original form.

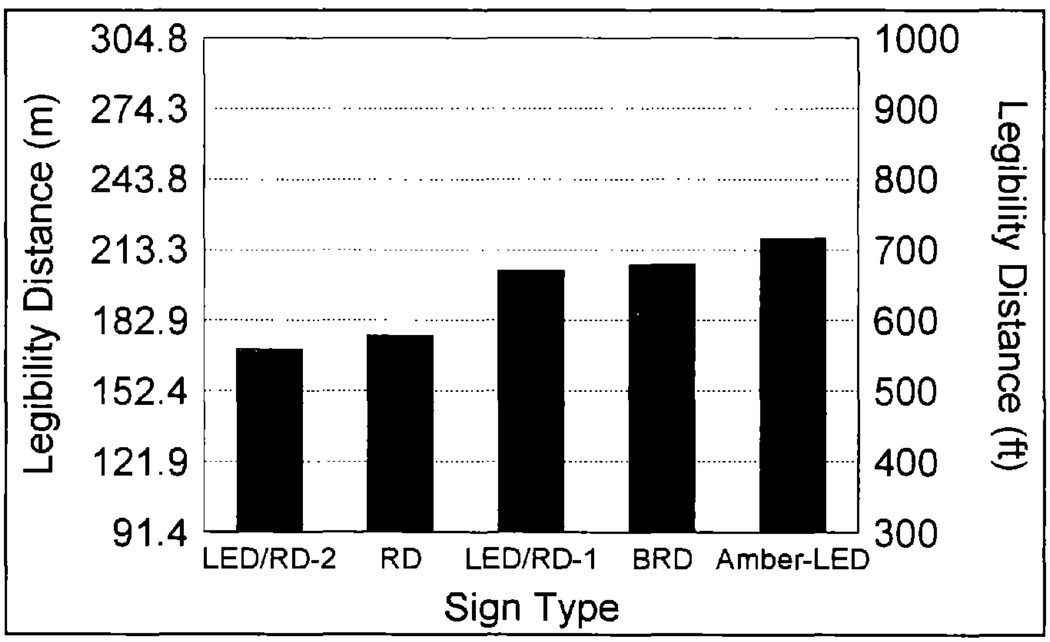


Figure 52. Mean daytime legibility distance.

A within-subject ANOVA evidenced a significant effect of sign and age group. Post hoc paired-sample T-tests were conducted at the p<0.01 level to determine which signs produced the main effect. These analyses showed that no significant difference occurred in legibility distance between LED/RD-2 and RD; the same was true among LED/RD-1, BRD, and amber-LED. However, the latter three signs produced significantly greater legibility distances than did the former two (figure 52).

Daytime Detection. A between-subject ANOVA on the effects of sign and age group on detection distance was conducted on four signs (RD, LED/RD-1, amber-LED, and LED/RD-2). As there was no character luminance effect on detection distance, amber-LED was analyzed using pooled data from all four luminance levels. BRD was dropped from the analysis because of the small sample size.

No significant difference was found between LED/RD-1 and LED/RD-2 (figure 53). Further analysis of this data with paired-sample T-tests revealed that these two signs produced significantly longer detection distances than RD and significantly shorter detection distances than amber-LED (p<0.01).

The initial ANOVA also exposed a main effect of age group and an interaction between age group and sign. The age group effect was further probed with a Tukey-HSD test that indicated no significant difference between the two old groups. The interaction was probed with three single-factor ANOVA's conducted separately for the three age groups (figure 54). All three analyses showed a main effect of the sign; however, with both of the old groups, the effect was all in amber-LED. There were no differences among RD, LED/RD-1, and LED/RD-2 (T-tests, p<0.01). For the young group, the detection results were identical to the main effect of the sign discussed in the previous paragraph.

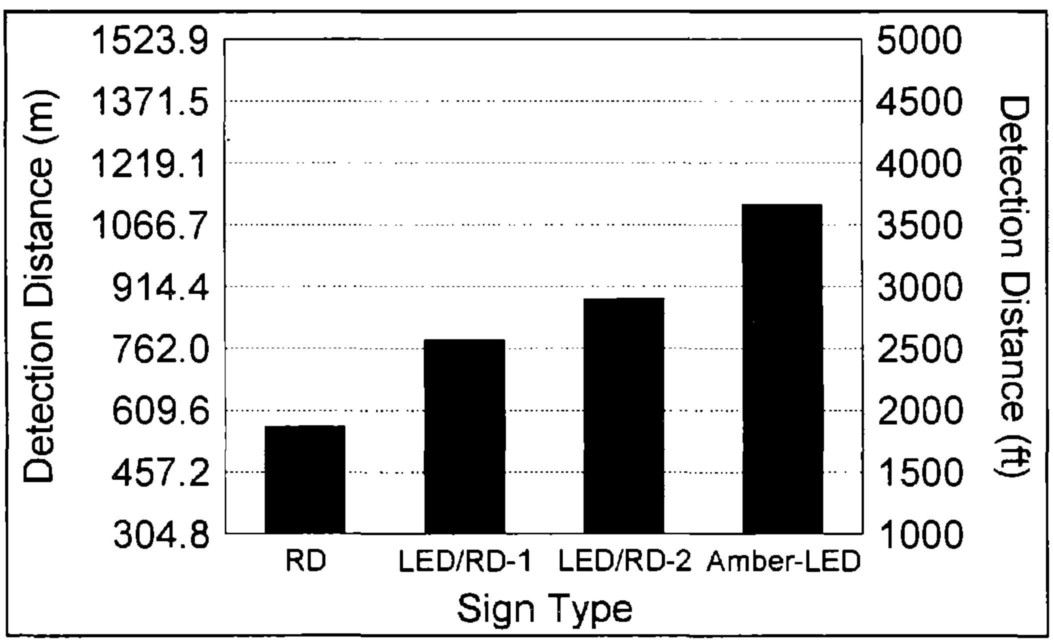


Figure 53. Mean daytime detection distance for four signs.

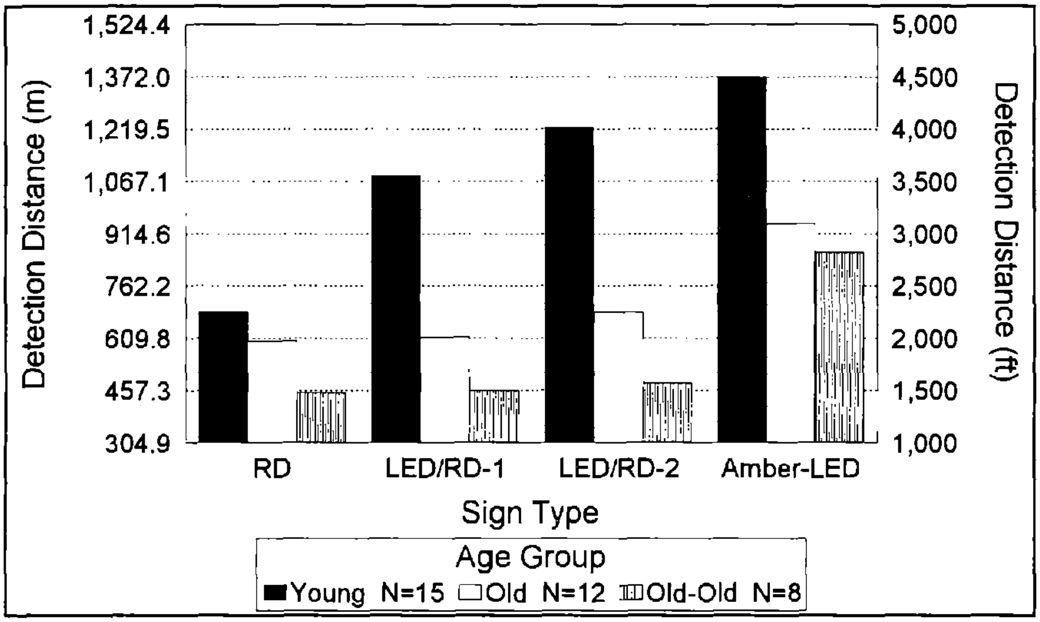


Figure 54. Interaction between age group and sign for daytime detection distance.

Nighttime Legibility. BRD, RD, LED/RD-1, amber-LED, and LED/RD-2 were used in the overall nighttime sign performance analyses for legibility. Because there was no significant difference in performance with the sign-lighting variable using BRD, the data for BRD were collapsed across the sign-lighting variable to increase the sample size. For the same reason, overall legibility performance of amber-LED and LED/RD-2 was analyzed with the data collapsed across character luminance levels. RD and LED/RD-1 were analyzed in their original form.

A within-subject ANOVA on sign and age group revealed significant effects of both variables and no interaction. The sign effect was probed with a series of paired-sample T-tests at the $p<0.01$ level. All of the signs produced significantly different legibility distances, with the exception of BRD, when compared to LED/RD-2 (figure 55).

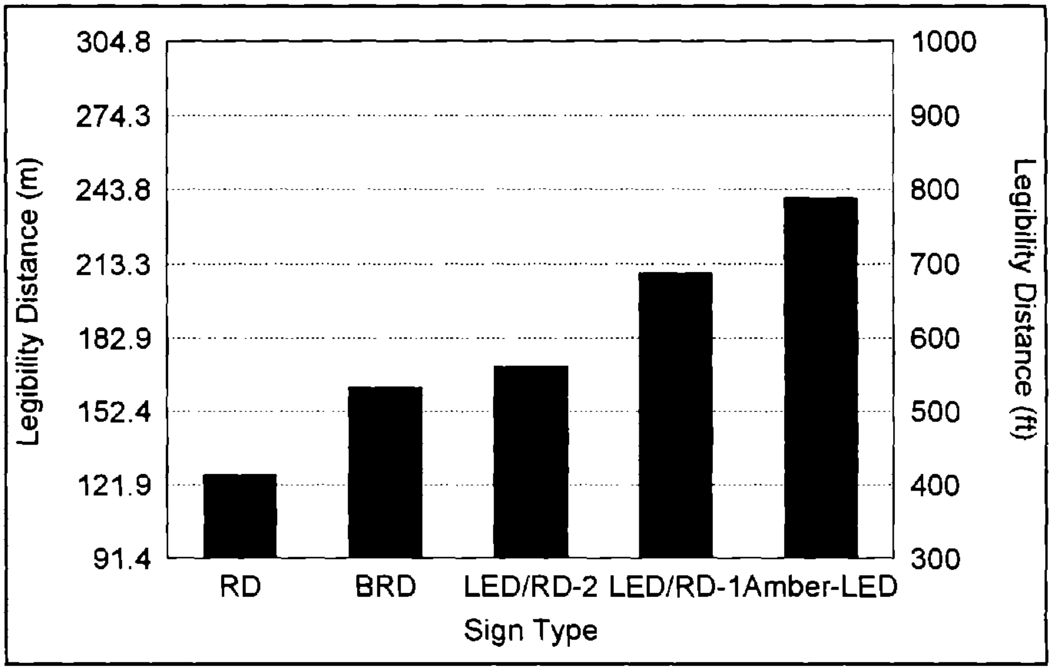


Figure 55. Mean nighttime legibility distances.

Nighttime Detection. Overall detection-distance performance was analyzed using RD, LED/RD-1, amber-LED, and LED/RD-2. Data on BRD were insufficient to allow its inclusion in this analysis. The data from amber-LED and LED/RD-2 were analyzed as described in the daytime legibility section. Again, the data from RD and LED/RD-1 were included in their original form. A within-subject ANOVA on age group and sign indicated a main effect of both variables. Further analysis of the sign effect was accomplished with paired-sample T-tests, again at the $p<0.01$ level. A comparison of RD and LED/RD-1 did not reveal a statistical difference in detection distances, nor did a comparison between amber-LED and LED/RD-2. The former two were found to have lower detection distances than the Amber LED (figure 56).

Daytime Percentile Analysis. Differences between levels of variables in terms of mean scores were described in previous sections. While this is a very useful way to determine the effectiveness of a given variable, no measure of central tendency adequately describes how a population of observers with specific characteristics will perform as a whole. To this end, we have plotted percentile legibility data for RD for the three age groups and the pooled data from amber-LED for young and old-old age groups (figure 57 [a] and [b]). The old group was omitted from this analysis as only five subjects participated at the two highest luminance levels.

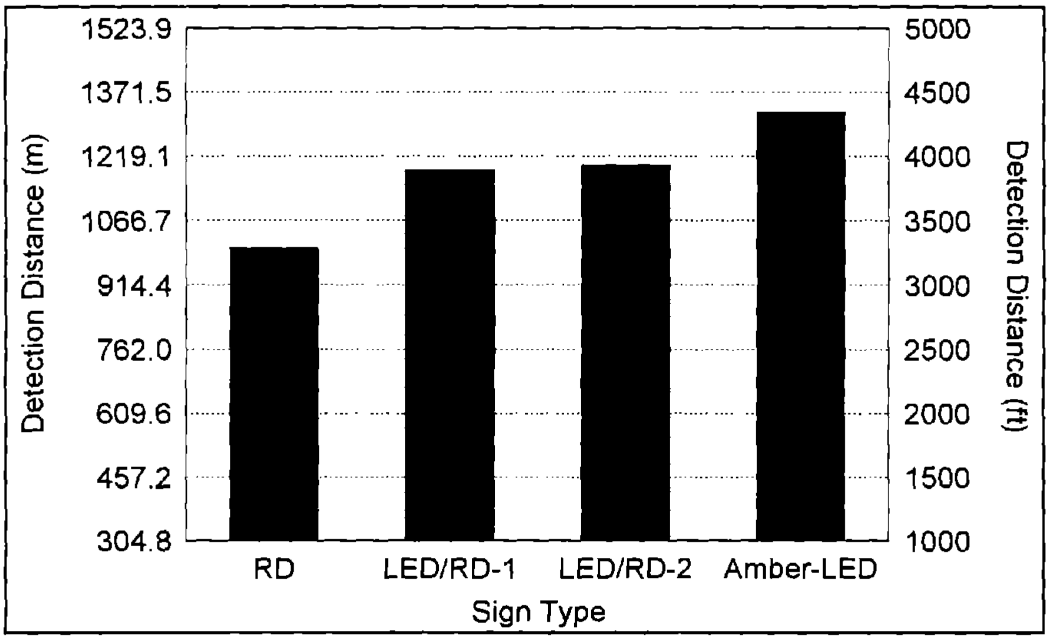


Figure 56. Mean nighttime detection distances for four signs.

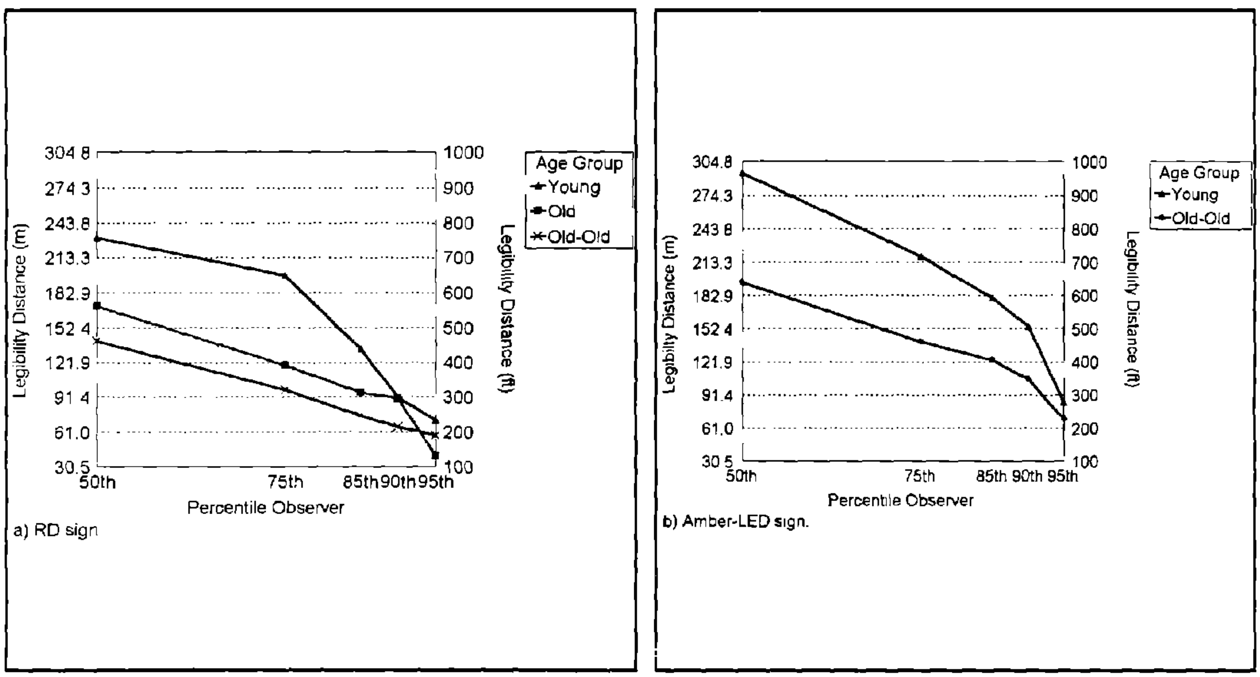


Figure 57. Daytime legibility thresholds for three age groups and various percentile drivers.

Selection of these two signs was based on performance; amber-LED produced the best overall performance and RD produced the worst performance. The number of subjects in the detection cells was too small to plot the data by age group. Although there was an age-group-by-sign interaction, the ranking of the signs was the same for the three age groups. Detection percentiles were, therefore, collapsed across age groups and are plotted in figure 58. This probably affords a conservative estimate, because the young group only comprises 15 of the 35 subjects in this analysis.

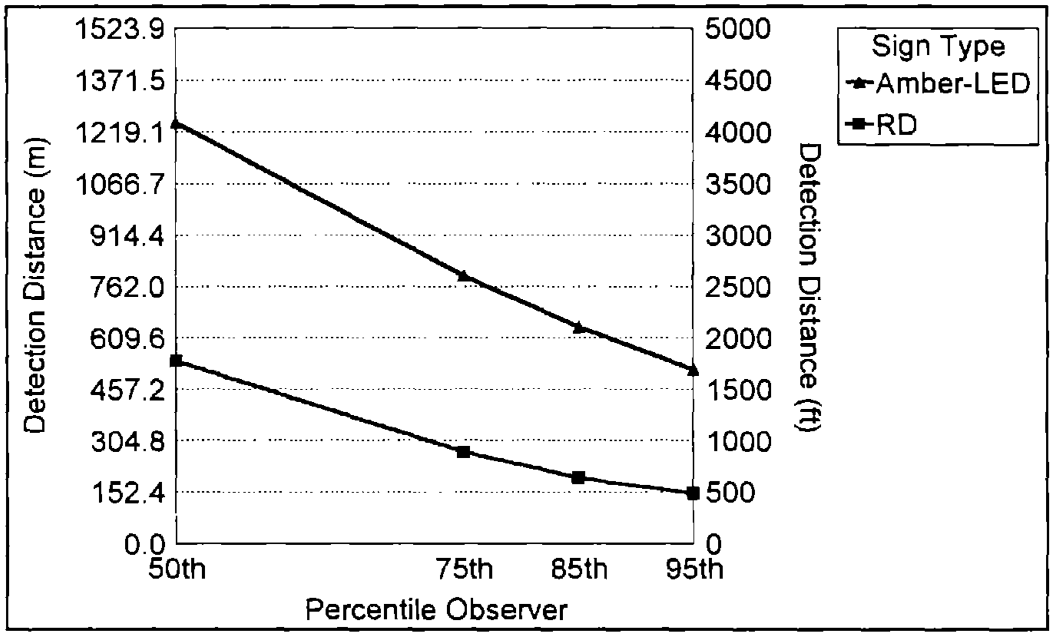


Figure 58. Daytime detection thresholds for various percentile drivers.

Figure 57 (a) and (b) show that 50th percentile observers in all age groups reached legibility distance threshold near the 198-m (650-ft) distance suggested by the literature review even for the worst sign tested. However, if the design driver is the 85th percentile old observer, even the best performing sign tested here would provide only 122 m (400 ft) of legibility distance. Even if 85 percent of young drivers were to be accommodated on signs like RD, legibility distances in the 122-m (400-ft) range also should be expected. Finally, figure 57 (a) and (b) show that 15 to 25 percent of the old-old observers had to be within 91.4 m (300 ft) of either of these signs to reach legibility threshold.

Figure 58 clearly demonstrates the discrepancy in detection distance performance on RD and amber-LED. The 85th percentile observer was only able to detect RD at about 183 m (600 ft) compared to 640 m (2100 ft) for amber-LED. From the 50th to the 95th percentiles, amber-LED was shown to substantially outperform RD.

Nighttime Percentile Analysis. For the same reasons listed in the daytime percentile analysis, RD and amber-LED are the focus of this section. Again, legibility distance percentiles were plotted separately for each age group (figure 59 [a] and [b]), and detection percentiles for RD and amber-LED were plotted on the same figure with the data collapsed across age groups (figure 60).

The poor legibility of RD was exacerbated at night. Even 50th percentile young observers barely exceeded 152-m (500-ft) thresholds; the 85th percentile old observers read the sign at about 46 m (150 ft). The better performing amber-LED provided the 50th percentile observers in all age groups with adequate legibility distances. Even the 85th percentile old observers were able to read this sign at 152 m (500 ft).

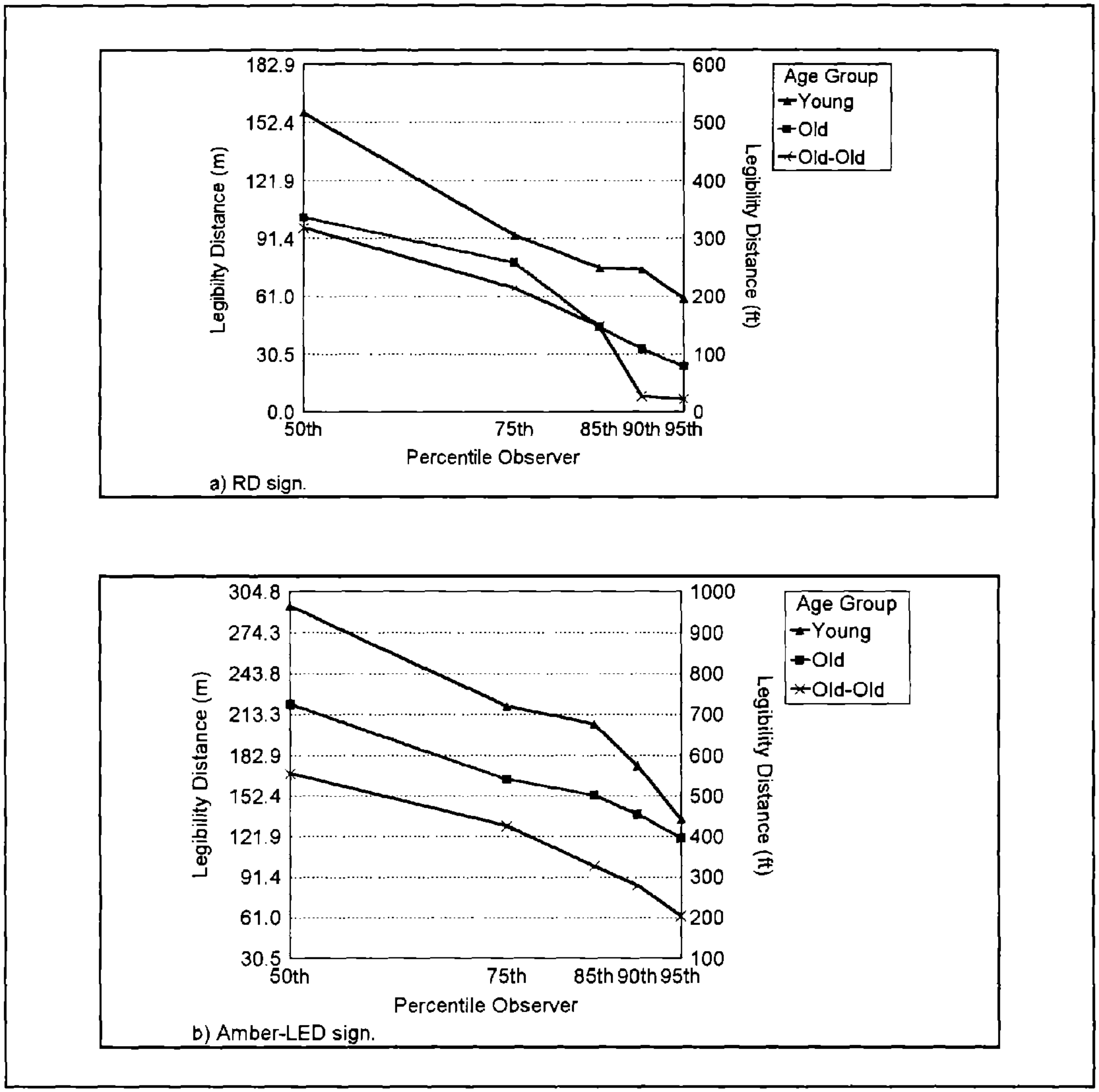


Figure 59. Nighttime legibility thresholds for three age groups and various percentile drivers.

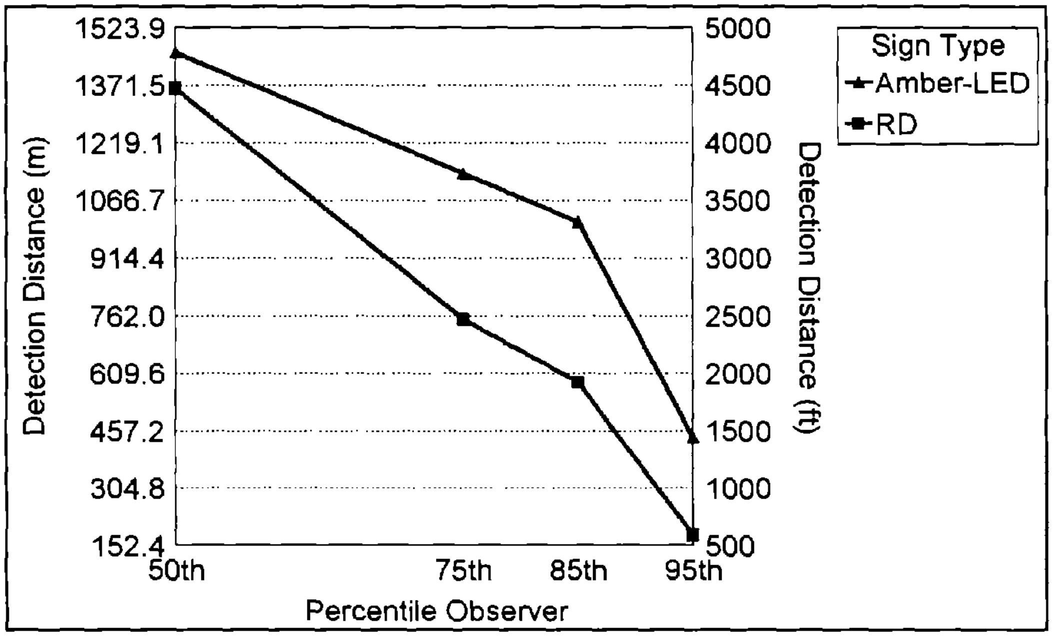


Figure 60. Nighttime detection thresholds for various percentile drivers.

The differences between the nighttime detection distances for RD and amber-LED are not as extreme as found in the daytime analysis. Figure 60 points out the problem with assessing performance based solely on a measure of central tendency. The performance of the 50th percentile observers is fairly close, around 1370 to 1430 m (4500 to 4700 ft). When the 75th and higher percentile observers are considered, it becomes readily apparent that amber-LED provided a great deal more detection distance.

Discussion

The large between-subject variability in performance, found even within age groups, resulted in statistically significant findings only with very large threshold differences between levels of a variable. Differences in legibility distances smaller than 30.5 m (100 ft) and detection distances smaller than 122 m (400 ft) seldom resulted in statistical significance. While this avoided the problem of statistical significance without practical importance, it may have masked the practical effects of some variables. For example, in 1 s a vehicle travels 25 m at 89 km/h (81 ft at 55 mi/h). Differences in legibility distances produced by this travel time would be outside the sensitivity of our analyses. A larger sample size would have decreased the differences in means necessary to reach statistical significance. An "at a glance" review of the dynamic study's findings may be found in table 37.

Ineffective Variables. Daytime ambient lighting condition was not found to have a strong or consistent effect on either legibility or detection distance (figure 48). The weather conditions did not facilitate a very powerful analysis of the variable. Only 25 of the 81 daytime sessions were conducted under sunny skies. By chance, mostly old observers were tested on these days. Therefore, the young group had to be omitted from the analysis.

Contrast orientation had no effect on daytime legibility or detection. In daylight, all of our subjects were able to find and read positive-contrast Y/B messages at as great a distance as the negative-contrast B/Y messages.

Character luminance had no consistent effect on nighttime legibility or detection (figure 51). This finding is not surprising given the fairly high level of 30 cd/m^2 for the lowest setting. The static field study found clear legibility to occur at 10 cd/m^2, even for old observers. An irradiation effect may have been expected at the 1200-cd/m^2 condition, but the results do not indicate a decrease in legibility performance with the higher levels.

Inter-letter spacing had no effect on legibility distance. This finding is contrary to the literature review, but is consistent with our computer simulations and static field studies that showed the need for even larger increases in inter-letter spacing to elicit improved performance.

Two tests of nighttime sign lighting were conducted in the dynamic study. Whether BRD was backlit or headlamp illuminated had no effect on legibility distance. The results of this test provide evidence that BRD's backup lighting (headlamps) is no less effective than its primary internal fluorescent lighting. No data on detection distance were collected.

Effective Variables. Age group was found to significantly affect legibility distance under all variables tested. In those instances where detection distance was analyzed between age groups, a consistent, significant age group effect was found. This effect was almost exclusively a young effect; that is, with the sole exception of nighttime detection for the sign variable, no significant difference was found between the two old groups. The only significant interactions between age group and any other variable occurred in the overall sign analyses for daytime detection. The detection analysis revealed that there was no difference in detection distance between RD, LED/RD-1, and LED/RD-2 for the old and old-old groups, whereas the performance for the young group was significantly influenced by these signs (figure 53).

Contrast orientation had a significant effect at night. The positive-contrast messages were read at a greater distance than their negative-contrast counterparts. This supports our hypothesis regarding increased irradiation with negative-contrast messages at night.

Character height had a large and significant effect on daytime and nighttime legibility distances and daytime detection distance. The messages with larger letters were found and read at a much greater distance than the messages with smaller characters. The increase in threshold distances, however, was less than proportional to the increase in character height.

Character luminance had a significant effect on daytime legibility. A significant increase occurred with each luminance step until the last, at 1200 cd/m^2, which performed as well as the 850-cd/m^2 level. These findings are consistent with the static field study that found legibility thresholds ranging from 50 cd/m^2 for 50th percentile young observers to almost 400 cd/m^2 for 85th percentile old observers.

Of special interest is the comparison between RD and LED/RD-2. These signs are identical with the single exception of nighttime lighting. At night, RD used ultraviolet lamps to illuminate the message, while LED/RD-2 had LED bundles placed behind the elements for this purpose. As expected, daytime legibility and detection performances were not significantly different. At night, LED/RD-2 had significantly greater legibility distance, but not detection. This is consistent with the reduced contrast produced by floodlighting a sign.

Which of the CMS's performed the best? This question needs to be qualified. Table 28 provides a description of the various signs with regard to the most important visibility characteristics. When we report that amber-LED had the best overall performance, it should be noted that this sign used 53-cm (21-in) characters compared to the 46-cm (18-in) characters used in all of the other signs. Also, when we say that overall, RD produced the poorest performance, it must be noted that this sign had the smallest width-to-height and stroke-width-to-height ratios of all the signs tested. Furthermore, some signs tested had a larger overall area than others, and some were more expensive than others. Perhaps it would be useful to establish several LI's that address these issues. For example, a legibility distance per unit area or per dollar could be derived. It is clear that additional research into the cost-effectiveness tradeoffs of improved CMS legibility is needed. Additional research and further analysis of existing data is also needed to determine the relative effects of the individual character and message variables on CMS visibility.

Table 37. Summary of dynamic field study: results and conclusions.

Independent Variables and Signs Tested	Results
Age Group: Young (19-40), Old (59-72), Old-Old (73-82)	Significant effects of age group in all analyses. Mostly the young group had the largest thresholds and the old and old-old groups did not differ. Very few interactions between age groups and other variables.
Daytime Ambient Lighting Condition: Frontlit, Backlit, Overhead, Rain; Signs: RD, LED/RD-1, and Amber-LED	Minimal effect of lighting condition on either legibility or detection distance. Only the old and old-old groups were analyzed.
Contrast Orientation: Positive (Yellow on Black), Negative (Black on Yellow); Sign: BRD	No daytime effect on either legibility or detection. 29% improvement in legibility distance with positive-contrast messages at night.
Character Height: 46 cm (18 in), 107 cm (42 in); Sign: BRD	Significantly longer legibility and detection distances in daytime for the 107-cm over the 46-cm letters. Significantly longer legibility distances in the nighttime portion. However, the improvement was less than proportional to the letter height increase.
Character Luminance: Day range: 350-1200 cd/m^2, Night range: 25-1200 cd/m^2; Signs: Amber-LED and LED/RD-2	Significantly longer daytime legibility with increases in luminance up to 850 cd/m^2; no effect on daytime detection. No consistent effect on nighttime legibility from 30 to 1200 cd/m^2; no effect on nighttime detection.
Inter-Letter Spacing: Single-Stroke Width, Double-Stroke Width; Sign: Red-LED	No difference in legibility distance between single-stroke and double-stroke spacing (nighttime-tested only).
Sign Lighting: Backlit vs. Headlights; Sign: BRD; Blacklight vs. LED; Signs: RD vs. LED/RD-2	No difference in legibility distance between internally lighted and externally lighted with headlamps (nighttime-tested only). LED/RD-2 resulted in significantly greater nighttime legibility distance than black-light-illuminated RD.
Overall Sign Performance: Signs: BRD, RD, LED/RD-1, Amber-LED, and LED/RD-2	Daytime legibility: (RD = LED/RD-2) < (BRD = LED/RD-1 = Amber-LED). Daytime detection: RD < (LED/RD-1 = LED/RD-2) < Amber-LED. Nighttime legibility: RD < (BRD = LED/RD-2) < LED/RD-1 < Amber-LED. Nighttime detection: (RD = LED/RD-1) < (Amber-LED = LED/RD-2).

APPENDIX A - DRAFT DESIGN GUIDELINES AND OPERATIONAL RECOMMENDATIONS FOR CMS VISIBILITY

OVERVIEW

The guidelines and operational recommendations for CMS visibility discussed below are the result of 2 years of intensive study. Initially, factors that most effect CMS visibility were found through a detailed critical review of the literature. Those variables that were determined to have the greatest impact on visibility were selected to undergo three levels of analysis. Level One consisted of a lab study using a computer simulation of CMS's. This stage assessed the effects of character width-to-height ratio, matrix density, font, color, contrast orientation, brightness, word length, inter-word spacing, inter-letter spacing, and inter-line spacing on the minimum letter size that observers could read. Level Two was a static field study where both a mock-up CMS, an actual CMS, and the observers were stationary. This second level of analysis measured the effects of time of day, sun position, character height, inter-letter spacing, font, and distance from the observer on minimum character brightness required for CMS legibility. The third level involved a dynamic field study using actual trailer-mounted CMS's on public roadways. Level Three assessed the influence of time of day, sun position, sign type, character brightness, contrast orientation, inter-letter spacing, and character height on the distance at which the signs could be found and read.

SCOPE

The term *CMS*, as used in this document, includes all matrix-type signs capable of variable message displays, and excludes any sign with a fixed message component such as rotating drums. The guidelines and recommendations contained in this document are applicable to any and all in-service or soon-to-be-available CMS hardware types, whether portable or permanently mounted. The capabilities of older and younger drivers are considered throughout. Several features of CMS's that may contribute to CMS visibility, however, are not included in this document. Message content issues, such as sequencing and use of symbols, were determined to be outside the scope of this report, as were treatments designed to improve conspicuity, which included the use of flashers, flashing messages, or borders. All original data reflected in these guidelines and recommendations were collected in a suburban/rural environment with low visual complexity. The applicability of the information contained in this document to urban, high visual demand situations has not been assessed.

Most attempts to improve the visibility of CMS's result in either greater initial expense, typically in the form of a larger sign, or increased maintenance costs. A formal cost-effectiveness analysis was outside the scope of this research; however, these guidelines and recommendations were written with a sensitivity to these issues. All recommendations that would result in substantial improvements in visibility distance are included. Those recommendations that appear to have a potential cost/benefit interaction are followed by some discussion of the implications.

AUDIENCE

This report is intended to provide enough specific detail to be useful to both CMS manufacturers in the design of signs, and to State and Federal transportation departments in their development of CMS visibility specifications and standards.

DESIGN GUIDELINES AND OPERATIONAL RECOMMENDATIONS

Character Components

The parts of a CMS that affect its visibility fall into two major classes: character components and message components. Character components can, in turn, be divided into element or "pixel" variables and character variables. A CMS element is the smallest individually addressable unit that can be used to create a character (figure 61). For example, the elements in a flip disc are the fluorescent discs, and the elements of a LED CMS are the bundles or groups of LED's. The character variables, while not structurally independent of the element variables, represent what the driver sees, for example, the character font.

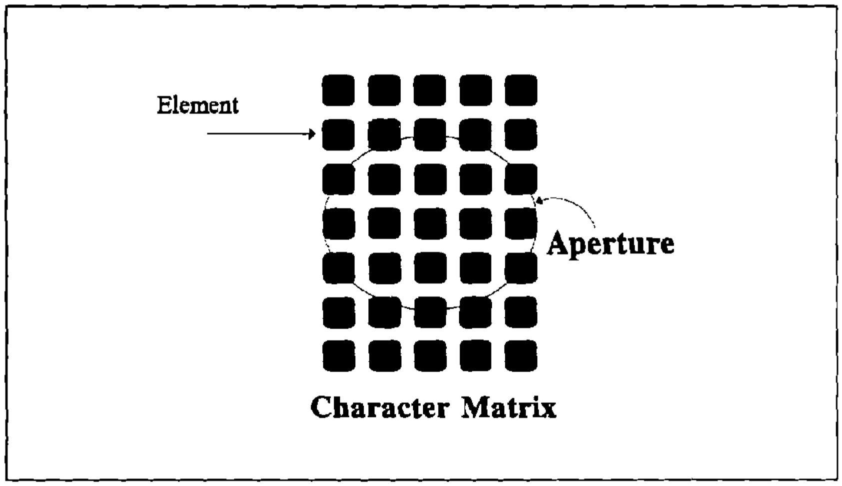


Figure 61. CMS character matrix and photometric aperture.

Element Variables

The design of the element variables, including size, shape, spacing, and luminance, can be flexible as long as the variables discussed under the *Character Variables* section below are within the recommended ranges. The color of the elements do not affect the legibility of CMS's if appropriate luminance levels and luminance contrast are maintained. However, color may have an affect on the detection of a CMS. Colors that are seldom used on the highway, such as the cobalt blue produced by ultraviolet (UV) flip-disc lamps, and the deep red that characterizes some LED's, may have greater target value because of their uniqueness. This uniqueness may eventually dissipate as drivers become accustomed to seeing a variety of CMS's. In addition, the novelty of these UV-lighted and LED signs may also prevent their recognition as traffic control devices.

Character Variables

Contrast. CMS contrast reduction is typically caused by glare reflecting off of the sign face (called veiling luminance) or insufficient brightness of the active elements. Veiling luminance is the result of sun angle or the sign's own lighting system. An appropriate black matte finish applied to the background portion of a CMS helps; however, the main reason for the loss of contrast is the reflection of light off the plexiglass sheeting used to protect the sign face. CMS's with new protective sheeting typically produce appropriate contrast levels; problems occur mainly when the sheeting is allowed to become dirty or scratched. Regular cleaning, and replacement when surfaces become excessively scratched, is highly recommended. Usually the protective sheeting can be cleaned with a mild non-abrasive detergent, warm water, and a soft cloth; however, the manufacturer's recommendations should be consulted.

The formula for determining the luminance contrast of a CMS is:

$$\frac{L_t - L_b}{L_b}$$

where:

L_t = luminance of a character module with all of the elements "on"
L_b = luminance of the character module with all elements "off"

The photometric procedure for contrast measurement is discussed below under the section entitled *Luminance*. Field contrast measurements should be conducted under the following five lighting conditions: sun directly on the sign; sun directly behind the sign; sun overhead; overcast; and at night. If the contrast falls below 5 under *any* ambient lighting condition, immediate cleaning or replacement of the protective sheeting is recommended. If the contrast is still low after the recommended maintenance procedure, the manufacturer should be consulted for the appropriate action. It may be that resurfacing of the discs is needed for reflective technologies or that diodes, lamps, or FO's need to be replaced or repaired for light-emitting technologies.

Luminance. Maintaining character luminance is perhaps the most important factor in ensuring the legibility of CMS's. Character luminance is defined as the weighted average of lighted elements and the unlighted spaces between elements. To establish CMS character luminance, measurements must be made with the character module "on" and the character module "off."

To obtain these two measurements, the aperture of a photometer is centered on a character module (figure 61). All of the elements in that module are turned on and a measurement is taken; all of the elements are then turned off and a second reading is taken. The character luminance is the difference between the on and off readings. The off reading represents the amount of light reflected by the background, glare screen, and any stray light entering the photometer.

Subtracting the off reading will give the true character luminance. The off reading also provides the background luminance value to be used in the contrast calculation discussed above.

It is not necessary to conduct field measurements of the luminance of light-*emitting* signs during daylight hours, because the luminance of these signs is not affected by the amount of light hitting the sign or sun position. However, daylight measures of the modules in the off mode will still need to be taken for contrast calculations. Furthermore, luminance measurements of light-reflecting CMS's will need to be conducted during daylight hours, as these measurements *are* dependent on daylight conditions. In order to fully describe the photometric qualities of light-reflecting CMS's, it is recommended that luminance measurements be taken during daylight hours with the sun behind the sign, the sun overhead, the sun on the sign, overcast, and at night.

It is recommended that for field measurement of CMS's with 31-cm (12-in) character widths, a photometer with a 6-minutes-of-arc aperture at 169 m (550 ft) for overhead signs, and a 20-minutes-of-arc aperture at 46 m (150 ft) for trailer-mounted CMS's be used. These distances and aperture settings will minimize the reduction in luminance found with some light-emitting CMS's at large measurement angles.

Recommended Levels. Two of the most important factors affecting appropriate levels of CMS luminance are driver age and the position of the sun in relation to the sign. If the sun is behind and above the CMS, the minimum luminance level should be 1000 cd/m^2. If the sun is shining directly on a sign with a clean, scratch-free protective sheeting, luminance levels should again be at least 1000 cd/m^2. These two conditions are known respectively as backlit and washout. Backlighting and washout present tremendous problems for CMS visibility, particularly with the older driver. When the sun is *directly* behind a CMS, there are no reasonable luminance levels that will enable the sign to be read by even a small percentage of observers. If the protective sheeting is scratched or dirty, washout conditions also cannot be overcome by increasing sign luminance.

On clear days with the sun overhead, the minimum luminance level should be above 850 cd/m^2. Under rainy or very overcast daytime conditions, CMS luminance levels should be between 350 and 600 cd/m^2. At night, CMS luminance levels should be between 30 and 150 cd/m^2. Table 38 provides a breakdown of recommended minimum luminance levels under various lighting conditions for older and younger drivers.

Table 38. Recommended minimum luminance values (cd/m^2) for CMS visibility.*

	Sun Behind Sign	Sun on Sign	Sun Overhead	Overcast/Rain	Nighttime
Young (16-40)	1000	1000	850	350	30
Old (65+)	1000**	1000**	1000	600	30

* 85th percentile driver accommodated at 198 m (650 ft).
**Will accommodate less than 50 percent of drivers at 198 m at any luminance level with extreme sun angles.

It is possible to change the luminance of light-emitting CMS's. All currently marketed light-emitting CMS's have a range of luminances that can be either manually or automatically manipulated. Although most light-emitting CMS's are capable of the range of luminances recommended here, particularly when new, periodic field measurement using the techniques outlined above should be conducted to ensure continued optimal performance.

In daytime, light-reflecting CMS's are illuminated by the sun and are therefore dependent on the very factors that they need to overcome (i.e., sun position and ambient brightness). The only way to enhance the luminance of these signs is to increase the amount of light hitting the sign face. Except when the sun is behind the sign, however, new light-reflecting signs, or those recently cleaned and with new reflective elements, are capable of supplying the recommended values of character luminance. Although, when the elements begin to fade, neither the minimum luminances for the overcast/rain nor the washout conditions can be met.

Contrast Orientation. Contrast orientation should always be positive, that is, with luminous characters on a dark or less luminous background. Legibility distance for negative-contrast CMS's is likely to be at least 25 percent shorter than that of positive-contrast messages. Furthermore, the increased light emitted by negative-contrast CMS's has not been shown to improve detection distances. Therefore, CMS designs that only allow for a background lighter than the text should be avoided.

Font and Matrix Form. A font similar to the one shown in figure 62 is recommended. This font type was derived from several fonts currently found on in-use CMS's. However, any reasonable set of alphanumerics that provide clean lines similar to Standard Highway fonts will likely produce equivalent legibility. Improving the "resolution" of CMS characters by increasing the number of elements in a character matrix from the nominal 35 found with a 5x7 character matrix has neither a negative nor a positive effect on legibility distance of uppercase letters.

So-called "double" fonts, which attempt to provide double-stroke widths within a 5x7 matrix, should be strictly avoided (figure 63). These double fonts yield legibility distances approximately 25 percent shorter than regular fonts.

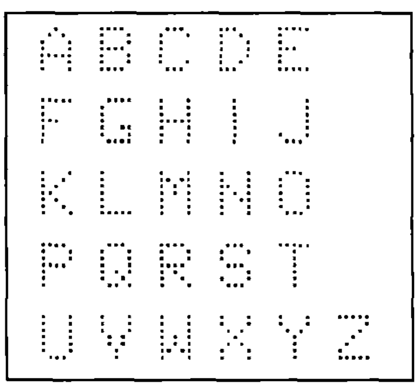


Figure 62. Recommended CMS font.

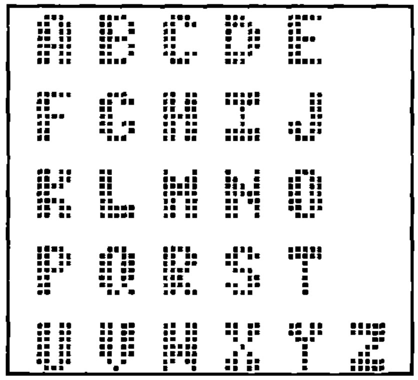


Figure 63. 5x7 double-stroke font.

Letter Height. Minimum letter height should be 457 mm (18 in) for CMS's on roadways with 89-km/h (55-mi/h) or greater speed limits. Properly illuminated 305-mm (12-in) letters would be acceptable for most younger drivers under these conditions; however, this size would fail to accommodate the majority of drivers over 60 years of age. Based on 198 m (650 ft) of legibility distance for 457-mm signs on an 89-km/h road, 305-mm letters could be used effectively on 56-km/h (35-mi/h) or slower roadways as these traffic speeds increase the message-reading time available to the driver.

Increases in letter height over 457 mm will not result in proportional increases in legibility distance. For example, observers should not be expected to read 914-mm (36-in) letters twice as far away as 457-mm letters. The operational recommendation is to increase the letter height by 1.5 times the proportional height. If, for example, you wanted the observers to read the signs at twice the distance that your 457-mm letters produced, you must increase the letter height to 1143 mm (45 in); if you wanted to increase the distance by half, use 813-mm (32-in) letter heights.

Width-to-Height Ratio. It is recommended that a width-to-height ratio (W:H) of at least 0.7 be used. This letter width, in combination with recommended levels of the other character variables, will provide adequate legibility distances for a substantial portion of the driving population. Widening the character W:H from 0.7 to 1.0 can increase legibility distance by as much as 10 to 15 percent; however, this will result in a 14-cm (5.4-in) increase in letter width using 457-mm-high letters and will add more than 1 m (3.5 ft) to the width of an eight-character CMS.

Stroke-Width-to-Height Ratio. The stroke width of RD CMS's is the width of a single element, or disc. The use of light-emitting elements makes it difficult to determine a character's stroke width. The luminous intensity of the element, time of day, amount of moisture in the air, and even observer characteristics such as age and visual acuity affect the perceived stroke width. The high contrast typically found with CMS's, particularly at night, creates halation or irradiation, blurring letters with wide stroke widths. Increasing the stroke-width ratio from 0.13 to 0.2 could reduce legibility distance by as much as 10 percent. Therefore, it is recommended that the stroke-width-to-height ratio be no greater than 0.13.

Message Components

Inter-Letter Spacing

Proportional Spacing. If a CMS has the capability of generating proportional spacing, it is recommended that three times the Standard Alphabet spacing for Series E letters be used. Proportional inter-letter spacing makes optimal use of the size of the sign, without loss of legibility, by using the shape of the letters to determine the spacing. For example, two letters with adjacent vertical contours, such as an O and a U, require a larger inter-letter spacing than does an LY combination. The reason for tripling the Standard Alphabet spacing is that CMS's, particularly at night, are very high-contrast, luminous signs with characters that blur together more readily than do those on standard signs. Even so, the largest spacings (e.g., BU) required when using this recommendation would be about 4/7 the letter height, or four elements on a 5x7 sign. The majority of the spacings would be equivalent to three elements (e.g., BC), and the rest of the spacings would be either two elements (e.g., CV) or one element (e.g., AY).

Fixed Spacing. An inter-letter spacing of 1/2 the letter height is recommended for signs that do not have the capability of proportional spacing. Applying this recommendation can increase nighttime legibility distances by 30 percent over the distances obtained with spacings of either 1/7 or 2/7 the letter height (i.e., "single element" or "double element" spacing). This improvement in legibility, however, would come at the cost of an additional 1.14 m (3.75 ft) over single-element spacing and 0.69 m (2.25 ft) over double-element spacing on signs with eight, 457-mm-high characters.

Inter-Word Spacing

Recommended inter-word spacing is dependent on inter-letter spacing. If inter-letter spacing is either proportional or 1/2 the letter height, inter-word spacing equal to letter height is recommended. For inter-letter spacing 3/7 the letter height or less, inter-word spacing equal to 5/7 the letter height is recommended.

Inter-Line Spacing

It is recommended that CMS's using more than two lines of text have an inter-line spacing of 70 percent of letter height. CMS's that use two lines of text can use an inter-line spacing as small as 20 percent of letter height without any appreciable loss in legibility. The larger inter-line spacing recommended for signs with three or more lines of text greatly enhances the legibility of the center line(s).

Hardware Components

Nighttime Lighting of "Disc-Matrix" CMS's

There are several methods currently available for nighttime illumination of the elements on non-light-emitting CMS's. The two most common techniques use either UV ("black light") tubes or discrete lamps mounted below the CMS in the manner of overhead guide signs. Both of these practices have problems with contrast reduction (as both the elements and the background are lighted) and uneven light distribution. If UV lamps are used, it is recommended that the lamps be of a non-high-intensity variety and that the tubes be placed above and below each line to light the upper and lower portion of the letters. If discrete external lamps are used, it is emphasized that the protective sheeting *must* be kept clean and relatively scratch-free if the reasonable contrast levels are to be achieved. It is recommended that instead of using three or five high-intensity lamps, an array of lower intensity, wide-angle lamps be used in order to produce a more even distribution of light across the sign.

Element Type (E.g., Flip Disc, LED)

Adequate daytime CMS legibility can be obtained with quality, well-maintained models that use any of the currently available technologies. RD signs work particularly well when the sun is directly on the sign, but experience major problems with "backlit" conditions. FO, lamp matrix, and LED signs can, to some extent, overcome the problem of backlighting; however, they have much more difficulty with "washout" when the sun is directly on the sign face. Pure light-emitting (e.g., LED, FO, lamp) and hybrid (e.g., LED/RD and FO/RD) types are recommended over pure reflective signs on the basis of nighttime performance.

Light-emitting signs exhibit superior performance at night. One reason for the improved performance is that light-emitting signs are capable of a higher degree of control over sign luminance. The lighting techniques commonly used with reflective signs are not readily amenable to "dimming" without resulting in uneven light distribution across the sign face. Because each of the elements are separately illuminated, light-emitting signs are also able to maintain high-contrast levels between the characters and the background. As previously mentioned, light-reflecting signs typically employ an external light source that washes over the entire sign face, illuminating both the characters and the background, thereby reducing contrast.

Table 39. Summary of recommended character/message variables for CMS visibility.

Design Feature	Optimal	Acceptable
Color	Matching MUTCD color-coding specifications	Red, Amber/Yellow, White, Orange
Contrast	Lt-Lb/Lb>5 to 50	Lt-Lb/Lb=5
Contrast orientation	Light letters on a darker background	Light on black Light on colored
Font and matrix form	Alphanumerics that most closely approximate Standard Highway font	Any reasonable non-serif font using at least a 5x7 matrix or equivalent
Letter height	46 cm	30.5 cm if legibility < 122 m is acceptable
Width:height	W:H=0.8	W:H=0.6 to 1.0
Stroke width:height	SW:H=0.13	SW:H=0.1 to 0.18
Inter-letter spacing	Three times Standard Alphabet Series E or 1/2 the letter height	3/7 the letter height
Inter-word spacing	Equal to letter height	Equal to 5/7 the letter height
Inter-line spacing	70 percent of letter height	20 percent of letter height with two-line CMS

1 cm = 0.3937 in; 1 m = 3.281 ft

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