Minimum Retroreflectivity Levels for Blue and Brown Traffic Signs

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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 yard	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		
		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 degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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	35.314	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 degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°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 March 2003)

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LIST OF ABBREVIATIONS

BS2	BASIC Stamp 2
CARTS	Computerized Analysis of Retroreflective Traffic Sign
EMS	emergency medical services
ERGO	Exact Roadway Geometry Output
FHWA	Federal Highway Administration
HID	high-intensity discharge
LI	legibility index
MOSFETs	metal-oxide semiconductor field effect transistors
MR	maintained retroreflectivity
MUTCD	Manual on Uniform Traffic Control Devices
NPS	National Park Service
PWM	pulse-width modulation
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation

CHAPTER 1. INTRODUCTION

Research recommendations for minimum maintained retroreflectivity (MR) levels for traffic signs in the United States were recently updated.[1,2] Although the updates addressed several of the most recent issues, a few issues remain that need to be addressed so that minimum MR levels cover additional typical signing situations. For instance, MR levels are established for five different background colors of traffic signs: white, red, green, yellow, and orange; however, they do not cover signs with blue or brown backgrounds. Furthermore, current minimum MR levels were based on dark rural environments. It is not uncommon to view signs in environments with visual complexity. Therefore, research was needed to address how these issues could be integrated into the existing minimum MR levels. The research described in this report was designed to resolve these issues so that the minimum MR levels cover a broader array of typical signing scenarios.

PROJECT OVERVIEW

This study was designed to follow previous experimental protocols to determine MR levels and to supplement the current minimum MR levels with considerations for broadening their coverage to represent additional typical signing conditions.

Objectives

The objectives for the study are to:

1. Conduct field studies to determine minimum luminance requirements for white-on-blue and white-on-brown traffic signs under various surround complexities.
2. Using the minimum luminance requirements from the field studies, estimate the minimum MR levels at the standard measurement geometry of 0.2 ° observation angle and -4.0 ° entrance angle that would produce those luminance levels.
3. Develop recommendations for white-on-blue and white-on-brown signs that can be incorporated into the most recent set of proposed minimum MR levels.
4. Investigate the development of adjustment factors for surround complexity that can be applied to the current set of minimum MR levels.

Research Activities

- The research team reviewed past work on minimum retroreflectivity, headlamp glare, and the effect of ambient lighting. A summary of the review is given in chapter 2, and a summary of the technique used to convert the required luminance to minimum retroreflectivity levels is given in chapter 3.

- During August 2005, the researchers conducted a nighttime field study to determine the minimum luminance needed to read white-on-blue and white-on-brown signs. The research team designed a nighttime field evaluation that used the legibility of blue and brown signs to determine the minimum sign luminance needed for legibility (in the case of text legends) and recognition (in the case of symbol signs). The evaluation included the use of a glare source to simulate an oncoming vehicle and the use of roadway lighting. The signs were designed based on current *Manual on Uniform Traffic Control Devices* (MUTCD) guidelines. Chapter 4 describes the field evaluation and subsequent findings.

- Chapter 5 includes the recommendations for minimum retroreflectivity levels using techniques similar to those found in earlier research.[1,2] The recommendations include levels for white-on-blue signs and white-on-brown signs. This chapter also includes findings based on the investigations into conditions with visually complex surroundings.

Chapter 2

CHAPTER 2. BACKGROUND RESEARCH

MINIMUM RETOREFLECTIVITY

Carlson and Hawkins researched minimum retroreflectivity for overhead guide signs and street name signs.(1) They conducted a threshold legibility luminance study using older drivers (age 55 and older) to determine the minimum sign luminance necessary for legibility at distances associated with legibility indices (LI) of 2.4, 3.6, and 4.8 m/cm (20, 30, and 40 ft/inch) of letter height. The researchers also conducted an in-depth sensitivity analysis of the factors that affect retroreflectivity, including vehicle headlamps, vehicle speed, vehicle type, sign position, and sheeting type. The researchers created a mathematical model for calculating minimum sign retroreflectivity based on the results of the sensitivity analysis and using the luminance data from their field experiments. The recommendations included a final level of sensitivity derived from two different subsets based on the age of the research participants. All of the participants were age 55 years and above. In order to establish an age-based sensitivity, the researchers grouped the research participants in two subsets: all research participants and research participants age 65 and above. The analyses were derived from these subsets and followed a guiding principle requiring 85th percentile accommodation within each age group. These age groups are identified by luminance level in the following tables because of their strong tie to luminance. Carlson and Hawkins' initial recommendations of minimum retroreflectivity are shown in table 1 and table 2.

Table 1. Initial MR values for legends of overhead guide signs.

Position	Speed	Luminance Level	ASTM Sheeting Type					
			I	II	III	VII	VIII	IX
Overhead	Any	55			290	290	250	230
		65				400	350	320

- Retroreflectivity (cd/lx/m^2) measured at observation angle = 0.2 ° and entrance angle = -4.0 °.
- Blank cells indicate that new sheeting will not provide sufficient levels of supply luminance to meet the demand luminance levels.
- ASTM = American Society for Testing and Materials.

Table 2. Initial MR values for legends of street-name signs.

Position	Speed	Luminance Level	ASTM Sheeting Type					
			I	II	III	VII	VIII	IX
Ground	> 40	55		140	145	180	140	70
		65			255	315	245	120
	30–40	55			240	290	285	80
		65		170	210	255	250	70
	≤ 25	55				710	660	135
		65						240
Overhead	Any	55			265	290	225	195
		65				510	400	340

- Retroreflectivity (cd/lx/m^2) measured at observation angle = 0.2 ° and entrance angle = -4.0 °.
- Blank cells indicate that new sheeting will not provide sufficient levels of supply luminance to meet the demand luminance levels.

In conjunction with additional research activities, the research team hosted four national workshops to solicit comments from public agencies regarding the implementation of minimum in-service retroreflectivity guidelines for traffic signs. The current research recommendations regarding the MR levels were presented and discussed at each workshop. The results of the workshops were used to develop the final minimum retroreflectivity recommendations (table 3).

Table 3. Recommended MR levels for overhead guide signs and street-name signs.

Sign Color	Position	ASTM Sheeting Type (ASTM D4956-01a)					
		I	II	III	VII	VIII	IX
White-on-green guide signs	Overhead	*/7	*/15	*/25	250/25		
	Shoulder	*/7	120/15				

Note: The levels in the cells represent legend retroreflectivity/background retroreflectivity (for positive-contrast signs). Units are cd/lx/m^2 measured at an observation angle of 0.2 ° and an entrance angle of -4.0 °.
* Sheeting type should not be used.

In addition to researching and developing MR levels for overhead guide signs and street-name signs, Carlson and Hawkins updated the existing published MR values for other types of traffic signs, including white-on-red, black-on-orange, black-on-yellow, and black-on-white signs.(2) Initial values were determined for each particular sign type (warning signs, symbol signs, regulatory signs, etc.) and then consolidated into one table. The results of the consolidation are shown in table 4.

Table 4. Updated MR levels for traffic signs.

Sign Color	Criteria	ASTM Sheeting Type (ASTM D4956-01a)					
		I	II	III	VII	VIII	IX
White on red	See note 1	35/7					
Black on orange or yellow	See note 2	*/*	50				
	See note 3	*/*	75				
Black on white							
White on green	Overhead	*/7	*/15	*/25	250/25		
	Shoulder	*/7	120/15				

Levels in cells represent legend retroreflectivity/background retroreflectivity (for positive contrast signs). Units are cd/lx/m^2 measured at an observation angle of 0.2 ° and an entrance angle of -4.0 °.
1. Minimum Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity).
2. For all bold symbol signs and text signs measuring 1,200 mm (48 inches) or more.
3. For all fine symbol signs and text signs measuring less than 1,200 mm (48 inches).
* Sheeting type should not be used.

GLARE

Roadway glare comes from a variety of sources such as street lighting and oncoming vehicle headlamps. Similarly, off-roadway glare can also be present and comes from sources such as sports fields, service stations, etc. There are also two types of glare: disability glare and discomfort glare. Disability glare is a reduction in visibility caused by scattered light in the eye. In other words, the luminance contrast of the visual scene (i.e., what the driver is viewing) is reduced. Discomfort glare is the sensations caused by a glare source in the field of view.(3) These phenomena often, but do not always, occur simultaneously.

The disability effect of a glare source can be determined by calculating veiling luminance, as shown in figure 1 below.

$$L_v = \sum_{i=1}^{n} \frac{9.5E_i}{\theta^2 + 1.5\theta}$$

Figure 1. Equation. L_v (veiling luminance).

Where:

L_v = veiling luminance (cd/m^2),
E_i = glare illuminance at the driver's eye (lux), and
θ = angle between line of sight and the glare source (degrees).

When multiple glare sources exist, veiling luminance is calculated for each glare source present (i.e., streetlights, headlamps) and summed. In the case of the roadway scene, the veiling luminance equation becomes the following (figure 2).

$$L_v = L_{v,streetlight} + L_{v,headlamp}$$

Figure 2. Equation. L_v (veiling luminance) for multiple glare sources.

McColgan et al. created veiling luminance profiles in a study of disability glare through computer simulation, derived using streetlights and vehicle headlamps as glare sources, singly and in combination.(3) Veiling luminance from an oncoming vehicle was modeled using tungsten halogen headlamps and high-intensity discharge (HID) headlamps. Streetlight veiling luminance was calculated from the manufacturer-supplied photometric profiles and from data supplied by an independent laboratory. The curves for the streetlights were divided into three groups: low veiling luminance, medium veiling luminance, and high veiling luminance. The peak values for these groups were below 0.3 cd/m^2, between 0.3 and 0.4 cd/m^2, and above 0.4 cd/m^2, respectively. Of the 23 fixtures tested, 19 exhibited low to medium veiling luminance with peak values between 0.2 and 0.4 cd/m^2. The researchers created combined profiles (headlamp and streetlight) and explored the effect of the location of the streetlight in relation to the glare source.

Veiling luminance profiles are shown in figure 3. The vehicle glare source is located at a starting point 100 m (328 ft) from the observer vehicle, and veiling luminance is modeled as the observer travels toward the glare source. The streetlight reference is modeled similarly, with the streetlight at the location of the glare source and the observer traveling toward the streetlight. The area under the curve is termed glare exposure. The researchers found the highest veiling luminance results when the streetlight and glare source are in the same line of sight. The results show that veiling luminance is dependent on location of streetlights and the closing distance. An example combined profile is shown in figure 4.

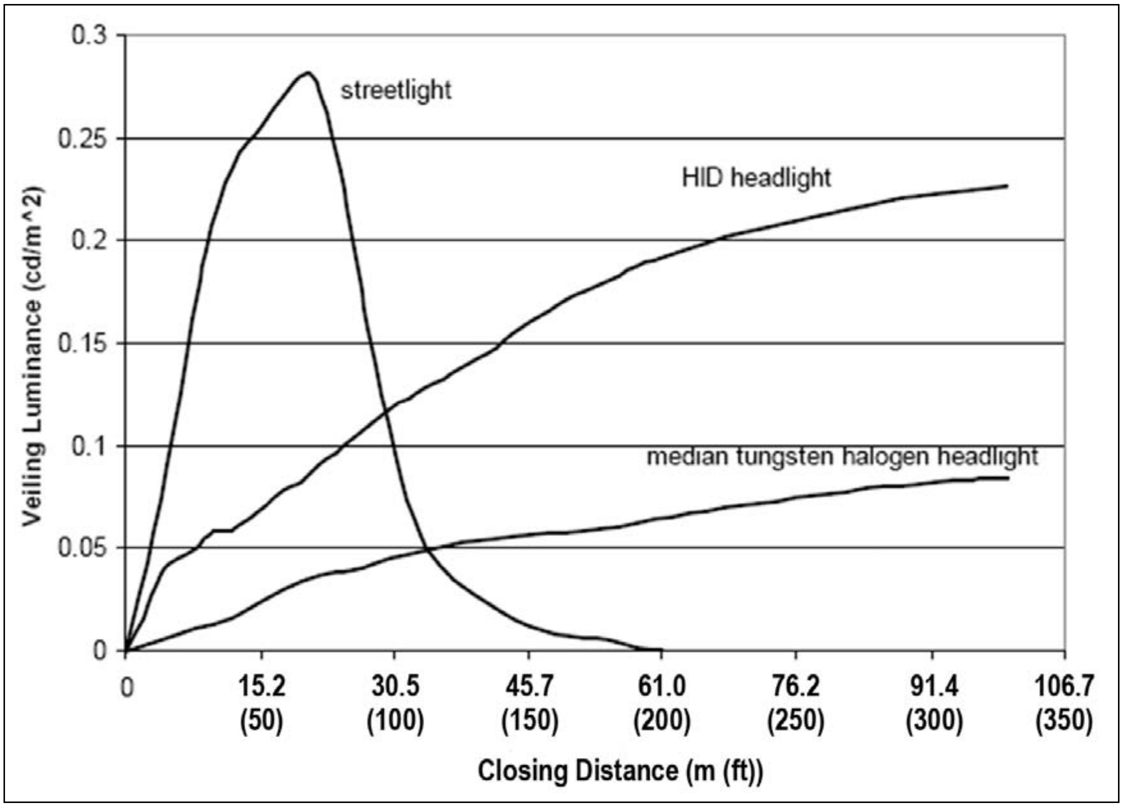


Figure 3. Line graph. Veiling luminance profiles.

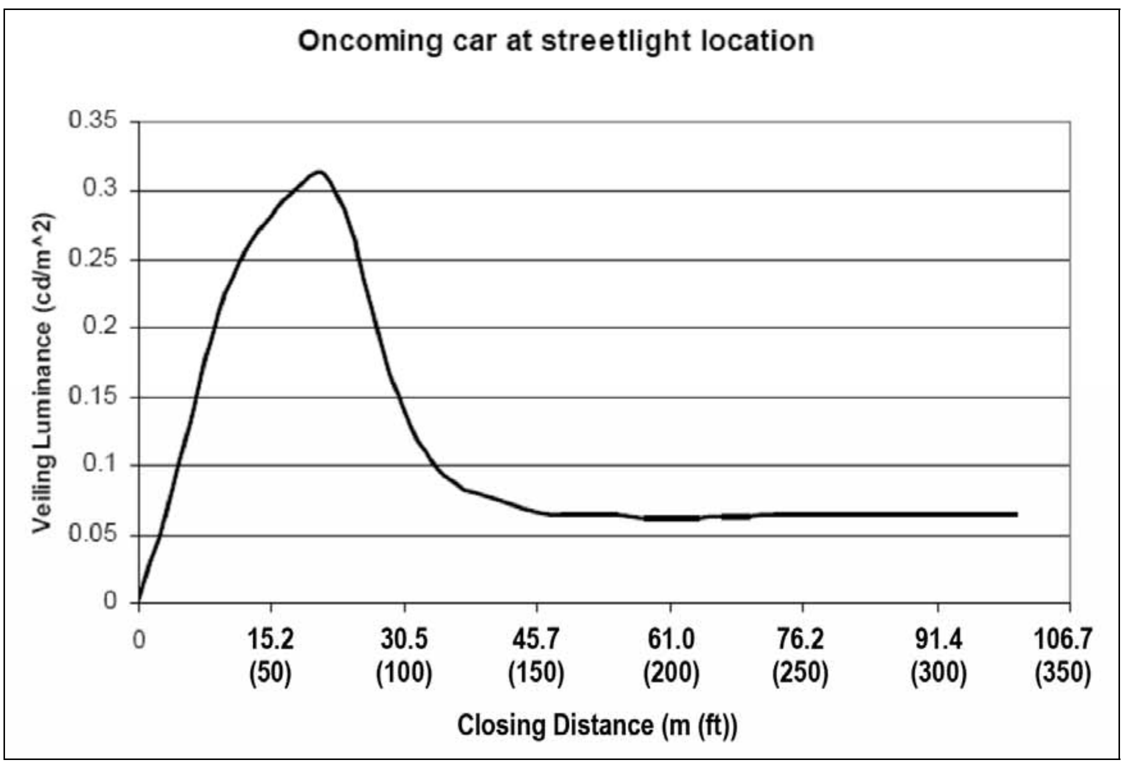


Figure 4. Line Graph. Combined veiling luminance profile.

As recently as 2004, Van Derlofsky et al. discussed glare in relation to headlamp design and location.(4) The researchers reviewed a collection of research on the topic of glare to determine threshold values for discomfort and disability glare. The researchers also reported that under normal driving conditions, typical glare illuminance from oncoming headlamps ranges from 0 to 10 lx. A value of 0.1 lx at the eye is enough to cause driver discomfort, whereas an illuminance level between 1 and 3 lx is sufficient to cause drivers to flash their headlamps at the oncoming vehicle. A level of 3 to 10 lx is sufficient to cause unbearable discomfort.

In another headlamp glare study, Bullough et al. investigated the impact of glare illuminance, glare spectral power distribution, and glare source on peripheral detection of small targets in the field of view.(5) With respect to disability glare, detection of peripheral targets worsened as the glare illuminance increased from 0.2 to 5 lx, as expected. Detection of high-reflectance targets (located 60 m ahead) was relatively unaffected by glare except for targets very close to the glare source and targets farthest from the line of sight. Neither the spectral power distribution (halogen, HID, or blue-filtered halogen) nor glare size (from 9 to 77 cm^2 (1.4 to 12 $inches^2$) in area) affected peripheral detection.

With respect to discomfort glare, high illuminance levels elicited subjective ratings of greater discomfort and were the most important determinant of discomfort. Spectral power distribution also affected discomfort (even though it did not affect visual performance) with HID headlamps eliciting ratings of greater discomfort than the halogen or blue-filtered halogen headlamps. Similar to disability glare, glare source size had no impact on rating of discomfort glare.

A similar study looked at survey data to analyze how drivers perceive glare with respect to age and gender.(6) Statistics from contingency analyses were used to establish associations indicating that about 30 percent of the respondents felt that glare was “disturbing,” while just over 50 percent of the respondents felt that glare was “noticeable but acceptable.” The researchers reported that the group between age 35 and 44 had the highest percentage of night drivers. They also reported that this same age group had the highest percentage reporting “disturbing” glare. Interestingly, female respondents of this age group were more of the opinion that the glare from oncoming and following vehicle was “disturbing” compared with other age groups. It was also reported that about 10 percent of the nighttime drivers are over the age of 65 years. About 12 percent of the nighttime drivers are age 55 to 64 years.

SURROUND COMPLEXITY

An experiment was conducted in the Photometric and Visibility Laboratory at the Federal Highway Administration’s (FHWA) Turner-Fairbank Highway Research Center in McLean, VA.(7) The study was conducted to determine the adequacy of the 1993 MR levels in situations of varying visual complexity and environmental illumination (because the retroreflectivity values were developed for a dark environment with a medium-complexity background). Subjects were seated in a 1996 Ford Taurus inside the darkened laboratory and asked to determine if a traffic sign was present and to identify the sign from a nighttime driving scene projected onto a screen. Using projected photographs supplemented with scaled retroreflective signs illuminated at various levels to represent different luminance levels, subjects completed a target search and recognition operation on a set of 11 traffic signs presented at 4 different background complexities.

The slides were produced by photographing three different nighttime roadway scenes of varying visual complexity: high, medium, and low. The image of the high-complexity scene, taken in a metropolitan setting, combined visual stimuli from streetlights, traffic signals, neon signs, and parked cars along a four-lane, one-way street to create a complex visual environment.

A suburban setting provided the medium-complexity scene. A large, internally lit sign along the right side of the four-lane road comprised the majority of the visual distraction in the image. Illumination from shop windows and roadway lights was also present.

The low-complexity scene was generated from a two-lane rural highway. The only illumination in the image was a set of headlamps pointing in the direction of travel. Finally, a fourth image was produced as a control to determine the effect, if any, of the other three scenes. This slide was made by exposing the slide film with the lens cap in place to produce a black image. The slides were shown to the subjects at approximately 70 percent of their real-world luminance (accomplished through the use of a xenon lamp and the glass-beaded screen).

Statistical testing of the within-subject effects resulted in an F-statistic of (1.845, 22.041), which is statistically significant at the $p \leq 0.005$ level, meaning that the background scene had a significant effect on subject responses. It was reported that subjects experienced more difficulty recognizing the sign shown with the suburban (medium-complexity) and metropolitan (high-complexity) background than with the low-complexity or no-background scenes. The suburban and metropolitan scenes had a greater percentage of "no sign" responses than the rural and no-background scenes (6.4 percent and 5.9 percent compared to 0.4 percent and 0.1 percent, respectively). Overall, the suburban and metropolitan background scenes did not vary significantly, with full recognition responses of 75 percent and 73.8 percent, respectively. The rural and no-background conditions did not vary significantly either, with full recognition responses of 80.8 percent and 80.2 percent, respectively, but the two groups did vary significantly from one another. These results indicate that there are differences between driving conditions with high-visual-complexity surroundings and low-visual-complexity surroundings.

It was reported that the overall results of the study indicated that the 1993 MR guidelines were adequate, as more than 90 percent of the responses were correct at the luminance levels used to derive the MR levels. In addition, it was also reported that all four background scenes had correct response frequencies above the 85^{th} percentile criterion at the guideline luminance levels. However, the findings do demonstrate that the there may be significant differences between surroundings with high complexity (metropolitan and suburban settings) and low complexity (dark and rural settings). Therefore, the investigation into the differences among visual surroundings conducted as part of the research described hereafter appears to be necessary and well justified.

Chapter 3

CHAPTER 3. MAINTAINED REFLECTIVITY MODEL

MODEL DESCRIPTION

To develop MR recommendations for blue- and brown-background signs, the researchers used the Texas Transportation Institute (TTI) MR model. The TTI MR model is a computational model that considers the relationships between the headlamps (source), sign (target), and the geometric relationship between these and the driver (receptor). It combines ideas from other models such as Computerized Analysis of Retroreflective Traffic Sign (CARTS) and Exact Roadway Geometry Output (ERGO), with refinements to address shortcomings in the previously developed models. The elements (source, target, receptor, and vehicle) of the model were addressed in the following manner:

- **Headlamps:** External databases are used to accommodate different headlamp profiles, such as CARTS50 or those published by the University of Michigan Transportation Research Institute.

- **Sheeting:** The model includes external retroreflectivity matrices for all types of sheeting. The data were obtained from the ERGO model with the permission of the model developer. The researchers conducted goniometric evaluations (using the Texas Department of Transportation (TxDOT) goniometer) of several materials to confirm the accuracy of the ERGO data and found it to be accurate.

- **Driver:** The model does not incorporate any human factor elements for driver considerations beyond the minimum luminance needed to read a sign at a specific distance.

- **Vehicle:** External databases are used to allow various vehicle designs to be studied. The database includes information about the location of the headlamps and the driver's eyes.

Once the driving scenario is defined by the user in Cartesian coordinates, the TTI MR model makes transformations in order to take advantage of vector algebra. Once unit vectors are defined, the model determines the exact magnitude and direction of the vectors needed to fully define the three-dimensional retroreflective space. These calculations are made separately for each headlamp. Multipoint quadratic lookup features are then applied to the headlamp and retroreflectivity data files to obtain accurate values for the headlamp intensity and the retroreflective properties of the sign material. The luminance from each headlamp is then determined and totaled to arrive at the total luminance.

Up to this point, the TTI model performs similarly to ERGO. However, after ERGO outputs sign luminance, its usefulness in terms of establishing MR levels has ended. This is where the TTI model expands the current state of the art by being able to determine the retroreflectivity needed to provide a user-defined threshold luminance.

The concept used to determine MR is provided below (figure 5). The terminology introduced will be used throughout the remainder of this report.

$$\text{Minimum R}_{\text{A}} = \text{New R}_{\text{A,SG}} \times \left(\frac{\text{Demand R}_{\text{A,NSG}}}{\text{Supply R}_{\text{A,NSG}}} \right)$$

Figure 5. Equation. Minimum R_A.

Where:

Minimum R_A	=	MR at standard measurement geometry (α = 0.2 °, β = -4.0 °) needed to produce assumed threshold luminance, $cd/lx/m^2$,
New $R_{A,SG}$	=	Averaged retroreflectivity of new sheeting at standard geometry, $cd/lx/m^2$,
Demand $R_{A,NSG}$	=	Retroreflectivity needed to produce the minimum luminance at the nonstandard geometry (back-calculated and determined for each scenario), $cd/lx/m^2$, and
Supply $R_{A,NSG}$	=	Retroreflectivity of new sheeting at nonstandard geometry (determined for each scenario), $cd/lx/m^2$.

If Demand $R_{A,NSG}$ > New $R_{A,NSG}$, then the material cannot provide the threshold luminance for the given scenario. As shown below (figure 6), Demand $R_{A,NSG}$ is determined from the illuminance falling on the sign, the viewing geometry, and the assumed threshold luminance needed for legibility.

$$\text{Demand R}_{\text{A,NSG}} = \frac{\text{Demand Luminance} \times \cos(\nu)}{\text{illuminance}}$$

Figure 6. Equation. Demand $R_{A, NSG}$.

Supply $R_{A,NSG}$ is found through a lookup table for each type of material. Nu is the viewing angle for the sign, using the driver as the observation point. The lookup tables contain almost 200,000 retroreflectivity values, depending on the applications system's four angles that are used to fully describe the performance of the retroreflective sheeting.

A full description of the MR computational model, including limitations and assumptions, is provided elsewhere.(1)

Chapter 4

CHAPTER 4. FIELD EVALUATION

The objective of the field evaluation was to determine the minimum luminance needed to read blue and brown guide signs and identify blue and brown symbol signs. To obtain the minimum luminance value, an experiment was designed that involved nighttime viewing of blue, brown, and green guide signs and symbol signs. Essentially, drivers were positioned in a closed-course, real-world driving scenario and were asked to read different retroreflective signs. The luminance of the signs was controlled so that they were initially too dim to read, and then the brightness (i.e., luminance) was systematically increased until the words were read correctly. This chapter summarizes the experimental procedure and findings.

EXPERIMENTAL VARIABLES

Dependent Variables

The dependent variables in this study design were correct word legibility or symbol recognition, depending on the target sign. These measures of effectiveness were used to determine the minimum luminance needed for blue and brown retroreflective signs. Trials began at a low level of sign luminance, and the luminance was increased until the test subject correctly identified the test word or symbol.

Independent Sign Variables

There were five independent variables related to the signs being studied: sign luminance, targets, sign position, ambient lighting, and glare.

Sign Luminance

Seventeen different headlamp illumination levels were used to vary the luminance of the test words. The headlamp illumination levels produced sign luminance values ranging from near zero (i.e., too dim to read) to 45.7 cd/m^2 (actual maximum sign luminance levels vary as distance from the test signs vary).

Targets

The research was based on the legibility of words and the recognition of symbols. Each word was composed of six letters. These words were "everyday" or common words and were not associated with the name of a city or destination. In all, there were 36 unique words. The words were developed for and used in a previous TxDOT/TTI study where legibility distances of shoulder-mounted guide signs were determined for drivers of various ages. The words included seven groups of neutral words and five groups of words with at least one ascender or one descender. Table 5 lists the words used in the evaluation. The symbols selected for this study simulated Tourist-Oriented Direction signs and Recreational and Cultural Interest Area signs and were taken from the Standard Highway Signs manual (see figure 7). The symbols were scaled down in size in order to provide approximate equivalent viewing distances to the legibility signs for the same LI.

Table 5. Words used for legibility.

Banner	Farmer	Burner
Basket	Jacket	Gasket
Garden	Carbon	Gender
Houses	Honors	Horses
Nerves	Nurses	Voices
Oceans	Ounces	Canoes
Batter	Putter	Gutter
Series	Senior	Sensor
Raffle	Battle	Kettle
Person	Prison	Poison
Expect	Report	Expert
Cancer	Corner	Career

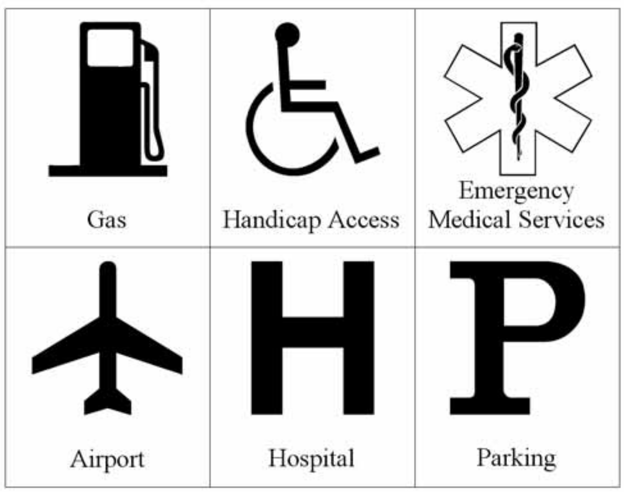
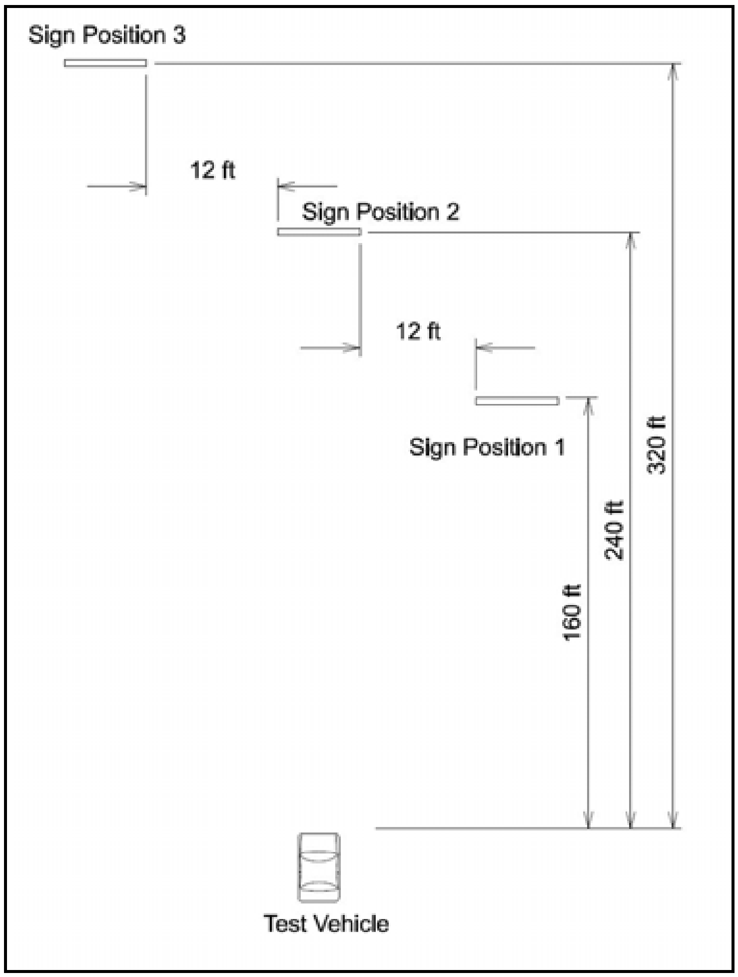


Figure 7. Illustration. Symbols used for recognition.

Sign Position

All of the signs with legends were viewed at three distances equal to LI of 2.4, 3.6, and 4.8 m/cm (20, 30, and 40 ft/inch) (figure 8). The symbol signs were shown at only the farthest distance. The sign offsets were chosen to maximize efficiency of data collection and produce more consistent results. Because of the sensitive relationship between retroreflective films and headlamp illumination in terms of sign luminance, the researchers designed the experiment to keep the vehicle and signs in a fixed position. Previous studies have proven that perfect realignment of a vehicle with respect to signing can be difficult and time consuming, especially when the research participant is behind the wheel. In addition, the positioning of the signs allowed variations on the glare source and impacts of the fixed roadway lighting.



1 ft = 0.305 m

Figure 8. Diagram. Test sign and vehicle layout.

Ambient Light Level

Ambient light was provided by four street lights installed along the study area. The street lights were mounted at a height of 9.1 m (30 ft) and set back 3 m (10 ft) from the edge of the runway. In relation to the study vehicle, the street light poles were offset approximately 10.4 m (34 ft) and located on the driver's side. Within the experiment design, the street lights were on at full output for one-half of a subject's sign readings and turned off for the remaining half. The measured illuminance of the street lights results in the isolux plot shown in figure 9. Illuminance was measured at driver's eye height in a vertical plane.

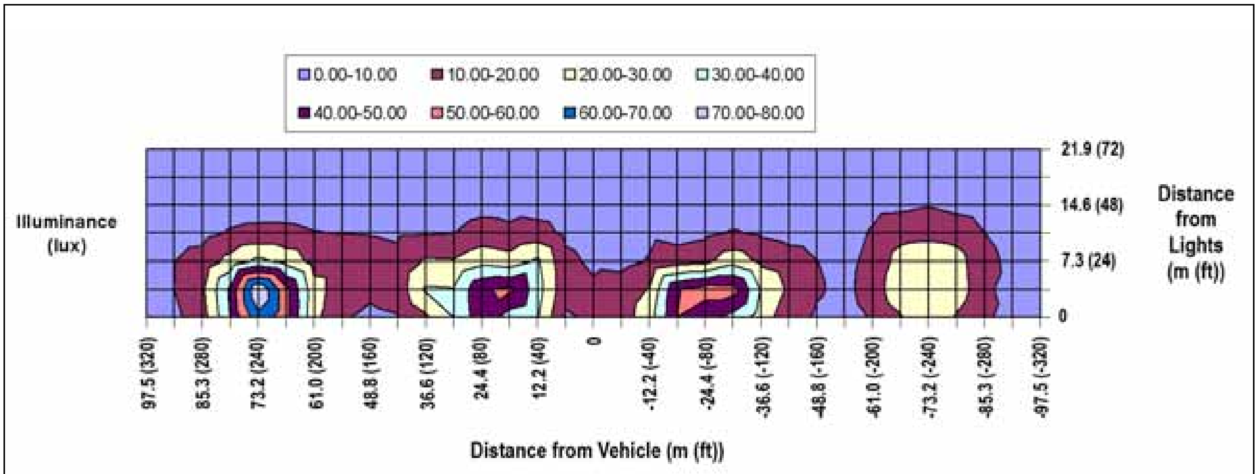


Figure 9. Graph. Isolux plot of roadway lighting illuminance along test course.

Glare

A glare source simulated an oncoming vehicle during testing. The glare was provided by a device attached to the hood of the study vehicle. The device was connected to the battery of the study vehicle and equipped with a voltage regulator. The power output of the glare device was modified by adjusting the supplied voltage. Using a hand-held illuminance meter, the researchers adjusted the voltage to produce an illuminance of 0.83 lx at the driver's eye. This value was based on simulating an oncoming vehicle on a two-lane highway at a distance of 50 m (164 ft).

Veiling Luminance

The roadway lighting and the glare source create a combined veiling luminance for the research participants. The veiling luminance from the roadway lighting and glare source was calculated using the equation presented in figure 1. The estimated veiling luminance levels caused by the roadway lighting and glare source are shown individually and cumulatively in table 6.

Table 6. Veiling luminance, L_V (cd/m²).

Sign Position (LI)	Roadway Lighting	Glare Source	Total
1: 2.4 m/cm (20 ft/inch)	0.018	0.052	0.080
2: 3.6 m/cm (30 ft/inch)	0.160	0.300	0.460
3: 4.8 m/cm (40 ft/inch)	0.069	3.907	3.976

Independent Sector Variables

Thirty subjects at least 55 years of age were recruited from the Brazos County, TX, area using advertisements at local senior center establishments and centers. Subjects received financial compensation equivalent to approximately $20 per hour. Each driver was required to possess a current Texas driver's license with no nighttime restrictions. In addition, visual acuity of the participants was screened using a standard Snellen eye chart.

Fixed Factors

- Type of vehicle—The study vehicle was a 2004 model year Ford Taurus. Every subject used the same vehicle.
- Subject position—Subjects were seated in the driver's seat of the study vehicle.
- Type of sheeting—All study signs were fabricated with white microprismatic sheeting meeting the requirements of Type IX sheeting in ASTM Standard Specification D4956-04.
- Font size and type—Two fonts were used in the evaluation: Standard Highway Series C and National Park Service (NPS) Roadway. All fonts were a 203-mm (8-inch) letter height. The NPS Roadway font is an upper/lowercase font.
- Inter-letter spacing—Spacing between letters was in accordance with the Standard Highway Alphabet as recommended by FHWA and the NPS UniGuide Standards.
- Inter-line spacing—Two words were shown at a time; however, each word was on its own sign. The spacing between the words was approximately 355 mm (14 inches). Only one symbol was shown at a time. Figure 10 and figure 11 illustrate the sign layout.
- Retroreflectivity—The retroreflectivity of the test signs is shown in figure 12 and figure 13.

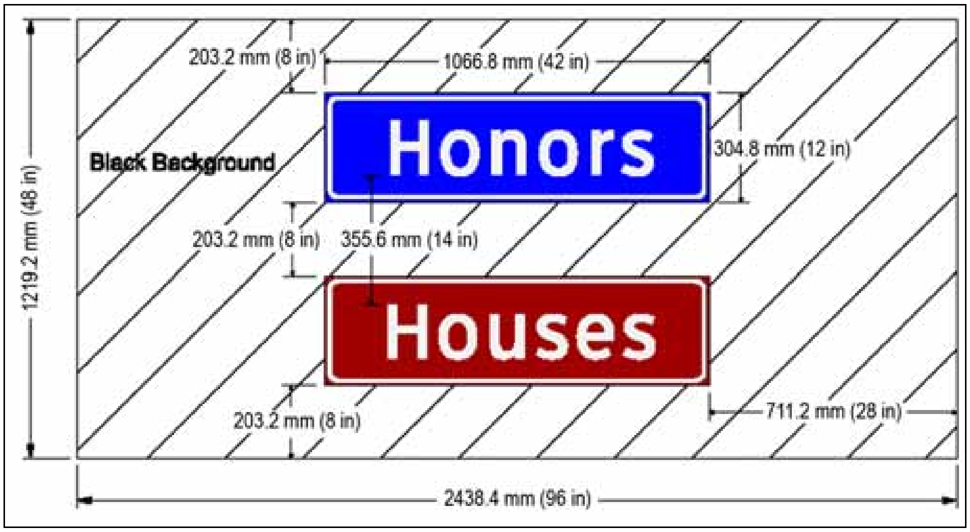


Figure 10. Diagram. Example legibility sign display.

Figure 11. Diagram. Example symbol sign display.

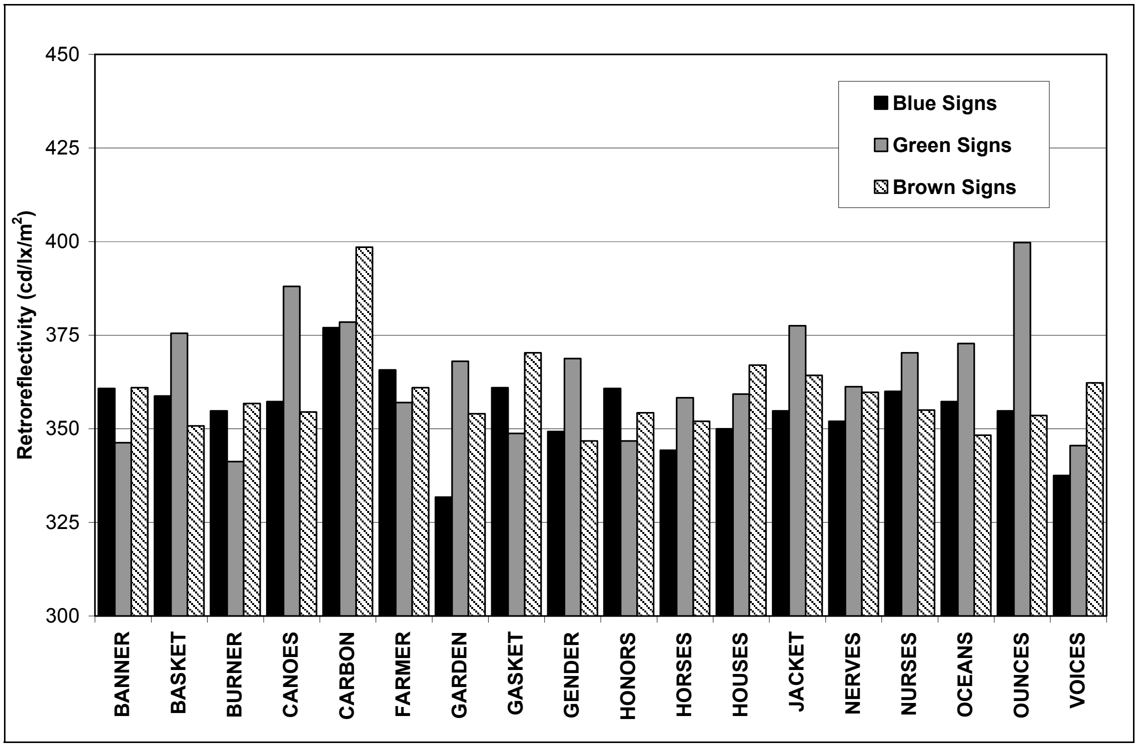


Figure 12. Bar graph. Coefficient of retroreflection (R_A) of test legend signs.

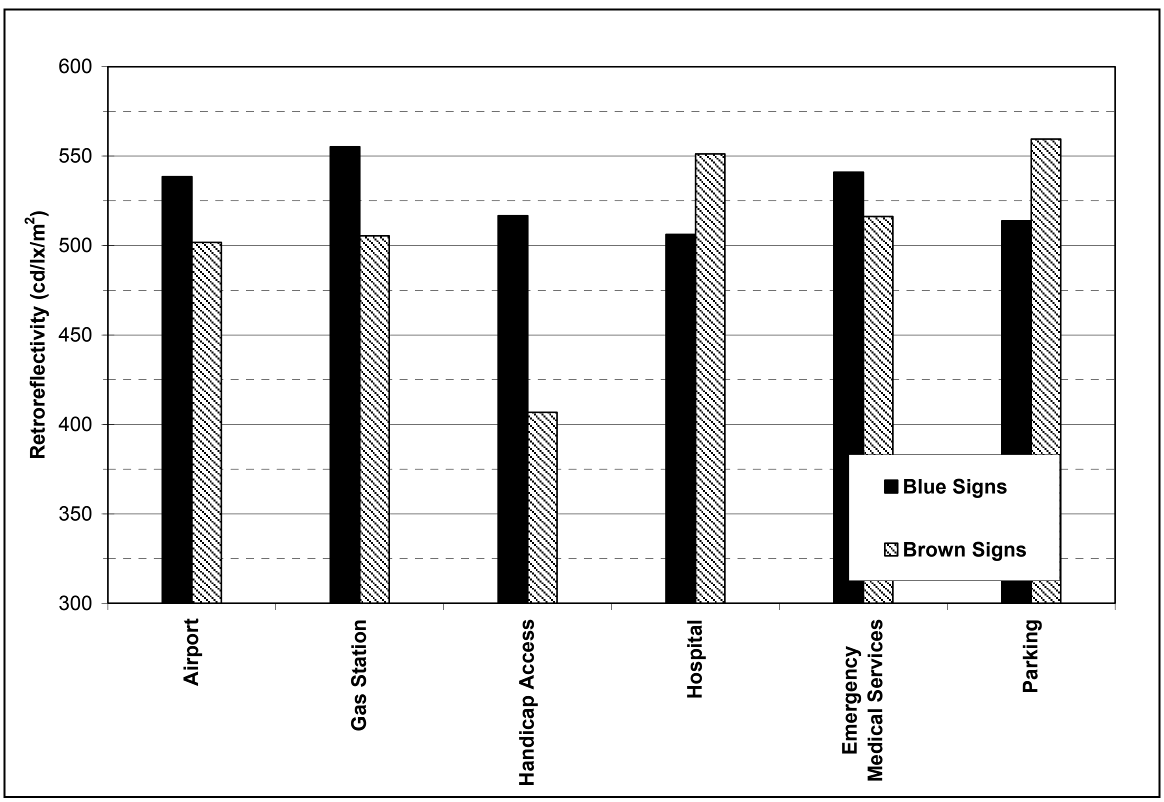


Figure 13. Bar graph. Coefficient of retroreflection (R_A) of test symbol signs.

STUDY VEHICLE

The same vehicle was used throughout the entire data collection effort—a 2004 Ford Taurus, model SE. The Taurus headlamps were tungsten-halogen visually/optically aimed style. Specifically, the driver's side headlamp was HB5 VOR LH DOT SAE AHRT5P2P 00T8 and the passenger's side headlamp was HB5 VOR RH DOT SAE AHRI5P2P 00T8. "VOR" indicates that the headlamp is to be visually/optically aimed using the right side of the cutoff, which is to be adjusted such that it is on the horizon line (at the same height as the center of the headlamp) when shown at a wall 7.6 m (25 ft) away. All subjects were tested from the driver's seat of the test vehicle. A researcher was in the passenger's seat at all times during data collection.

SUPPLIED LUMINANCE LEVELS

Using the low beams only, the researchers were able to provide 17 different, but precisely controlled, headlamp illumination levels to vary the luminance of the test words. The headlamp illuminance levels produced sign luminance values ranging from near zero (i.e., too dim to read) to that allowed by the maximum output (actual maximum sign luminance levels varied as the distance from the test signs varied). The researchers tried to control the headlamp illuminance levels so that the intervals producing sign luminance values near the general threshold range of 2 to 4 cd/m^2 would be small. Table 7 and table 8 summarize the luminance values that were supplied for each sign position. In order to make these measurements, 0.37-m^2 (4-ft^2) panels were made with the same sheeting as the targets so that a spot photometer could be used to measure the luminance at the appropriate distances.

Table 7. Supplied legend luminance values (cd/m^2) without roadway lighting.

Dial Position	2.4 m/cm (20 ft/in)		3.6 m/cm (30 ft/in)		4.8 m/cm (40 ft/in)	
	Top	Bot.	Top	Bot.	Top	Bot.
1	0.1	0.2	0.3	0.5	0.1	0.2
2	0.3	0.4	0.6	1.1	0.3	0.4
3	0.5	0.7	0.9	1.9	0.5	0.7
4	0.6	0.7	1.7	2.5	0.7	1.0
5	0.8	1.2	2.1	3.4	0.9	1.2
6	1.0	1.6	2.7	4.2	1.2	1.5
7	1.4	1.8	3.4	5.2	1.5	1.8
8	1.5	2.3	4.1	6.3	1.8	2.1
9	1.8	2.5	4.8	7.0	2.1	2.5
10	2.0	2.9	5.5	7.8	2.4	2.9
11	2.2	3.2	5.9	8.6	2.6	3.1
12	2.8	4.0	7.3	10.2	3.2	3.9
13	2.9	4.4	7.8	11.3	3.5	4.3
14	3.4	4.8	8.7	12.5	3.8	4.7
15	3.4	5.1	9.5	13.2	4.0	5.0
16	3.9	5.8	10.7	14.9	4.5	5.7
17	5.6	7.4	13.9	21.0	5.0	6.8

Table 8. Supplied legend luminance values (cd/m^2) with roadway lighting.

Dial Position	2.4 m/cm (20 ft/in)		3.6 m/cm (30 ft/in)		4.8 m/cm (40 ft/in)	
	Top	Bot.	Top	Bot.	Top	Bot.
0	1.7	1.6	0.6	0.5	0.7	1.3
1	1.9	2.0	1.5	2.1	1.5	2.1
2	2.2	2.4	2.5	3.8	2.3	2.9
3	2.9	2.9	3.7	5.9	3.1	3.9
4	2.9	3.3	4.7	7.5	3.8	4.8
5	3.1	3.8	5.9	9.8	4.6	5.6
6	4.0	4.4	7.4	13.0	5.6	6.8
7	4.1	5.1	9.2	15.8	6.6	8.2
8	4.9	5.6	10.6	18.5	7.7	9.6
9	5.0	6.2	12.3	20.8	8.6	10.7
10	5.8	6.8	13.5	23.1	9.9	13.0
11	5.9	7.4	15.3	26.6	10.3	12.2
12	7.0	8.9	18.5	31.7	12.6	16.3
13	7.6	9.3	20.4	33.7	13.7	17.5
14	7.8	10.3	21.8	36.9	14.4	18.7
15	8.7	10.7	23.0	39.4	15.4	19.6
16	9.1	12.0	26.9	45.7	17.7	22.6
17	11.1	14.2	32.5	35.2	20.8	25.4

Dimmer Switch

Pulse-width modulation (PWM) was used to adjust the luminance of the signs. This method applies full voltage to the headlamps at all times but is interrupted at rapid and controllable rates. With the voltage turning on and off 2,000 times per second, the ratio between the on-time and the off-time impacts the light available from the headlamps to light the signs. For example, if the voltage to the lamps were on for 50 µs and off for 450 µs, repetitively, the overall effect would be that the lamp would only be receiving power 10 percent of the time.

Precise control of the light output is then possible using a numeric processor or embedded microcontroller, such as a Parallax BASIC Stamp 2 (BS2). The BS2 contains a computer chip, serial input and output, 16 binary input/output lines, data storage, and memory. The BS2 is programmed with a standard laptop computer and retains the program until programmed again. A 16-position binary rotary switch controlled headlamp output. The four-line output from the switch was sensed by the BS2 and, using a lookup table, produced the required PWM signal to the headlamp drivers. Since the percentage of on-time does not easily equate to the percentage of light output, a switch position versus light output table was generated empirically with a laptop and an illuminance meter and was programmed into the BS2. This method produced a highly repeatable set of test conditions that could easily be reprogrammed if necessary. The BS2, selector switch, and power switches were located in a small box that was held by the experimenter (figure 14).

Power metal-oxide semiconductor field effect transistors (MOSFETs) were used to switch the headlamps on and off at 2,000 times per second. The common wire to each headlamp was cut and connected to the drivers located on each fender. Since the common wire to the headlamp is normally connected to the cathode of the battery, a special "high side" driver circuit was used.

By controlling the common wire to the headlamps, dimming was achieved on both the low and high beams. The internal resistance of these MOSFETs is very low (0.02 Ω), so there is little heat generated and there is very little voltage drop across them, allowing nearly normal full voltage to the headlamps. To allow the vehicle to be operated at night without the controller turned on, a relay was added to each driver box. This relay, through the normally closed contacts, bridges the power MOSFET to provide full voltage to the headlamp. This relay is actuated when power is applied at the control box, allowing the headlamp voltage to pass through the power MOSFET. The system was wired so that both headlamps were controlled together by the device shown in figure 14.

Figure 14. Photo. Headlamp controller box.

Finally, a solid-state 4-mW red laser was powered from the control box through a switch. This laser, located in the vehicle's grill area and pointing forward, provided a means to align the vehicle (headlamp) each time the vehicle returned to the test course. The laser device was aimed using set screws that were part of the bracket attaching the laser to the grill area. The target was a rectangular section of white reflective sheeting. This alignment target was attached to the sign board at sign position 2. The vehicle was considered correctly aligned when the laser spot was located approximately in the center of the alignment target.

Control panels were created for each sign color. The control panels were manufactured with the same retroreflective sheeting material and electrocuttable film used to make the target signs. Each night that observations were made, the luminance values of the control panels at each sign position and headlamp output dial setting were measured using a spot photometer to ensure the test conditions were consistent. Precise control was needed to accurately reproduce the luminance values from one night to another. For example, the researchers had to be in the same position (e.g., seated in the front), and there could be no substantial difference in the weight distribution throughout the car (e.g., another observer seated in the back or substantial differences in fuel levels). The contents of the trunk were removed to ensure no shifting of weight, and the headlamp lens and windshield were cleaned each night before the evaluations began. The researchers also topped off the fuel after each night of data collection. It was also important to keep the photometer at the same height for each reading.

TEST SUBJECTS

Thirty participants were recruited from the Brazos Valley, TX, area. Participants received financial compensation of $40. Participants were required to have a current Texas driver's license with no nighttime restrictions. Table 9 and table 10 list subject demographic data.

All 30 participants were at least 55 years of age. Ten were between ages 55 and 65, and 15 were age 66 or older, with the oldest participant being 80 years of age. The average age was 68 years, and the participants were split evenly by gender. Because legibility is a function of vision, the visual acuity of each participant was measured using a standard Snellen eye chart at a distance of 6.1 m (20 ft). Two participants had visual acuity better than 20/20. Twenty-six participants had visual acuity of 20/20 to 20/30. Two participants had visual acuity greater than 20/30; one had a visual acuity of 20/50.

ENVIRONMENTAL CONDITIONS

No external sign lighting (the type of lighting designed to illuminate overhead signs) was used in this experiment. Two levels of ambient lighting were used: a light level consistent with an unlighted, rural highway and a light level provided by four luminaires. The area in which the study was performed can be considered rural with low ambient light. A glare source was provided to simulate an oncoming vehicle located approximately 50 m (164 ft) from the study vehicle. The vehicle instrument panel also provided some glare. The instrument lighting was maintained at the highest setting throughout the experiment. All data were collected under dry conditions (i.e., no rain or dew on the signs).

Table 9. Research participant demographics.

No.	Gender	Age	Visual Acuity	Employment	Education	Living Area	Vision Problems
1	F	74	20/30	Retired	High school graduate	Rural area	None
2	F	65	20/25	Retired	Some college or vocational school	Rural area	None
3	F	73	20/20	Retired	Some college or vocational school	City	Glasses (trifocals)
4	M	75	20/20	Retired	Graduate degree	City	Astigmatism; nearsighted
5	F	73	20/30	Retired	Some college or vocational school	Rural area	None
6	M	77	25/20	Retired	Some college or vocational school	Rural area	None
7	M	NR	20/30	Retired	Graduate degree	Rural area	None
8	F	63	20/30	Retired	College graduate	Rural area	Could use glasses for distance, not required
9	F	NR	20/30	NR	NR	NR	None
10	M	71	20/25	Retired	Graduate degree	NR	None
11	F	60	20/20	Full time	Some college or vocational school	City	Cataract, Wear glasses
12	M	55	20/15	Retired	Some college or vocational school	Rural area	Nearsighted, glasses
13	F	64	20/25	Retired	High school graduate	Rural area	None
14	M	69	20/20	Retired	High school graduate	Rural area	None
15	M	69	20/25	Part time	Graduate degree	City	Glasses
16	M	60	20/20	Retired	High school graduate	Rural area	None
17	F	61	20/25	Retired	College graduate	City	None
18	M	63	20/20	Retired	Graduate degree	City	None
19	M	65	20/25	Retired	Some graduate school	City	Nearsighted, corrected
20	F	65	20/20	Retired	High school graduate	City	Wear glasses
21	F	NR	NR	Full time	High school graduate	Rural area	None
22	F	75	20/30	Homemaker	Some college or vocational school	City	None
23	M	76	20/25	Retired	Graduate degree	City	None
24	M	56	20/20	Retired	High school graduate	Rural area	None
25	M	67	20/20	Full time	High school graduate	City	None
26	F	57	20/15	Full time	Some college or vocational school	City	None
27	M	74	20/20	Retired	Graduate degree	City	None
28	M	79	20/25	Retired	Never went to high school	City	None
29	F	80	20/50	Homemaker	College graduate	City	Cataract surgery
30	F	73	20/20	Homemaker	Some college or vocational school	City	Start of cataracts

No. = Participant number.

Table 10. Research participant driving characteristics.

No.	Age	Years Driving Experience	How often do you…		
			Drive?	Drive at night?	Act as the "navigator"?
1	74	25+	A few times a week	A few times a week	A few times a year
2	65	25+	A few times a week	A few times a week	A few times a month
3	73	25+	A few times a week	A few times a month	A few times a week
4	75	25+	Several times a day	A few times a week	A few times a year
5	73	25+	Once a day	A few times a week	A few times a month
6	77	25+	Once a day	A few times a week	A few times a month
7	NR	25+	Once a day	A few times a month	A few times a year
8	63	25+	Once a day	A few times a month	A few times a year
9	NR	NR	NR	NR	NR
10	71	25+	Several times a day	A few times a week	A few times a year
11	60	25+	Several times a day	A few times a week	A few times a year
12	55	25+	Several times a day	A few times a week	A few times a week
13	64	25+	Several times a day	A few times a week	A few times a year
14	69	25+	Once a day	A few times a week	A few times a year
15	69	25+	Several times a day	Several times a day	A few times a year
16	60	25+	Once a day	A few times a week	A few times a month
17	61	25+	Several times a day	Several times a day	Several times a day
18	63	25+	Several times a day	Several times a day	Several times a day
19	65	25+	Several times a day	A few times a week	A few times a year
20	65	25+	Once a day	A few times a month	A few times a year
21	NR	16–20	Several times a day	A few times a week	A few times a year
22	75	25+	Once a day	A few times a week	A few times a week
23	76	25+	Several times a day	A few times a week	A few times a month
24	56	25+	Several times a day	Several times a day	Several times a day
25	67	25+	Several times a day	A few times a week	A few times a year
26	57	25+	Several times a day	Once a day	A few times a year
27	74	25+	Several times a day	Several times a day	A few times a month
28	79	25+	Several times a day	Several times a day	Several times a day
29	80	25+	Once a day	A few times a week	NR
30	73	25+	Once a day	A few times a month	Several times a day

No. = Participant number.
NR = Not recorded.

RESEARCH PROTOCOL

The objective of the experimental plan was to determine the minimum luminance needed to read white-on-blue and white-on-brown signs. The minimum luminance was needed to accurately determine the MR. Subjects participating in the study were asked to meet the researchers at Texas A&M University's Riverside Campus. Subjects were asked to wear corrective lenses if they normally wear them while driving.

Upon arriving at the Riverside Campus, the researchers explained the study in general terms and asked the subjects to sign an informed consent waiver. Once the waiver had been signed, the researchers evaluated the subjects' visual acuity and contrast sensitivity at normal indoor luminance levels. These activities were conducted inside a building at the Riverside Campus where a room was set up to perform the visual assessments. Upon completion of the vision tests, the researcher drove the test vehicle to the testing area with the subject in the passenger's seat. Upon arrival, the subject and researcher switched seats. The researcher then reiterated the test instructions and procedure and familiarized the subject with the vehicle controls.

The experiment design randomized which sign position each subject viewed first. The sign positions were viewed in order following the initial sign position; i.e., if the testing began with sign position 2, then sign position 3 followed, and sign position 1 was last. All subjects started in a dark ambient environment. For each sign position, one-half of the subjects began with the glare source illuminated while the other half began with the glare source turned off. The streetlights were turned on one-quarter of the way through testing and turned off at the three-quarter mark. The streetlights were allowed time to warm up to full output before testing continued. "Incremental lighting" was used because the researchers did not want subjects going from total darkness to having both glare and street lighting at the same time.

The test began with the vehicle headlamps off and the glare source on or off as required. The first set of words was installed on the sign board. The researcher turned the headlamps on at the lowest illumination setting. The subject was then asked to read the words. If the subject could not read both words correctly, the illumination level was increased one level and the subject was asked to read the words again. This procedure continued until the subject read both words correctly two consecutive times. At this point, the headlamps were turned off and two new words were installed (the selection of the test words was performed randomly throughout the experiment). The increasing illumination procedure was repeated until the subject consecutively read both words correctly. This procedure was repeated 18 times at each sign position, corresponding to LI of 2.4, 3.6, 4.8 m/cm (40, 30, and 20 ft/inch).

The total evaluation time ranged from 60 to 90 minutes. The time was dependent upon how fast the subject was able to identify the test words.

The researchers recorded the responses at each illumination level, regardless of whether or not the subject could read the word(s). The researchers also recorded all errors that the subjects made in reading the words.

Once the subjects completed the legibility evaluation, they were escorted back to the vision testing room. The researchers then conducted a brief exit interview and compensated the subject for his or her time.

To ensure experimental control, the researchers remeasured the supplied luminance values to verify the repeatability of the initial luminance readings and to provide confidence that nothing had changed during the evaluations.

In other efforts to obtain the best experimental control possible, the test vehicle was dedicated exclusively to this project throughout the duration of the data collection activities. No other individual was permitted to use the vehicle. Furthermore, the test vehicle did not leave the research site. These precautions were implemented to avoid the possibility of anything happening to the vehicle that could cause headlamp misalignment. In addition, every test subject who participated in the study received the same set of instructions. This included directions to not guess at the legibility of a word. Rather, subjects were asked only to respond when they were reasonably confident in their answer.

RESULTS

All 30 subjects completed the study. There were a total of 1,980 sign observations. The most efficient way to illustrate the resulting data is by cumulative distribution graphs showing how much luminance is needed to accommodate the various percentages of the study sample. In addition, the results are shown in tabular form. The next sections describe the results by type of sign.

White-on-Blue Legend Signs

The results of the white-on-blue legend signs are shown in table 11 and figure 15. These results indicate the minimum luminance required for sign legibility for a given percentage of the older driver subject sample. The data are divided by roadway lighting condition (on or off) and presence of glare (on or off).

Table 11. Luminance requirements for white-on-blue sign legends (cd/m^2).

Percent Accommodation	Roadway Lighting						No Lighting					
	Glare Off			Glare On			Glare Off			Glare On		
	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)
10	1.59	1.50	1.50	1.59	2.07	2.24	0.10	0.30	1.27	0.10	0.60	2.80
25	1.59	2.07	2.20	1.59	3.70	3.45	0.10	0.50	2.00	0.17	1.13	3.90
50	1.65	2.50	3.90	1.65	4.73	5.60	0.17	0.93	3.30	0.40	2.13	7.10
75	2.23	4.06	8.00	1.95	7.47	10.30	0.42	1.90	6.26	0.67	3.37	11.10
85	2.91	8.70	9.60	2.61	9.80	13.03	0.67	2.70	8.29	1.19	7.81	14.55
95	5.92	20.37	14.13	3.89	23.03	18.46	1.80	5.41	14.95	5.60	14.73	22.28
98	7.51	22.82	16.37	4.80	27.68	19.22	4.04	7.25	19.25	6.03	21.00	26.60

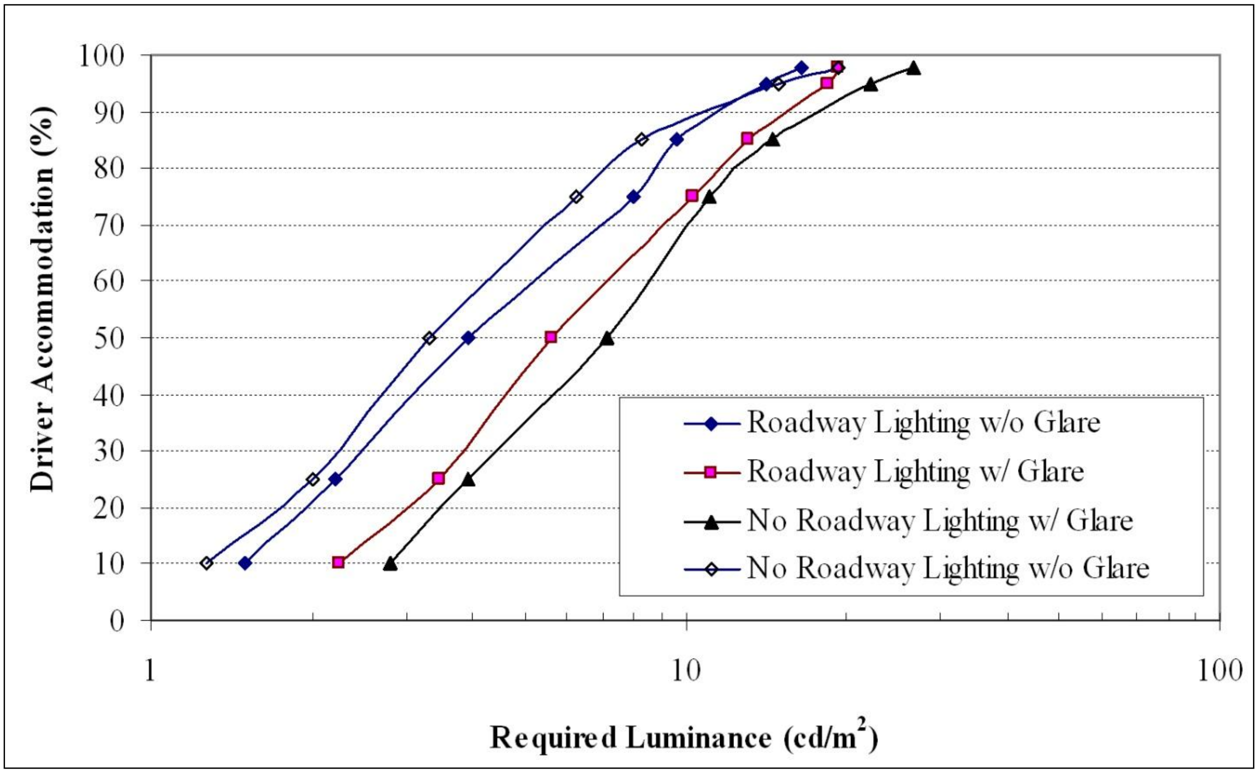


Figure 15. Graph. Luminance required for white-on-blue signs (LI = 4.8 m/cm (40 ft/inch))

White-on-Brown Legend Signs

The results of the white-on-brown legend signs are shown in table 12 and figure 16. These results indicate the minimum luminance required for sign legibility for a given percentage of the older driver subject sample. The data are divided by roadway lighting condition (on or off) and presence of glare (on or off).

Table 12. Luminance requirements for white-on-brown sign legends (cd/m^2).

Percent Accommodation	Roadway Lighting						No Lighting					
	Glare Off			Glare On			Glare Off			Glare On		
	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)	2.4 m/cm (20 ft/in)	3.6 m/cm (30 ft/in)	4.8 m/cm (40 ft/in)
10	1.59	1.50	2.30	1.59	2.07	3.01	0.10	0.50	2.10	0.10	0.60	3.80
25	1.59	2.07	3.30	1.65	2.50	4.40	0.10	0.50	3.10	0.17	1.13	5.85
50	1.65	4.28	5.90	1.65	5.87	7.20	0.17	1.13	6.40	0.40	1.90	9.60
75	2.28	7.91	10.50	2.85	9.66	12.80	0.52	2.11	10.30	0.67	4.20	14.40
85	3.45	12.50	12.73	3.07	12.68	16.28	0.79	4.91	12.24	0.94	7.78	16.90
95	7.27	22.10	18.00	6.82	36.49	18.30	2.59	6.65	18.12	4.32	12.05	19.29
98	7.80	23.53	23.51	7.67	46.11	18.79	4.16	7.32	18.23	5.17	13.95	21.27

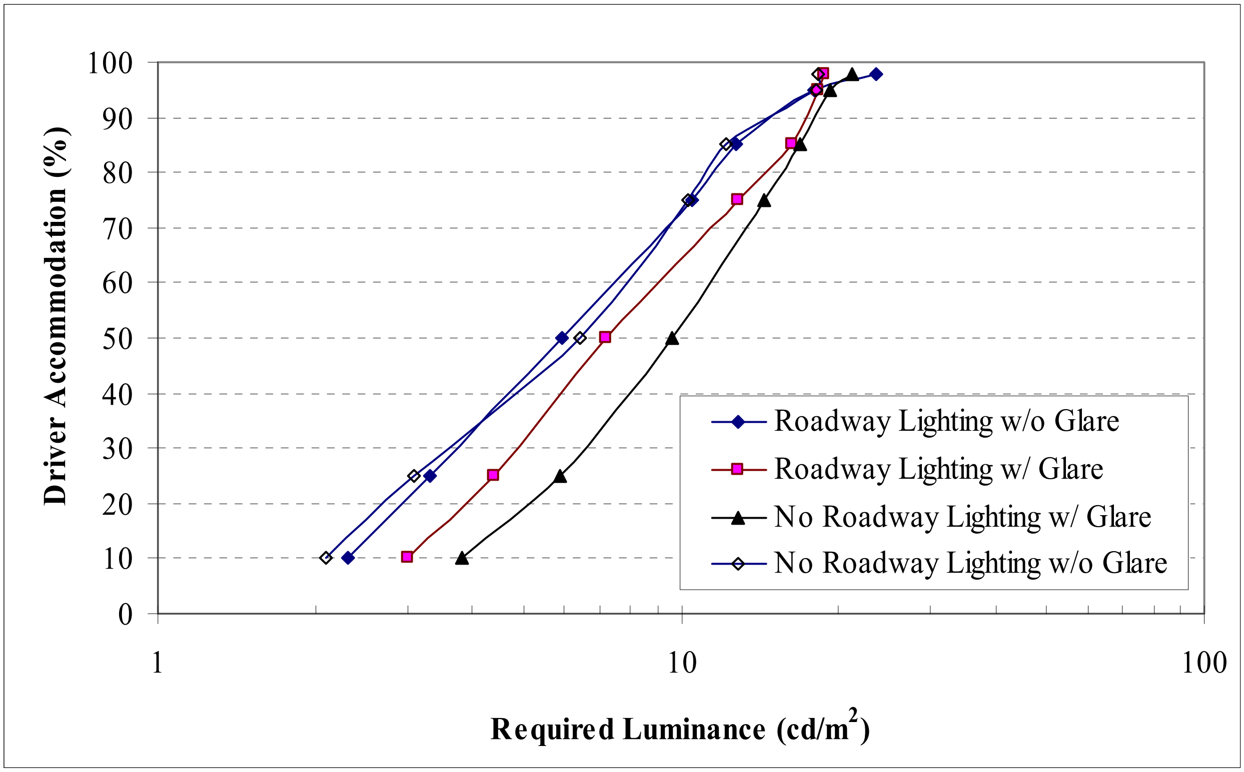


Figure 16. Graph. Luminance required for white-on-brown signs (LI = 4.8 m/cm (40 ft/inch))

Recognition of Symbol Signs

The symbol sign recognition task revealed some surprising results that warrant discussion before the required luminance results are presented. Symbol signs were used in this study because blue and brown signs are used with both symbols and legends. The particular symbols that were used in this study were selected to yield results that would also be usable in a secondary effort to investigate the required luminance of bold symbol signs and fine symbol signs.

Three hundred sixty observations were recorded with the symbol signs, split approximately equally among the six sign designs. Overall, only 63 percent of the observations were correctly identified, even with full illumination of the signs. Table 13 shows a breakdown by sign type.

Table 13. Recognition of symbol signs.

Symbol*	Percent Correct		
	TOTAL	**Blue**	**Brown**
Gas	52	42	67
Emergency medical services	48	60	36
Handicap access	52	45	60
Parking	74	78	70
Hospital	89	100	80
Airport	65	70	60

* See figure 7 for symbol representations.

The symbols chosen for this study were intended to be relatively common symbols used for blue and brown signs. The fine symbol signs were the emergency medical services (EMS) and handicap access signs. The gas symbol sign was chosen as a bold sign but with the expectation that it might be hard to identify as such because it lacks unique design characteristics.

Whereas the results appear to indicate that fine symbol signs need more luminance near their threshold recognition distance than bold symbol signs, one confounding factor that is important to mention is that many of the participants commented post-study that they were unfamiliar with the EMS sign. Likewise, although many recognized the gas symbol sign after the study, many commented that it appeared like an uppercase letter "I" both during the study and afterward.

Therefore, the results for symbol signs were divided into four categories by color (blue and brown) and by symbol design (fine and bold, using the EMS and handicap access data for fine symbol signs and the parking, hospital, and airport data for the bold symbol signs).

Symbol Signs

Table 14 shows the luminance requirements for symbol signs. Figure 17 shows the same data as a cumulative distribution graph for the minimum luminance required for symbol recognition for a given percentage of the older driver subject sample.

Table 14. Luminance requirements for symbol signs (cd/m^2).

Percent Accommodation	Blue		Brown	
	Fine	Bold	Fine	Bold
10	1.20	0.43	1.47	0.70
25	1.95	1.05	1.95	1.30
50	3.40	2.10	3.00	2.10
75	7.65	4.58	6.40	3.90
85	11.00	6.80	8.40	8.00
95	14.00	11.93	11.10	12.20
98	16.00	12.20	12.50	16.10

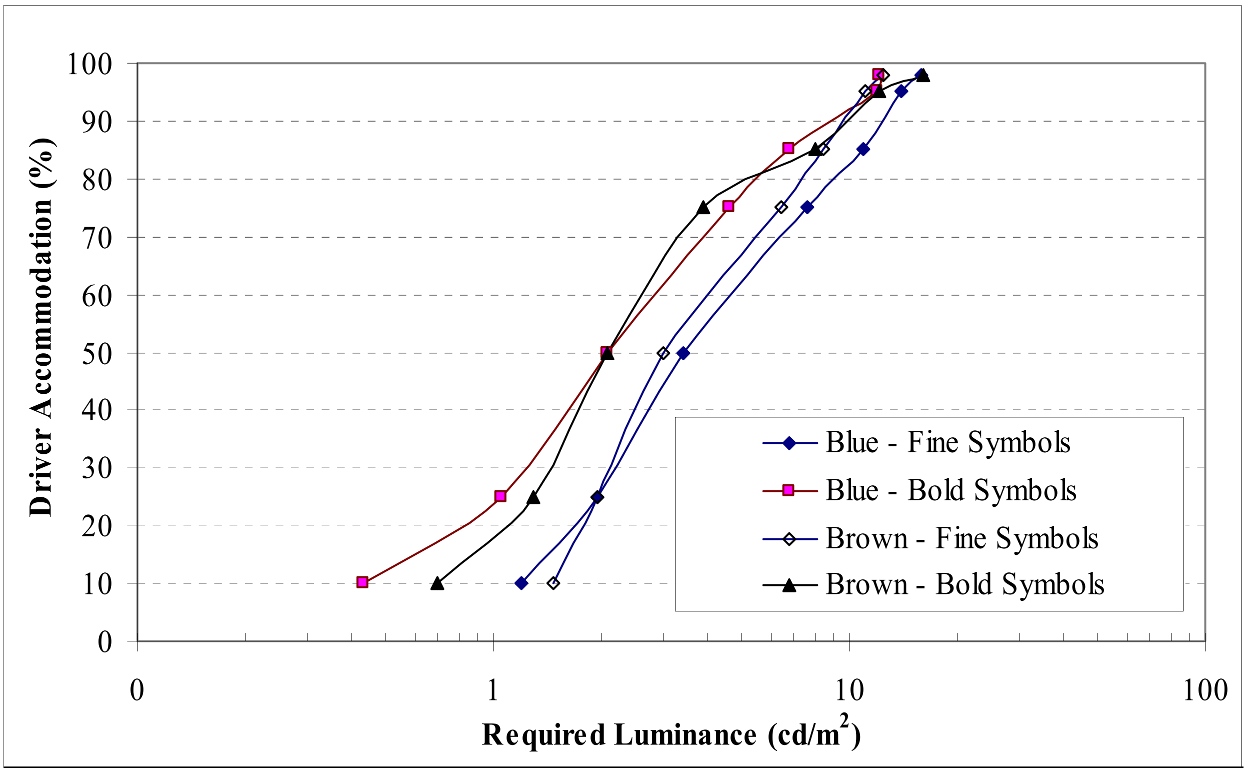


Figure 17. Graph. Luminance required for symbols signs.

COMPARISON TO PREVIOUS MR RESEARCH

In the field evaluation, subjects viewed white-on-green signs in addition to the white-on-blue and white-on-brown signs. The white-on-green signs were viewed to enable the research team to compare the results of this study with previous work on minimum retroreflectivity and sign luminance.[(1)] This activity was used to validate the repeatability of the previous experimental protocol and as reassurance that the study described in this report was similar.

White-on-Green Legend Sign Results

Using the accommodation values from the previous MR research, a comparison was made using the luminance results for distances associated with an LI of 4.8 m/cm (40 ft/inch).[1] Figure 18 illustrates that the measured luminance data are similar to those data for white-on-green overhead and street name signs collected approximately 5 years earlier, identified as "Overhead" and "Streetname."

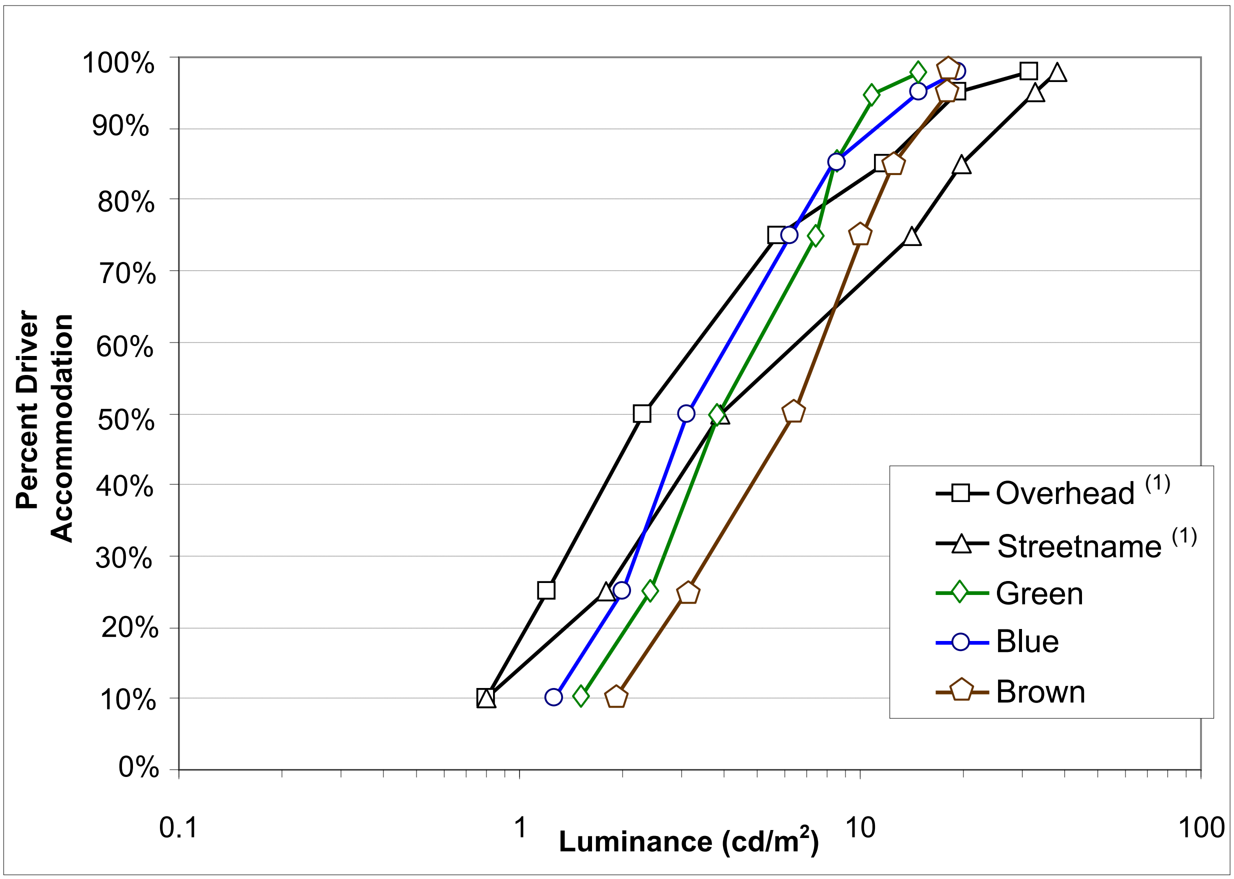


Figure 18. Graph. Comparison of luminance requirements (LI = 4.8 m/cm (40 ft/inch))

Figure 18 shows that the results for white-on-green signs in this study are consistent with the results of the previous research on white-on-green signs. In addition, the results also show that the white-on-blue signs require slightly less luminance than the white-on-green signs and that the white-on-green signs require slightly less luminance than the white-on-brown signs. These findings are similar in terms of luminance needs by color to those found by Forbes in his landmark luminance research 30 years ago.[8]

Chapter 5

CHAPTER 5. FINDINGS AND RECOMMENDATIONS

The minimum luminance accommodation levels determined in the previous chapter were used in conjunction with the TTI MR model to determine the MR values for blue- and brown-background signs with white legends. These MR levels are based on 50 percent accommodation at 4.8 m/cm (40 ft/inch) LI. They are presented to be compatible with MR levels the FHWA has used in rulemaking (Federal Register, July 30, 2004, at 69 FR 45623) to amend the MUTCD to include traffic sign retroreflectivity maintenance levels.

LUMINANCE THRESHOLD LEVELS

In order to determine the MR levels for the different sign types, it is important to identify the luminance threshold levels that were selected as a result of the human subject testing described in the previous chapters. The first item considered was the difference in luminance thresholds from previous work to define MR levels.(1) In this previous work, it was shown that overhead and street name signs required different luminance levels because of the differences in the legend used on these signs. It was determined that overhead signs needed 2.3 cd/m^2 and street name signs needed 3.9 cd/m^2 (at LI = 4.8 m/cm (40 ft/inch) and using 50 percent accommodation levels). For this study, the threshold luminance levels used to generate the MR levels for text and symbol signs are shown in table 15 and table 16.

Table 15. Luminance criteria for legends.

Color	Lighting	Glare	Luminance (cd/m^2)
Blue	No Light	No Glare	3.3
Blue	No Light	Glare	7.1
Blue	Light	No Glare	5.6
Blue	Light	Glare	3.9
Brown	No Light	No Glare	6.4
Brown	No Light	Glare	9.6
Brown	Light	No Glare	5.9
Brown	Light	Glare	7.2

Table 16. Luminance criteria for symbols.

Color	Design	Luminance (cd/m^2)
Blue	Bold	2.3
Blue	Fine	3.9
Brown	Bold	3.3
Brown	Fine	7.1

The results for conditions without roadway lighting and without glare showed that green and blue signs require nearly the same luminance values for equal legibility, but brown signs must provide a higher level of luminance. The font of the brown signs is more difficult to read, as noted by the higher luminance required and anecdotal comments from a few research participants indicating that the serifs made words less legible with higher luminance levels. However, the combination of white on brown appears to require more luminance in general, as demonstrated by the symbol sign luminance criteria (the same six symbols were used for each color).

When glare was added to the testing conditions, the amount of luminance needed to correctly read the signs increased by 215 percent for the blue signs and 150 percent for the brown signs. The difference can be explained, perhaps, by the need for more luminance to read brown signs without glare and our generally accepted human psychophysical logarithmic response to brightness requirements. If so, it is reasonable to expect that green signs would need about twice as much luminance with glare present.

Adding fixed roadway lighting to the testing conditions without adding glare resulted in mixed findings that are somewhat more difficult to explain. For the white-on-blue signs, 170 percent more luminance was needed. However, for the white-on-brown signs, only 92 percent of the original luminance was needed. When lighting was present and glare was added, the lighting reduced the impact of the glare. Overall, the addition of glare when lighting was present resulted in only a 15 percent increase in required luminance. This is a significant finding in that it supports previous research and the intuition that fixed roadway lighting can mitigate the impacts of oncoming glare.

The symbol sign luminance results show that fine symbol signs need about as much luminance as legend signs of the same color for unlit and no-glare conditions. Less luminance is needed for bold symbol signs.

MINIMUM RETROREFLECTIVITY LEVELS

Following the same procedures outlined in chapters 7 and 8 of FHWA-RD-03-082, the researchers developed preliminary minimum retroreflectivity levels to accommodate the luminance criteria established in this report. To ease the use of the results in the field, the work aimed to develop minimum retroreflectivity levels for white-on-blue signs and white-on-brown signs that could be integrated into the previously developed table of MR levels. In addition, the study was also conducted to develop adjustment factors for conditions with visual complexities, if needed.

As a result, the levels shown in table 17 are recommended to cover the white-on-blue signs and the white-on-brown signs. It is recommended that the design of the signs (legend or symbol) not be included in the factors that distinguish between threshold retroreflectivity levels. The luminance levels for symbol recognition are similar to those needed for legend legibility. In addition to the MR levels presented in table 17, the findings indicate that complex visual conditions (roadways with glare) require about twice as much retroreflectivity. However, according to the findings of this research, if fixed roadway lighting is added to the complex visual conditions, the retroreflectivity needed increases by about 15 percent.

Table 17. Minimum MR levels.

Sign Color	Sheeting Type (ASTM D4956-11a)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VIII, IX, XI	
White on green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Ground mounted
White on blue	W*; B ≥ 3	W*; B ≥ 5	W*; B ≥ 12	W ≥ 250; B ≥ 12	Overhead
	W*; B ≥ 3	W ≥ 120; B ≥ 7			Ground mounted
White on brown	W*; Br ≥ 1	W*; Br ≥ 5	W*; Br ≥ 10	W ≥ 350; Br ≥ 10	Overhead
	W*; Br ≥ 1	W ≥ 150; Br ≥ 5			Ground mounted
Black on yellow or black on orange	Y*; O*	Y ≥ 50; O ≥ 50			①
	Y*; O*	Y ≥ 75; O ≥ 75			②
White on red	W ≥ 35; R ≥ 7				③
Black on white	W ≥ 50				—

The minimum MR levels shown in this table are in units of $cd/lx/m^2$ measured at an observation angle of 0.2 ° and an entrance angle of-4.0 °.

① For text and fine symbol signs measuring at least 1,200 mm (48 inches) and for all sizes of bold symbol signs.

② For text and fine symbol signs measuring less than 1,200 mm (48 inches).

③ Minimum Sign Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity).

* This sheeting type shall not be used for this color for this application.

Bold Symbol Signs

- W1-1, -2 – Turn and Curve
- W1-3, -4 – Reverse Turn and Curve
- W1-5 – Winding Road
- W1-6, -7 – Large Arrow
- W1-8 – Chevron
- W1-10 – Intersection in Curve
- W1-11 – Hairpin Curve
- W1-15 – 270 Degree Loop
- W2-1 – Cross Road
- W2-2, -3 – Side Road
- W2-4, -5 – T and Y Intersection
- W2-6 – Circular Intersection
- W3-1 – Stop Ahead
- W3-2 – Yield Ahead
- W3-3 – Signal Ahead
- W4-1 – Merge
- W4-2 – Lane Ends
- W4-3 – Added Lane
- W4-5 – Entering Roadway Merge
- W4-6 – Entering Roadway Added Lane
- W6-1, -2 – Divided Highway Begins and Ends
- W6-3 – Two-Way Traffic
- W10-1, -2, -3, -4, -11, -12 – Highway-Railroad Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3 – Deer Crossing
- W11-4 – Cattle Crossing
- W11-5 – Farm Equipment
- W11-6 – Snowmobile Crossing
- W11-7 – Equestrian Crossing
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow
- W16-5p, -6p, -7p – Pointing Arrow Plaques
- W20-7a – Flagger
- W21-1a – Worker

Fine Symbol Signs – Symbol signs not listed as Bold Symbol Signs.

Special Cases

- W3-1 – Stop Ahead: red retroreflectivity ≥ 7
- W3-2 – Yield Ahead: red retroreflectivity ≥ 7; white retroreflectivity ≥ 35
- W3-3 – Signal Ahead: red retroreflectivity ≥ 7; green retroreflectivity ≥ 7
- W3-5 – Speed Reduction: white retroreflectivity ≥ 50
- For non-diamond-shaped signs such W14-3 (No Passing Zone), W4-4p (Cross Traffic Does Not Stop), or W13-1, -2, -3, -5 (Speed Advisory Plaques), use largest sign dimension to determine proper minimum retroreflectivity level.

AREAS FOR FUTURE RESEARCH

- The study in this report was conducted with one glare source that was static in both position and intensity (meant to represent an oncoming passenger car on a two-lane highway at about 46 m (150 ft)). This single glare source is not representative of all possible conditions of surround complexity. More research is needed to define surround complexity and quantify its effect on the nighttime driving task.

- One of the key voids associated with minimum retroreflectivity levels is their link to safety in terms of reduced crashes. Research is needed to establish a link between retroreflectivity and crashes (or crash surrogates).

- Research is needed to identify a set of retroreflective sheeting material measurement geometries that better represents the driving task and could contribute to a more meaningful classification scheme than that used herein (the classification defined in ASTM D4956-04 was used for this paper).

- Key modeling factors related to the supply luminance were straight and flat roadways (i.e., no curves), vehicle dimensions representing a contemporary-style sport utility vehicle, and signs installed normal to the roadway. These factors should be fully researched to determine their impacts.

CHAPTER 6. REFERENCES

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