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Minimum Retroreflectivity Requirements for Traffic Signs

Summary Report

Research and Development
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FOREWORD

This summary report presents minimum retroreflectivity requirements for traffic signs in a format that can be implemented by practitioners. These minimum requirements seek to balance the need for accuracy from a driver performance perspective with the need for simplicity for ease of field implementation. This report will be of interest to anyone involved in the selection, installation, inspection, and maintenance of retroreflective traffic signs.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State highway agency. Direct distribution is being made to division offices.

Lyle Saxton
Director, Office of Safety and
Traffic Operations Research
and Development

NOTICE

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16. Abstract

Currently, national guidelines regarding the nighttime visibility of signs are limited to the stipulation in the *Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD)* that all warning and regulatory signs be illuminated or reflectorized to show the same color and shape by day or night. There are no objective measures that can be used to determine when a sign has reached the end of its service life and needs to be replaced. This study seeks to fill that need by establishing minimum retroreflectivity requirements for traffic signs.

Given the wide range of visual, cognitive, and psychomotor capabilities of the driving population and the complexity of the relationships between the driver, the vehicle, the sign, and the roadway, a mathematical modeling approach was selected. The model determines the distance at which a driver needs to see a sign, uses this distance to determine the luminance required, and then calculates the coefficient of retroreflection at standard measurement angles. This model is called Computer Analysis of Retroreflectance of Traffic Signs (CARTS).

The CARTS model was executed for each sign in the MUTCD at various vehicle speeds, sign sizes, and sign placements. The results are summarized and presented in a format that can be implemented by practitioners. Retroreflectivity values are given for both yellow and orange warning signs, white on red regulatory signs, white regulatory signs, and white on green guide 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 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.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	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	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		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	megagrams	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	psi

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

(Revised August 1992)

INTRODUCTION

This study is part of the Federal Highway Administration (FHWA) retroreflectivity research program. This program has two primary goals: (1) to define the minimum nighttime visibility requirements for traffic control devices; and (2) to develop the measurement devices and computer management tools necessary to effectively implement the requirements. This study addresses part of the first goal, that is, determining the minimum nighttime visibility requirements for signs.

Currently, national guidelines regarding the nighttime visibility of signs are limited to the stipulation in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) that all warning and regulatory signs be illuminated or reflectorized to show the same color and shape by day or night.[1] There are no objective measures that can be used to determine when a sign has reached the end of its service life and needs to be replaced. This study seeks to fill that need by establishing the minimum sign retroreflectivity requirements.

The nighttime visibility problem can be viewed as one of supply and demand. The retroreflective materials of the sign combine with the light output of the vehicle headlights to "supply" a certain level of luminance and therefore provide a certain visibility distance. On the other hand, the driver "demands" the information at a particular distance in order to take the proper action at a given vehicular speed. When the luminance supplied by the sign falls below that demanded by the driver the sign must be replaced. The goal of this study was to determine the level of sign retroreflectivity at the point where the supply and the demand are equal.

Given the wide range of visual, cognitive, and psychomotor capabilities of the driving population and the complexity of the relationships between the driver, the vehicle, the sign and the roadway, a mathematical modeling approach was deemed most appropriate. The model developed is called Computerized Analysis of Retroreflectorized Traffic Signs (CARTS).

This report begins with background information on the basic principles associated with sign visibility and sign retroreflectivity. The components of the CARTS model are then presented along with the reference conditions used in executing the model. Finally, the recommended minimum sign retroreflectivity values, as determined by this research, are presented along with a framework for their implementation.

BACKGROUND

When illuminated by external lighting sources such as automotive headlamps, traffic signs appear bright in proportion to their ability to redirect the incident illumination back toward the driver. The term luminance is used to quantify the amount of light that is redirected by the sign. Luminance is expressed as candelas per square meter (cd/m^2).

The majority of modern traffic signs employ retroreflective materials (materials that redirect the incident light back towards the light source). The retroreflective performance of a sign is commonly measured in terms of the coefficient of retroreflection (R_a). Simply put, R_a is the ratio of reflected light to incident light. This phenomenon is expressed as candelas per lux per square meter ($cd/lx/m^2$).

There are a variety of retroreflective materials available from a number of different manufacturers. For traffic signs, the materials are classified into the following ASTM types:

Type I:	A medium intensity sheeting. An enclosed lens glass-bead material.
Type II:	A medium-high intensity sheeting. An enclosed glass-bead material.
Type III:	A high intensity sheeting. An encapsulated glass bead or prismatic material.
Type IV:	A high intensity sheeting. A non-metallized micro-prismatic element material.
Type VII: (proposed)	A super-high intensity sheeting. A non-metallized micro-prismatic element material.

The R_a for retroreflective sign material is sensitive to two geometric relationships (1) the angle between the light source, the observer, and the surface (observation angle α), and (2) the angle between the incident light path and the reference axis (usually normal) of the retroreflector (entrance angle β). These angular relationships are presented in figure 1.

While the R_a is sensitive to changes in both α and β it is much less sensitive to β, except at large angles. For ASTM Type I, II, and III signing materials substantial change in R_a does not occur at entrance angles less than 20° and for some materials significant change does not begin until β exceeds 30°.

Unlike the case of the entrance angle, even the slightest change in the observation angle can have dramatic effects on R_a. Since the distance between the driver's eye and the light source is fixed, every time the distance between the observer and a sign is doubled, the observation angle (α) is cut in half. Due to its high degree of sensitivity, α plays the most important role in the calculation of R_a.

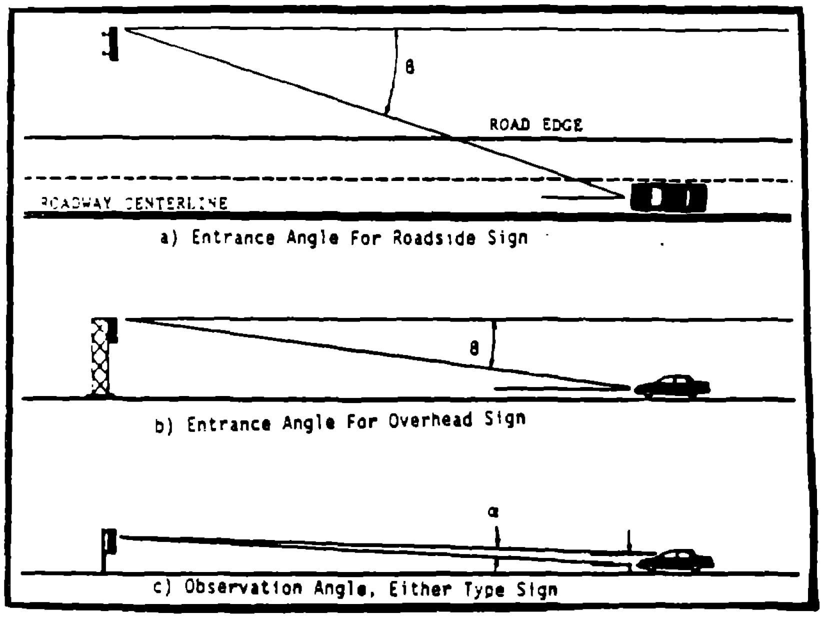

Figure 1. Entrance and observation angles in retroreflectivity measurement.[2]

CARTS MODEL

As outlined in the introduction, this research effort used a model-based approach to establish minimum visibility requirements. A computer model (CARTS) was developed to account for the time/distance required to identify and respond to a sign, the luminance required for sign detection and recognition at the requisite distance, and the retroreflectivity level needed to ensure the required performance level.

The model components performing the functions identified above are, the Minimum Required Visibility Distance (MRVD) submodel, the Inverse-Programmed Detect (IPDET) submodel, and the Standardized Retroreflectivity Measurement (SRM) submodel. The CARTS model is the integration of these three submodels, simply illustrated to show the sequential flow of data by:

CARTS : MRVD ---> IPDET ---> SRM

MRVD Submodel

The purpose of the MRVD is to determine the minimum distance at which a sign must be visible to enable drivers of varying visual, cognitive, and psychomotor abilities to respond safely and appropriately. The MRVD approach evolved from the concept of *Decision Sight Distance (DSD)* as developed by Alexander and Lunenfeld and later refined by others.[3] Alexander and Lunenfeld defined decision sight distance as:

> the distance at which a driver can detect a signal in an environment of visual ... clutter, recognize it ..., select an appropriate speed and path, and perform the required action safely and efficiently.

McGee, et al. translated this concept into operational values through the development and field testing of a hazard avoidance model.[4] This model essentially states that there is a sequence of events that must take place for a motorist to avoid a hazard; these are:

1. Detection of an object or situation.
2. Recognition of the object or situation as a hazard.
3. Decision making about the alternative actions to avoid the hazard.
4. Initiation of the response.
5. Completion of the response maneuver prior to the hazard.

By assuming that these events are sequential and by developing time increments for each component, McGee calculated decision sight distance values using the operating speed to translate from time to distance. The time requirements for each step were initially estimated based on an extensive literature review, then adjusted according to the findings of an empirical field study.

The decision sight distance concept was further refined by Perchonok, et al. for determining the detection and legibility requirements for retroreflective traffic signs.[5] Driver response requirements for effective use of retroreflective traffic control devices (TCD) were carefully defined and time values were assigned based on the then-current state of knowledge. The serially summed nature of the process was retained, on the assumption that, in the worst case the driver must accomplish each element of the process in order, one after the other.

The MRVD model conceptualized by Perchonok was enhanced as part of the current research effort. This included updating the model to include recent results identified in the literature; research in specific areas to improve model weaknesses; and adjustments to accurately represent traffic sign considerations, such as the placement of signs relative to the maneuver completion location and distance the sign is out-of-view.

The MRVD submodel computes the distance required by the driver to respond safety and efficiently to the requirements of a specified traffic sign. Included in the submodel are the components of detection, recognition, decision making, response initiation, and maneuver. The submodel is based primarily on information drawn from previous research, supplemented by a controlled field study conducted as part of this effort, and by engineering judgement where appropriate. To use the MRVD submodel the user provides information on driver characteristics (age), roadway characteristics (visual complexity, lane width, etc.), traffic characteristics (speed, volume) and sign characteristics (MUTCD code) and from this the submodel computes the MRVD for the given sign.

IPDET Submodel

Having determined the visibility distance needs with the MRVD submodel, the next step was to determine the sign luminance and retroreflectivity requirements. Determining luminance requirements (and ultimately retroreflectivity) depends on a variety of factors including the visual characteristics of the driver, the characteristics of the vehicle, the geometry of the roadway, the surrounding environment (fixed lighting, complexity, etc.) and the sign size and placement.

As with the development of the MRVD, a thorough review of the literature was conducted. The seeing distance model developed by Bhise et al. and Matle and Bhise was found to include many of the variables of interest.[6,7] This seeing distance model, named PCDETECT, is based on the human visual-performance model published by the International Commission on Illumination (CIE).[8] This is the model most generally accepted among highway visibility researchers. It is an analytical approach to determining detection threshold based on luminance contrast, accounting for the effects of glare and of adaptation level.

The PCDETECT model was developed to establish the distance at which traffic control devices were detectable under various illumination and glare conditions. The MRVD established the minimum distance required based on drivers' needs to respond to TCD's. The minimum sign luminance at the MRVD must now be established. This is the inverse of the problem solved by the PCDETECT models. Accordingly, the Inverse-PCDETECT (IPDET) model was formulated for determining the required luminance at a specified distance.

The IPDET submodel uses the distances computed by the MRVD submodel along with specified sign characteristics (MUTCD code, location), driver characteristics (age, acuity, eye height), vehicle characteristics (headlamp type, height, and spacing), roadway characteristics (number of lanes, lane width, background complexity, curvature and grade), and traffic characteristics (speed, volume, glare), to compute the required sign luminance. With this luminance and knowing the total candlepower from the specified vehicle headlamps falling on the sign, IPDET computes the required retroreflectivity value. It should be noted that this retroreflectivity value is specified at the entrance and observation angles associated with the geometric relationships of the vehicle and the sign at the MRVD.

SRM Submodel

Since as discussed earlier, all retroreflective materials are sensitive to entrance and observation angles, the R_a at the MRVD must be translated into a required R_a value at standard observation and entrance angles (0.2° and -4°) that can be measured by retroreflectometers. The third component in the CARTS model, the Standardized Retroreflectivity Measurement (SRM) submodel, performs this conversion.

This translation is necessary for two reasons: (1) since the MRVD varies from sign to sign, if the R_a values were not specified at the standard angles there would be no basis for grouping or summarizing the results, (2) it would not be practical to measure each sign at a different observation and entrance angle.

The translation of the R_a values requires establishment of the relationship between observation and entrance angles and R_a. To develop the necessary relationship, data for all known manufacturers and all known material types were collected in the FHWA Photometric and Visibility Laboratory. For each material, R_a values were measured for observation angles ranging from 0.2° to 2.0° and entrance angles ranging from -4° to 50°. Since the relationship between the observation and entrance angles and R_a varies by material type, the data were then grouped according to the ASTM material types and a generic (non-manufacturer specific) curve was developed for each type. In general, within each material type the variation between manufacturers was small. Figure 2 illustrates the relationship between R_a and observation angle for each of the ASTM material types. The SRM uses these generic curves to convert retroreflectivity values at the MRVD entrance and observation angles (typically 0.40° to 0.75°) to the standard value (0.2°).

A mathematical function was estimated separately for each material type and separate equations were also developed for the range of entrance angles outlined above.

CARTS EVALUATION AND CALIBRATION

As noted above, the CARTS model, relies heavily on published literature supplemented by laboratory and controlled field studies conducted as part of this study, as well as engineering judgement. Given the complexity of the CARTS model, it was not possible to conduct a complete validation of the model. Rather specific components of the model were evaluated and calibrated using published data and other models. It is reasonable to expect that the CARTS model as developed in this project will undergo continued refinement as new information concerning the performance of sign materials, headlight systems, and driver sensory, perceptual, and cognitive functions becomes available.

CARTS REFERENCE CONDITIONS

As discussed throughout this report, the development of minimum retroreflectivity requirements for traffic signs is a complex process involving the interaction between the sign properties, driver characteristics, the vehicle headlamp system, traffic operations, and roadway geometry. This section describes the reference conditions that were established for the development of the "base" minimum values. It is recognized that additional adjustments may be required to account for factors that are not captured in the base values.

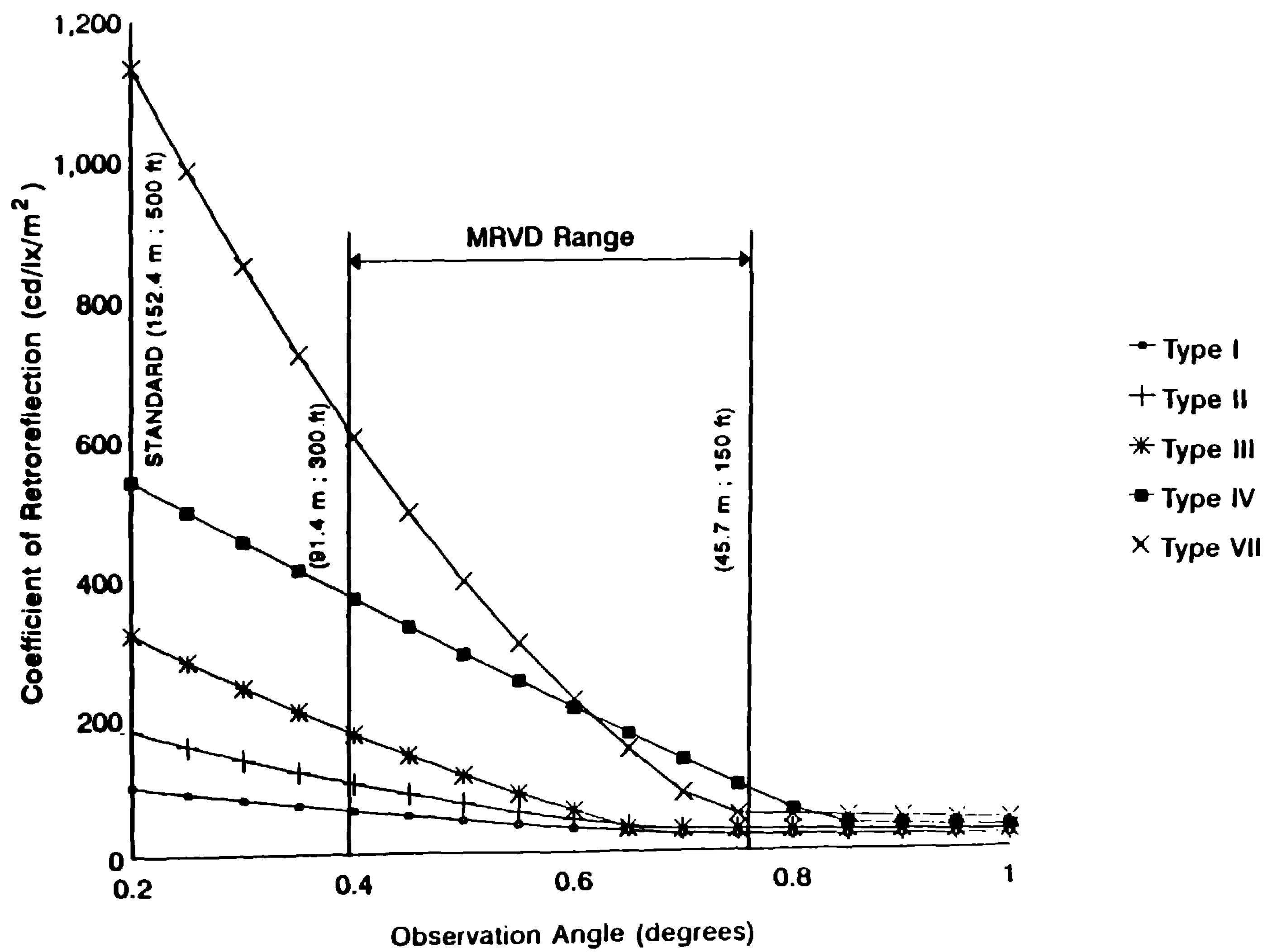

Figure 2. Relationship between coefficient of retroreflection and observation angle.

Sign Characteristics

The typical placement (left, right, overhead, median) and the roadway type where it is predominately found (urban, rural) were designated for each sign in the MUTCD. The lateral offsets are measured from the left or right edgelines depending on the sign position. Heights for median and left mounted signs are similar to those for right-mounted signs. The reference conditions are shown in table 1.

Table 1. Reference conditions for lateral offset and height.

Sign Position	Lateral Offset	Height
Right, rural	12 ft (3.7 m)	5 ft (1.5 m)
Right, urban	2 ft (0.6 m)	7 ft (2.1 m)
Shoulder Guide	30 ft (9.1 m)	5 ft (1.5 m)
Median	2 ft (0.6 m)	---
Left	12 ft (3.7 m)	---
Overhead	0	17 ft (6.1 m)

Driver Characteristics

Distribution tables for visual acuity, age, and contrast threshold are used to relate driver age and visual performance. As all three distributions relate a measure (age, acuity, or contrast threshold) to a population percentile, they can be used in combination to relate each measure to the others. Given a driver's age, the percent of drivers at or below that age can be derived and used to determine the level of visual acuity corresponding to the percent of drivers below the specified age. Similarly, the threshold contrast yields a value representative of the population percentile. This process can be done starting with acuity as well, producing a representative age and contrast sensitivity corresponding to a given acuity level. Also, if contrast threshold is known, a corresponding age and acuity can be determined. A final alternative is to specify the desired driver percentile, which is then used to look up age, acuity, and contrast sensitivity.

The CARTS model interface screen provides for using the measures of age, acuity, log contrast threshold, and percent accommodated; all are available for display and modification. Changing any of the four measures causes the other three measures to be recalculated based on the tables. The recalculated measures are then redisplayed.

After conducting a sensitivity testing of the model (by executing the model at various driver percentile levels and comparing the levels of retroreflectivity to those from previous research), a base driver was selected. In the CARTS model this was a 66th percentile driver who is 47 years old, has 20/20 acuity, and log contrast sensitivity of 0.257. While this percentile driver may appear to be low, the actual percentile driver served by the final guideline values is expected to be significantly higher. This issue is discussed in greater detail later in this report.

Vehicle Characteristics

Of primary concern in the development of minimum retroreflectivity values is the type of headlamp that is assumed. As discussed earlier the CARTS model determines the amount of luminance required by the driver at the MRVD, determines the intensity of light falling on the sign face, and then determines the amount of retroreflectivity required to supply the required luminance. The greater the light intensity the lower the retroreflectivity required.

Since there is a wide variation in headlamps in use in the United States it was judged that it would be inappropriate to select any single headlamp as being representative. Rather a composite headlamp developed by Mace as part of a vehicle headlamp study for the National Highway Traffic Safety Administration was used. This headlamp was developed using the 50th percentile intensities derived from a sample of 26 sealed beam and replaceable bulb headlamps commonly used in the United States. The photometric table of this headlamp was then used to represent both the left and the right headlamps in the CARTS model.

A mounting height of 0.61 m (2 ft) above ground level and a spacing of 1.22 m (4 ft) was assumed. The driver eye height was set at 1.06 m (3.5 ft) and the lateral position of the driver was set at 0.45 m (1.5 ft) left of the vehicle centerline. A windshield transmittance of 70 percent was used. These assumptions are judged to be representative of the conditions found on the U.S. vehicle fleet.

Roadway Characteristics

For the base condition a dark (ambient luminance = 0.01 cd/m^2 (0.0029 fL)), straight and level roadway was assumed. The visual complexity was assumed to be of a medium level and no opposing glare sources were included. Vehicle location and placement conditions were established as outlined in table 2.

Table 2. Roadway reference conditions.

Number of lanes	2
Lane width	3.7 m (12 ft)
Observer lane	right for right-mounted, guide, or overhead; left for left-mounted or median-mounted

Traffic Characteristics

The traffic volume was assumed to be medium, and the traffic speed was varied from 104 km/h (65 mi/h) to 48 km/h (30 mi/h).

MINIMUM RETROREFLECTIVITY REQUIREMENTS FRAMEWORK

The development of a framework to implement minimum retroreflectivity requirements involves balancing the desire for simplicity for ease of implementation with the desire for precision from a driver needs perspective.

While it might be advantageous from an implementation perspective to have only one value for all signs or a single value for each color of material, this type of implementation will not serve either the motorist or the responsible jurisdictions. For one value to satisfy motorist needs, the value would have to be so high for all signs that resources would be wasted by replacing signs with years of useful life.

On the other hand, it is not practical to execute a computer model like CARTS to compute minimum retroreflectivity values for each sign in a jurisdiction. The level of precision selected must take into consideration that many of the factors involved are out of the user's knowledge and/or control.

Establishing different values that consider the major traffic and geometric factors, allows the standards to be responsive to driver needs while decreasing the economic impact of implementing the minimum requirements. Some of the variables were addressed through the establishment of the reference conditions above. From the remaining variables the following were selected as both having a significant effect and being under the user's knowledge or control:

Traffic Speed: The MRVD is directly dependent on the speed of the vehicle. The time necessary to perform each of the required steps in the sign detection and recognition process is translated to distance; based on the vehicle speed.

Sign Size: The ability of a driver to detect and recognize a sign is dependent on the size of the legend. Within reasonable limits, as the size of the sign is increased, the size of the legend increases, thereby decreasing the retroreflectivity required.

Sign Legend: The design of the sign legend affects the required retroreflectivity. This effect is greatest for symbolic signs where the retroreflectivity required for bold, simple, symbols is significantly less than that for symbols with fine detail.

Material Type: As outlined above, the type of material used significantly affects the required R_a value. Since the effect of sign observation and entrance angles vary with material type, for a given sign, the R_a required at the standard entrance and observation angles will depend on the material used.

Sign Placement: The location of a sign determines the amount of light (from the vehicle headlights) that will fall on the sign. Signs on the left and those mounted overhead typically receive much less light from headlamps than signs mounted on the right. Because they receive less illumination some research has suggested that signs on the left and overhead require greater retroreflectivity than signs on the right. All things being equal, this would be true. However, it was assumed in this study, left-mounted signs are predominately found on multilane roadways and that drivers needing to see these signs would be in the left lane and not the right lane. In the left lane drivers are closer to the sign on the left than drivers in the right lane are to signs on the right because drivers sit on the left side of the vehicle. Because of this, the out of view distance is shorter for left-mounted signs which results in a significant decrease in the MRVD for legibility. The shorter MRVD results in a lower luminance threshold than for the same sign mounted on the right. The lower luminance threshold compensates for the lower illuminance on the sign, resulting in similar retroreflectivity requirements for both left and right-mounted signs. Location is therefore not a critical variable unless the sign is mounted overhead.

MINIMUM REQUIRED RETROREFLECTIVITY VALUES

The importance of each of the variables identified above will change, depending on the type of sign being examined. Therefore, the framework was further refined and simplified by selecting the critical variables for each sign type. This section of the report will first present the critical variables for each sign type and then provide minimum inservice retroreflectivity values organized around those critical variables. The CARTS model was used to provide guidance on the effect of the critical variables and levels of retroreflectivity that are required. It should be recognized that engineering judgement was used in interpreting the results from the CARTS model and in selecting values that were reasonable and consistent.

Black-on-Yellow and Black-on-Orange Warning Signs

The first type of signs examined were black-on-yellow and black-on-orange warning signs. The CARTS model was run varying each of the key variables and examining the effect these variables have on the minimum required retroreflectivity values. Only the critical variables were selected for inclusion in the final guidelines. These variables are discussed below:

Traffic Speed: Since signs in this category are used to warn drivers, they are located in advance of the hazard, and since there is little reading time needed for warning signs, the minimum values are not sensitive to changes in speed. Therefore, traffic speed was not selected as a critical variable.

Sign Size: The amount of retroreflectivity required for legibility at the MRVD significantly decreases as the sign size increases. Therefore, sign size was selected as a critical variable for warning signs. Three sign size categories were selected representing the typical sizes of warning signs currently used.

Sign Legend: Warning signs include a wide range of letter and symbol sizes and therefore a wide range of critical details. The amount of retroreflectivity required for legibility at the MRVD significantly decreases as the size of the critical detail increases. Therefore, sign legend was selected as a critical variable for warning signs. Two sign legend categories were selected representing bold, simple messages and finer, complex messages.

Material Type: Since the MRVD for warning signs generally falls in the 0.75° to 0.4° observation angle range (91 to 152 m; 150 to 300 ft), the minimum retroreflectivity values must be corrected back to the standard of 0.2° observation angle and -4° entrance angle. As discussed earlier and as illustrated in figure 2, this correction is dependent on material type, therefore, it is a critical variable. Four material type categories were selected representing the materials commonly used in practice.

Sign Placement: Since warning signs are generally not mounted overhead, sign placement was not selected as a critical variable.

Table 3 illustrates the final framework and values for black-on-yellow and black-on-orange signs. It includes three critical variables: sign size, sign legend, and material type. For bold legends, the values shown were established using the values required for detection based on research conducted by Mace and Olson.[9,10] The CARTS values for legibility for these signs were lower than the retroreflectivity needed for detection. Since detection takes place at an observation angle of 0.2° or less, no correction for material type was needed for these signs and the values were collapsed into a single material type group. Signs with bold legends are listed in table 4, all other warning signs are considered to have finer messages.

For the finer, more complex legends the values in the table 3 were selected by using 85th percentile values for all signs that were included within each given cell. Since, as illustrated in figure 2, the relationship between observation angle varies by material type, in order to provide an equivalent level of luminace at the MRVD distance, different retroreflectivity values must be specified for each material type.

Table 3. Minimum retroreflectivity guidelines for black-on-yellow and black-on-orange warning signs.

Legend Color: Black
Background Color: Yellow or Orange

	Sign Size:	>=48-in[1]	36-in[1]	<=30-in[1]
Legend	Material Type			
Bold Symbol	ALL	15	20	25
Fine Symbol & Word	I	20	30	45
	II	25	40	60
	III	30	50	80
	IV & VII	40	70	120

[1]cd/lx/m^2
1 in = 25.4 mm

Table 4. Warning signs with bold symbols.

MUTCD Code	Sign Type
W1-1	Turn
W1-2	Curve
W1-3	Reverse Turn
W1-4	Reverse Curve
W1-5	Winding Road
W1-6	Large Arrow
W1-8	Chevron
W2-1	Cross Road
W2-2	Side Road
W2-4	T Intersection
W2-5	Y Intersection
W4-2	Lane Reduction
W6-1	Divided Highway Begins
W6-2	Divided Highway Ends
W6-3	Two-Way Traffic

White-on-Red Regulatory Signs

The second type of signs examined were the white-on-red regulatory signs. This category includes stop, yield, do not enter and wrong way signs. The signs in this group have distinctly different characteristics and applications. Stop and yield signs are used at a wide variety of intersection and interchange locations and are recognized primarily based on their shape and color. "Do not enter" and "wrong way" signs are used primarily at locations where drivers can enter the wrong way against oncoming traffic (such as entrances to one-way streets or ramps). These signs rely more on their legends for message recognition. Since the number of types of signs in this category is small, rather than have two separate frameworks it was decided to use a single framework based primarily on the critical variables for stop and yield signs and to select values that would be sufficient to cover all four signs. Since all of these signs are fully retroreflective, values are specified for both the legend and the background. Each of the key variables is discussed below:

Traffic Speed: Stop signs and yield signs are placed at the point of the hazard and require action prior to reaching the sign. Therefore, traffic speed was selected as a critical variable. Two traffic speed categories were selected to represent high-speed rural and lower speed urban conditions.

Sign Size: The amount of retroreflectivity required for legibility at the MRVD significantly decreases as the sign size increases. Therefore, sign size was selected as a critical variable.

Sign Legend: Since there are so few signs in this category, legend was not selected as a critical variable.

Material Type: Since the MRVD for the stop and yield signs falls in the 0.4° to 0.2° observation angle range (91 to 152 m; 300 to 500 ft), the effect of correcting the minimum retroreflectivity values back to the standard of 0.2° observation angle and -4° entrance angle is minimal. Therefore, material type was not selected as a critical variable.

Sign Placement: Since these regulatory signs are rarely placed overhead, sign placement was not selected as a critical variable.

Table 5 illustrates the final framework and values for the red-and-white regulatory signs. It includes two critical variables: traffic speed and sign size. Since both the legend and the background of these signs is retroreflectorized a minimum maintained contrast ratio of 4:1 has also been established. This value was selected based on previous research.[9] If the retroreflectivity value for the white material divided by the retroreflectivity value of the red material is less than four, the sign should be replaced. The contrast ratio is particularity critical for signs made by screening, since the red color fades with time allowing the white material to show through thus increasing the retroreflectivity and reducing the contrast ratio.

Table 5. Minimum retroreflectivity guidelines for white on red regulatory signs.

Legend Color: White
Background Color: Red

Traffic Speed:	45 mi/h or greater						40 mi/h or less					
Sign Size:	>=48-in		36-in		<=30-in		>=48-in		36-in		<=30-in	
	W[1]	R[1]	W[1]	R[1]	W[1]	R[1]	W[1]	R[1]	W[1]	R[1]	W[1]	R[1]
All Signs	50	10	60	12	70	14	30	6	35	7	40	8

[1] cd/lx/m^2
1 mi/h = 1.6 km/h
1 in = 25.4 mm

Black-on-White Regulatory and Guide Signs

The third type of signs examined were the black-on-white (and black-and-red-on-white) regulatory signs. Parking series signs and signs intended solely for pedestrians and bicyclists are not included in this category. Each of the key variables is discussed below:

Traffic Speed: As with the other regulatory signs, the signs in this category are placed at the point of the hazard or require action prior to reaching the sign. Therefore, traffic speed was selected as a critical variable.

Sign Size: The amount of retroreflectivity required for legibility at the MRVD significantly decreases as the sign size increases. Therefore, sign size was selected as a critical variable for regulatory signs.

Sign Legend: While there is variation in the critical detail size for regulatory signs, this variation was not as great as for warning signs and the importance of the sign legend variable was not deemed to be as great as other variables. Therefore, sign legend was not selected as a critical variable.

Material Type: Since the MRVD for this group of regulatory signs generally falls in the 0.5° to 0.4° observation angle range (61 to 91 m; 200 to 300 ft), the minimum retroreflectivity values must be corrected back to the standard of 0.2° observation angle and -4° entrance angle. This correction is dependent on material type, therefore, it was selected as a critical variable.

Sign Placement: Since regulatory signs are placed overhead, sign placement was selected as a critical variable for warning signs. Since overhead, placements are primarily used at intersections, values are only shown for lower-speed situations.

Table 6 illustrates the final framework and values for this group of regulatory signs. It includes four critical variables: traffic speed, sign size, sign placement, and material type. The values in the table were developed using the CARTS data from a representative group of regulatory signs. This group was selected to ensure that the values are both representative of the category as a whole and sensitive to the most critical regulatory signs. Signs were selected from each of the major types of black on white regulatory and guide signs. The values in the tables represent 85 percentile values based on these signs.

White-on-Green Guide Signs

The fourth type of signs examined were the white-on-green guide signs. Since these signs are fully retroreflectorized values are specified for both the legend and the background. Each of the key variables is discussed below:

Traffic Speed: Although guide signs generally do not require a maneuver prior to reaching the sign, the vehicle speed does affect the amount of time available for reading the sign and ultimately the distance at which the sign must be seen. Therefore, traffic speed was selected as a critical variable for guide signs.

Sign Size: Since there are no standard sizes for most green-on-white guide signs it was not practical to specify different values for different sign sizes. Therefore, size was not selected as a critical variable.

Sign Legend: Given the wide variation in the type and amount of legend on guide signs, this variable could not be practically implemented. Therefore, sign legend was not selected as a critical variable.

Material Type: Since the MRVD for this group of guide signs generally falls in the 0.4° to 0.2° observation angle range (91 to 152 m; 300 to 500 ft), the effect of correcting the minimum retroreflectivity values back to the standard of 0.2° observation angle and -4° entrance angle is minimal. Therefore, material type was not selected as a critical variable.

Sign Placement: Since guide signs are often located overhead, sign placement was selected as a critical variable.

Table 6. Minimum retroreflectivity guidelines for black on white regulatory and guide signs.

Legend Color: Black and/or Black and Red
Background Color: White

	Traffic Speed:	45 mi/h or greater			40 mi/h or less		
	Sign Size:	>=48-in[1]	30-36-in[1]	<=24-in[1]	>=48-in[1]	30-36-in[1]	<=24-in[1]
	Material						
Ground-Mounted	I	20	35	50	15	20	35
	II	25	45	70	20	30	55
	III	30	60	90	25	45	75
	IV & VII	40	80	120	35	60	100
Over-head Mounted	I				40	50	100
	II				50	75	135
	III				65	115	185
	IV & VII				90	150	250

[1] $cd/lux/m^2$
1 mi/h = 1.6 km/h
1 in = 25.4 mm

Table 7 illustrates the final framework and values for this group of guide signs. It includes two critical variables: traffic speed and sign placement. The values for this table were developed using "typical" guide signs. This typical sign was developed using the guidelines for letter size provided in the MUTCD. Since both the legend and the background of these signs are retroreflectorized a minimum contrast ratio of 4:1 has also been established. If the retroreflectivity value for the white material divided by the retroreflectivity value of the green material is less than four, the sign should be replaced.

Table 7. Minimum retroreflectivity guidelines for white-on-green guide signs.

Legend Color: White
Background Color:Green

Traffic Speed:	45 mi/h or greater		40 mi/h or less	
	White[1]	Green[1]	White[1]	Green[1]
Ground-Mounted	35	7	25	5
Overhead-Mounted	110	22	80	16

[1]$cd/lx/m^2$
1 mi/h = 1.6 km/h

INTERPRETATION OF RESULTS

In examining the results of this research, two questions are of primary interest: (1) what percentile of drivers will be accommodated by the retroreflectivity values, and (2) how many signs will have to be replaced. While there is not a simple way to answer either of these questions, some information can be provided and some insight drawn from previous research.

Percentile Driver Accommodated

As discussed above, although the CARTS model was run using the CARTS 66 percentile driver, the final values shown in the table are believed to provide for a higher percentile driver. This belief is based on the following: (1) the MRVD distance serially accounts for all of the time and distance required by the driver. In actual driving some of the events may occur in a parallel manner. As a result, the MRVD distances are likely to be conservative. (2) The driver visual characteristics in CARTS are based on 66 percentile values from the population as a whole. Research by Decina, et al. indicates that the 66 percentile CARTS "driver" would be equivalent to the 75 percentile licensed driver.[(11)] (3) In general, the values in the table were selected using the 85 percentile value for all of the signs within each cell. Many of the signs with the highest required retroreflectivity values are relatively infrequently used. These are signs with small, complex legends and/or long word messages. A more desirable way to arrive at the 85 percentile cell value would be to weight each sign value by the frequency of use. Since the data to do the weighing were not available, the resultant values should satisfy a higher driver percentile for the majority of the signs.

The CARTS results were compared to previous visibility research conducted by Olson, Morales, Sivak and Olson, and Jenkins and Gennaoui. (See references 10, 12, 13, 14.) Based on these limited comparisons, it is believed that on the whole the retroreflectivity values shown in the tables 3, 5, 6 and 7 above provide a reasonable level of driver accommodation (80th to 90th percentile) for most driving situations. For high-speed and/or high-complexity environments the user should consider higher levels of retroreflectivity, larger signs, and/or supplemental signing.

Further driver accommodation data is being collected as part of an ongoing in-house research project being conducted by FHWA. This effort will examine selected retroreflectivity values from the tables above and assess the percent of drivers that would be accommodated.

Percent of Signs Requiring Replacement

From the viewpoint of the individual responsible for managing the maintenance and replacement of signs the critical question is the impact of the recommended replacement values on the current inventory of signs. Of particular concern is the economic consequences in terms of the numbers of existing signs that would have to be replaced.

As part of the program to develop minimum retroreflectivity requirements, a National Cooperative Highway Research Program (NCHRP) study was conducted by Black, et al., to investigate the economic impact of various replacement strategies.[15] In this study retroreflectivity measurements were taken on a random sample of 8,000 regulatory, warning, and guide signs in 1989.

The minimum values in this report were compared to the data from the NCHRP effort to estimate the percentage of existing signs that would have to be replaced. It is assumed that the sample of signs measured in the NCHRP study in 1989 is representative of the condition of the signs currently in use.

Since the data from the NCHRP study could not be subdivided to match the framework used in this report, an aggregate retroreflectivity value was developed for yellow, white, red and green materials. These aggregate values were used to assess the overall impact of the proposed values. The results are shown in table 8.

These estimates are deemed to be conservative since they assume all signs to be at the standard size. Larger size signs would require lower levels of retroreflectivity, thus resulting in lower replacement rates.

Based on the estimates contained in table 8 it appears the implementation of the recommended replacement values would require between 8 percent to 16 percent of existing signs to be replaced with the greatest impact at the city level. Even so the overall level of replacement is not unrealistic given that signing materials are generally expected to last from 7 to 12 years which would result in replacement rates of 8 percent to 14 percent.

Further data on the effect of these sign retroreflectivity values are expected to be available as a result of an ongoing FHWA effort to solicit input from States and local jurisdictions. As part of this effort, participating agencies will provide representative sign retroreflectivity data from their jurisdiction. These data will be collected in a form that will allow direct comparison to the values specified in tables 3, 5, 6 and 7.

Table 8. Estimated sign replacement by jurisdiction type.

Type of sign (Color)	Aggregate Replacement Value[1]	State	County	City	Town	Combined
Warning (Yellow)	42	7%	4%	10%	1%	8%
Regulatory (Red)	11	10%	6%	23%	16%	16%
Regulatory (White)	58	7%	8%	17%	4%	10%
Guide (Green)	6	12%	7%	11%	0%	11%

[1] $cd/lx/m^2$

SUMMARY

It should be recognized that the development of minimum retroreflectivity values is not an exact process. This is a complex problem involving many driver, vehicle, roadway, and sign factors. The approach used in this report has attempted to consider the major factors that affect the luminance "demanded" by the driver and that "supplied" by the sign.

It is believed that the retroreflectivity values provided in tables 3, 5, 6 and 7 above balance the desire to satisfy all drivers in all situations and the need to provide practical, implementable values. Based on current knowledge, the recommended replacement values should provide an acceptable level of driver accommodation while not putting an undue burden on highway agencies in terms of percentage of signs to be replaced.

These values should provide highway agencies with objective values that can be used for implementing a maintenace schedule for traffic signs. However, the minimum retroreflectivity values or sign replacement are only a tool that must be used in conjunction with sound engineering judgement. The user must consider the characteristics at each sign installation to determine if the values shown will provide adequate sign visibility for the motorist. In unique geometric situations or areas with high background complexity, higher levels of retroreflectivity, larger signs, or supplemental information may be necessary to provide the motorist with sufficient visibility for detection and recognition.

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