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Minimum Retroreflectivity Requirements for Traffic Signs

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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			
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
	VOLUME			
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
	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/m²	cd/m²
	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			
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi²
km²	square kilometers	0.386	square miles	
	VOLUME			
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
	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/m²	candela/m²	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)

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CHAPTER 1. 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 first determines Minimum Required Visibility Distance (MRVD) for signs. The MRVD is "the distance at which a driver should detect a sign, recognize it, select an appropriate speed and path, and perform any required action safely and efficiently." The MRVD model serially sums the times associated with model components and converts that time to the distance required for appropriate reactions to a sign's message, at the specified vehicle speed.

Next the model uses the characteristics of the headlights, the roadway environment, and the driver to determine the luminance required to satisfy the driver visual demands at the MRVD. The model then calculates the retroreflectivity values (in terms of the coefficient of retroreflection (R_a)) necessary to provide the required luminance.

Finally, the minimum required sign retroreflectivity values are converted to values at standard measurement angles that can be measured by commercially available instruments. The resulting model is called Computer Analysis of the Retroreflectance of Traffic Signs (CARTS).

This report begins with background information on some of the major considerations involved in establishing minimum visibility requirements for traffic signs and summarizes previous research in this area. The next three chapters present each of the components of the CARTS model in detail. Chapter 6 includes findings from model evaluation and calibration efforts. Chapter 7 establishes the reference conditions that were used in executing the model. Finally, chapter 8 presents and discusses the recommended minimum sign retroreflectivity values as determined by this research.

CHAPTER 2. BACKGROUND

The goal of this chapter is to provide the uninitiated reader with a basic understanding of the significant issues related to minimum visibility requirements for traffic signs. This chapter will provide background information on sign performance measures, the visual processes involved in sign detection and recognition, and previous research on minimum visibility requirements.

A. SIGN PERFORMANCE MEASURES

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). R_a is defined as the ratio of the luminance of a surface viewed from a particular direction, to the illuminance at that surface on a plane perpendicular to the direction of the incident light. 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.

Research results on minimum visibility requirements for traffic signs are typically expressed in terms of luminance or retroreflectivity. While the use of luminance is more desirable from a driver needs perspective (because it is independent of the type of retroreflective sheeting), from a practical perspective the requirements must ultimately be specified in terms of retroreflectivity. The reason for this is two-fold. First, retroreflectivity is strictly a property of the sign material, while luminance is a function of both the material and the vehicle headlamps. If luminance were used as a minimum requirement it would also require that the light source and measurement geometry be specified. Secondly no commercially available devices exist that can be used to effectively measure luminance in the field. Hand-held retroreflectometers are widely available, and development of a mobile retroreflectometer for rapid measurement is underway. Currently, only laboratory research devices are available to measure luminance.

B. SIGN DETECTION AND RECOGNITION

The driver's visual experience of obtaining information from a sign in the roadway environment begins with the sensory detection that something is there and continues to recognition of the sign (e.g., legibility). While the detection process is characterized by greater and greater certainty as the driver moves closer to the sign, the precise nature of the dynamic process is unknown. The sensory detection threshold of a sign is generally taken as the minimum luminance contrast of the sign against its surround (the background environment) necessary for the driver to become aware that something is present. Contrast ratio is defined as the luminance at an object's edge divided by the luminance of the background. If the contrast ratio is close to one, the object will probably not be seen. For sign detection the contrast between the sign legend and the sign panel is defined as the internal contrast and the contrast between the sign panel and the background environment is referred to as the external contrast.

The likelihood of detection of a traffic control device located along the line of sight is dependent on five factors:

1. Luminance of the device.
2. Device's external contrast.
3. Device's size, color, and shape.
4. Viewing or observation time.
5. Angle of eccentricity.

In a real driving environment the driver must also be able to distinguish the sign from other competing targets (light sources, billboards, commercial signs, etc.). The ease with which the sign is capable of attracting the driver's attention when these other competing targets are present is called its conspicuity. A conspicuous sign is one that, by definition, stands out from its visual surroundings and, therefore, has a high probability of being detected in a short period of time. The conspicuity of a sign is a function of the detection factors cited above as well as the number, size, similarity, proximity and the relative position of other nearby visual elements in the surround.

Following detection of a sign are successive levels of identification and recognition, where various perceptual qualities about the sign become apparent, such as its specific location in space, its general shape and color, and message. Legibility is the end point of the recognition continuum when the observer can read a text message or accurately determine the form of a symbolic message.

One of the most important variables in determining the point at which a sign will become legible is the critical detail of the legend. The critical detail of an object is the smallest part of that object that must be discerned for recognition to occur. Knowledge of the critical detail for a sign legend coupled with an individual's visual acuity enables fairly accurate estimates of the legibility distance for that sign. For alpha-numeric messages the standard convention is to define the critical detail of a sign using the stroke width of the letters. Determining the critical detail of a symbol sign is a more difficult task. Unlike alpha-numeric signs there is no consistent aspect of symbol signs that can define the critical detail. The critical detail must either be estimated analytically or determined empirically. It is important to recognize that the critical detail (and thus the recognition distance) can vary from sign to sign (depending on the size and stroke width of the legend) and that the size of the sign directly affects the size of the critical detail. Chapter 6 contains a detailed discussion of how the sign critical detail was determined in this study.

In addition to the critical detail, other factors affecting sign recognition include the luminance of the sign, the internal contrast of the sign (the contrast between the luminance of the sign legend and the luminance of the sign background), and glare from opposing headlights and other light sources.

C. PREVIOUS RESEARCH

A significant amount of visibility research has been conducted focusing on individual components of the visual process associated with sign detection and recognition. This research was heavily drawn upon in the development of the CARTS model. A discussion of the pertinent studies is included in the following chapters.

Much less conclusive results are in the area of establishing minimum visibility requirements. As outlined in the introduction, the establishment of sign visibility requirements involves consideration of the complex relationship between the driver, the vehicle, the roadway, and the sign. Research in this area has been underway in various forms since as early as the late 1940's. This review of the literature is not meant to be all inclusive, but rather to highlight the results from some of the most significant efforts. The goal is to provide the reader with an appreciation for the difficulty of establishing minimum visibility requirements and the range of values that are found in the literature.

A good starting point for reviewing this literature is a 1983 report by Sivak and Olson.[2] This effort provided a summary of the research conducted to that point. Table 1 outlines the minimum visibility requirements as summarized in that report.

Table 1. Pre-1983 visibility requirements research.[2]

Author(s)	Year	Technique	# of Subjects	Subject Age	Result (Luminance)
Smythe	1947	Field	6	unspecified	4.6 cd/m^2
Allen & Straub	1955	Field Laboratory	8 19	25-30 20-35	3.0 cd/m^2
Allen	1958	Field	48	17-63	2.0 cd/m^2
Allen, et al.	1967	Field	45	18-58+	7.0 cd/m^2
Hills & Freeman	1970	Laboratory	3	unspecified	2.0 cd/m^2
Richardson	1976	Field	6	young	0.9 cd/m^2
Olson, et al.	1983	Laboratory	17	20-72	1.3 cd/m^2

The results shown in table 1 demonstrate the wide range of values that have been reported in the literature. The discrepancies can be attributed to a variety of reasons including, small sample sizes, different subject ages and visual acuities, differences in the experimental procedure used and the type of legibility task required, and difficulties associated with interpretation of results by researchers not involved in the original data collection.

In their report, Sivak and Olson attempt to provide a summary recommendation by computing the geometric mean of the results shown above. This value (2.4 cd/m^2) was used as the recommended replacement luminance for partially retroreflectorized signs and the legend luminance for fully retroreflectorized signs.

Based on this luminance value they went on to recommend the replacement coefficients of retroreflection (assuming U.S. type low-beam headlamps) for various driver percentile levels shown in table 2.

Table 2. Signs replacement criteria recommended by Sivak and Olson.[2]

		Sign Location			
Level	Luminance	Left[1]	Overhead[1]	Right[1]	Right Guide[1]
50th %	2.4 cd/m^2	90	114	24	27
75th %	7.2 cd/m^2	270	342	72	81
85th %	16.8 cd/m^2	630	798	168	189

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

Since 1983 several additional efforts have been undertaken in this area. Mace, King, and Dauber furthered the research by developing and field testing an objectively determined figure of merit for visual complexity that was directed toward determining sign luminance requirements for detection or conspicuity.[3] The field study required (15 alerted) subjects of ages ranging from 22 to 64 to drive a 38-km (24-mi) route, identifying yellow warning signs at three luminance levels in areas of high and low visual complexity. Detection and recognition distances were measured for each stimulus sign. It was found that sign luminance improved both recognition and legibility distances, but that visual complexity had no effect on legibility. Based on this study they recommended retroreflectivity values of 18 $cd/lx/m^2$ for low complexity situations, and 36 $cd/lx/m^2$ for high complexity situations, respectively. They also indicated that for certain high complexity situations larger signs, advance warning signs, or higher minimum retroreflectivity levels may be required.

As part of a research effort to establish minimum luminance requirements for signs Mace et al., examined a number of issues relevant to the present effort.[4] They evaluated the reasonableness of the values developed by Sivak and Olson by comparing the replacement decisions using their strategies versus subjective nighttime evaluations of 65 signs made by knowledgeable highway personnel. Given the amount of data it was not possible to fully evaluate Sivak and Olson's recommendations, but using the R_a value of 24 for right-mounted warning signs resulted in agreement between the criteria and the subjective evaluation.

Mace, et al., point out the effect that sign design features such as the stroke width of the legend (related to the critical detail), the height of the legend (related to the size of the sign), and the color of the sign, have on the establishment of minimum requirements.

The Mace study also documented efforts to determine minimum internal contrast ratios. From the literature they found a variation in the recommended minimums for this ratio as illustrated in table 3.

Table 3. Minimum internal contrast ratios.[5]

Source	Year	Minimum Ratio
Smyth	1947	3.3:1
Hills and Freeman	1970	6:1 to 10:1
Forbes, et al.	1976	3:1 to 7:1
Hahn, et al.	1977	3.85:1

In another effort, Morales conducted a study to determine retroreflective requirements for stop signs.[5] He used a controlled field study to obtain the relationship between sign retroreflectivity and recognition distance under ideal conditions. The study involved 20 subjects, including both younger and older drivers, viewing (0.76-m (30-in) stop signs covering a wide range of retroreflective characteristics. Table 4 provides a summary of results from this study for the 85th percentile test subject.

Olson also investigated the minimum luminance requirements for detection of signs by varying surround visual complexity, subject age, sign retroreflectivity, and sign color, and measuring the distances at which the test sign panels were identified.[6] A field study was conducted on public streets measuring the distances at which subjects driving a test vehicle were

Table 4. Minimum overall retroreflectivity values for stop signs recommended by Morales.[5]

Speed (mi/h)	Minimum Overall R_a [1]
25	3
35	5
40	7
45	10
50	18
55>	40

Overall $R_a = (0.76 * R_{red}) + (0.24 * R_{white})$

[1] cd/lx/m²
1 mi/ = 1.6 km/h

able to first detect and then identify the color of yellow, orange, red, green, blue, and white sign panels. Each panel had five retroreflectance levels and was viewed in three levels of visual complexity. Test drivers included 15 young (20 to 46 years) and 15 older (58 to 75 years) subjects; all were alerted. Visual complexity, age, retroreflectivity, and color were found to affect conspicuity. High-complexity areas required 10 times the sign retroreflectivity of low-complexity areas. Red, orange, green, and blue signs were shown to have substantially greater conspicuity than yellow signs (due to data collection problems, a conclusion on white signs could not be made). The older subjects needed three times the retroreflectivity of the younger drivers to obtain the same identification distances as the younger subjects.

Table 5 provides the recommended minimum red retroreflectivity values for stop signs. These values are for 0.76-m (30-in) stop signs and are corrected for driver expectancy. Where no values are shown and where values are unattainable by current signing materials, the authors recommend the use of supplemental warning signs.

It should be noted that when the correction for alerted drivers is removed these values compare favorably to those reported by Morales.

Table 5. Minimum red retroreflectivity values for stop signs recommended by Olson.[6]

	Area Complexity		
Speed (mi/h)	High[1]	Medium[1]	Low[1]
65	---	---	150
60	---	---	71
55	---	155	30
50	170	63	14
45	70	25	8
40	30	11	4
35	16	5	3
30	8	3	2

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

For warning signs Olson recommended minimum retroreflectivity values as a function of speed, complexity and the number of choices presented to the driver. Table 6 illustrates his recommendations for signs with 0 or 1 choices.

Table 6. Minimum yellow retroreflectivity values for warning signs recommended by Olson.[6]

	Area Complexity		
Speed (mi/h)	High[1]	Medium[1]	Low[1]
65	230	15	15
60	173	15	15
55	144	15	15
50	110	15	15
45	80	15	15
40	63	15	15
35	52	15	15
30	38	15	15

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

For overhead guide signs Olson considered the speed, area complexity, and the number of words on the sign. Table 7 illustrates the recommended minimum values for overhead guide signs with 6 words.

Table 7. Minimum green retroreflectivity values for overhead guide signs recommended by Olson.[6]

	Area Complexity		
Speed (mi/h)	High	Medium	Low
70	82	31	15
60	70	25	13
50	54	20	11
40	40	15	9
30	33	12	8

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

The most recent effort reported in the literature is also the study that most closely parallels the approach presented in this report. Australian researchers Jenkins and Gennaoui conducted a series of laboratory and field studies to "establish a minimum performance criterion of retroreflectivity, a terminal value, below which a sign would be ineffective."[7] The study included a subjective nighttime evaluation of inservice signs by experienced staff to select those signs which were near end of life. The mean and maximum values are shown in table 8. It should be noted that the authors felt that the mean values were low because some of the signs selected may have been well beyond their effective life.

The Australian effort also included laboratory studies of sign conspicuity and legibility using 10 subjects aged 24 to 57. From these studies they established a minimum luminance value of 3.2 cd/m^2 (0.9 fL) for signs with white legends (based on 16.2 cd/m^2 (4.7 fL) for the legend and 2.3 cd/m^2 (0.7 fL) for the background) and 9.7 cd/m^2 (2. 8fL) for warning and regulatory signs with black legends. They also found that a minimum internal contrast of three was desirable for fully retroreflectorized signs. To determine minimum retroreflectivity requirements the authors developed a computer modeling approach that considers the minimum distance required for legibility, the illumination falling on the sign, and the minimum luminance values found in the laboratory. In concept this approach is very similar to the CARTS procedure outlined in the following chapters.

While the authors did compute the minimum values for various sheeting colors and situations (table 8), they only used them for comparison of the subjective field evaluation and do not recommend that these values be used to implement the results of this research. They note that "the necessary retroreflectivity for a sign to be effective depends on the function of the sign and on the traffic situation and geometry in which it is placed." They recommend the use of their computer model to calculate appropriate retroreflectivity values for the individual sign and situation.

In comparing the model values shown in table 8 with those from the field survey, the authors note that the large difference between the model and the field values for yellow warning signs may be attributed to the fact that the very bold legends on many warning signs require very little retroreflectivity to be seen at night.

D. SUMMARY

The information presented above illustrates the complexity of the visual detection and recognition process and the difficulty associated with the selection of a single sign luminance (or retroreflectivity) replacement value or even a small number of values. As demonstrated in the literature, there are many factors that affect the amount of retroreflectivity demanded by the driver (age and visual characteristics of the driver, action to be taken, speed of the vehicle, background complexity, etc.) and the amount of retroreflectivity supplied by the sign (headlamp characteristics, internal contrast, sign color , sign size, etc.). The following chapters will attempt to address these issues by using a modelling approach to examine the relationship of these factors. The results will be presented in a structure that captures the most important factors in a way that they can be used by field personnel responsible for sign replacement.

Table 8. Minimum retroreflectivity values from report by Jenkins and Gennaoui.

			Field Survey	
Color	Application	Model R_a[1]	Mean R_a[1]	Max. R_a[1]
White (background)	Rural	75	---	---
White (background)	Urban	50	16	60
White (legend)	Stop Sign	40	10	55
White (legend)	Urban Guide	60	---	---
White (legend)	Rural Guide	100	---	---
Yellow	All	47	6	26
Red	All	5	4	14
Green	Urban Guide	8	2	12
Green	Rural Guide	13	---	---

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

CHAPTER 3. MINIMUM REQUIRED VISIBILITY DISTANCE (MRVD) SUBMODEL

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, as summarized in the next three chapters 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

This chapter discusses the MRVD submodel. The purpose of the MRVD was 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 elements that contribute to this distance are detection, recognition, decision making, (vehicle control) response initiation, and response performance and completion. Thus, the main components of the MRVD submodel are based on the drivers visual ability, "preparedness," and ability and opportunity to perform any required or desired maneuver.

A. BACKGROUND

A through review of the literature was conducted to examine the previous research on driver visibility needs. While numerous studies were found, it was felt that the concept of *Decision Sight Distance (DSD)* as developed by Alexander and Lunenfeld and later refined by others, best captured the entire process.[8] The DSD concept formed the basis for the development of the MRVD model. 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.[9] 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. Decisionmaking 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.

While the primary application of the decision sight distance concept was for hazard avoidance, it was easily modified and refined by Perchonok and Pollack and Mace, et al. for determining the detection and legibility requirements retroreflective traffic signs.[10,4] 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. Time requirements for lane change and speed change maneuvers; reaction time; decision time as a function of decision complexity; recognition time as a function of message length, complexity, and viewing angle; and detection time including eye fixations on and off the intended target and eye movement were used in the model. 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. This model is illustrated in figure 1.

B. MRVD OVERVIEW

The MRVD model conceptualized by Perchonok and Pollack was refined and 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 resulting MRVD model computes times and associated distance requirements for individual components of the model pertaining to critical events between the time of sign detection through the performance of an appropriate driver response (maneuver).

Mace and Gabel[11] developed a microcomputer-based implementation of the MRVD. This computerized MRVD requires the user to input the MUTCD code of a standard sign (or to describe nonstandard TCD's) and other needed information which varies with the specific sign. User supplied information includes specification of the driver's lane, lane width, visual complexity of the location, and traffic volume. Included in this program is a sign dictionary containing data describing the sign (e.g., number of lines of text, number of symbols, number of choices, type of response required, etc.).

For guide signs where there are no standard signs (only standard design guidance) and for recreational and service signs where complete design information is not available, "generic" signs were added to the sign dictionary. These generic signs, listed in table 9, were developed to be representative of typical inservice signs.

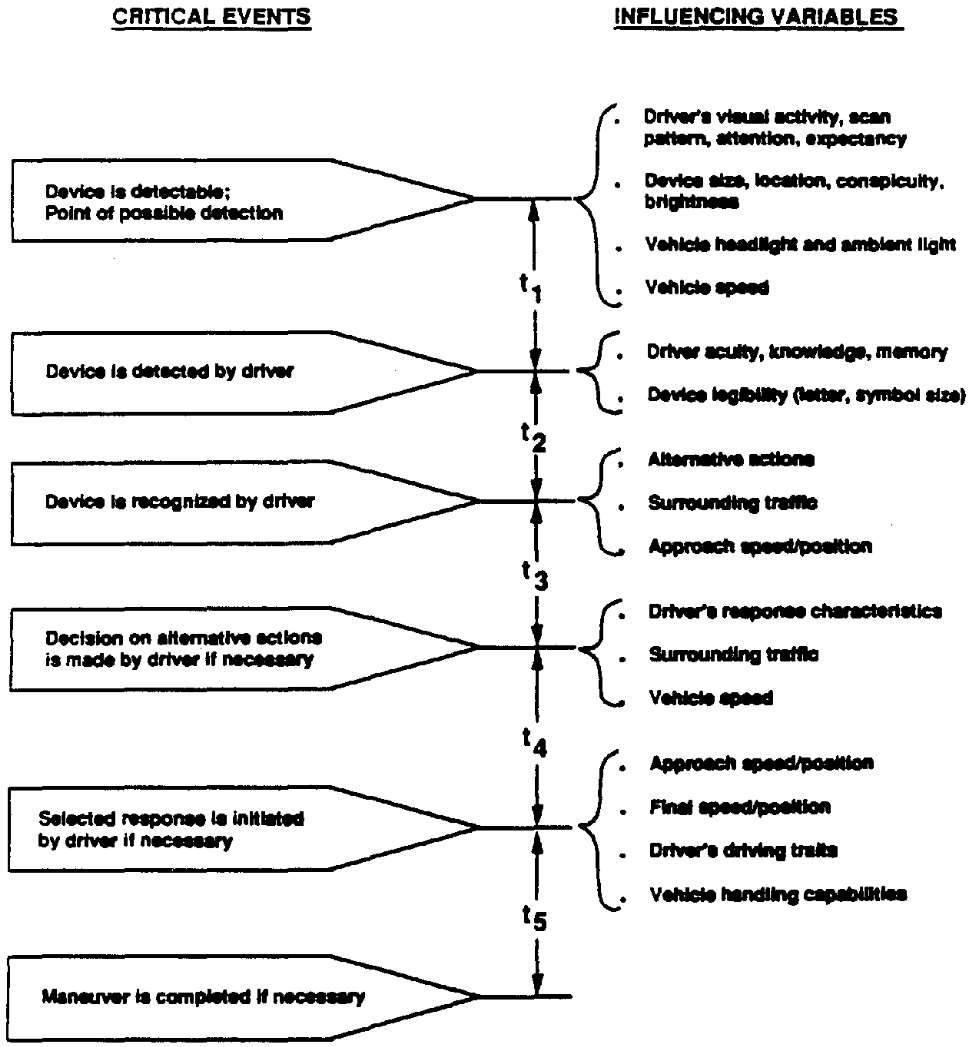


Figure 1. Analytical model of visibility requirements for signs.

Table 9. Generic signs included in the sign dictionary.

MUTCD Code	Sign Description
OG-1	Overhead Guide Sign
SG-1	Shoulder Guide Sign
RM-1	Recreational Information
RG-1	Service Information

These signs are used by the model as generic signs for a class of similar signs. The parameter values provided for these signs in the sign dictionary are sufficient for most non-symbol signs with Series D and E letters.

Not all signs demand detection distances that include all components of the MRVD model. Therefore, in the sign dictionary signs are classified according to those elements of the hazard avoidance process that are to be included in estimating the time during which they must be in the driver's field of view. Sign class is the variable by which the sign dictionary communicates to the MRVD model which components are to be included in the overall distance requirements. The sign classification system recommended by Perchonok and Pollack was used to classify the signs listed in the sign dictionary into three classes, based on what the driver must accomplish before reaching the sign.[10] The signs listed in the MUTCD were classified according to the scheme described below.

Meetings of FHWA personnel, project staff, and consultants resulted in the development of criteria for the classification of the signs to be evaluated by CARTS. Three sign classes were thus defined, and the classification system subsequently was embodied in the Sign Dictionary of CARTS. It should be noted that the original classification system developed by Perchonok and Pollack contained four sign classes. The definition of class II and class III signs were not felt to be significantly different and for the purposes of this research were all included as class III signs.

Class I signs are those that require the driver to complete all five of the critical events in the MRVD model: detection, recognition, decision, response, and maneuver before reaching the sign. It is assumed that class I signs are placed at a hazard and that the maneuver must be completed before the sign/hazard is reached. A vehicle maneuver is any required change in vehicle path or velocity. The STOP sign is an example of a class I sign - the vehicle must decelerate to a full stop between the time the driver sees the sign and reaches it.

Class III signs require a driver to detect and recognize the sign and make a decision before reaching the sign. Response and maneuver, if any, may occur after the sign is passed. The decision may concern any action that the driver decides to take or not to take as a result of the information received from the device. Advance warning and advance guide signs (but not guide signs at the decision point) fall into class III, as they prepare a driver for what may or may not be ahead, and imply that an action may be required downstream of the sign.

Their placement in advance of a hazard allows sufficient distance for maneuver completion, if necessary, after the sign is passed.

A Class IV sign requires only that the motorist detect and recognize the device itself. Neither a decision nor a response is required based upon this device alone. A Post-Interchange Distance sign (E7) provides the guidance information that may be helpful in the driving task but does not call upon the motorist to make a decision or take any action (at least not prior to passing the device).[1] General Service signs (D9) are other examples of Class IV devices.

The basic philosophy is to classify signs according to the reasonable worst-case scenario of situational and driver requirements. A worst-case scenario for a YIELD sign would be one in which a driver must come to a complete stop at a ramp entering a freeway to wait for an acceptable gap in traffic. The YIELD sign is therefore placed in the class I category. When a warning sign is placed at the point of a hazard (W1-7 two-directional large arrow placed across a "T" intersection, for example), the sign is categorized as a class I sign, rather than class III, because class III signs are erected in advance of a hazard.

Destination, marker, and information signs are classified as follows:

- Class I - when used in a gore area, or after a maneuver completion point (i.e., D-3 street name, D9-2 hospital with arrow, E5-1A exit number with arrow).

- Class III - when used at an approximate maneuver distance to maneuver point, and used to indicate a junction or need to turn to reach an identified destination or route, and includes either a junction panel or directional arrow (i.e., D1-1, D1-2, D1-3, M4-5, M5-1).

- Class IV - when used to give advance information where no maneuver is possible or required within a reasonable maneuver distance. (i.e., D2-1, D2-2, D2-3, which give mileage estimates to towns and cities, and I10-1, I10-2, I10-3, I10-4, I10-5, which give information about what city, borough, village, township, or county through which a motorist is traveling).

C. MRVD SUBMODEL COMPONENTS

The logic underlying the computation for each of the MRVD components is discussed below. The components include (1) detection, (2) reading or information processing, (3) decision, (4) driver response initiation, and (5) vehicle maneuver, and (6) out-of-vision.

Detection

The first phase of the information gathering process is the detection phase. This phase includes the process of "seeing" the device, although not recognizing or perceiving it as such. The process of detection during night conditions was discussed at length in an unpublished technical memorandum.[(11)]

In that memo, the detection process was described as a "progressive differentiation of the visual field" and six levels were defined as an attempt to describe the continuum of detection. The memo also describes a refinement of the operational limit given for the detection time used in the Decision Sight Distance Model used by McGee *et al.*[9]

The recommendation from that discussion was that the detection process include: (1) time for a driver fixation in an area away from the target, equal to 1.6 s; (2) time for the latency from peripheral detection of target to onset of eye movement, equal to 0.20 s; (3) time for eye movement to the target, equal to 0.05 s; and (4) time for fixation on the target, equal to 0.3 s. This sums to a total time required for detection, once the target is detectable as relevant to driving, of 2.15 s. If it can be assumed that the motorist is not fixating in an area away from the target, then time for a fixation away from the target is not needed and the required time would be only 0.55 s.

Data from Hooper and McGee were used to determine the time a driver might spend looking at road objects before looking at the sign.[13] Depending on the percentile driver, this time varies from 0.94 s to 1.25 s/object fixated. MRVD assumes 1 object fixated when visual complexity is low, 2 when visual complexity is medium, and 4 when visual complexity is high. This is to account for the fact that under higher volume levels the driver may have to switch back and forth between the sign and road objects several times before the information is acquired.

Reading (or symbol recognition)

This is the time the motorist needs to read and understand the sign. The time begins when the driver's eye first dwells on an element of the message or symbol and ends when the entire message is understood. "Understanding the message" is particularly relevant to symbol messages because the motorist first has to distinguish the symbol and then translate it into a message.

The MRVD contains two models, one based on Jacobs and Cole[14] for text messages and one by Halpern for symbols.[15] The Jacobs and Cole "resolution limited" model for message recognition is expected to provide greater accuracy than other reading models because it considers the length of text which may be resolved by the eye in one fixation. The comprehension time model for symbol signs is based upon research by Halpern which provides different estimates for young and for older drivers.

The recognition time models make a number of assumptions which are necessary to apply the data to all signs in the sign dictionary. First, MRVD provides a minimum reading time of 1 s. This value may be changed by the user. If the sign is designated an ICON, the recognition time is set equal to this minimum value. Second, MRVD assumes that all symbols are somewhat familiar and have equal difficulty. Finally it is assumed that either the reading model or symbol recognition model may be applied to signs containing both text and symbols.

The traffic Sign Dictionary provides a code which indicates whether the sign is primarily text or primarily symbol. This determines which model is applied. The traffic Sign Dictionary provides a code which indicates whether the sign is primarily text or primarily symbol. This determines which model is applied. The Sign Dictionary also provides MRVD with the number of symbols, words, and lines of text on the sign. MRVD assumes that all lines are of equal length and all symbols are of equal difficulty. If this assumption seems inappropriate, the user may change the number of symbols or number of lines in the sign dictionary to reflect more or less reading difficulty.

Symbol Signs: For symbols, the data from Halpern provided mean reaction times and standard deviations for four warning and four regulatory signs. Subjects were familiar with the symbols, which restricts the ability to generalize the results to symbols which are not familiar or readily understood. Data were provided for drivers under 25 and over 65.

Text Signs: If the sign is primarily a text sign, MRVD establishes the length of the legend to be read and the maximum glance time. The time and distance to read the sign text is computed according to the resolution limited model (RLM) of Cole and Jacobs.[16] The model has been made dynamic by increasing the distance where each segment of text is read to account for the distance traveled both while reading previous segments and while looking away from the sign as necessary to look at the road. The RLM is used to compute the maximum length of text readable in one fixation at the current distance (a text segment). If the entire legend is not readable in one fixation, the current distance is adjusted to account for distance traveled while reading the segment, and another fixation time is added to the reading time. RLM is then used again to calculate the next text segment length, and so on until the entire legend is accounted for. During this process, whenever the reading time exceeds the maximum glance time, the model adds a block of time, for the time required to look at the road. The current distance is also adjusted to account for this time.

The maximum glance time (MGT) is used to establish an upper limit to the time a driver is allowed to read a sign. Earlier versions of MRVD and the DSD model allowed the driver as much time as needed. MGT was introduced to provide a more realistic limit to the time a driver will read a sign before looking back at the road. The model included is based upon the concepts presented by Bhise and Rockwell and data supplied by Zwahlen.[17,18] The maximum glance time is 5 s, the minimum is 1 s. Zwahlen recommended a maximum occlusion time of 2 when the auxiliary task was operating a CRT touch panel inside a vehicle. Zwahlen also reported that occlusion times between 2 s and 4 s resulted in poor tracking performance. MRVD allows values of 4 s and 5 s maximum glance time with lower volumes and 3.7 m (12 ft) or greater lane widths. This is believed acceptable because the road may still be viewed peripherally when reading most traffic signs and therefore Zwahlen's results are not directly related.

For every sign the dictionary contains information on the number of lines of text on the sign and the proportion of the sign's width containing text. The layout of text on the sign is therefore ignored and the total legend is treated as a continuous stream by the model. MRVD assumes that all lines on one sign are the same proportion of the sign width (generally not true), and that this proportion remains the same over various widths of all signs with the same MUTCD code (generally true for standard signs). Using the width of the longest line may provide a total reading time that is conservative. In some cases it may be advisable to use a lower value to avoid an excessive reading time in the model.

The Cole and Jacobs resolution limited model (RLM) is conservative in that it applies to random sequences of familiar words from traffic signs. Shorter reading times might be observed with non-random sequences. Some evidence for this supposition was presented in a subsequent article by Jacobs and Cole.[14] The latter article also suggested that the RLM might overestimate reading time for signs with two or more lines of text. This issue is addressed in the MRVD by selecting between 50th, 75th, 85th and 95th percentile models (95th percentile data were used by Jacobs and Cole to derive the formula in their report).

If the distance at which a line of text must be read results in a detail size with a visual anyle less than about $^2/_3$ arc minutes, RLM returns a segment size of zero. This means that no message is resolvable at this distance. In order to provide some answer to the question of the required distance, the model assumes that all remaining lines of text are read at the rate of two lines per second.

An upper limit for reading time is placed on the model's results also. This is based on the number of words in the sign legend, rather than its physical length. Total reading time will be no more than the number of words in the sign legend divided by the number of driver eye fixations per second (currently 2).

Decision

During the decision period, drivers process the information obtained from a sign or device, assess any alternative courses of action, and select the intended action. The amount of time it takes for this phase depends upon the driver, the complexity of the information and alternatives, and the traffic density. Complexity of the information and alternatives has two components, complexity introduced by the road geometry and its visual delineation, and complexity introduced by the signed message and its regulatory basis.

Precise data on how long it takes a driver to handle information and make a decision are scarce. Forbes and Katz note that "...whenever the driver must judge a complex set of visual or other stimuli and make choices, judgments and decisions, his response time may increase to 2, 3, 5 or even 10 or more seconds."[19] Lunenfeld reported a relationship giving the information handling time as a function of information content.[20]

Using the data from Lunenfeld and engineering judgment, the values of 0.5, 2.5 and 4.5 s for low, medium and high decision complexity were recommended by Perchonok and Pollack and are used as default values in MRVD.[11] These default decision time values may be altered by the CARTS user.

MRVD selects a value from this table based upon the number of choices as coded in the Sign Dictionary and user input concerning traffic volume. This is done using table 10 taken from Perchonok and Pollack.

Table 10. Decision complexity as a function of traffic volume and number of choices.[11]

	Number of Choices		
VOLUME	0-1	2-3	> 3
Low	Low	Low	Med
Medium	Low	Med	High
High	Med	High	High

Response initiation

In the hazard avoidance model, the response phase occurs when the motorist performs a hand or foot movement after deciding what to do. This element is similar to reaction time in laboratory or controlled studies. A typical required response to a traffic sign is to take the foot off the accelerator and depress the brakes, or to dim the headlights from high beam to low beam. Brake reaction time was studied by Johansson and Rumar.[21] Using 321 drivers they found reaction times (in a dynamic situation) from 0.3 s to 2.0 s with an 85th percentile of 0.95 s. Since their subjects were in an alerted condition, they suggested a correction factor of 135 percent which raises the 85th percentile to 1.28 s. MRVD is applicable to the alerted condition since time has already been allowed for making a decision to brake. Therefore, the adjustment is not appropriate.

Data on other types of responses, such as steering wheel change or dimming lights, have not been identified, but they are not likely to exceed 1.0 s for a majority of the situations.

Considering the above findings, Perchonok and Pollack concluded that a value of 1.00 s could be used for the reaction component of driver detection requirements.[10] They saw no reason for establishing a range for this element, and noted that even the influence of age is small; consequently, the one value was used for all response times. MRVD follows this recommendation with the modification that a required response involving both a lane change and a deceleration is treated as two responses, each with its own initiation time.

Maneuver

Three critical maneuvers are typically performed in response to traffic signs. They are (1) stop, (2) speed reduction, and (3) lane changes. For stops and speed reduction, MRVD sets deceleration rates in all analysis cases to the American Association of State Highway and Transportation Officials (AASHTO) convention of 0.25 g, or 8 ft/s^2 (2.44 m/s^2).[22]

A review of existing literature on lane changing revealed a weakness in the existing state of knowledge. A controlled field study was conducted in this project to obtain data on the time required by drivers of a wide range of ages to perform lane change maneuvers under conditions of varying traffic volume and varying speeds of the driver's own vehicle and surrounding vehicles.

The two components to lane changing are searching for acceptable gaps in the adjacent lane and the actual lane change maneuver. The time (and distance) it takes to perform a lane change is a function of vehicle speed and traffic density (i.e., gap availability) of the adjacent lane. Under high-volume, high-speed conditions, it may take a considerable time for the motorist to identify an acceptable gap. Also, what constitutes an acceptable gap varies as a function of the motorist's risk-taking threshold.

In developing the original DSD values, the pre-maneuver element of lane changing, i.e., identifying acceptable gaps, was not considered in the maneuver element but rather in the decision process. Perchonok and Pollack recommended that gap searching time be considered part of the maneuver element.[10] Therefore, in computing MRVD, the decision component of the perception and reaction time should consist of only the time that it takes for a motorist to decide to change lanes.

The distance it takes to change lanes can be determined by computing the time required for search and maneuver at a given speed. For simplicity, MRVD assumes that the speed is constant during the lane change process.

The total search time consists of (1) visual input or processing times for the three principal sources of information - mirrors, rear window, and side window; (2) visual loss due to eye-hand movement; and (3) visual input time remaining for road ahead, traffic, etc.

The lane change maneuver study was conducted on a closed section of highway at three levels of speed: low/residential speed (40 km/h; 25 mi/h), moderate/ arterial speed (64 km/h; 40 mi/h), and high/freeway speed (88 km/h; 55 mi/h). A subject's decision to execute or delay a required maneuver was governed by the presence or absence of simulated traffic following the subject (decisional difficulty manipulation), in the adjacent left lane. The lane-change maneuver included three levels of decisional difficulty: no other vehicle in the left adjacent lane, a single vehicle in the adjacent lane following closely (small gap), and a single vehicle in the adjacent lane at a nonconflicting distance (large gap). The distances between the vehicles in the left lane again depended on vehicle speeds.

It may be noted that decisional difficulty was simulated by means of black and white videotaped images of a vehicle following the driver at varying degrees of closeness and moving at varying speeds in relation to the subject's vehicle. The scenes were presented on one of two small television monitors with a 0.13-m (5-in) diagonal screen placed where the outboard left side-view mirror and inside rear-view mirror are normally placed. Scenarios for the stop and speed reduction maneuvers were presented on the inside rear-view "mirror."

The dependent measures for each trial type were response latency, maneuver time, and total time. A computer-generated tone commanded subjects to check their rear view or side view "mirror" before executing each maneuver. This tone represented the point in the driver model at which the subject had detected, read, and understood the sign and the maneuver to be performed. Lane change response latency was defined as the elapsed time between the tone onset and the commencement of the subject turning the steering wheel to the left. The results of the maneuver field study were used in the calculation of components of the MRVD model for lane changes. Parametric data on lane change maneuver execution time, with estimates of the proportion of the driving population executing the maneuver within the times specified, are entered into the MRVD calculation procedure as a look-up table.

Lane change maneuver times derived from the controlled field study are shown in table 11 for initial speed (3 levels), traffic volume (3 levels) and percent of the driving population accommodated (4 levels) as determined in the field trials. The results at three levels of traffic volume are based on simulated gap conditions corresponding to freeway service levels A (low traffic volume), C (medium volume), and D (high volume).[22]

MRVD makes no distinction between left and right lane changes. No provision is made for multiple lane changes. It is assumed that the maneuvers for multiple lane changes are unlikely to be under the control of a single sign.

Table 11. Lane change maneuver times (s).

Speed (mi/h)	Traffic Volume	Driving Population Accommodated (percent)			
		50	75	85	95
<35	Low	3.1	3.7	4.2	4.9
	Med	3.2	3.5	4.0	4.6
	High	3.3	4.1	5.4	5.3
35-45	Low	3.0	3.5	3.9	4.2
	Med	3.0	3.6	4.0	6.0
	High	2.9	3.7	4.0	5.3
>45	Low	3.0	3.5	3.9	4.6
	Med	2.9	3.4	4.0	4.4
	High	3.1	3.7	4.1	7.3

1 mi/h = 1.6 km/h

Out of vision

The out-of-vision distance (OVD) is the distance determined by the maximum horizontal or the maximum vertical reading angles, which ever distance is larger. The horizontal angle reflects the location where a driver may no longer read a sign without losing peripheral sight of the roadway ahead. The vertical reading angle reflects the windshield's vertical cutoff as well as the motorist's field of clear vision. The maximum horizontal and vertical angles are set at 10° and 7.5° respectively. A number of references for these values are supplied by McNees.[23] The computation of OVD using the maximum horizontal angle is based on the values supplied to the program for sign offset, number of lanes, lane width, shoulder width, and sign width. The computation of OVD using the maximum vertical angle is based upon the value supplied for sign height and a driver eye height of 1.1 m (3.5 ft). The user may change the value for the maximum horizontal angle. If this angle is set to zero, OVD will be zero. If the sign offset is zero or the sign height is zero the corresponding angles are set equal to zero. Out of vision distance is set equal to the largest of the two components (OVD computed using the maximum horizontal angle and OVD computed using the maximum vertical angle). If both are zero, out of vision distance is zero.

D. SUMMARY

The MRVD submodel computes the distance required by the driver to respond safely 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.

CHAPTER 4. INVERSE-PROGRAMMED DETECT (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.

This chapter discusses the IPDET submodel. The purpose of this submodel is to use the distance supplied by the MRVD submodel and to determine the sign luminance required to provide this visibility distance. The luminance value is then converted to a retroreflectivity value.

A. BACKGROUND

As with the development of the MRVD, a thorough review of the literature was conducted. Given the large number of variables involved and the complexity of the relationships between these variables, a mathematical modeling approach was deemed most appropriate. This was the same conclusion reached by Jenkins and Gennaoui as outlined in chapter 2.[7] From the literature review, the seeing distance model developed by Bhise et al. and Matle and Bhise was found to include many of the variables of interest.[24,25] This seeing distance model, named PCDETECT, is based on the human visual-performance model published by the International Commission on Illumination (CIE).[26] 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.

Originally designed as the module that calculated seeing distances as part of a comprehensive headlamp evaluation model, the predecessor to PCDETECT, DETECT was a public domain FORTRAN mainframe computer program for computing seeing distances to targets such as roadway delineation, pedestrians, vertical squares and traffic cones under a wide range of conditions. The program user provides input information by defining the headlamp types for observer and opposing vehicles, target characteristics such as size and the reflectivity coefficient, road geometry and certain environmental factors. The program calculates the threshold visibility distance (50 percent probability of detection) with or without glare from opposing vehicles and/or fixed lighting sources. The visibility calculations are based on Blackwell's contrast threshold data which represent highly practiced and alerted subjects, as noted by Sivak and Olson,[27] and incorporate the Fry glare equation for the effect of disability glare.[28]

The application of the Blackwell and Fry laboratory-based formulations to the detection of roadside and roadway targets was demonstrated and validated in limited field studies conducted by the Ford Motor Company. Contrast threshold multipliers were developed to account for the effects of target complexity, transient adaptation, age related visual performance degradation, driver alertness, and different threshold requirements for redundant (delineation) targets and for unique (pedestrian or sign) targets. A revised version of DETECT, renamed PCDETECT, has been developed for operation on IBM-compatible personal computers.[29] The PCDETECT model incorporates a number of improvements. Included are Blackwell's most recent contrast sensitivity research and new procedures for calculating contrast thresholds which account for driver age-related performance differences, target size, background luminance and individual observer differences.

B. IPDET OVERVIEW

As described below and in material previously published by Farber and Matle, DETECT and PCDETECT are headlamp-seeing distance models. They use human contrast sensitivity formulations to calculate the distance at which various types of objects (referred to as "targets") illuminated by headlamps first become visible to approaching drivers. PCDETECT deals with several types of targets, including traffic signs.

An understanding of the logic which PCDETECT uses to calculate a target's visibility distance is central to discussion of the present technical approach. To begin, the definition of "visibility" depends on the target. For all target types except pavement markings and traffic signs, the visibility distance is the distance at which the driver is first able to <u>see</u> the target as a separate target. No assumptions are made regarding the relationship between seeing and recognition. The algorithms assume an attentive driver. For traffic signs, PCDETECT calculates both the seeing distance to the sign panel itself and the legibility distance of the sign elements, i.e., letters or symbols.

Briefly, the core of the model is an algorithm for determining the threshold luminance contrast between a target and its background. The threshold contrast is the contrast at which the target is just discernable to an attentive observer. PCDETECT uses an iterative procedure to increase and decrease the distance between the observer's vehicle and the target until it finds the distance at which the target is at the threshold, i.e., is just visible to the observer-driver. In the model, the distance between the observer's vehicle and the glare source is held constant throughout the iteration process. This means that in PCDETECT, the glare car moves back and forth with the observer's car during the distance iteration process. PCDETECT also provides the option of multiple glare vehicles whose distances from the observer's car are based on traffic volume. Extensive testing under laboratory conditions with subjects spanning a large range of ages have provided norms which include the variability of performance within age groups.

This model does not take into account the cognitive effects of aging such as the drop in efficiency of directed visual search and the diminished capability to disregard irrelevant information in a scene, since the laboratory task upon which the normative data are based did not include complex scenes. However, the model lends itself to quantitative treatment and was found to correlate well with the subjective visibility ratings of drivers who assigned judgements to objects placed on a roadway under night lighting conditions.

The PCDETECT model was developed to establish the <u>distance</u> at which traffic control devices were detectable under various illumination and glare conditions. The MRVD submodel established the minimum distance required based on drivers' needs to respond to TCD's. The minimum sign <u>luminance</u> at the MRVD must now be established. This is the inverse of the problem solved by the DETECT/PCDETECT models, but it is also derived from the CIE visibility model, i.e., the luminance required is based on normative data that allow specification of the percentile level of any observer's visual ability compared to other observers of the same age. Accordingly, the Inverse-PCDETECT (IPDET) model was formulated determining for the required luminance at a specified distance. 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.

A critical component of the CIE model (and therefore of IPDET) analysis logic is the assignment of an appropriate visibility level (VL) to define the luminance that is adequate for a particular visual task. Visibility level is the ratio of the contrast of a particular visual task to the contrast of the reference visual task. The reference visual task consists of detection of the presence or absence of a 4-min arc disk located on the visual axis, presented for 200 ms in 1-s trains, at a background luminance of 100 cd/m^2 (29.2 fL). At a VL of 1, the reference visual task yields a 50 percent correct target detection rate. The luminance of a target that produces this correct detection rate yields the threshold contrast for a particular observer. At a VL of approximately 2, target contrast is high enough to produce maximum correct detection performance under laboratory conditions. For the reference visual task, this maximum rate is 100 percent correct detection, although other tasks may be made difficult enough to preclude 100 percent correct detection no matter how easily visible the target(s).

By comparing the performance of the same observer on the reference task and on any other visual task under conditions in which the task contrast is known, visibility levels corresponding to the reference task can be assigned. Normative data on a large number of observers have made it possible to determine the performance of observers at one background luminance and generalize to other luminance levels, as well as other comparisons between a wide variety of visual stimulation conditions. However, the performance of observers on the reference visual task compared to the task of correctly identifying TCD's in a dynamic environment has not been conducted. Therefore, the assignment of the VL that is appropriate to the detection and recognition of TCD's under road conditions, for the purpose of developing the computerized implementation of the CIE visibility model, assumed a required VL of 1 for legibility (or recognition). In the case of conspicuity, a VL of 10 was assumed to be necessary to provide the luminance for an unaltered driver to detect a target. Performance norms based on the distribution of visual abilities in the driving population were used to generalize to individual observer norms, and the criterion visibility levels were adjusted to predict the minimum required luminance for specific signs.

For fully retroreflectorized signs, minimum retroreflectivity values are required for both the legend and the sign panel. In order to ensure that the luminance of the panel is sufficient for color recognition an iterative program has been written which adjusts the retroreflectance of a color and calculates the luminance. The luminance is then compared with the minimum required luminance for color recognition provided by Forbes.[30] Forbes' data were obtained under a variety of background luminance; however, only the values appropriate for an ambient background, equal to 0.127 cd/m^2 (0.04 fL), were incorporated into the CARTS program. The IPDET submodel is then used to determine the required contrast, which given the retroreflectance of the panel determines the retroreflectance of the legend.

C. SUMMARY

The IPDET submodel is based on the PCDETECT "seeing distance" model. This model in turn is based on the CIE visual-performance model. 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. The required retroreflectivity at the MRVD entrance and observation angles is computed using this luminance value.

CHAPTER 5. STANDARDIZED RETROREFLECTIVITY MEASUREMENT (SRM) SUBMODEL

As outlined in chapter 4, the IPDET submodel determines the luminance required at the MRVD distance. This luminance is then translated into a required retroreflectivity. However, this retroreflectivity is specified at the entrance and observation angles which exist at the MRVD. Since 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 entrance and observation 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.

The SRM is based on measurements of retroreflective sign materials, at a range of entrance and observation angles and basic geometric principles. The SRM defines a straightforward nighttime visibility system consisting of a vehicle, retroreflective target, and observer; and allows a user to mathematically model the component aspects of the system so that the R_a values specified at the MRVD can be translated into required R_a values at standard entrance and observation angles.

A. BACKGROUND

The R_a for 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 plan view in figure 2.

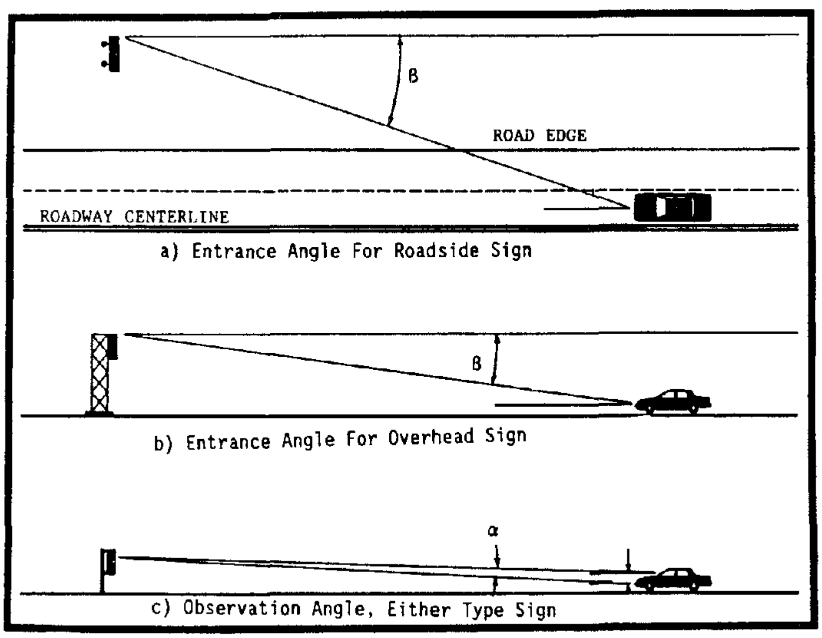


Figure 2. Entrance and observation angles in retroreflectivity measurement.[31]

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 target TCD 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.

B. SRM OVERVIEW

As was noted above, the SRM provides the translation of R_a values specified at the MRVD entrance and observation angles to values at the standard observation and entrance angles (0.2° and -4°). 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 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 3 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°).

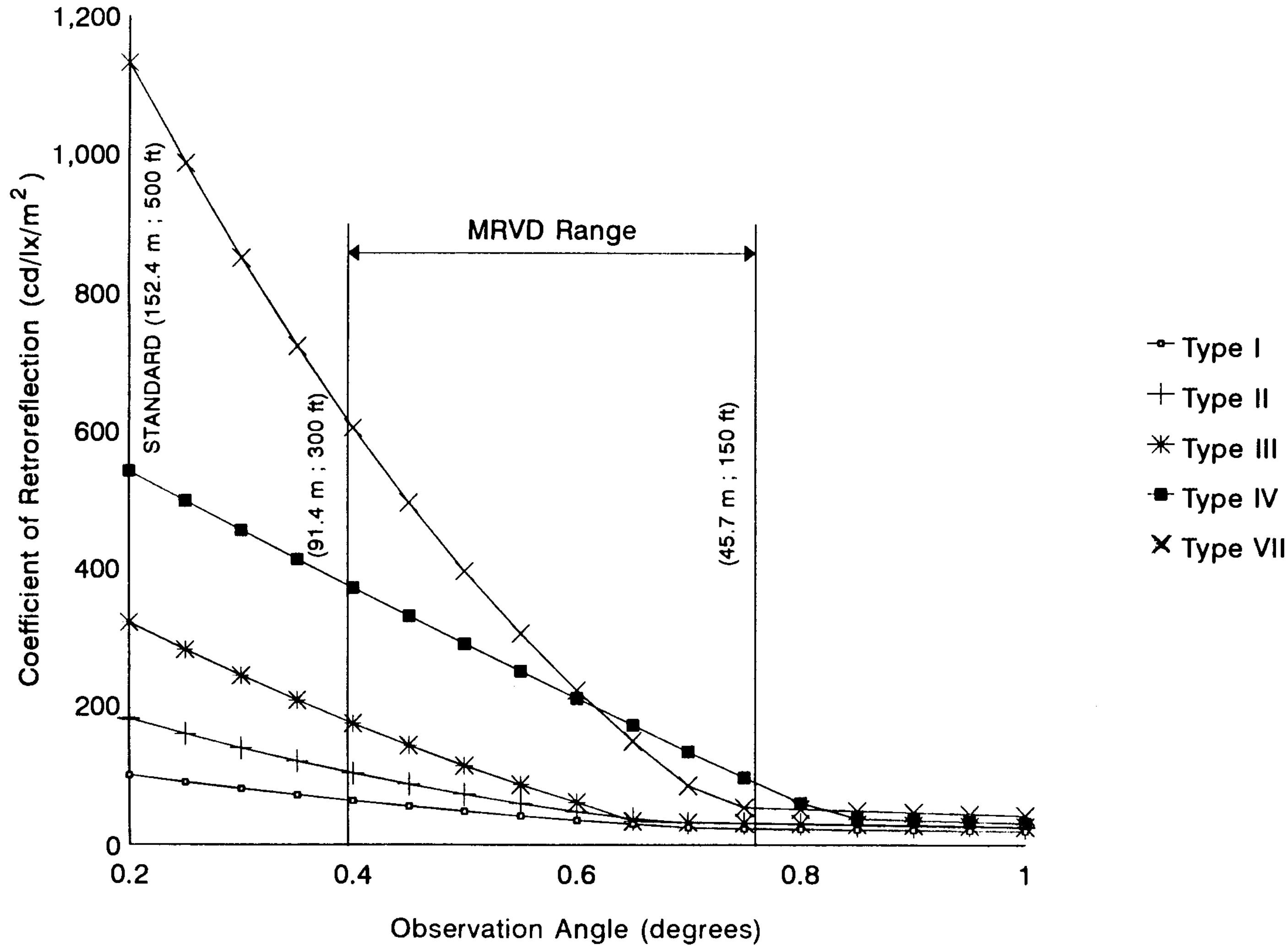
The model used to fit the curves is a continuous piecewise function in which a quadratic equation is used for observation angles less than approximately 0.7° and a linear equation is used for observation angles greater than 0.7°. The precise transition point between the quadratic and linear pieces varied among the sheeting types. The mathematical form of the model is:

$$R_a = b_0 + b_1A + b_2S + b_3AS + b_4(1-S)A^2$$

where

A = observation angle
S = "switch" variable, with value of zero before the transition point and a value of 1 after the transition point.

Figure 2. Relationship between coefficient of retroreflection observation angle



The function is estimated separately for each material type and separate equations are also developed for nine entrance angles covering the range outlined above.

It should be noted that log-linear models as well as various transformations of retroreflectivity were attempted. All were rejected using the "pure error" F test which compares the sum of squared errors for the model to the sum of squares for pure error. The sum of squares for pure error is the sum of squared error which would result if the predicted mean retroreflectance was exactly equal to the actual mean retroreflectance at each observation angle. The piecewise model was the only one which passed the lack of fit tests, with a p-value greater than 0.05, over all signing types and entrance angles. Although the model does not provide insight into the relationship between retroreflectivity and observation angle it does provide an excellent fit for interpolation and prediction.

Equation coefficients were estimated using the laboratory data for white sheeting materials. Curves for the other colors were determined to be proportional to the white curves. Coefficients of proportionality were estimated for each color by sheeting type combination.

C. SUMMARY

The SRM submodel provides the mechanism to translate the retroreflectivity values which are specific to the MRVD entrance and observation angles to values at the standardized observation and entrance angles. This translation must be performed separately for each material type since the relationships between retroreflectivity and observation and entrance angles varies by material.

CHAPTER 6. CARTS EVALUATION AND CALIBRATION

As noted in the earlier chapters, 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.

A. CARTS MODEL CALIBRATION

One of the primary areas of concern in the operation of the CARTS model was the estimate of critical detail size of the legend. The critical detail (CD) of an object is the smallest part of that object that must be discerned by the driver in order for recognition to occur. As discussed in chapter 2, the critical detail of the sign legend is a key variable that affects the recognition of a sign.

Knowledge of an object's critical detail coupled with an individual's visual acuity enables fairly accurate estimates of the threshold legibility distance for that object and subject. Critical detail is operationally defined as the stroke width (SW) for acuity measurements using letters such as those used on Snellen charts or standard alpha-numeric traffic signs as targets. While there is some question as to whether SW must be discerned by drivers's for recognition of all alphabetic characters under all standard FHWA letter series, the convention of describing the critical detail of letters via their SW has at least provided a consistent and relatively reliable predictor of individual performance based on acuity scores.

Determining the critical detail of a symbol sign was a more difficult task. Unlike alpha-numeric signs, there is no consistent aspect of symbol signs that can define the critical detail; each symbol must therefore be analyzed individually to determine the component necessary and sufficient for recognition to occur. An analytical assessment of the CD for highway symbol signs was conducted as part of the current project. These estimates of critical detail, were based upon a judgement of the smallest important detail. In many cases where there is little or no variability in detail size, such as the curve warning or road narrows symbols, we would expect this judgement to be quite accurate, i.e. the CD should equal the SW of the bar. In other cases, where there is a lot of variability in detail size, such as a deer symbol, a sizeable error might have occurred in the analytical estimate.

The critical detail of every sign is stored in the sign dictionary as a height-to-stroke-width ratio. The ratio is multiplied by the height of the letter (or symbol) to obtain the critical detail. The height of a letter (and therefore the critical detail) varies with the size of the sign.

The CARTS model uses the critical detail in the determination of the minimum luminance requirements. One goal of the CARTS calibration was to use empirical data to provide better CD estimates for symbol signs. The empirical data were obtained from studies conducted as part of this effort as well as from the literature.

A procedure for empirically determining the critical detail of symbols was suggested by Howett.[32] Using known acuity scores for a subject, or group of subjects, the minimum detail that can be discriminated by that subject or group is calculated for the threshold distance of any symbol sign.

As part of this study, a laboratory study was conducted to provide empirical data on the critical detail of symbols.

Thirty-three signs were included in the laboratory study. These signs were selected to cover a broad range of colors, shapes, legend types, letter series, stroke widths, and complexities found in use. To test the validity of the Howett procedure, the critical detail of six signs containing alphabetic characters of varying stroke widths was calculated. The data for these six signs were averaged for all subjects in both high and medium luminance conditions. The results are plotted in figure 4. The data plotted represents the predicted stroke width of the letters versus their actual stroke width. The straight line represents perfect agreement between stroke width of the letters and predicted critical detail. Only one sign ("Use Lane With Green Arrow") resulted in a serious error in estimating critical detail.

The analytically estimated CD size for 28 symbol signs were then compared to empirically estimated values obtained from the laboratory study and an earlier effort by Paniati.[33] Table 12 presents the results of this comparison. Both the critical detail and the CD/height ratio are reported for each symbol for each study and the analytically derived value contained in the initial sign dictionary. The CD/height ratios allow the comparison of CD sizes for different size signs and different size symbols. Of the eight symbols common to both empirical studies, the critical detail estimates are similar for all but the "Deer Crossing" symbol.

A comparison of the laboratory study data and Paniati's data with the analytical estimates suggests that for most symbols the analytical CD/height (and thus the CD size) is larger than the empirically derived values. This means that the distance at which drivers recognize symbols is shorter than the distance at which the smallest detail would be resolved by the eye. This finding may be explained by the fact that some symbols are larger and more complex than letters, therefore the eye may have to resolve more than one feature before recognition occurs. Since the experimental paradigms included movement toward the sign, then the time required for recognition may have resulted in shorter legibility distances and therefore larger predicted CD size.

Table 12. Comparison of analytically defined vs. empirically estimated CD size.

MUTCD CODE	SYMBOL DESCRIPTION	SIGN SIZE	SYMBOL HEIGHT	CRITICAL DETAIL LABORATORY	CRITICAL DETAIL PANIATI	CD/HEIGHT LABORATORY	CD/HEIGHT PANIATI	CD/HEIGHT ANALYTICAL
R4-7	Keep Right	24	25.00	1.59		0.064		0.147
R9-3a	No Ped Xing	18	11.00	0.65		0.059		0.086
W1-1	Turn	30	15.94		2.16		0.136	0.274
W1-4	Reverse Curve	30	24.88		1.54		0.062	0.180
W1-5	Winding Road	30	30.16		1.55		0.052	0.135
W2-1	Cross Road	30	25.00	2.12	2.55	0.085	0.102	0.200
W2-2	Side Road	30	25.00		1.93		0.077	0.200
W2-4	T-Intersection	30	20.63		2.14		0.104	0.242
W3-1a	Stop Ahead	36	13.70		2.25		0.167	0.444
W3-2a	Yeild Ahead	36	24.25	1.71	2.20	0.071	0.091	0.150
W3-3	Signal Ahead	36	31.50		2.37		0.753	0.364
W4-1	Merge Arrow	30	24.00	1.43	1.04	0.060	0.043	0.252
W4-2	Lane Reduction	36	28.00	1.81	1.85	0.065	0.065	0.143
W4-3	Added Lane	48	28.00		1.56		0.056	0.333
W5-2a	Narrow Bridge	36	24.00	1.10	0.72	0.046	0.030	0.031
W6-1	Divided Hwy Ahead	36	26.00	1.90	2.11	0.073	0.081	0.154
W6-3a	Two-Way Traffic	30	21.88		1.71		0.078	0.171
W7-1	Hill	30	9.25		1.03		0.111	0.079
W8-3a	Pavement Ends	36	3.70		0.70		0.189	0.172
W8-5	Slippery When Wet	30	12.50		0.80		0.064	0.083
W8-9a	Low Shoulder	30	15.00		0.83		0.055	0.048
W11-1	Bicycle Crossing	30	20.00		1.33		0.067	0.088
W11-2	Pedestrian	30	27.00		1.04		0.039	0.882
W11-3	Deer Xing	30	23.50	1.66	0.64	0.071	0.027	0.014
W20-7a	Flagger	36	28.13	1.60	1.90	0.057	0.068	0.060
W21-1a	Worker	36	28.88		0.90		0.031	0.156

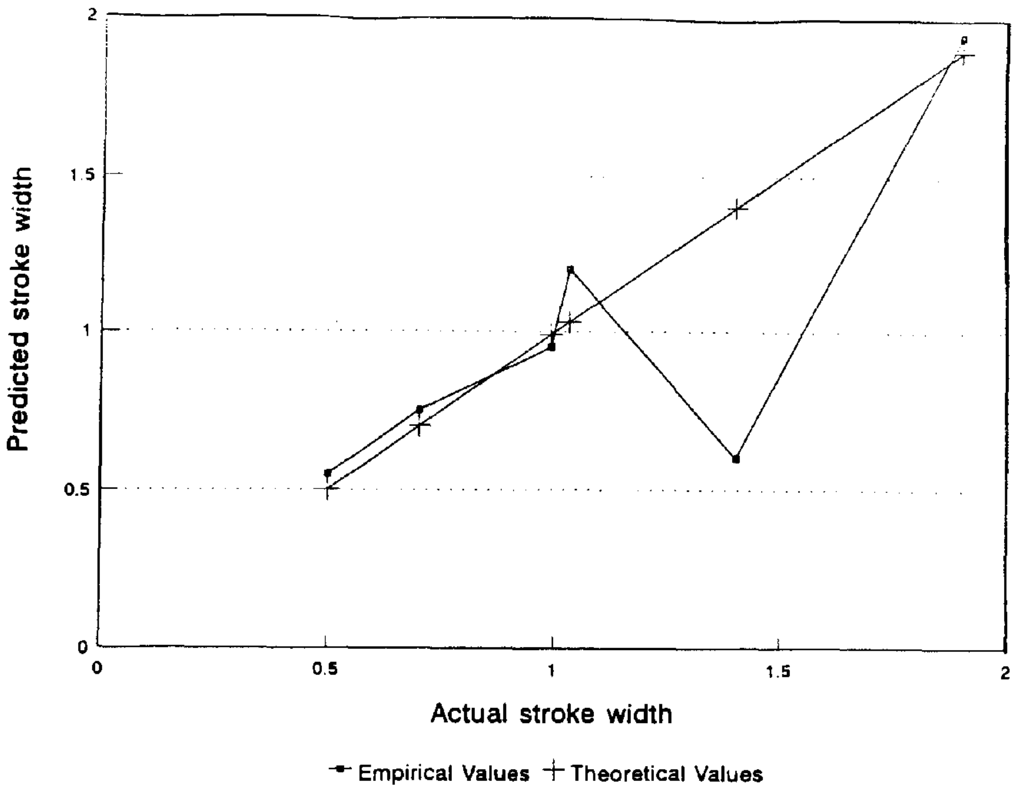


Figure 4. Comparison of actual and predicted stroke widths.

A further comparison of the analytic and empirical data was made by dividing the empirical CD/height ratio by the analytical CD/height ratio. An examination of the empirical/analytical data revealed that the values could be grouped and thus the symbols were divided into the five classes which are shown in tables 13 through 17. The first three groups (tables 13 through 15) contain symbols that require more detail than the analytic estimate (values less than 1.0). The largest class (table 14) consists of those symbol signs that have symbols with elements of generally constant stroke width as well as a few other signs (pedestrian, worker) that have similar empirical to analytic ratios. The standard error of the critical detail for these symbols was computed and found to be in the range of 0.02 to 0.05. This suggests that there are no real differences between the symbols in this group.

Table 13. Signs with empirical CD size 20 percent of analytic CD size.

MUTCD	SIGN TYPE	LABORATORY	PANIATI
W4-1	Merge	.24	.17
W3-3	Signal Ahead		.21

Table 14. Signs with empirical CD size 45 percent of analytic CD size.

MUTCD	SIGN TYPE	LABORATORY	PANIATI
W1-4	Reverse Curve		.34
W3-1a	Stop Ahead		.38
W1-5	Winding Road		.38
W2-2	Side Road		.39
W2-4	T-Intersection		.43
R4-7	Keep Right	.43	.43
W11-2	Pedestrian		.43
W6-3	Two-Way Traffic	.45	.46
W4-2	Lane Reduction	.45	.46
W1-1	Turn		.50
W2-1	Cross Road	.42	.51
W6-1	Divided Highway Ahead	.48	.53
W21-1a	Worker		.60
W3-2a	Yield Ahead	.47	.61

Table 15. Signs with empirical CD size 75 percent of analytic CD size.

MUTCD	SIGN TYPE	LABORATORY	PANIATI
R9-3a	No Ped Xing	.69	
W11-1	Bicycle Crossing	.72	.76
W8-5	Slippery When Wet		.77
W4-3	Added Lane		.79

There were four symbols in table 16, for which the analytic estimate of CD size seems accurate. Three symbols in table 17 appear to be recognizable with less than the analytic detail being resolved. The deer is recognized without the small antler, the hill symbol without the tow bar, and the MUTCD S1-1 pedestrian symbol is recognized without resolution of the narrowest leg.

Table 16. Signs with empirical CD size equal to analytic CD size.

MUTCD	SIGN TYPE	LABORATORY	PANIATI
W5-2a	Narrow Bridge	1.48	.94
W8-3a	Pavement Ends		1.11
W20-7a	Flagger	.95	1.13
W8-9a	Low Shoulder		1.15

Table 17. Signs with empirical CD size greater than analytic CD size.

MUTCD	SIGN TYPE	LABORATORY	PANIATI
W7-1	Hill		1.43
S1-1	School Advance		1.55
W11-3	Deer Xing	5.04	1.94

With the exception of the constant stroke width symbols, the critical detail in the sign dictionary was replaced with the empirical estimate. Since the Paniati data were quite similar to the Ketron data, and since their were more symbols in the Paniati set, we used the estimate of CD size from the Paniati data whenever one was available. The KETRON data were only used when a corresponding number was not available in the Paniati set. With regard to the Deer Crossing symbol which reflected the largest difference in the two sets of data, the choice of the Paniati estimate resulted in a more conservative estimate. The analytic critical detail of all signs with constant stroke width were reduced by a factor of .45. These signs are listed in table 18.

Table 18. Signs for which CD size was reduced by 45 percent.

MUTCD Code	Sign Description
R 3-1	No Right Turn
R 3-2	No Left Turn
R 3-4	No U-Turn
R 3-5	Arrow
R 3-6	Mandatory Movement
R 3-8	Lane-Use Control
R 3-9a	Two Way Left Turn Only
R 4-8	Keep Left
W 1-2	Curve
W 1-3	Reverse Turn
W 1-6	Large Arrow
W 1-7	Double Head Large Arrow
W 1-8	Chevron Alignment
W 2-3	Oblique Side Road
W 2-5	Y Intersection
W 6-2	Divided Highway Ends
W12-1	Double Arrow (Traffic To Either Side)
M 5-1	Advance Turn Arrow
M 5-2	Advance Oblique Turn Arrow
M 6-1	Turn Arrow
M 6-2	Oblique Turn Arrow
M 6-3	Straight Arrow
M 6-4	2-Headed Arrow
M 6-6	Right Angle 2-Headed Arrow
M 6-7	Acute Angle 2-Headed Arrow

Once the changes were made to the constant stroke width symbols and all other signs for which empirical estimates were available, there were very few other signs which required CDS estimates. Three signs were given CDS estimates from similar signs for which empirical data did exist. For the MUTCD R5-6 No Bicycle sign, the estimate for a W11-1 Bicycle Crossing sign, was substituted. For the W11-2a Pedestrian Crossing sign, the CD size of W11-2 Advance pedestrian crossing was substituted. For the S2-1 School Crossing sign, the the CD size of the S1-1 School advance sign was used.

For other symbols; where emperical data were not available we were unable to find a consistent rule that would allow us to estimate the critical detail. Due to the absence of a basis for change, the analytic CD size was retained for the six symbols in table 19.

Table 19. Symbol signs using analytic CD size.

MUTCD Code	Sign Description
R5-2	No Trucks
R7-201a	Tow Away Zone
W10-1	Railroad Advance Warning
D9-2	Hospital
D5-5a	Picnic Area
I-5	Airport

B. CARTS EVALUATION

The evaluation of the CARTS model centered on the ability of the model to accurately compute threshold contrast and luminance. The CARTS model was systematically exercised and the results compared with values reported in related literature. The literature included CIE 19/2.1 to compare the graphs describing Blackwell's threshold contrast formulae with the implementation of those formulae in the program; Howett to compare CARTS output with the acuity data of Kaneko; and several studies reported by Forbes to compare field study results regarding legibility distance as a function of sign panel brightness. (See references 26,32,34,35)

CIE 19/2.1.

The first investigation was done to verify the threshold contrast computation in CARTS. The model was repeatedly executed with the goal of replicating the *Visibility Reference Function* of *CIE 19/2.1* which contains the threshold sensitivity model which is the basis of IPDET.[26] This function determines the "reference threshold contrast" for given levels of reference (background) luminance. This first investigation proved that the model accurately reflects the Blackwell formula for threshold contrast given *CIE 19/2.1*. The reference conditions specified a visibility target spanning 4 min of visual arc and an observer between 20 and 30 years of age.

Further verification compared CARTS results against the relative contrast sensitivity (RCS) graphs in *CIE 19/2.1*. RCS is defined for a particular reference luminance as the ratio of the visibility reference function at that reference luminance to the value of the visibility reference function at a luminance of 100 cd/m^2 (29.2 fL). The RCS reference function from *CIE 19/2.1* including the effects of detail size on RCS, were also duplicated by the CARTS model. The age-dependent multipliers m_1, m_3, m_4, T, and S reported in *CIE 19/2.1* were also verified, as the model produced the expected values.

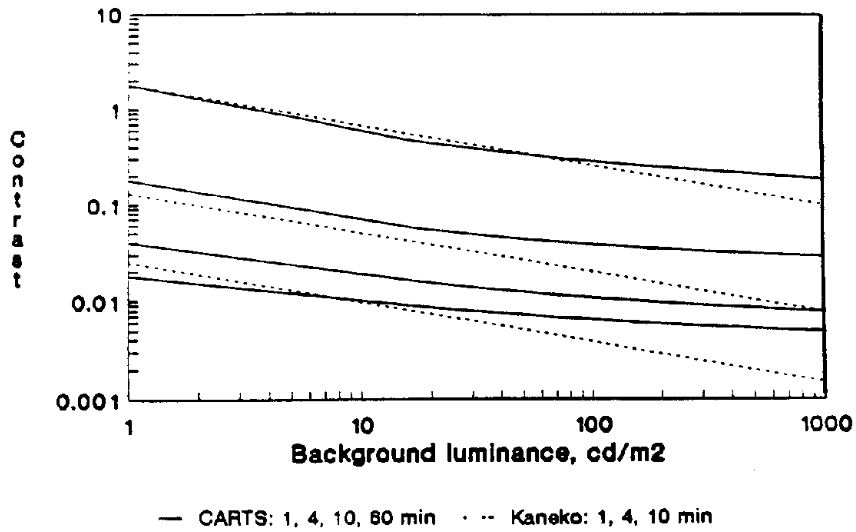
Howett

Howett reported a formula by Kaneko which relates the background luminance of a target and the visual acuity of an observer to the required target-background contrast.[32] In order to compare this formula with the CARTS program, the formula was programmed to solve for the required contrast given the background luminance and the target size, which is derived from the observer's acuity. Again, the CARTS model was exercised and the resulting threshold contrast compared to the Kaneko formula, as shown in figure 5. The functions are not identical; the Kaneko formula is log-linear while the Blackwell formula is curved, but in the range of background luminance for which the Kaneko formula is claimed to be valid and for target sizes of 1 and 4 minutes, the functions are very similar.

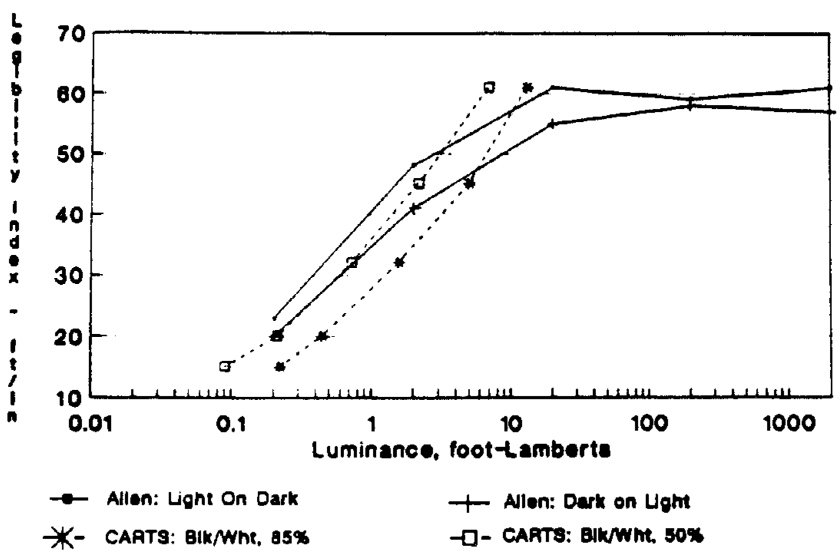
A maximum critical detail size of 4 minutes of visual arc for legibility was set in CARTS, as the validity of the model is questionable with much larger sizes that result in very small reflectivity requirements. Whenever CARTS is asked to determine the reflectivity requirement of a critical detail greater than 4 minutes, the value of 4 minutes is substituted.

Forbes

Forbes summarized the results of several studies on sign legibility.[34] These data show the effect of sign panel luminance on legibility index (feet of legibility distance per inch of letter height). CARTS was evaluated using these data by predicting the required panel luminance for given legibility distances. The resulting data points are plotted in figure 6 along with similar data from Allen, *et al* that was summarized by Forbes.[35] Figure 6 includes CARTS predictions for contrast sensitivities of 50 and 85 percentiles. The 50th percentile line is much closer to the empirical data for black on white signs.

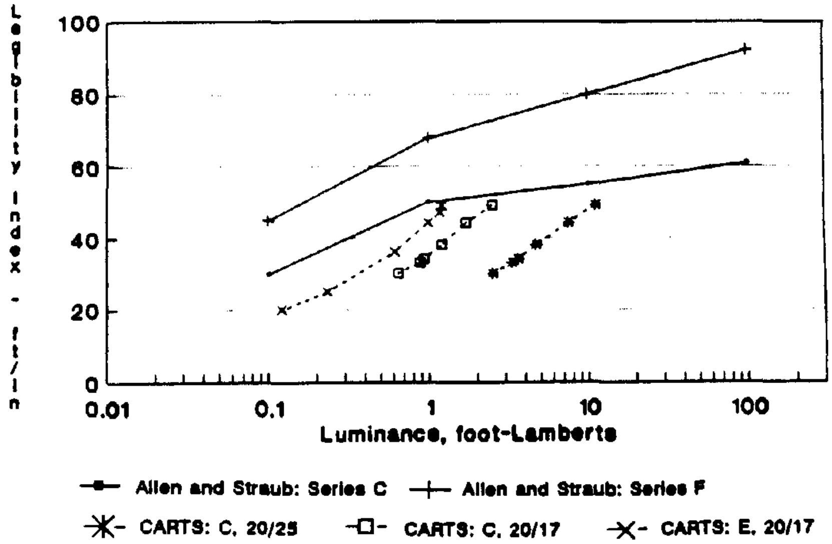


(1 cd/m^2 = 0.29 fL)
Figure 5. Comparison of CARTS and Kaneko formulas.



(1 fL = 3.42 cd/m^2)
Figure 6. Comparison of CARTS with Forbes data.

Forbes also summarized results of a study by Allen and Straub using subjects with acuities ranging between 20/17 and 20/25, reading FHWA sign letter series C and F.[36] These data are included in figure 7, along with corresponding CARTS results. Since the sign dictionary used by CARTS does not include any signs with letter series F, CARTS predictions are given for a series E sign and a series C sign. For the series C sign, two acuities were used to examine the effect of this variable. The series E sign is represented by only one acuity in order to avoid clutter in the graph.



(1 fL = 3.42 cd/m^2)
Figure 7. Comparison of CARTS with Allen and Straub data.

It was observed that the output from the CARTS model matched the data for Kaneko very well when target size was below 4 min of arc, which is typical of most signs. The CARTS model also compared favorably with the data reviewed by Forbes, over estimating the luminance requirements for partially retroreflectorized signs for large visual angles (20 to 40 ft/in; 0.24 to 0.48 m/mm) of letter height), and underestimating luminance requirements at small visual angles (60 ft/in; 0.72 m/mm) of letter height). The estimates around the nominal 50 ft/in (0.6 m/mm) of letter height were in close agreement. For these reasons the calibration of CARTS was deemed satisfactory and the model was left unchanged, including the retention of a visibility level of 1.0.

C. SUMMARY

In summary, the empirical estimates of critical detail for symbol signs were found to vary significantly from analytical values obtained as part of this research and those found in the literature. The CARTS model was calibrated by using the analytic to adjust the empirical values originally contained in the model.

The CARTS model was also evaluated by comparing the predicted data to those found in the literature. The CARTS predictions were found to be well within the range of expected performance and appear to provide reasonable values. This evaluation, however, is limited to this application of predicting the retroreflectivity and contrast requirements of traffic signs for legibility.

CHAPTER 7. 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.

A. SIGN CHARACTERISTICS

The typical placement (left, right, overhead, median) and the roadway type where it is predominately found (urban, rural) was 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 20.

Table 20. 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)

B. DRIVER CHARACTERISTICS

Distribution tables for visual acuity, age, and contrast threshold are used to relate driver age and visual performance. The distribution of acuity levels for U.S. adults is from the National Center for Health Statistics Series 11 Number 30, *Monocular-Binocular Visual Acuity of Adults, United States 1960-1962*.(36) Rates for corrected central distance vision in the better eye were used, as this is the type of vision used to read traffic signs. The distribution is shown in table 21.

The assumption was made that the driving population has the same distribution of corrected acuity as the general population. It is likely that this assumption underestimates the actual acuity of the driving population, as people with extremely poor corrected vision probably do not drive. From this table it can be seen that the median acuity (50th percentile) is better than 20/20. Interpolation produces a median acuity of 20/17.5 and an 85th percentile acuity of 20/27.9.

The publication *Highway Statistics 1988* was the source for the distribution of licensed drivers by age.(39) The relevant part of the publication's driver age distribution is provided in table 22.

Table 21. Corrected visual acuity distribution for U. S. adults.[38]

Acuity, 20/	Percentile
10	0.9
15	33.8
20	65.9
30	90.1
40	94.5
50	96.9
70	98.2
100	99.1
200	99.6
>200	100.0

Table 22. Driver age distribution in the U. S.[37]

Age, years	Percentile
<16	0.1
16	1.0
17	2.5
18	4.3
19	6.1
20	8.0
21	9.9
22	12.0
23	14.2
24	16.5
25-29	29.0
30-34	41.4
35-39	52.6
40-44	62.1
45-49	69.6
50-54	75.8
55-59	81.5
60-64	87.2
65-69	92.2
>69	100.0

The sample of the population contrast threshold distribution is shown in table 23. This is the population distribution of contrast sensitivity, in particular, the log contrast threshold for a 4-min target at a background luminance of 1.7 cd/m^2 (0.5 fL). Logs are to the base 10. The log values are used because the contrast threshold distribution is log normal.

Table 23. Population contrast threshold distribution.

Log contrast threshold	Percentile
-0.90	00.1
-0.45	33.2
0.04	85.0
0.45	98.6
0.90	100.0

This distribution was created by drawing a random sample of 10,000 contrast thresholds. For each of the 10,000 elements, a random driver age was drawn form the distribution of driver ages given in the 1988 *Highway Statistics*. Then a random normal deviate was drawn, based on the standard deviation of log thresholds for that age, and added to the mean log threshold for that age. The resulting value is a random log contrast value. Note that the index values in the complete table represent the upper boundary of an interval 0.05 units wide. Most important, note also that the percentile value reflects the "accommodation" percentiles, i.e., 85th percentile means that 85 percent of drivers in the overall population are accommodated.

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 from table 22. The information in table 21 is then used to determine the level of visual acuity corresponding to the percent of drivers below the specified age. Similarly, the threshold contrast table 23 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.

The simultaneous calculation of visual performance measures can lead to mistaken assumptions, for example that a given acuity is representative of a given age. In fact, different age groups have different acuity distributions, so that an acuity level of 20/20 may correspond to the 85th percentile for drivers under age 35, but only to the 10th percentile for drivers older than 75 years. Table 24 demonstrates the effect of these acuity distributions on percent accommodated by age, given overall percent accommodated.

Table 24. Population age, visual acuity, and accommodation relationship.

Overall Percent Accommodated:	50	75	85	95
Representative Acuity, 20/	17.5	23.8	27.9	42.1
Age Group	Percent of Group Accommodated			
18-24	66.9	87.2	93.8	99.0
25-34	68.8	89.8	94.6	98.5
35-44	64.6	88.5	94.1	98.5
45-54	44.1	72.4	84.0	95.5
55-64	24.6	56.1	74.0	92.1
65-74	15.0	42.8	61.1	83.3
75-79	5.6	27.0	45.5	72.1

For the base condition, a 66th percentile driver who is 47 years old and has 20/20 acuity and log contrast sensitivity of 0.257 was used. 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 in chapter 8.

C. 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 headlamps are listed in table 25. Each value in the photometric table of the nominal headlamp was the 50th percentile value of the corresponding cell in the photometric tables of each headlamp in the sample. An Iso-candela diagram of this derived 50th percentile headlamp is shown in figure 8.

Table 25. Headlamps used to derive the 50th percentile headlamp.

FILE	TYPE	BRAND	VEHICLE/MODEL
M90004	2A1	KOITO	H4656
M90005	2A1	KOITO	H4656
M90006	2A1	KOITO	H4656
M90008	2A1	WAGNER	H4656
M90009	2A1	WAGNER	H4656
M90012	2B1	IKI	H6054
M90013	2B1	IKI	H6054
M90015	2B1	SYLVANIA	H6054
M90017	2E1	PHILIPS	H4666
M90019	2E1	SYLVANIA	H4666
M90021	2E1	SYLVANIA	H4666
M90022	2E1	SYLVANIA	H4666
M90024	LF	GUIDE/GM	H4703
M90027	LF	GUIDE/GM	H4703
M90031	2A1	WAGNER	H4656
M90034	HB1	SYLVANIA	TOYOTA/CRESSIDA 86
M90035	HB1	SYLVANIA	TOYOTA/CRESSIDA 86
M90036	HB1	STANLEY	TOYOTA/CRESSIDA 86
M90041	HB1	SYLVANIA	FORD/TAURUS 87
M90042	HB1	SYLVANIA	FORD/TAURUS 87
M90046	HB4	SYLVANIA	CHEVEROLET/CELEBRITY 87
M90049	HB4	PHILIPS	CHEVEROLET/CELEBRITY 87
M90053	HB4	SYLVANIA	CHEVEROLET/CORSICA 87
M90059	HB4	SYLVANIA	HONDA/ACCORD 90

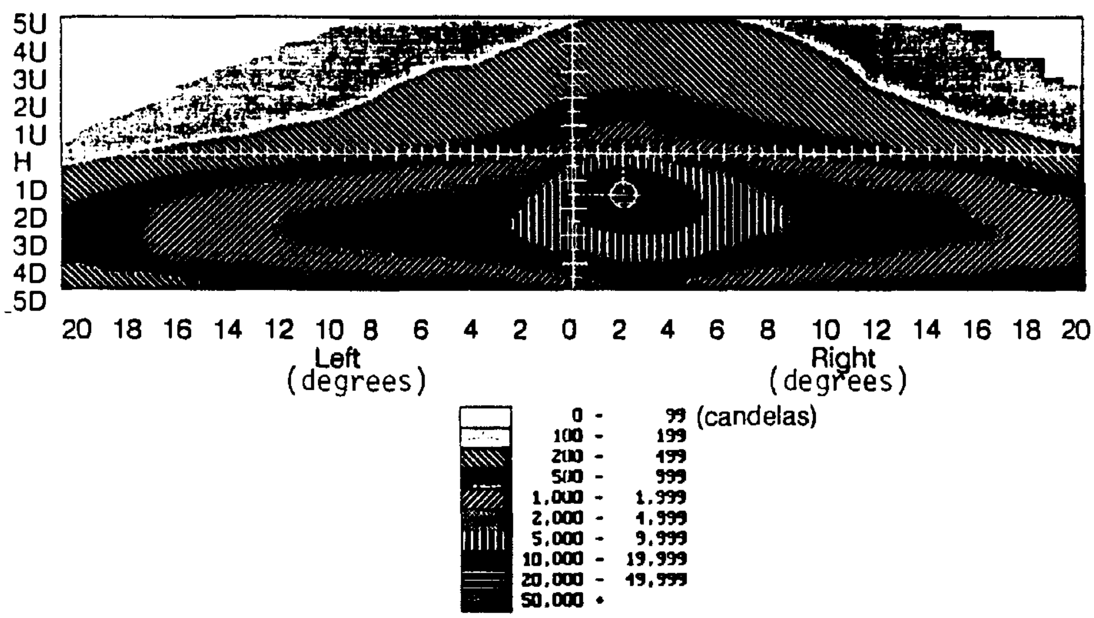


Figure 8. Iso-Candela Diagram of the 50th Percentile Headlamp.

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.

D. ROADWAY CHARACTERISTICS

For the base condition a dark (ambient luminance = 0.01 cd/m^2 (0.0029 fL)), a 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 26.

Table 26. 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

E. TRAFFIC CHARACTERISTICS

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

CHAPTER 8. RESULTS AND CONCLUSIONS

The presentation of the results from this effort includes an example from the CARTS model, a discussion of a framework for the minimum retroreflectivity requirements, minimum retroreflectivity values, and interpretation of the results. Rather than report the detailed output from the model, this report seeks to present the results in a format that can be implemented by practitioners.

A. CARTS EXAMPLE

To illustrate how the CARTS model was used to generate the minimum retroreflectivity values, examples of the CARTS input screens and output have been included for a partially retroreflectorized warning sign and a fully retroreflectorized Stop sign. Figure 9 illustrates the CARTS interface screen for the yellow warning sign Right (or Left) Lane Ends (MUTCD sign code W9-1). In the upper portion of the screen the user specifies the size of the sign (width), the placement of the sign (offset from right edge and height above shoulder elevation), the traffic characteristics, the placement of the vehicle, and the driver characteristics. In the center section the program displays information about the sign that is stored in the sign dictionary.

Finally, at the bottom of the screen the model outputs are displayed. These include information about the detection and recognition distances, the panel retroreflectivity at the MRVD entrance and observation angles (13.44 cd/m^2/lux; 13.44 cd/ft^2/ft-c) and the panel retroreflectivity at the standardized entrance and observation angles (30.29 cd/m^2/lux; 30.29 cd/ft^2/ft-c). In this case since the legend is black the values for the legend are zero.

```
            Sign-Only CARTS interface (12.21.92, using MRVD 8.04)
DEBUG ON                                                        ENGLISH
MUTCD SIGN CODE W 9- 1    (LEFT/RIGHT) LANE ENDS

SIGN WIDTH(in) 36(Exp)   OFFSET(f) 12   HEIGHT(f) 5   FINAL SPEED(mph) 55

DESIGN SPEED (mph) 55     VISUAL COMPLEXITY Med       TRAFFIC VOLUME Med

         NUMBER OF LANES 2                 OBSERVER LANE 1

OBSERVER AGE 46.53    VISION %ILE 65.9    ACUITY 20/ 20    C.T.(Log) -.257

CLASS CRITICALITY MANEUVER #LINES CHOICES SYMBOL FAMILIAR LSERIES   COLORS
  4       2          0        3      1       0       0        D     Blk/Ylw
WIDTHS  24(Min)  30(Std)  36(Exp)  48(Fwy)
((LEFT/RIGHT) LANE ENDS) ()
 RECOGNITION DISTANCE    DETECTION DISTANCE    PERCEPTION-REACTION TIME
     202.60 Feet             413.14 Feet             0.00 Seconds
    LETTER HEIGHT         LEGIBILITY INDEX           DETAIL SIZE
        6 in                  34 ft/in           0.9 in =  1.32 min
 Legend Ref    0.00 -> SIA    0.00  Panel Ref   13.44 -> SIA   30.29
F1 - HELP   F2 - CALCULATE   F3 - UNITS   F4 - DEFAULT VALUES   F5 - DEBUG
F6 - MODEL  F7 - SOLVE FOR  F8 - CARTS PARAMS   F9 - NEW SIGN   F10 - EXIT
```

Figure 9. CARTS Interface Screen.

Figure 10. displays the CARTS results screen which provides more detail about the information that was used in the calculations. This includes the entrance and observation angles, the headlight intensity, the luminance, and the retroreflectivity values at both the MRVD entrance and observation angles (panel reflectance, legend reflectance) and the standard entrance and

observation angles (LRI-1 panel, LRI-1 legend). The LRI-1 indicates that the generic curves, (discussed in chapter V) for ASTM material type I were used to determine the retroreflectivity requirements at the standard geometry.

Sign-Only CARTS interface (12.21.92, using MRVD 8.04)

DEBUG ON — ENGLISH

MUTCD SIGN CODE W 9- 1 (LEFT/RIGHT) LANE ENDS

CARTS Results

Calculation: Panel set for legibility with fixed legend reflectivity

	Detection	Recognition
Distance, ft:	413	203
Visual arc, min:	28.1	1.35
Entrance angle, deg:	2.53	5.15
Observation angle,deg:	0.276	0.527
Intensity from Observer, cd:	10649	2759
Illumination on Sign, lux:	0.685	0.752
Ambient illum, cd/m2:	0.010	N/A
Panel Luminance, cd/m2:	9.211	10.100
Legend Luminance, cd/m2:	N/A	0.001
Panel Reflectance, cd/m2/lux:	N/A	13.439
Legend Reflectance, cd/m2/lux:	N/A	0.001 (fixed)
Contrast:	920.1	-1.0
LRI-1 (panel), cd/m2/lux:	N/A	30.287
LRI-1 (legend), cd/m2/lux:	N/A	Black

Press any key to continue

Figure 10. CARTS Results Screen.

Figure 11 illustrates the CARTS Parameters Screen. This screen is used to fix the CARTS parameters for the vehicle characteristics and to select the sheeting type.

CARTS Fixed Parameters

Ambient luminance, cd/m2	.01
Front of car to driver, feet	-4.5
Centerline of car to driver, feet	-1.5
Height of driver eye above ground level, feet	3.5
Windshield transmissivity multiplier	.7
Width of one lane, feet	12
Width of the median, feet	0
Conspicuity Visibilty Level (CVL)	10
Legibility Visibility Level (LVL)	1
Observer headlamp lateral separation, feet	4.0
Observer headlamp mounting height, feet	2.0
Observer headlamp intensity file name	carts50.lmp
Observer headlamp vertical misaim, degrees	0.0
Observer headlamp horizontal misaim, degrees	0.0
Sign horizontal aim, degrees	0
Sign vertical aim, degrees	0
Sign panel reflectance, cd/m2/lux	
Opaque Letter/symbol reflectance, cd/m2/lux	.001
Sheeting Manufacturer	LRI
Sheeting Type	1

F2 - Store values, return to CARTS F4 - Use default values Esc - cancel

Figure 11. CARTS Parameters Screen.

Figure 12 provides an example of the CARTS interface screen for a fully reflectorized sign (Stop sign). In this case, retroreflectivity values are specified for both the legend and the background. The fact that the corrected panel retroreflectivity (11.30 cd/m^2/lux; 11.30 cd/ft^2/ft-c) is less than the panel retroreflectivity at the MRVD (12.58 cd/m^2/lux; 12.58 cd/ft^2/ft-c) indicates that the observation angle at the MRVD is smaller than the standard value of 0.2°.

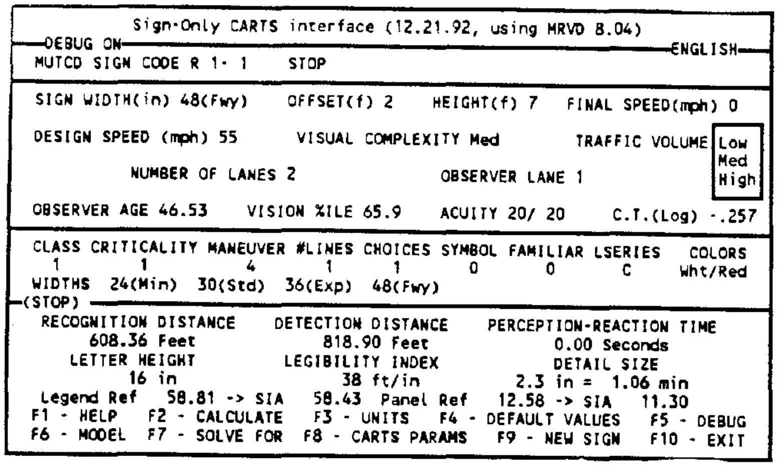


Figure 12. CARTS Interface Screen - Stop sign example.

B. 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 desirable 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.

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. This conclusion is similar to that reached by Jenkins and Gennaoui in their effort to establish minimum retroreflectivity values in Australia. In their report they conclude that "...it would not be possible to recommend a single terminal value for signs or even a single terminal value for a class of signs (e.g. regulatory, warning, guide, etc.). The necessary retroreflectivity for a sign to be effective depends on the function of the sign and on the traffic situation and geometry in which it is placed. This requires the consideration of many variables which will influence the minimum retroreflectivity requirements."

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

In an effort to strike the proper balance between research and implementation, the key variables effecting sign retroreflectivity were reviewed. Some of the variables were addressed through the establishment of the reference conditions in chapter 7. 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: As discussed throughout this report, the ability of a driver to detect and recognize a sign is dependent on the size of the critical details of the sign. Within limits, as the size of the sign increases, the size of the critical detail also increases, decreasing the level of 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 in chapter 5, 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 larger CD size, and 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.

C. 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. A specific discussion of the process used to arrive at the values in the tables is included. 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 for the table that were reasonable and consistent.

Tables 27, 29, 30, and 32 represent the outcome from an effort to simplify the CARTS results so that users do not need to understand the full CARTS model in order to inspect traffic signs and make a decision on replacement due to insufficient retroreflectivity.

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 repeatedly on the minimum required retroreflectivity values. Only the critical variables were selected for inclusion in the final guidelines. Each of the critical variables is 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 very little reading time required for warning signs, the minimum values for these signs are not sensitive to changes in traffic 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 in use.

Sign Legend: Warning signs include a wide range of letter and symbol sizes and therefore a wide range of critical details. The amount of retro-reflectivity 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, more 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; 300 to 500 ft), the minimum retro-reflectivity 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 . 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 27 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[3] and Olson.[6] The CARTS values for legibility for these signs were lower than these values 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 sign material type group. Signs with bold legends are listed in table 28, all other warning signs are considered to have finer messages. Since as illustrated in figure 3, the relationship between observation angle varies by material type, in order to provide an equivalent level of luminance at the MRVD distance, different retroreflectivity values must be specified for each material type.

For the finer, more complex legends the values in the table 27 were selected by using 85th percentile values for all signs that were included within each given cell. As illustrated in figure 3, the relationship between observation angle varies by material type. To provide an equivalent level of luminance at the MRVD distance, required that different retroreflectivity values be specified for each material type.

Table 27. 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/m²
1 in = 25.4 mm

Table 28. 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 29 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 are retroreflectorized a minimum maintained contrast ratio of 4:1 has also been established. This value was selected based on the previous research cited in table 3. 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.

Table 29. 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 for this group of regulatory signs.

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 significant 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 30 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 list of signs used is shown in table 31. The values in the tables represent 85 percentile values based on these signs.

Table 30. 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 31. Regulatory and guide signs selected for analysis.

	MUTCD Code	Sign Type
Ground-mounted	R2-1	Speed Limit
	R2-5b	Reduced Speed
	R3-1	No Right Turn
	R3-7	Left Lane Must Turn Left
	R4-1	Do Not Pass
	R4-7,7a	Keep Right
	R6-1,2	One Way
	R11-2	Road Closed
	R15-1	Railroad Crossing
	M1-4	U. S. Route Marker
	M3-1	Cardinal Direction Marker
	M6-1	Directional Arrow
Overhead	R3-5,6	Lane Use Control
	R3-9a	Two Way Left Turn Only
	R10-11a,12	Traffic Signal 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 white on green guide signs it was felt that specifying different values for different sign sizes would not be practical. 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, it was not reasonable to capture this variable in a practically implementable manner. 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 many guide signs are located overhead, sign placement was selected as a critical variable.

Table 32 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 the "typical" guide signs described in chapter 3. 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 32. 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/hr = 1.6 km/hr

D. 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.[(38)] (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.

As noted in the discussion of previous research in chapter 1, there has been only limited research in the area of minimum visibility requirements and even less in the area of minimum retroreflectivity requirements. Since none of the previous research in the area of retroreflectivity requirements considered either the sign size or the type of material used, the comparisons discussed below are limited to Type I sign sheeting materials and standard sign sizes as specified in the MUTCD. The first comparison that was made was to use the conspicuity research conducted by Olson to examine the validity of the values from a detection standpoint. The 85 percentile values developed by Olson for stop, warning, and guide signs (shown in tables 5, 6 and 7, respectively), were used to evaluate the retroreflectivity values in tables 27, 29, 30 and 32. The values for material type I, presented in this report, compare favorably to Olson's values for medium and low complexity situation at all but the highest speed situations and/or high speed situations special measures such as supplemental signing, (88 km/h and above; 55 mi/h) increased sign size, and/or increased brightness may be warranted.

A similar comparison with the Morales stop sign values in table 4, results in the same finding. Using Morales' approach for computing an overall R_a value (see table 4) using the data from table 29 for 76 cm (30 in) signs results in overall R_a values of 16 cd/lx/m^2 (cd/ft-c/ft^2) for speeds of 40 mi/h or less and 27 cd/lux/m^2 (cd/ft-c/ft^2) for speeds of 72 km/h (45 mi/h) and higher. These values compare favorably to Morales' values except at speeds of 88 km/h (55 mi/h) or more where he recommends an overall R_a of 40 cd/lx/m^2 (cd/ft-c/ft^2).

From a legibility perspective, the most comprehensive effort available in the literature is the work by Sivak and Olson cited in chapter 1. This effort developed a summary recommendation for replacement luminance using the results from a number of previous studies. Based on this luminance they developed the replacement criteria for various driver percentiles shown in table 2. The luminance values used in CARTS to calculate the minimum retroreflectivity guidelines presented in tables 27, 29, 30 and 32 generally fall between 7 cd/m^2 (2.0 fL) and 15 cd/m^2 (4.4 fL). According to the values developed by Sivak and Olson this would suggest a driver accommodation in the 75th to 85th percentile range.

As noted in the discussion of previous research, the approach taken by Jenkins and Gennaoui was similar to that used in this research. However, there are two important differences that make a direct comparison difficult. First, Jenkins and Gennaoui based their minimum values on threshold (0.56 percent correct response) luminance obtained from a laboratory study, while this effort utilized the PCDETECT model and the work by Blackwell. The luminance recommended by Jenkins and Gennaoui tend to be slightly higher than those used in this effort. However, they also fall in the 75th to 85th percentile range as defined by Sivak and Olson. Secondly, Jenkins and Gennaoui used a 1983 European style low-beam headlight in their model. This effort used a composite low-beam headlamp developed by measuring 26 sealed-beam and replaceable bulb headlamps and developed 50th percentile values. Even given these differences the results from the two efforts appear to be of similar magnitude.

As noted in the discussion of the results by Jenkins and Gennaoui, the authors did not feel comfortable in recommending minimum values. However, if one uses the maximum replacement values from their nighttime evaluation shown in table 8 they are of the same magnitude as the retroreflectivity values from this effort. Based on these limited comparisons, it is believed that on the whole the retroreflectivity values shown in the tables 27, 29, 30 and 32 above provide a reasonable level of driver accommodation 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.

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 overall effort 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 candidate replacement strategies.[39] As part of this effort 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 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 following assumptions were made in developing this aggregate value.

- Standard MUTCD sign size.
- 50 percent on roads with traffic speed of 72.4 km/h (45 mi/h) or greater and 50 percent on roads with speeds of 72.4 km/h (45 mi/h) or less (based on the fact that the NCHRP sample was 54 percent urban).
- 60 percent Type I material and 40 percent Type III material (reported by Black, et. al)
- No overhead signs (these were not included in the survey).

These aggregate values were then compared to the NCHRP data and replacement and generated. The results are shown in table 33.

Table 33. 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] $cd/lx/m^2$

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 33 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.

E. 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 considered 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 27, 29, 30 and 32 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 maintenance schedule for traffic signs. However, the minimum retroreflectivity values for sign replacement are only a tool that must be used in conjuction 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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