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DEVELOPING UPDATED MINIMUM IN-SERVICE RETROREFLECTIVITY VALUES FOR TRAFFIC SIGNS

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ABSTRACT

The purpose of this paper is to describe the background and current status regarding the development of updated minimum in-service retroreflectivity values for traffic signs in the U.S. A summary of the initial work, conducted in the late 1980s to mid 1990s, is provided along with descriptions of the relevant validation work. Factors leading to a second round of research are then described, including the work that has been recently completed. A summary of a second round of national minimum retroreflectivity workshops is also provided. Finally, the most recent set of recommended minimum retroreflectivity levels for traffic signs is presented along with a list of suggested research topics based on the limitations associated with the recommendations.

INTRODUCTION

The development of minimum levels of retroreflectivity (end-of-service-life values) for traffic signs is one of the latest steps in the evolution of providing a safe and efficient road transportation system. The progression of this concept in the U.S. was significantly accelerated in 1984 when the Center for Auto Safety petitioned the FHWA to establish retroreflectivity standards for signs and markings (*1*). In 1993, Congress required the Secretary of Transportation to revise the Manual on Uniform Traffic Control Devices (MUTCD) to include "a standard for a minimum level of retroreflectivity that must be maintained for pavement markings and signs which apply to all roads open to public travel (*2*)." In 2000, when the FHWA revised the MUTCD, a new section (Section 2A.09) was introduced in Part 2, which stands as a placeholder for minimum retroreflectivity standards for traffic signs (*3*).

Also in 1993, because of work in progress, the FHWA sponsored research was able to develop an initial set of minimum in-service retroreflectivity recommendations for traffic signs (*4*). In 1998, after a variety of events including a series of national workshops, the initial 1993 values were revised (*5*). One of the 1998 revisions included the removal of minimum values for overhead signs because of significant variability associated with headlamp luminous intensity directed toward overhead signs. After the NHTSA revised the Federal Motor Vehicle Safety Standard Number 108, "Lamps, reflective devices, and associated equipment" (FMVSS 108) in 1997 (the document that sets the minimum and maximum luminous intensities for headlamps, headlamp mounting heights, and standardization of headlamps on *new* vehicles sold in the U.S.), the FHWA sponsored additional research to develop minimum values for overhead signs, and street name signs, which were not accounted for by the initial 1993 or revised 1998 values. The research for overhead and street name signs was completed in early 2001 (*6,7*). Although the overall approach was different than what had been used for the initial 1993 and revised 1998 values, several of the same assumptions were maintained. One of the significant contributions of the overhead and street name sign research was a demonstrated need to update some of the fundamental assumptions associated with the development of minimum retroreflectivity values. Consequently, since early 2001, researchers at TTI have been working on updated minimum in-service retroreflectivity levels for traffic signs. This paper summarizes the early work that led to the initial 1993 and revised 1998 values. It also describes the recently completed work related to updating the minimum values.

Initial Values – 1993

The initial set of minimum in-service retroreflectivity values were published in 1993 and derived from a theoretical computer model called Computer Analysis of Retroreflectance of Traffic Signs, or CARTS (*4*). CARTS is comprised of several submodels that work in series to determine retroreflectivity needs based on user selected inputs. The first submodel determines the minimum distance a sign must be legible in order for a motorist to respond appropriately and safely. This distance is termed the Minimum Required Visibility Distance, or MRVD, and is the sum of distances associated with the following factors: detecting the sign, recognizing or reading the sign, deciding on the appropriate action, initiating the response, and completing the required maneuver (depending on the sign message, the latter factors may not be needed).

Using the computed MRVD value, the next submodel estimates the threshold legibility luminance needed for the sign. The heart and soul of this submodel is a visibility model called PCDETECT (*8*). PCDETECT is based on data from the classical Blackwell experiments of the 1940s where subjects were tasked with the identification of circular targets against uniform backgrounds (*9*). The last submodel takes the MRVD and estimated threshold legibility luminance and back-calculates the retroreflectivity needed at the standard measurement geometry of 0.2 and -4.0 degrees for the observation and entrance angles, respectively (*10*).

Because of the infinite number of possible scenarios in terms of the combination of sign types, sign locations, driver needs, headlamp performance variations, and the like, several scenarios were selected to represent typical or design conditions. For instance, the driver was assumed to be 47 years old and the dimensions of the vehicle approximated a large passenger sedan. The assumed headlamp was a composite headlamp representing the median value of 26 headlamps from model year passenger cars ranging from 1985 to 1990.

The results of this initial work were summarized in four tables of minimum retroreflectivity values, distinguished by the color of sign. There was a table for white signs, one for yellow and orange signs, one for green signs, and one for red signs. Depending on the table, other factors that were included were speed, sign size, type of retroreflective sheeting, sign location for green signs, and type of legend (symbol versus text). There was also a minimum contrast ratio required for white on red and white on green signs. Because this research was conducted in the early 1990s, the only types of microprismatic sheeting included were ASTM Types IV and VII (but Type IV is no longer made).

Revised Values – 1998

After the 1993 values were published, the developers of CARTS received many comments indicating that the modeling was incorrect in that it assumed one headlamp with the driver directly above the headlamp (also called cyclops modeling). In reality, this modeling represents a motorcycle rather than a four-wheeled vehicle. Because of retroreflective sheeting materials' sensitivity to observation angle, a cyclops modeling assumption can produce significantly different values than a model with the proper positioning of the headlamps in respect to the driver's eye. In July 1994, the developers of CARTS provided a refined version that accounted for the effect of two headlamps on observation angle (*11*).

Shortly thereafter, the FHWA sponsored two research projects to determine the adequacy of the initial minimum in-service retroreflectivity values (*12, 13*). During the same period, the FHWA also sponsored three national workshops to solicit input regarding the initial minimum in-service retroreflectivity values for signs. In 1998, McGee authored two related reports; one that addressed various implementation strategies for transportation agencies and another that investigated the impacts of the recommended retroreflectivity values on transportation agencies (*5, 14*). These reports also included revised minimum in-service retroreflectivity values. McGee and Paniati listed the following reasons for revising the minimum in-service retroreflectivity values (*5*).

1. The results from research that utilized a human factors and mathematical modeling approach to consider the range of visual, cognitive, and psychomotor capabilities of the driving population and the complexity of the relationships between the driver, the vehicle, the roadway environment, and the sign [in other words, the second version of CARTS].
2. The results of human factors research to evaluate the percent of drivers than would be accommodated by signs with varying levels of retroreflectivity [in other words, the Mercier et al. research (*11, 12*)].
3. The results from measurement made on over 20,000 in-service signs in over 50 states and local jurisdictions [data from three different reports (*14,15,16*)].
4. Input received from the more than 40 state and local jurisdictions represented at the three regional workshops held in Baltimore, MD, Kansas City, MO, and Denver, CO in late 1995.
5. Input from public agency and private industry representatives received at numerous presentations given at such forums as the Transportation Research Board (TRB) Annual Meeting, the Institute of Transportation Engineers Annual Meeting, the American Traffic Safety Services Annual Meeting, the TRB Visibility Symposium, and state-sponsored safety and traffic engineering workshops.

These revisions resulted in a mixed effect but the largest change was the removal of all minimum values for overhead signs because of many unresolved issues with vehicle headlamp performance specification and the difficulty in measuring overhead sign retroreflectivity (*5*). The minimum values for red, yellow, and orange signs were slightly reduced. Most of the values for white signs were reduced but a few were raised. The minimum values for ground mounted green signs, which did not include street name signs, stayed the same.

Overhead and Street Name Sign Values - 2001

In March 1997, the NHTSA implemented a final rule that revised *FMVSS 108* in order to address the issue of headlamp misaim, which was believed to be a significant factor related to the amount of glare and the variability of headlamp luminous intensity directed toward overhead signs. The rule reflects the consensus of the negotiated rulemaking concerning the improvement of headlamp aimability performance and visual/optical headlamp aiming.

The new rule established improved headlamp aiming features that provide more reliable and accurate aiming, and help vehicle operators to more easily determine the need for correcting aim. The rule introduced Visually/Optically Aimed (VOA) headlamps to the U.S. The term "VOA" generically describes two types of visually/optically aimed headlamps: VOR and VOL headlamps. The VOL headlamp is a low beam with a horizontal cutoff to the Left side of the beam. The VOR headlamp is a low beam and has a horizontal cutoff to the Right side of the beam. VOL headlamps can reduce glare to oncoming drivers compared to conventional U.S. low beams. VOR headlamps have less ability to reduce oncoming glare but produce luminous intensity distributions more similar to conventional U.S. low beams.

As a result of the NHTSA's revision to *FMVSS 108* in 1997, the FHWA sponsored a research project focused on the development of minimum in-service retroreflectivity values for overhead signs. In order to complete the initial set of minimum retroreflectivity recommendations, the FHWA also wanted minimum values for street name signs.

Researchers at TTI were awarded the contract, which was completed in early 2001. The research included the development of a model to determine minimum in-service retroreflectivity values from a host of user input factors including luminance. To determine adequate threshold legibility luminance values, the researchers performed a study with full-scale guide signs and street name signs. Special emphasis was devoted to accommodating older drivers. The results of the study were used to determine a set of minimum in-service retroreflectivity values for overhead and street name signs (*7*).

Besides providing minimum in-service retroreflectivity recommendations, the researchers also performed sensitivity analyses to determine the impact of the assumed design driver capabilities, the headlamp type, and the vehicle type. This research identified a need to update some of the assumptions of the initial and revised set of minimum in-service retroreflectivity values (which included the 1998 revision of the initial 1993 values). In addition, there was a need to develop minimum values for the various types of retroreflective sheeting that have been introduced to the market in the meantime.

Validation Efforts

There have been at least three studies that were either completely or partially focused on determining the adequacy of the initial 1993 and/or revised 1998 minimum in-service retroreflectivity values. These studies are summarized below.

The first review of the minimum values came from Mercier et al. and was published in 1995, two years after the initial values were published (*11,12*). In this study, the researchers concluded that 85 percent or more of all drivers would be accommodated by the initial 1993 values for nearly all signs tested. They also concluded that the minimum retroreflectivity values are fairly conservative, allowing a margin for safety.

However, their study did not specifically evaluate the retroreflectivity values, or the CARTS modeling techniques. Rather, it focused on a static laboratory study which resulted in the determination of luminance thresholds needed to read or recognize 25 different signs (comprising a mix of sign types (symbol and text warning signs, regulatory signs, and guide signs) and sign sizes). The ambient lighting was 0.01 cd/m^2, mimicking a dark rural environment.

Using a 50 percent scale, the researchers simulated CARTS's MRVD for each of the 25 signs (which were also scaled to 50 percent). For each sign, the researchers systematically increased the sign luminance until subjects were able to correctly read or recognize the sign.

Scatter plots were then generated which included the luminance thresholds by subject age. The minimum luminance from CARTS was then superimposed on the scatter plots. Figure 1 shows an example of the reported findings for one specific sign.

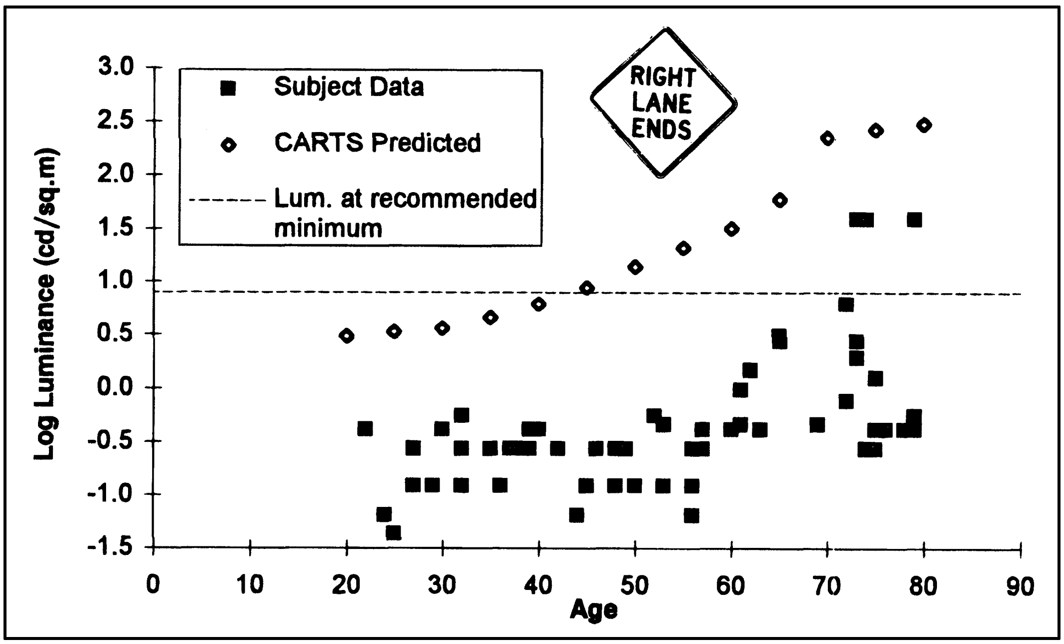


Figure 1. Minimum Luminance Data for Warning Signs (*11*)

Figure 1 indicates that the minimum luminance levels from CARTS are substantially higher than the study findings, which means that the minimum retroreflectivity values generated from the CARTS minimum luminance levels should be higher than what is actually needed. It is important to emphasize that the researchers' conclusions stating that the minimum retroreflectivity levels are fairly conservative is based on luminance threshold data and *not* retroreflectivity values.

In 2001, a long awaited report documenting a follow-up study to the Mercier et al. study was finally published (*13*). This laboratory study was conducted to determine the adequacy of the initial 1993 minimum in-service retroreflectivity values in situations of varying visual complexity and environmental illumination (because the retroreflectivity values were developed for a dark environment with a medium complexity background). Subjects completed a target search and recognition task on a set of eleven traffic signs presented at four different background complexities and three different luminance levels, including luminance levels produced by CARTS and used to generate the initial 1993 guidelines. A recognition response frequency of 90.3 percent (across all treatments) at the CARTS luminance levels was enough for the researchers to conclude that the 1993 guidelines were adequate for the general driving public.

While both of these validation studies concluded that the initial 1993 values were adequate, both used the CARTS luminance values as their benchmark and compared measured luminance at threshold conditions. Consequently, both validation studies assumed that CARTS's calculation from luminance to retroreflectivity at a standard measurements geometry were correct. Instead, these studies only validated that the threshold legibility luminance values produced by CARTS adequately accommodate nighttime motorists. They did not validate the minimum retroreflectivity values.

Probably the most direct comparison of the minimum in-service retroreflectivity values was published in 2001 by Hawkins and Carlson (*17*). In this study, state DOT maintenance personnel subjectively evaluated the nighttime adequacy of 49 different roadside signs in a controlled environment with no distracting traffic or fixed lighting. The subjective results were compared to the signs' retroreflectivity values. The findings showed that while only one sign failed to meet the revised 1998 values, the maintenance personnel rejected more than half of the signs (26 of 49 signs). While factors other than retroreflectivity were found to be associated with maintenance personnel's opinions regarding the signs' adequacy (including uniformity of the sign face and sheeting type), this study provided the first direct evaluation of minimum in-service retroreflectivity values. The research concluded that the revised 1998 values were lower than TxDOT's maintenance personnel's subjective opinions.

UPDATED VALUES – 2002

As a result of the demonstrated need to update the minimum in-service retroreflectivity values for traffic signs, FHWA sponsored additional research focused on the investigation and sensitivity of updated factors such as the driver age, headlamps, vehicle types, and retroreflective sheeting. More specifically, this work has included using an older design driver, newer style headlamps, larger vehicle types such as SUVs, and much more robust retroreflectivity prediction tools. The remainder of this paper describes the research that has been conducted in order to update the minimum values.

Nighttime Driver Needs

The concept used in the development of minimum in-service retroreflectivity values for overhead and street name signs was based on threshold legibility luminance curves developed at TTI using a full-scale experiment at a decommissioned Air Force base (*7*). Because this data set only included white on green signs and the update effort included other sign types, additional threshold legibility luminance data were needed. However, insufficient time and funds were available to repeat the full-scale experiment for colors other than white on green. Fortunately, another threshold legibility luminance data set derived from actual traffic signs was available. The data was published by Mercier et al. and sponsored by FHWA (*11*).

A comparison of the threshold legibility luminance data for white on green signs showed a good correlation between the TTI data (which only included white on green signs) and the Mercier at al. data (which included white on green, white on red, black on yellow, and black on white signs). This comparison was completed in order to test the compatibility between the two data sets. It should also be noted that the researchers wanted to use threshold luminance values derived from signs rather than arbitrary targets such as discs like the Blackwell data, which most visibility models use as their basis. Figure 2 shows an example scatterplot of the Mercier et al. data and the TTI data compared to CARTS data for white on green signs.

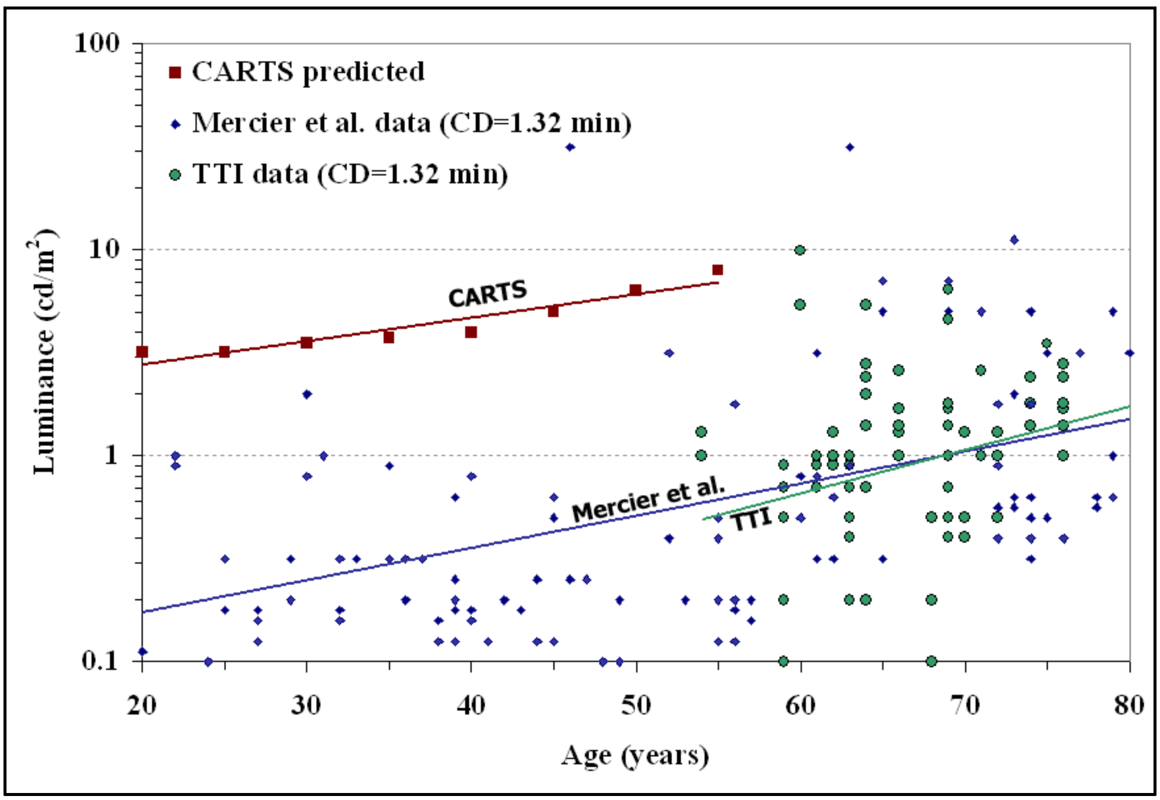


Figure 2. Scatterplot of Mercier et al. Data and TTI Data

Figure 2 shows that the Mercier et al. data collected for white on green signs at distances resulting in a critical detail of 1.32 minutes show nearly identical patterns as the corresponding TTI data. The TTI study only included subjects 55 and older and therefore there are no TTI data points shown below 55 years. The lines shown in Figure 2 are best fit regression lines which are shown in order to make relative comparisons of the data sets. It is obvious that a large amount of variation exists in both data sets. However, Figure 2 shows that the minimum threshold is much less than that predicted by CARTS. The slope of the Mercier et al. best fit line is flatter than the

TTI data but that can possibly be explained by the larger range in subject age and the tendency for luminance demand to practically asymptote as driver age increases.

In order to better compare the two data sets, all of the subjects younger than 55 were excluded from the Mercier et al. data set. Then, using data representing critical detail levels in addition to 1.32 minutes, cumulative distribution plots were generated to compare the spread in the data sets. Figure 3 shows these cumulative distribution curves.

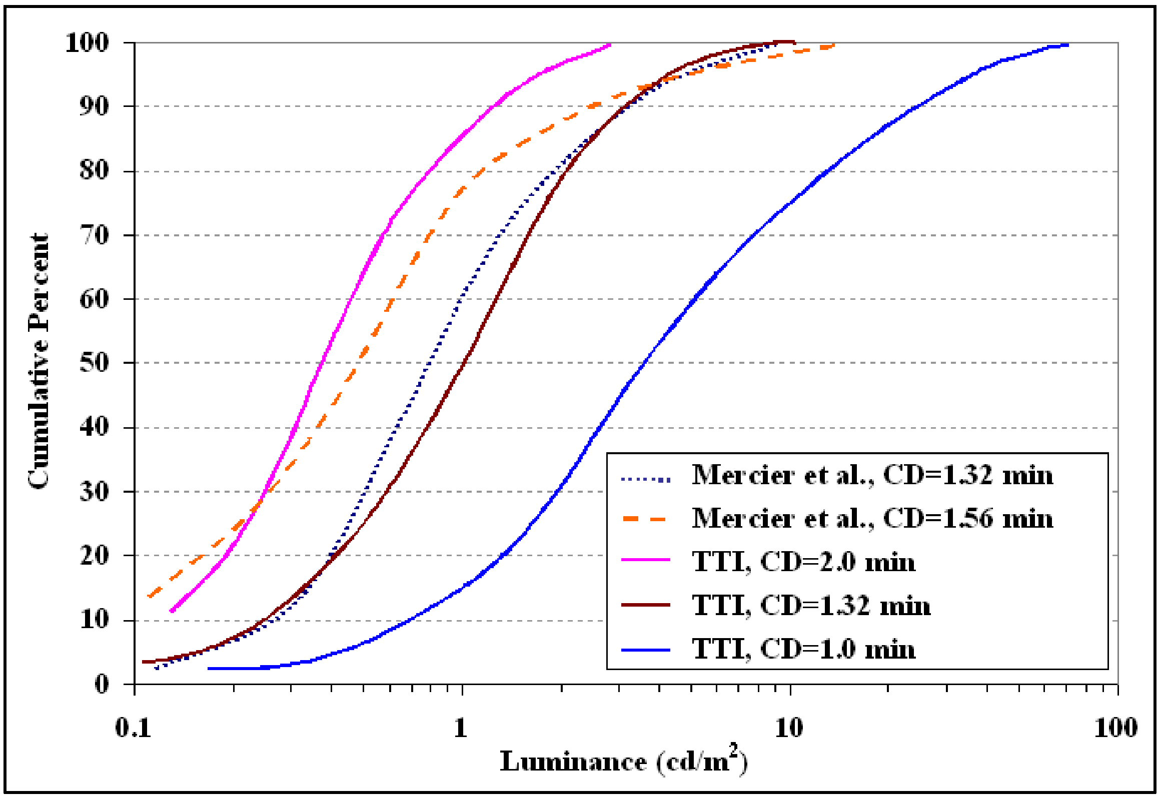


Figure 3. Comparison of Data for Older Drivers Only

Figure 3 shows that the smaller the critical detail, the more luminance is needed. The TTI data represent Series C legends and the Mercier et al. data represent Series D legend. There is good correlation in this figure as well. Consequently, the researchers felt comfortable using the Mercier et al. data for sign colors other than white on green.

Using the threshold legibility luminance concept, minimum in-service retroreflectivity values were derived for warning, construction, distance, destination, and guide signs at distances associated with a legibility index (LI) of 40 feet per inch of letter height (corresponding to a *MUTCD* recommendation), which results in various distances depending on the assumed letter height. At distances associated with a LI of 40 feet per inch of letter height, Series E letters subtend 1.25 min and Series D letters subtend 1.13 min of critical detail.

For signs that require maneuvers before reaching the sign (e.g., speed reduction or lane change), the distance provided by an LI of 40 feet per inch is not always valid, especially at higher speeds. In such cases, the distance associated with perception, reaction, and braking time can be greater than the distance provided by using the LI concept. For these type of signs, such as Stop signs, the MRVD values from CARTS were used. By using the LI concept, the burden of providing adequate visibility is appropriately placed upon the choice of the proper sign size. The substitution of the CARTS distance introduces the possibility that sign size may not be sufficient for recognition at MRVD. The distance determined by the legibility index is a measure of the critical detail supplied, while the distance determined by CARTS is a measure of the critical detail required. Because signs like the Stop sign often have iconic value, recognition may be accomplished without legibility, so that the critical detail supplied at MRVD is as great as that required.

Initially, the researchers developed legibility luminance threshold curves for drivers aged 55 and older. However, the researchers have also considered threshold legibility luminance curves derived from subject data with the lower bounds set at 65 years. Using these data, the researchers were able to analyze the sensitivity of age, which remains an on-going effort.

For either set of legibility luminance threshold curves, an accommodation level had to be established (i.e., the percent of drivers assumed to be accommodated). For both the 55 and 65 year old data sets, the 50th percentile level has been used to develop a preliminary set of updated minimum in-service retroreflectivity values. Data from the National Personal Transportation Survey of 1995 can be used to estimate the actual levels of driver accommodation that these 50th percentile levels represent. According to Figure 4, approximately 89 percent of the nighttime drivers are under 55 years and almost 96 percent are under 65 years. However, the updated age-related minimum in-service retroreflectivity assumption refers to an accommodation level of 50 percent of the drivers above the minimum age criteria. Therefore, the legibility accommodation levels actually corresponds to levels well above 90 percent for both cases (either 89 percent or 96 percent under the age criterion plus 50 percent of drivers over the age criterion).

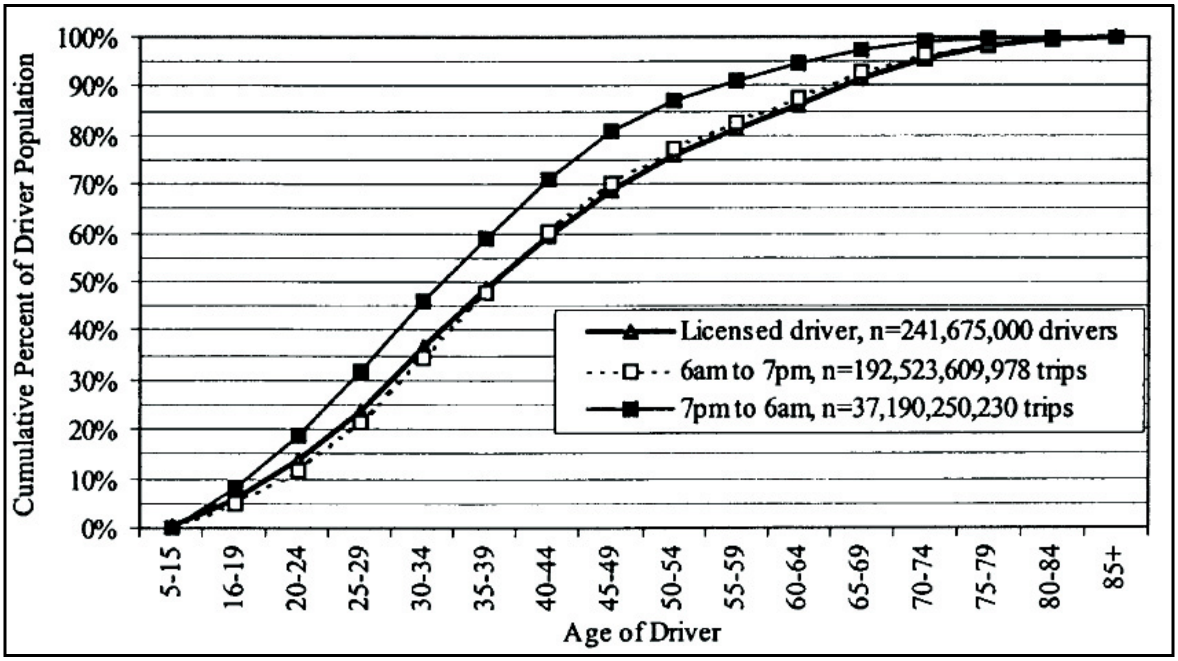


Figure 4. Cumulative Percentage of Driver Population as a Function of Driver Age for Trips at Different Time of the Day (Source: National Personal Transportation Survey, 1995)

Headlamps

In 2001 Carlson and Hawkins completed a sensitivity analysis of the then available headlamp isocandela profiles (*6*). They used typical guide sign and street name sign placements to compare sign illuminance values at various distances. The results showed that headlamp output directed toward overhead signs decreased by about 30 to 40 percent between the mid 1980s and mid 1990s. For street name signs the drop was not as severe but still substantial at 20 to 30 percent.

Carlson and Hawkins also benchmarked seven headlamp profiles against field illuminance measurements recorded in the mid 1990s along a flat tangent section of rural Interstate in Kansas (*18*). The results showed that the headlamp profile representing vehicles from the mid 1980s with halogen sealed beam headlamps had the best correlation to the field measurements. Keeping in mind that the average age of U.S. vehicles is nine years (*19*) and the field measurements were recorded before the introduction of VOA headlamps (in 1997), the results provide the earliest validation of the assumed correlation between the illuminance results of modeling headlamp isocandela data and actual field illuminance measurements. Chrysler et al. have recently provided additional confirmation of this modeling assumption (*20*).

After Carlson and Hawkins completed their analyses, UMTRI published headlamp isocandela data representing model year 2000 vehicles (*21*). The UMTRI 2000 headlamp isocandela profiles were the first available headlamp data that included a sample from VOA headlamps. These headlamp types were studied by UMTRI and shown to produce even less light for nighttime sign visibility (*22*). For example, compared to the conventional U.S. headlamps of the mid 1990s, the VOA headlamp (which generically describes two subclasses: VOR and VOL) reduces overhead sign illumination by 28 and 18 percent, for the VOL and VOR headlamps, respectively.

More recently, a newer style of headlamps has entered the U.S. market and its popularity is slowly growing. These headlamps, termed HID for High Intensity Discharge, use an arc capsule where an arc jumps between two electrodes. This arc is used as the light source, instead of a glowing filament like in a conventional halogen headlamp. UMTRI's latest headlamp profile representing model year 2000 vehicles does not include representation from HID headlamps. Therefore, the researchers purchased the six HID low beam headlamp profiles from model year 2000 vehicles (Audi A8, Audi TT, BMW 328ci, Acura 3.2, Mercedes S500, and Lexus GS400). Each headlamp profile included 45,551 luminous intensity values covering a distribution from 10 degrees up to 10 degrees down and 45 degrees left to 45 degrees right (in 0.2 degree intervals). The six individual profiles were averaged into a composite HID profile and the composite HID profile was compared to various other headlamp profiles including U.S. headlamps from the mid 1980s to 2000 and a European headlamp representing vehicles sold in Europe in model year 2000 (see Table 1). The researchers used three typical sign placements for the analysis: right shoulder, left shoulder, and overhead. The results were mixed. However, a consistent finding was that at distances greater than 500 ft, the composite HID headlamp profile consistently provided the least amount of illumination (of the five U.S. headlamp profiles) for the typically placed traffic signs under consideration. Figure 5 shows a comparison of the composite HID headlamp profile and the UMTRI 2000 headlamp profile.

Table 1. Headlamp Descriptions

Name	**Description**	**Reference**
Pre 1985	Average of 2 halogen sealed beam headlamps (2A1).	TTI data
1985-1990	50th percentile low beam headlamp derived from 26 U.S. headlamps from vehicle model years 1985-1990.	FHWA-RD-93-077 (*4*)
1997	50th percentile market-weighted low beam headlamps from 35 headlamps from 23 best selling vehicles for model year 1997. Does not include VOAs or HIDs.	UMTRI-97-37 (*23*)
2000	50th percentile market-weighted low beam headlamps from 20 headlamps from 20 best selling vehicles for model year 2000. Does not include HIDs.	UMTRI-2001-19 (*21*)
2000-Euro	50th percentile market-weighted low beam headlamps from 20 headlamps from 20 best selling vehicles in 17 countries for model year 2000.	
2000-HID	50th percentile of HID headlamps from 6 MY 2000 passenger cars.	TTI data

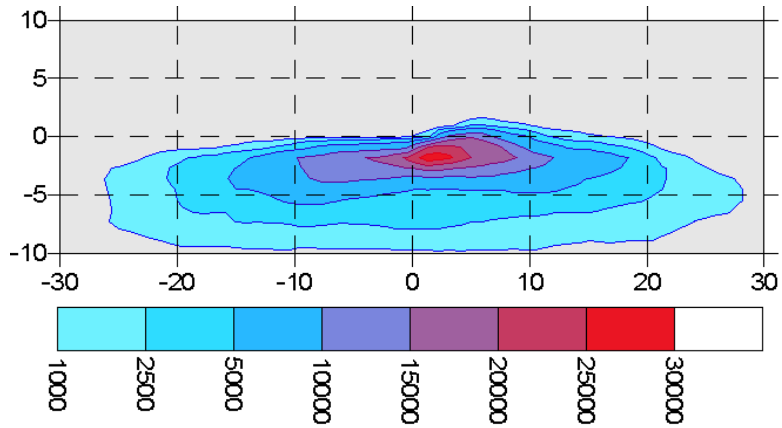
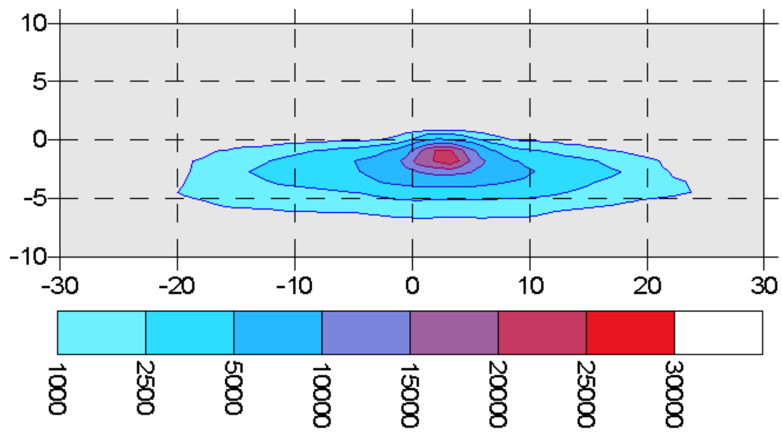
Composite HID low beam	
UMTRI's 50th percentile U.S. model year 2000 low beam	

Figure 5. Headlamp Isocandela Profiles

In order to further investigate the distance-related illuminance differences, the composite HID profile was compared to UMTRI's U.S. low-beam 50th percentile profile for 2000 model year vehicles. Simulation runs were developed to compare the two headlamp profiles using the illuminance reaching three sign positions. Illuminance ratios were calculated and the results are shown in Figure 6. The sign offset values shown in Figure 6 are referenced from the right edge line of the travel lane (with the vehicle centered in the travel lane).

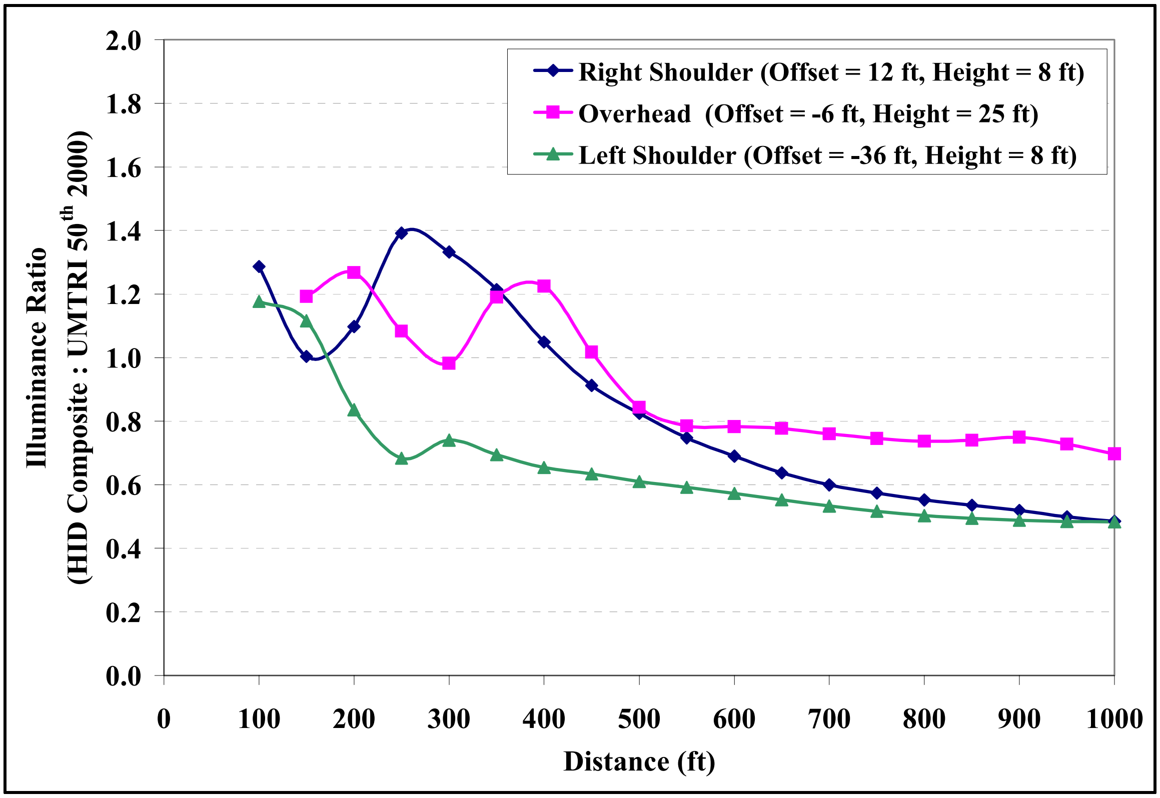


Figure 6. Relative Performance of HID and UMTRI-2000-50% Profiles

The results of Figure 6 can be interpreted as follows:

	< 1.0,	HID composite profile provides less light to sign
for, Illuminance ratios:	= 1.0,	HID composite profile provides the same amount of light
	> 1.0,	HID composite profile provides more light to sign

Considering text-based left- and right-mounted shoulder signs with 5-inch letter heights and an assumed legibility threshold of 40 ft per inch of letter height (i.e., 200 ft), the composite HID headlamp profile provided 84 and 110 percent of UMTRI's 2000 headlamp profile, respectively. For overhead signs at 640 ft, the composite HID headlamp profile provided 78 percent of the UMTRI 2000 headlamp profile.

Based on the mixed results of these analyses, and the slow growth of HID headlamps on new vehicles sold in the U.S., UMTRI's U.S. low-beam 50^{th} percentile profile for 2000 model year vehicles was selected for establishing minimum retroreflectivity levels for traffic signs. However, it is important to note that as technologies, specifications, and the composition of the vehicle fleet evolves, there will be a need to revisit the headlamp issues associated with minimum retroreflectivity development.

Vehicle Type

In their initial minimum in-service retroreflectivity work for overhead and street name signs, Carlson and Hawkins used the same vehicle dimensions that had been used in 1993 initial development of minimum retroreflectivity values for traffic signs in the U.S. The resulting vehicle is large passenger sedan. However, U.S. model year 1999 vehicle sales statistics show that for the first time since records have been maintained, trucks (defined as pickups, sport-utility vehicles and minivans) have outsold cars (for that year, trucks had about 50.1 percent of the new-vehicles market versus 49.9 percent for cars). This trend continued for the year 2000.

Over the last decade, the number of registered passenger cars decreased by 0.1 percent while the percent of trucks has increased over 60 percent (*19*). Based on these data, the researchers decided to use an updated vehicle that better represents the trends in the U.S. vehicle fleet. This decision was also made because it provides no compromises in terms of reducing nighttime visibility. Vehicles such as passenger cars generally have headlamp and seating arrangements that result in smaller observation angles compared to larger vehicles such as trucks, and the performance of retroreflective sheeting increases as the observation angle decreases.

In November 2001, researchers at TTI measured the pertinent dimensions of the top ten selling light trucks, minivans, and sport utility vehicles for model year 2000. The results were averaged to develop a set of dimensions representing a typical light truck/minivan/sport utility vehicle that could be used to develop minimum retroreflectivity values. The overall impact of this change is a larger observation angle associated with the vehicle dimensions (see Table 2).

Table 2. Vehicle Dimensions

Vehicle Description	Headlamp Height	Driver Eye Height	Headlamp Separation	Driver Eye Setback	Driver Eye Offset
Averaged Truck/Minivan/SUV (in)	33.5	58.1	52.6	86.4	15.8
CARTS passenger car (in)	24	42	48	54	18

Sign Sheeting Materials

When the first set of recommended minimum retroreflectivity levels were published in 1993, traffic engineers did not fully understand the way retroreflectivity performed. Since then, traffic engineers have learned much about retroreflectivity and as a result, there are more data available in the public domain and newly developed computer tools to analyze retroreflective sheeting performance (such as ERGO and TarVIP).

The first set of minimum retroreflectivity levels recommended for traffic signs used rather crude regression functions to predict the performance of retroreflectivity sheeting (*4,5*). The impacts of both the orientation and rotation angles were completely neglected.

The updated retroreflectivity values use look-up functions to extract a subset of retroreflectivity values from four dimensional matrices that include over 250,000 data points per sheeting type. The matrices of retroreflectivity include observation angle, entrance angle, orientation angle, and rotation angle. The minimum retroreflectivity values are based on new retroreflective sheeting performance data available in ERGO and used with permission (*24*).

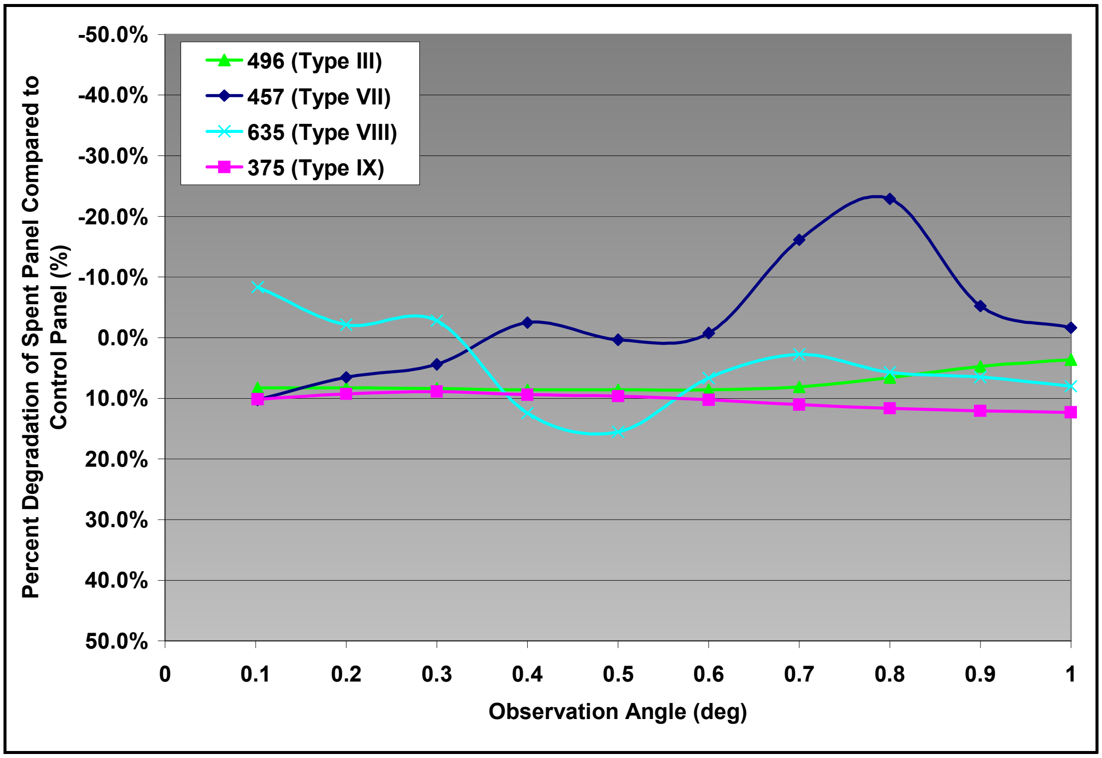
One assumption is that the retroreflective sheetings degrade uniformly over the range of observation angles. In order to test this assumption, the researchers obtained and measured three year NTPEP panels (NTPEP weathers panels for a maximum of three years at a 45 degree orientation facing south). Table 3 includes a description of the panels and the measurements that were made at FHWA's Photometric/Visibility Lab.

Table 3. Description of NTPEP Panels Measured

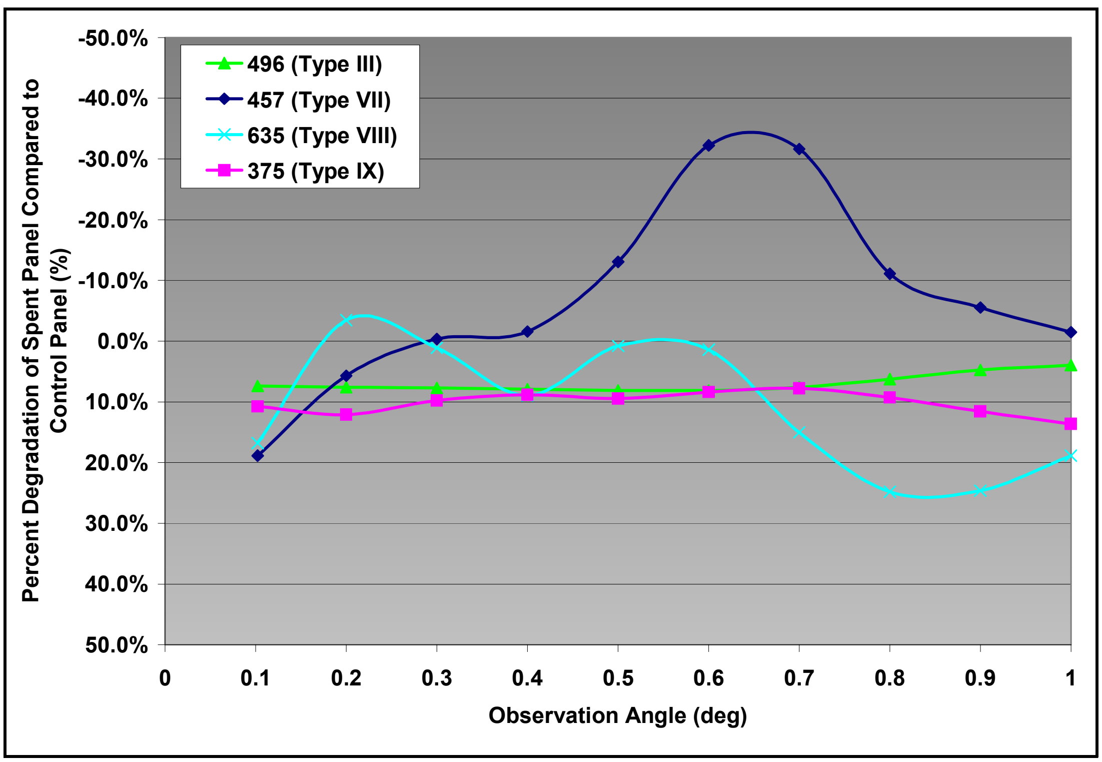
States	AZ, LA, VA
Color	White
Material	ASTM Types III, VII, VIII, IX
Control	Unweathered panels (one of each type)
Weathered	3-years facing south at 45-degrees (two of each type)
Measurements	Observation angle (α): 0.102, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 Entrance angle ($\beta 2$, $\beta 1$=0): 4, 16, 30, 45 Epsilon (ε): 0, 90 (measurements were averaged for the analyses)

The practice of weathering panels at a southern orientation and at 45 degrees doubles the degradation rate compared to a standard vertically mounted sign. Therefore, the weathered panels have been effectively weathered for six years.

The results of the measurements and subsequent analyses showed that, as expected, the retroreflective sheeting made with glass beads degrades uniformly but retroreflective sheetings made with microsized prisms does not. Although the extent of the variations depends on the sheeting type and weathering location, for all sheetings the variation of degradation rate increases with increased observation and entrance angles. Figure 7 shows an example of the results for the panels from Louisiana.



a. Percent Degradation of Louisiana Panels, Beta= 4°



b. Percent Degradation of Louisiana Panels, Beta= 30°

Figure 7. Variation in the Uniformity of Sheeting Degradation

The results showed that further weathering and subsequent analyses are needed. Because weathering takes time, an efficient way to obtain weathered data beyond 3 years would be to continue weathering the NTPEP panels (which have been stored in such a manner to prevent further degradation). In May 2002, the results summarized herein were presented to the NTPEP Sign Sheeting committee and a request for permission to weather spent NTPEP panels past three years was submitted. The researchers are currently waiting for approval from NTPEP.

Another issue related to the weathering of sheeting materials is the rotational sensitivity. According to a presentation by Ealding at the 2002 NTPEP meeting in New Orleans, the rotational sensitivity of microprismatic sheeting materials can change over time. This issue needs to be further evaluated, especially in regards to the ongoing HITEC evaluation of sign retroreflectometers.

Until the long term performance of retroreflective sheetings, especially those made with microsized prisms, is fully understood, the shortcomings described above will remain. Fortunately, a solution exists although it will take time to weather, measure, and analyze the subsequent data.

MINIMUM RETROREFLECTIVITY WORKSHOPS

Over the summer of 2002, the FHWA conducted a second round of national workshops dedicated to the minimum retroreflectivity concept (the first workshops were held in 1995). A total of four workshops were held in Lakewood, Colorado, Hudson, Wisconsin, College Station,, Texas, and Hanover, Maryland. The goal of the workshops was to solicit comments from public agencies regarding the implementation of minimum in-service retroreflectivity guidelines for traffic signs. During the workshops, draft *MUTCD* language for Section 2A.09 was presented and revisions were suggested by the workshop participants. The workshops also included a nighttime demonstration of a variety of signs at various levels of retroreflectivity. The then most current research recommendations regarding the minimum retroreflectivity levels were presented and discussed (as the workshops were conducted, the research regarding the recommended minimum retroreflectivity levels progressed). The workshop handouts, including the recommended minimum retroreflectivity levels from each workshop, can be obtained at the following web site: http://tcd.tamu.edu/.

RECOMMENDATIONS

The recommended minimum retroreflectivity levels are shown in Table 4. They represent the most current research recommendations, but are subject to change as additional research is performed and implemented. Additional details regarding the development of the recommendations shown in Table 4 can be found in the final report (*25*).

Table 4. Updated Minimum Retroreflectivity Levels for Traffic Signs

Sign Color	Criteria	Sheeting Type (ASTM D4956-01a) (*10*)					
		I	II	III	VII	VIII	IX
White on Red	See Note ①	35 ∕∕ 7					
Black on Orange or Yellow	See Note ②	∗	50				
	See Note ③	∗	75				
Black on White		50					
White on Green	Overhead	∗ ∕∕ 7	∗ ∕∕ 15	∗ ∕∕ 25	250 ∕∕ 25		
	Shoulder	∗ ∕∕ 7	120 ∕∕ 15				

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

Bold Symbol Signs

- W1-1 – Turn
- W1-2 – Curve
- W1-3 – Reverse Turn
- W1-4 – Reverse Curve
- W1-5 – Winding Road
- W1-6 – Large Arrow (One direction)
- W1-7 – Large Arrow (Two directions)
- W1-8 – Chevron
- W1-9 – Turn & Advisory Speed
- W1-10 – Horizontal Alignment & Intersection
- W2-1 – Cross Road
- W2-2, W2-3 – Side Road
- W2-4 – T Intersection
- W2-5 – Y Intersection
- W2-6 – Circular Intersection
- W3-1a – Stop Ahead
- W3-2a – Yield Ahead
- W3-3 – Signal Ahead
- W4-3 – Added Lane
- W6-1 – Divided Highway Begins
- W6-2 – Divided Highway Ends
- W6-3 – Two-Way Traffic
- W10-1, -2, -3, -4 – Highway-Railroad Intersection Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3 – Deer Crossing
- W11-4 – Cattle Crossing
- W11-5 – Farm Equipment
- W11-5p, -6p, -7p – Pointing Arrow Plaques
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow

Special Case Signs

- W3-1a – Stop Ahead
  - Red retroreflectivity ≥ 7, White retroreflectivity ≥ 35
- W3-2a – Yield Ahead
  - Red retroreflectivity ≥ 7, White retroreflectivity ≥ 35
- W3-3 – Signal Ahead
  - Red retroreflectivity ≥ 7, Green retroreflectivity ≥ 7
- W14-3 – No Passing Zone
  - Use dimension B in *Standard Highway Signs*, (2002 Edition)
- W4-4p – Cross Traffic Does Not Stop
  - Use dimension A in *Standard Highway Signs*, (2002 Edition)
- W13-2, -3, -1, -5 – Ramp & Curve Speed Advisory Plaques
  - Use dimension B in *Standard Highway Signs*, (2002 Edition)

FUTURE WORK

The next step in the process of establishing minimum retroreflectivity levels for traffic signs is the development of proposed MUTCD language for Section 2A.09. The FHWA will develop the language and publish a notice of proposed rulemaking for comment in the *Federal Register*. Agencies will have at least 60 days from the date of the proposed rule to provide comment.

Looking further down the road, there is a need for additional research in order to address the limitations of the current set of recommendations. Therefore, the following list of research topics are proposed by the research team.

- Research is needed that should focus on the contrast needed for iconic signs such as most white on red signs like the Stop sign.
- Weathering research to determine uniformity assumption validity.
- Validation of retroreflectivity levels from a driver's point of view.
- Rural versus urban (including glare source study) demand luminance study.
- Impacts of horizontal curves.
- Impacts of heavy vehicles.
- Methods to manage nighttime sign visibility, including the development of an on-the-fly luminance van.
- Identification of better technologies or procedures to measure nighttime visibility.
- Identification of retroreflective sheeting material measurement geometries that represent the driving task, which would preferably lead to a more meaningful classification (compared to the ASTM D4956-01a classification currently used).

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