Use of High Intensity Reflective Sheeting in lieu of External Lighting of Overhead Roadway Signs
(Final Report)

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SI CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS USED

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

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		AREA		
in^2	Square inches	645.2	square millimeters	mm^2
ft^2	Square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		VOLUME		
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		FORCE and PRESSURE or STRESS		
lbf	Pound force	4.45	Newton	N
lbf/in^2	Pound force per square inch	6.89	kilopascals	kPa

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16. Abstract

Effective highway signing is an important component of driver decision making, comfort, and safety. Like many agencies across the country, overhead sign lighting has been used by the Florida Department of Transportation (FDOT) to improve visibility. However, the availability of newer and more efficient retroreflective materials has created a new challenge for state transportation agencies going through sign upgrade programs and considering the need for sign lighting. FDOT initiated this study to investigate whether high intensity reflective sheeting can be used to replace overhead sign lighting.

Field data was collected to assess the conditions of Florida signs in terms of the MUTCD minimum maintained retroreflectivity levels. In addition, a luminance computation model was developed to calculate sign legend luminance under various situations, including different sign lighting technologies, different geometrics and sign locations, and different amounts of sign dirt and sign aging. By comparing the calculated luminance of a specific sign at a specific situation with the legibility luminance levels required by older drivers, sign lighting needs were assessed.

A life-cycle cost spreadsheet was developed and used to calculate the cost of replacing the current sign sheeting in Florida with high reflective sheeting and the cost of installing/upgrading sign lighting. Based on this analysis, we found that under the conditions considered (either on straight and flat roadways or horizontal curves, in rural areas or urban areas), the most cost effective approach to maintain overhead guide luminance is to use (installing or replacing with) induction or LED luminaires. The results also indicate that a viable alternative (in terms of maintaining luminance and being cost effective) would be to use either Type VIII or Type XI legend sheeting materials and forgo sign lighting. For Type XI sheeting materials, sign lighting would be needed along horizontal curves in rural areas with radii of 880 ft and horizontal curves in urban areas with radii of 2500 ft or less.

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EXECUTIVE SUMMARY

Effective highway signage is an important component of driver decision making, comfort, and safety. Like many agencies across the country, overhead sign lighting has been used by the Florida Department of Transportation (FDOT) to improve visibility. However, the availability of newer and more efficient retroreflective sign sheeting materials has created a new challenge for state transportation agencies going through sign upgrade programs and reconsidering the need for sign lighting. There is a general consensus that sign lighting is not needed for overhead guide signs with high intensity reflective sheeting in rural areas; but in developed areas or along highways with unique geometrics, there is concern about removing or turning off overhead guide sign lights. Another issue of concern is in areas of frequent dew, fog, or frost. FDOT initiated this study to investigate whether high intensity reflective sheeting can be used to replace overhead sign lighting, i.e., whether it can perform and meet retroreflectivity standards; whether it can satisfy elderly drivers' visibility demands at night; and whether it is cost-effective.

Field data were collected in Florida and used to assess the conditions of Florida signs in terms of the MUTCD minimum maintained retroreflectivity levels. All measured signs made with prismatic sheeting materials were found to be well above the minimum MUTCD retroreflectivity levels. However, some guide signs with beaded materials were in need of care in order to be considered in compliance with the new MUTCD regulations.

A luminance computation model was also developed to calculate sign legend luminance under various situations, including different headlamps, different sign lighting technologies, different geometrics and sign locations, and different amounts of sign dirt and sign aging. By comparing the calculated luminance of a specific sign at a specific situation with the legibility luminance levels required by older drivers, it is possible to identify if high intensity sign sheeting can replace the need for sign lighting; and if not, then determine where overhead signs with lights should be required in lieu of high intensity reflective sheeting in Florida.

Finally, a life-cycle cost spreadsheet was developed and used to calculate the cost of replacing the current sign sheeting in Florida with high reflective sheeting and the cost of installing/upgrading sign lighting. Based on this analysis, we found that under the conditions considered (either on straight and flat roadways or horizontal curves, in rural areas or urban areas), the most cost effective approach to maintain overhead guide luminance is to use (installing or replacing with) induction or LED luminaires. The results also indicate that a viable alternative (in terms of maintaining luminance and being cost effective) would be to use either Type VIII or Type XI legend sheeting materials and forgo sign lighting. For Type XI sheeting materials, sign lighting would be needed along horizontal curves in rural areas with radii of 880 ft and horizontal curves in urban areas with radii of 2500 ft or less.

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INTRODUCTION

Effective highway signage is an important component to driver decision making, comfort, and safety. Given the high number of elderly drivers, nighttime visibility of highway signage is especially important in Florida. Like many agencies across the country, overhead sign lighting has been used by the Florida Department of Transportation (FDOT) to ensure sign visibility. However, the availability of newer and more efficient retroreflective materials has created a new challenge for state transportation agencies in considering the need for sign lighting. There is a general consensus that sign lighting is not needed for overhead guide signs with high intensity [1] reflective sheeting in rural areas; but in developed areas or along highways with unique geometries, there is concern about removing or turning off overhead guide sign lights. Another issue of concern is in areas of frequent dew, fog, or frost.

When state transportation engineers refer to the current standards and specifications, they find little to no assistance with such considerations. The pertinent sections of the engineer's resources (such as the MUTCD) were written when turning off or removing sign lights was the exception. Without guidelines for providing effective nighttime performance of overhead guide signs as a function of site-specific situations and covering elderly drivers' demands of reading guide signs clearly at night, site-specific research is needed to address whether high intensity reflective sheeting is a safe and effective substitute for lighting on overhead signs in Florida.

BACKGROUND

When overhead signs were first being used, they were constructed with porcelain enamel materials that were not retroreflective, and then later, the legends were made with button copy demountable letters and numbers. The need for overhead sign lighting was not questioned at that time [2]. As retroreflective sign sheeting materials have become more efficient in terms of returning headlamp illumination back to drivers, there has been a trend to turn off and or remove most overhead guide sign lighting (despite less overhead illuminance provided by vehicle headlamps). The results of surveys of state transportation agencies document a trend away from use of overhead guide sign lighting when signs are upgraded using efficient retroreflective materials. But overhead sign lighting continues in Florida. FDOT is currently interested in determining whether high intensity reflective sheeting can be used to replace overhead sign lighting, i.e., whether it can perform and meet retroreflectivity standards, whether it can satisfy elderly drivers' visibility demands at night; and whether it is cost-effective.

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1 The definition of "high intensity" in this report is different from that in ASTM D4956. In ASTM D4956, ASTM Type III and IV sheeting materials refer to as "high intensity". However, in this report, "high intensity" refers to sheeting materials with high reflective properties, especially prismatic sheeting.

2 As late as 1987, research including a national survey of 24 states concluded that the best practice for overhead guide signs included retroreflective backgrounds, legends, and sign lighting (*1*).

TASK 1: REVIEW PERTINENT LITERATURE

This task consisted of a review of the applicable background, literature, national policies, and guidelines related to the nighttime visibility of overhead guide signs. In this review, specific voids with respect to objective performance criteria related to the nighttime visibility of overhead guide signs are emphasized. In addition, relevant research findings are described to demonstrate areas in need of research.

Visibility Factors of Traffic Signs

The influencing factors related to sign visibility are overwhelming, which were categorized into four main headings in Table 1.1, with their corresponding design elements. All of the elements in Table 1.1 can be reduced to three main components that impact visibility.

Table 1.1 Visibility Factors of Traffic Signs (*2*)

Sign	Vehicle	Driver	Environment/Road
• Position o Ground-mounted - Right - Left - Lateral offset o Overhead - Height - Lane positioning - Tilt • Size • Shape • Color o Background o Legend • Legend o Symbol o Alphabet - Font - Size - Stroke width - Letter spacing - Line spacing • Lighting • Retroreflective material	• Type o Sports car o Passenger car o Pickup truck/SUV o 18-wheeler • Headlamp o Type - Halogen-tungsten - High-intensity discharge o Illumination distr. o Aim o Cleanliness • Windshield o Transmissivity o Cleanliness • Constant voltage	• Visual characteristics o Acuity o Contrast sensitivity o Color deficiency o Other • Awareness • Mental load • Alcohol/drugs	• Atmospheric conditions o Rain o Fog o Haze o Other • Background complexity o Urban - Residential - School - Commercial - Industrial o Rural • Time of day o Day o Dusk o Night • Horizontal alignment • Vertical alignment • Sight distance • Pavement reflectance

- *Retroreflectivity*: the ratio of light reflected back to the receptor compared to the amount that is emitted by the source.
- *Illuminance*: the light received by the viewing surface (e.g., sign face). Light dissipates with distance and illuminance depends on the distance between the vehicle and the sign.
- *Luminance*: the amount of light that is viewed by the driver and is commonly referred to as the brightness of a sign; it is what the driver sees.

These three main components should be combined with some other factors to determine the luminance of traffic signs. For instance, the visual ability of the driver, weather condition and background complexity impact the required luminance for drivers in order to see the signs. Therefore, the following literature review is focused on the three components, while including the other influencing factors.

Retroreflective Sheeting Material

Traffic signs use retroreflective sheeting to help ensure that the signs communicate the same message day and night. Retroreflectivity is an optical property of a material that enables incoming light to be reflected back to its source. Various sign sheeting types have been developed with differing retroreflective capabilities.

Retroreflective Sheeting Specifications

The American Society of Testing and Materials (ASTM) developed a specification for all retroreflective sign sheeting types, referred to as ASTM specification D4956. In the late 1980s, American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) adopted the ASTM specification as the national specification for traffic signs. For decades the two coincided. However, in 2010, AASHTO developed their own sign sheeting specification, different from ASTM.

As of June 2011, the ASTM D4956 sign sheeting classifications for rigid signs are Types I, II, III, IV, VIII, IX, and XI. ASTM established the initial classification from numerically based performance and retroreflective capabilities. For instance, Type III High Intensity sheeting outperforms Type II Super Engineering Grade. The original performance-based classification was intended to simplify sign sheeting selection. After 1989, newly developed sign sheeting materials were added in chronological order of development as opposed to the original numerically-based performance. As a result, the current classification system does not indicate relative performance. For example, Type IX sheeting is less bright at longer distances than Type VIII, but Type IX is generally brighter at shorter distances.

AASHTO’s new sign sheeting specification is a little different. There are four classes of materials labeled A through D. Class A is the low end of the scale and is similar to Type III in the ASTM specification. The AASHTO classification then ramps up the retroreflectivity criteria for each class based on an increasing level of retroreflectivity at the 0.5 degree observation angle. In an indirect way, the AASHTO specification is more driver needs oriented than the ASTM specification. The Texas Department of Transportation (TxDOT) is currently going through a process to adopt the AASHTO specification into their state specifications. Most state agencies, including Florida, developed their own state specification based on the ASTM specification and some states employ the ASTM D4956 specification without any modifications (*3*).

Pertinent Research Findings of Sign Retroreflectivity

In December of 2003, the FHWA published a report with recommendations for minimum maintained retroreflectivity levels for overhead guide signs and street name signs (2). That report includes a thorough review of visibility issues related to overhead guide signs and street name signs. The report includes a list of visibility issues, relevant research findings up to that point, and a survey of current practices. Chapter 2 of the report includes a thorough literature review (http://www.fhwa.dot.gov/publications/research/safety/03082/02.cfm#Toc62621495).

The standards for minimum levels of retroreflectivity, which are detailed in the MUTCD, are based on the above research. Meanwhile, each state has their own method to test and maintain minimum levels of sign retroreflectivity. *Florida Method of Test for Sign Sheeting Materials* is based on ASTM standards (http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/fstm/methods/fm5-571.pdf). Not a lot of research was found related to sheeting retroreflectivity in Florida. Rogoff's study found that over half of the stop signs in one county in Florida failed to meet the recommended coefficient of retroreflection. It was explained that the failure to meet satisfaction was due to the signs' inability to achieve a white-to-red contrast ratio of 3:1 which is recommended (*4*). Rogoff's research utilized a retroreflectometer to measure the retroreflectivity from signs in Hillsborough County, FL. No details about the instrument used were provided in the journal.

On the other side, the availability of newer materials has created a new challenge for State transportation agencies going through sign upgrade programs and considering the need for sign lighting. A lot of research has been done on the visual performance of overhead signs using various materials with and without external sign lighting.

Back in the 1960s, research was conducted by TTI on the legibility of different combinations of overhead guide sign materials. It was concluded that many combinations of material types might provide satisfactory legibility without the use of sign lighting, though the conclusion was drawn based on the results from younger drivers (*5*).

In the 1970s, research (*6,7*) was conducted about the performances of different retroreflective guide sign sheeting. It was recommended that overhead sign lighting could be eliminated when the sign sheeting was Type III with a straight approach to the sign. It was also suggested that sign lighting be used on curves or where only the low beams of vehicle headlamps were allowed.

In 1984, Gordon summarized the nighttime visibility research performed on overhead signs and examined the request by the California Department of Transportation (CALTRANS) for using non-illuminated opaque overhead signs (*8*). The CALTRANS review team concluded that button copy signs with opaque backgrounds functioned satisfactorily without external sign lighting. In addition, it was recommended to maintain sign lighting for freeway off-ramps and lane-assignment signs that call for immediate lane changes, and to use sign lighting where fog and dew were frequent occurrences.

A study in Ohio (*9*) was conducted on unlighted overhead guide signs in 2002. The performance of four different retroreflective overhead sign sheeting combinations was evaluated with and without exterior sign lighting. Based on the field and photometric evaluation results, it was concluded that either white Type VII or Type IX legends on green beaded Type III backgrounds could provide adequate appearance, conspicuity, and legibility without additional sign lighting.

Another study (*10*) on unlighted overhead guide signs was conducted using older drivers in 2003. Six sign material and lighting combinations on US Route 30 near Mansfield, Ohio were evaluated using twenty older drivers, aged 63 to 81. The results indicated that using appropriate materials for signs without exterior sign lighting may improve the visual performance of signs. Older drivers noticed that unlighted Type IX on Type IX and Type VII on beaded Type III had a higher performance than the lighted beaded Type III on beaded Type III. In addition, it was found that overhead signs using Type VII on beaded Type III or Type IX on Type IX materials provided better visual performance for older drivers when the sign lighting was eliminated.

Bullough et al. completed a study (*11*) about the legibility of traffic signs. The research team tested the signs that were installed along the major expressway in an urban area that were made of new retroreflective materials (Type VII, VIII and IX) without sign lighting and also lighted signs made with commonly used materials (Type I and III). Based on the photometric measurements of the signs (luminance and luminance contrasts) and the resulting relative visual performance and visual response time values, it was indicated that when viewed from 100 meters away, the calculated visibility of the measured unlighted signs was similar to that of the signs equipped with external sign lighting (which met *Roadway Lighting Design Guide* 2005 recommendations for sign illumination).

Indiana DOT developed an evaluation in 2009 to assess the feasibility of using overhead guide signs on freeways without lighting at nighttime (*12*). The evaluation consisted of comparing the conspicuity, legibility, and appearance of selected signage materials in nine legend-background combinations. The evaluation concluded that it was feasible to eliminate the lighting of overhead guide signs by using prismatic Type IX, Type VIII, or Type IV legends on Type IV backgrounds (which had higher retroreflectivity).

Lighting Sources of Signs

The main lighting sources of traffic sign at night are sign lighting, vehicle headlamp and roadway lighting. They all provide illuminance falling on the sign and therefore drivers can see them when the light reflects back to drivers' eyes. The following sections focus on the technology, performance, trends and relative policies regarding the three lighting sources.

Guide Sign Lighting

As described by the Illuminating Engineering Society of North America (IESNA) RP-19-01 *Recommended Practice for Roadway Sign Lighting* (*13*), sign lighting aids drivers to recognize and understand the sign's message rapidly and accurately at night, which accordingly improves safety because drivers are not inclined to reduce speed in order to read signs. Sign lighting is also helpful when the volume of traffic increases, the complexity of highway design increases, adverse weather is prevalent in specific locations, and ambient luminance increases.

RP-19-01 states that overhead sign lighting should be used for three reasons (*13*):

1. Retroreflective sheeting of signs may not provide sufficient sign legibility by reflecting lights from headlamps with main beams projecting downward;
2. Though roadway lighting can provide some sign illumination when the sign lighting is out of service, it is not intended to be used for activating or lighting overhead signs;
3. With sign lighting, sight distance for sign recognition is increased.

The basics of sign lighting

According to IESNA RP-19-01 (*13*), sign lighting can be classified into two categories: external lighting and internal lighting. For overhead guide signs, the lighting source is usually externally installed. Therefore, all the lighting discussed in this section refers to external sign lighting. For external sign lighting, there are three locations for installation: top mounted, bottom mounted and ground/remote located. Overhead sign lighting is usually mounted at the bottom of signs. More details about the effects of the sign lighting locations can be found in IESNA RP-19-01 (*13*).

Table 1.2 shows the lamp types commonly used for sign lighting, as well as their efficacy and lamp life. However, more and more state agencies/departments (including FDOT) are looking into new sign lighting technologies, such as induction and LED lighting.

Table 1.2 Lamp Characteristics (*13*)

Lamp Family	Efficacy* (Lumens/Watt)	Lamp Life (Hours)
Incandescent	15 to 25	750 to 8,000
Fluorescent	45 to 93	7,500 to 12,000
Mercury		
Deluxe	40 to 49	24,000+
Other types	34 to 45	24,000+
Metal Halide	69 to 110	7,500 to 24,000
Sodium		
High pressure	81 to 125	24,000+
High pressure (color improve)	52 to 94	10,000 to 15,000
Low pressure	80 to 150	10,000 to 18,000

*Approximate total efficacy at 100 hours shown for lamps and ballasts at wattages normally considered for roadway sign lighting application. Includes nominal ballast losses where applicable. Lamp-life hours is rated average life of typical lamps considered for this use. (These data are current as of 2001 and are subject to improvement.) For data on individual lamp types, consult manufacturer's catalog.

National policies and guidelines for sign lighting

The next several sections discuss the applicable national policies and guidelines related to the nighttime visibility of overhead guide signs.

Manual on Uniform Traffic Control Devices (MUTCD): The MUTCD is the first place that State agencies go for guidance concerning traffic control devices such as overhead signs (*14*). The MUTCD provides guidance for overhead guide signs but falls short of describing how to achieve *high visibility* and *high legibility* other than stating that guide signs should be illuminated unless an engineering study shows that illumination is not needed. However, there is no reference provided to determine how one evaluates whether lighting is needed or how to go about conducting an engineering study aimed at determining if sign lighting is needed.

AASHTO Roadway Lighting Design Guide: Without the necessary information provided in the MUTCD to assess the nighttime visibility of overhead guide signs, the next place a State agency engineer might look for guidance is the *AASHTO Roadway Lighting Design Guide* of 2005 (*15*). Though the AASHTO document provides additional information beyond the MUTCD, it still falls short of providing guidelines on how to determine if and when sign lighting is needed to achieve adequate nighttime visibility for overhead guide signs. The concept of ambient luminance levels stated in AASHTO document has merit from an intuitive perspective but leaves the State agency engineer without a tool to perform an engineering study as required by the MUTCD.

Illuminating Engineering Society of North America: The referenced material in the AASHTO *Roadway Lighting Design Guide* comes from the Illuminating Engineering Society of North America (IESNA). The IESNA RP-19-01 (*13*) document does not include warrants or guidelines to determine if lighting is needed but it does provide a nice source of information once lighting is determined.

Limitations of Applicable Policies and Guidelines: Beyond the question of whether sign lighting is needed or not, there is also an interesting conflict between the AASHTO guidelines and the MUTCD. AASHTO provides lighting level recommendations for different classes of ambient luminance and, as described by AASHTO, low ambient luminance represents rural areas with little to no background or commercial lighting. For these areas with low ambient luminance, AASHTO recommends maintained sign luminance levels of 22 to 44 candelas per square meter. The MUTCD now contains minimum maintained retroreflectivity levels for signs, including guide signs. The minimum retroreflectivity levels were derived from human factors studies aimed at determining the guide sign luminance needed for older driver nighttime legibility. The research was performed in a dark rural setting that would clearly meet the qualitative description provided by AASHTO for low ambient luminance. The luminance requirements derived from the FHWA research that was used to set the MUTCD minimum maintained retroreflectivity levels were only about 3 candelas per square meter, or about 10 times less than the AASHTO guidelines for low ambient luminance levels. In a follow-up FHWA study, sign lighting and glare sources were added and the required guide sign luminance was again determined for older driver nighttime legibility. Under these conditions, which might be more representative of the AASHTO medium ambient luminance class, the luminance requirements were peaked around 10 candelas per square meter, but the AASHTO guidelines are 44 to 89 candelas per square meter. In addition, the same discrepancy exists between IESNA guidelines and the MUTCD with respect to these suggested lighting levels.

Another limitation of current policies and guidelines exists in the older drivers' demands of reading guide signs clearly at night. There is no specific consideration of sign luminance levels needed for older drivers. Further guidelines for using sign lighting should cover older drivers' demands.

Sign lighting trends

Lighting signs requires a capital investment and continued maintenance. Besides the cost of lighting overhead guide signs, the growing interest to determine when sign lighting is needed follows the evolution of retroreflective sign sheeting materials. As retroreflective sign sheeting materials have become more efficient in terms of returning headlamp illumination back to the driver, there has been a trend to turn off and or remove most overhead guide sign lighting. A newly approved font (Clearview) has been introduced and designed to perform best with newer versions of retroreflective sign sheeting materials, thus adding more legibility to overhead guide signs and further pushing the issue of whether sign lighting is needed. A couple of recent surveys of state transportation agencies have shown a trend away from the use of overhead guide sign lighting when upgrading to more retroreflective sheeting materials. The next few sections describe the results of recent surveys regarding sign lighting practices in the U.S.

Wisconsin DOT Survey in 2008. In 2008, the Wisconsin Department of Transportation (WSDOT) surveyed State transportation agencies to determine their policies regarding overhead sign sheeting and sign lighting (*16*). In summary, the WSDOT survey reported that the States that have turned off their sign lighting have had little to no public complaints. It also reported that six of the thirty states that responded to the survey indicated that they have performed some type of evaluation. The biggest concern about not lighting overhead signs was maintaining adequate visibility during dew, frost, fog, snow, or when unusual roadway geometrics limit the amount of headlamp illumination reaching the sign.

Joint Technical Committee Survey in 2010. Another survey called the *Joint Technical Committee on Roadway Lighting Survey of AASHTO Members* was conducted by the AASHTO Joint Technical Committee (JTC) in December 2010 (*17*). The result indicates that 21 out of 36 state DOTs (61.8%) have deactivated sign lighting of existing signs, mainly due to the improvement in retroreflective sheeting. The survey results also show that the fifteen states that still use overhead sign lighting use it for urban areas, freeways, and exit signs. In addition, 30 out of 35 (85.7%) of transportation agencies responded that they did not use additional sign lighting in the design of new projects.

Kansas Survey in 2011. An email survey was conducted between February and March 2011, regarding sign sheeting usage, measurements, and maintenance, as well as the use of overhead guide sign lighting on state highways (*18*). The total response rate of this survey was 28 out of 50 state DOTs (56%). Each state was also questioned on their use of overhead sign lighting. Most states are moving away from overhead sign lighting, especially outside city limits, but more generally, half of the states (14 out of 28, or 50%) are eliminating sign lighting in all places. When asked why the states are moving away from overhead sign lighting, the most common response was because the move to higher retroreflective signs had eliminated the need for additional lighting.

Vehicle Headlamp

Headlamps have evolved since the 1880s, when vehicle headlamps were first used. Accordingly, the performance of vehicle headlamps has improved steadily. There are three major types of vehicle headlamps used in the U.S.: tungsten-halogen, HID, and LED. Tungsten-halogen headlamps use tungsten filaments inside a halogen gases-filled bulb, HID headlamps use electrical arcs instead of the tungsten filaments used in conventional headlamps, and LED headlamps are a collection of multiple diodes.

Headlamp trends

In general, the modern headlamps have more flexibility than the previous ones, in terms of the light sources, optics, and their specified aiming method (*19*). In 1997, as a drastic compromise between the U.S. philosophy of maximizing visibility versus the European philosophy of minimizing glare, the FMVSS Standard 108 was revised to accommodate the U.S. specification along with the European and Japanese specifications in order to create a global headlamp specification, or "harmonized beam patterns" (*20*). Accordingly, there were several compromises that changed the standard in U.S. vehicles. The most significant compromise was that less light is allowed to be projected above the horizontal plane, which in turn reduces the amount of light available for overhead signs. A report shows that for overhead signs there are consistent trends showing decreased illumination above the horizontal at approximately 500 ft away (*21*). It was also stated that headlamps tend to have sharper vertical gradients due to the introduction of visual/optical aiming in the late 1990s, increased usage of projector lamps, and the appearance of HID headlamps (*22*).

Other factors impacting the lighting from vehicles, such as headlamp height and degradation of the headlamp lenses, have changed over the years. The minimum mounting height of headlamps was 2.0 feet prior to the 1980s, and has since been reduced to 1.8 feet, which reduces the amount of light that can be projected to overhead signs since relatively less light could reach those signs.
Meanwhile, as headlamps changed from sealed beam headlamps to replaceable bulbs, degradation conditions came into play, since replaceable bulbs suffer from yellowing and fogging caused by factors like acid rain, condensation, and high heat. Therefore, it is important to consider the aging or degradation of headlamps for light illuminance of over-head signs (*23*).

In addition, a survey developed by Schoettle et al. summarized the recent trends of the market-weighted headlamps in the U.S. by comparing samples in the years 1997, 2000, 2004, and 2007 (*19*). There are a few main conclusions found from the study:
1. There was a trend of using single-filament lighting sources and four-lamp systems.
2. Most headlamps shifted from lens-based optics to reflector-based ones.
3. The aiming methods of headlamps changed from mechanical aim to visual/optical aim, mainly using visual/optical right side (VOR) aiming. A previous study (*22*) showed that overhead

illumination is reduced by 18 percent for the VOR headlamp and by 28 percent for the visual/optical left headlamp.

Roadway Lighting

Though roadway lighting is not intended to properly activate or light overhead retroreflective signs, it can provide some sign illumination when the sign lighting is out of service (*13*). However, it is not always straightforward depending on the position of the signs relative to the lighting. A review of roadway lighting is provided below.

Roadway lighting trends

With the development of lamps, using energy saving-light sources, such as LED and induction lamp, is a definite direction for roadway lighting. In addition, due to the increased concerns of energy costs from the economic downturn and concern over the pollution issue, traffic agencies are considering developing new policies for roadway lighting using advanced techniques, such as practicing lighting curfews or adaptive lighting, both of which are explained in the next two sections.

Lighting Curfew. As previously mentioned, the practice of the lighting curfew was described in the 2005 AASHTO design guide, and is intended to use advanced controls to reduce or eliminate parts of or whole lighting systems during part of the nighttime hours as justified by reduced traffic volume, favorable weather, and other conditions suitable for driving without roadway lighting (*15*). In Florida, the public had suggested lighting curfews to reduce lighting glow, but DOT responded by justifying lighting expenditures based on nighttime traffic and nighttime crash rates for unlit roadways.

Adaptive Lighting. Lighting curfew is meant to switch off parts or all of roadway lighting for some night hours, but this leads to a uniformity issue of luminance or illuminance (*24*). This issue could be overcome by another lighting operation: adaptive lighting (or dynamic lighting). Adaptive lighting is intended to dim roadway lighting to reduce the normal level of average luminance as allowed. Design guides of adaptive lighting have been included in the 2010 CIE report (*24*). Many countries have used adaptive lighting techniques, including the Netherlands, England, France and China. It is concluded from their practices that adaptive lighting has (1) greater installation costs, but less operation costs; (2) provided significant reduction in energy consumption compared with continuous nighttime lighting; (3) reduced pollution to the environment; (4) kept the uniformity of luminance level, which is more important for drivers than average luminance level.

Luminance of Signs

There is a common misperception that retroreflectivity is the premiere metric for assessing nighttime sign performance. Perhaps the new MUTCD minimum maintained sign retroreflectivity levels have sustained this common misperception. However, the brightness of the reflected light is the most useful sign metric in terms of identifying driver needs. The brightness of that reflected light is termed luminance, and luminance is the most desirable and relevant sign performance metric. As mentioned before, the MUTCD minimum maintained sign retroreflectivity levels were derived from minimum luminance requirements for older drivers during a nighttime field study (2).

Retroreflectivity is useful from a quality control perspective because it is a property of the sign material. However, it does not provide a direct correlation to sign performance on the road. Luminance is a function of the retroreflective characteristics of the sign material, the illumination characteristics of the vehicle headlamps, and the geometric relationship between the sign and the vehicle. That is why luminance is the desired metric for in situ sign performance. Even so, luminance has not been traditionally used in research or in signage standards because there has not been a measurement device available to effectively measure luminance in the field. Taking luminance measurements in the past was time consuming and required lane closures.

Pertinent Research Findings of Sign Luminance

As retroreflective materials evolved, so did the research conducted to analyze them regarding sign luminance. Sign luminance research began to diverge into two paths: studies conducted in the field and studies conducted in a laboratory. Both lab and field have their advantages and disadvantages, and researchers must consider all aspects when creating an experimental design.

Laboratory Studies

Early laboratory-based research employed practices similar to a common eye exam. In 1977, Richards (*25*) used a static vision testing method by seating subjects 20 ft from an eye chart. The chart was constructed of a rotating disk with letters printed on it to be seen through a slice taken out of the panel in the front of the disk. The letters decreased in size toward the center of the disk. Four luminance levels were presented by supplying light from a projector calibrated to simulate a vehicle’s headlamp. The light source was adjusted to filter light at 10, 1, 0.1, and 0.01 foot-lamberts (0.03 to 34 cd/m^2). Results were averaged for each decade of age collected (26–35, 36–45, etc.). Richards found not only that acuity decreases with age, but also that the acuities at each luminance value exponentially decreased with test letter contrast.

In 1995, Mercier et al. (*26*) modified Richards’ approach by conducting a study using a projection system with signs on a rotating display device. There were five signs on the device that were presented one at a time to the subject. Subjects viewed the scaled signs from distances of 83 and 102 ft, which corresponded to the visibility indices for speeds of 30 and 55 mph, respectively. At these positions, the luminance of the display was incrementally adjusted until the subjects were able to identify the messages.

In 2004, Schnell et al. (*27*) further built upon this method of using projectors and screens. Schnell et al. presented subjects with an image of a 2-inch symbolic sign 64 ft away. To accomplish this, a mirror was set up to reflect the image from a high resolution projector onto a screen. The background of the scene was presented in a lower resolution to provide sufficient contrast between the sign and the scene. Luminance was measured by a color Charge-Coupled Device (CCD) from the front of the screen. Subjects then walked toward the screen until the symbol was identifiable. This setup provided an efficient means for collecting data and adjusting the luminance of the image. Schnell et al. found that the projector and mirror combination was a cheap, easy, and reliable method for adjusting the luminance of any sign presented. Further, the high resolution of the projector demonstrated that overglow was not a consequence for negative contrast signs for luminance levels up to 942 cd/m^2. Results lead to the conclusion that 82 cd/m^2 was the maximum background luminance beyond which no improvement was witnessed.

The experiment conducted by Schnell et al. accomplished its goal of effectively decoupling sign luminance requirements from specific sheeting materials and headlamps, but the conditions of the procedure did not simulate real world driving conditions. Following the Positive Guidance approach, the dynamic task of driving involves more than walking in a darkened room. As such, values obtained from this and similar subsequent studies may not represent or correspond to real-world driving situations.

Field Studies

In 1976, Forbes (*28*) analyzed the effects of color combinations as a function of legibility distance. Forbes found that low beam headlights in the field resulted in longer legibility distances than previous lab measurements. The study also determined that signs with higher luminance levels produced shorter subject glance durations. The color combination analysis identified that the interaction between the background and legend produced a substantial impact on sign legibility, regardless of the luminance. The color combinations of black on white and black on yellow achieved the longest legibility distances and white on gray performed the worst.

Padmos (*29*) in 2000 found that the color recognition of a sign took place at a much greater distance than sign legibility. The results showed that the standardization of highway signs allowed drivers to recognize those colors at lower luminance levels. Padmos defined the lower limit of luminance as “the lowest luminance that turns it sufficiently conspicuous for detection as such and sufficiently legible in order to be identified at a safe distance.”

In 2001, Carlson and Hawkins (*2*) completed a project aimed at identifying the minimum required luminance through minimum retroreflectivity requirements for elderly drivers. The proposed minimum requirements were based on field data that were obtained at the Riverside test facility. The study analyzed subject legibility distances as a function of varying luminous intensity. The luminous intensity of a test vehicle’s headlamps was adjusted to produce 32 different levels. In the study, subjects viewed overhead guide signs and were asked to read the sign content. Signs were viewed under different luminance levels. Figure 1.1 illustrates the effect of increased luminance on the percentage of correct responses of sign content. The three lines in the figure represent legibility indices according to the three positions used to read the signs.

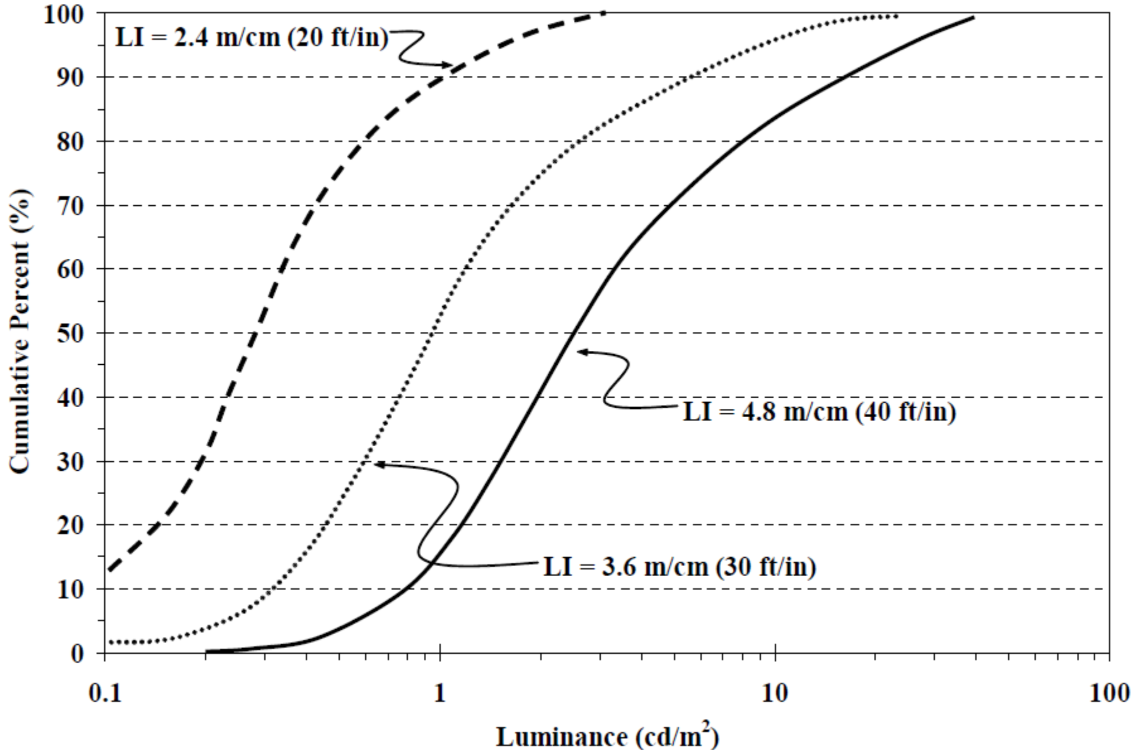

Figure 1.1 Minimum Sign Luminance (*2*)

Main Factors of Demanded Luminance

Drivers' visual ability

Over the past few decades, millions of retirees have come from the Northeast and Midwest to Florida, which results in the problems of infirm and elderly drivers in Florida (*30*). Statistics indicated that for year 2002 to 2003, over 16 percent of drivers in Florida are in the age of 65 and above (*31*). Three major declining functions due to the drivers' aging process were reported by the National Cooperative Highway Safety Research Program in 2002: visual impairment, cognitive changes and reductions in motion. Visual impairment affects functions including static and dynamic visual acuity, contrast sensitivity, and glare sensitivity (*31*), which makes senior drivers harder to see traffic signs at night. Therefore, more luminance of signs is required for elderly drivers.

In 1986, Mace et al., provided an excellent literature summary based on the determination of minimum brightness standards for sign legibility (*32*). It was concluded that minimum luminance requirements for legibility for overhead signs increased with the age of the observer. In 1989, Stein et al., conducted a laboratory study to explore conspicuity issues for the nighttime performance of overhead guide signs (*33, 34*). Detection distance was found to decrease as the driver's age increases, which indicates older drivers need more luminance.

Background complexity

There is a general belief that with lower background complexity (i.e., low background luminance) of traffic sign, less sign luminance is required by drivers, as visibility is dependent on the difference between the target luminance and background luminance. TTI conducted a research project with full-scale guide signs of the following color combinations: white on green, white on blue, and white on brown, including roadway lighting and adding glare to increase the visual background complexity (*35*). One of the major features of this research project was generating findings to compare what levels of retroreflectivity were needed for nighttime legibility under four different scenarios: rural/dark environment, rural/dark with roadway lighting, rural/dark with glare, rural/dark with roadway lighting and glare. When glare was added to the rural/dark conditions, the amount of luminance needed to correctly read the signs about doubled. Adding fixed roadway lighting to the rural/dark conditions without adding glare resulted in mixed findings. For the white-on-blue signs, 170 percent more luminance was needed. However, for the white-on-brown signs, only 92 percent of the original luminance was needed. When both lighting and glare were added to the rural/dark conditions, the roadway lighting countered the impact of the glare and only about a 15 percent increase in luminance was needed to achieve the same legibility performance.

Adverse weather

Adverse weather conditions are another factor that must be considered when evaluating visibility. TxDOT recently utilized the research services of TTI to evaluate pavement markings during wet weather conditions at night (*36*). Similar evaluations of traffic signs during wet weather conditions at night are not found in the literature, leaving knowledge gaps that require research. Specifically, rain and fog can be especially debilitating to driver perception at night.

Rain and fog lead to a larger amount of moisture in the air, which accordingly result in less light penetrating through the air and reaching signs. In addition, some of the scatter from the headlamps is reflected off droplets directly back to the driver as “backscatter,” which reduces the contrast of everything in the driver’s field of view. Therefore, the visibility level of signs is lower in rain and fog weather, which leads to increased luminance demands for signs. The impacts of inclement weather can be quantified through “atmospheric transmissivity.” Atmospheric transmissivity is defined as transmittance of light per unit distance, which is controlled by the humidity and dust content in the air. The transmissivity values for various weather conditions are listed on the following page in Table 1.3.

Dirt

There is no doubt that dirt impacts sign visibility, cleanliness and reflectivity, as several of the past studies of maintenance of reflective signs acknowledge the concern of dirt on sign. Back in 1980s, the impacts of dirt on enclosed-lens engineer-grade sheeting were assessed in the examination of the deterioration of reflective sign sheeting in New York State (*37*). It was found that brightness loss due to dirt was significant in winter, though most signs recovered the brightness after spring rains. In addition, Wolshon et al. found about a 25% increase in retroreflectivity when Type III signs were washed (*38*). In contrast, the Bischoff and Bullock study concluded that sign washing did not significantly affect the retroreflectivity (*39*). However, little research has been done to assess actual field conditions of sign sheeting and to quantify how much does dirt effects sign visibility.

Table 1.3 Transmissivity Coefficients for Various Weather Conditions

Code Number	Weather	Maximum Meteorological Optical Range (kilometers)	Maximum Extinction Coefficient (per Meter)	Maximum Transmissivity (per Kilometer)	(per statute mile)	(per nautical mile)
9	Exceptionally clear	50+	0.00006-	0.94+	0.91+	0.89+
8	Very clear	50	0.00006	0.94	0.91	0.89
7	Clear	20	0.00015	0.86	0.79	0.76
6	Light haze	10	0.00030	0.74	0.62	0.57
5	Haze	4	0.00075	0.47	0.30	0.25
4	Thin fog	2	0.0015	0.22	0.090	0.062
3	Light fog	1	0.0030	0.050	0.0081	0.0039
2	Moderate fog	0.5	0.0060	0.0025	0.000065	0.000015
1	Thick fog	0.2	0.015	3.1×10^{-7}	3.4×10^{-11}	9.0×10^{-13}
0	Dense fog	0.05	0.060	9.5×10^{-27}	1.3×10^{-42}	6.5×10^{-49}
	Very dense fog	0.03	0.10	4.3×10^{-44}	1.6×10^{-70}	4.8×10^{-81}
	Exceptionally dense fog	0.015	0.20	1.8×10^{-87}	2.6×10^{-140}	2.3×10^{-161}

TASK 2: EVALUATION OF THE IMPACTS OF DIRT AND ADVERSE WEATHER CONDITIONS ON GUIDE SIGN PERFORMANCE

During this task, the researchers evaluated the impacts of field conditions on guide signs in Florida, including dirt and adverse weather conditions. The retroreflectivity of guide signs facing North, South, East, and West were measured before and after cleaning to assess the impacts of dirt and degradation caused by more sun exposure on the South and West facing signs. In addition, weather data were collected for some representative cities in Florida to assess the severity of adverse nighttime weather conditions.

Determine Impacts of Dirt on Sign Surfaces

In order to evaluate the impacts of dirt on the visibility of overhead signs in use in Florida, researchers collected the retroreflectivity measurements for 52 guide signs both before and after cleaning in the summer of 2012. See Figure 2.1 for researchers collecting sign retroreflectivity measurements. For safety and cost considerations, shoulder-mounted guide signs (rather than overhead signs) were measured in this study. In addition, there is no known reason why the degradation of sheeting on overhead sign would be different than ground-mounted signs, everything else being equal. For all of the 52 signs, except for the retroreflectivity readings before and after cleaning, sheeting type, sign installation time (sign age), location and direction were documented. Among those signs, 15 signs were collected from I-95 (seven facing South and eight facing North), 22 signs from I-10 (11 facing West and East), and 15 signs facing North on I-75 (see Appendix for the summary of the collected data). In terms of sheeting type, 18 out of 52 background sheeting materials were prismatic and the rests were are beaded. For the legends, 21 out of 52 were prismatic and rests were beaded. The signs were installed between 1995 and 2012. All of the retroreflectivity measurements were made at an observation angle of 0.2 degrees and an entrance angle of -4.0 degrees.

Figure 2.1 Researchers Collected Sign Retroreflectivity Measurements

Based on the data collected, comparisons of the retroreflectivity readings before and after cleaning are shown in Figure 2.2 and Figure 2.3 for background and legend respectively. A straight line in both figures represents the condition of having identical retroreflectivity measurements before and after cleaning (in other words, no impact of dirt).

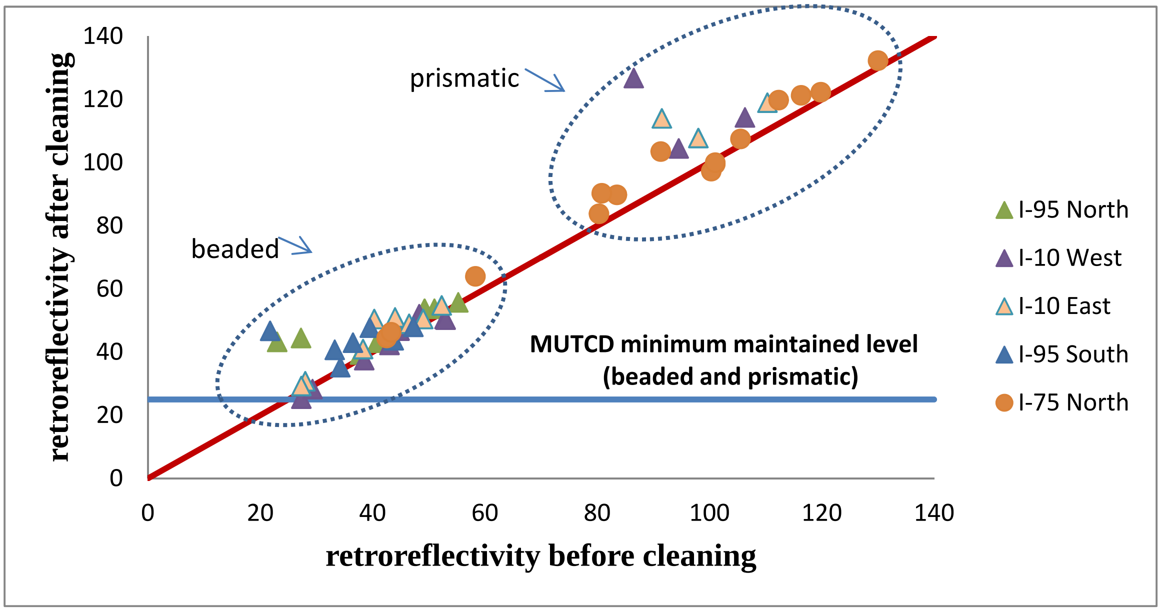

Figure 2.2 Comparison of Background Retroreflectivity Measurements before and after Cleaning (cd/lx/m^2)

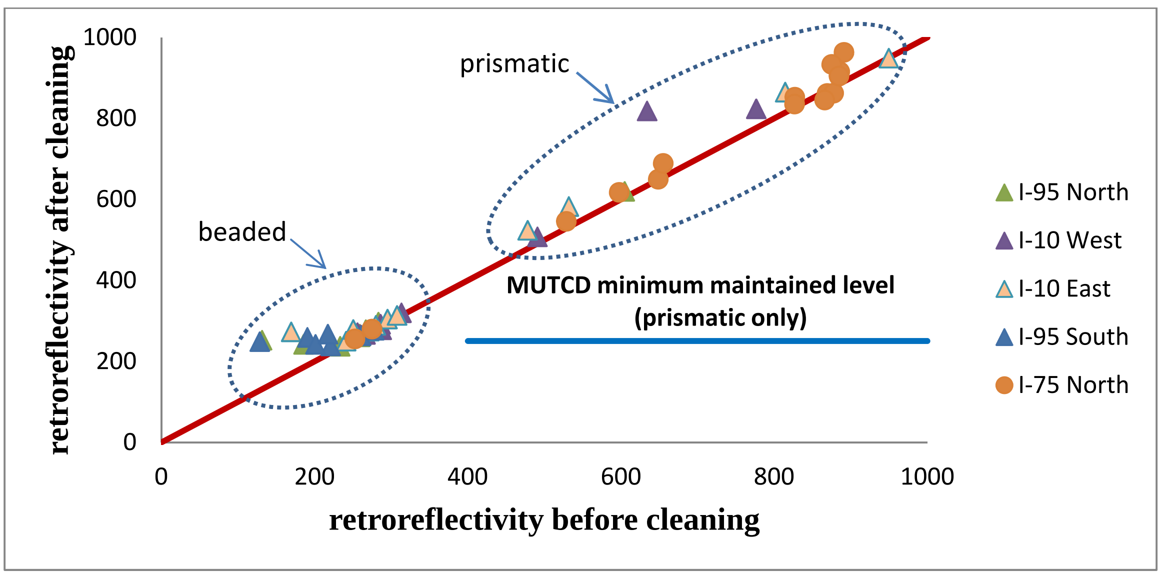

Figure 2.3 Comparison of Legend Retroreflectivity Measurements before and after Cleaning (cd/lx/m^2)

The MUTCD minimum maintained retroreflectivity levels were also graphed in Figure 2.2 and Figure 2.3. For the background of overhead guide signs, the minimum required retroreflectivity is 25 cd/lx/m^2 for both Type III beaded and prismatic sheeting materials. The retroreflectivity measurements show that backgrounds made with prismatic sheeting materials are all above the MUTCD minimum maintained requirement. However, there were two beaded signs below the MUTCD minimum maintained requirement although they met the requirement after cleaning.

For legends, the MUTCD minimum maintained requirement is 250 cd/lx/m^2 for prismatic sheeting materials. The retroreflectivity measurements show that legends made with prismatic sheeting materials are all above the MUTCD minimum maintained requirement. The MUTCD does not allow the use of beaded sheeting materials for legends. To be in compliance, these signs will have to be replaced or remain lit. However, the meaning of being in compliance is somewhat ambiguous at this point. On May 14, 2012, rule-making was published that removed the requirement to maintain guide signs at the MUTCD minimum maintained levels. The same rule-making also eliminated dates to have signs with inadequate retroreflectivity removed. The FHWA is now saying that guide signs should be added to an agency's sign retroreflectivity maintenance program as resources allow.

In terms of the effect of dirt, overall, for both background and legend, the retroreflectivity readings increase after cleaning regardless of the sign direction and sheeting type of the sign. After cleaning, background retroreflectivity measurements increased an average of about 12 percent. For the legends, the increase was about 10 percent. However, as shown in Figure 2.2 and Figure 2.3, there are some data points located below the straight line which indicates that the sign retroreflectivity reading dropped after cleaning. We attribute this to the retroreflectometer device repeatability bias (we used a calibrated RetroSign from Delta).

As described above, for the signs measured in this study, dirt on average reduces retroreflectivity about 10 to 12 percent. In order to further analyze the retroreflectivity measurements, we also evaluated other influencing factors such as sheeting type, sign direction and sign age. The data were collapsed by each factor and the changes of retroreflectivity measurements after cleaning are compared below.

Effect of Dirt by Sheeting Type

The percent changes of retroreflectivity measurements after cleaning are separated by two sheeting types: beaded and prismatic. The sign retroreflectivity readings for each sign and their average value are plotted by sheeting type in Figure 2.4 and Figure 2.5 for background and legend respectively. For background, the average percent changes are about 13 percent for beaded sheeting, and 9 percent for prismatic sheeting; for legend, the percentages are about 14 percent for beaded and 5 percent for prismatic. Due to the large variances of the values, it is not statistically robust to conclude that the dirt has a larger effect on beaded sheeting than the prismatic sheeting, but at least it is true on average for both sheeting types. The beaded sheeting materials (installed between 1995 and 2008) were generally older than the prismatic sheeting materials (installed between 2008 and 2012) and this may explain why there was a slightly larger impact on the beaded sheeting materials. More information is subsequently provided on the age of the materials.

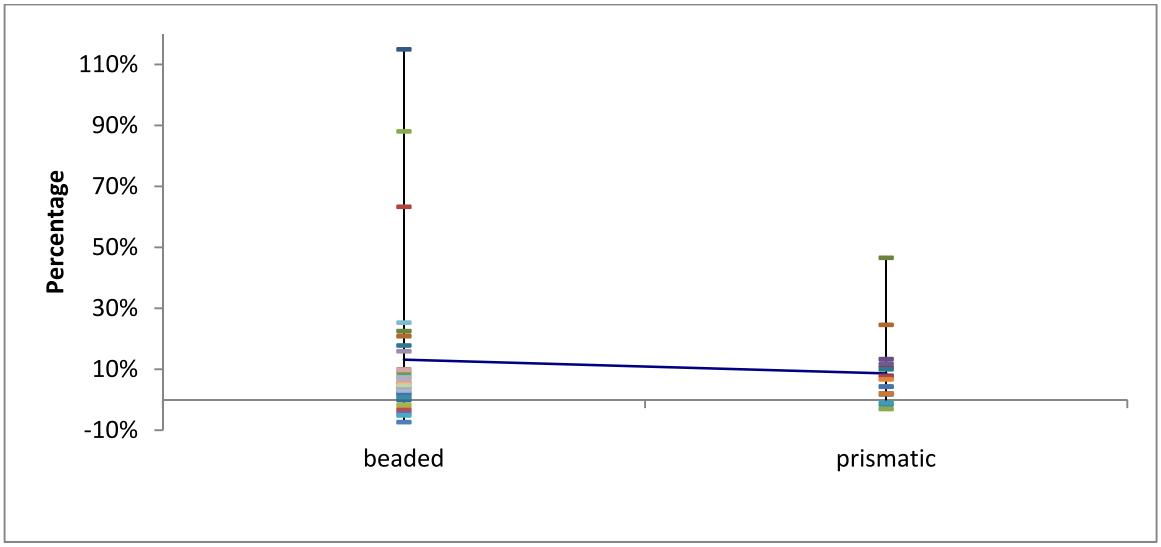

Figure 2.4 Percent Change of Background Retroreflectivity Measurements after Cleaning by Sheeting Type

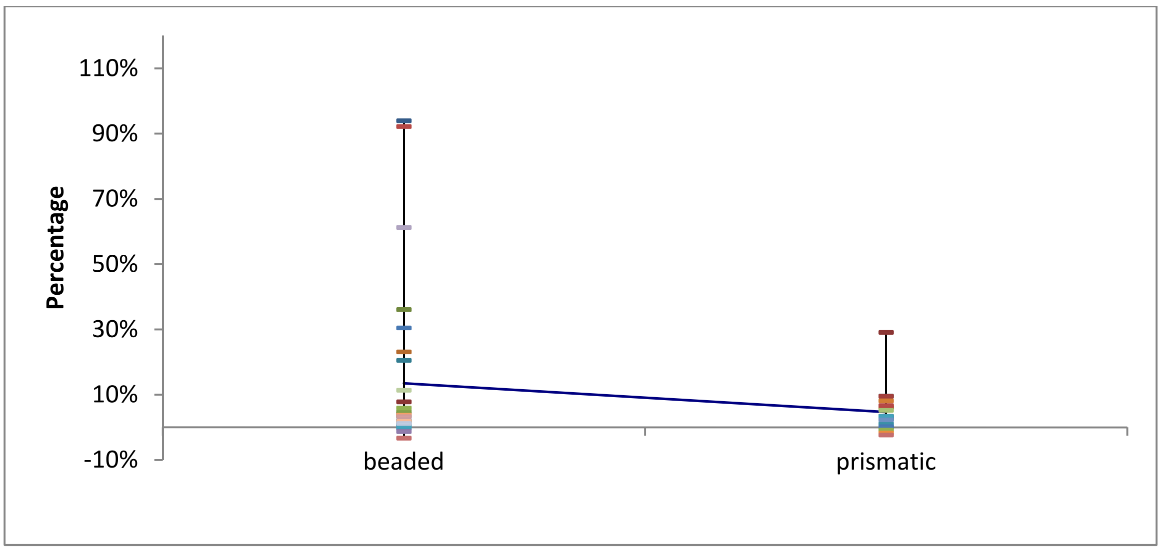

Figure 2.5 Percent Change of Legend Retroreflectivity Measurements after Cleaning by Sheeting Type

Effect of Dirt by Sheeting Age

The 52 measured signs were installed between 1995 and 2012 (the range is 17 years). Because the beaded sheeting materials were older than the prismatic materials we graphed each sheeting type separately. Figure 2.6 and Figure 2.7 show the impacts of dirt by sheeting age for beaded sheeting materials, while Figure 2.8 and Figure 2.9 for prismatic sheeting. From Figure

2.6 and Figure 2.7, for beaded sheeting (both background and legend), except for nine-year-old sign (installed in 2003), the change fluctuates within 10 percent and there is no apparent pattern. For those six signs installed in 2003, they are all located on I-95 facing South. Figure 2.8 and Figure 2.9 also show no apparent pattern. Therefore, we cannot conclude that the slightly larger impact of dirt on the beaded sheeting materials is due to the age.

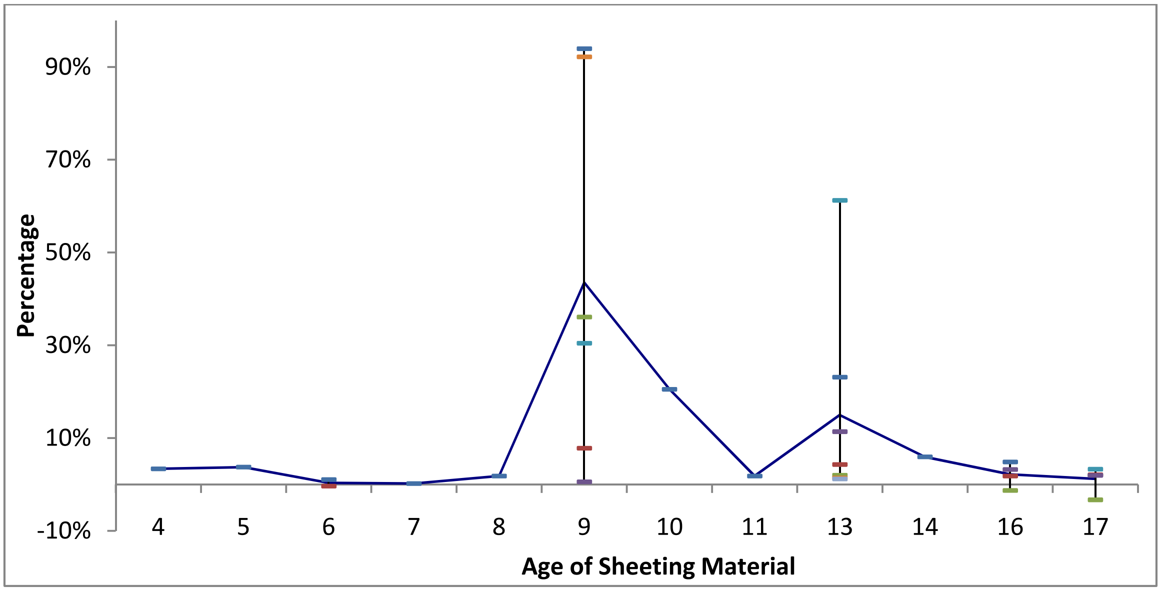

Figure 2.6 Percent Change of Legend Retroreflectivity Measurements after Cleaning for Beaded Sheeting

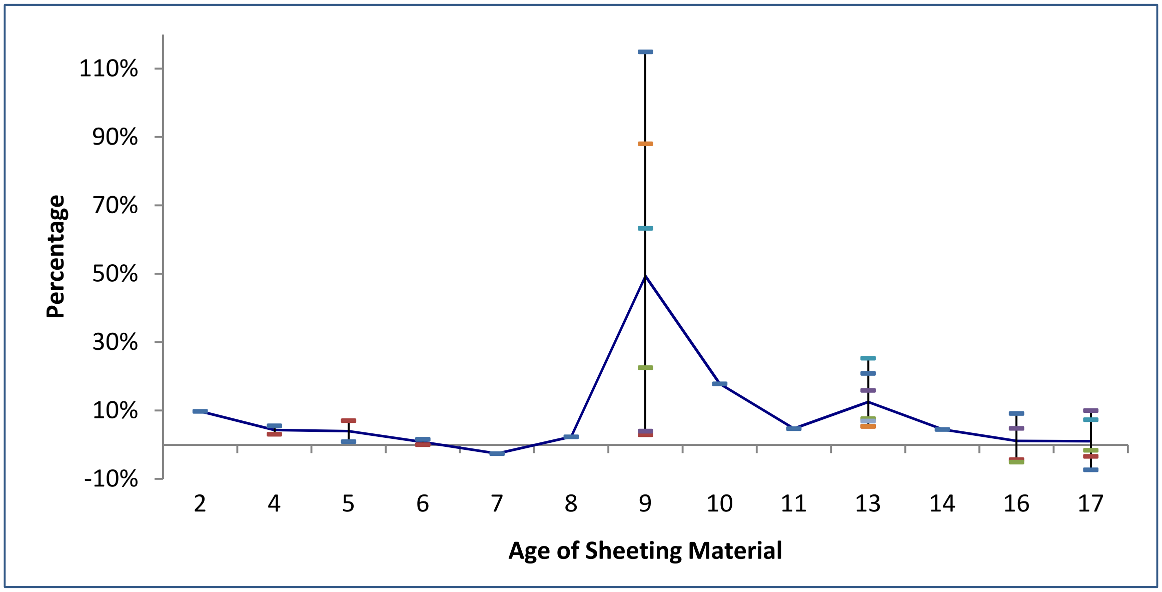

Figure 2.7 Percent Change of Background Retroreflectivity Measurements after Cleaning for Beaded Sheeting

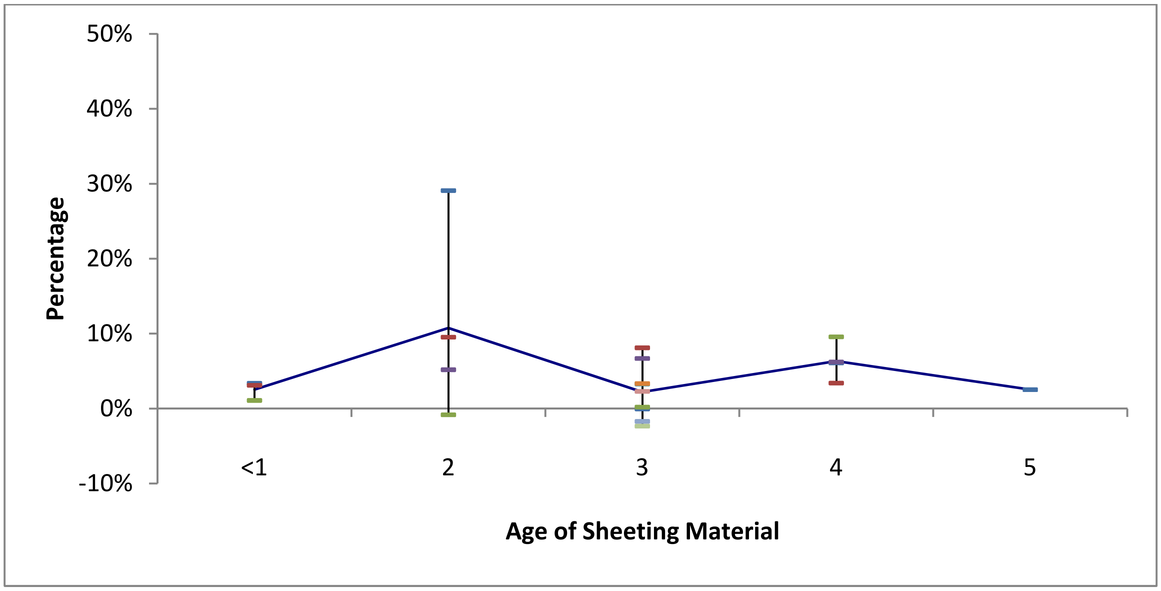

Figure 2.8 Percent Change of Legend Retroreflectivity Measurements after Cleaning for Prismatic Sheeting

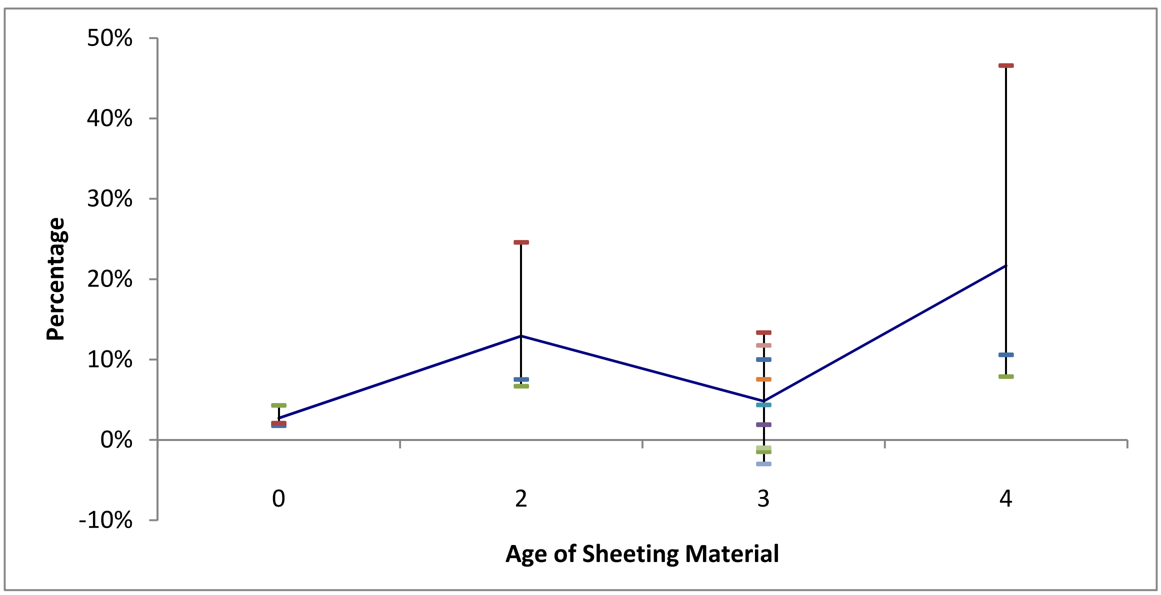

Figure 2.9 Percent Change of Background Retroreflectivity Measurements after Cleaning for Prismatic Sheeting

Effect of Dirt by Road/Direction

The percent change of retroreflectivity measurements after cleaning each road (region) and direction are shown in Figure 2.10 and Figure 2.11 for background and legend, respectively.

On average, signs on I-95 (for background, 22 percent for signs facing North and 26 percent for those facing South; for legend, 18 and 26 percent for facing North and South, respectively) have a slightly larger percent change of retroreflectivity measurements than other roads after cleaning but with a greater variance as well. The average values of signs on I-10 and I-75 are close for both background and legend (close or under 10 percent).

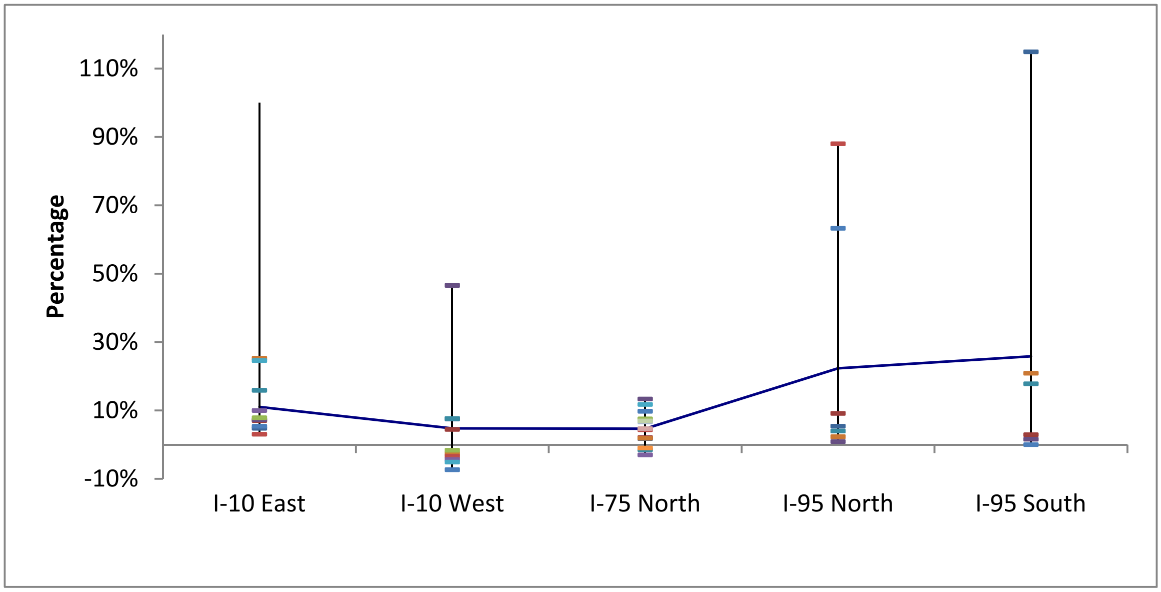

Figure 2.10 Percent Change of Background Retroreflectivity Measurements after Cleaning by Road and Direction

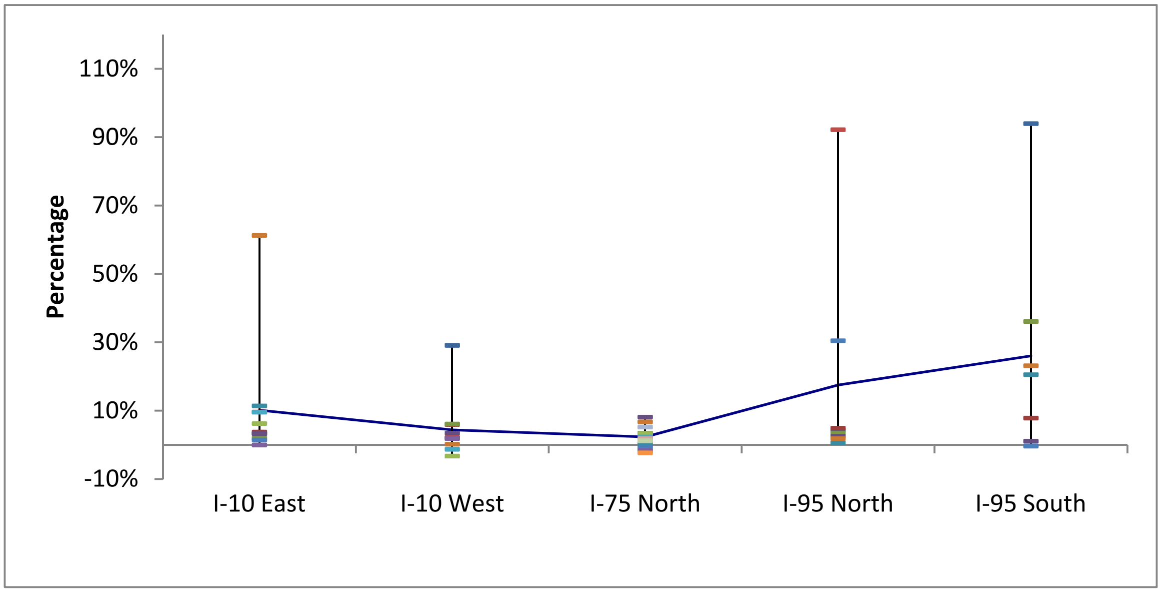

Figure 2.11 Percent Change of Legend Retroreflectivity Measurements after Cleaning by Road and Direction

Because there is more sun exposure on south- and west- facing signs, we further assessed the impacts of dirt and degradation. The data were broken down into two direction groups: South & West, and North & East. First, we used the retroreflectivity measurements before cleaning to compare the sign degradation conditions between the above two direction groups. The retroreflectivity measurements before cleaning for the two direction groups are shown in Figure 2.12 and Figure 2.13 for background and legend, respectively. On average, signs facing North and East have a higher retroreflectivity than those facing South and West for both background (73 vs. 55 cd/lx/m^2) and legend (540 vs. 344 cd/lx/m^2). However, this difference does not result from direction per se, but sheeting type. In other words, our random selection of signs resulted in having more signs made with prismatic sheeting material facing North and East (15 out of 34) compared to facing South and West (3 out of 18).

Therefore, we further studied the direction impacts on sign degradation using signs made with beaded sheeting materials. For backgrounds, the average green retroreflectivity was 42 cd/lx/m^2 for signs facing North and East versus 40 cd/lx/m^2 for South and West. For legends, the average white retroreflectivity was 247 for signs facing North and East versus 248 cd/lx/m^2 for South and West. These differences were statistically insignificant using a t-test at the 0.05 level of significance. Consequently, we cannot conclude direction has effects on sign degradation in Florida. These results are similar to a recent study conducted in Texas, where nearly 1400 signs were measured (*40*).

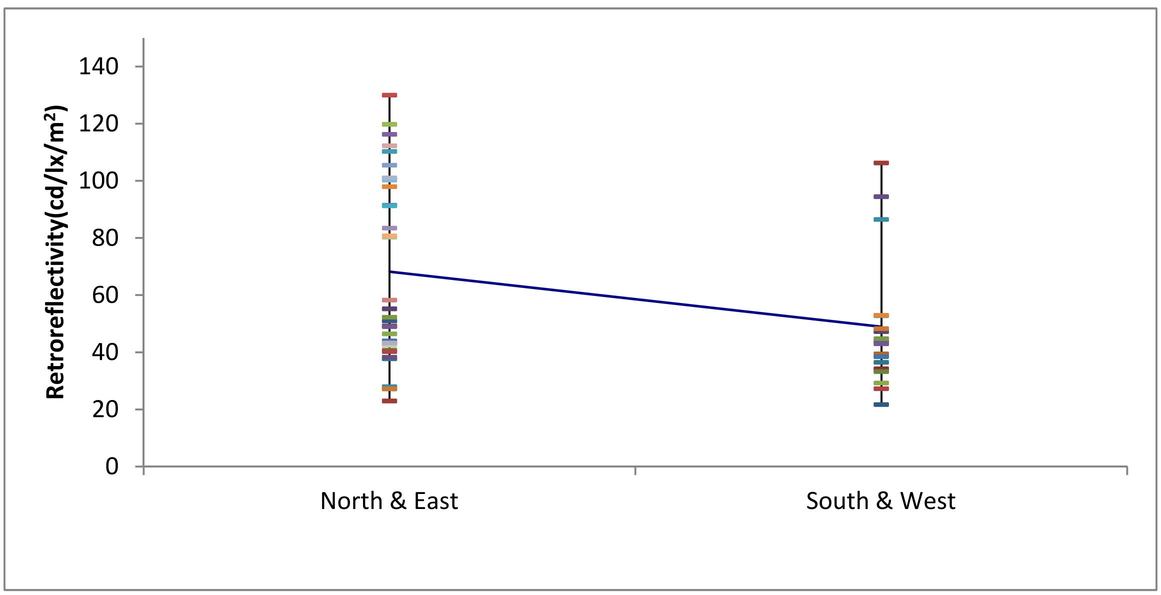

Figure 2.12 Background Retroreflectivity Measurements before Cleaning by Direction

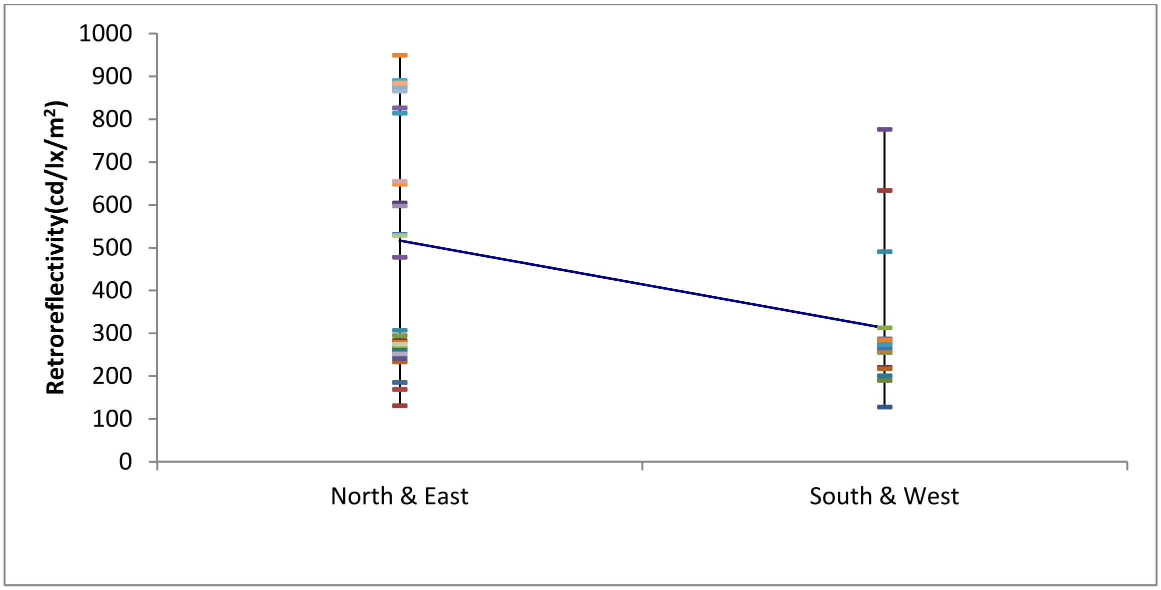

Figure 2.13 Legend Retroreflectivity Measurements before Cleaning by Direction

Based on the analysis of data collected in Florida and the sign study in Texas, direction is not a significant variable for sign retroreflectivity in Florida, but we are also interested in whether it is a factor on how dirt impacts sign sheeting performance. Figure 2.14 and Figure 2.15 show the percent change of retroreflectivity after cleaning by direction for legend and background, respectively. On average, signs facing South and West were found to have slightly larger impacts from dirt. The average percent changes are 13 percent on South & West vs. 8 percent on North & East for legend, 11 percent vs. 13 percent accordingly for background. However, this difference is not significant using a t-test at the 0.05 level of significance. Therefore, it is not adequate to conclude that the impacts from dirt on sign retroreflectivity measurements are related to the direction the sign faces.

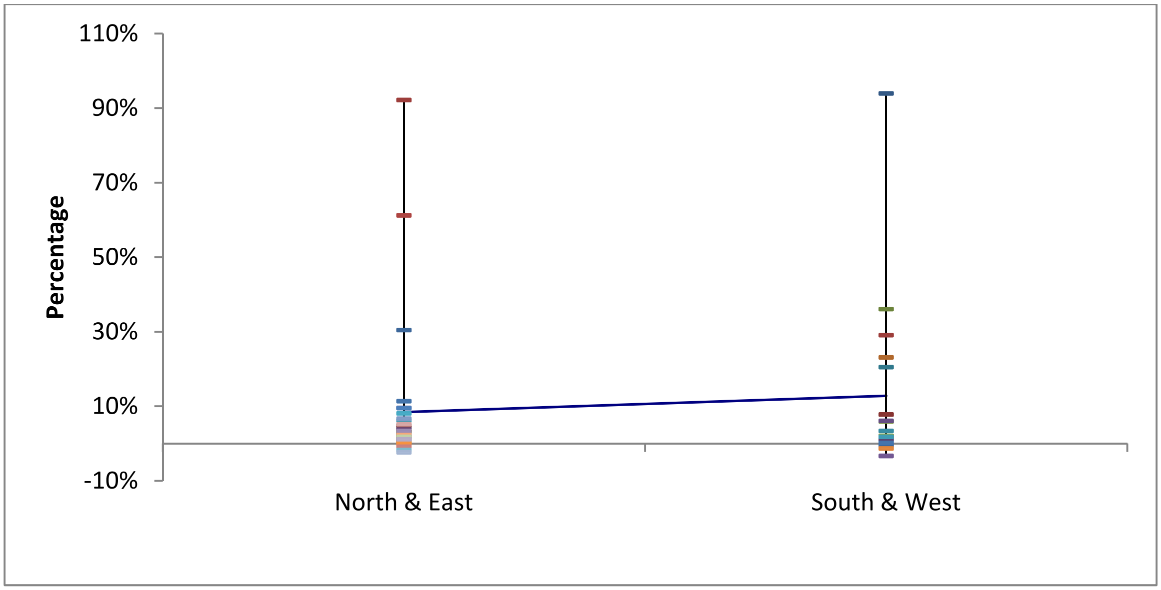

Figure 2.14 Percent Change of Legend Retroreflectivity Measurements after Cleaning by Direction

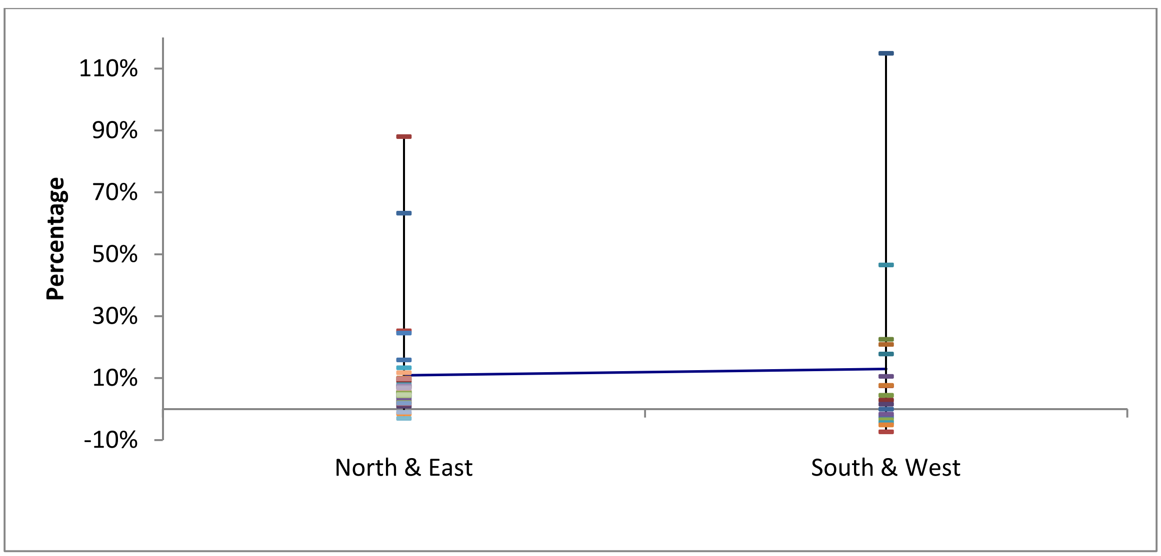

Figure 2.15 Percent Change of Background Retroreflectivity Measurements after Cleaning by Direction

Determine Impacts of Weather on Overhead Signs

In order to address the severity of adverse weather during nighttime conditions, climatic data were collected for the five geographically representative cities (Tallahassee, Jacksonville, Orlando, Tampa and Miami) in Florida for three years (from 2009 to 2011). The geographical distribution of the five cities is shown in Figure 2.16. The data were obtained from the National Climatic Data Center (NCDC) (http://cdo.ncdc.noaa.gov/qclcd/QCLCD), which is reported by Automated Surface Observing System (ASOS). ASOS is a multi-sensor system installed at more than 900 airports across the United States to measure wind speed and direction, temperature, dew point, cloud coverage, visibility, precipitation, and even barometric pressure (*41*). The weather information collected from ASOS is used by pilots and airport-based weather personnel.

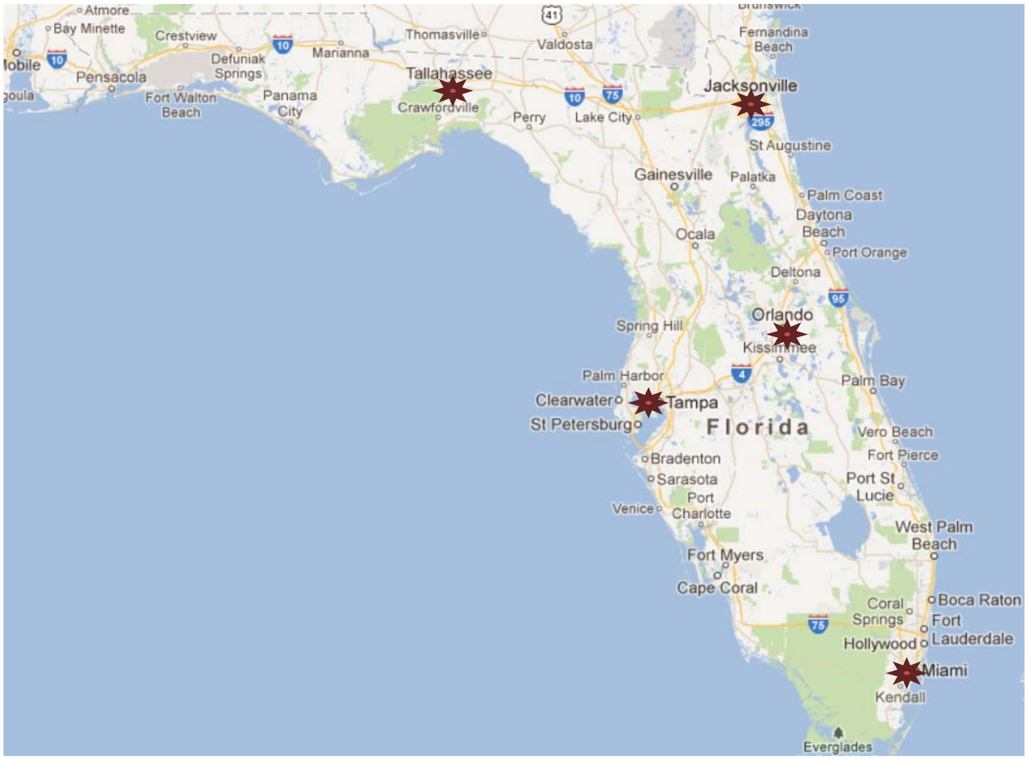

Figure 2.16 Geographical Distribution of the Five Studied Cities in Florida

Nighttime Weather Conditions in Florida

Five typical weather conditions were selected which were deemed to have effects on the visibility by the atmospheric losses upon the illuminance at the observer's eye: rain, fog, moisture/fog, haze and smoke. The total lasting time percentage of these weather conditions during nighttime are summarized for the five cities in Table 2.1. Table 2.1 shows that the majority of nighttime hours (over 90 percent) in Florida are clear and dry. In addition, there is no apparent difference among the five cities for the percentage in each weather condition, except that Jacksonville has slightly more moisture/fog condition than the other four cities.

Table 2.1 Time Percentage of Five Weather Conditions in Five Cities for Nighttime

City	rain	fog	moisture/fog	haze	smoke
Tallahassee	3.5%	6.5%	6.1%	0.1%	0.8%
Jacksonville	2.7%	1.7%	9.7%	<0.1%	0.5%
Orlando	2.6%	2.4%	3.5%	0.1%	0.4%
Tampa	2.3%	0.4%	2.5%	<0.1%	<0.1%
Miami	3.1%	0.1%	2.1%	<0.1%	0.1%

Nighttime Visibility in Florida

Though the weather conditions in Florida have been summarized above, a further analysis related to visibility was performed. In this report, we used visibility information from the NCDC dataset reported by ASOS. The visibility from ASOS is not directly achieved by human observations, but using a complicated algorithm. A brief summary of the algorithm related to ASOS visibility is described below.

ASOS uses a Belfort forward-scattering sensor to measure forward scattering of light by the extinction coefficient (the spatial rate of diminution or extinction of transmitted visible light) and then convert it to visibility (also called as "meteorological visibility distance") using two different formulas for daytime and nighttime, as shown in Equation 2.1 and Equation 2.2 (*42*). For the daytime, the visibility calculated by Equation 2.1 represents the greatest distance where a black object of suitable dimensions can be seen and recognized against the horizon sky (*43*). For the night time, Equation 2.2 should be used to calculate the visibility distance which is derived based on the greatest distance where a black object could be seen and recognized if the general illumination is raised to the normal daylight level (*42*).

Daytime:

$$V=3.0/\sigma \qquad \text{(Equation 2.1)}$$

Nighttime:

$$0.00336= e^{(-\sigma *V)}/V \qquad \text{(Equation 2.2)}$$

where,

V is the visibility, mile;

σ is the extinction coefficient, mile^{-1}, and its relationship to the atmospheric transmissivity (transmittance per unit distance) T is shown by Equation 2.3.

$$T = e^{-\sigma} \quad \text{(Equation 2.3)}$$

According to Equation 2.1 to Equation 2.3, it is easy to find that visibility has a direct relationship with atmospheric transmissivity. Transmissivity is controlled by the humidity and dust content in the air. Rain, haze, and fog lead to moisture in the air while smoke leads to particles in the air—both of which results in less light penetrating through the air and reaching signs. Therefore, the visibility level of signs is reduced in those weather conditions.

The current reportable ASOS values of visibility in statute miles are: <0.25, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10+ (*41*). Though the visibility from ASOS is not directly from human observations, it correlates to the human observations using Equation 2.1 and 2.2. It is possible that ASOS and human observations would differ. However, ASOS is designed to measure the clarity of the air objectively rather than subjectively making the measurements by observers. In addition, after years of development ASOS has been proved to correlate closely with human observations most of the time (*44*).

For the five cities in Florida, the percentages of nighttime for each visibility level are summarized in Table 2.2 (including all weather conditions). As shown in Table 2.2, low visibility is rare during nighttime in all five cities and the majority of the nights have visibility larger than 10 miles. In addition, based on Table 2.1 and Table 2.2, weather and visibility distribution among the five cities does not show any obvious difference which indicates that weather and visibility are not location related in Florida.

Table 2.2 Time Percentage of Visibility levels in Five Cities for Nighttime

Visibility (mile)	Tallahassee	Jacksonville	Orlando	Tampa	Miami
<0.25	0.5%	0.1%	0.3%	<0.1%	<0.1%
0.25	1.9%	1.0%	0.3%	0.4%	0.1%
0.5	1.3%	0.6%	0.4%	0.3%	<0.1%
0.75	0.4%	0.2%	0.1%	0.1%	<0.1%
1	0.5%	0.6%	0.1%	0.1%	0.1%
1.25	0.1%	0.1%	<0.1%	<0.1%	<0.1%
1.5	0.2%	0.3%	0.1%	0.1%	0.1%
1.75	0.2%	<0.1%	<0.1%	<0.1%	<0.1%
2	0.6%	0.9%	0.4%	0.2%	<0.1%
2.5	0.3%	0.2%	0.1%	0.1%	<0.1%
3	0.8%	1.0%	0.5%	0.3%	0.2%
4	0.8%	1.4%	0.5%	0.3%	0.3%
5	1.3%	2.2%	0.8%	0.3%	0.5%
6	2.1%	3.2%	1.2%	0.7%	1.3%
7	1.9%	5.0%	1.4%	1.0%	1.4%
8	2.1%	4.4%	1.6%	1.6%	2.1%
9	2.8%	5.1%	2.0%	2.0%	3.6%
>=10	82.3%	73.6%	90.2%	92.3%	90.1%

Quantify Weather Effects on Overhead Signs

According to Table 2.1 and Table 2.2, both influencing weather conditions and low visibility are rare in Florida for nighttime which indicates that weather is not a critical factor for nighttime overhead sign detection in Florida. However, the rare events would still be covered by modeling the impacts of the inclement weather in the luminance computation model by atmospheric transmissivity. Based on Allard's Law (*45*), the relationship between illuminance of a light source at a certain distance with atmospheric transmissivity is shown in Equation 2.4.

$$E = (I * T^x)/x^2 \qquad \text{(Equation 2.4)}$$

where,

E is illuminance of light source (lx);
I is luminous intensity of light source in direction of target (cd);
T is atmospheric transmissivity (per mile);
x is distance between light source and target (mile).

Accordingly, the relationship between the luminance of sign in clear weather and inclement weather is shown in Equation 2.5. Equation 2.5 quantifies the effects of adverse weather on sign luminance through transmissivity.

$$L' = L * T^x \qquad \text{(Equation 2.5)}$$

where,

L' is sign luminance in inclement weather (cd/ m^2);
L is sign luminance in clear weather (cd/ m^2).

There are two ways to determine the transmissivity. One way is to calculate transmissivity based on the visibility data reported by ASOS. By combining Equation 2.2 (as we are only interested in nighttime condition) and Equation 2.3, it comes to Equation 2.6 which formularizes the relationship between visibility and transmissivity. Therefore, as long as the visibility at nighttime for a given condition is known, atmospheric transmissivity can be calculated.

$$0.00336 = T^V/V \qquad \text{(Equation 2.6)}$$

Where,

V is the visibility, mile;
T is atmospheric transmissivity (per mile).

Another way is to find the transmissivity values for a certain weather condition in Table 1.3. The transmissivity values in Table 1.3 were calculated for daytime and the visibility (maximum meteorological optical range) should not be used for visibility for nighttime.

However, if we assume transmissivity is the same for daytime and nighttime (which has not been documented in the previous research), the transmissivity values in Table 1.3 can be used for the listed weather conditions.

Summary

In this task, the impacts of dirt and adverse weather conditions were studied based on guide sign retroreflectivity measurements and historical weather data. To study the impacts of dirt on sign sheeting, 52 signs were measured along three highways (I-95, I-10, and I-75).

On average, dirt was found to reduce sheeting retroreflectivity about 10 percent. It was also found that dirt impacts beaded sheeting materials slightly more than prismatic sheeting materials. The direction a sign faces has little impact on the retroreflectivity degradation or the amount of dirt accumulated on the sign. However, signs in heavily shaded areas were notably dirtier than signs in open areas. In Task 3, we will use these results when determining the luminance levels supplied by guide signs.

In order to study the impact of adverse weather conditions, historic climatic data were obtained from five geographically representative cities (Tallahassee, Jacksonville, Orlando, Tampa and Miami) in Florida for three years (from 2009 to 2011). Based on the climatic data, adverse weather and low visibility conditions were rare during nighttime in Florida. However, we can use these findings to model sign performance in the rare conditions of severe nighttime weather in Florida (Task 3).

We also used the field data to assess the conditions of the signs in terms of the MUTCD minimum maintained retroreflectivity levels. All of the signs made with prismatic sheeting materials were well above the MUTCD minimum maintained retroreflectivity levels. However, signs made with beaded materials had different results. The MUTCD allows guide sign backgrounds to be made with beaded materials but not guide sign legends. For those signs with beaded background materials, many were just above the MUTCD minimum maintained retroreflectivity levels, and two were actually below the minimum level before they were cleaned. Therefore, signs with beaded backgrounds will likely need to be replaced or lit to maintain them in accordance with the MUTCD.

That being said, the meaning of being in compliance is somewhat ambiguous at this point. On May 14, 2012, rule-making was published that removed the requirement to maintain guide signs at the MUTCD minimum maintained levels. The same rule-making also eliminated dates to have signs with inadequate retroreflectivity removed. The FHWA is now saying that guide signs should be added to an agency’s sign retroreflectivity maintenance program as resources allow.

TASK 3: MODEL VISIBILITY OF OVERHEAD SIGNS

During this task, the researchers modeled the visibility of overhead signs using luminance as the primary performance metric. The purpose of the study is to identify if high performing retroreflective sign sheeting can replace the need for sign lighting; and if not, then determine where overhead signs with lights are needed.

For this task, we used the human factors research from previous overhead guide sign research conducted at TTI for the FHWA (*35*). This previous work identifies the luminance needed for legibility. In this task, we compared the legibility luminance needed to the luminance provided under various situations, including different headlamps, different sign lighting technologies, and different amounts of sign dirt and sign aging. We also performed an analysis of the costs associated with upgrading sign sheeting and sign lighting.

Evaluate the Minimum Luminance Levels

In previous work, the minimum luminance needed for overhead guide signs was determined at legibility indices ranging from 40 ft/inch to 20 ft/inch, in 10 ft/inch intervals for elderly drivers and for complex visual conditions that include glare from oncoming headlamps and fixed roadway lighting (*35*). The resulting data are summarized in a tabular form (see Table 3.1), divided by roadway lighting condition (on or off) and presence of glare (on or off). The research determined that the white legend luminance needed for legibility was nearly the same regardless of whether the background color was green or blue.

Table 3.1 Luminance Requirements for Guide Sign Legends (cd/m^2) (*35*)

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

Since the MUTCD now uses a legibility guideline of 30 ft/inch of letter height, 30 ft/inch was also selected as the legibility index for this study (*14*). In addition, for overhead signs, the minimum legend size for destinations is 16-inch uppercase and 12-inch lowercase Series E (Modified) alphabet. Therefore, a distance of 480 ft between vehicles and overhead signs is reasonable for study in terms of the legibility index of 30 ft/inch. The cumulative distribution graph on how much luminance is needed to accommodate the various percentages of the study sample for a legibility index of 30 ft/inch is shown in Figure 3.1. Using Figure 3.1, researchers can develop the luminance values needed to accommodate the various percentages of the study sample.

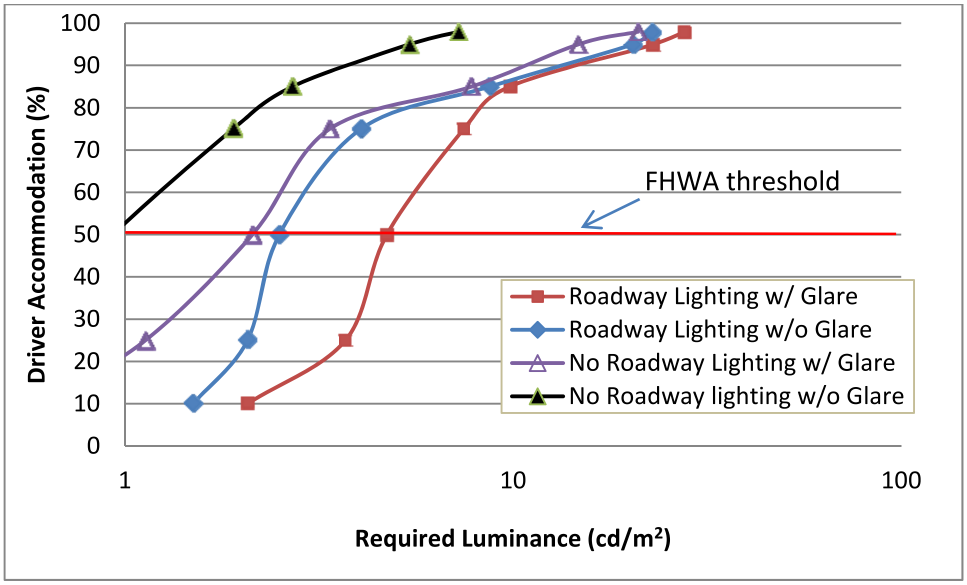

Figure 3.1 Legend Luminance Required for Guide Signs (legibility index=30 ft/inch)

The information in Figure 3.1 describes how much luminance is needed for elderly drivers to read guide signs at a distance coinciding with the requirements of the 2009 MUTCD. To accommodate nearly all older drivers, one would need to provide luminance levels indicative of the levels shown at the 100 percent accommodation level. However, transportation agencies rarely design to accommodate all road users as the cost would be prohibitive. For reference, the FHWA chose to use the 50th percentile levels in their decisions concerning the development of minimum retroreflectivity levels for the MUTCD.

Develop Luminance Computation Model for Signs

Using a luminance computation model, by defining the following inputs: sheeting material type, headlamp type, sign position, sign height, geometry of the roadway and luminance by sign lighting, supplied luminance of signs can be calculated. The effects of weather and dirt from Task 2 were also included in the model. Since luminance of signs is determined by many influencing factors (all the inputs to the model), it is economically infeasible to measure it under all types of scenarios. Therefore, the luminance computation model is a valuable way to evaluate the supplied luminance under many different conditions.

The luminance computation model used for this effort is an extension of MR model TTI developed for earlier research on sign visibility with enhancements to account for dirt and weather, sign lighting, newer sign sheeting materials, and updated vehicle headlamps (*1*). The calculation procedures are listed in Figure 3.2 and explained step by step.

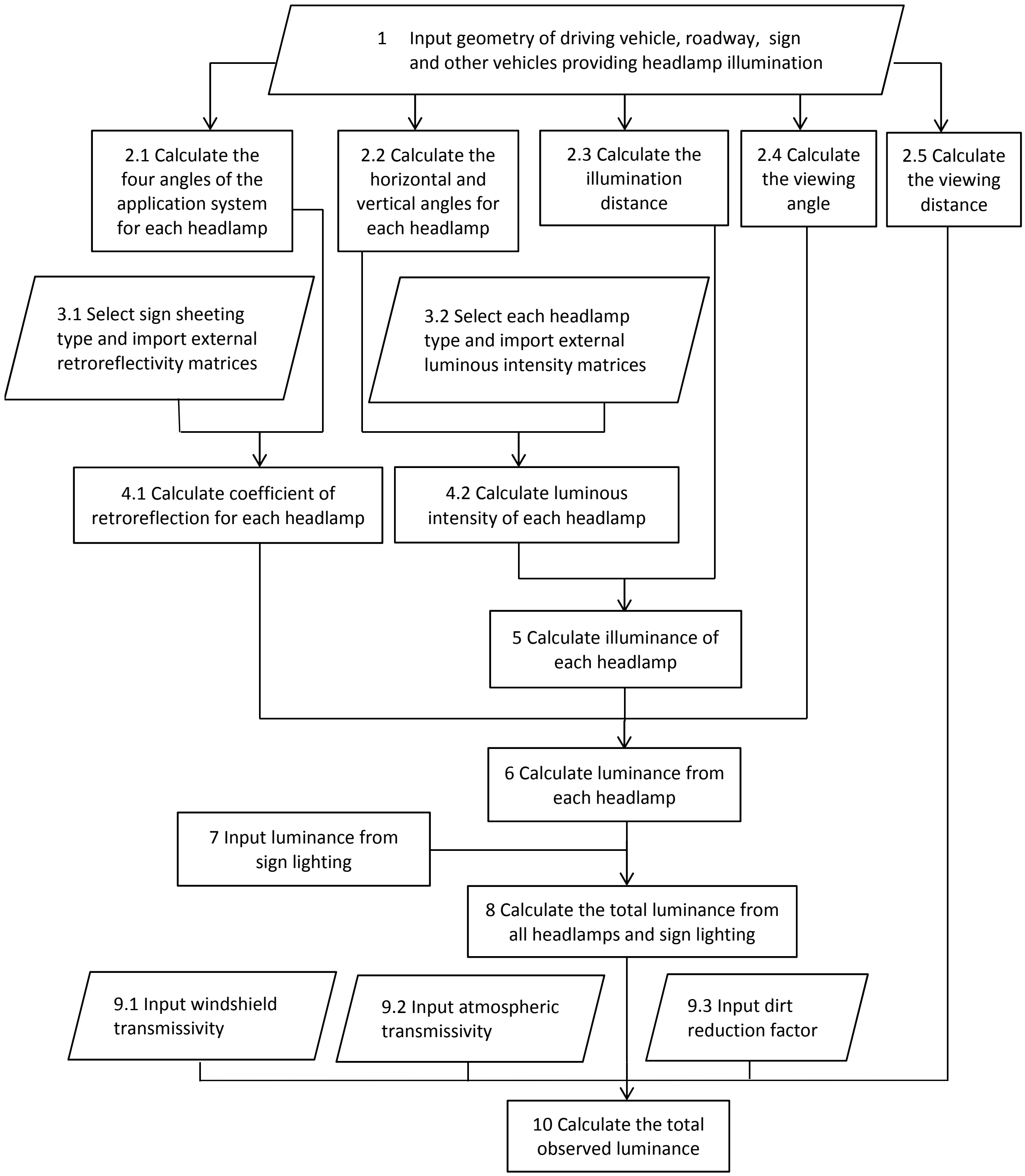

Figure 3.2 Flow Chart of Calculation Procedures in the Luminance Computation Model

Step 1

First, input the geometries of the four elements into the model: target vehicle, roadway, sign and other vehicles, as listed in Table 3.2. Accordingly, the driving system has been defined in Cartesian coordinates based on the relative positions of the four elements.

Table 3.2 Geometry Inputs of the Luminance Computation Model

Element	Geometry Input				
Target vehicle	Distance between headlights	Headlamp height above road	Eye height above road	Eye setback from headlamps	Eye distance left of vehicle centerline
Roadway	Lane width	Total number of lanes	Lane number of driving vehicle	Horizontal/vertical curvature and length	Distance from the front of driving vehicle to the sign
Sign	Sign offset to the edge of driving lane	Sign height			
Other vehicles providing illumination	Distance between headlamps	Headlamp height above road	Longitudinal distance from the sign	Lane number of vehicles (in place of lateral distance)	

Step 2

Using the results of Step 1, the illumination distance (d_I), which is the distance between each headlamp and sign, and the viewing distance (d_V), which is the distance between the driver and sign, can be calculated in Cartesian coordinates in Steps 2.3 and 2.5 (shown in Figure 3.2), respectively. Furthermore, using the vector mathematics described by Johnson (*46*), the driving system in the Cartesian coordinates can be transformed into the angular system. Therefore, some angles needed in the model are ready to be calculated.

The retroreflectivity of sign sheeting is dependent on its angularity in the application system, which includes: observation angle (α), entrance angle (β), rotation angle (ε) and orientation angle (ω_s). Figure 3.3 (*47*) depicts the interrelationship of these angles which are needed for obtaining the coefficient of retroreflection (R_a) of sign sheeting. They are calculated in Step 2.1 (shown in Figure 3.2) for each headlamp of a vehicle.

Luminous intensity (I) of a vehicle headlamp changes based on its horizontal and vertical angles to the sign. Therefore, in Step 2.2, the angles of both vehicle headlamps are calculated in the angular system. In step 2.4, the viewing angle of the driver is calculated. Viewing angle (υ) is the angle between the driver's line of sight to the sign and retroreflector axis, which is normal to the sign surface (see Figure 3.3). Viewing angle will be used in the calculation of the luminance.

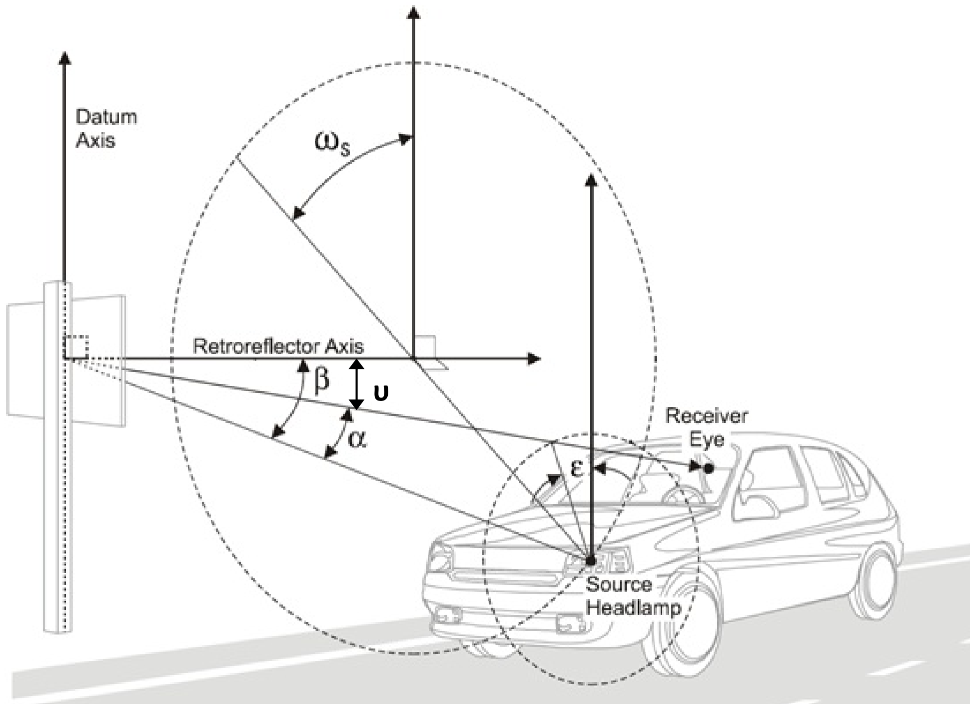

Figure 3.3 the Interrelationship of the Angles in the Application System (*47*)

Step 3

There are two external databases for the luminance computation model. One includes the retroreflectivity matrices for all types of sheeting and the other includes luminous intensity matrices to accommodate different headlamp profiles. The retroreflectivity matrices include beaded materials as well as ASTM Types IV, VIII, IX, and XI. Once a specific sign sheeting type is selected in Step 3.1(shown in Figure 3.2), its retroreflectivity matrices are used to calculate the coefficient of retroreflection for each headlamp geometry. The retroreflectivity matrices are adjusted using the degradation factor to account for the field conditions based on sheeting age.

The age degradation factor was obtained from TTI's long-term weathering tests on retroreflective sign sheeting products. As Texas and Florida have similar climatic conditions, it is reasonable to use the age degradation factor from signs in Texas for those in Florida. The testing started since 1999 at the Texas A&M University Riverside Campus with the sheeting samples placed on aluminum substrates. To accelerate deterioration rate, the researchers placed the samples on weathering racks facing south and oriented at a 45 degree angle, as shown in Figure 3.4. Therefore, the testing, which lasted for over ten years, produced a 20-plus year simulation.

Figure 3.4 Weathering Racks Used for Accelerated Sign Degradation

At approximately yearly intervals, researchers removed each sample from the weathering racks to clean and measure its retroreflectivity. Figure 3.5 and 3.6 are plots of retroreflectivity for white ASTM Types I, II and III sheeting (beaded) and ASTM Types IV, VIII, and IX sheeting (prismatic). No beaded material can be used for the legends of overhead guide signs, per MUTCD. Therefore, any signs with beaded white legend sheeting should to be replaced with signs using prismatic material for the legends. According to the MUTCD, white prismatic sheeting can be used for overhead signs as long as the retroreflectivity remains above 250 $cd/lx/m^2$. According to the TTI weathering rack data, all prismatic white materials will maintain 250 $cd/lx/m^2$ for 20 years. In addition, the green prismatic materials maintained retroreflectivity levels above the MUTCD minimum threshold for at least 20 years. Figure 3.7 and 3.8 are plots of retroreflectivity for green beaded and prismatic sheeting. As pointed in both figures, the minimum values of these green ASTM Types are 7, 15 and 25 $cd/lx/m^2$ for Type I, II, and III respectively, and 25 $cd/lx/m^2$ for all prismatic sheeting.

As legends are the study targets in the luminance computation model, degradation factors are summarized for white sheeting using TTI data. Figure 3.9 and 3.10 are plots of the percentage of initial retroreflectivity retained in each white sample throughout the testing for beaded and prismatic sheeting respectively. Linear prediction models for each sheeting type were summarized in Table 3.3 for the degradation (prismatic data were combined for the prediction model due to the optical similarity of all the prismatic materials). Therefore, with a known age of specific sheeting, a degradation factor is easily obtained to adjust the coefficient of retroreflection of new sheeting.

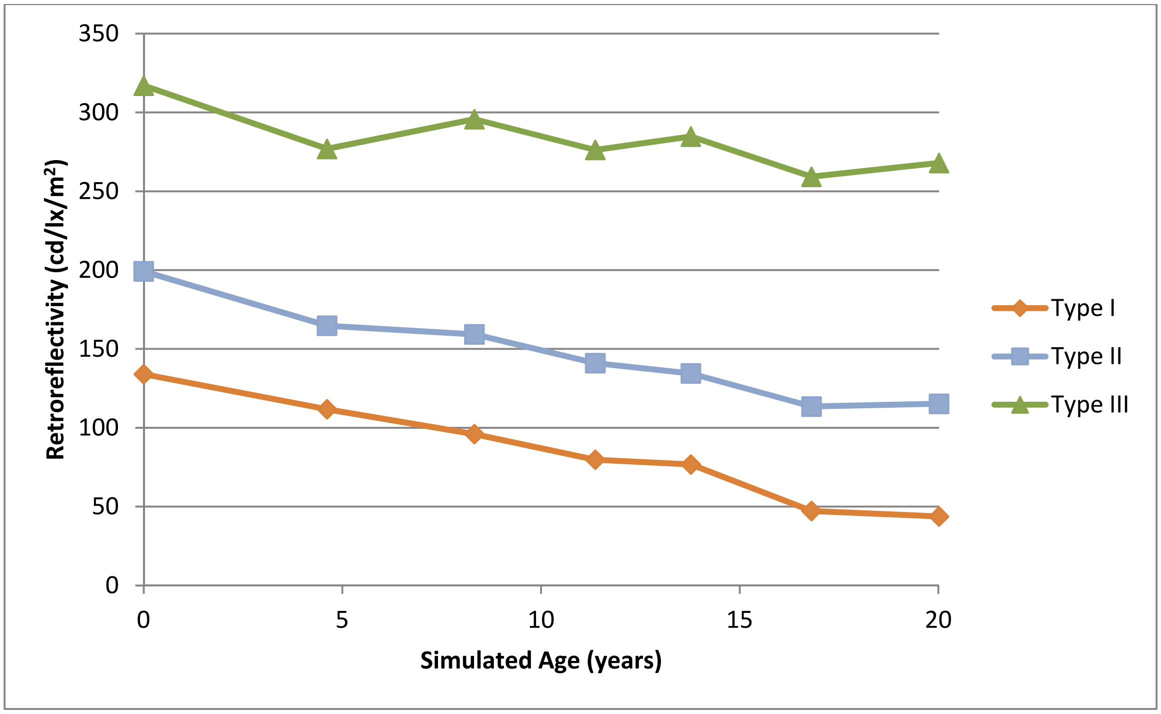

Figure 3.5 Retroreflectivity of White ASTM Type I, II and III Sheeting (Beaded)

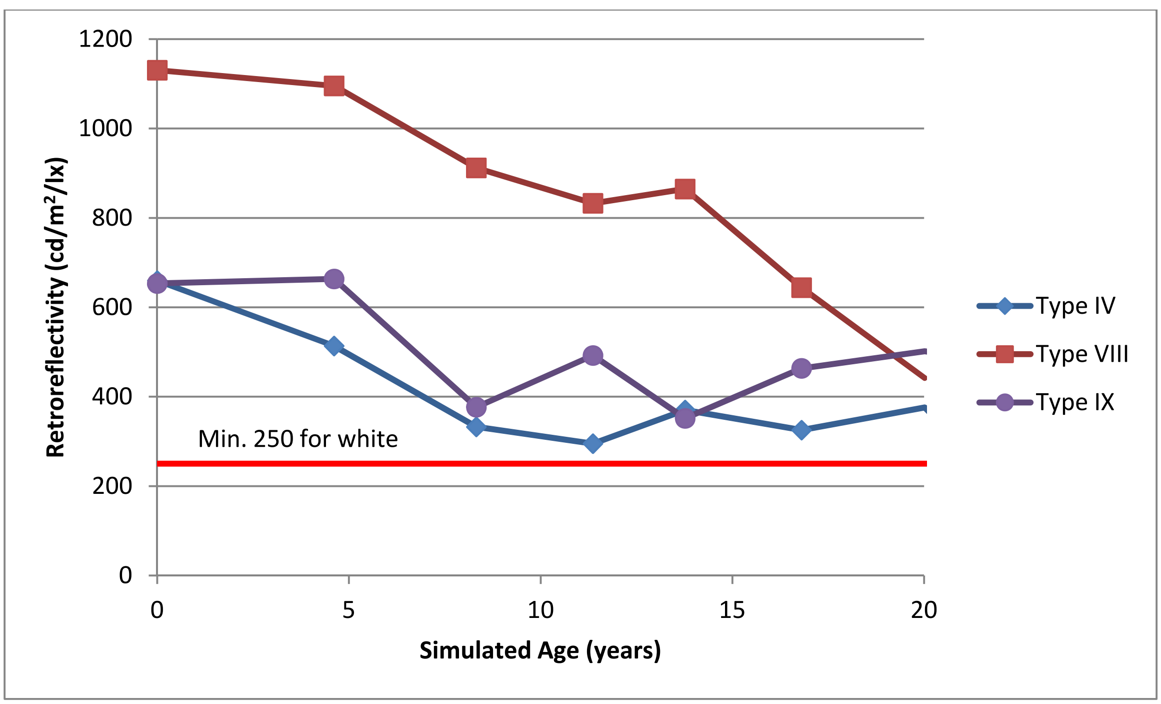

Figure 3.6 Retroreflectivity of White ASTM Type IV, VIII and IX Sheeting (Prismatic)

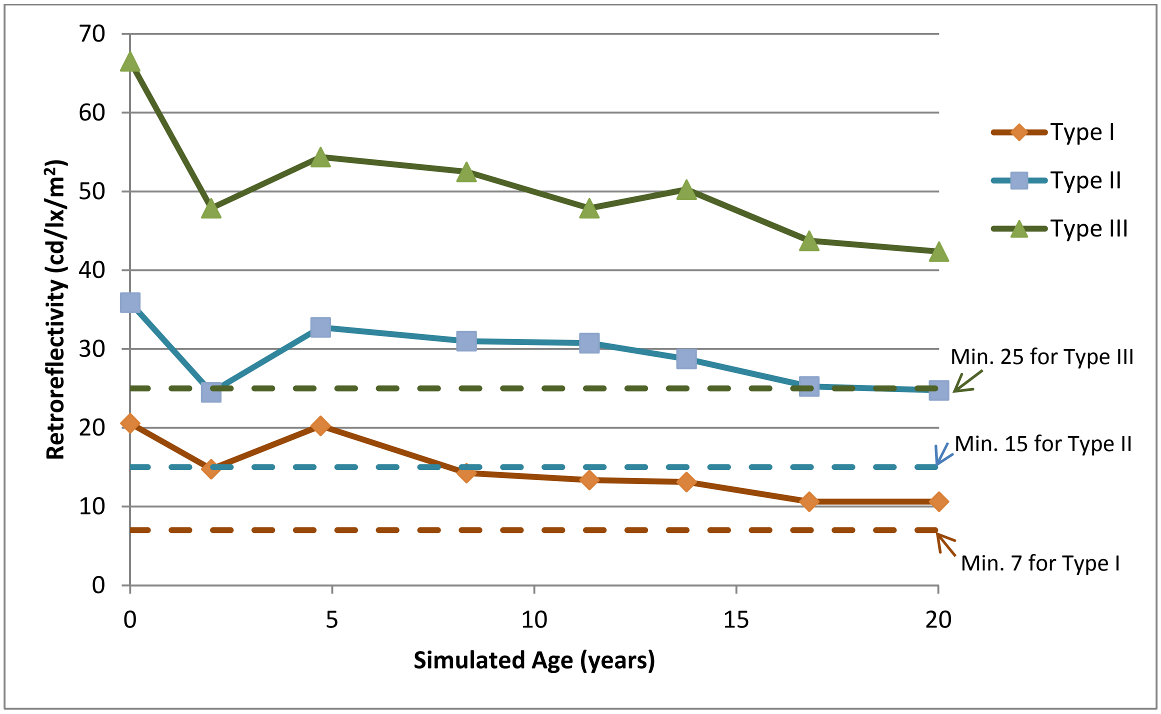

Figure 3.7 Retroreflectivity of Green ASTM Type I, II and III Sheeting (Beaded)

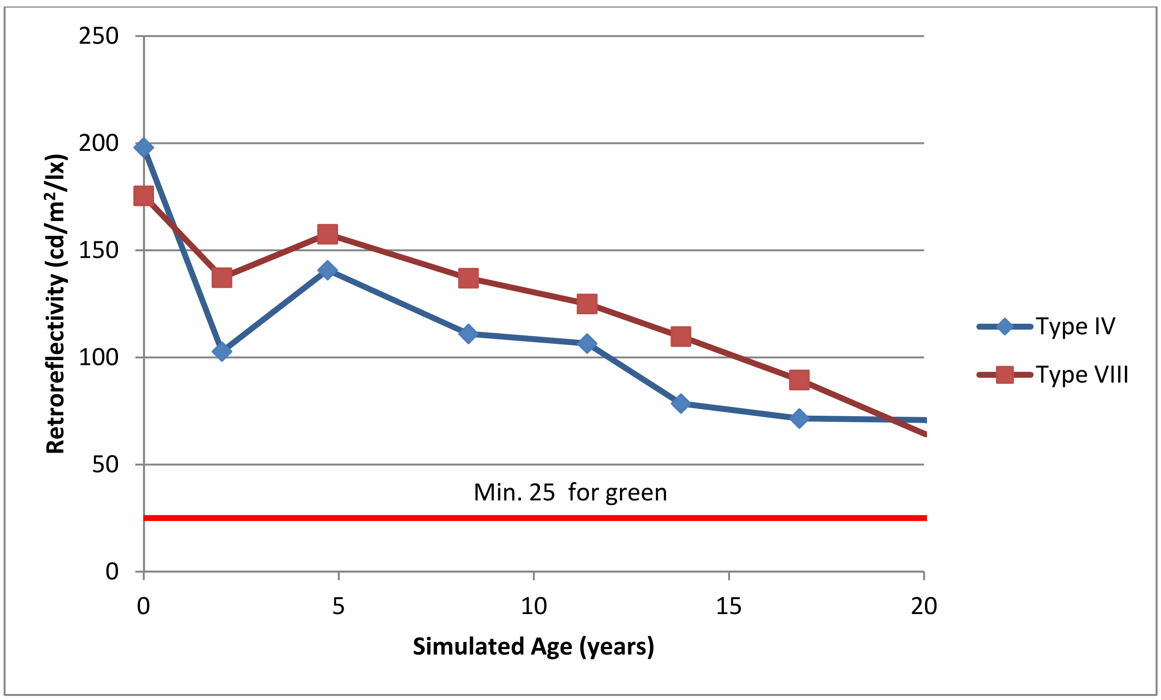

Figure 3.8 Retroreflectivity of Green ASTM Type IV and VIII Sheeting (Prismatic)

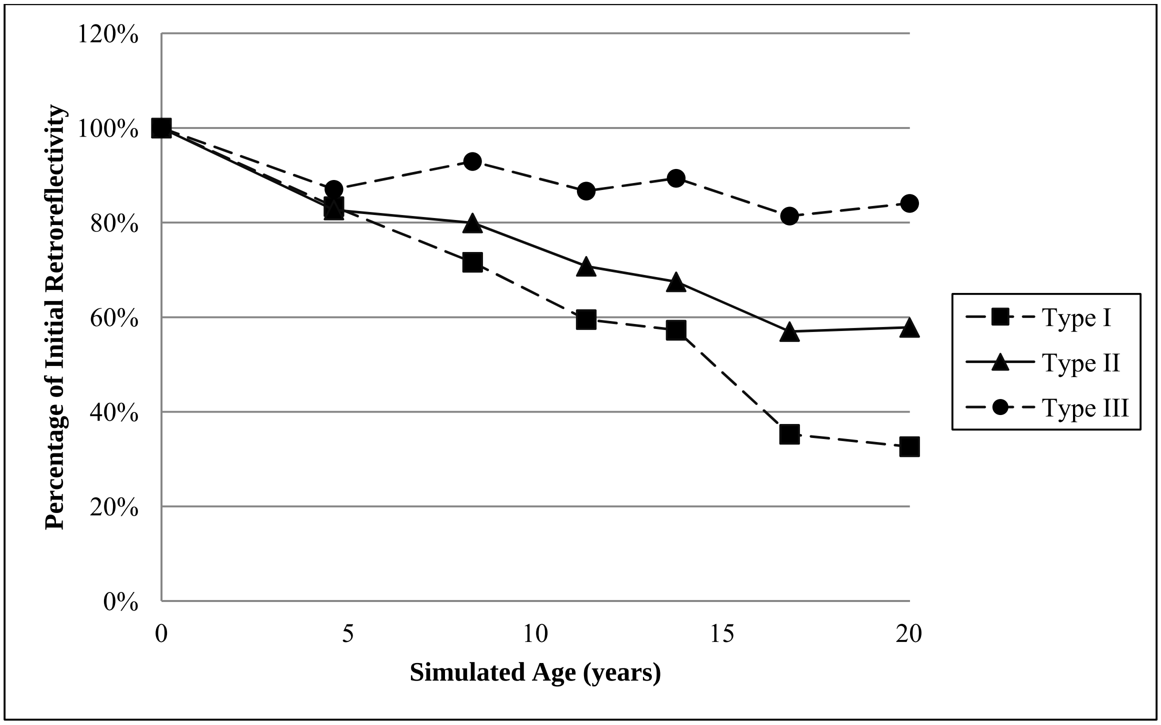

Figure 3.9 Percentage of Initial Retroreflectivity for White Beaded Sheeting

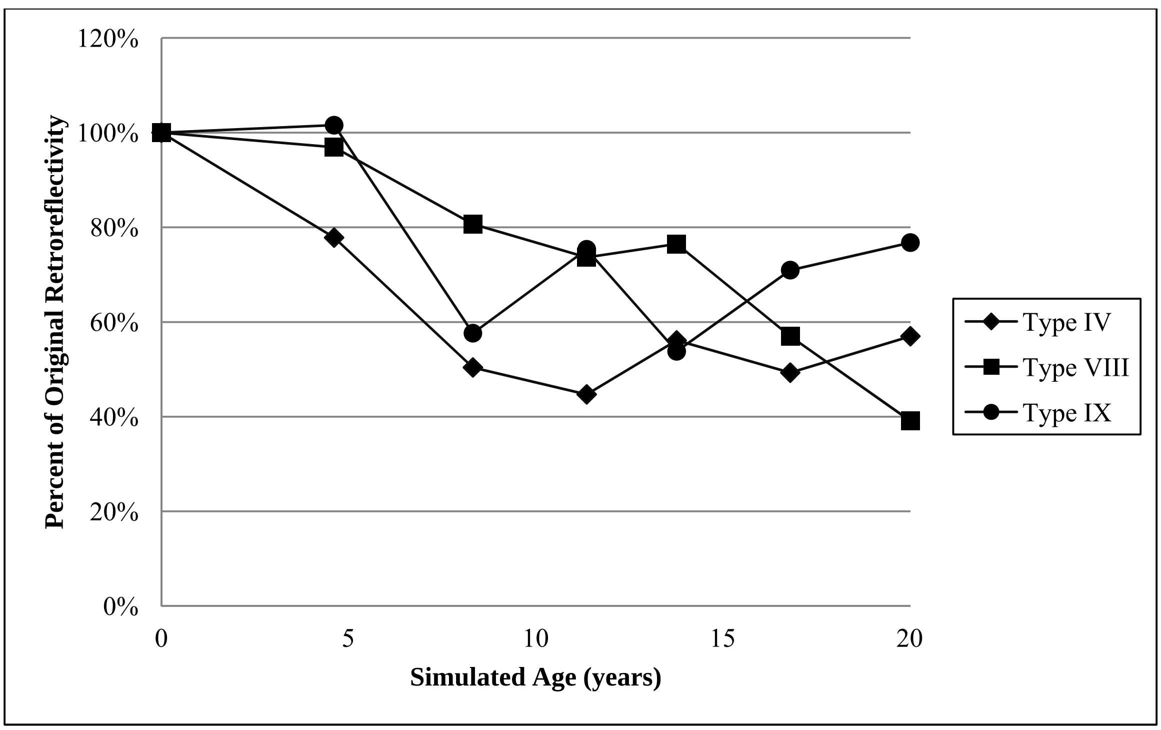

Figure 3.10 Percentage of Initial Retroreflectivity for White Prismatic Sheeting

Table 3.3 Predictive Models for Sign Sheeting Degradation

ASTM Sheeting Type		Prediction Model	R Square Value
Beaded	Type I	1-0.0335*Age	0.97
	Type II	1-0.0224*Age	0.90
	Type III	1-0.009*Age	0.53
Prismatic	Type IV, VIII, IX	1-0.0246*Age	0.49

Within the last 10 years, headlamps have evolved and their performances have improved steadily and the headlamp profiles in the ERGO model are outdated. Two headlamp profiles are included in the model: US2004 and US2011, representing the market weighted 50th percentile of U.S. low beam headlamp photometric output. Once the headlamp type is selected in Step 3.2 (shown in Figure 3.2), the external luminous intensity matrices are imported in the model for the calculation of luminous intensity.

Step 4

Using the results of Steps 2.1 and 3.1 (shown in Figure 3.2), the coefficient of retroreflection (R_a) for each headlamp can be obtained by using a multipoint quadratic lookup and interpolation feature, in Step 4.1. In other words, find the closest value of R_a for each headlamp in the retroreflectivity matrices by the calculated α, β, ε and ω_s. Using the results of Steps 2.2 and 3.2, luminous intensity (I) of each headlamp can be found in the luminous intensity matrices of its type by the calculated horizontal and vertical headlamp angles to the sign, in Step 4.2. A two-way quadratic lookup and interpolation feature is used.

Step 5

Based on the results of Steps 2.3 and 4.2, the illuminance (E) of each headlamp is calculated by Equation 3.1, which is known as the Inverse Square Law.

$$E = I/d_I^2 \qquad \text{(Equation 3.1)}$$

Where, E is the illuminance, in lx; d_I is the distance between each headlamp and sign, in m; and I is the luminous intensity, in cd.

Step 6

Combining the results of Steps 4.1, 2.4 and 5 (shown in Figure 3.2), the supply luminance (L) of a retroreflective sign from each headlamp, directed toward the driver, is estimated using Equation 3.2:

$$L=(R_A*E)/\cos(\upsilon) \qquad \text{(Equation 3.2)}$$

Where, R_A is the coefficient of retroreflection of the sign corresponding to each headlamp of a vehicle, and υ is the viewing angle for the sign.

Step 7

If there is sign lighting, the combined retroreflective and diffuse sign luminance from the sign luminaires is added to the retroreflected luminance generated by the vehicle headlamps. Different types of sign luminaires provide different luminance to the sign, depending on their output and positioning. As induction light and LED light are the types of sign luminaires FDOT is targeting, both of these luminaires were measured at the TTI Riverside Campus in order to account for them in the calculations.

Measurement Design

Five 3M DG3 (ASTM Type XI) white 2 ft octagons were attached to a sign structure, as shown in Figure 3.11. In this image, the sign structure has an induction fixture (Versa flood III Induction fixture from GE) or a LED fixture (Flood LED fixture from Beta) attached to a pole, and the light was adjusted to be 6 ft longitudinally away from the sign, 1 ft below the bottom of the sign structure. As shown in Figure 3.12, the sign structure was raised using a forklift so that the bottom of the sign structure was 18 ft from the surface of the pavement.

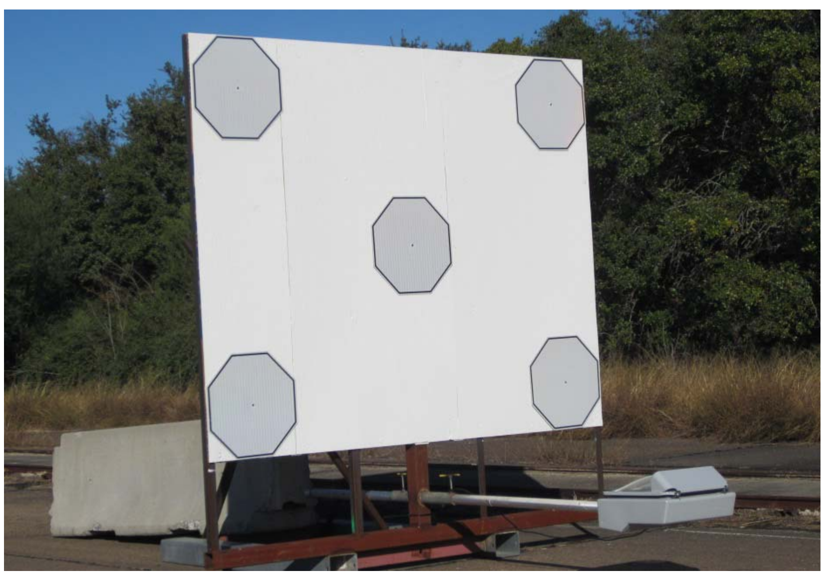

Figure 3.11 Five Signs on a Sign Structure

Figure 3.12 Sign Structure Lifted by a Forklift

Measurement Steps

Step 1. The signs were measured using a Zemax Radiant Imaging Prometric 1600 CCD Photometer set in the driver's position of a minivan (Dodge Caravan). The vehicle was positioned in the lane immediately left of the sign. The measurements started with the vehicle 1000 ft away from the sign. Measurements were made at 100 ft increments until the vehicle was 200 ft from the sign (see Figure 3.13). At each distance, measurements were made with the low-beam headlights and the sign lighting on and off.

Figure 3.13 Measurements Starting 1000 ft away from the Sign

Step 2. The vehicle was moved to the immediate right lane of the sign structure and all the measurements are the same as those in Step 1.

Data Analysis

The luminance data were collected for all the five octagons on the sign structure at each distance between the testing vehicle and the sign structure, and the average luminance, maximum luminance and the minimum luminance were calculated accordingly. For the sign luminance provided by induction light (or LED light) only, the maximum-to-minimum ratio is between 2 and 3 regardless of distance. Therefore, the induction light and LED light meet IESNA RP-19-01 required maximum-to-minimum uniformity ratio of 6 to 1 for external sign lighting.

In terms of induction light, the average luminance of the five octagons by distances is summarized in Figure 3.14 and Figure 3.15 for the vehicle in the immediate left and right lane of the sign structure, respectively. As shown in Figure 3.14 and Figure 3.15, the induction light provides diffuse light to the sign, with its provided luminance values approximately constant at 7.7 cd/m^2. No obvious changes were found from the figures when the vehicle moved longitudinally and laterally (shifted lanes) from the sign. In addition, headlights of the vehicle provided additional luminance to the signs and more values were observed when the vehicle got farther from the sign within the study range. No significant difference was found for the luminance provided by headlights when the vehicle changed the driving lane from left to the right but with the same lateral distance to the sign structure.

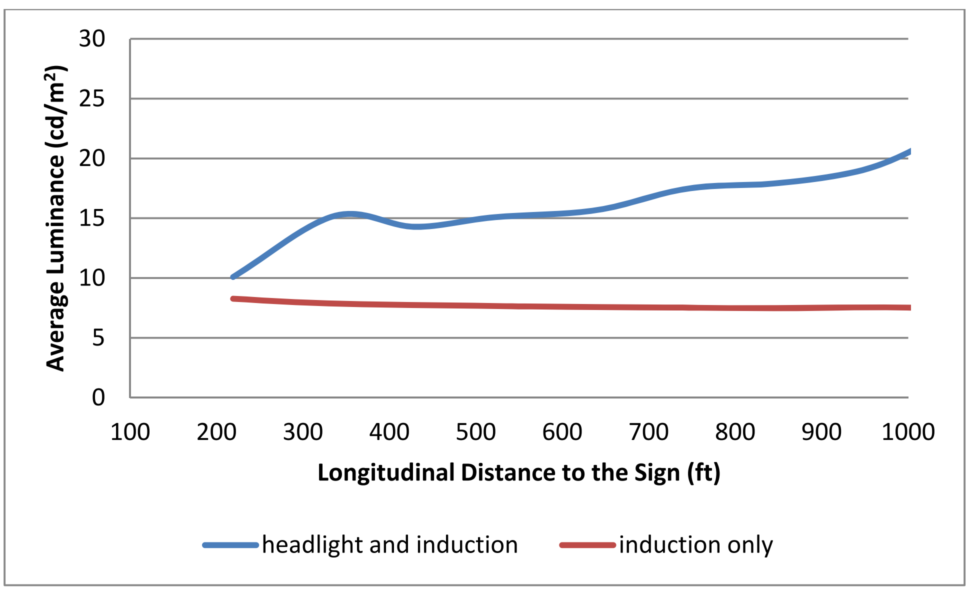

Figure 3.14 Legend Luminance for the Vehicle in the Left Lane

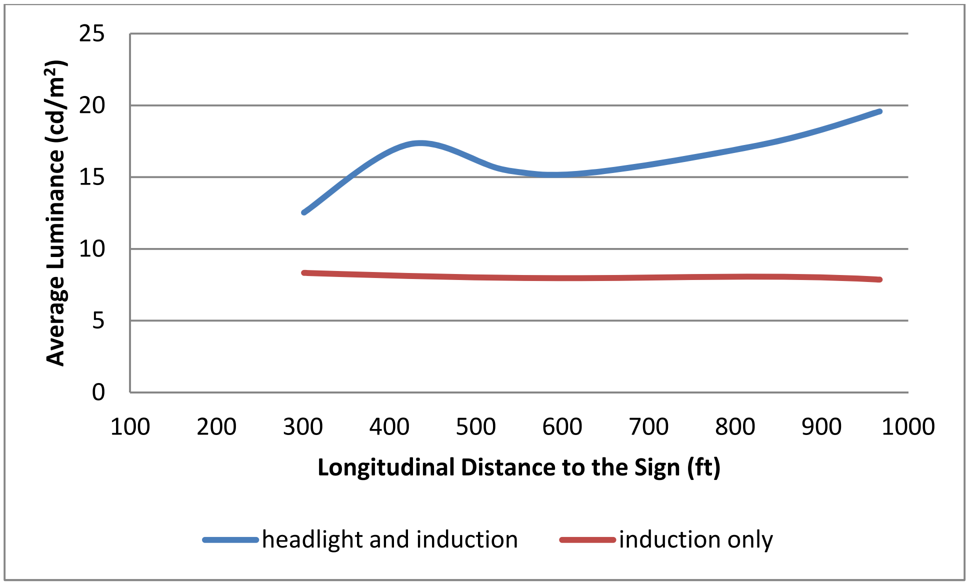

Figure 3.15 Legend Luminance for the Vehicle in the Right Lane

In order to study the luminance distribution of the sign from the induction light, the average luminance provided by induction light of the five octagons on the sign structure is plotted in Figure 3.16 and Figure 3.17 for two different driving lane positions. From Figure 3.16 and Figure 3.17, each of the five octagons keeps the consistent luminance from the induction light with the change of the vehicle distance to the sign and the lane position, as the induction light provides diffuse lighting to the sign. This is consistent with the previous finding associated with the average luminance of the five octagons. In addition, it is found that luminance changes with the position on the sign. The center octagon on the sign structure has the highest luminance. The luminance difference among the four corner octagons are slight, though the two bottom octagons have slightly larger luminance than the top two octagons as the former ones are closer to the induction light.

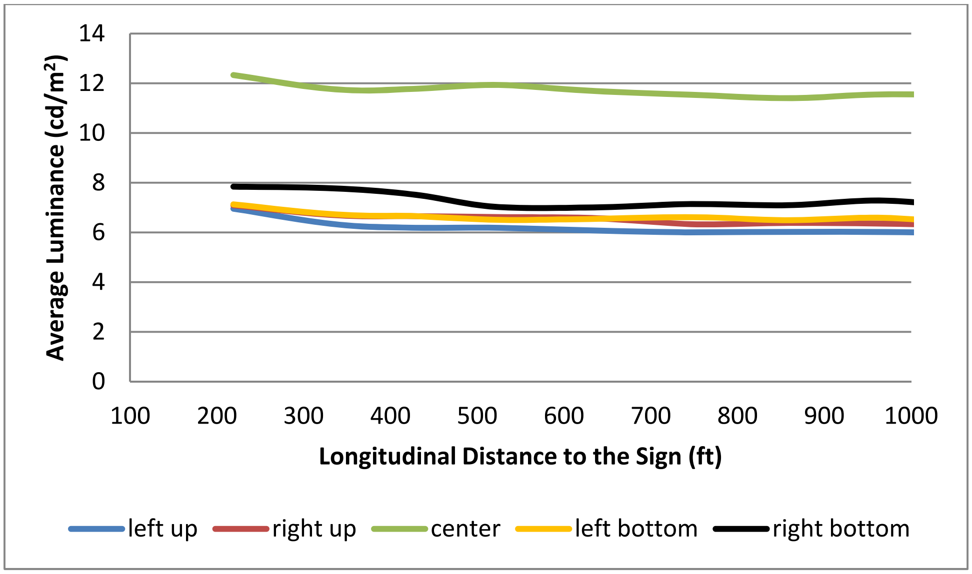

Figure 3.16 Legend Luminance Distribution for the Vehicle in the Left Lane

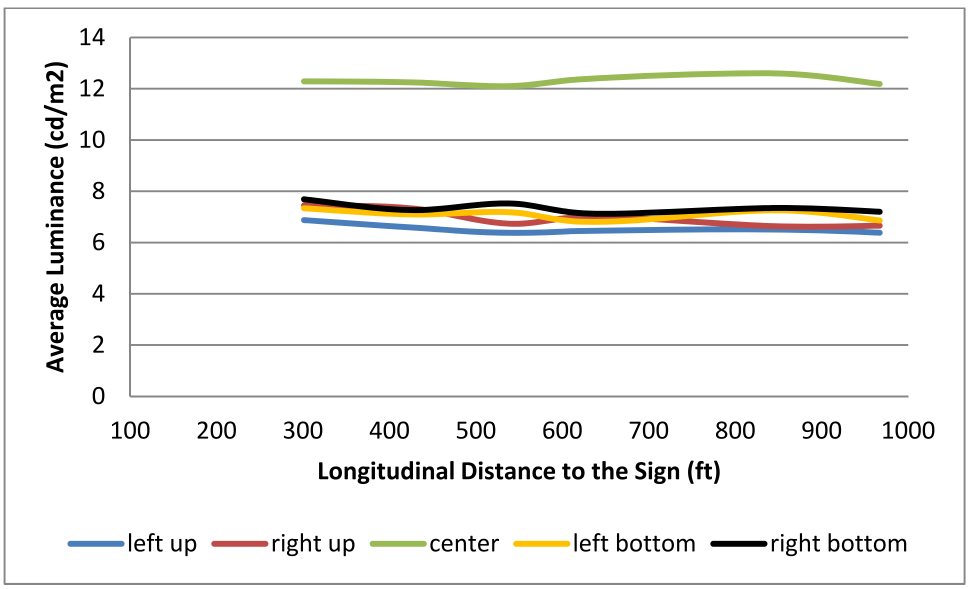

Figure 3.17 Legend Luminance Distribution for the Vehicle in the Right Lane

As the legends of the sign are usually located around the center of the sign, the distribution of the sign luminance was not used in the luminance computation model. By taking the average of the luminance of the center octagon (12 cd/m^2) and the average luminance of the corner octagons (7 cd/m^2), we assumed that 9.5 cd/m^2 would be a representative luminance value for induction lighting on ASTM Type XI legend sheeting for overhead guide signs.

Using the same method of measurement and analysis, LED light (a Flood LED fixture) provides about 11.5 cd/m^2 luminance with ASTM Type XI sheeting. In this case, the LED luminaire provided more luminance than the induction lighting but many factors can be adjusted to change these numbers (such as mounting position, mounting angle, and power). While the field measurements of the lighting were made with ASTM Type XI sheeting, we assumed the added luminance from the luminaires to be equivalent regardless of what type of retroreflectivity sheeting was assumed for the legend.

As the measurement is based on a new and clean fixture, the effects of system aging need to be taken into account for the decrease of the light level. Light loss factor is usually applied to account for actual field conditions of luminaires, including the reduced output from lamp lumen depreciation, dirt accumulation and equipment factor (*48*). For simplicity, we assume the annual light loss factor as 0.97 for induction luminaires, which leads to the total light loss factor at around 0.6 for their whole service life. Therefore, sign luminance provided by the induction light decrease at the rate of 0.97 yearly.

Step 8

Due to the additive characteristics of luminance supplied by different lighting, the total luminance of a sign (L_{sum}) is the sum of luminance from each headlamp and sign lighting (if available). Step 8 is calculating L_{sum} based on each headlamp luminance in Step 6 and input sign luminance value in Step 7.

Step 9

The above calculation of luminance does not consider any effect of the environment. However, the driving environment is not perfect and there are at least three adjustment factors to account for: windshield transmissivity, atmospheric transmissivity (*1*), and dirt.

Light traveling from the sign to the driver is partially absorbed by the vehicle windshield before it reaches the driver's eyes. The windshield transmissivity factor (F_w) is a multiplicative effect between 0 and 1 used to adjust the luminance. It was found that a typical value for windshield transmissivity is 0.72 (*1*). The input of windshield transmissivity is required in Step 9.1.

In addition, as stated in Task 2, atmospheric transmissivity (T) can be used to quantify weather effects on overhead signs. Based on the historic climatic data from five geographically representative cities, adverse weather and low visibility conditions were found rare during nighttime in Florida. Therefore, a default atmospheric transmissivity of 0.86/km was used in the model, which represents a typical clear condition. Accordingly, the atmospheric transmissivity factor (F_a) can be calculated based on atmospheric transmissivity and viewing distance (see more details in Task 2). The value is identified in Step 9.2.

In terms of the dirt effect, based on the study in Task 2, dirt was found to reduce sheeting retroreflectivity about 10 percent for legends. Thus, a default dirt factor (F_d) of 0.9 was set in the model, which is identified in Step 9.3.

Step 10

Step 10 is to calculate the total supplied luminance is by Equation 3.3:

$$L_{supplied} = L_{sum} * F_w * F_a * F_d \quad \text{(Equation 3.3)}$$

Where, L_{obs} is the supplied luminance; L_{sum} is the ideal luminance from all headlamps in the traffic; F_w is the windshield transmissivity factor; F_a is the atmospheric transmissivity factor; and F_d is the dirt factor.

Model Design and Analysis

With the steps of the model described above, the model can be used to estimate sign luminance in terms of different sign-vehicle geometry, sign type, sheeting material, sheeting age and vehicle type. In this study, some typical situations were selected. For overhead signs, the height of the sign (from center of the sign to the ground) is assumed to be 23 ft, and the sign is above the middle of a driving lane. Two vehicle types were included in the study: a passenger car and a light truck or SUV. Their dimensions are listed in Table 3.4. Three types of sheeting materials are used in the study: ASTM Type IV, VIII and XI as prismatic sheeting, and ASTM Type III as a beaded material. Vehicle headlamps are US2004 and US2011. Lane width is set as 12 ft, and the vehicle is assumed to be always driving in the middle of a lane. In addition, the distance between overhead signs and vehicles is set to be 480 ft based on the legibility index of 30 ft/inch as stated before.

Table 3.4 Vehicle Dimensions (*4*)

Vehicle Description	Headlamp Height	Driver's Eye Height	Headlamp Separation	Driver's Eye Setback	Driver's Eye Offset
Passenger car (ft)	2.0	3.5	4.0	4.5	1.5
Truck/SUV (ft)	2.8	4.8	4.4	7.2	1.3

Therefore, supplied luminance values were calculated for various scenarios using the luminance computation model. By comparing the supplied luminance with the required legibility luminance, we can assess the adequacy of the sign performance in terms of nighttime legibility.

The results are summarized in Figure 3.18, 3.19, 3.20 and 3.21 for passenger cars, and Figure 3.22, 3.23, 3.24 and 3.25 for trucks/SUVs. It needs to be noted that the dash lines in the figures are the 50th percentile minimum luminance demands (legibility index=30 ft/inch) at the different ambient conditions from Figure 3.1. Three ambient conditions are selected for analysis: one urban condition (roadway lighting with glare) and two rural conditions (no roadway lighting with and without glare), with the according threshold luminance levels as 4.7, 2.1, and 0.9 cd/m^2 for those three conditions. From the values, it is obvious that with more ambient background visual clutter and glare, drivers have higher visual demands on overhead guide signs.

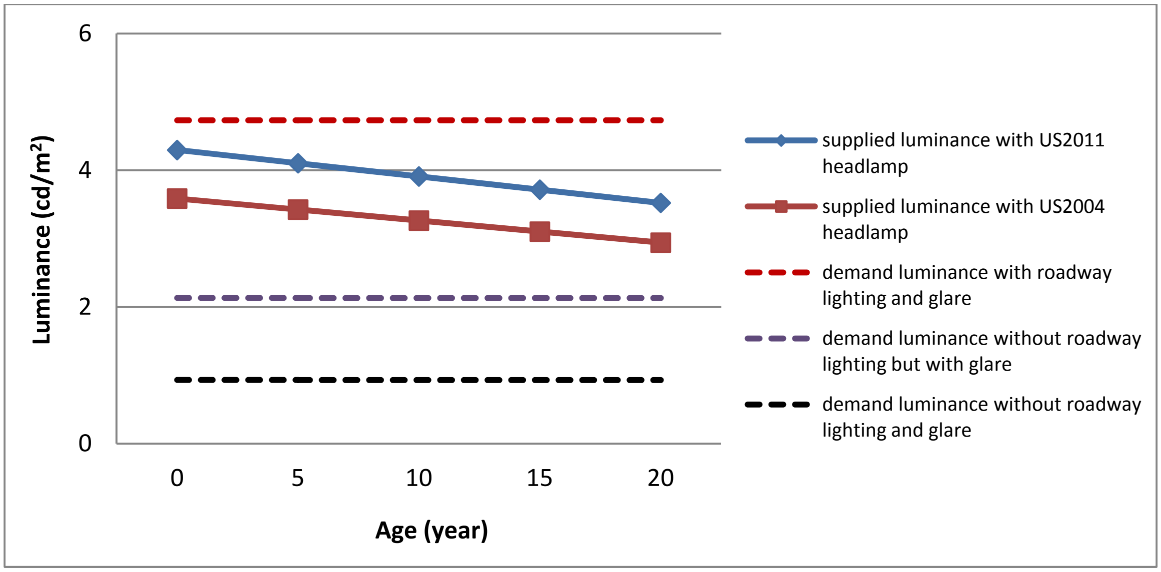

Figure 3.18 Supplied Luminance vs. Legibility Luminance (for ASTM Type III Sheeting and Car)

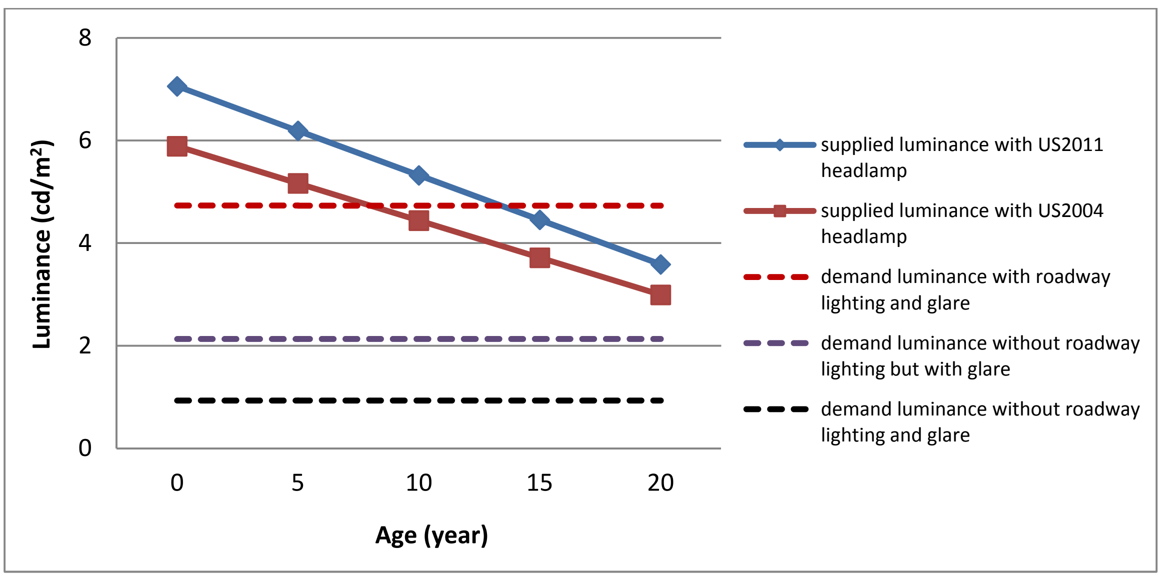

Figure 3.19 Supplied Luminance vs. Legibility Luminance (for ASTM Type IV Sheeting and Car)

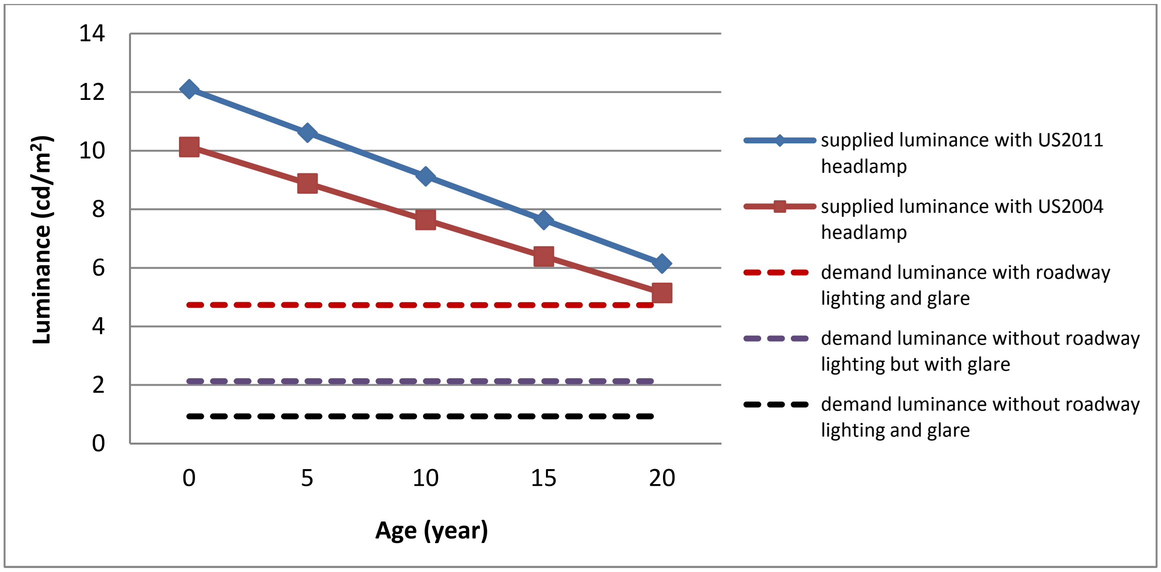

Figure 3.20 Supplied Luminance vs. Legibility Luminance (for ASTM Type VIII Sheeting and Car)

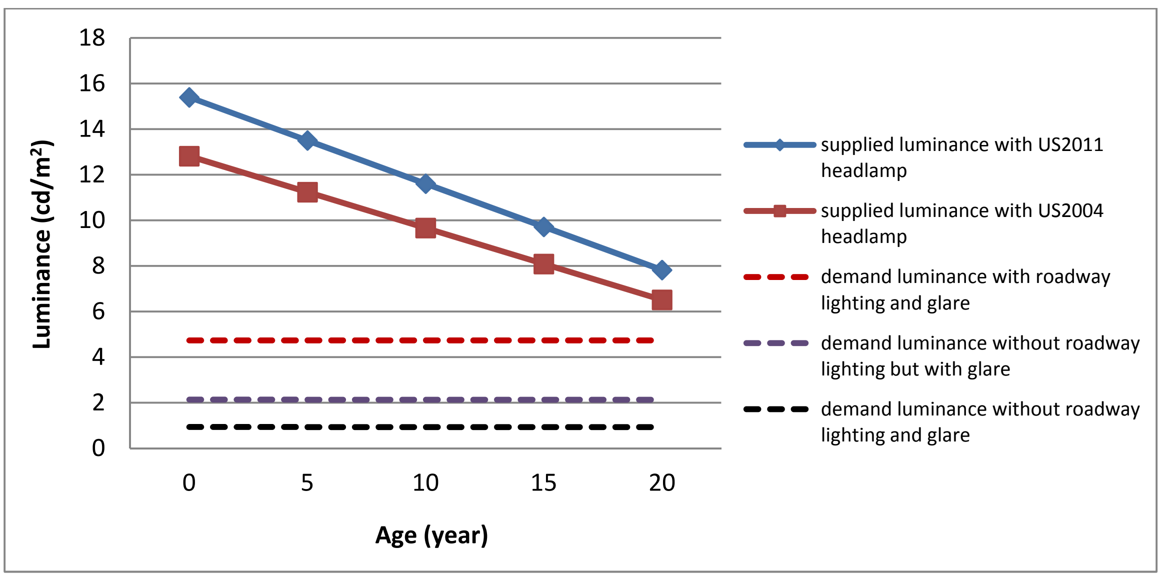

Figure 3.21 Supplied Luminance vs. Legibility Luminance (for ASTM Type XI Sheeting and Car)

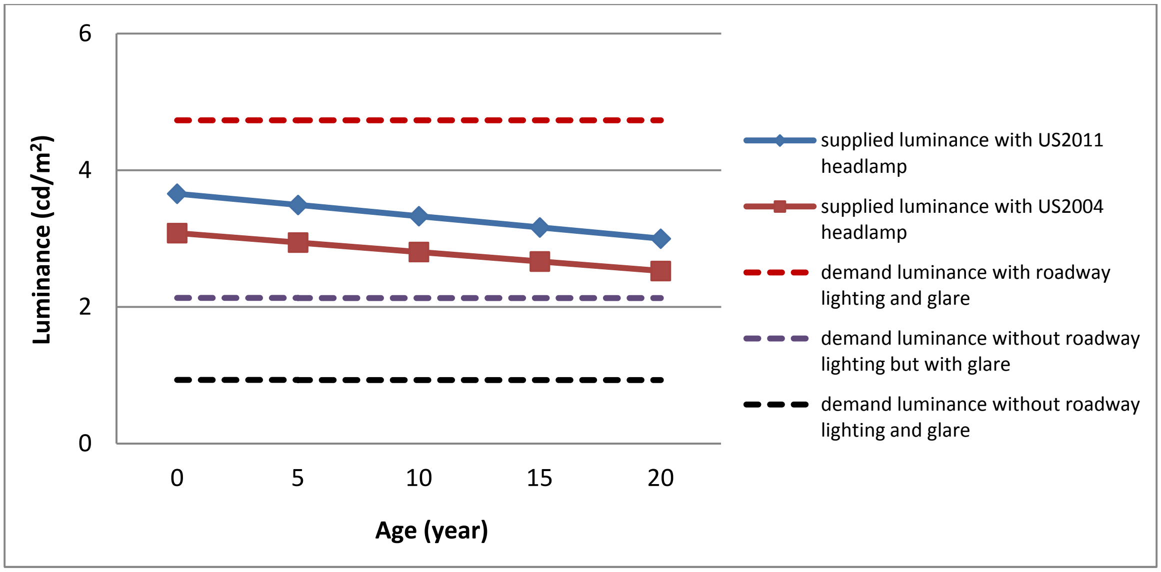

Figure 3.22 Supplied Luminance vs. Legibility Luminance (for ASTM Type III Sheeting and Truck)

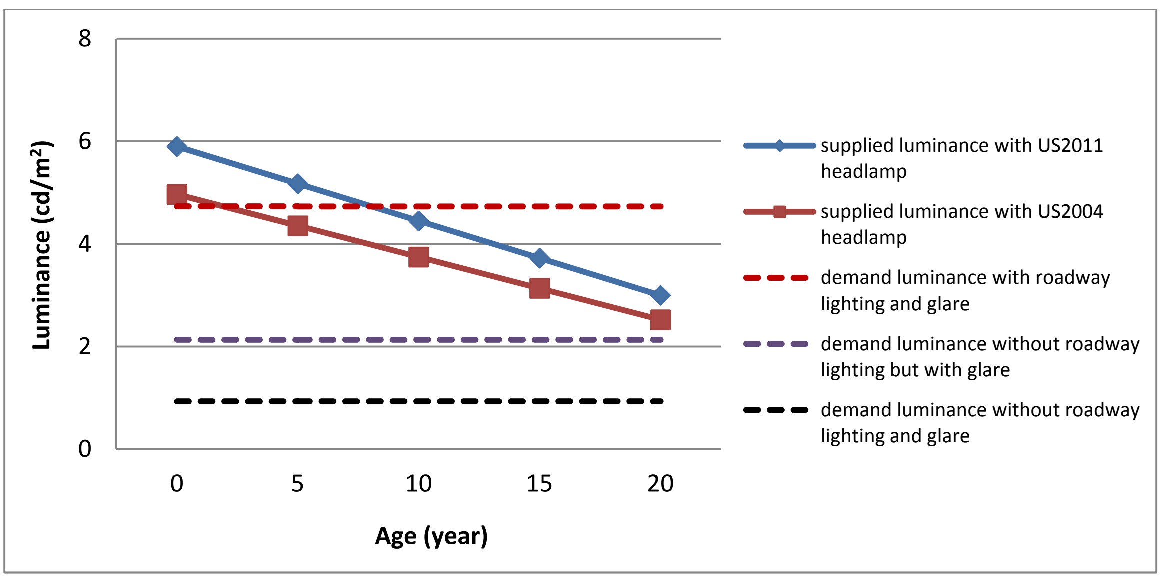

Figure 3.23 Supplied Luminance vs. Legibility Luminance (for ASTM Type IV Sheeting and Truck)

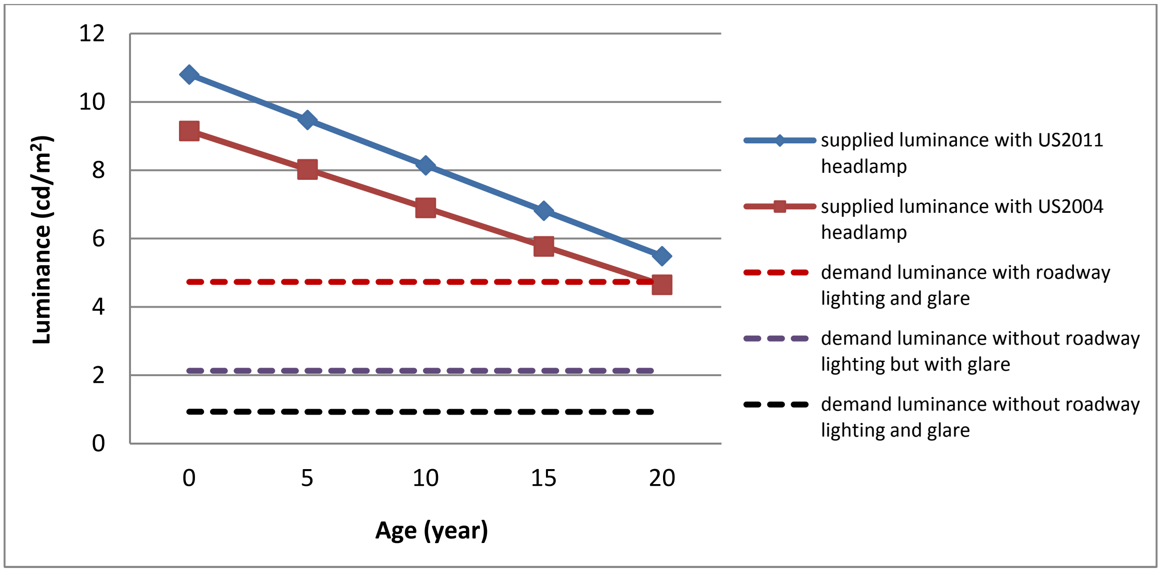

Figure 3.24 Supplied Luminance vs. Legibility Luminance (for ASTM Type VIII Sheeting and Truck)

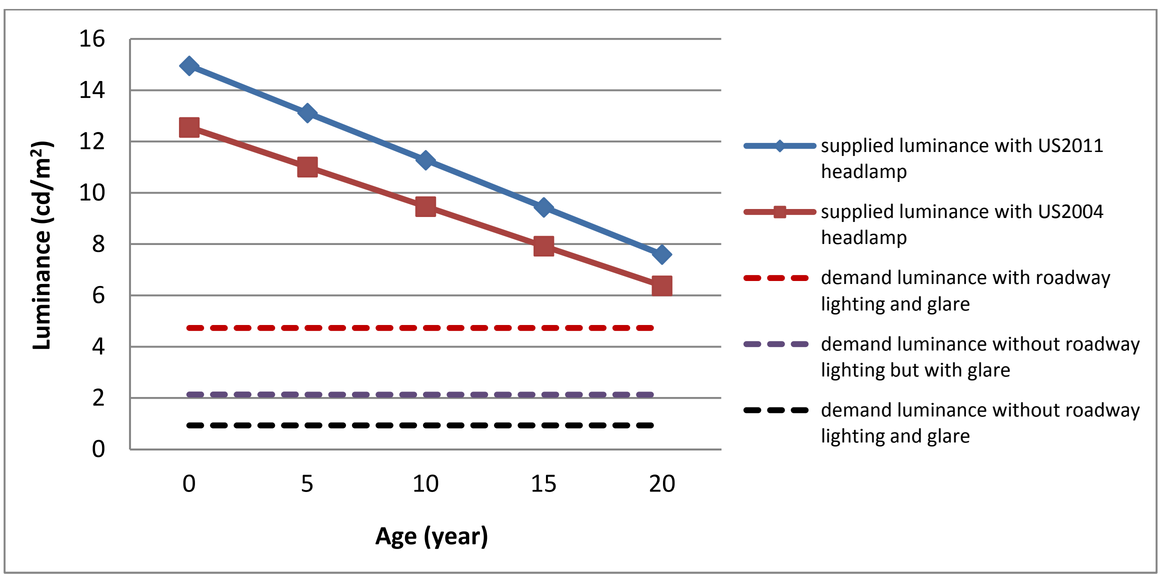

Figure 3.25 Supplied Luminance vs. Legibility Luminance (for ASTM Type XI Sheeting and Truck)

From Figure 3.18 to Figure 3.25, using US2011 as vehicle headlamps in the model leads to higher luminance than using US2004. Drivers in passenger cars enjoy more overhead guide sign luminance than those in trucks/ SUVs. For trucks/ SUVs, the driver's eyes are placed higher from the headlamps, which leads to larger observation angles.

For the conditions considered, the luminance of prismatic sheeting (ASTM Type IV, VIII and XI) is higher than that of the beaded materials (ASTM Type III). ASTM Type VIII sheeting is brighter than Type IV, and Type XI sheeting is brighter than Type VIII. The data in the previous graphs show that ASTM Type III and Type IV sheeting materials are not adequate for overhead guide sign legends in urban areas considering their brightness after 20 years, but adequate in rural areas. However, if induction/LED luminaires are used as sign lighting, sign luminance increase significantly. Using the initial luminance provided by an induction luminaire of 9.5 cd/m^2 and the annual light loss factor of 0.97 (as stated before), the supplied luminance is shown in Figure 3.26 and 3.27 for ASTM Type III and Type IV sheeting respectively. As noted, both figures show the luminance for a truck/SUV, as a truck/SUV requires larger luminance for drivers than a passenger car. The supplied luminance in terms of LED luminaires is not plotted here as LED provides larger luminance than induction light.

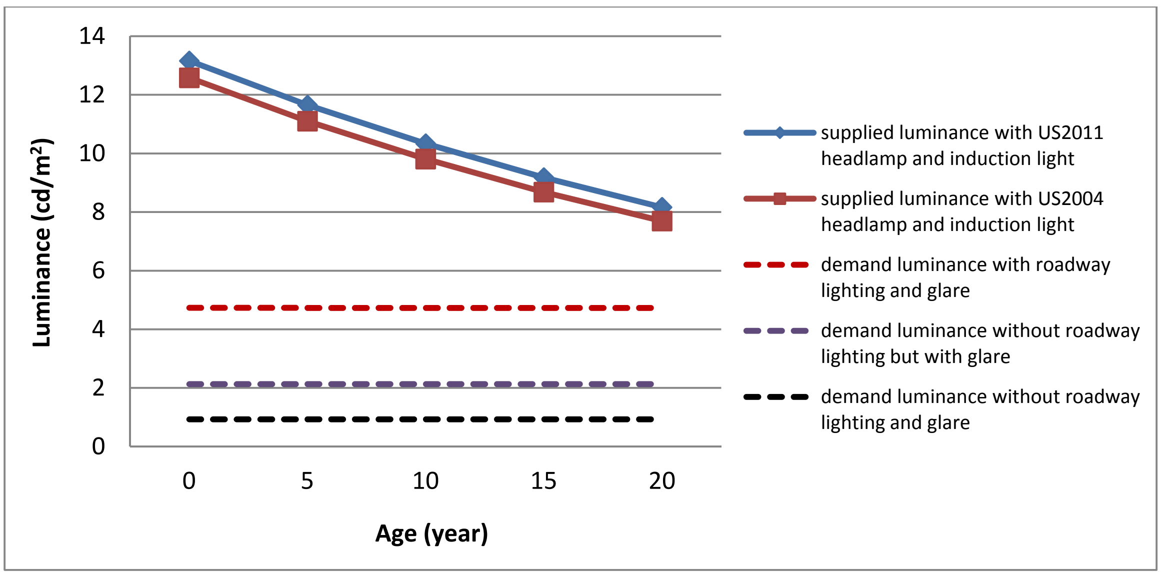

Figure 3.26 Supplied Luminance (with Induction Lighting) vs. Legibility Luminance (for ASTM Type III Sheeting and Truck)

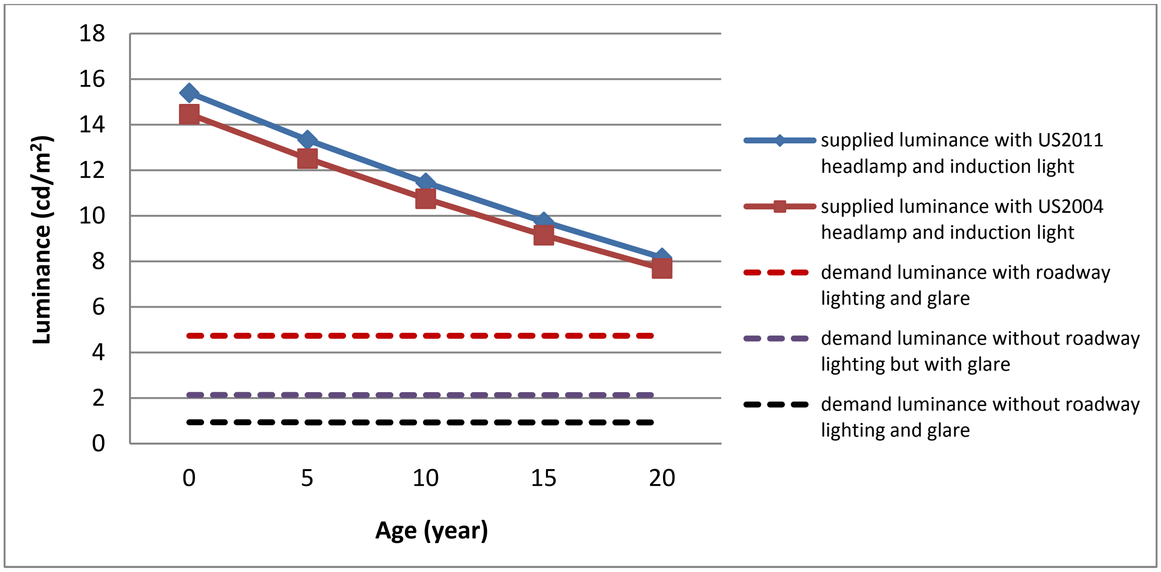

Figure 3.27 Supplied Luminance (with Induction Lighting) vs. Legibility Luminance (for ASTM Type IV Sheeting and Truck)

From Figure 3.26 and 3.27, it is found that ASTM Type III and Type IV sheeting materials can be used without replacement for more than 20 years in any condition (both urban and rural areas), when the sign is lit by induction or LED luminaires. Furthermore, it is possible that the induction or LED fixture can be dimmed from the maximum output and will still be adequate for up to 20 years.

From Figures 3.20, 3.21, 3.24 and 3.25, ASTM Type VIII sheeting can be used without replacement for at least 20 years in rural areas. When it comes to urban areas, ASTM Type VIII sheeting still performs well, but it is too much to expect it to be sufficient for up to 20 years in all conditions. However, ASTM Type XI sheeting can be used without replacement for at least 20 years in any of the conditions (except dew conditions, which sign lighting can overcome).

The above luminance analysis was based on straight and flat roadways, i.e., no horizontal or vertical curvature for roadway geometry. However, horizontal curves can have significant effects on sign luminance. Based on the Florida green book (*49*), the minimum radii of horizontal curves in terms of design speeds for both rural and urban areas are shown in Table 3.5.

Table 3.5 Horizontal Curvature Requirements in Florida (*49*)

RURAL Based on e_{MAX} = 0.10			URBAN High-Speed Highways and Streets Based on e_{MAX} = 0.05		
Design Speed (MPH)	Max. Degree of Curvature	Min. Radius (FEET)	Design Speed (MPH)	Max. Degree of Curvature	Min. Radius (FEET)
15	104° 45'	55	---	---	---
20	57° 45'	100	---	---	---
25	36° 15'	160	---	---	---
30	24° 45'	230	30	20° 00'	285
35	17° 45'	320	35	14° 15'	400
40	13° 15'	430	40	10° 45'	535
45	10° 15'	555	45	8° 15'	695
50	8° 15'	695	50	6° 30'	880
55	6° 30'	880	55	5° 00'	1125
60	5° 15'	1095	---	---	---
65	4° 15'	1345	---	---	---
70	3° 30'	1640	---	---	---

In order to study the breakpoint in terms of curve radius where sign lighting is needed, additional analyses were completed using varying radii. By running the luminance computation model for a truck with US2011 headlamps and sheeting materials up to 20 years old, the supplied luminance of all sheeting types was calculated and compared to the demand luminance in urban areas (with roadway lighting and glare) and rural areas (without roadway lighting and glare). The breakpoint radii were achieved when the supplied luminance reached a point equal to the demand luminance. Table 3.6 and 3.7 show the breakpoint radii of curves for different sheeting types in rural and urban areas, respectively. As shown in both tables, two relative locations of the vehicle and sign were considered for the analysis: both the vehicle and sign are in the curve; the vehicle is on the approach tangent and the sign is in the curve (with three different distances to the point of curve (PC)).

The breakpoint radii in the tables represent the condition at which either a more efficient sign sheeting material is needed or sign lighting is needed. Please note that according to the results in Table 3.7, both sheeting materials ASTM Type III and IV cannot produce the luminance required in urban areas for the conditions studied.

Table 3.6 Breakpoint Radii of Horizontal Curves in Rural Areas (ft)

Legend sheeting	Both vehicle and sign in curve	Sign in curve (Distance from PC)		
		(250 ft)	(300 ft)	(350 ft)
Type III	925	200	335	470
Type IV	920	335	450	595
Type VIII	810	330	420	510
Type XI	880	370	460	555

Table 3.7 Breakpoint Radii of Horizontal Curves in Urban Areas (ft)

Legend sheeting	Both vehicle and sign in curve	Sign in curve (Distance from PC)		
		(250 ft)	(300 ft)	(350 ft)
Type III	N/A			
Type IV				
Type VIII	3650	980	1410	1930
Type XI	2500	1210	1420	1650

In summary, modeling examples described above demonstrate that by adjusting the input of lighting and/or sheeting types at different geometries, we can determine if overhead signs need lighting on straight and flat roadways or curves (horizontal curves were studied in the research), and if so, how much lighting is needed. We can also evaluate whether the luminance of a sign, replaced by new high reflective sheeting, will be sufficient. In addition, if sign lighting is available, the additional sign luminance provided by sign lighting can also be calculated by the model. For horizontal curves, the breakpoint radii needing new sheeting or sign light for different sheeting types have also been derived by comparing the supplied luminance with the demand luminance in the model.

The results in Tables 3.6 and 3.7 provide the information needed to develop a simple and conservative recommendation for when sign lighting is needed. For instance, if ASTM Type XI material is used for overhead sign legends, then sign lighting would be needed in rural areas when the curve has a radius of 880 ft or less. In urban areas sign lighting would be needed when the curve has a radius of 2500 ft or less. Less restrictive criteria could be developed for other conditions where the vehicle is on the approach tangent and the sign is in the curve.

Summary

In this task, a luminance computation model was developed to calculate sign legend luminance under various situations, including different headlamps, different sign lighting technologies, different geometrics and sign locations, and different amounts of sign dirt and sign aging. By comparing the calculated luminance of an overhead guide sign with a certain sheeting material at a specific situation to the legibility luminance levels required by older drivers, it is possible to identify if high intensity sign sheeting can replace the need for sign lighting; and if not, then determine where overhead signs with lights should be required in lieu of high intensity reflective sheeting in Florida.

For illustration purpose, the luminance computation model was used to calculate the overhead sign luminance for ASTM sheeting Type III, IV, VIII, and XI along a straight and flat roadway, as well as in horizontal curves in rural and urban areas. By comparing the calculated sign luminance with the 50th percentile minimum luminance demands at the different ambient conditions, it is found that for straight and flat roadways ASTM Type VIII and XI sheeting is sufficient for up to 20 years in any condition, while ASTM Type III and IV sheeting are only adequate for 20 years if they are supplemented with sign lighting.

To assist with design decisions, breakpoint radii were derived to determine when sign lighting is needed based on the horizontal curvature. Two relative locations of the vehicle and sign were considered for the analysis: both the vehicle and sign are in the curve; the vehicle is on the approach tangent and the sign is in the curve (with the distance to the point of curve (PC) as 250 ft, 300 ft or 350 ft). Following this approach, and assuming Type XI materials are used for the legends, then sign lighting would be needed in rural areas when the horizontal curvature has radii of 880 ft or less and in urban areas when the horizontal curvature has radii of 2500 ft or less.

TASK 4: LIFE-CYCLE COST ANALYSES

The objective of the life-cycle cost analysis is to compare the cost of installing an overhead sign light to the cost of replacing the current sign sheeting with high reflective sheeting, as well as the costs of different combinations of sign lighting and sheeting materials based on the demanded legibility luminance. Benefits, including visibility and safety, are not quantified in the life-cycle cost analysis. As the actual number of overhead signs and their lights used statewide is not known, costs were quantified on a per unit basis for comparison.

Life-cycle Cost of Sign Sheeting

For replacing an overhead sign with high reflective sheeting, the costs include: sheeting materials and replacement of sign panels. We used three potential prismatic sheeting materials for the analysis as requested. The cost and service life vary with sheeting types, and service life is also different for various environmental conditions. Because of the inherent visibility disadvantages associated with driver eye position relative to the headlamp position for light trucks and/or SUVs, higher levels of retroreflectivity are needed to produce equivalent luminance levels as those experienced by drivers of passenger cars. Therefore, the service life in Table 4.1 is based on the analyses from a light truck and/or SUV and for tangent sections of roadways. Based on Figure 3.22 to Figure 3.25 and by taking the average of service life for vehicle headlamps US2004 and US2011, the service life values are summarized in Table 4.1. The unit cost of each sheeting type is shown in Table 4.1 as well. However, as stated in Task 3, Type III and Type IV can provide adequate luminance in urban area for 20 years if the signs are lit.

Table 4.1 Unit Cost and Service Life for Different Legend Sheeting Types

Legend Sheeting Type	2011 Unit Cost ($/ft^2)	Expected Service Life (year)	
		Urban area	Rural area
Type III* (in use now)	1.15	0	20
Type IV	1.15	4 (see Fig 3.23)	20
Type VIII	2.8	20	20
Type XI	3.79	20	20

* Shown only for comparisons

For this analysis, we assumed that the currently used material was ASTM Type III. When conducting the analysis of other types of sheeting materials, we varied the legend material but kept the background material constantly set as an ASTM Type IV material. We considered combinations of materials using ASTM Types IV, VIII, and XI for the legend. We used a size of 18 ft×12 ft for the sign. The sheeting used as backgrounds is about the same size as the sign panel and the size of sheeting used to cut legends is assumed to be 8 ft×2 ft for three lines. Therefore, the area of sheeting needed for backgrounds is 18 ft×12 ft=216 ft^2 and 3×8 ft×2 ft=48 ft^2 for legends. Accordingly, the sheeting material costs per each sign are calculated for all the potential combinations, listed in Table 4.2.

Table 4.2 Total Cost of Replacing Sign Sheeting with Various Legend Sheeting Types

Legend Sheeting Type	Background Sheeting Type	Legend Cost per Sign ($)	Background Cost per Sign ($)	Sheeting Cost per Sign ($)	Overlay Cost ($)	Total Cost ($)
Type IV		55.2	248.4	303.6		6,812
Type VIII	Type IV	134.4	248.4	382.8	6,508	6,891
Type XI		181.9	248.4	430.3		6,938

In terms of the costs of sign panel replacement, sign panel overlaying cost is found to be \$30.13/ft^2 for overhead signs based on FDOT Maintenance Contract Cost Summary. The approximate cost of replacing an 18 ft×12 ft sign is \$30.13 /ft^2 × 216 ft^2 = \$6,508. Accordingly, the total cost of replacing an overhead sign with high reflective sheeting is the sum of the sheeting cost and overlay cost, which is listed in Table 4.2 as well. Other costs are negligible, such as the disposal cost of old sheeting and sign panel and regular maintenance labor cost. Therefore, the average annual cost for the life cycle of each sheeting material can be calculated by the total costs listed in Table 4.2 and the service life of sheeting in Table 4.1, as shown in Table 4.3 for different ambient conditions.

Table 4.3 Average Annual Cost of Replacing Sign Sheeting with Various Legend Sheeting Types

<table>
<tr><th rowspan="2">Legend Sheeting Type</th><th colspan="2">Annual Cost ($/year)</th></tr>
<tr><th>Urban area</th><th>Rural area</th></tr>
<tr><td rowspan="2">Type IV</td><td>1,703*
(without sign light)</td><td rowspan="2">341</td></tr>
<tr><td>341
(with sign light)</td></tr>
<tr><td>Type VIII</td><td colspan="2">345</td></tr>
<tr><td>Type XI</td><td colspan="2">347</td></tr>
</table>

*Note: expected life is 4 years in urban area (see Table 4.1).

From Table 4.3, it is found the annual cost of Type IV sheeting varies in urban and rural areas with the change of service life. In urban area, with external sign lighting, Type IV sheeting is sufficient for 20 years in terms of luminance demands and the annual replacing cost of sheeting drops to the same amount as in rural areas. Among the three sheeting materials, Type IV sheeting has the highest annual cost when used in urban area but has the lowest cost when used in rural area.

Life-cycle Cost of Installing Sign Lights

In addition to the replacement of older sheeting by newer and more efficient sheeting, sign lighting can also be installed in order to meet drivers' visibility demands. In Florida, many overhead signs are currently lit with mercury vapor luminaries. For signs which have no sign lighting in use, the costs of installing sign lights include costs of induction or LED luminaires, cost of maintenance of traffic (MOT), equipment cost, installation labor, operating cost (i.e., electricity cost) and maintenance cost. For this analysis, the maintenance cost was considered negligible based on the information attained from FDOT. For the existing signs which have mercury vapor luminaires in use, the costs of replacing the luminaires with induction or LED luminaires include costs of luminaires, cost of maintenance of traffic (MOT), equipment cost, retrofitting labor, and operating cost (i.e., electricity cost).

For an 18 ft×12 ft sign, two luminaires are typically used. The unit costs and service life spans of different types of luminaires are summarized in Table 4.4. Considering sign lights are turned off during daytime, the lamp life span in hours is converted to the year base using 11 working hours per day. The MOT cost is about $700 per sign. The equipment cost and installation labor are about $900 for installing two luminaires for signs without sign lighting in use.. For signs having mercury vapor luminaires in use, the equipment cost and retrofitting labor to replace with induction or LED luminaires are about $200. Thus, the annual installation costs and annual retrofitting cost of two luminaires per sign are averaged by the lamp life span, shown in Table 4.4 and Table 4.5, respectively.

The annual electricity cost of two luminaires for each sign is calculated based on the power of each type of luminaire. The unit cost of power is about $ 0.143 per kilowatt (kw) and sign lights are on for 11 hours per day. For instance, for induction or LED luminaires with a wattage of 100 watt, the annual electricity for lighting an overhead sign is $2 \times 100/1000$ (kw) × 11 hours/day × 365 days/year × $ 0.143 /kw = $115 /year. The annual electricity costs for each luminaire type are summarized in Table` 4.4. Accordingly, the annual life-cycle cost of newly installed sign lights for each sign is the sum of the annual installation cost and annual electricity cost, as shown in Table 4.4. Meanwhile, the annual life-cycle cost of retrofitted sign lights for each sign is the sum of the annual retrofitting cost and annual electricity cost, as shown in Table 4.5.

Table 4.4 Life-cycle Cost of Newly Installed Sign Lights per Guide Sign

<table>
<tr><th>Luminaire type</th><th>Material cost ($)</th><th>Equipment cost & installation labor ($)</th><th>MOT cost ($)</th><th>Lamp life span (hr)</th><th>Lamp life span (year)</th><th>Power (watts)</th><th>Annual installation cost ($/year)</th><th>Annual electricity cost ($/year)</th><th>Annual cost ($/year)</th></tr>
<tr><td>Mercury Vapor*</td><td>300</td><td rowspan="2">900</td><td rowspan="2">700</td><td>24000</td><td>6.0</td><td>212</td><td>93</td><td>243</td><td>611</td></tr>
<tr><td>Induction or LED</td><td>700</td><td>75000</td><td>18.7</td><td>100</td><td>161</td><td>115</td><td>275</td></tr>
</table>

* Shown only for comparison

Table 4.5 Life-cycle Cost to Retrofitted Existing Mercury Vapor Sign Lights per Guide Sign

Luminaire type	Material cost ($)	Equipment cost & installation labor ($)	MOT cost ($)	Lamp life span (hr)	Lamp life span (year)	Power (watts)	Annual retrofitting cost ($/year)	Annual electricity cost ($/year)	Annual cost ($/year)
Induction or LED	700	200	700	75000	18.7	100	123	115	238

Comparison of Life-cycle Costs

Based on the analysis in Task 3, for straight and flat roadways, ASTM Type VIII and XI sheeting were found to be sufficient for up to 20 years in terms of the required legibility luminance in both rural and urban areas, but ASTM Type III and IV sheeting need to be supplemented with sign lighting in order to be used as long as 20 years in urban areas. Therefore, in order to meet sign luminance requirements for 20 years, there are various combinations of sheeting and lighting. Assuming the current FDOT practice is using ASTM Type III sheeting for legends, we compared the annual costs of current practice with other possible sheeting/lighting options, as shown in Table 4.6.

Table 4.6 Life-Cycle Cost of Different Combinations of Legend Sheeting and Lighting on Straight and Flat Roadways

<table>
<tr><th rowspan="2">Current usage</th><th rowspan="2">Treatment</th><th colspan="2">Annual Cost($/year)</th></tr>
<tr><th>Urban area</th><th>Rural area</th></tr>
<tr><td rowspan="5">ASTM Type III with no sign lighting</td><td>Install Induction or LED</td><td colspan="2">275</td></tr>
<tr><td>Replace ASTM Type III with IV legends & install Induction or LED</td><td colspan="2">616</td></tr>
<tr><td>Replace ASTM Type III with IV legends</td><td>1703</td><td>341</td></tr>
<tr><td>Replace ASTM Type III with VIII legends</td><td colspan="2">345</td></tr>
<tr><td>Replace ASTM Type III with XI legends</td><td colspan="2">347</td></tr>
<tr><td rowspan="4">ASTM Type III with mercury vapor sign lighting</td><td>Replace Mercury vapor with Induction or LED</td><td colspan="2">238</td></tr>
<tr><td>Replace ASTM Type III with IV legends & no light</td><td>1703</td><td>341</td></tr>
<tr><td>Replace ASTM Type III with VIII legends & no light</td><td colspan="2">345</td></tr>
<tr><td>Replace ASTM Type III with XI legends & no light</td><td colspan="2">347</td></tr>
</table>

Note: the treatments assume an appropriate background material is used to provide adequate contrast

As shown in Table 4.6, the annual costs of sheeting and lighting combination are different in urban and rural areas. In rural areas, all the four sheeting materials (ASTM Type III, IV, VIII and XI) meet the legibility luminance requirements without sign lighting. However, there are horizontal curve radii where the selection of sign sheeting materials and the need for sign lighting become more limiting (see Tables 3.6 and 3.7).

Summary

In this task, a life-cycle cost analysis was completed to calculate the cost of replacing the current sign sheeting with more efficient retroreflective sheeting and the cost of installing/upgrading sign lighting. In addition, based on the required legibility luminance, different combinations of sign lighting and sheeting material were considered for overhead guide signs on straight and flat roadways and in horizontal curves in both rural and urban areas.

The life-cycle costs were based on an overhead guide sign with the size of 18 ft ×12 ft. In the conditions studied herein, the most cost effective approach to provide adequate overhead sign luminance with the current infrastructure is to either replace existing lighting with, or install, induction or LED luminaires. Alternatively, another approach is to use either Type VIII or Type XI legend sheeting materials and forgo sign lighting. For Type XI sheeting materials, sign lighting would be needed along horizontal curves in rural areas with radii of 880 ft and horizontal curves in urban areas with radii of 2500 ft or less.

In addition, the results of the study do not include dew effects on sign sheeting. Currently there is no known retroreflective sheeting material available today that can overcome the effect of dew. Where dew is a frequent concern, lighting may be needed.

It needs to be mentioned that the study results are based on some assumptions which are listed below.

- A 20 year period was used for analysis. However, using a different period for the analysis could change the results.
- Legibility luminance requirements were based on the 50th percentile levels of drivers' luminance demands.
- Recommendations were based on an analysis of legibility for the luminance of the legend, assuming an appropriate contrast ratio supplied by retroreflective background materials. However, the analysis was not dependent on the specific types of retroreflective material used on the background.
- The sign and the vehicle were assumed to be in the same lane.
- Maintenance costs associated with sheeting and sign lighting were not included in the life-cycle cost analysis.
- The current FDOT practice was assumed to use ASTM Type III legend sheeting without sign lighting or ASTM Type III legend sheeting with mercury vapor sign lighting (former practice and many still in place).
- In the cost study, sign size was assumed to be 18 ft×12 ft, and two luminaires per sign were assumed.

FINDINGS & CONCLUSIONS

Effective highway signage is an important component of driver decision making, comfort, and safety. Like many agencies across the country, overhead sign lighting has been used by the Florida Department of Transportation (FDOT) to improve visibility. However, the availability of newer and more efficient retroreflective sign sheeting materials has created a new challenge for state transportation agencies going through sign upgrade programs and reconsidering the need for sign lighting. There is a general consensus that sign lighting is not needed for overhead guide signs with high intensity reflective sheeting in rural areas; but in developed areas or along highways with unique geometrics, there is concern about removing or turning off overhead guide sign lights. Another issue of concern is in areas of frequent dew, fog, or frost. FDOT initiated this study to investigate whether high intensity reflective sheeting can be used to replace overhead sign lighting, i.e., whether it can perform and meet retroreflectivity standards; whether it can satisfy elderly drivers' visibility demands at night; and whether it is cost-effective.

Field data were collected in Florida and used to assess the conditions of Florida signs in terms of the MUTCD minimum maintained retroreflectivity levels. All measured signs made with prismatic sheeting materials were found to be well above the minimum MUTCD retroreflectivity levels. However, some guide signs with beaded materials were in need of care in order to be considered in compliance with the new MUTCD regulations.

A luminance computation model was also developed to calculate sign legend luminance under various situations, including different headlamps, different sign lighting technologies, different geometrics and sign locations, and different amounts of sign dirt and sign aging. By comparing the calculated luminance of a specific sign at a specific situation with the legibility luminance levels required by older drivers, it is possible to identify if high intensity sign sheeting can replace the need for sign lighting; and if not, then determine where overhead signs with lights should be required in lieu of high intensity reflective sheeting in Florida.

Finally, a life-cycle cost spreadsheet was developed and used to calculate the cost of replacing the current sign sheeting in Florida with high reflective sheeting and the cost of installing/upgrading sign lighting. Based on this analysis, we found that under the conditions considered (either on straight and flat roadways or horizontal curves, in rural areas or urban areas), the most cost effective approach to maintain overhead guide luminance is to use (installing or replacing with) induction or LED luminaires. The results also indicate that a viable alternative (in terms of maintaining luminance and being cost effective) would be to use either Type VIII or Type XI legend sheeting materials and forgo sign lighting. For Type XI sheeting materials, sign lighting would be needed along horizontal curves in rural areas with radii of 880 ft and horizontal curves in urban areas with radii of 2500 ft or less.

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APPENDIX: SIGN RETROREFLECTIVITY MEASUREMENTS

Sign Retroreflectivity Measurements Collected on I-95

Sign No.	Direction	Mile Post	Date of Fabrication(month/year)	Date of Installation (month/year)	Mean Retroreflectivity			
					As-Is Condition		Cleaned Surface	
					Green	White	Green	White
1	South	328	10/03	/03	22	128	47	249
2	South	322.4	6/03	6/03	34	221	35	238
3	South	316.3	6/03	7/03	33	191	41	259
4	South	296.5	2/06	10/06	47	261	48	263
5	South	275	/02	8/02	37	201	43	242
6	South	256	/98	6/99	40	217	48	268
7	South	250		7/06	44	278	44	277
8	North	256.7		4/99	51	267	54	278
9	North	263.7		4/18/96	49	283	54	297
10	North	272	5/07	2/08	41	259	43	268
11	North	298.5	4/07		55	605	56	620
12	North	304.5	9/03		38	259	39	261
13	North	317	6/03	3/04	43	233	44	238
14	North	319	6/03	7/03	27	186	45	242
15	North	327	8/03	/03	23	131	43	252

Sign Retroreflectivity Measurements Collected on I-10

Sign No.	Direction	Mile Post	Date of Fabrication(month/year)	Date of Installation (month/year)	Mean Retroreflectivity			
					As-Is Condition		Cleaned Surface	
					Green	White	Green	White
1	West	350.5		6/10	106	634	114	819
2	West	350.25	9/98	10/12/98	45	256	47	271
3	West	149	11/08		95	777	105	824
4	West	343	5/08		87	491	127	508
5	West	342.5	1/99	/99	48	260	52	266
6	West	337.25	7/05		39	266	38	267
7	West	336	12/95		27	286	25	292
8	West	335.75	12/95		29	313	28	320
9	West	335	/95		43	288	42	278
10	West	333	3/96		53	274	51	279
11	West	333	3/96		53	285	50	281
12	East	334	3/96		52	295	55	305
13	East	335	4/07		38	241	41	250
14	East	336			28	308	31	314
15	East	337	12/95		27	280	29	289
16	East	340.5	1/99	/99	44	250	51	279
17	East	342	1/99	/99	40	169	51	273
18	East	343	1/99	/99	47	271	49	275
19	East	344.25	7/08		49	478	51	524
20	East	347	11/08		110	814	119	865
21	East	349	11/08	7/09	98	950	108	949
22	East	350	6/10	6/10	92	532	114	583

Sign Retroreflectivity Measurements Collected on I-75

Sign No.	Direction	Mile Post	Date of Fabrication(month/year)	Date of Installation (month/year)	Mean Retroreflectivity			
					As-Is Condition		Cleaned Surface	
					Green	White	Green	White
1	North	194.5	4/12	5/12	130	885.5	132.3	915.5
2	North	195	4/12	6/12	119.8	826.8	122.3	852.5
3	North	196.75	4/12	5/12	116.3	826.5	121.3	835.5
4	North	201.5	1/09	4/29/09	91.3	891	103.5	963.3
5	North	202	8/09		101	648.5	99.5	649.8
6	North	202.25	1/09	4/29/09	105.5	875	107.5	933.5
7	North	202.75		12/10	58.3	869	64	861.8
8	North	204.5	6/09	10/09	80.3	528.5	83.8	545.8
9	North	205	8/09		83.5	597.5	89.8	617.5
10	North	209.5	6/09	1/09	100.3	877.5	97.3	862.5
11	North	210	1/09	6/09	80.8	884.5	90.3	904.8
12	North	213	6/09	6/09	101	865.8	100	845.5
13	North	216.25	2/10	3/10	112.3	655	119.8	689
14	North	220	11/01	/01	42.5	274.8	44.5	279.8
15	North	241	6/99	12/99	43.3	252.5	46.3	255.5