Report No. K-TRAN: KSU-11-6 ▪ FINAL REPORT ▪ January 2015

Overhead Guide Sign Retroreflectivity and Illumination

Mohammed Obeidat
Malgorzata Rys, Ph.D.
Eugene R. Russell, Sr., Ph.D., P.E.

Kansas State University Transportation Center

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Kansas
Department of Transportation

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<tr><td>1 Report No.
K-TRAN: KSU-11-6</td><td>2 Government Accession No.</td><td>3 Recipient Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4 Title and Subtitle
Overhead Guide Sign Retroreflectivity and Illumination</td><td>5 Report Date
January 2015</td></tr>
<tr><td>6 Performing Organization Code</td></tr>
<tr><td colspan="2">7 Author(s)
Mohammed Obeidat, Malgorzata Rys, Ph.D., Eugene R. Russell, Sr., Ph.D., P.E.</td><td>7 Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9 Performing Organization Name and Address
Kansas State University Transportation Center
Department of Industrial and Manufacturing Systems Engineering
2118 Fiedler Hall
Manhattan, Kansas 66506</td><td>10 Work Unit No. (TRAIS)</td></tr>
<tr><td>11 Contract or Grant No.
C1889</td></tr>
<tr><td colspan="2" rowspan="2">12 Sponsoring Agency Name and Address
Kansas Department of Transportation
Bureau of Research
2300 SW Van Buren
Topeka, Kansas 66611-1195</td><td>13 Type of Report and Period Covered
Final Report
November 2010–December 2013</td></tr>
<tr><td>14 Sponsoring Agency Code
RE-0549-01</td></tr>
<tr><td colspan="3">15 Supplementary Notes
For more information write to address in block 9.</td></tr>
</table>

Roadway guide sign visibility during darkness is fundamental to driver safety, especially elderly drivers. Guide sign visibility can be improved by external sign illumination or the use of retroreflective sheeting on signs. Because energy conservation is essential in the midst of a worldwide energy crisis, various Departments of Transportation have investigated usage of energy-efficient lighting technology with overhead guide signs.

This report presents results of a survey related to overhead sign lighting usability by states, a laboratory experiment to compare the light distribution of five light sources used to illuminate overhead guide sign by several states, a cost analysis for the tested light sources, a field experiment to compare the visibility of three retroreflective sheeting used by states, a cost analysis for the tested retroreflective guide signs, and an analysis by determining the most cost-effective method of increasing overhead guide sign visibility to drivers during nighttime.

A laboratory experiment was conducted to compare the light distribution of three conventional light sources: Metal Halide, Mercury Vapor, and High Pressure Sodium, and two new generation light sources: Induction lighting, and Light Emitting Diode. Combining two decision criteria, the light distribution and the cost, resulted in finding the Induction lighting to be the recommended light source for those states that want to continue illuminating their overhead guide signs. A field experiment was conducted to compare three types of sign sheeting, Engineering Grade (type I), Diamond Grade (type XI), and High Intensity (type IV), in order to determine the sign sheeting material that best improves sign visibility. Combining the decision criteria to compare these three retroreflective sheeting, the visibility and the cost, High Intensity (type IV) is the recommended sign to be used by DOTs, followed by Diamond Grade (type XI).

In comparing the best options used to increase sign's visibility, sign illumination and sign retroreflectivity, it is found that using retroreflective sheeting is more cost effective than sign illuminating.

<table>
<tr><td colspan="2">17 Key Words
Guide Signs, Sign Visibility, Sign Illumination, Retroreflectivity, Energy-Efficient Lighting</td><td colspan="2">18 Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.</td></tr>
<tr><td>19 Security Classification (of this report)
Unclassified</td><td>20 Security Classification (of this page)
Unclassified</td><td>21 No. of pages
144</td><td>22 Price</td></tr>
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Final Report

Prepared by

Mohammed Obeidat
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Eugene R. Russell, Sr., Ph.D., P.E.

Kansas State University Transportation Center

A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

KANSAS STATE UNIVERSITY TRANSPORTATION CENTER
MANHATTAN, KANSAS

January 2015

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Drivers of all ages are faced with the challenges of nighttime driving. Compared to daylight driving, nighttime driving is more demanding because of visibility issues, such as a driver's visual acuity, contrast sensitivity, distance judgment, and color discrimination (Lagergren, 1987). Overhead highway signs are very important for enhancing driver guidance. The objective of these signs is to provide roadway drivers with information regarding destinations and other driving maneuvers required to safely reach specific destinations.

Roadway guide sign visibility during darkness is fundamental to driver safety, especially elderly drivers. Guide sign visibility can be improved by external sign illumination or the use of retroreflective sheeting on signs. Because energy conservation is essential in the midst of a worldwide energy crisis, various Departments of Transportation have investigated usage of energy-efficient lighting technology with overhead guide signs.

In 2012, a lighting survey for overhead guide signs was sent to each of the 50 Departments of Transportation in the United States. Results showed that 57% of states currently illuminate overhead guide signs, while 43% do not. For those states that illuminate signs, light sources are divided between conventional light sources and new generation light sources.

A laboratory experiment was conducted to compare the light distribution of three conventional light sources: metal halide, mercury vapor, and high-pressure sodium, and two new generation light sources: induction lighting, and light-emitting diode. The high-pressure sodium light distribution was found to be the best distribution among the conventional light sources, and the best light distribution among the new generation group was the induction lighting. A cost analysis for the five light sources was conducted and resulted in having the induction lighting as the most cost effective followed by the light-emitting diode. Combining the two decision criteria, the light distribution and the cost, resulted in finding the induction lighting to be the recommended light source for those states that want to continue illuminating their overhead guide signs.

A field experiment was conducted to compare three types of sign sheeting, Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV), in order to determine

the sign sheeting material that best improves sign visibility. The low beam of vehicle's headlights was divided into 16 brightness levels and, at each level, illuminance was measured on a sign. Statistical analysis was performed to analyze the illuminance level as a dependent factor, including independent factors such as car distance from the sign and sign retroreflective sheeting type, and human participants' age. Based on the experimental analysis, Diamond Grade (Type XI) retroreflective sheeting is the most visible sign for drivers, followed by High Intensity (Type IV). A life cycle cost analysis was applied for the three retroreflective sheeting types, and the results show that High Intensity (Type IV) is the most cost-effective sheeting, followed by Engineering Grade (Type I), and Diamond Grade (Type XI). Combining the decision criteria to compare these three retroreflective sheeting, the visibility and the cost, High Intensity (Type IV) is the recommended sign to be used by DOTs, followed by Diamond Grade (Type XI).

In comparing the best options used to increase sign visibility, sign illumination and sign retroreflectivity, it is found that using retroreflective sheeting is more cost effective than sign illuminating.

This report presents results of a survey related to overhead sign lighting usability by states, a laboratory experiment to compare the light distribution of five light sources used to illuminate overhead guide sign by several states, a cost analysis for the tested light sources, a field experiment to compare the visibility of three retroreflective sheeting used by states, a cost analysis for the tested retroreflective guide signs, and an analysis by determining the most cost-effective method of increasing overhead guide sign visibility to drivers during nighttime.

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1.1 Introduction

One primary mission of the Federal Highway Administration (FHWA) is to improve roadway safety in the United States (US). According to the National Highway Traffic Safety Administration's (NHTSA) 2011 Fatality Analysis Reporting System (FARS), 32,367 people were killed in motor vehicle traffic crashes in the US in 2011, while this number was 32,999 in 2010 (NHTSA, 2012). Statistics show that 25% of all motor vehicle travel occurs at night, but approximately 50% of all traffic fatalities occur during nighttime hours (FHWA, 2008). As a result, FHWA has adopted new traffic sign retroreflectivity requirements to increase road sign visibility.

Drivers of all ages often experience more difficulty driving at night as compared to daytime driving. Different issues related to the driver that may control visibility of the road include driver's visual acuity, contrast sensitivity, distance judgment, and color discrimination (Lagergren, 1987). Guide signs are typically green signs located along a highway to notify drivers of destinations and exit information. Overhead highway signs are important for improving driver guidance. The objective of these signs is to provide drivers with information regarding destinations and necessary instructions for reaching specific destinations. In fact, "overhead highway signs must be highly visible and legible so that drivers can detect, read and interpret the information contained on the signs in time to respond appropriately" (Bullough, Skinner, & O'Rourke, 2008).

Many Departments of Transportation (DOTs) are considering whether to add light sources to current highway overhead guide signs or replace these signs with modern retroreflective sheeting to improve nighttime visibility for drivers, especially older drivers. This could possibly reduce potential accidents due to driver confusion and improper maneuvers. As a requirement in the Manual on Uniform Traffic Control Devices (MUTCD), overhead guide signs must either be illuminated or retroreflective (FHWA, 2009). The objective of the new minimum retroreflectivity requirement is to improve safety on US roadways, especially highways, and to ensure that roadway users, especially the elderly, are able to detect and react to traffic signs in order to facilitate safe, uniform, and efficient travel (Ré & Carlson, 2012).

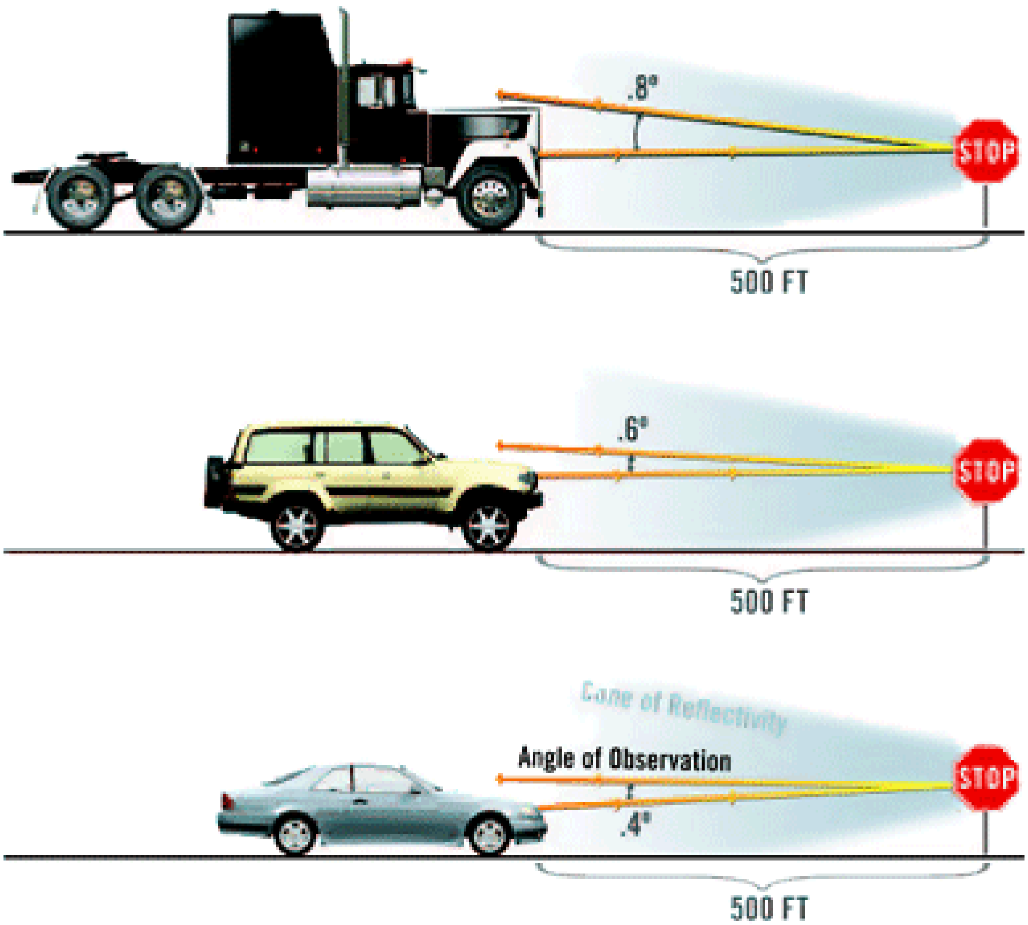
Guide signs can be illuminated from the back (back-illuminated), by using external light sources that illuminate signs on its face (front). Another way of illuminating guide signs is by using luminous sources or elements such as light-emitting diodes (LED) to produce required characters of the signs. High intensity retroreflective sheeting materials can also be used to enhance highway overhead guide sign visibility for drivers. Retroreflective signs either include individual “button” elements, which produce characters on a sign, or retroreflective sheeting material that provides retroreflection capability over the entire surface of the sign (Bullough, et al., 2008).

Signs manufactured from retroreflective sheeting materials are commonly used on US highways. One important advantage of using retroreflective sheeting materials is that they do not require electrical power because they rely on efficient passive retroreflection of oncoming vehicle headlamps (illuminance) which are reflected back toward the vehicle (luminance). Based on Bullough et al. (2008), the observation angle between light rays from the driver’s vehicle headlights and sight line to a roadway sign is relatively small, especially for far-viewing distances.

1.2 The Observation Angle

The observation angle can be defined as the angle between a retroreflected beam toward an observer’s eye and the line formed by the light beam striking a surface, as shown in Figure 1.1. The observation angle will be larger for the driver of a truck or bus than for a driver of a standard passenger vehicle. If a driver in a vehicle is closer to a retroreflective sign or device, the observation angle will be larger (ORAFOL, 2012).

Understanding observation angles is helpful when installing signs with retroreflective materials so that light is accurately reflected from headlamps back toward a driver’s eyes, thus enhancing visibility and sign luminance. An inverse relationship exists between the observation angle and the luminance amount of retroreflective material. In other words, as the angle increases, the luminance of the retroreflective sign decreases. The entrance angle is the angle between a headlamp ray to the sign and a line perpendicular to the sign face, as shown in Figure 1.2. Large differences in the entrance angle are a function of sign location and orientation.

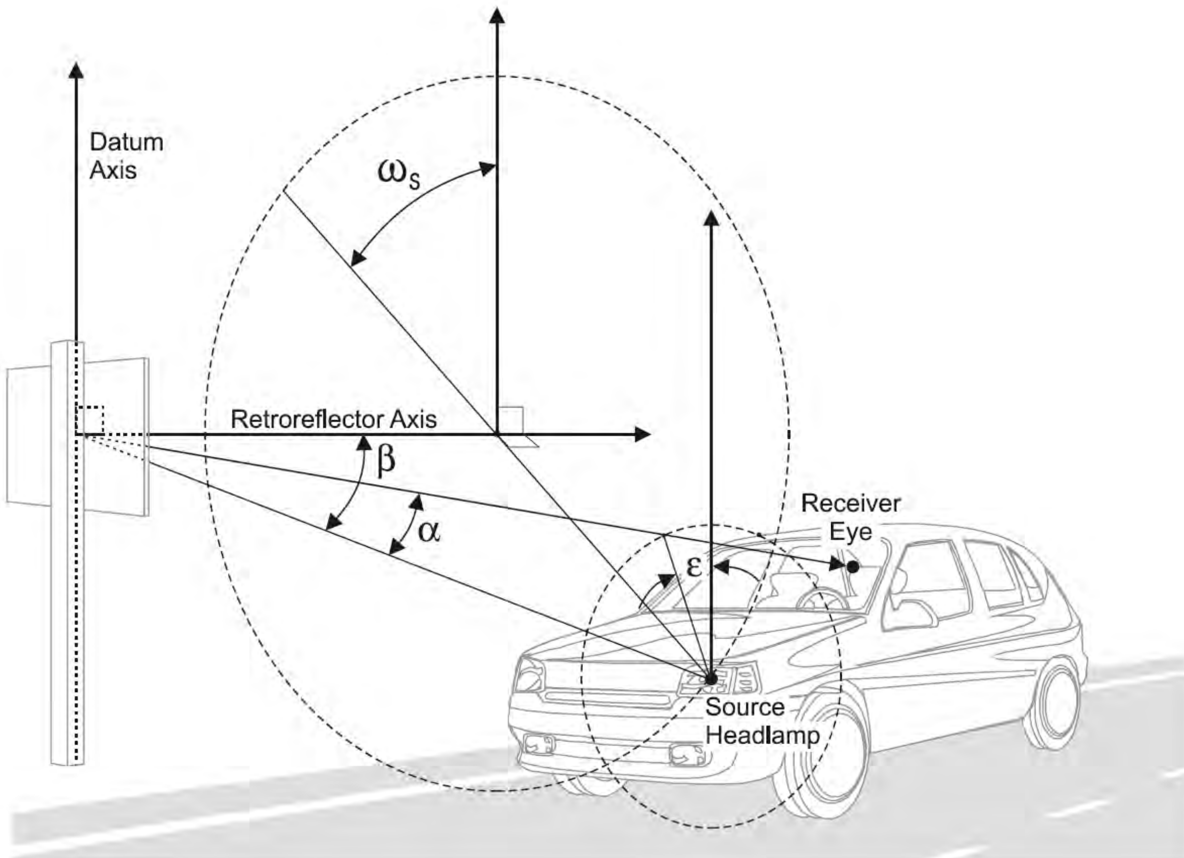


Source: MyParkingSign.com, 2012

Figure 1.1: Observation Angle and Variation with Vehicle Size

1.3 Retroreflective Traffic Sign Sheeting Materials

The American Society for Testing and Materials (ASTM) details components of sheeting materials that can be used in constructing retroreflective guide signs. ASTM D4956 describes types of retroreflective sheeting materials that can be used on traffic signs. "Retroreflective sheeting shall consist of white or colored sheeting having a smooth outer surface and that essentially has the property of a retro-reflector over its entire surface" (ASTM, 2011).



Source: Brich, 2002

Figure 1.2: Interrelationship of Application System Angles, Where: Observation Angle is (α), Entrance Angle is (β), Rotation Angle is (ε), and Orientation Angle is (ω_s)

The 2009 MUTCD minimum retroreflectivity requirements refer to sheeting types as defined in ASTM D4956 (2011). A common problem associated with retroreflective sheeting, however, is that even though a particular type of sheeting may initially meet minimum retroreflectivity levels, it may quickly degrade below minimum retroreflectivity levels because of weather or other environmental causes. The MUTCD has no instructions about the longevity of sheeting materials used for overhead guide signs. Agencies may overcome this problem by using higher performance sheeting which may have a higher initial cost but remain above the minimum retroreflective requirement longer and provide a more efficient life-cycle cost.

1.4 Guide Signs

"Guide signs are essential elements to direct road users along streets and highways, to inform them of intersecting routes, to direct them to cities, towns, villages, or other important destinations, to identify nearby rivers and streams, parks, forests, and historical sites, and generally to give such information as will help them along their way in the most simple, direct manner possible" (FHWA, 2009).

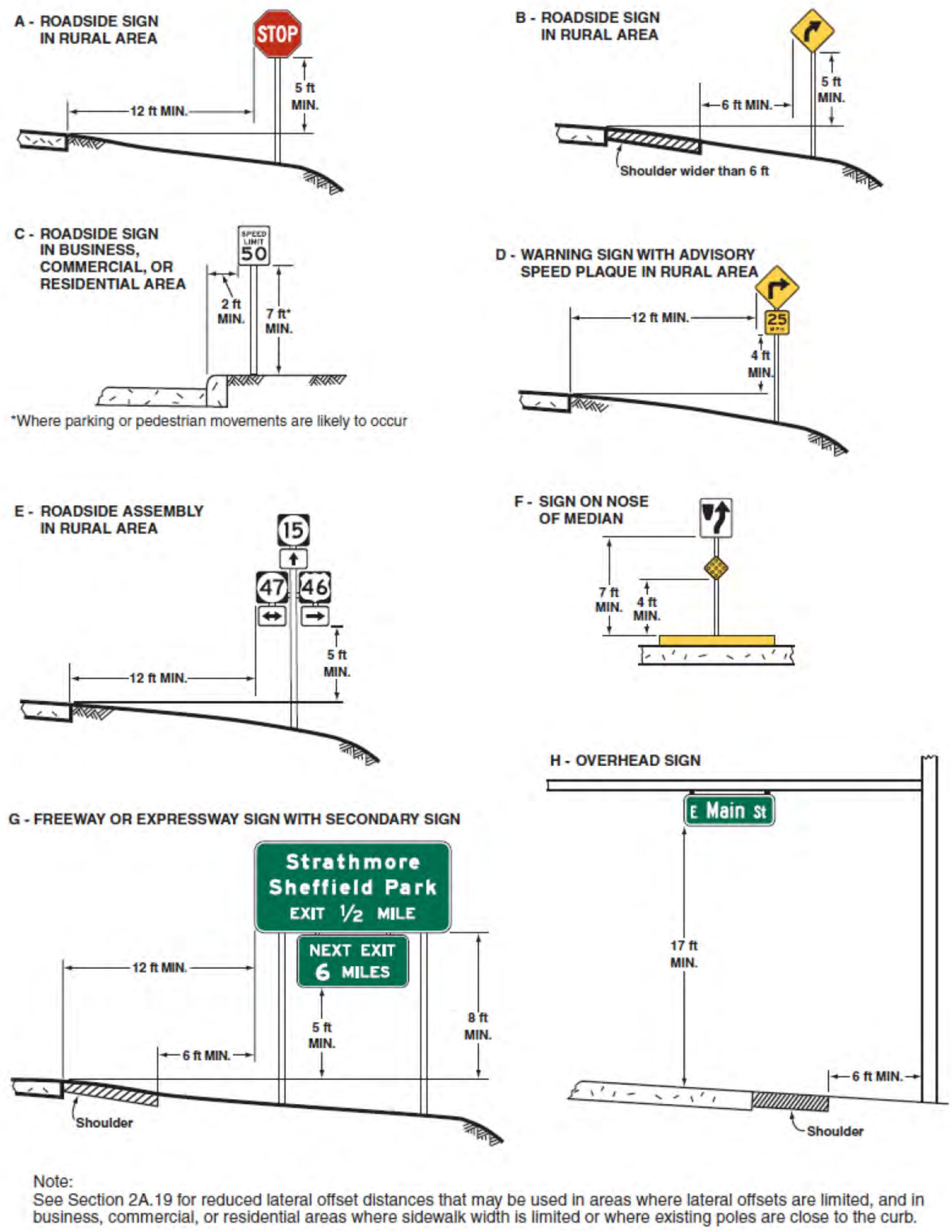
1.5 MUTCD 2009 Standards Regarding Guide Signs

Guide signs must be visible and clear for intended drivers in order to allow for proper driving response time. Desirable attributes for guide signs include high visibility during day and night and high legibility. Legibility is defined as adequately-sized letters, symbols, or arrows, and a short legend for quick comprehension by a road user approaching a sign (Gowda, 2010). Many standard requirements are set in the MUTCD regarding guide signs, including the following essential sections: section 2A.07, section 2A.08, section 2A.10, section 2D.01- 2D.55, and section 2E.01- 2E.54 (FHWA, 2009).

1.5.1 Standardization of Guide Sign Location

According to the MUTCD, signs should be located on the right-hand side of the roadway where they are easily recognized and understood by road users. Signs in other locations should be considered only as supplementary to signs in normal locations, except as otherwise detailed in the MUTCD. Signs should also be individually installed on separate posts or mountings except where one sign supplements another, or route or directional signs are grouped to clarify information to motorists. Examples of heights and lateral locations of signs for typical installations are shown in Figure 1.3.

One standard in the MUTCD is: "signs requiring separate decisions by the road user shall be spaced sufficiently far apart for the appropriate decisions to be made. One of the factors considered when determining the appropriate spacing shall be the posted or 85^{th} percentile speed" (FHWA, 2009).



Source: FHWA, 2009

Figure 1.3: Examples of Heights and Lateral Locations of Signs for Typical Installations

1.5.2 Lettering Style and Size on Conventional Road Guide Signs

According to the MUTCD, design of uppercase letters, lowercase letters, numerals, route shields, and spacing should meet the criteria provided in the "Standard Highway Signs and Markings" book. Names of places, streets, and highway lettering on conventional road guide signs should be a combination of lowercase letters with initial uppercase letters. The nominal loop height of lowercase letters should be ¾ the height of the initial uppercase letter. This proportion must be used to determine the height of lowercase letters when a mixed case legend letter height is specified, referring only to the initial uppercase letter. When the height of a lowercase letter is referenced, the reference is made to the nominal loop height and height of the initial uppercase letter should be determined by this proportion. All other word legends should be in uppercase letters on conventional road guide signs. For each of the Standard Alphabet series, unique letter forms should not be stretched, compressed, warped, or otherwise manipulated (FHWA, 2009).

Sign legibility is a function of letter size and spacing (FHWA, 2009). Legibility distance must be sufficient to give drivers or road users enough time to read and comprehend information provided by a sign. Under optimal conditions, a guide sign should be read and understood in a brief glance. Many factors affect legibility distance, such as inattention, blocked view by other vehicles, inclement weather, driver's inferior eyesight, and various other causes that may delay or slow reading (Gowda, 2010). Repetition of guide information on successive signs gives road users more than one opportunity to obtain the information needed (FHWA, 2009).

1.5.3 Lettering Style and Size on Freeway and Expressway Guide Sign Standards

For all freeway and expressway signs that do not have a standardized design, message dimensions should be determined first and then followed by determining the outside dimensions. Word messages in the legend of expressway guide signs must be at least 8 inches high. Guide signs at or in advance of interchanges should contain larger lettering. All names of places, streets, and highways on freeway and expressway guide signs should be composed of lowercase letters with initial uppercase letters. The nominal loop height of the lowercase letters should be ¾ of the height of the initial uppercase letter (FHWA, 2009). Lettering size on freeway and expressway signs should be identical for both rural and urban conditions.

Figure 1.4 shows minimum letter and numeral sizes for guide signs according to MUTCD 2009 guidelines, while Figure 1.5 shows freeway or expressway guide signs and plaque sizes according to MUTCD 2009 guidelines.

1.6 Clearview Font

The Clearview font is a relatively new font developed to increase traffic sign legibility and improve the ease with which traffic legends can be recognized. Clearview font is referred by ClearviewHwy^{TM} font and was developed by Donald Meeker and Christopher O'Hara of Meeker and Associates, Inc., a graphic design firm, after a decade of research beginning in the early 1990s (Terminal Design, 2004d).

Clearview font developers claim that this font reduces irradiation or halation. Irradiation or halation is "a phenomenon where in the stroke is so bright that it bleeds into the character's open spaces, creating a blobbing effect that reduces character legibility" (Gowda, 2010). Irradiation phenomenon observed in different font styles can be shown in Figure 1.6. The open spaces of Clearview font allow irradiation without decreasing the distance at which alphabets are legible (Gowda, 2010).

Type of Sign	Minimum Size
A. Pull-Through Signs	
Destinations — Upper-Case Letters	13.33
Destinations — Lower-Case Letters	10
Route Signs	
1- or 2-Digit Shields	36 x 36
3-Digit Shields	45 x 36
Cardinal Directions — First Letters	12
Cardinal Directions — Rest of Word	10
B. Supplemental Guide Signs	
Exit Number — Words	8
Exit Number — Numerals and Letters	12
Place Names — Upper-Case Letters	10.67
Place Names — Lower-Case Letters	8
Action Messages	8
Route Signs	
Numerals	12
1- or 2-Digit Shield	24 x 24
3-Digit Shield	30 x 24
C. Interchange Sequence or Community Interchanges Identification Signs	
Words — Upper-Case Letters	10.67
Words — Lower-Case Letters	8
Numerals	10.67
Fraction Numerals	8
Route Signs	
Numerals	12
1- or 2-Digit Shield	24 x 24
3-Digit Shield	30 x 24
D. Next XX Exits Sign	
Place Names — Upper-Case Letters	10.67
Place Names — Lower-Case Letters	8
NEXT XX EXITS — Words	8
NEXT XX EXITS — Number	12

Type of Sign	Minimum Size
E. Distance Signs	
Words — Upper-Case Letters	8
Words — Lower-Case Letters	6
Numerals	8
Route Signs	
Numerals	9
1- or 2-Digit Shield	18 x 18
3-Digit Shield	22.5 x 18
F. General Services Signs (see Chapter 2I)	
Exit Number — Words	8
Exit Number — Numerals and Letters	12
Services	8
G. Rest Area, Scenic Area, and Roadside Area Signs (see Chapter 2I)	
Words	10
Distance Numerals	12
Distance Fraction Numerals	8
Distance Words	8
Action Message Words	10
H. Reference Location Signs (see Chapter 2H)	
Words	4
Numerals	10
I. Boundary and Orientation Signs (see Chapter 2H)	
Words — Upper-Case Letters	8
Words — Lower-Case Letters	6
J. Next Exit and Next Services Signs	
Words and Numerals	8
K. Exit Only Signs	
Words	12
L. Overhead Arrow-Per-Lane and Diagrammatic Signs	
See Table 2E-5	

Note: Sizes are shown in inches and where applicable are shown as width x height

Source: FHWA, 2009

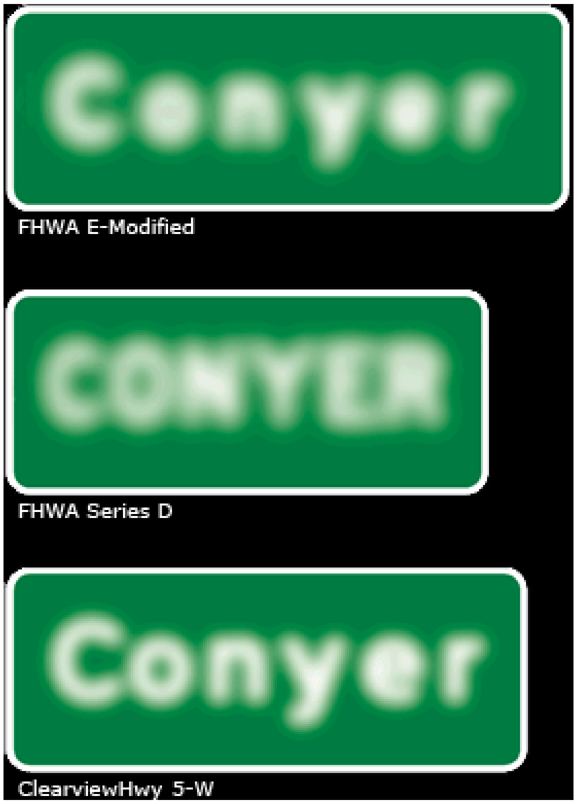
Figure 1.4: Minimum Letter and Numeral Sizes for Expressway Guide Signs According to Sign Type

Type of Sign	Type of Interchange (see Section 2E.32)				Overhead
	Major		Intermediate	Minor	
	Category a	Category b			
A. Advance Guide, Exit Direction, and Overhead Guide Signs					
Exit Number Plaques					
Words	10	10	10	10	10
Numerals & Letters	15	15	15	15	15
Interstate Route Signs					
Numerals	24/18	—	—	—	18
1- or 2-Digit Shields	48 x 48/ 36 x 36	—	—	—	36 x 36
3-Digit Shields	60 x 48/ 45 x 36	—	—	—	45 x 36
U.S. or State Route Signs					
Numerals	24/18	18	18	12	18
1- or 2-Digit Shields	48 x 48/ 36 x 36	36 x 36	36 x 36	24 x 24	36 x 36
3-Digit Shields	60 x 48/ 45 x 36	45 x 36	45 x 36	30 x 24	45 x 36
U.S. or State Route Text Identification (Example: US 56)					
Numerals & Letters	18	18/15	15	12	15
Cardinal Directions					
First Letters	18	15	15	10	15
Rest of Words	15	12	12	8	12
Auxiliary and Alternative Route Legends (Examples: JCT, TO, ALT, BUSINESS)					
Words	15	12	12	8	12
Names of Destinations					
Upper-Case Letters	20	20	16	13.33	16
Lower-Case Letters	15	15	12	10	12
Distance Numbers	18	18/15	15	12	15
Distance Fraction Numerals	12	12/10	10	8	10
Distance Words	12	12/10	10	8	10
Action Message Words	12	12/10	10	8	10
B. Gore Signs					
Words	12	12	12	8	—
Numeral & Letters	18	18	18	12	—

Notes: 1. Sizes are shown in inches and where applicable are shown as width x height
2. Slanted line (/) signifies separation of desirable and minimum sizes

Source: FHWA, 2009

Figure 1.5: Minimum Letter and Numeral Sizes for Freeway Guide Signs According to Interchange Classification

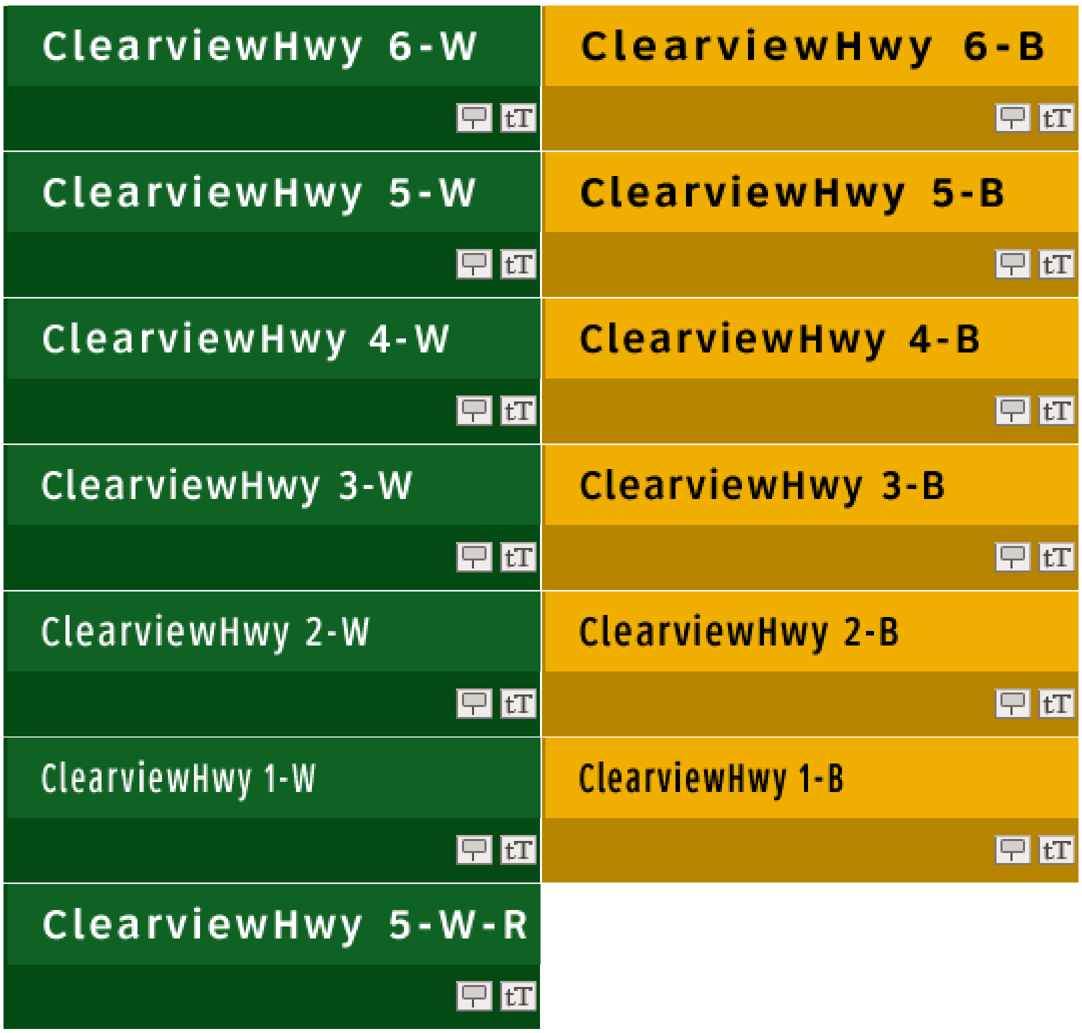


Source: Terminal Design, 2004c

Figure 1.6: Irradiation or Halation Phenomenon for Three Font Styles

1.6.1 Clearview Font Development

The ClearviewHwy font software is used to produce Clearview font. ClearviewHwy font software contains kerning data (kerning refers to data included in a font that specifies how to adjust spacing) in addition to approved letter spacing in default mode. This software is compatible with all standard computer operating systems and sign manufacturing software tools. After 10 years of research and development, ClearviewHwy evolved into a type system of six distinct weights with each weight having a version for positive and negative contrast applications (Terminal Design, 2004a). Contrast application may be positive or negative. The positive contrast application showcases lighter tone letters on a dark background, while the negative contrast version displays darker tone letters on a light background (Gowda, 2010). Clearview font is available in both positive and negative contrast. The positive contrast shows white letters on a dark green background, while the negative contrast displays black letters on a fluorescent yellow, fluorescent orange or white background. Figure 1.7 shows the Clearview distinct weights and two contrast types.



Source: Terminal Design, 2004b

Figure 1.7: The Clearview Font Distinct Weights. Right Side is Negative Contrast and Left Side is Positive Contrast

1.7 Guide Sign Enhancements

Traveling on United States roadways can be confusing and challenging for all drivers if driving routes are not easily understood or clearly marked, especially when the driver is unfamiliar with the driving location. This issue can be enormous for older drivers, especially those who have cognitive or physical disabilities (Amparano & Morena, 2006). However, various engineering opportunities such as sign placement, legibility of sign lettering, retroreflectivity, and sign size can enhance a driver's ability to detect signs and comprehend sign messages.

1.7.1 Guide Sign Placement

According to the MUTCD (FHWA, 2009), one common guide sign placement strategy is to double the use of signs by placing redundant signs on the left side of the roadway opposite the primary sign on the right side. Signs must be placed at locations that have unobstructed visibility and minimum background clutter. Based on the MUTCD, at intersection and interchange locations, preferred placement is overhead, creating optimum sign visibility. In addition, signs can be placed in a driver's direct line of sight. For example, at T-intersections, the MUTCD recommends a one-way sign be placed directly opposite the center of the approaching lane of traffic.

1.7.2 Sign Legibility

Legibility is defined as "the readability of a particular writing style, or font" (Amparano & Morena, 2006). The FHWA defines standard typefaces used for highway signs on United States roadways by the Standard Alphabets section in the MUTCD. There are seven typefaces currently used for roadway signs. Clearview font provides faster recognition at greater distances by optimizing the legibility of letters and reducing halos around text messages. Recent studies show that Clearview's alphabet legibility represents a 16% improvement in distance recognition by older drivers and a 12% increase in legibility for all drivers when compared to the existing standard (series E [modified]) for guide signs (Amparano & Morena, 2006). These results imply that the Clearview font results in faster reading, recognition, comprehension, and reaction times for drivers, especially senior drivers. States such as Arizona, Iowa, Kentucky, Maryland, Michigan, Pennsylvania, Texas, and Virginia have adopted Clearview font for use on guide signs throughout all or part of their transportation systems.

Another approach states have considered to increase legibility is to expand letter heights on guide and street name signs. The minimum requirement for letter size is set in the MUTCD in order to meet the driver's requirements, especially elderly drivers. The use of uppercase and lowercase letters also adds to enhanced legibility on guide signs. In the 2009 MUTCD, the minimum size for uppercase letters is 8 inches (200 mm) and 6 inches (or 150 mm) for lowercase letters. These sizes are used on multi-lane streets with speed limits greater than 40 mph (or 65 km/hr) (FHWA, 2009).

1.7.3 Sign Retroreflectivity

The use of retroreflective sheeting materials for signs is beneficial in making them more conspicuous, especially in high visual "noise" locations. Research performed at the University of South Dakota shows that the time required by senior drivers to detect signs in complex backgrounds can be reduced significantly by using super-high-intensity sheeting materials (Amparano & Morena, 2006). Also, detection distance for fluorescent signs is significantly greater than non-fluorescent signs for both younger and older drivers, with older drivers benefitting the most. The Kansas Department of Transportation (KDOT) currently uses High Intensity (Type IV) sheeting material for guide signs in various locations throughout the state.

Increasing sign size is essential to improving sign visibility, resulting in improved roadway safety for drivers and users. The MUTCD recommends the minimum sizes of different sign types as mentioned previously (FHWA, 2009).

1.8 Illuminating Guide Signs

1.8.1 Light Sources

A light source is a device that actually converts electrical energy to visible light in a specific manner based on source type. Because of the human eye's shift response to light levels at nighttime, light sources that produce greater short-wavelength (blue) light are relatively more effective for vision than those associated with little short-wavelength light, even if the level of measured light is the same (Bullough, 2012a). Light sources used for roadway illuminating devices can be categorized into conventional light sources which include incandescent lamps, electric discharge lamps, and new light sources generation which include LED, induction lighting, and light-emitting plasma (LEP).

It is important to distinguish between two important terms: "efficiency" and "efficacy." "Efficiency" is used when both input and output units are equal, meaning that "efficiency" is without unit. The term "efficacy" is used when both input and output have two different units; in the luminous efficacy, the input unit is in "watt" and the output is in "lumen" (U.S. DOE, 2009b).

1.8.1.1 Incandescent Lamps

According to Lopez (2003), two prominent types of incandescent lamps exist: the common incandescent and the tungsten halogen. The common incandescent has relatively low initial and operating costs but has a low efficacy (lumens per watt) and a short lifespan ranging between 1000 and 2000 hours (Taub, 2009). The tungsten halogen (quartz iodide) is not used for highway lighting (Lopez, 2003).

1.8.1.2 Electric Discharge Lamps

There are five common types of electric discharge light sources according to Lopez (2003):

- Conventional Fluorescent: it has a relatively medium initial cost, long life, and high efficacy (30-70 lm/watt). The main disadvantage of this type is that light varies with ambient temperature.
- Induction Fluorescent: some types have a high efficacy up to (75 lm/watt) with extremely long life (100,000 hours). Induction fluorescent is suitable for low mounting heights and other special applications (Lopez, 2003).
- Mercury Vapor (MV): two types of MV light sources are available on the market, clear light and phosphor-coated light. MV light sources include a phosphor-coated light source primarily used for sign lighting. The disadvantage of an MV light source is the extremely high initial cost. Some advantages of MV light include relatively long life and high efficacy (30-65 lm/watt). MV produces a smaller light than fluorescent.
- High-Pressure Sodium (HPS): light is produced by an arc in a ceramic tube containing sodium and other elements. It provides light primarily in the yellow spectrum but other elements inside the bulb provide light in blue, green, orange and red to improve color rendition. This type of light source requires a starting aid to provide a pulse to begin the arc stream. HPS light has advantages such as relatively low initial cost, long useful life, high efficacy (45-150 lm/watt), and the ability to maintain relatively high light output throughout the lifespan (lumen maintenance) (Bullough, 2012b). Eighty percent of street and highway lighting in New York are HPS (Bullough, 2012a).

- Low-Pressure Sodium (LPS): light is produced by an arc in long tubular glass envelope (bulb) containing sodium only. Light is monochromatic yellow with poor color rendering. The main disadvantage is the relatively high initial cost. Some of the advantages are moderately long life and high efficacy (145-185 lm/watt).
- Metal Halide (MH): the MH principle is similar to that of the mercury light sources, but it contains various metal halides in addition to mercury which provide excellent color rendering and result in a white light. MH light sources have been available for several decades, but primary problems associated with it in the past were low efficacy, low useful life, and poor lumen maintenance. This information regarding disadvantages of MH's light source is outdated because recent technology has resulted in increasing the efficacy of MH light sources, increasing the useful life, and improving lumen maintenance (Bullough, 2012b). New MH light sources with ceramic arc tubes and new methods of starting the source have increased efficiency, lifespan, and lumen maintenance. KDOT currently uses 250 W of MH light sources at various locations as an external source of illumination for guide signs. According to Bullough's survey in New York, the only two types of light sources used on streets and highways in New York are HPS and MH (Bullough, 2012a).

1.8.1.3 Light-Emitting Diodes

Recent technologies and advances in solid-state lighting have resulted in an LED light source that produces white light by using short wavelength LED that produces blue light in combination with phosphor, thus converting blue light into yellow and resulting in a white mixture (Bullough, 2012b). LED-based roadway lighting products offer a number of key advantages over traditional lighting technologies. In terms of luminous efficacy, product life cycle, field or lumen maintenance requirements, color, and environmental considerations, technology employed in LED lighting is vastly superior to other light source technology. Solid state LED-based products are designed to provide long life through light source design, power supply, optics, and mechanical housing. LED light sources are also free of lead and mercury and are compliant for Restriction of Hazardous Substances (RoHS) (Tri-State LED, 2012).

A study that was conducted along the main street of Woodridge, NY, found that twelve 40-watt (W) LED light sources replaced eight 150 W HPS light sources, and the residents of that village judged LED light installation as having more visual effectiveness and brighter appearance than HPS (Brons, 2009). Cook, Shackelford, and Pang (2008) concluded that LED roadway lighting can provide equivalent overall performance to HPS roadway lighting at lower energy levels. An LED or an induction light source with 65 W power can replace a 100 W HPS light source in order to achieve the same average unified light source (Bullough, 2012a).

LED light source for roadway lighting is able to meet the American Association of State Highway and Transportation Officials (AASHTO) requirements published in 2005 with approximately 7% reduction in energy. An energy savings of 30% to 50% can be achieved by replacing HPS with LED or induction lighting in residential areas, and 35% to 40% by replacing HPS with LED or induction lighting at rural intersections where peripheral visibility is essential (Bullough, 2012a).

1.8.1.4 Induction Lighting

Induction lighting in modern fluorescent lamps use radio frequencies to stimulate lamp material to produce light, unlike conventional fluorescent lamps that use electrodes at either end of the lamp tube. They use these radio frequencies or microwaves to create induced electrical fields which, in turn, excite gases to produce light. Induction lighting have the same color as conventional fluorescents and share their diffuse appearance, but they do not require the longer tabular shape of most fluorescent sources. A crucial disadvantage of induction fluorescent lamps is the large lamp size needed to provide uniform distribution of light on roadways as compared to HPS and MH (Bullough, 2012b).

Induction lights have a rapid start-up and work at peak efficiency with minimal warm-up time, much like LED technology. Disadvantages of induction lighting include high initial cost, limited directionality when compared to LEDs, and the presence of lead. Rapidly evolving LED technology has led to limited adoption of induction-based roadway lighting systems (Deco Lighting, 2010).

1.8.1.5 Light-Emitting Plasma

Plasma is a solid state, high-intensity, lighting technology that utilizes a single, very small electrode-less lamp and an electronic power driver (Thomasnet, 2011). The driver generates high radio frequency energy to create a plasma light source with 23,000 lumens of brilliant white light. This powerful output far exceeds LED fixtures that require many LEDs in a single housing. Due to the miniature lamp size, plasma light sources are much smaller in size with more efficient optical designs than any high-intensity discharge (HID), floodlight, or architectural area fixture. Advantages of LEP include powerful clean white light, energy savings of 50% or more than HID lighting, efficacy as high as 115 lm/watt at the source, 50,000 hour life, excellent color, and dimming capability (controlling light intensity) up to 20% (Thomasnet, 2011).

1.9 Guide Sign Retroreflectivity Studies

Lagergren (1987) performed a study to measure retroreflectivity of traffic signs (limited to stop and warning signs) using trained observers. In this study, a sign rating scale from 0 to 4 was used to train selected observers. This scale was explained as 0 refers to worst sign visibility and 4 to best visibility throughout the experiment. Observers were trained to rate traffic signs in a dark laboratory and on a straight, level section of road using a stationary car. Signs were located ranging from 100 to 300 ft. After observers became well-trained, the experiment was performed at night on a highway where observers rated 130 signs, including some signs with retroreflective sheeting. The retroreflectivity of those signs was measured using a retroreflectometer. Ratings were then obtained by observers for the selected signs and were compared to ratings obtained by the retroreflectometer. Results showed that a high percentage of signs were rated correctly by the observers. Recommendations of this study include:

- The participating observers should take an evaluation procedure before the start of participation in the research;
- Sign criticality should be considered while replacing signs because states use different levels of retroreflectivity for different highway classifications; and
- Agencies should develop a training program for personnel who perform sign replacement decisions.

Paniati and Mace (1993) performed a study aimed at identifying minimum nighttime visibility required for traffic signs. They created a number of measuring devices and a computer management system to implement these minimum requirements in an efficient manner. They developed a Computerized Analysis of Retroreflectorized Traffic Signals (CARTS) which considered time and distance required to identify and respond to a traffic sign, the amount of luminance required for sign detection and recognition, and retroreflectivity levels required to ensure the necessary performance level.

In a study performed by McGee and Paniati (1998), they created an implementation guide for determining minimum retroreflectivity requirements for traffic signs to assist governmental and private agencies in the establishment of a cost-effective program for the replacement of ineffective traffic signs. This research provided an explanation of retroreflectivity which includes concepts of retroreflection, luminance, the entrance angle, the observation angle, and coefficient of retroreflection (R_a). The researchers provided a description of different types of retroreflective sheeting materials and the difference among them according to the coefficient of retroreflection at different entrance and observation angles. They also quoted minimum retroreflectivity values for four groups of signs based on earlier research. In addition, the report presented the concept of Sign Management System that was defined by a coordinated program of policies and procedures, ensuring that highway agencies provide a sign system that meets drivers' needs according to budget constraints (McGee & Paniati, 1998). The researchers explained the concept of sign inventory and its purpose of assisting in targeting sign replacement, problem identification, minimizing tort liability, planning and budgeting for sign replacement, and maximizing productivity. They also suggest planning and developing an effective sign inventory process, including the involvement of key personnel, selecting a location as a reference system, selecting data elements, selecting inventory software, preparing for data collection, starting initial data collection, and maintaining inventory.

An additional study performed by Russell, M. Rys, A. Rys, and Keck (1999) determined the minimum value for overhead highway sign illumination by discovering whether vehicular headlamp luminance on the highway is sufficient to provide minimum required luminance for nighttime drivers. Researchers began the first phase of the study by conducting an experiment in the Photometric and Visibility Building at Turner-Fairbank Highway Research Center in McLean, Virginia, in which observers drove toward signs with unknown words, at a speed of 4.97 mph (8 km/hr). Observers were asked to push a button to turn off the lighted sign when the sign became legible. After each experiment, the observer reported what words were written on this sign to ensure the sign was legible to them. If they recognized the word(s) correctly, the distance travelled by the observers was recorded and their distance to the sign was determined. Russell et al. (1999) also performed two field tests in this study. They performed the experiment in straight, flat level sections on I-70 and I-435, using seven photometers "5 Minolta T-1 illuminance meters and 2 international light IL-1700 luminance meters" which were sensitive to very low values. Researchers collected illuminance values measured at the photometers which were placed at various heights above the roadway and corresponded to typical shoulder and overhead sign heights. These illuminance values were collected from a sample of approximately 2,500 vehicles approaching in the right lane and using low beam headlamps. Marker plate numbers were read and motor vehicle records provided so manufacturer and model of vehicle could be determined. Analysis of variance (ANOVA) was conducted to find differences in illuminance levels between various vehicle types. The research team initially found that illuminance values detected were higher than those forecasted because of a substantial amount of light reflected from the pavement, and this was included in the luminance readings. Thus, it was decided to obtain additional data with the reflected light removed (Russell, et al., 1999).

Russell et al. (1999) performed a second field test in which pavement reflection was eliminated from luminance readings by using optical occluders. The sample in this study was divided between 50 known vehicles along with 1,500 unknown vehicles which passed through the data collection location. Statistical analysis was performed on the sample in two parts: one for the 50 known vehicles, and the other part for the unknown 1,500 vehicles. Results of this study showed that sufficient light was available for ground mounted signs on the left and the right of highway shoulders, but insufficient light was available for overhead guide signs. Researchers concluded that the values of minimum luminance for overhead guide signs were 0.316 cd/ft^2 at 275.59 ft in distance (3.4 cd/m^2 at 84 meter), 0.334 cd/ft^2 at 374.015 ft in distance (or 3.6 cd/m^2 at 114 meter), and 0.344 cd/ft^2 at 498.687 ft in distance (3.7 cd/m^2 at 152 meter) (Russell, et al., 1999).

In a study performed by Carlson and Hawkins (2003) to find minimum retroreflectivity levels for overhead guide signs and street name signs, researchers developed a computational model based on the relationship between headlights and sign, and the geometric relationship between headlights, sign, and driver. They developed Equation 1.1 for determining minimum retroreflectivity:

$$\boldsymbol{Minimum\ R_A = New\ R_{A,SG} \times \left(\frac{Demand\ R_{A,NSG}}{Supply\ R_{A,NSG}}\right)} \qquad \textbf{Equation 1.1}$$

Where; Minimum R_A = minimum retroreflectivity at standard measurement geometry (observation angle = 0.2 degree and entrance angle of -4.0 degree)

New $R_{A,SG}$ = averaged retroreflectivity of new sheeting at standard geometry (cd/lx/m^2)

Demand $R_{A,\ NSG}$ = retroreflectivity needed to produce minimum luminance at the nonstandard geometry (cd/lx/m^2)

Supply $R_{A,\ NSG}$ = retroreflectivity of new sheeting at the nonstandard geometry (cd/lx/m^2)

Carlson and Hawkins (2003) also conducted a field study on a sample of 30 subjects ages 55 or older, using 32 different headlight illumination levels. The field study was performed during real world driving conditions on a closed course. Selected subjects were asked to read different types of retroreflective signs. This study analyzed various factors impacting minimum retroreflectivity levels for overhead guide signs, including distance, location of the sign, retroreflective sheeting material, headlamp illumination, accommodation level, vehicle speed, and vehicle type. In this study, three factors determined the model applicability in real life situations: 1) sign position relative to position of the vehicle; 2) accommodation level of drivers ages 55 or older; and 3) rounding the minimum retroreflectivity level for overhead and street name signs to the nearest integer that is dividable by five. Carlson and Hawkins (2003) performed follow up research that included updated factors such as the effect of changing accommodations of nighttime drivers, updated vehicle headlamp profiles, larger observation angles representing typical headlamps of many vehicles (truck, SUV, sedan, and minivan) used in developing minimum retroreflectivity levels for overhead guide signs were based on minimum luminance values of 2.3 and 3.2 cd/m^2 for drivers 55 and 65 years of age, respectively.

Zwahlen, Russ, and Vatan (2003) performed nighttime field evaluations of four different retroreflective overhead sign sheeting combinations. When externally lighted and unlighted (by low-beam headlight only), the sheeting materials were compared for appearance, legibility, and conspicuity. These sign sheeting material combinations were tested photometrically under low-beam illumination at distances ranging from 200 to 1,000 ft. The sheeting material combinations used in this study were as follows:

- Group A: Beaded Type III legend on beaded Type III background
- Group B: Type IX legend on beaded Type III background
- Group C: Type IX legend on Type IX background, and
- Group D: Type VII legend on beaded Type III background

Zwahlen et al. (2003) research was performed in two separate phases: 1) expert panel field evaluation, and 2) photometric evaluation. They concluded that the practice of external lighting of overhead signs can be discontinued if either white Types VII or IX legend are used on green beaded Type III backgrounds. They recommend that this change from lighted to unlighted overhead signs with white micro prismatic legends on green Type III backgrounds will provide many benefits. This includes eliminating the need for luminary installation, lower maintenance cost, and lower electricity cost.

In a study performed by Bullough et al. (2008), a three-phase project was conducted to measure luminance and luminance contrast values of signs installed along a specific highway. The function of this study was to measure the appearance of signs under different luminance contrast values and to estimate the signs' visual performance for approaching drivers compared to externally lighted signs that meet AASHTO recommendations for exterior sign lighting (AASHTO, 2005). A specific location was selected in order to perform photometric measurements of the sign luminance. This location was visited two times in 2006. Nighttime measurements were made during the visits, and the daytime measurement was performed in the later visit only. Measurements were made using a spectroradiometer equipped with a telephoto lens. The spectroradiometer was mounted onto a tripod in a Dodge Caravan vehicle, driven along the highway, and stopped approximately 328.08 ft (or 100 meter) and maximum 354.33 ft (or 108 meter) from the sign. The lens of the spectrometer was kept as close as possible to the driver's eye level. Nine signs were installed in the location using the following types of retroreflective sheeting materials to make the signs in the study:

- Two from VIIIa: meet ASTM (2007) Type VIII specifications.
- Two from VIIIb: meet ASTM (2007) Type VIII specifications.
- Four from IX: meet ASTM (2007) Type IX specifications.
- One from the proposed XI: meet proposed Type XI and existing ASTM (2007) Type IX specifications.

Luminance measurements were made by positioning the measurement spot of the spectroradiometer onto three background and three character locations of the signs. Luminance contrasts were calculated using Equation 1.2:

$$\boldsymbol{C = \frac{|L_c - L_b|}{max(L_c, L_b)}} \qquad \textbf{Equation 1.2}$$

Where; C is the luminance contrast, L_c is the luminance of the character in cd/m^2, and L_b is the luminance of the background in cd/m^2

Luminance measures obtained for the new signs were compared to those obtained for regular signs along the same location of the study. This model provides some basis for calculating accuracy and speed at which visual information can be processed given the following input parameters: a) size of the visual target; b) background luminance around the visual target; c) luminance contrast between the visual target and its background; and d) age of the observer. The third phase was about subjective evaluations. The apparatus used in the evaluation consisted of two main systems: a tower with a dynamic presentation system and a computer-controlled system. Side-by-side observations were conducted during nighttime sessions. Observers sat in a vehicle parked behind a properly aimed Halogen headlamp set located at a distance of 328.083 ft (or 100 meter) from the apparatus. During the first session, some observers noticed that the letter "E" on the sign panel was difficult to read. Another session was performed at a 196.85 ft (or 60 meter) distance and the rating data obtained from both sessions were combined. Ratings were provided and three repetitions at each luminance contrast were conducted. ANOVA was conducted to analyze the differences. Sequential viewing observations in this phase were conducted as side-by-side observations during nighttime. The same headlamp set was used, but both sessions used a viewing distance of 196.85 ft (or 60 meter) from the sign panel. Three repetitions at each luminance contrast were observed as in side-by-side viewing, ratings were recorded, and ANOVA was used in the analysis.

In the study by Bullough et al. (2008), researchers concluded that measured luminance values, resulting calculated luminance contrasts, and visual response values all indicated that, in terms of visual performance, unlighted highway signs and new signs constructed from four types of retroreflective materials are similar to externally lighted signs when compared to externally lighted signs meeting AASHTO (2005) recommendations for guide sign illumination from a 328.083 ft (or 100 meter) viewing distance (Bullough, et al., 2008). Important related factors included location of the signs relative to vehicles, headlight condition, ambient illumination, and other factors affecting actual luminance of sign background and characters.

Ré and Carlson (2012) performed a research study in which four states (New York, Minnesota, Arizona, and Missouri) were selected to provide examples of effective and beneficial practices demonstrating how various agencies meet the MUTCD roadway sign retroreflectivity requirements. They used three sources to gather information: 1) existing published research; 2) existing guidance and policies; and 3) a telephone survey. The survey included 14 questions, and 48 public agencies participated. Survey findings identified several strategies and techniques that were considered effective practices among the states. Among participating states and local agencies, the decision to replace a sign was made based on four methods: 1) The expected sign life method was the most selected method for replacing signs (approximately 37.5%); 2) The most popular practice among participating states was nighttime visual inspection, involving training programs to ensure inspector proficiency (32.5%); 3) Twenty percent of agencies performed the blanket replacement method; 4) Five percent of agencies used the process of measuring retroreflectivity. However, the process of measuring retroreflectivity and control sign methods is associated with high cost due to the retroreflectometer used and time spent taking measurements. Cost and time are crucial deciding factors in whether to use these methods or not. Purchasing a retroreflectometer can be expensive; however, resulting measurements could be valuable enough to justify the extension of sign replacement periods. Replacing signs based on retroreflectivity measurements can be time-consuming, though. If an agency has a retroreflectometer, maximum benefit is derived when used in conjunction with daily routine maintenance.

Chapter 2: Survey and Survey Analysis

2.1 Introduction

A guide sign illumination survey was distributed to the 50 state Departments of Transportation (DOTs) via e-mail during the period between August 9 and September 15, 2012. The survey consisted of six questions focused on the following:

- Current usage of overhead guide sign lighting,
- Light source types and optical package used in illuminating overhead guide signs,
- Policy and/or procedures used in designing and installing overhead guide signs, and
- Any new types of guide sign illumination used or planned to be used in the future.

2.2 Results and Discussion

During the survey period, responses were received from 31 of the DOTs (62%). In addition to the DOT survey, another survey by Gund (2011), administered between February and March 2011, was studied to enhance responses received to the DOT survey. In addition, some related material that enhanced the DOT survey was reported by the AASHTO joint technical committee in December 2010 (AASHTO, 2011). Responses to the DOT survey questions are shown, followed by related material found in either Gund or AASHTO references:

Question 1: Does your state currently use lighting for some overhead guide signs?

As shown in Table 2.1, among the 31 states that responded, responses to this question were divided into two scenarios for analysis:

A. 12 states (38.71%) responded "Yes," 14 states (45.16%) responded "No," and five states (16.13%) responded that they had used sign lighting in the past, but were currently phasing it out.
B. Considering the states that are currently lighting their guide signs but phasing it out to be as those who are illuminating their overhead guide signs, 17 (54.84%) of these states responded "Yes," and 14 (45.16%) of these states responded "No."

Table 2.1: Overhead Guide Sign Lighting Currently Used Throughout the United States: Verbatim Responses from DOT Survey

	State	Response	Usage
1	Alabama	Some older overhead guide signs are illuminated; however, several years ago we stopped including lighting when installing new overhead guide signs.	Yes, phasing out
2	Alaska	No dedicated sign illumination. The limited number of overhead signs is illuminated by adjacent roadway illumination.	Yes, phasing out
3	Arkansas	We do not use lighting for any overhead guide signs. We did at one time but they became a maintenance issue.	No
4	Connecticut	The Connecticut Department of Transportation (ConnDOT) no longer utilizes sign lighting.	No
5	Delaware	No, We use all Type IX sheeting or above.	No
6	Florida	Yes	Yes
7	Hawaii	No	No
8	Idaho	Yes	Yes
9	Illinois	Yes, but current policy is no sign lighting.	Yes
10	Indiana	Currently INDOT does not light overhead guide signs.	No
11	Iowa	Existing lighting is maintained, but no new lighting is being installed with overhead guide signs.	Yes, phasing out
12	Kentucky	Kentucky does not light our overhead guide signs.	No
13	Louisiana	No, Louisiana does not light overhead signs.	No
14	Mississippi	Does not light any overhead guide signs.	No
15	Michigan	The Michigan Department of Transportation does not light overhead signs.	No
16	Nebraska	Yes	Yes
17	New Mexico	We don't use any lighting for our overhead signs. There are a few left from the past that we are phasing out! We are also a dark sky state[1]. The fixtures must be full cutoff with flat glass. HID or any other lighting over 70 watts cannot be used 90 degrees above nadir.	Yes, phasing out
18	North Carolina	Yes	Yes
19	Ohio	No	No
20	Oklahoma	No	No

1 An e-mail follow-up to the contacted person for the New Mexico response, asking about the meaning of dark sky state, answered: "We have night sky protection act that passed through our legislature in the year 2000. This limits the amount of light above horizontal. The intention is to limit light pollution" (A. Jian, personal communication, November 28, 2012).

21	Oregon	Yes	Yes
22	Rhode Island	No	No
23	South Carolina	Yes. We use sign lighting in areas that have large amounts of ambient light from other sources.	Yes
24	South Dakota	South Dakota DOT just this summer added lighting to 4 overhead signs.	Yes
25	Tennessee	We do not use overhead guide sign lighting in the State of Tennessee.	No
26	Texas	We still have some sign lighting, but have been phasing it out over the last several years in favor of reflective sheeting.	Yes, Phasing out
27	Utah	Yes	Yes
28	Vermont	For overhead signs, we require signs to be sheeted with a minimum of AASHTO Type IX sheeting for both the background and the legend.	No
29	Virginia	Yes, at one time VDOT lit most overhead signs. During that period, we used an ASTM Type III sheeting. Many of these signs/sign lighting installations remain in place today. Beginning in 2005, we moved to using Clearview fonts on guide signs and required that the lettering and borders be an ASTM Type VIII or IX. With the use of these “premium” prismatic letters and borders, we advised our designers and maintenance staffs that the need for Overhead sign lighting had diminished and that the use of sign lighting should be an engineering decision based in several factors (see response to question 6).	Yes
30	West Virginia	Yes	Yes
31	Wyoming	Yes	Yes

In the survey performed by Gund (2011), regarding guide sign retroreflectivity, two questions were related to the DOT survey: questions 17 and 18. Answers to these two questions resulted in including three additional states to the DOT survey (Missouri, Kansas, and Wisconsin). Their answers are shown in Table 2.2.

“17) Does your agency use external illumination for overhead guide signs? (Yes or No)

18) If your answer to the above question is ‘Yes,’ what source does your agency use for external illumination of the overhead guide signs?” (Gund, 2011)

Table 2.2: Related Results from Gund Survey

	State	Response	Usage
1	Missouri	Our lighting structures are lit using metal halide lamps for color clarity and we have a couple of test LED fixtures that are under evaluation.	Yes
2	Kansas	Electricity, Hooked into Westar energy.	Yes
3	Wisconsin	Wisconsin DOT still illuminates some overhead signs in the Milwaukee metropolitan area. These are signs with the encapsulated bead high intensity legend and background (ASTM D4956-09 Type II sheeting). As these signs are replaced to our new sheeting standard of Type IX or better, the lights are being turned off. Effectively, WisDOT is phasing out the usage of overhead sign lighting. No new overhead sign lighting is being installed. WisDOT uses 250-watt mercury vapor sign lighting luminaires at various voltages. The lamp that is used is a deluxe mercury vapor.	Yes, phasing out

Source: Gund, 2011

In a survey conducted by the AASHTO (2011) Joint Technical Committee, data was found for one additional state, Massachusetts, and this state does not illuminate highway signs.

In combining the three surveys, DOT, Gund, and AASHTO, a total of 35 states responded (31 to the DOT survey, three to the Gund survey, and one to the AASHTO survey). The following scenarios, with modified statistics on overhead guide sign lighting, are:

A. In regard to whether they were using overhead guide sign lighting, 14 states (40%) responded "Yes," 15 states (42.86%) responded "No," and six states (17.14%) responded that they had used overhead guide sign lighting in the past but were currently phasing it out.
B. Considering only those who had responded that they are phasing out overhead guide sign lighting, 20 states (57.15%) responded "Yes" and 15 states (42.85%) responded "No."

Question 2: What lamp type is currently used in the illumination of overhead guide signs in your state? (e.g. standard metal halide, ceramic metal halide, induction lighting, LED, or others)

For the 17 states (54.84%) that responded to the survey and answered that they light overhead guide signs, the lamp types used for illumination were standard MH, HPS, induction, MV and the LED. Table 2.3 shows responses from the DOTs. Results shown in Table 2.2 are added to the calculations, as well.

Table 2.3: Lamp Types Reported in DOT Survey as Used for Overhead Guide Sign Illumination: Verbatim Responses from DOT Survey

	State	Response	Usage
1	Alabama	We use standard metal halide lamps.	Yes, phasing out
2	Alaska	Typically overhead sign illumination is from adjacent roadway illumination, including some high mast lighting systems rather than illumination positioned beneath the overhead sign. As a result HPS is typical.	Yes, phasing out
3	Arkansas	---[2]	No
4	Connecticut	Prior to the installation of more highly reflective signs, ConnDOT specified the use of 250 and 400-watt metal halide with prismatic glass lens, Holophane Panel-Vue sign lights.	No
5	Delaware	---	No
6	Florida	Induction	Yes
7	Hawaii	---	No
8	Idaho	Our currently approved sign lighting fixtures use 150-watt HPS lamps.	Yes
9	Illinois	High-pressure sodium (usually 150 W).	Yes
10	Indiana	If required, 250 W MV/HPS currently.	No
11	Iowa	HPS	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	High-pressure sodium.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Others – high-pressure sodium and mercury vapor.	Yes
19	Ohio	N/A	No
20	Oklahoma	We did use 150-watt HPS.	No
21	Oregon	Metal halide.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We used mercury vapor until recently. We now use metal halide.	Yes
24	South Dakota	LED	Yes

2 --- Means the state did not respond to this question.

25	Tennessee	---	No
26	Texas	All the remaining sign lighting is still mercury vapor.	Yes, phasing out
27	Utah	Mostly HPS (typically 250 W), and some induction (70 W – 165 W).	Yes
28	Vermont	---	No
29	Virginia	HPS	Yes
30	West Virginia	Mostly metal halide, but we are currently looking at LED.	Yes
31	Wyoming	Metal halide.	Yes

Among the 20 states that use lighting for overhead guide signs, including states in Gund's survey, five states (25%) (Alabama, Missouri, Oregon, West Virginia, and Wyoming) use MH lighting only. Six states (30%) (Alaska, Idaho, Illinois, Iowa, Nebraska, and Virginia) use HPS and two states (10%) (Wisconsin and Texas) use MV. One state (5%), Florida, uses induction lighting, and South Dakota (5%) uses LED lighting. When combined (25%), the remaining states use two types of lighting. For example, Kansas and North Carolina use MV and HPS, South Carolina uses MV for greater light clarity, and Utah uses HPS and some induction lighting. One state, New Mexico, did not disclose what type of lighting they use. Three states (Connecticut, Indiana, and Oklahoma) answered "No" to whether they used overhead guide sign lighting, but in their response to question 2 (type of lamp used), they mentioned the type of lighting they used for illuminating overhead guide signs. This could mean they are using guide sign lighting but are phasing it out.

Question 3: Which optical package is typically used for the lighting in your state? (e.g. reflector/clear flat glass, refractor, stippled flat glass, or others)

Among states that responded that they light overhead guide signs, 17 states out of 31 respondents stated that several types of optical packages such as reflector with clear flat glass, full cut-off road side luminaire, high mast heads, refractor, and prismatic glass lens (glass diffuser) are used for guide sign lighting. Detailed responses are shown in Table 2.4. These answers include some optical package types related to street lighting, but only two types of glass that are related to overhead guide sign lighting, clear glass and prismatic glass, are considered.

Table 2.4: Optical Packages Used for Overhead Guide Sign Lighting

	State	Response	Usage
1	Alabama	We use reflector/clear flat glass.	Yes, phasing out
2	Alaska	Clear flat - full cut-off road side luminaire, and high mast heads.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Prismatic glass lens.	No
5	Delaware	---	No
6	Florida	Reflector/clear flat glass, refractor.	Yes
7	Hawaii	---	No
8	Idaho	We have a combination of reflector/clear flat glass and refractor.	Yes
9	Illinois	Refractor	Yes
10	Indiana	Refractor	No
11	Iowa	---	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	Reflector/clear flat glass.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Glass diffuser.	Yes
19	Ohio	N/A	No
20	Oklahoma	Reflector/clear glass.	No
21	Oregon	Reflector and refractor.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We typically use Holophane sign lights with refractors.	Yes
24	South Dakota	LEDs	Yes
25	Tennessee	---	No
26	Texas	Reflector with clear flat glass.	Yes, phasing out
27	Utah	Most of the old HPS's have a refractor lens. The inductions have a reflector with clear flat glass.	Yes
28	Vermont	---	No
29	Virginia	Reflector with flat glass is typical.	Yes
30	West Virginia	Flat Glass.	Yes
31	Wyoming	Reflector/clear flat glass.	Yes

Question 4: Are AASHTO or Illuminating Engineering Society (IES) sign lighting levels used in the design of your overhead guide sign lighting or are installations based on historical practice and/or experience?

Among the 17 states that responded that they light their overhead guide signs, three states (17.65%) (Idaho, South Carolina, and South Dakota) follow AASHTO standards, four states (23.53%) (Alabama, Illinois, West Virginia, and Wyoming) use IES standards, three states (17.65%) (Florida, North Carolina, and Utah) use both AASHTO and IES standards, three states (17.65%) (Alaska, Oregon, and Texas) follow historical practice and experience, one state (5.87%), Virginia, has its own standards and policies, and three states (17.65%) (Iowa, Nebraska, and New Mexico) have or use no standards or specifications. Detailed responses are shown in Table 2.5.

Indiana and Oklahoma responded that they use historical data, meaning, as in question 3, their response seemingly contradicts their "No" answer to question 1. A possible explanation may be those two states are phasing out the lighting.

Table 2.5: States' Standards for Designing Overhead Guide Sign Illumination

	State	Response	Usage
1	Alabama	In the past, our designers used IES sign lighting levels.	Yes, phasing out
2	Alaska	I'd say historical practice/experience.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	N/A - ConnDOT no longer specifies the illumination of overhead signs.	No
5	Delaware	---	No
6	Florida	Yes	Yes
7	Hawaii	---	No
8	Idaho	Yes, when possible AASHTO recommendations are met for average Fc levels and Max/Min uniformity.	Yes
9	Illinois	IES RP-19	Yes
10	Indiana	Historical practice based on the size of the sign.	No
11	Iowa	N/A	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	?	Yes

17	New Mexico	---	Yes, phasing out
18	North Carolina	Yes, AASHTO & IES lighting levels are used.	Yes
19	Ohio	N/A	No
20	Oklahoma	Installations were based on historical practice.	No
21	Oregon	Historical practice, currently no new sign lighting designed.	Yes
22	Rhode Island	N/A	No
23	South Carolina	Our lighting systems are designed using AASHTO's roadway lighting guide.	Yes
24	South Dakota	AASHTO standards.	Yes
25	Tennessee	---	No
26	Texas	Historical practice/experience.	Yes, phasing out
27	Utah	I would suspect a combination of both, but more recent installations have been AASHTO-based.	Yes
28	Vermont	---	No
29	Virginia	VDOT Specification for sign luminaires is based in a simple approach. It reads: Sign Luminaires: Luminaires shall be shielded to eliminate glare or extraneous light on the roadway and shall provide a maximum-to-minimum uniformity ratio of 1:1 to 6:1 when installed. When tested at the center of a 10-foot-square test panel, the luminaire shall provide at least 30 average initial foot candles and a gradient (ratio of illumination on any two adjacent square feet of sign surface) of 2:1 or less. Designers are required to design in compliance with IES Standards.	Yes
30	West Virginia	IES	Yes
31	Wyoming	IES	Yes

Question 5: Are you looking at other emerging sources for your overhead guide signs lighting? (e.g. ceramic metal halide, induction lighting, LED, plasma, or other)

Among the 17 states which answered "Yes" to question 1 in the DOT survey, 11 states (64.7%) answered "Yes," and six states (35.3%) answered "No." The states that answered "Yes" are divided into four groups according to their reported future plans. The first group of six states (54.55%) (Florida, Idaho, South Dakota, South Carolina, Virginia, and West Virginia) includes those looking to switch to LED lighting. The second group includes two states (18.18%) (Oregon, and Wyoming), that are transitioning to induction lighting. The third group, comprised of two states (18.18%) (North Carolina and Utah) includes those hoping to use or upgrade retroreflective sheeting on overhead guide signs. The last group is comprised of one state (9.09%) (Illinois) which is trying to eliminate overhead guide sign lighting. (For more details, reader may refer to Illinois' answer to question 6). States that answered "No," such as Alabama, Alaska, Iowa, Nebraska, Texas, and North Carolina are attempting to eliminate guide sign lighting by using retroreflective sheeting guide signs. (For more information, reader may refer to the answer for question 6 by these states). Detailed responses to this question are shown below in Table 2.6.

Table 2.6: States' Emerging Sources for Overhead Guide Sign Illumination

	State	Response	Usage
1	Alabama	No. (See response to question 1.)	Yes, phasing out
2	Alaska	No	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Not at this time.	No
5	Delaware	----	No
6	Florida	LED	Yes
7	Hawaii	---	No
8	Idaho	Yes. We are currently experimenting with LED. We have 4 signs lit using LED fixtures with good results and an approx. 80 percent reduction in power.	Yes
9	Illinois	Yes, but not officially since current policy is no sign lighting for new installations.	Yes
10	Indiana	N/A	No
11	Iowa	No	Yes, phasing out
12	Kentucky	---	No
13	Louisiana	N/A	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	No	Yes
17	New Mexico	We are not	Yes, phasing out
18	North Carolina	No - we are moving towards using higher retroreflective sign sheeting.	Yes
19	Ohio	No	No
20	Oklahoma	We are discontinuing using overhead sign lighting due to the numerous hits on the structures that have overhead sign lighting.	No
21	Oregon	Induction lighting.	Yes
22	Rhode Island	N/A	No
23	South Carolina	We are looking at LED technology and have	Yes

		retrofitted one system with LED fixtures to examine how they compare with traditional fixtures.	
24	South Dakota	LED	Yes
25	Tennessee	---	No
26	Texas	No, we are phasing out sign lighting.	Yes, phasing out
27	Utah	We have opted to eliminate sign lighting altogether. Our new standard is a Type XI sheeting requirement with no sign lighting. We will remove sign lighting as old signs are replaced with upgrades.	Yes
28	Vermont	---	No
29	Virginia	At this time we are considering pursuing an evaluation of LEDs, including a comparison of the total cost of ownership of other technologies, and we are evaluating news and information as it is released. We have recently had the developer of a "Public/Private Partnership" roadway propose to use LED for sign lighting.	Yes
30	West Virginia	Yes, LED	Yes
31	Wyoming	Yes, induction	Yes

Question 6: What does the future look like for overhead guide signs lighting in your state? (Continue its use, modify where/when it is used, or eliminate with use of different sign materials)

Responses to this question are shown in Table 2.7. In summary, some states are moving towards discontinuation of overhead guide sign illumination and transitioning to brighter grade retroreflective sheeting materials. Other states are modifying the lighting and moving toward new energy efficient light source types such as LEDs and induction lighting. They will maintain the procedure of illuminating guide signs. Others have already eliminated overhead guide sign lighting and will not illuminate guide signs. Others are transitioning to new lighting methods or retroreflective sheeting, and some states leave the decision of maintaining overhead guide sign illumination or using brighter retroreflective sign sheeting to their engineers who decide according to the situation.

Table 2.7: Future Plans or Trends for Overhead Guide Signs in Various States

	State	Response	Usage
1	Alabama	We are moving towards eliminating lighting for overhead guide signs. We believe that the new Federal retroreflectivity requirements will make that type of lighting unnecessary.	Yes, phasing out
2	Alaska	No change from today.	Yes, phasing out
3	Arkansas	---	No
4	Connecticut	Maintain policy of no longer illuminating highly reflective signs.	No
5	Delaware	---	No
6	Florida	Modify where/when it is used.	Yes
7	Hawaii	We have started to use Type XI reflective sheet for overhead signs and removing the sign lighting. This approach seems to be working well.	No
8	Idaho	We are considering two options: 1) upgraded sheeting and no sign lighters, and 2) upgraded sheeting with LED sign lighters (either new or upgraded existing).	Yes
9	Illinois	Highly retroreflective sheeting material has eliminated the need for most sign lighting.	Yes
10	Indiana	INDOT already eliminated lighting the overhead guide signs.	No
11	Iowa	Do not plan to light overhead guide signs because of the new sign sheeting.	Yes, phasing out
12	Kentucky	Do not plan to pursue sign lighting.	No
13	Louisiana	We stopped using sign lighting in 1986 when we started using High Intensity Beaded Sheeting (AASHTO Type III). We are now using High Intensity Prismatic Sheeting.	No
14	Mississippi	---	No
15	Michigan	---	No
16	Nebraska	Replacing with sign material as signs are replaced.	Yes
17	New Mexico	---	Yes, phasing out
18	North Carolina	Elimination	Yes
19	Ohio	Continue not using.	No
20	Oklahoma	As mentioned in previous question and answer, we are discontinuing overhead sign lighting. We are using Type III sheeting for a background and Type IX sheeting for legends and borders. That combination is working out well for Oklahoma.	No
21	Oregon	Not much of new installation. Remove existing sign lighting when we upgrade signs.	Yes
22	Rhode Island	We have no plans to change our overhead sign lighting policy. We have no plans to install lighting on overhead signs.	No

23	South Carolina	We will continue to use sign lighting in areas around larger metropolitan areas where extraneous light is most intense.	Yes
24	South Dakota	SDDOT is currently in the process of reviewing its practice of lighting overhead signs.	Yes
25	Tennessee	---	No
26	Texas	Eliminate with use of different sign materials.	Yes, Phasing out
27	Utah	See Question 5.	Yes
28	Vermont	---	No
29	Virginia	In 2008 Virginia was going through a transformation regarding lighting of overhead signs. Central Office Traffic Engineering instituted a policy about seven years ago that all new positive contrast overhead signs should use Clearview font and premium grade prismatic sheeting for the lettering and border. Basically, that equates to all new guide signs being fabricated with a Grade VIII or IX lettering on a Type III background. At nearly the same time, VDOT launched a statewide maintenance project that, in part, resulted in the removal of all OH sign maintenance "cat walks" as they lacked all the safety features that would be desirable. In doing that, we removed a large number of the existing lighting fixtures. Ultimately, we tested the remaining signs for adequate visibility. If it failed to provide the perceived human need, the sheeting was replaced with the premium prismatic sheeting and the lights were left off. Beginning with projects advertised in February of 2011, VDOT moved to requiring all signs be fabricated using ASTM Type IX sheeting, thus that a very high level of light return (headlamp) would be achieved. That specification may be viewed at: http://www.virginiadot.org/business/resources/const/07RevDiv_II.pdf Use word search: SS24701 to access the Special Provision Copied Note that goes with all projects. Today VDOT takes a position that the choice to use or not to use lighting on overhead signs is an engineering decision. We recommend it should remain as such. We presume that sign lighting is not necessary unless present and projected volumes, design speed, degree of horizontal curvature right, degree of horizontal curvature left, percent of positive grade change, percent of negative grade change, amount of ambient light present, amount of potential future ambient light, number of signs or length of messages being presented at one location, etc. Our designers maintain the concept that all new overhead signs structures are engineered to accommodate the future installation of sign lighting and a light retrieval system. It is our thought that	Yes

		while this may add a very small initial cost to the structures, it will, more importantly, allow for the addition of lighting in the future should unexpected volume increases occur, should the speed change, or should an unexpected increase of ambient lighting take place, but more than that, it would allow for adding lighting at locations that prove themselves to need it in spite of the best engineering decision that indicated it would not be needed. We made no public announcement about this change in stance and thus far public comments have not materialized, positive or negative.	
30	West Virginia	Modify where/when it is used.	Yes
31	Wyoming	Eliminated 95% to date. The remaining 5% is needed.	Yes

2.3 Summary

Based on the DOT survey analysis, including analysis of the two other surveys (Gund and AASHTO), states have two procedures or future plans for improving overhead guide sign visibility during nighttime: either illuminating signs, usually with newer, more efficient light sources, or by using newer, brighter retroreflective sheeting materials. The main objective is to provide adequate sign visibility while saving energy and reducing cost. The most common light sources currently used in illuminating overhead guide signs, according to states that responded to the surveys and illuminate signs, are MH, MV, HPS, induction, and LED.

In designing overhead guide sign lighting, states may refer to AASHTO standards, IES standards, both AASHTO and IES standards, historical practices and experiences, or to the state's own standards.

Future plans for states are distributed between modifying existing overhead guide sign lighting into new, more efficient methods of illumination which save energy and cost, or toward the use of new, brighter retroreflective sheeting on overhead guide signs.

From the DOT survey, some states reported that they will continue using guide sign illumination, but they are seeking the best type of light source from two points of view: lighting efficiency and energy saving. Some states responded by saying they are transitioning from one type of light source to another, specifically to new lighting technologies: LED and induction. South Dakota started using LED lighting in the summer of 2012 for four overhead guide signs (as demonstrated by responses in question 1). In an email follow-up to the contacted person for

South Dakota, the answer was, “the reason for the selection had more to do with maintenance of the lights, i.e., South Dakota DOT wanted the longest life possible due to the location of the signs” (D. Martell, personal communication, October 9, 2012). In addition, in testing for LED efficiency, Idaho and South Carolina are using LED lighting to illuminate some overhead guide signs. (Refer to question 5). Two states are currently using induction lighting (Florida and Utah), and two states are looking into the use of induction lighting for overhead guide signs (Oregon, and Wyoming).

Chapter 3: Light-Emitting Diodes

3.1 Introduction

Personal security, traffic flow operations, and safety can be improved by efficient roadway lighting (Medina, Avrenli, & Benekohal, 2013). Roadway lighting is a basic public requirement that leads to a safer environment for both drivers and pedestrians. Drivers can easily recognize street conditions and geometry of the roadway with availability of proper roadway lighting. Proper roadway lighting also contributes to highway safety by increasing drivers' visual comfort and reducing drivers' fatigue (Illinois Department of Transportation, 2002).

Energy conservation is essential in the midst of a worldwide energy crisis. As of 2007, in the US, total street and area light number was 131.356 million with a total annual consumption of 178.3 billion kilowatt hours (kWh) (Navigant Consulting Inc., 2008). Table 3.1 shows street and area lights installed in 2007. In addition, US road lighting is estimated to be 14 billion kWh of annual energy, which represents approximately 3% of its total electricity consumption. Similarly, the public lighting system in China represents 6% consumption out of the annual electricity demand, making energy consumption essential in China (Li, D. Chen, Song, & Y. Chen, 2009). In addition, 24% of the energy consumed by municipalities in South Africa is contributed to street lighting (Avrenli, Benekohal, & Medina, 2012). All previous examples resulted in making energy conservation an essential priority in the midst of a spreading energy crisis due to decreasing oil and gas reserve levels and increasing demand.

Table 3.1: Street and Area Lights Installed in the United States as of 2007

Light source	Percentage	Number of lights (million)
Incandescent	2.4	3.159
Halogen quartz	7.5	9.917
Fluorescent	5.7	7.530
Mercury vapor	13.5	17.675
Metal halide	29.2	38.330
High-pressure sodium	41.7	54.745
Total	100	131.356

Source: Navigant Consulting Inc., 2008

LEDs are fourth generation light sources. LEDs have recently proven that they are an energy efficient solution to street lighting. When an electrical current runs through an LED, which is a semiconductor, light is emitted (Avrenli, et al., 2012).

Until a few years ago, LED lighting technology was limited for use as architecture or a niche-type white color lighting application because of LED characteristics being too dim and very expensive. Recently, new LED technology has created an evolution in the overall technology of lighting as it shows enormous improvement in high LED brightness, which has resulted in increasing and expanding usage of LEDs in street lighting, parking garage lighting, and commercial and residential area lighting. The value of using LEDs includes a very long life, energy efficiency, and a lower cost. In addition, LED is a robust lighting source that does not use any glass or filaments which support their usage in high vibration areas such as mining or power generation. Moreover, LEDs cause no concern with the environment and they are free of mercury and heavy metals such as lead (Neary & Quijano, 2009).

Despite all LED benefits, transitioning to LEDs is challenging because the development of conventional lighting was around standard lamp style technologies and retrofitting existing fixtures can be achieved after careful engineering design and, in many cases, it does not fully optimize technology performance (Neary & Quijano, 2009). LEDs have drawbacks and limitations, however.

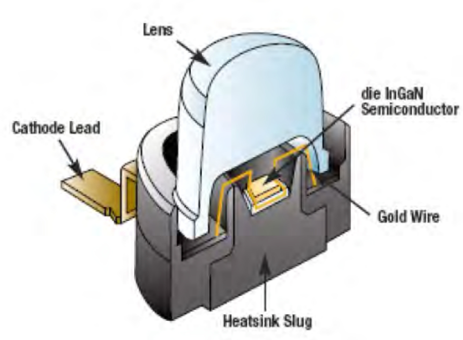
3.2 LED Illumination System

LED street lamps consist of the following: LED chip (package), LED module, driver or power supply, control circuit, optics, and heat sink for thermal management (Neary & Quijano, 2009).

3.2.1 LED Chip (Package)

As shown in Figure 3.1, the LED chip consists of a thin layer of semiconductors that emit light when a voltage runs through. In order for an LED chip to be a source of functional light, it must be encased in a highly transmissive material such as epoxy with metallic leads like gold, a heat sink, and light reflector. All together these are referred to as "the LED chip or package"

(Ton, Foster, Calwell, & Conway, 2003). The used operating current ranges from 350 milliamperes (mAmps) to 1 ampere, while the range of luminous flux is between 20-150 lumens (Neary & Quijano, 2009).



Source: Neary & Quijano, 2009

Figure 3.1: Common LED Chip

3.2.2 LED Module

The building block of the larger system of the LED module is constructed from a circuit board with several LEDs and many other electronic components that may be used as a driver circuit or a current-regulating circuit (Neary & Quijano, 2009). In addition, the LED module may also have secondary optics to better focus, intensify, or direct optical energy for the desired application (Neary & Quijano, 2009; Ton, et al., 2003). Generally, the light distribution of most LEDs is in the range of 80º to 120º depending on the manufacturer and the LED package (Neary & Quijano, 2009).

3.2.3 Driver or Power Supply

LEDs will fail if they are subjected to reverse voltage. Similarly, the life of LEDs may be shortened if they are subjected to high peak electrical currents. Therefore, LEDs must be protected from reverse voltage and should be surged for output current regulations (Nuttall, Shuttleworth, & Routledge, 2008). For that reason, LED systems require a driver or power circuit to convert the alternative current (AC) line voltage to appropriate direct current (DC) and voltage because LEDs are best operated with a constant current power supply (Neary & Quijano, 2009). The converted direct current usually ranges from 2 to 4 volts and 20 to 1,000 mAmps to obtain a high LED brightness (United States Department of Energy [U.S. DOE], 2009a). The standard high brightness LED is characterized by the minimum operating current of 350 mAmps and with higher levels of luminous flux that can be obtained using higher operating currents but will present additional challenges of thermal management (Neary & Quijano, 2009).

3.2.4 Control Circuit

The control circuit of LEDs is the unit that regulates the current flow (Avrenli, et al., 2012).

3.2.5 Optics

Optical components of LEDs can either be lenses or reflectors, and the main function of the optical component is to shape the pattern of radiation. Success of LED light fixtures relies heavily on used optical components. The use of lenses is recommended for small LED light sources that have 1 to 4 dies. Since the lens has at least three surfaces, the light beam will be controlled efficiently. In contrast, the cost of lens will be high if the light source consists of an array of dies beneath a common layer of phosphor. In this case, the lens will be large (Avrenli, et al., 2012). In some cases, mixing more than one lens will be required to obtain a required specific radiation pattern of light, especially in street lighting (Kuntze, 2009).

3.2.6 Heat Sink for Thermal Management

The main function of the heat sink is to provide heat removal from the LED to the immediate surroundings. Heat sink size depends on thermal properties of the material produced from the heat sink, and heat amount that has to be dissipated by (U.S. DOE, 2007):

- “Conduction, which is defined as heat transfer from one solid to another.
- Convection, which is defined as heat transfer from a solid to a moving fluid.
- Radiation, in which heat transfer from two bodies of different surface temperatures occurs via electromagnetic waves.”

Approximately 90% of LED heat removal dissipated via conduction (Avrenli, et al., 2012).

3.3 LED Advantages

Major advantages of LEDs include energy efficiency, longer life, improved performance in mesopic vision conditions, high quality color, instant lighting, directional light, compact size, environment friendly characteristics, reduced light pollution, vibration and breakage resistance, and dimming capabilities (U.S. DOE, 2009a). The following subsections provide a detailed discussion about LED advantages.

3.3.1 Energy Efficiency

The most important advantage of LEDs is their low energy consumption which is approximately 80% compared to other conventional light sources (Navigant Consulting Inc., 2008). Table 3.2 provides a summary of LED replacement power wattage as compared to different conventional light sources as of 2007. These power amounts were computed based on identical amounts of lumens delivered by the mentioned conventional light sources. LED replacement wattages shown in Table 3.2 also factor in 30-50% depreciation in light output from HID and fluorescent over their lifespans (Avrenli, et al., 2012). Results clearly show that LEDs are more efficient than all other conventional light sources.

Table 3.2: Conventional Light Sources Wattage and their LED Replacement Wattage

Light source	Conventional source wattage	LED replacement wattage as of 2007	LED saving power
Incandescent	150	26	82.7%
Halogen quartz	150	31	79.3%
Fluorescent	159	151	5%
Mercury vapor	254	108	57.5%
Metal halide	458	327	28.6%
High-pressure sodium	283	276	2.5%

Source: Navigant Consulting Inc., 2008

In the United States, it is estimated that if the market used LEDs with an average lumen efficacy of 57.5 lumens per watt with a 100% complete penetration, an annual savings of 44.7 billion kWh in energy could be achieved. According to statistics from 2007, this savings constitutes 25% of electrical energy used for street lighting in the United States. The 44.7 billion kWh is equal to 482 trillion British thermal units (TBtu) per year, which is equivalent to the annual electricity consumption of seven large (100 MW) electrical power plants or the consumption of 3.7 million residential households (Navigant Consulting Inc., 2008). Moreover, it is estimated that if LEDs dominated the Chinese lighting market in 2010, one third of power consumption in China will be saved (Luo, Xiong, Cheng, & Liu, 2009; Luo, Cheng, Xiong, Gan, & Liu, 2007).

3.3.2 The Longer Life of LED

Lamp life can be defined as “the period in which a particular percentage of the tested lamps fail.” This percentage is 40% for MH and 50% for MV and the HPS lamps (Avrenli, et al., 2012). The biggest advantage of LEDs is that they are not failing catastrophically, thus making their life defined differently as the point at which LED light output falls below a certain threshold of lumen output at installation, typically 70% (Neary & Quijano, 2009). The average life of conventional street light sources is approximately 50,000 hours (Timinger & Ries, 2008). Manufacturers claim that LEDs lifespan may last up to 100,000 hours with less than 40% of lumen depreciation (Tetra Tech EM Inc., 2003). In contrast, the expected lifespan of some conventional street lamps such as HPS, MH, and MV is approximately 24,000 hours, 20,000 hours, and 10,000 hours, respectively (Timinger & Ries, 2008; U.S. DOE, 2009b).

Although LEDs have a longer life than conventional light sources, their replacement can be difficult. Due to the high cost of labor needed to fix the failed LED, it may be more cost-effective to install a new LED luminaire rather than replace failed LEDs. In comparison, HID light sources are designed to be utilized for a minimum of 30 years, and the only thing requiring replacement when it fails is the lamp. Replacement is very simple (Avrenli, et al., 2012). Since LED street lights can last more than 10 years, it is recommended to be used in locations where it is difficult or costly to replace the light source, such as tunnels and bridges (U.S. DOE, 2009b). LEDs can be considered relatively maintenance-free, allowing them to be used in isolated lands and high mountainous regions (Aoyama & Yachi, 2008).

3.3.3 Improved Performance in Mesopic Vision Conditions

In the human retina, there are two types of photoreceptors: rods and cones. Both are responsible for sending visual signals to the brain. Cones are the principle photoreceptor of high light levels in photopic vision conditions; whereas rods are the main photoreceptors at low light levels in scotopic vision conditions (M. Costa, G. Costa, dos Santos, Schuch, & Pinheiro, 2009). Mesopic vision can be defined as the light levels at which cones and rods contribute to human vision. In general, scotopic vision conditions can prevail below 0.001 cd/m^2, while photopic conditions prevail above 3 cd/m^2 (Avrenli, et al., 2012).

Currently, researchers are trying to combine the effect of Mesopic light sensitivities, color rendering, and color temperature on the human perception of brightness. White light emitted by LEDs can be perceived as brighter and more intense than conventional light sources when the lumen output is the same (Avrenli, et al., 2012). The spectrum of LED light has considerable blue content because most white LEDs consist of a yellow emitting phosphor material and a blue emitting chip. Under mesopic vision conditions, more light can be detected by the human eye if the light spectrum has significant blue content (Whitaker, 2007). As a result, LED light spectrum with higher bluish content can render LEDs brighter than other conventional light sources when lumen output is the same (Avrenli, et al., 2012).

3.3.4 High Quality Color

One of the aspects of light source quality is color rendering and appearance. The correlated color temperature (CCT) describes the relative color appearance of the light source, and CCT indicates whether a source of light appears to be more bluish or more yellowish. The CCT indicates the appearance of a black body when it is heated to high temperatures. When the black body is heated increasingly, its color turns to red, orange, yellow, white, and blue, respectively, based on temperature level. The unit of CCT is degrees Kelvin, and "CCT of a light source gives the temperature in degrees Kelvin at which the color of the heated black body matches the color of the light source in the question" (Avrenli, et al., 2012).

The color rendering index (CRI) shows how the colors of an object are rendered by a source of light (Avrenli, et al., 2012). The CRI has a scale from 0 to 100 with a comparison to a reference light source with a similar color index value. Increasing the CRI value means achieve a better source of light to render an object colors (U.S. DOE, 2008). Color rendering is a major advantage of LEDs. Most LEDs used to have the CCT value of 5,000 Kelvin and a cool bluish-white appearance, but recently, natural and warm white LEDs have become available (U.S. DOE, 2009a). LEDs designed for street lighting and parking lots have a range of CRI between 85 and 90 (Avrenli, et al., 2012). The higher color rendering index of LEDs is helpful for improving traffic safety because the available lights allow pedestrians and drivers to easily see street signs and other objects illuminated by the lighting fixtures, thus resulting in a reduction of drivers' reaction times (Hamburger, Doornkamp, & Landau, 2008; Nuttall, et al., 2008).

3.3.5 Instant Lighting

Conventional light sources such as MH, MV, and HPS require re-strike time, or several minutes at startup until the light source reaches its full brightness. In contrast, LEDs do not need a re-strike time to warm up, and they can instantly turn on to full brightness, allowing manufacturers to design LED street lights that contain an intelligent control coupled with instant sensors (Avrenli, et al., 2012). These sensors can be programmed and adjusted according to environmental conditions, which leads to more energy savings (Wang & Liu, 2007).

3.3.6 Directional Light

According to street lighting regulations, an observer should either obtain certain lumens level or certain average levels of illuminance, either of these should be maintained within a target area (Timinger & Ries, 2008). LEDs can be designed to emit light in a specific direction since they enable more optical control. This design reduces the number of reflectors and diffusers required (Avrenli, et al., 2012). Approximately 30-50% of conventional light sources light output may be lost inside the fixtures (U.S. DOE, 2009b).

3.3.7 Compact Size

Compared to conventional light sources, one advantage of LEDs is their small size which allows a wide flexibility in design and forms, allowing manufacturers to produce many patterns of LED luminaires. Because of the compact size of LEDs, they allow for the development of unique fixtures with new light patterns (Neary & Quijano, 2009) and different colors can be mixed to fulfill required conditions. In addition, the small size of LEDs allows more optical control (Tetra Tech EM Inc., 2003). One drawback of the LED small size is that a large number of LEDs is required in roadway light sources to produce appropriate lumen output.

3.3.8 Environment Friendly Characteristics

New laws restricting the disposal of mercury-based light sources have raised concerns over environmental waste and disposal (Neary & Quijano, 2009). Compared to other conventional light sources, LED light sources are free of toxic materials such as mercury, which make it safe for landfills and also compliant with the RoHS directive of the European Union (Hamburger, et al., 2008). In addition, the process of manufacturing and assembling LEDs is free of the use of heavy metals like lead (Neary & Quijano, 2009). Moreover, while LEDs are running, they do not produce infrared or ultraviolet lights, which make them more environmentally friendly as compared to conventional lights (Ann Arbor, 2008).

One important factor that also causes LEDs to be environmentally friendly is that they may contribute to considerable reductions of greenhouse gas emissions (Avrenli, et al., 2012). In Toronto, it is estimated that if 160,000 street lights are converted into LEDs, greenhouse gas emissions can be reduced annually by 18,000 tons, equivalent to removing 3,600 cars from roadways (Whitaker, 2007). In Japan, if an LED street light system is adopted, approximately 6 to 9 million tons of CO_2 can be reduced (Aoyama & Yachi, 2008).

3.3.9 Reduced Light Pollution

Five kinds of light pollution are most common: light trespass, over illumination, glare, sky glow, and clutter. Unwanted light that enters one's property is called light trespass (Avrenli, et al., 2012). An example of light trespass is light that enters one's house through a window during night, possibly resulting in sleep deprivation. Over illumination is defined by excess use of light. Over illumination accounts for approximately 2 million oil barrels wasted every day in the United States (Lay-Ekuakille, et al., 2007). Glare can be defined as "stems from excessive contrast between bright and dark areas in the field of view" (Avrenli, et al., 2012). Glare is a serious concern in road safety because it complicates needed adjustments to differences in brightness during nighttime driving. Clutter can be defined as "the excessive grouping of lights, such as badly designed streetlights or brightly lit advertising boards surrounding roadways"

(Avrenli, et al., 2012). Clutter may reduce traffic safety because it can confuse drivers and pedestrians and cause a distraction. Sky glow is the light effect that can be seen over populated areas caused by reflected light and due to badly directed light (Avrenli, et al., 2012). Careful consideration of street light design must be achieved so that a certain contrast level within the targeted area must not be exceeded in order to overcome the five types of light pollution.

3.3.10 Vibration and Breakage Resistance

Conventional light sources contain filament, arc tube, or fragile glass components that are affected by vibration. In comparison, LEDs do not contain any of these components. They offer a more robust light with more resistance to breakage and vibration. As a result, using LEDs in areas of high vibration, such as mining operations or on bridges, is more suitable and efficient (Neary & Quijano, 2009).

3.3.11 Dimming Capabilities

Intelligent control and dimming is a method that can be employed for the purpose of saving energy (Avrenli, et al., 2012). Traffic always decreases at night and early mornings and, during these times, energy consumption may be reduced by limiting illumination levels offered by light sources. The amount of energy saving due to dimming may reach 30%. MH and MV lights have poor dimming capabilities (Timinger & Ries, 2008). For HPS, dimming can be achieved by changing illuminance steps by using ballasts of multi-levels (Li, et al., 2009). On the other hand, LED light intensity can be modified by adjusting the relative pulse and time between these pulses, called modulation of pulse width (Long, Liao, & Zhou, 2009). LEDs can be dimmed as low as 10% of their maximum output and, with the use of pulse width modulation; they can be dimmed as low as 0.05% of their maximum output (Avrenli, et al., 2012).

3.4 Disadvantages of LEDs

Though LEDs have many advantages and benefits, there are many disadvantages related to their luminous efficacy, heat conversion rate, cost of installation, issues in obtaining white color, and the use of LEDs module arrays. The following subsections describe these problems in detail.

3.4.1 Luminous Efficacy

Luminous efficacy can be calculated by dividing the total luminous flux of that source by lamp power in wattage with the unit of lumen per watt. As with the luminaire, efficacy is calculated by dividing the total luminous flux by luminaire power.

The main challenge to LED outdoor lighting technology is luminous efficacy. LED street lights are not significantly superior to conventional light sources. Measured lumen output of the conventional light sources of MH, MV, and HPS are in the ranges of 60-110, 30-60, and 40-120 lumens per watt, respectively (Timinger & Ries, 2008; Tetra Tech EM Inc., 2003). In comparison, luminous efficacy of available commercial LEDs has recently approached 100 lumens per watt (Li, et al., 2009).

3.4.2 Heat Conversion Rate

While LEDs operate, they produce cold light, usually below 60^{o}C (or 140^{o}F), while HPS light sources operate based on molten metal inside an arc tube at a temperature greater than 300^{o}C (572^{o}F). LED has a higher rate of power to heat conversion as compared to other conventional street light sources (Avrenli, et al., 2012). The high power chips of LED generally transform approximately 80% of input power into heat, meaning that the remaining 20% of the input power is converted into light. In comparison to conventional street light sources, which have a heat removal mechanism based primarily on infrared radiation, LED heat removal mechanism is based mostly on conduction, resulting in the addition of thermal management challenges. Table 3.3 shows a comparison of heat removal mechanisms of different light sources. Table 3.3 clearly shows that, for the HID light sources, more than 90% of heat removal is lost by radiation, while in the case of LED, more than 90% of heat removal is lost by conduction and less than 5% is lost by radiation.

Table 3.3: Comparison of Heat Removal Mechanism of Light Sources

Light source	% of heat Lost by radiation	% of heat lost by convection	% of heat lost by conduction
Incandescent	>90	<5	<5
Fluorescent	40	40	20
HID	>90	<5	<5
LED	<5	<5	>90

Source: Arik, Setlur, Weaver, Haitko, & Petroski, 2007

3.4.3 Issues in Obtaining White Light with LEDs

Light emitted by a single LED source falls within a very narrow wavelengths band in the visible spectrum, which means that LED emit virtually monochromatic light (Avrenli, et al., 2012). The emission of monochromatic light classifies LED sources as very efficient in the use of colored lights applications such as traffic signal lights. Three methods enable white light extraction from LED light sources (U.S. DOE, 2008; IESNA Light Sources Committee, 2005):

- RGB (Red, Green, and Blue) systems in which white light is obtained by mixing multiple monochromatic (green, red, and blue) LEDs. To “fill in” the yellow region of the spectrum, an amber chip can also be added.
- Binary Complementary Wavelength Conversion in which cool white LEDs are obtained by using yellow phosphor to coat the blue or near-ultraviolet LED chip, usually by cerium-doped yttrium aluminum garnet. In this case, the typical CCT will be 5,500 Kelvin for LED. A typical CCT of 3,200 Kelvin can be produced in the case of warm white LED by adding secondary red phosphor.
- Ultraviolet Wavelength Conversion is a tri-color phosphor that is agitated with the use of a single ultraviolet LED, which then creates a white light.

Currently, most white LED chips are obtained by using phosphor conversion (Avrenli, et al., 2012).

3.4.4 Use of LED Module Arrays

Illumination generated by a single LED package is significantly weaker as compared to other conventional street light sources such as HPS and MH. The power used to generate illumination using HPS light source is commonly sized at 100 W, 250 W, 400 W, and higher, while for a single LED chip or package, the power used in lighting ranges from 1 W to 10 W (Sá, Antunes, & Perin, 2007). LEDs can be used to illuminate roadways only if numerous LED chips are incorporated together into a module of LED, and then several LED modules are incorporated into an LED module array (Avrenli, et al., 2012).

The use of LED module arrays provides redundancy in lighting, thus enabling the entire fixture to stay illuminated even if one or more of the chips fail (Neary & Quijano, 2009). The LED module arrays have some disadvantages, such as increasing the chance of component failure when the number of LED chips used is increased. If this type of breakdown occurs, a significant amount of time and energy is required to repair the LED module array. The reliability of an LED module array increases with decreasing the number of series connections and increasing the number of parallel connections (Aoyama & Yachi, 2008).

An additional disadvantage of the LED module array is that it may result in having distinct multiple shadows which makes drivers and pedestrians visibility to be uncomfortable. Multiple shadows become more distinguishable as the light distribution of each LED module is narrowed, or as the spacing between the LED modules increases (Avrenli, et al., 2012).

The last disadvantage of the LED module arrays is the overdriving of individual LEDs in the array as LEDs begin to fail. In the array, LEDs require a better driver otherwise each failed LED results in causing the remaining LEDs to be driven harder, resulting in increased temperature and reduction of life of the overall system (Avrenli, et al., 2012).

Chapter 4: Light Distribution Evaluation of Different Light Sources

4.1 Introduction

Based on results presented in Chapter 2, the most common light sources used by various states for illuminating overhead guide signs are MH, MV, HPS, induction lighting, and LED. KDOT provided the Kansas State University (KSU) Research team with two light source types: 250 W MH and 250 W MV. Lumi Trak, Inc. supported the KSU research team with three additional light sources: 62 W LED, 250 W HPS, and 85 W induction lighting. Lights obtained by the KSU research team are classified into traditional light sources and new generation light sources. Conventional light sources include the MH, MV, and HPS, while new generation light sources include the LED and induction lighting.

The following sections present details regarding the five light source types received, and the experimental setup and procedure used for testing. Results obtained for each light source type and a comparison of light distribution results for different angle-light source type combinations are also presented. In addition, a comparison between the five light sources light distribution types tested at KSU is included.

4.2 Light Source Details

As mentioned, two light source types currently used to illuminate overhead guide signs in Kansas were received from KDOT. The first light source was the 250 W MH. The fixture of this light source is shown in Figure 4.1. According to the manufacturer, Holophane, "the optical system consists of vandal resistant, non-yellowing prismatic borosilicate glass refractor unaffected by environmental contaminants or ultra-violet radiation and a formed, anodized aluminum inner reflector to direct light onto the sign face with maximum uniformity" (Holophane, 2010). The input voltage was 480 volts. The second light source was the 250 W MV, shown in Figure 4.2. This light source has a clear, flat glass and input voltage of 480 volt.

Three light sources were received from Lumi Trak Company. The first light source was the 62 W LED, shown in Figure 4.3. This light source is manufactured by Lumi Trak and includes independent and adjustable LED arrays with glass diffuser. The input voltage was 120 volts. The second light source was the 250 W HPS, shown in Figure 4.4. The input voltage of this light is 120 volts. The last light source is the 85 W induction lighting, shown in Figure 4.5. The 85 W induction lighting is manufactured by Holophane and distributes light through the borosilicate glass refractor. The input voltage of this light was 120 volts.

Figure 4.1: MH Light Unit

Figure 4.2: MV Light Unit

Figure 4.3: LED Unit

Figure 4.4: HPS Light Unit

Figure 4.5: Induction Lighting Unit

4.3 Overhead Guide Sign Lighting Recommendations

According to AASHTO, overhead guide sign light sources may be placed on the bottom of the sign, top of the sign, or remotely on an adjacent support (AASHTO, 2005). Positioning the lighting unit on the bottom of the sign is preferred because:

1. "The reflected light is less likely to reduce the visual performance of the sign message or produce reflected glare into the eyes of motorists.
2. The lighting units do not produce daytime shadows and reflections from the sun on the face of the sign.
3. The lighting units are easier to access for maintenance.
4. The lighting unit may collect snow or dirt, but may also be cleaned by rain.
5. The face of the sign may only partially shield the light that spills onto traffic approaching from the rear of the sign. However, a separate shielding mechanism can be provided on the lighting units that will minimize this effect.

6. Express sky-glow or light pollution may be inherent. However, a separate shielding mechanism can be provided on the lighting units or optical control equipment can be utilized in order to minimize these effects.
7. The lighting units may obstruct the view of the sign message at some viewing angles. However, proper placement and installation of the lighting units can minimize this problem." (AASHTO, 2005).

In this experiment, the preceding AASHTO recommendations were followed by positioning the light source fixture at the bottom of the sign.

4.4 Experimental Setup

The purpose of this experiment was to find optimal light distribution for five light sources: MH, MV, LED, HPS, and induction lighting, and determine which light source is the best based on the light distribution. According to KDOT, no specific size of overhead guide sign exists (Gund, 2011) because the size of the overhead guide sign depends upon length of the destination name. The general size of an overhead guide sign for one line of legend is 15 ft in width and 9 ft in height (4.572 meters by 2.743 meters). For two lines of legend, general size is 15 ft by 12 ft (4.572 meters by 3.658 meters) (Gund, 2011). In a meeting with KDOT in May 2012, the state signing engineer and the permanent signing specialist stated that KDOT is considering the installation of large overhead guide signs on some highways, 48 ft wide by 18 ft in height (14.630 meters by 5.486 meters) (E. Nichol & D. Gwaltney, personal communication, May 26, 2012).

The experiment was conducted in the casting workshop in the Industrial and Manufacturing Systems Engineering (IMSE) Department at KSU. Black cardboard was used to cover all windows, and the emergency light in the room was turned off to ensure the room was completely dark. A white sheet of paper 15 ft in width and 9 ft in height was hung on the wall, representing an overhead guide sign of similar size. A grid of 1 ft increments was drawn on the paper as shown in Figure 4.6. At a height of 7 ft from the floor, the line on the paper was named row "A" and the line at 1 ft height was row "G." Similarly, the vertical line at the left side of the paper was named column "1" and the vertical line on the right side was column "14".

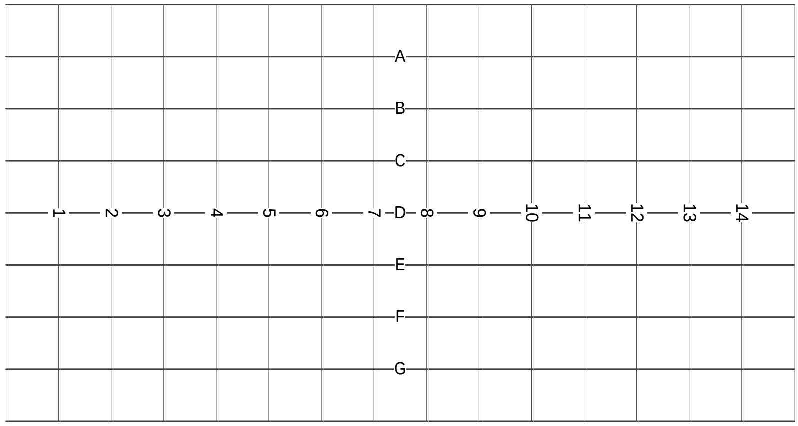


Figure 4.6: Grid Naming Mechanism of White Paper

KDOT has a standard for distance between the light source unit and the sign. Based on a drawing provided to the KSU research team from KDOT, shown in Appendix A, the horizontal distance between the light source unit and the sign is between 5 ft and 6.5 ft. In this experiment, the light source unit was centered in front of the sign on the floor at a distance of 5 ft. This distance was measured horizontally from the white sheet on the wall to the nearest edge of the light source.

The Minolta Illuminance meter was used to measure illuminance (in lux) at each grid intersection (row-column intersection) starting from the top row (row A), left side of the white sheet of paper (column 1), to the bottom right side. Three measurement readings were taken at each intersection and the average was calculated at each intersection point. Illuminance in general can be measured in lux, which is lumen/m^2. Illuminance can also be measured by foot-candle, which is lumen/ft^2. When running the experiment, each light source was given a suitable warming period by being turned on at least 45 minutes before starting illuminance readings to ensure the light source would run at its maximum luminance output. In addition, the Minolta Illuminance meter was calibrated before beginning each experimental run.

4.5 Results and Discussion

Data obtained in this experiment was studied to eliminate any outliers or errors. At each row-column intersection on the white sheet of paper, the average of the filtered readings was calculated and used for further calculations. Illuminance readings for each light source for all angles used are summarized, and best light distribution for each light source is shown for each light source being tested.

4.5.1 The MH Light Source

For the 250 W MH light source, the light source unit was set in front of the white sheet of paper at four different angles. These angles were measured between the bottom of the light source unit and the floor. These angles were 0^o, 5^o downward (clockwise from the glass face toward the white sheet of paper), 10^o downward, and 15^o downward. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 4.1 shows illuminance readings average at each intersection point at the specified angle for the 250 W MH light source. The MUTCD specifies minimum retroreflectivity values for signs, but it does not specify maximum retroreflectivity values. This information will be used in illuminance analysis sections, meaning that when illuminance readings on the white sheet of paper increase by changing the angles from 0^o to 5^o down, from 5^o to 10^o down, and from 10^o to $15\ ^o$ down, as shown in Table 4.1, sign visibility for drivers will be much better. Therefore, the best light distribution of the 250 W MH light source is found when the angle is 15^o down.

Figure 4.7 shows the best light distribution of the 250 W MH light source, found at 15^o angle down. The distribution appears to be more uniform, and illuminance values range between 200 and 700 lux, approximately. This light distribution should enable motorists to see the legend on the overhead guide signs wherever it is located on the sign, while meeting MUTCD requirements when the sign is illuminated with a 250 W MH light source installed at a 15^o angle downward with the horizontal.

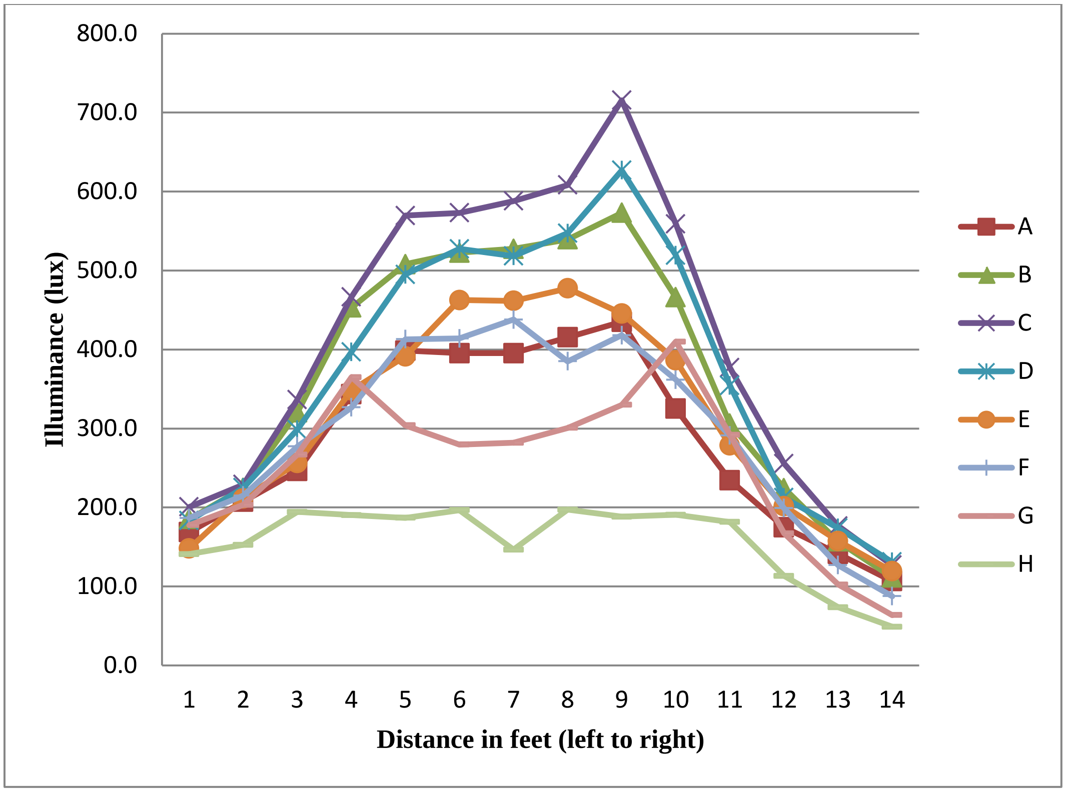


Figure 4.7: The Best Light Distribution of MH (Angle 15° down)

4.5.2 MV Light Source

For the 250 W MV light source, the light source unit was set in front of the white sheet of paper at four different angles. These angles were measured between the bottom of the light source unit and the floor. These angles were 0°, 5° upward, 5° downward, and 10° downward. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 4.2 shows illuminance readings average at each intersection point at the specified angle for the 250 W MV light source. Table 4.2 indicates that when the angle changes from 0° to 5° upward, the illuminance reading for all the rows decreases, meaning that movement in this direction (upward) is not correct. Therefore, the KSU research team selected the opposite rotation direction. When illuminance readings for 0° and 5° down angles are compared, illuminance readings increase, indicating that this move is in the correct direction of rotation. When illuminance readings between 0°, 5° down, and 10 ° down are compared, illuminance readings are increasing. Maximum illuminance readings are observed when the angle is 10°

down, meaning that the best light distribution of the 250 W MV is obtained when the angle is 10^o down.

Figure 4.8 shows the best light distribution of the 250 W MV light source at 10^o down. The distribution appears to be more uniform, and illuminance values range with maximum illuminance of 160 lux. For row “H,” the average illuminance level is approximately 110 lux. This light distribution should ensure that motorists can see the legend on signs wherever it is located on the sign when illuminated using a 250 W MV light source installed with a 10^o angle downward with the horizontal.

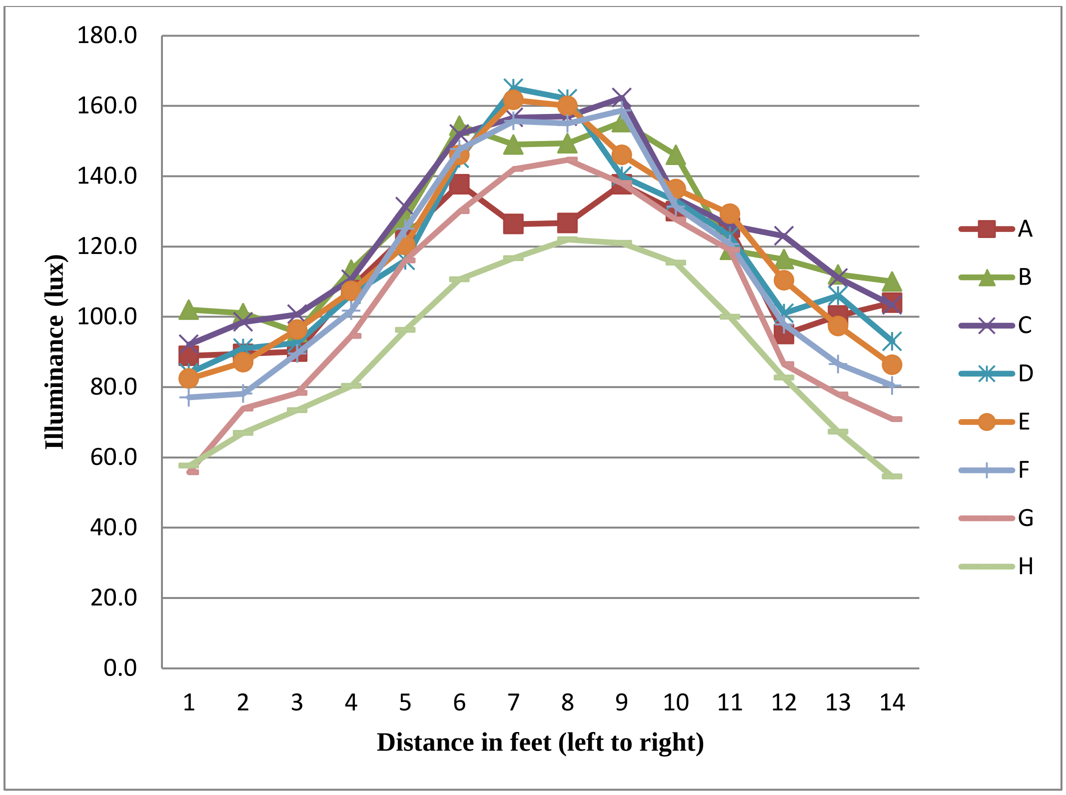


Figure 4.8: The Best Light Distribution of MV (Angle 10^o down)

Table 4.1: Illuminance Readings of the MH Light Source at Different Angles

	Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0 degree	125.0	140.0	171.3	176.0	213.3	201.7	194.3	196.0	188.3	174.3	159.3	147.0	116.3	83.7
	5 degree	147.3	181	213.5	277.3	308	320.5	297.7	311.3	310.7	295.7	277.7	191.7	151	109.7
	10 degree	168	210.3	274	359	389.3	387	404.5	422	480.3	411.3	301.7	242	157	114
	15 degree	168.7	207.3	246	343.3	398.5	395.3	395.3	415.5	435	325	234.5	175	141.3	106.7
B	0 degree	119.7	144.7	155	188.3	204.3	217.3	200.3	214.3	217.3	199.7	187	117.7	115.3	92.4
	5 degree	147.3	165	197.3	252.3	299.7	290.3	269	288.7	283.7	257.3	252.3	183.3	134	106
	10 degree	169.7	204.7	261	348.3	383.3	412.3	395	417.3	441	408	379.5	220	154.7	114
	15 degree	185.3	224.7	320.3	453	508	522.7	527.5	539.3	573	466	306	224.3	157	111.3
C	0 degree	116	141.3	170.3	200.7	197	221	213.7	206.7	206	204.3	173	127.3	93.4	83.8
	5 degree	134.7	156.7	184	235.3	250.5	278.5	281	293.5	282.5	257.7	223.7	162.7	126.3	98
	10 degree	161	199.5	239.7	294.3	371	383.3	359.7	379	410.3	366.3	297.3	190	149	113
	15 degree	200.7	229	336.7	466.7	569.5	573	588	608.3	715.7	559	377	255.5	176.7	127
D	0 degree	122.3	154	187	206.3	216	204	220.7	203.3	194.7	208	196.7	151.7	113.7	79.8
	5 degree	128.3	151.7	207.7	233	255.7	272.7	281.5	300	260	255	201	161	128	92.5
	10 degree	139.7	174.7	212	268	297.5	339	346	356	347.3	315	247.5	171.7	135.3	105
	15 degree	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
E	0 degree	136.7	151.3	205.3	220.3	189.5	177.7	178	190	179	199	233	146.7	109	74.1
	5 degree	154	176	223.5	271.5	240.3	244	265.3	249.7	239	262	232.5	172.5	133.7	88.5
	10 degree	130.5	181	224.5	265	304	323	347	317	310	310.3	241.5	167	124.7	89.8
	15 degree	148	211.3	256.3	348.3	391.3	462.7	461.7	477.3	445.7	386.3	278.7	201.7	157.5	119.3
F	0 degree	100.3	115.3	158.7	147.3	143.7	152.7	120.0	144.0	148.0	134.7	160.0	118.3	80.9	57.0
	5 degree	167	180	239.3	277.3	202.7	200.7	197	213.7	207.3	220.7	261	166	113	78.4
	10 degree	175.3	198	248	313.3	288.5	275	273.3	272	302.5	348	275.5	175	111.7	66.8
	15 degree	186.7	215	277.3	326.7	413	414	438	385	418	361.7	291	199	127	87.6
G	0 degree	91.6	84.7	81.5	78.5	91.1	102	92.7	93.5	96.5	70.9	80.7	73.6	52.2	37.2
	5 degree	106	122.3	135.7	147	142	154.7	115	136	137	133.3	124.5	99.2	74.6	51.1
	10 degree	135.3	151.7	205.5	223	199	194.3	155.3	213	203.7	213.3	224	133	92.6	57.7
	15 degree	177.7	203.3	267	365	304	279.7	282	300.7	330	410	292	167.3	102.3	63.7
H	0 degree	54.2	53.9	47.4	40.3	53.9	72.7	65.5	61.5	58.4	39.3	39.1	45	35.5	30.9
	5 degree	93.2	83.4	66.3	66.8	79	98.5	88.3	86.7	86.6	64.6	55.8	62.6	44.4	36.1
	10 degree	98.9	90	94.5	99.7	109.3	127.3	109.3	116.3	113.3	94.5	92.3	79	55.2	43.3
	15 degree	141.0	152.7	194.3	190.3	187.0	196.7	146.7	197.3	188.3	190.7	181.7	113.3	73.7	48.9

Table 4.2: Illuminance Readings of the MV Light Source at Different Angles

	Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0 degree	55.6	59.1	60.6	62.9	67.1	73.1	84.8	84.7	79.2	71.7	68.2	61.7	61.8	53.6
	5 degree Up	46.9	45.8	49.6	56	58.7	61.1	70.3	61	65.7	67	61.2	50.5	49.9	47.2
	5degree Down	70.1	70.7	74.4	81.2	92.1	117.7	114	111	104.7	98.5	96.8	75.5	74	73.4
	10 degree	88.9	89.4	90.1	108.3	123	137.7	126.3	126.7	137.7	130	125.3	95	100.3	104
B	0 degree	58.8	60.7	62.5	69.1	75.1	83.3	85.5	86	79.5	74.6	74.4	64.6	59.8	53.3
	5 degree Up	44.6	47.7	47	53.1	49	65.7	71.8	70.2	67.8	64.5	65.7	61.9	53.4	48.7
	5degree Down	74.5	74.1	73.8	85.3	88.7	110	111.7	122.5	105	95.7	95.1	83.3	77.3	71.1
	10 degree	102	101	95.6	113.3	128	154.3	149	149.3	155.3	146	119	116.3	112	110
C	0 degree	54.3	60.7	64.7	69.8	78.8	89.7	97.2	98.9	92.5	78.8	74.7	64.6	61.5	54.1
	5 degree Up	43.5	46.6	50.3	50.3	55.8	64.4	75.5	75.7	76.7	82.4	71	64.7	57	50.3
	5degree Down	72.4	72.7	73.9	87.2	96.2	112.3	120.5	122	119.3	97.5	97.8	85.2	76.6	69.4
	10 degree	92.1	98.5	100.7	110.7	131.3	152	156.7	157	162.3	133.7	126	123	111	103.3
D	0 degree	58.6	60	65.2	71.8	82.1	93.4	99.7	97.4	87.8	86.9	79.7	66.7	64.7	54.1
	5 degree Up	40.6	47.1	50.5	57.6	65.9	76.5	82.1	82.2	82.4	74.8	76	58	57.3	50.2
	5degree Down	69.5	78.8	79.6	85.6	100.5	109.3	124	128	117.3	101.7	99	78.2	77.3	68.6
	10 degree	84	91	92.6	106.3	116	145	165	162	140	133	123	101	106	93
E	0 degree	54.3	56.6	63.4	73.3	81.5	94.8	98.1	98.1	99.6	99.3	92.9	88.1	71.4	52.6
	5 degree Up	43.7	45	46.7	49.4	58.1	66	77.4	81.5	85.5	84.6	77.7	58.7	56.4	48.9
	5degree Down	69.9	70.2	80.6	86.2	100.1	118.3	123.7	124.7	116.7	101.2	102.3	85.5	79.9	65.4
	10 degree	82.4	87	96.4	107.3	120.3	146	161.7	160	146	136.3	129.3	110.3	97.3	86.3
F	0 degree	46.3	47.3	65.1	74.5	84.0	98.7	97.1	98.0	99.3	91.3	88.1	65.5	59.0	49.6
	5 degree Up	40.4	44.4	48.6	59.8	60.1	70.9	72.4	81.3	87.3	83.7	78.9	64.1	53.6	44.6
	5degree Down	72.6	67.6	73.6	85.7	90.8	117.7	126	125	125.7	112	104	85.3	75.1	63.4
	10 degree	77.1	78.1	89.5	101.7	125	147.7	155.7	155	158.7	131.3	120.7	97.8	86.5	80.4
G	0 degree	42.6	51.9	62.2	64.0	68.8	84.2	83.3	87.1	90.0	91.7	83.3	64.3	55.6	44.4
	5 degree Up	25.6	29.9	36.4	41.1	48.2	50.2	35.1	45.6	61.9	67.9	63.8	44.4	34.8	14.3
	5degree Down	66.6	60.9	68.7	76.8	86.1	107.3	112	114.7	116.3	102	104.3	73	64.6	55.8
	10 degree	55.8	73.9	78.3	94.5	116.0	130.0	142.0	144.7	138.0	127.7	119.0	86.5	77.9	70.9
H	0 degree	38.1	42.6	45	56.1	61.4	68.5	58.9	64.6	76.8	78.1	71.4	52.2	46.6	33.7
	5 degree Up														
	5degree Down	48.1	54.1	61.9	65.4	74.1	91.1	88.4	94.5	96.3	90.9	79.1	68.9	57	45.2
	10 degree	57.6	67.0	73.4	80.3	96.2	110.7	116.7	122.0	121.0	115.3	100.0	82.7	67.3	54.5

Table 4.3: Illuminance Readings of the Induction Lighting Source at Different Angles

	Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0 degree	97.4	110.7	116.7	111.0	111.0	111.0	115.0	119.0	117.3	113.7	114.3	120.7	109.7	90.7
	5 degree	102.7	119.7	117.7	115	123.3	124.3	124.3	127.3	123	118	116.3	107.3	108	99.3
	10 degree	121.3	132	141.7	130.7	134.3	132.7	127.3	129	135.3	137.3	134.7	122.3	115.7	101
	15 degree	110.7	116.3	126.7	122	123.3	126.3	120	120.3	121	126	117.3	106	103.3	89.6
B	0 degree	105.7	117.3	120.3	127.7	129	132	125	124	126.3	124.3	125.3	123	101.7	86.7
	5 degree	122.3	135	143.3	142	143.3	148	137.3	135	134.7	131.7	131.7	129.7	113.3	94.4
	10 degree	124.7	148.3	156	150.7	154.3	164.7	153	152.7	150.3	145.3	142	135.7	119.7	101.7
	15 degree	126	149.3	155.3	154.7	158.7	159.3	150	149	151	145.3	138.7	133	116.3	99
C	0 degree	103.3	112.7	117.3	127.3	129.3	139.3	134	135	144.7	130	130	127.7	104	89.4
	5 degree	115.3	131	154	159	158	168	155	154.3	172	157	159	147	118	97.9
	10 degree	132.7	158	179.3	182.7	184.7	192.3	184.7	183.3	197	176.7	175.7	175.3	138	110
	15 degree	140.3	152.3	184.3	194.7	197.7	203	195	194.7	219	190.7	185.3	184.3	141.3	115.3
D	0 degree	94.1	98.8	104.3	125	126.7	124.7	128.3	129.3	131.7	129	129.3	117.3	105	89.7
	5 degree	110	129	140.7	160	164.3	164.3	169	171	165.7	163.3	157.3	138.7	117	97.1
	10 degree	130.3	144.7	177	201	215.3	203.3	205	205.3	207.7	208	206	175	140.7	112
	15 degree	138	177.3	209.7	235	247.7	247.7	251.3	253	243.3	240	229.3	199.3	157.7	123
E	0 degree	90.2	97.5	102.3	113.3	134	121	120	121	125	133.7	130.7	117.7	103	87.4
	5 degree	101.3	112.7	122	159.7	170.7	163	155	156.3	154.7	159.3	153.3	135.3	117	95.6
	10 degree	121.7	146	170.3	210.3	215.3	216.3	222	223	221.7	215	202.3	170.3	139.3	111.3
	15 degree	130	172	207.7	270.7	288	280.3	281	280	285	284.7	271	214.7	164	126.7
F	0 degree	81.8	88.9	104.7	127.3	145.0	128.0	117.7	116.0	123.0	132.0	125.0	110.3	96.6	84.1
	5 degree	90.3	105.7	129	151	170.3	145.7	138	136	143.3	155	144	127.7	107	90.7
	10 degree	104.7	129.7	156.3	202	211.7	190.7	190	191.7	189.7	197.7	181.3	155.7	131	104
	15 degree	124	153.3	191.7	266.3	303.3	285.7	291	294	282.3	275.7	245.3	209	153.7	119
G	0 degree	74.3	83.4	95.5	108.7	125.3	131	135.7	134	125	125	115.7	99	89.2	75.5
	5 degree	85.7	97.5	119.7	136	152	139	137	133.7	134	139	128	108	97.7	84.3
	10 degree	75.2	114.7	125.7	149.3	181.3	167.7	153.3	152	160	173.3	157.3	133	115	96.7
	15 degree	107.3	138	169.7	209.7	238.3	224	223.7	225	219	232.7	206.3	174	141	112.3
H	0 degree	61.6	69.2	76.3	92.8	117	137	144.3	142	132.3	116	102	93.8	79.3	64.7
	5 degree	76.4	79.7	94	113.7	124.3	145.3	151.7	150.3	137.3	128	117.3	103.3	85.6	73
	10 degree	81.7	90.3	105.3	122.7	150.3	161.7	167.7	163.7	155.3	138	117	100.7	82.7	71.3
	15 degree	106.0	111.0	133.7	168.0	194.7	191.3	180.0	175.0	185.7	193.3	170.0	142.3	121.7	101.3

4.5.3 Induction Lighting Source

For the 85 W induction light source, the light source unit was set in front of the white sheet of paper at four different angles. These angles were measured between the bottom of the light source unit and the floor. These angles were 0^o, 5^o downward, 10^o downward, and 15^o downward. At each angle, illuminance readings were taken using the Minolta Illuminance meter.

Table 4.3 shows the illuminance reading average at each intersection point at the specified angle for the 85 W induction light source. When comparing illuminance readings for the 0^o and 5^o down angles, increase occurred at 5^o angle, meaning this move is in the correct direction of rotation. When illuminance readings between 0^o, 5^o down, and 10^o down are compared, the illuminance readings are increasing for rows B to H. Through rows A to H, the maximum illuminance readings were shown when the angle was 15^o down with one exception for row A. When moving from 10^o to 15^o, illuminance values at 10^o angle are a little bit higher. In general, for the 85 W induction light source, the best light distribution is produced when the angle is 15^o.

Figure 4.9 shows optimal light distribution of the 85 W induction light source at 15^o down, indicating that better light distribution exists compared to the 10^o angle distribution for rows B to H. The distribution appears to be more uniform and illuminance values range with maximum illuminance around 300 lux. This light distribution should ensure that motorists can see the legend on overhead guide signs wherever it is located on the sign when illuminated using an 85 W induction light source installed with a 15^o angle downward with the horizontal.

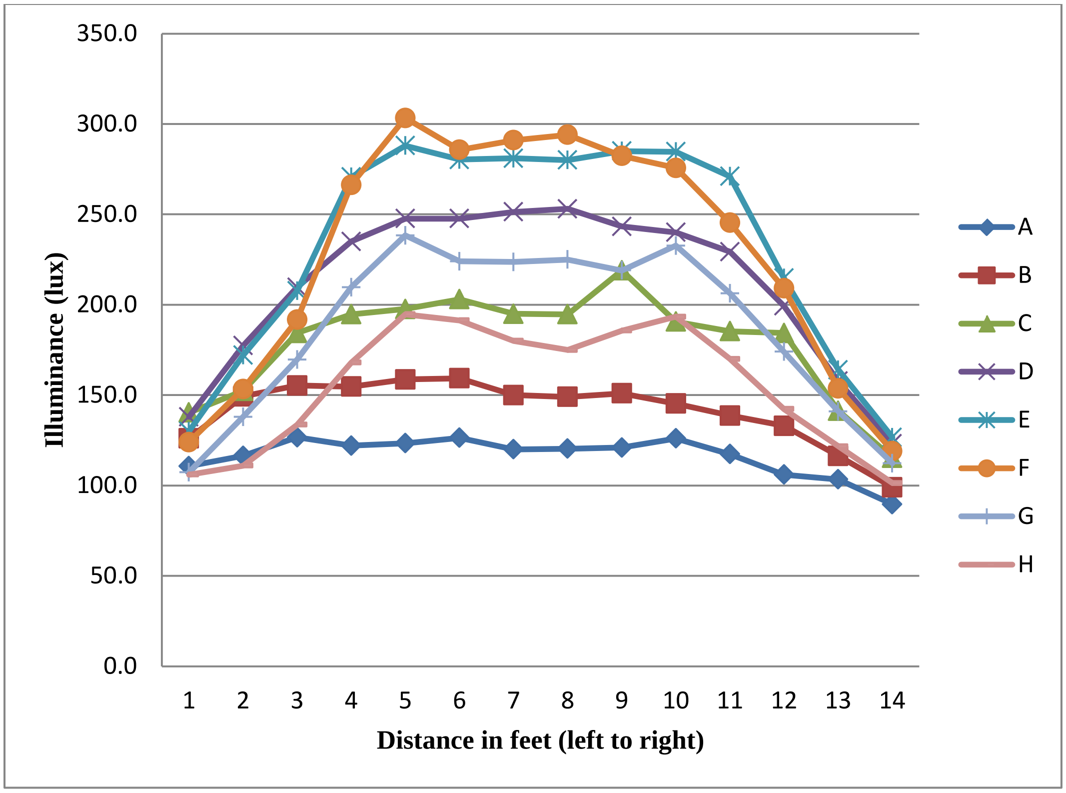


Figure 4.9: Optimal Light Distribution of Induction Lighting (Angle 15° down)

4.5.4 HPS Light Source

For the 250 W HPS light source, the light source unit was set in front of the white sheet of paper at 0° angle only because the output luminance was very high. Illuminance readings were taken using the Minolta Illuminance meter.

Table 4.4 shows the illuminance reading average at each intersection point at the specified angle for the 250 W HPS light source. Light distribution for the HPS at 0° angle was considered the best because the measured illuminance values were very high, thus allowing motorists to see the sign, as shown in Table 4.4. Figure 4.10 shows the best light distribution of the 250 W HPS light source at 0°. The light distribution appears to be uniform, and illuminance values range with maximum illuminance value around 800 lux. This light distribution should ensure that motorists can see the legend on overhead guide signs wherever it is located on the sign when illuminated using a 250 W HPS light source fixed with a 0° angle with the horizontal.

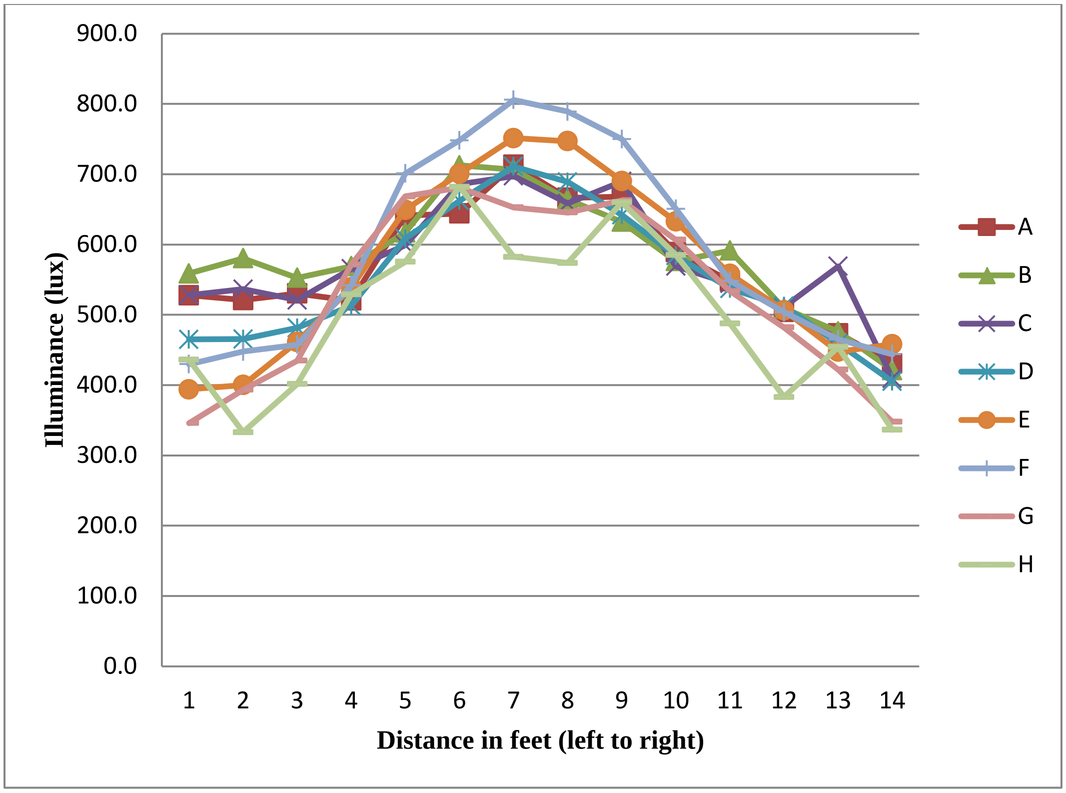


Figure 4.10: Optimal Light Distribution of HPS Light Source

4.5.5 LED Light Source

For the 62 W LED light source, the light source unit was set in front of the white sheet of paper at 0^o angle because the design of this LED includes independent and adjustable LED arrays. By rotating these arrays, the LED light can be focused to any place on the sign. The Lumi Trak Company manager informed the KSU research team that this LED unit is ready to be installed since the angles of LED arrays are already fixed to the appropriate position to focus light along a sign of similar size to the sheet of paper. Illuminance readings were taken using the Minolta Illuminance meter.

Table 4.5 shows the illuminance reading average at each intersection point at the specified angle for the 62 W LED light source. Light distribution for the LED at 0^o angle was considered the best because the LED arrays are already fixed to the appropriate position to focus the light. Figure 4.11 shows the best light distribution of the 62 W LED light source at 0^o. The distribution appears to be uniform, and illuminance values range with maximum illuminance value around 165 lux. This light distribution should ensure that motorists can see the legend on overhead guide signs wherever the legend is located on the sign when illuminated using a 62 W LED light source fixed with a 0^o angle with the horizontal.

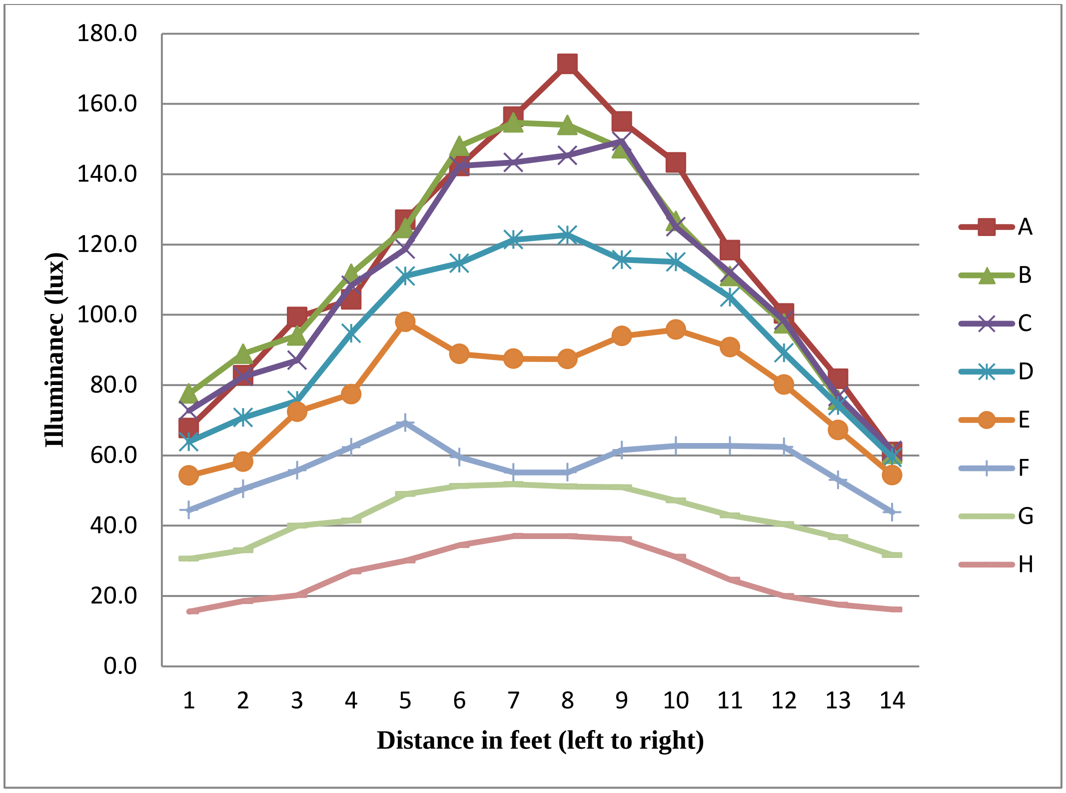


Figure 4.11: The Best Light Distribution of LED Light Source

4.6 Light Sources Comparison Based on Light Distribution

Table 4.6 includes illuminance reading at the best light distribution of the five light sources studied. Based on Table 4.6, for all rows (A to H), the HPS light source has the highest illuminance readings, meaning that it is the best light source among the studied sources. The MH is the next, followed by induction lighting, MV, and LED. In summary, the HPS light source is the best among traditional light sources, followed by MH and MV. Among the new generation light sources, induction lighting is recommended light source.

Table 4.4: Illuminance Readings of the HPS Light Source at 0^{o} Angle

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	527.7	521.0	530.3	520.3	641.0	644.0	713.3	666.3	668.0	589.0	547.7	504.0	473.7	430.7
B	558.7	580.3	552.7	569.0	617.0	712.7	706.3	664.0	632.3	576.3	591.3	509.0	476.0	421.3
C	528.0	536.3	521.0	565.3	598.7	686.0	697.3	658.3	689.7	569.0	544.3	511.0	569.0	409.3
D	465.0	465.3	481.3	512.7	608.3	662.3	711.0	689.0	642.0	584.0	537.3	512.3	459.0	405.0
E	394.0	400.0	461.3	539.0	649.3	700.7	751.3	747.0	690.3	632.7	558.0	506.3	447.3	458.0
F	429.7	447.7	457.3	541.7	701.0	748.0	805.7	789.0	750.0	650.7	548.3	503.7	465.0	443.7
G	346.0	393.3	434.7	571.3	668.3	680.7	652.7	645.3	662.7	606.7	533.7	482.0	422.0	347.7
H	436.0	333.0	401.3	529.0	575.3	682.0	582.3	573.7	660.0	585.0	487.7	383.0	454.3	336.3

Table 4.5: Illuminance Readings of the LED Light Source at 0^{o} Angle

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	67.8	82.7	99.3	104.3	127.0	142.3	156.3	171.3	155.0	143.3	118.3	100.3	81.8	60.9
B	77.6	88.9	94.1	111.7	124.7	148.0	154.7	154.0	147.3	126.7	111.0	97.5	75.8	60.4
C	72.7	82.4	87.0	108.3	118.7	142.3	143.3	145.3	149.3	125.0	112.0	98.4	76.7	61.4
D	63.9	70.7	75.6	94.7	111.0	114.7	121.3	122.7	115.7	115.0	105.0	89.2	74.1	59.4
E	54.3	58.2	72.4	77.4	98.0	88.8	87.5	87.4	93.9	95.8	90.8	80.1	67.2	54.4
F	44.4	50.4	55.7	62.3	69.3	59.5	55.1	55.2	61.5	62.7	62.7	62.4	53.0	43.8
G	30.6	33.0	40.0	41.5	49.0	51.3	51.8	51.1	50.9	47.1	42.9	40.4	36.7	31.6
H	15.5	18.5	20.2	26.9	30.0	34.4	37.0	37.0	36.2	31.1	24.6	20.0	17.5	16.1

Table 4.6: Comparison of the Best Light Distribution of the Five Light Sources

	Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	MH	168.7	207.3	246	343.3	398.5	395.3	395.3	415.5	435	325	234.5	175	141.3	106.7
	MV	88.9	89.4	90.1	108.3	123	137.7	126.3	126.7	137.7	130	125.3	95	100.3	104
	HPS	527.7	521.0	530.3	520.3	641.0	644.0	713.3	666.3	668.0	589.0	547.7	504.0	473.7	430.7
	Induction	110.7	116.3	126.7	122	123.3	126.3	120	120.3	121	126	117.3	106	103.3	89.6
	LED	67.8	82.7	99.3	104.3	127.0	142.3	156.3	171.3	155.0	143.3	118.3	100.3	81.8	60.9
B	MH	185.3	224.7	320.3	453	508	522.7	527.5	539.3	573	466	306	224.3	157	111.3
	MV	102	101	95.6	113.3	128	154.3	149	149.3	155.3	146	119	116.3	112	110
	HPS	558.7	580.3	552.7	569.0	617.0	712.7	706.3	664.0	632.3	576.3	591.3	509.0	476.0	421.3
	Induction	126	149.3	155.3	154.7	158.7	159.3	150	149	151	145.3	138.7	133	116.3	99
	LED	77.6	88.9	94.1	111.7	124.7	148.0	154.7	154.0	147.3	126.7	111.0	97.5	75.8	60.4
C	MH	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
	MV	92.1	98.5	100.7	110.7	131.3	152	156.7	157	162.3	133.7	126	123	111	103.3
	HPS	528.0	536.3	521.0	565.3	598.7	686.0	697.3	658.3	689.7	569.0	544.3	511.0	569.0	409.3
	Induction	140.3	152.3	184.3	194.7	197.7	203	195	194.7	219	190.7	185.3	184.3	141.3	115.3
	LED	72.7	82.4	87.0	108.3	118.7	142.3	143.3	145.3	149.3	125.0	112.0	98.4	76.7	61.4
D	MH	183.3	225	298.5	397	495	527.5	518.3	547.3	627	519.3	354.5	212.3	174	131
	MV	84	91	92.6	106.3	116	145	165	162	140	133	123	101	106	93
	HPS	465.0	465.3	481.3	512.7	608.3	662.3	711.0	689.0	642.0	584.0	537.3	512.3	459.0	405.0
	Induction	138	177.3	209.7	235	247.7	247.7	251.3	253	243.3	240	229.3	199.3	157.7	123
	LED	63.9	70.7	75.6	94.7	111.0	114.7	121.3	122.7	115.7	115.0	105.0	89.2	74.1	59.4
E	MH	148	211.3	256.3	348.3	391.3	462.7	461.7	477.3	445.7	386.3	278.7	201.7	157.5	119.3
	MV	82.4	87	96.4	107.3	120.3	146	161.7	160	146	136.3	129.3	110.3	97.3	86.3
	HPS	394.0	400.0	461.3	539.0	649.3	700.7	751.3	747.0	690.3	632.7	558.0	506.3	447.3	458.0
	Induction	130	172	207.7	270.7	288	280.3	281	280	285	284.7	271	214.7	164	126.7
	LED	54.3	58.2	72.4	77.4	98.0	88.8	87.5	87.4	93.9	95.8	90.8	80.1	67.2	54.4

Table 4.6: Comparison of the Best Light Distribution of the Five Light Sources (Cont.)

F	MH	186.7	215	277.3	326.7	413	414	438	385	418	361.7	291	199	127	87.6
	MV	77.1	78.1	89.5	101.7	125	147.7	155.7	155	158.7	131.3	120.7	97.8	86.5	80.4
	HPS	429.7	447.7	457.3	541.7	701.0	748.0	805.7	789.0	750.0	650.7	548.3	503.7	465.0	443.7
	Induction	124	153.3	191.7	266.3	303.3	285.7	291	294	282.3	275.7	245.3	209	153.7	119
	LED	44.4	50.4	55.7	62.3	69.3	59.5	55.1	55.2	61.5	62.7	62.7	62.4	53.0	43.8
G	MH	177.7	203.3	267	365	304	279.7	282	300.7	330	410	292	167.3	102.3	63.7
	MV	55.8	73.9	78.3	94.5	116	130	142	144.7	138	127.7	119	86.5	77.9	70.9
	HPS	346.0	393.3	434.7	571.3	668.3	680.7	652.7	645.3	662.7	606.7	533.7	482.0	422.0	347.7
	Induction	107.3	138	169.7	209.7	238.3	224	223.7	225	219	232.7	206.3	174	141	112.3
	LED	30.6	33.0	40.0	41.5	49.0	51.3	51.8	51.1	50.9	47.1	42.9	40.4	36.7	31.6
H	MH	141	152.7	194.3	190.3	187	196.7	146.7	197.3	188.3	190.7	181.7	113.3	73.7	48.9
	MV	57.6	67	73.4	80.3	96.2	110.7	116.7	122	121	115.3	100	82.7	67.3	54.5
	HPS	436.0	333.0	401.3	529.0	575.3	682.0	582.3	573.7	660.0	585.0	487.7	383.0	454.3	336.3
	Induction	106	111	133.7	168	194.7	191.3	180	175	185.7	193.3	170	142.3	121.7	101.3
	LED	15.5	18.5	20.2	26.9	30.0	34.4	37.0	37.0	36.2	31.1	24.6	20.0	17.5	16.1

Chapter 5: Sign Retroreflectivity Evaluation Based on Statistical Analysis of Field Experiment Data

5.1 Introduction

Sign visibility can be improved with the utilization of brighter retroreflective sheeting on sign. KDOT provided the KSU research team with three signs with various retroreflective sheeting to be used on overhead guide signs. These sheeting types are all produced by 3M Company and can be categorized into the following sign sheeting categories: Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV). A field experiment was performed using human participants of different age categories in order to determine which sign sheeting provides best visibility to drivers from a specific distance during nighttime. This experiment was approved by the Committee on Research Involving Human Participants at Kansas State University, and the approval letter is shown in Appendix B.

In this experiment, the low beam headlight of a vehicle was divided into 16 brightness levels using an illumination controlling device produced in electrical engineering laboratory at KSU. For each brightness level, the illuminance on one sign at the specified distance was measured using Minolta Illuminance meter. A statistical analysis was run using Statistical Analysis System (SAS) software to determine significant variables that contribute to sign visibility and to conclude which sign was judged to be the best. The following sections provide the experiment details.

5.2 Retroreflective Sheeting Details

Three signs were used in the field experiment. Sign letters were a combination of an uppercase letter for the initial word and lowercase letters for the other letters. Uppercase letters were 6 inches (2.362 cm) in height, and lowercase letters were 4.5 inches (1.772 cm), as required in the MUTCD. The legend font on all signs used was Series E (Modified). The signs were 5 ft (152.4 cm) wide and 1.5 ft (45.72 cm) in height. Figures 5.1, 5.2, and 5.3 show Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV) signs used in the experiment, respectively.

Retroreflectivity of each sign background and legend was measured using a 920 SEL retroreflectometer in the Human Factors Laboratory in the IMSE Department at KSU. Retroreflectivity of the background was measured by dividing each sign into 10 columns and four rows. At each row-column intersection, the 920 SEL retroreflectometer measured retroreflectivity at the green background of the sign and then the sign's background retroreflectivity values were averaged to find the overall background retroreflectivity. For the sign legend, the 920 SEL retroreflectometer measured retroreflectivity of the first letter of each word on signs 'M' three times, and the average of these readings was calculated to obtain the overall legend retroreflectivity value. This procedure was repeated for the sheeting of all three signs. Retroreflectivity values are shown in Table 5.1. As shown in Table 5.1, the three signs have the minimum retroreflectivity values for both legend and background as required in the MUTCD.

Table 5.1: Retroreflectivity Values of the Three Signs' Sheeting

Sign Sheeting	**Background Retroreflectivity ($cd.m^{-2}.lux^{-1}$)**	**Legend Retroreflectivity ($cd.m^{-2}.lux^{-1}$)**
Engineering Grade (Type I)	32.9	64.9
Diamond Grade (Type XI)	140.9	716.3
High Intensity (Type IV)	97.3	553.3

Figure 5.1: Engineering Grade (Type I) Sheeting Sign

Figure 5.2: Diamond Grade (Type XI) DG3 Sheeting Sign

Figure 5.3: High Intensity (Type IV) Sheeting Sign

5.3 Building an Illumination Controlling Device

An illumination controlling device (also called a Pulse-Width-Modulation [PWM] headlight dimmer module) for vehicle headlamps was built in the electrical engineering laboratory at KSU. In this device, the PWM headlight dimmer uses a PWM to allow the user to dim vehicle headlights to one of 16 brightness levels recorded in even increments between 0 and 15.

On startup, the PWM peripheral microprocessor is configured to produce a 12.5 kHz square wave with a variable duty cycle, and the Periodic Interrupt Timer (PIT) of the microprocessor generates a software interrupt every millisecond. When the PIT interrupts, the microprocessor reads the value of the duty cycle selector knob, which is a 16-position binary encoder. When the value of the duty cycle is changed since the last time it was read, the microprocessor retrieves a new configuration value for the PWM peripheral from the duty cycle lookup table. Then, the microprocessor reconfigures and enables the PWM module to produce a waveform with the desired duty cycle. The custom analog breadboard contains four headlight driver circuits controlled by the PWM signal from the microprocessor. Large P-channel power

Metal Oxide Semiconductor Field Effect Transistors (MOSFET) act as a voltage-controlled current switch connected in series with the vehicle's headlight. The P-channel model number is IRF9540. Changing the duty cycle of the generated PWM waveform changes how long the current is allowed to flow through the headlights, increasing or decreasing their brightness. Power transistors are mounted on external heat sinks, allowing the dissipation of heat generated by large headlight currents. Because the microprocessor is unable to directly drive the gates of the large power Field Effect Transistor (FET), the PWM signal to each headlight driver circuit is buffered by a 74HC04 hex inverter and a smaller 2N7000 n-channel MOSFET.

The PWM headlight dimmer module is connected to the vehicle's electrical system by custom fuse-connector cables. To connect the dimmer to the vehicle, the vehicle headlight fuses must be removed and the dimmer's cable must be plugged into the empty sockets. When the dimmer is switched on, the current that normally flows to the headlights is routed through the dimmer's power MOSFETs, thus replacing vehicle headlight fuses with voltage-controlled switches. To ensure the headlights are still protected, headlight fuses are then inserted in special inline fuse holders built into the dimmer cables. The PWM headlight dimmer is compatible with all vehicles that utilize Auto or Mini-style blades fuses. The dimmer can be powered if headlight fuses are located in the fuse boxes in the driver's cabin or the dimmer module can be plugged into the car cigarette lighter. If the headlight fuses are located in the fuse box under the vehicle's hood, dimmer power can be obtained by connecting dimmer to the vehicle's battery terminals.

After connecting the PWM headlight dimmer to the vehicle, the user starts the vehicle and turns on the headlights. Then, the user turns the PWM dimmer's power switch on and powers the headlights by turning the duty cycle select knob located on top of the dimmer. Figure 5.4 shows the headlight dimmer with its knob, the power FETs, and the printed-circuit boards of the microcontroller and custom analog breadboard.

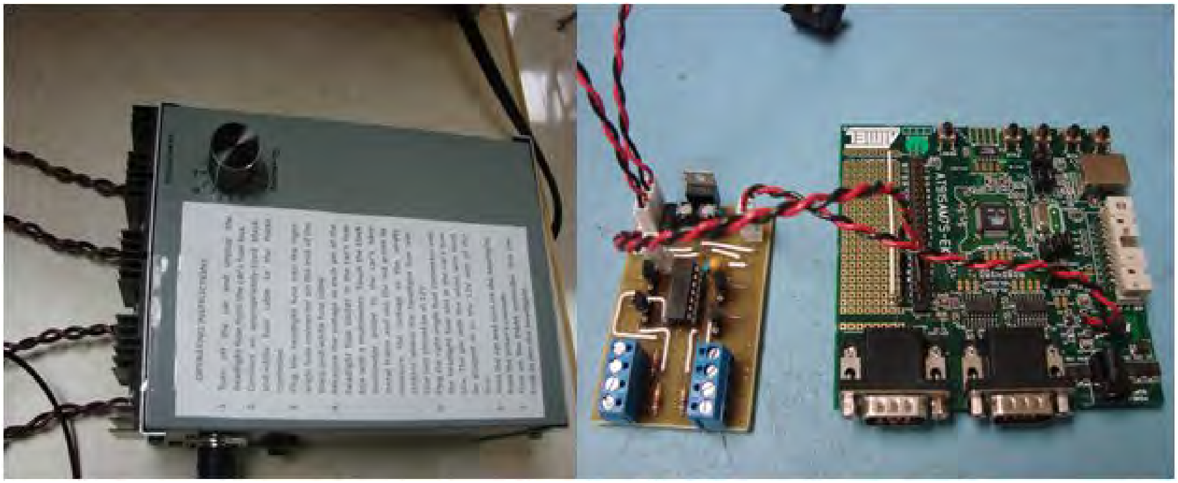


Figure 5.4: PWM Headlight Dimmer, Printed Circuit Board, and Custom Analog Breadboard

5.4 Experimental Setup

The field experiment was performed at the St. Thomas More Catholic Church rear parking lot at night after 8:30 pm to ensure a complete darkness. All lights in the church building and parking lot were turned off by church management to ensure darkness. No moon was present, guaranteeing that the only source of present light was the vehicle's headlight. The vehicle used was a 2011 Chevrolet Impala from the KSU Motor Pool. A total of 43 human subjects of various age groups were selected to find the effect of driver's age on nighttime visibility.

A post was designed in the IMSE workshop to mount the signs while conducting the experiment, as shown in Figure 5.5. The post height was 8 ft (243.84 cm), measured from the bottom of the sign to the road surface. This height is in compliance with MUTCD requirements. The lateral offset for the post was 6 ft (182.88 cm) from the edge of the driving lane to the nearest edge of the sign. The lateral offset is also in compliance with MUTCD requirements.

While running the experiment, the vehicle was stationary at two distances from the sign on the parking lot driving lane - 240 ft and 180 ft.

Figure 5.5: Post Used in the Experiment with One Mounted Sign

5.5 Procedure

The field experiment was carried out at night, and the illumination control device (PWM headlight dimmer) which controls vehicle headlight brightness at 16 levels was connected to the vehicle fuse box located under the vehicle hood. Fuses of the vehicle front safety lights were removed to ensure only light from the headlights were the main source of illuminating while performing the experiment. The sign post was placed on its specified position according to the MUTCD requirements. The field experiment was conducted in 30 minutes sessions; only one human subject was present at the experiment location for each session. At the beginning of each session, the subject was asked to complete a consent form shown in Appendix C. The age of each subject was also recorded.

Before beginning the experiment, instructions were given to each participant:

- You will be seated in the driver's seat of a sedan vehicle and one of the experimenters will be seated in the passenger seat.
- Initially, the vehicle headlights will be turned off and then turned on to level 0 of the illumination.
- You will be asked to read the legend on the sign without stressing your eyes. If you cannot read the word on the sign without stressing your eyes, ask the experimenter to go to the next level of illumination.

- When you are able to see the word on the sign, read it aloud so the experimenter knows that you have read the word and he can record the reading.
- This procedure is repeated for two more signs.
- After the first stage, you will be taken to the other location and the same procedure will be repeated for a total of three signs.

5.6 Results

Data collected from the 43 subjects are shown in Table 5.2. For each subject, the subject number, age, and knob position of illuminance controlling device at which the subject read the legend on each sign at the specified distance was recorded.

The Minolta Illuminance meter was used to measure the illuminance level for each of the 16 brightness levels. When measuring illuminance for each brightness level, three positions on the sign legend were selected: the right side, the center, and the left side. For each position, three illuminance readings were taken and then the readings average was calculated. The average of illuminance readings at each headlights brightness level was calculated as shown in Table 5.3.

Table 5.2: Field Experiment Data of Human Subjects

Subject	Age	240 ft Distance			180 ft Distance		
		Type I	Type XI	Type IV	Type I	Type XI	Type IV
1	20	6	3	4	5	3	3
2	20	Can't read	14	11	10	5	12
3	20	14	8	14	15	6	9
4	23	Can't read	5	10	14	5	10
5	20	9	4	6	8	5	4
6	24	7	4	5	4	3	4
7	20	12	4	5	6	3	4
8	20	Can't read	4	Can't read	11	4	6
9	20	Can't read	5	7	13	4	6
10	21	10	4	4	7	3	4
11	22	12	4	5	8	5	5
12	20	15	5	7	9	4	7
13	20	9	4	4	7	3	4
14	20	8	3	6	7	3	5
15	21	9	3	4	5	3	3
16	21	14	4	6	7	3	5
17	37	Can't read	Can't read	11	Can't read	7	Can't read
18	30	15	7	7	7	4	6
19	46	Can't read	7	11	11	5	5
20	35	6	3	4	5	3	3
21	34	Can't read	6	Can't read	10	4	9
22	31	13	4	4	9	4	4
23	58	Can't read	10	10	Can't read	6	7
24	56	10	5	6	7	4	6
25	39	9	3	4	6	3	4
26	20	7	4	5	6	3	5
27	20	6	2	3	4	1	3
28	34	12	4	6	6	3	5
29	33	7	3	4	7	2	5
30	21	5	3	4	4	3	4
31	23	Can't read	5	Can't read	14	4	5
32	20	7	3	3	5	2	4
33	79	15	6	8	9	4	7
34	81	13	8	11	8	4	9
35	64	Can't read	4	6	6	3	4
36	59	5	2	3	4	2	3
37	52	10	3	5	6	3	3
38	77	15	5	6	9	4	6
39	73	7	3	5	5	3	5
40	53	Can't read	8	Can't read	15	6	13
41	34	Can't read	3	6	5	3	5
42	37	8	4	5	5	2	4
43	35	7	2	5	4	2	3

Table 5.3: Illuminance Readings for Each Brightness Level at Two Locations from the Sign

Knob Position	240 ft Distance				180 ft Distance			
	Left	Center	Right	Average	Left	Center	Right	Average
0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
3	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03
4	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04
5	0.05	0.05	0.05	0.05	0.06	0.05	0.06	0.06
6	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07
7	0.08	0.07	0.07	0.07	0.10	0.09	0.09	0.09
8	0.09	0.09	0.08	0.09	0.12	0.11	0.11	0.11
9	0.11	0.11	0.11	0.11	0.14	0.14	0.13	0.14
10	0.14	0.13	0.12	0.13	0.17	0.16	0.16	0.16
11	0.15	0.15	0.14	0.15	0.20	0.19	0.18	0.19
12	0.18	0.17	0.17	0.17	0.22	0.22	0.21	0.22
13	0.20	0.20	0.19	0.20	0.25	0.25	0.24	0.25
14	0.23	0.22	0.21	0.22	0.29	0.28	0.27	0.28
15	0.26	0.25	0.23	0.25	0.32	0.31	0.30	0.31

5.6.1 Refining and Analyzing Data

A total of 43 subjects participated in the experiment. Refining the collected data resulted in 41 subjects, 12 females and 29 males, used for statistical analysis using SAS. Data collected from two subjects were dropped because they had vision problems. Subject ages were between 20 and 81 years old. The subjects were divided into three groups according to age: 20-29, 30-49, and above 50 years old. For each sign, the frequency of subjects when reading the sign legend at each brightness level (knob position) was calculated and presented in Table 5.4. As shown, some subjects could not read sign legends at the 240 ft distance.

Table 5.4: Frequency of Human Subjects at Each Knob Position when Reading Signs

Knob Position	180 ft Distance			240 ft Distance		
	Type I	Type XI	Type IV	Type I	Type XI	Type IV
0	0	0	0	0	0	0
1	0	1	0	0	0	0
2	0	5	0	0	3	0
3	0	17	7	0	11	3
4	5	10	11	0	12	9
5	7	5	9	2	6	8
6	6	3	5	3	2	7
7	7	0	3	6	2	3
8	2	0	0	2	3	1
9	4	0	3	4	0	0
10	2	0	1	3	1	2
11	2	0	0	0	0	3
12	0	0	1	2	0	0
13	1	0	1	2	0	0
14	2	0	0	2	1	1
15	2	0	0	4	0	0
Can't read	1	0	0	11	0	4

In order for SAS to read and analyze the data, a number coding was assigned for the used signs: number 1 for Engineering Grade (Type I) sign sheeting, number 2 for Diamond Grade (Type XI) sign sheeting, and number 3 for High Intensity (Type IV) sign sheeting. The data were arranged so that SAS could analyze the data with the repeated measure design format. SAS codes used to analyze the data are shown in Appendix D. SAS input variables included subject, age group, distance, sign type number, knob position, and illuminance level. Among these variables, the dependent variable can be the illuminance level or knob position; the illuminance level was chosen to be the dependent variable when analyzing data. The independent variables were sign, distance, and age group. The blocking factor was the subject in this design. Since the age group variable is associated with each subject, it is considered a fixed variable nested in the subject. In this design, units for the selected variables are: illuminance in lux, distance in feet, and age in year.

For the Engineering Grade (Type I) sign at 180 ft, the highest frequency of subjects read the sign's legend at knob positions 5, 7, 6, 4, and 9 in sequence, with a total of 29 subjects out of

40 after removing the disqualifying subject. Corresponding illuminance values were 0.06 lux, 0.09 lux, 0.07 lux, 0.04 lux, and 0.14 lux, respectively, with an average of 0.08 lux. At 240 ft for Engineering Grade (Type I) sign, 11 subjects did not read the legend. The highest frequency of subjects who read the legend were at knob positions 7, 15, 9, and 10 in sequence, with a total of 17 subjects out of 30 after removing the disqualifying subjects. Corresponding illuminance values were 0.07 lux, 0.25 lux, 0.11 lux, and 0.13 lux, respectively, with an average of 0.14 lux. For the Diamond Grade (Type XI) sign at 180 ft, the highest frequency of subjects read the sign's legend at knob 3 and 4 in sequence, with a total of 27 subjects out of 41. Corresponding illuminance values were 0.03 lux, and 0.04 lux, respectively, with an average of 0.035 lux. At 240 ft for Diamond Grade (Type XI) sign, the highest frequency of subjects who read the sign's legend were at knob positions 4, 3, and 5 in sequence, with a total of 29 subjects out of 41. Corresponding illuminance values were 0.04 lux, 0.02 lux, and 0.05, respectively, with an average of 0.037 lux. Finally, for the High Intensity (Type IV) sign at 180 ft, the highest frequency of subjects who read the sign's legend at knob positions 4, 5, 3, and 6 in sequence, with a total of 32 subjects out of 41. Corresponding illuminance values were 0.04 lux, 0.06 lux, 0.03 lux, and 0.07 lux, respectively, with an average of 0.05 lux. At 240 ft for the High Intensity (Type IV) sign, four subjects could not read the sign's legend. The highest frequency of subjects who read the sign's legend were at knob positions 4, 5, and 6 in sequence, with a total of 24 subjects out of 37 after removing the disqualifying subjects. Corresponding illuminance values were 0.04 lux, 0.05 lux, and 0.06 lux, respectively, with an average of 0.05 lux.

5.7 Statistical Analysis

Repeated measures experimental design was used to analyze collected data. This design analyzes statistical data in which identical measures are collected multiple times for the same subject but under varying conditions. The term "repeated" means that any factor for which each subject is measured is repeated at every level for that factor. This design involves a repeated measurement on the unit of analysis in one or more independent variables (Neter, Kutner, Nachtsheim, & Wasserman, 1996). These designs are often called mixed designs or designs with within-subjects factors.

The selected SAS procedure was "PROC MIXED," which is a generalization of the General Linear Model (GLM) procedure because "PROC GLM" fits standard linear models and "PROC MIXED" fits the wider class of mixed linear models (Wolfinger & Chang, 1995). Both procedures have similar Class, Model, Contrast, Estimate, and LSMEANS statements, but their RANDOM and REPEATED statements differ.

5.8 Discussion

Based on SAS output, 230 observations were used in the analysis instead of 246. The missing 16 observations were cancelled by SAS because some subjects could not read the sign legend for all 16 levels of illumination controlling device. For the missing values, an illuminance level could not be fitted as a dependent value using the Minolta Illuminance meter because the maximum headlight brightness level was obtained at the last knob position.

The backward elimination procedure will be considered to select the significant variables and to fit the final model. This means the full statistical model will be found first, and then the least significant variable or variable interaction will be removed from the model. Table 5.5 is the SAS output for type 3 tests of the fixed effects of the full model. Based on p-value and considering a significance level of 0.05, the significant variables were the distance, the sign, and the distance-sign interaction because their p-values are 0.0043, less than 0.0001, and 0.0387, respectively, and all of them are less than the significance level considered (0.05). Age group variable was insignificant. Based on Table 5.5, it is clearly shown that all two and three-way variable interactions are not significant according to their p-value.

Table 5.5: Type 3 Tests of Fixed Effects for the Full Model

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	175	8.39	0.0043
Sign	2	174	93.17	<.0001
Distance*Sign	2	174	3.31	0.0387
Agegroup	2	37.3	0.76	0.4743
Distance*Agegroup	2	175	1.13	0.3249
Sign*Agegroup	4	174	0.29	0.8839
Distanc*Sign*Agegrou	4	174	0.95	0.4388

The next model will be run after removing the three-way interaction term (Distance*Sign*Agegroup) from the model. Table 5.6 shows the SAS output for type 3 tests of the fixed effects for the new reduced model. Based on the reduced model shown in Table 5.6, the significant variables are distance and sign according to their p-value. Agegroup variable and all the two-way interactions are insignificant.

Table 5.6: Type 3 Tests of Fixed Effects for the Model without Three-Way Interaction

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	179	8.03	0.0051
Sign	2	178	92.71	<.0001
Agegroup	2	37.3	0.76	0.4748
Distance*Sign	2	178	2.22	0.1112
Distance*Agegroup	2	178	0.92	0.3993
Sign*Agegroup	4	178	0.33	0.8609

The least significant variable interaction in Table 5.6 will be removed, which is Sign*Agegroup. Table 5.7 shows the SAS output for type 3 tests of the fixed effects for the new reduced model. Based on this Table, distance and sign variables are significant. Agegroup variable, Distance*Agegroup, and Distance*Agegroup interactions are insignificant.

The least significant variable in Table 5.7 will be removed, which is Distance*Agegroup. Table 5.8 shows the SAS output for type 3 tests of the fixed effects for the new reduced model. It is clearly shown that distance and sign variables are significant, while Agegroup and Distance*Sign variables are not.

Table 5.7: Type 3 Tests of Fixed Effects for Model with No Sign*Agegroup Interaction

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	183	8.19	0.0047
Sign	2	182	104.70	<.0001
Agegroup	2	37.2	0.73	0.4893
Distance*Sign	2	182	2.27	0.1064
Distance*Agegroup	2	182	0.94	0.3911

Table 5.8: Type 3 Tests of Fixed Effects for Model with No Distance*Agegroup Interaction

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	185	6.58	0.0111
Sign	2	184	104.76	<.0001
Agegroup	2	37.2	0.73	0.4896
Distance*Sign	2	184	2.23	0.1099

The least significant variable in Table 5.8 will be removed, which is Agegroup. Table 5.9 shows the SAS output for type 3 tests of the fixed effects for the new reduced model. It is clearly shown that distance and sign variables are significant, while Distance*Sign interaction is insignificant.

Table 5.9: Type 3 Tests of Fixed Effects for Model with No Agegroup Variable

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	185	6.57	0.0112
Sign	2	184	104.59	<.0001
Distance*Sign	2	184	2.24	0.1099

The last step is to remove the least significant variable in Table 5.9, which is the Distance*Sign interaction. Table 5.10 shows the SAS output for type 3 tests of the fixed effects for the new reduced model in which all the variables are significant.

Table 5.10: Type 3 Tests of Fixed Effects for the Final Reduced Model

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	186	5.75	0.0175
Sign	2	186	100.95	<.0001

The SAS output of the least square means of the three significant variables (distance, sign) is shown in Table 5.11. Based on the p-value for all levels of distance (180 ft and 240 ft), and sign levels (sign 1, sign 2, and sign 3), all are significant. Since the objective of this study is to find the minimum amount of illuminance that enables the driver to read the sign, the estimates of each variable's level can be used for driver's visibility and legibility of each sign. For the distance variable, the estimate of the 180 ft distance is 0.07456 which is smaller than the estimate of the 240 ft distance (0.08632). This means shorter distance between the vehicle and the sign provides the driver with higher visibility of the sign which makes him/her see and read the sign better at short distances. For sign variables, the estimate of sign 2 (Diamond Grade 'Type XI') is

0.04280, which is the smallest among the other sign levels: sign 3 (High Intensity 'Type IV') is 0.07085 and for sign 1 (Engineering Grade 'Type I') is 0.1277. This means sign 2 requires less illuminance for visibility, so the best visible sign for drivers is sign 2, followed by sign 1.

Table 5.11: Least Square Means of the Significant Variables

Least Squares Means							
Effect	Distance	Sign	Estimate	Standard Error	DF	t Value	Pr > |t|
Distance	180		0.07456	0.006822	49.2	10.93	<.0001
Distance	240		0.08632	0.006963	53.1	12.40	<.0001
Sign		1	0.1277	0.007446	68.3	17.15	<.0001
Sign		2	0.04280	0.007206	60.8	5.94	<.0001
Sign		3	0.07085	0.007277	62.9	9.74	<.0001

Table 5.12 shows SAS output for the difference of least square means for the variables distance and sign. This SAS output shows pairwise comparison for the different variable levels. The difference of least square means output can be used to find significant variables based on the p-value.

Based on Table 5.12, when comparing the three signs sheeting in pairs, a difference exists between the following combinations of signs: sign 1 (Engineering Grade 'Type I') and sign 2 (Diamond Grade 'Type XI'); sign 1 (Engineering Grade 'Type I') and sign 3 (High Intensity 'Type IV'); and sign 2 (Diamond Grade 'Type XI') and sign 3 (High Intensity 'Type IV'). The difference occurs because the p-value of each combination is smaller than 0.05. Similarly, comparing the two distances result in a difference between them based on the p-value which is smaller than 0.05.

Based on the subjects' frequency data at each brightness level of vehicle headlights shown in Table 5.4, results show that the legend of the Diamond Grade (Type XI) sign sheeting was read by all subjects at 180 ft and 240 ft, while 11 subjects could not read the legend of the Engineering Grade (Type I) sign sheeting at 240 ft, four subjects could not read the legend of the High Intensity (Type IV) sign sheeting at 240 ft, and one subject could not read the Engineering Grade (Type I) sign at 180 ft, meaning that visibility of the Diamond Grade sign is the best. In addition, the highest frequency of human subjects when reading the legend of the Diamond Grade (Type XI) was at knob positions 3 and 4, totaling 27 subjects with an average illuminance of 0.035 lux at 180 ft, and at knob positions 4, 3, and 5 in sequence, for a total of 29 subjects with an average illuminance of 0.037 lux at 240 ft. Because the four subjects who could not read the High Intensity (Type IV) sign legend at 240 ft is less than the 11 subjects who could not read the legend on the Engineering Grade (Type I) sign at 240 ft, the High Intensity (Type IV) sign sheeting visibility is better than the Engineering Grade (Type I) sign sheeting. In addition, the highest frequency of human subjects who read the legend of the High Intensity (Type IV) occurred at knob positions 4, 5, 3, and 6 in sequence for a total of 32 subjects with illuminance average of 0.05 lux at 180 ft distance, and at knob positions 4, 5, and 6 in sequence for a 24 subjects with an average illuminance level of 0.05 lux at 240 ft. For Engineering Grade (Type I), the highest human subjects frequency at 180 ft was at knob positions 5, 7, 6, 4, and 9 in sequence for 29 subjects with illuminance average of 0.08 lux and at 240 ft, knob positions 7, 15, 9 and 10 in sequence for a total of 17 subjects with average illuminance of 0.14 lux. Comparison of the average illuminance values enabling the subject to read the signs reveals that the minimum illuminance values were for Diamond Grade (Type XI) sign's legend at the both distances, followed by the High Intensity (Type IV) sign.

5.9 Summary

According to statistical analysis results using SAS, distance and sign sheeting material type are the significant variables. This is due to their individual p-value which is less than the significant level of 0.05, as shown in Table 5.10. Agegroup variable was not significant, meaning that sign visibility is not affected by the age of the subject. A possible explanation to this is that any subject, regardless of age, with a vision problem was using corrective lenses or glasses at the time of the experiment. As a result, all participants have good vision.

Based on the frequency of human subjects at each headlights brightness level, the Diamond Grade (Type XI) sign was read by a majority of subjects at lower illuminance averages: 0.035 lux and 0.037 lux at 180 ft and 240 ft, respectively. In addition, all participating subjects read the legend on the Diamond Grade (Type XI) sign, but not the High Intensity (Type IV) and Engineering Grade (Type I) sheeting. Therefore, the Diamond Grade sign has the best visibility compared to High Intensity (Type IV) and Engineering Grade (Type I) signs.

Table 5.12: Differences of Least Square Means

Differences of Least Squares Means											
Effect	Distance	Sign	_Distance	_Sign	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P
Distance	180		240		-0.01176	0.004906	186	-2.40	0.0175	Tukey-Kramer	0.0175
Sign		1		2	0.08487	0.006039	186	14.05	<.0001	Tukey-Kramer	<.0001
Sign		1		3	0.05683	0.006090	186	9.33	<.0001	Tukey-Kramer	<.0001
Sign		2		3	-0.02804	0.005829	186	-4.81	<.0001	Tukey-Kramer	<.0001

Chapter 6: Cost Analysis of Overhead Guide Signs Light Sources and Retroreflective Sheeting Materials

6.1 Introduction

Sign visibility for drivers during the nighttime can be improved by adding external illumination sources or by using retroreflective sheeting on signs. The cost of various sign illuminating sources studied in Chapter 4 is evaluated in this chapter to ascertain the cost-effective source. From the traditional light sources category, the 250 W HPS, 250 W MH, and 250 W MV are evaluated, and from new generation light sources, the 62 W LED and 85 W induction lighting also have been evaluated. Similarly, the cost of various sign retroreflective sheeting, such as Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV), is evaluated to find the cost-effective sheeting.

Several companies were contacted regarding the cost of light sources and retroreflective sheeting materials used with overhead guide signs. Three companies, Holophane, Lumi Trak, and LEDtronics, returned valuable information regarding the cost, maintenance, and lifespan of the studied light sources. The obtained information is for light sources that have a 250 W HID equivalent.

Similarly, several companies (3M Traffic Safety Systems, Nippon Carbide Industries, and Grimco) were contacted regarding the cost of retroreflective sign sheeting and their lifespan. Information on these companies' web sites was used as well. Cost information and expected lifespan were specifically related to the following retroreflective sheeting material: Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV).

6.2 Energy Independence and Security Act of 2007

The Energy Independence and Security Act (EISA) of 2007 issued a new energy standard to make efficient use of United States energy resources and to increase United States energy independence. This energy standard is commonly known as the "light bulb" law because screw-based light bulbs use fewer watts for similar lumen output. This standard means that any type of bulbs can be sold in the United States as long as they meet the corresponding efficiency requirement. According to this law, the 250 W MV, the 250 W HPS, and the 250 W MH are no longer allowed to be sold in the United States (EISA, 2007). The first phase of this law went into effect January 2012. Table 6.1 shows the law requirement and effective date.

Table 6.1: EISA Light-Bulb Law of 2007 Requirement and Effective Date

Today's bulbs (2007)	After the standard	Standard effective date
100 watt	≤72 watt	January 1, 2012
75 watt	≤ 53 watt	January 1, 2013
60 watt	≤ 43 watt	January 1, 2014
40 watt	≤ 29 watt	January 1, 2014

Source: EISA, 2007

A lumen identifies how bright the light is and watt describes how much energy the light bulb uses or consumes. Light bulbs can be compared in the following manner. A standard 60 W incandescent light bulb provides 13 to 14 lumens per watt, the compact fluorescent bulbs (CFBs) provide the equivalent of 55 to 70 lumens per watt, and the LED equivalent provides 60 to 100 lumens per watt. The second phase of the light bulb law requires that a majority of light bulbs be 60 to 70% more efficient than standards require for the incandescent bulb in 2007. This phase will go into effect in 2020 (EISA, 2007).

6.3 Light Source Cost Analysis

A detailed cost comparison of the 62 W LED, the 85 W induction, the 250 W MH, the 250 W HPS, and the 250 W MV light sources was completed. Calculations were based on light source usage for an average of 11 hours per night with a cost of \$0.08 per kW for electricity consumed. Costs related to labor are not included.

6.3.1 The 62 W LED

Based on information obtained from Lumi Trak, manufacturer of the 62 W LED, the average lifespan of an LED is 50,000 hours and the initial cost is \$600. Electrical consumption for this LED is 62 watt per hour, or 0.682 kW per night. The daily operating cost is \$0.05456 (0.682 kW × \$0.08), and the annual operating cost is \$19.91 (\$0.05456 × 365 day). Based on an 11-hour night, the 62 W LED will operate for 12.45 years (approximately 12.5 years). No maintenance cost is required after or during the lifespan of this LED because the entire light source unit must be replaced after 12.5 years. The 62 W LED consumes 248.9 kW per year and 3,100 kW during its lifespan, with a total operating cost of $248 per lifespan. According to Lumi Trak, no defrost option is required.

6.3.2 The 85 W Induction

Based on information obtained from Holophane, manufacturer of the 85 W induction lighting source, the average lifespan of this light source is 100,000 hours, and the initial cost is $678.30. The 85 W induction lighting source consumes 85 watt per hour, or 0.935 kW per night. The daily operating cost is $0.0748 (0.935 kW × $0.08), and the annual operating cost is $27.30 ($0.0748 × 365 day). Based on an 11-hour night, the 85 W induction lighting source will operate 24.91 years (approximately 25 years). The lamp requires replacement after 25 years, at a cost of $75, not including installation. The 85 W induction lighting source consumes 341.3 kW per year and 8,500 kW during its lifespan, with a total operating cost of $680 per lifespan.

6.3.3 The 250 W MH

The average lifespan of the 250 W MH light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is $0.22 (2.75 kW × $0.08), and the annual operating cost is $80.30 ($0.22 × 365 day). Based on an 11-hour night, the 250 W MH light source will operate 7.472 years (approximately 7.5 years). According to companies' information, lamp replacement is the only required maintenance, costing $30, excluding labor cost. The 250 W MH light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of $600 per lifespan.

6.3.4 The 250 W HPS

According to information from several manufacturers, the average lifespan of the 250 W HPS light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is $0.22 (2.75 kW × $0.08), and the annual operating cost is $80.30 ($0.22 × 365 day). Based on an 11-hour operation day, the 250 W HPS light source will operate 7.472 years (approximately 7.5 years). Companies' information indicates that the only required maintenance is lamp replacement, costing $16, excluding labor cost. The 250 W HPS light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of $600 per lifespan.

6.3.5 The 250 W MV

According to information from several manufacturers, the average lifespan of the 250 W MV light source is 30,000 hours, and the initial cost is $678.30. This light source consumes 250 watt per hour, or 2.75 kW per night. The daily operating cost is $0.22 (2.75 kW × $0.08), and the annual operating cost is $80.30 ($0.22 × 365 day). Based on an 11-hour night, the 250 W MV light source will operate 7.472 years (approximately 7.5 years). Based on company information, the only required maintenance is lamp replacement, costing $25, excluding labor cost. The 250 W MV light source consumes 1,003.75 kW per year and 7,500 kW during its lifespan, with a total operating cost of $600 per lifespan.

6.4 Overhead Guide Sign Lighting Sources Cost Comparison

A 50-year cycle is considered to determine the maintenance effect for various light sources by time. Table 6.2 compares the light sources in detail, and the provided cost analysis includes initial, operating, and maintenance cost components of each light source. Based on cost analysis results shown in Table 6.2, the 85 W induction lighting source is the cost-effective light source, followed by the 62 W LED, 250 W HPS, 250 W MV, and 250 W MH.

Some light source manufacturers doubt the 100,000-hour lifespan of induction lighting since no real experimental testing has been performed. Therefore, another cost comparison of the five light sources was performed using a 50,000-hour lifespan for the 85 W induction lighting. Updated cost results are shown in Table 6.3. The lifespan change of the 85 W induction lighting had no effect on previous results of the cost-effective light source based on cost, i.e., the cost-effective light source continued to be the 85 W induction lighting.

Table 6.2: Cost Comparison of the Five Light Sources

	Details	62 W LED	85 W Induction	250 W MH	250 W HPS	250 W MV
1	Initial cost ($)	600	678.30	678.30	678.30	678.30
2	Life (hours)	50,000	100,000	30,000	30,000	30,000
3	Life (years)	≅ 12.5	≅ 25	≅ 7.5	≅ 7.5	≅ 7.5
4	Power used per day (kW)	0.682	0.935	2.75	2.75	2.75
5	Power used per year (kW)	248.93	341.3	1,003.75	1,003.75	1,003.75
6	Power used per life (kW)	3,100	8,500	7,500	7,500	7,500
7	Number of light source replacements in 50 years	3	1	5.66	5.66	5.66
8	Total power (kW) used in 50 years	12,446.5	17,065	50,187.5	50,187.5	50,187.5
9	Maintenance required	A[1]	C[2]	C	C	C
10	Daily operating cost ($)	0.05456	0.0748	0.22	0.22	0.22
11	Annual operating cost ($)	19.91	27.30	80.30	80.30	80.30
12	Life operating cost ($)	248	680	600	600	600
13	Maintenance cost ($/each time required)	600	75	30	16	25
14	Maintenance cost during 50 years ($)	1,800	75.00	170	90.67	141.67
15	Total operating cost during 50 years ($)	995.60	1,365	4,015	4,015	4,015
16	Total cost during 50 years ($)[3]	3,395.60	2,118.30	4,863.30	4,783.97	4,834.97
17	Total cost per year ($)[4]	67.91	42.37	97.27	95.68	96.70

[1] Replacing the whole light fixture.
[2] Replace the lamp only.
[3] Adding rows 1, 14, and 15.
[4] Dividing row 16 by 50.

Table 6.3: Cost Comparison of Light Sources after Changing the 85 W Induction Lifespan

	Details	62 W LED	85 W Induction	250 W MH	250 W HPS	250 W MV
1	Initial cost ($)	600	678.3	678.3	678.3	678.3
2	Life (hours)	50,000	50,000	30,000	30,000	30,000
3	Life (years)	≅ 12.5	≅ 12.5	≅ 7.5	≅ 7.5	≅ 7.5
4	Power used per day (kW)	0.682	0.935	2.75	2.75	2.75
5	Power used per year (kW)	248.93	341.3	1,003.75	1,003.75	1,003.75
6	Power used per life (kW)	3,100	4,250	7,500	7,500	7,500
7	Number of light source replacements in 50 years	3	3	5.66	5.66	5.66
8	Total power (kW) used in 50 years	12,446.5	17,065	50,187.5	50,187.5	50,187.5
9	Maintenance required	A[1]	C[2]	C	C	C
10	Daily operating cost ($)	0.05456	0.0748	0.22	0.22	0.22
11	Annual operating cost ($)	19.91	27.30	80.30	80.30	80.30
12	Life operating cost ($)	248	340	600	600	600
13	Maintenance cost ($/each time required)	600	75	30	16	25
14	Maintenance cost during 50 years ($)	1,800	225	170	90.67	141.67
15	Total operating cost during 50 years ($)	995.60	1,365	4,015	4,015	4,015
16	Total cost during 50 years ($)[3]	3,395.60	2,268.30	4,863.30	4,783.97	4,834.97
17	Total cost per year ($)[4]	67.91	45.37	97.27	95.68	96.70

6.5 Retroreflective Sign Sheeting Cost Analysis

A detailed cost analysis was completed for the following retroreflective sheeting materials: Engineering Grade (Type I), Diamond Grade (Type XI), and High Intensity (Type IV). Labor and equipment costs for installing or reinstalling the sign sheeting are similar for all three retroreflective sheeting, and this cost is estimated to be $200 for initial sign installment, or replacement.

[1] Replacing the whole light fixture.
[2] Replace the lamp only.
[3] Adding rows 1, 14, and 15.
[4] Dividing row 16 by 50.

6.5.1 Engineering Grade Retroreflective Sheeting

Based on information obtained from the three sign sheeting manufacturers or distributers, the average cost of one square feet of Engineering Grade (Type I) retroreflective sheeting is \$0.80, and the average expected lifespan for this type of sheeting is seven years. Considering a sign 15 ft in width by 9 ft in height, the sheeting cost for this sign will be \$108 (15 ft × 9 ft × \$0.8). The yearly cost will be \$15.43 based on the sign lifespan (\$108/7 years).

6.5.2 Diamond Grade Retroreflective Sheeting

Based on information obtained from the three sign sheeting manufacturers or distributers, the average cost of one square feet of Diamond Grade (Type XI) retroreflective sheeting is \$3.93, and the average expected lifespan is 12 years. Considering a sign 15 ft in width by 9 ft in height, the sheeting cost for this sign will be \$530.55 (15 ft × 9 ft × \$3.93). The yearly cost will be \$44.21 based on the sign lifespan (\$530.55/12 years).

6.5.3 High Intensity Retroreflective Sheeting

Based on the information obtained from the three sign sheeting manufacturers or distributers, the average cost of one square feet of the High Intensity (Type IV) retroreflective sheeting is \$1.45, and the average expected life for this type of sheeting is 10 years. Considering a sign of size 15 ft in width by 9 ft in height, the cost of the sheeting for this sign will be \$195.75 (15 ft × 9 ft × \$1.45). The yearly cost will be \$19.58 based on the sign lifespan (\$195.75/10 years).

6.6 Retroreflective Sheeting Materials Cost Comparison

A detailed comparison between the three retroreflective sheeting materials is presented. Labor costs and equipment are identical for the three types of retroreflective sheeting material and are not included in calculations. A 50-year life cycle is considered to obtain the replacement effect for the three retroreflective sheeting based on lifespan. Table 6.4 compares the retroreflective sheeting costs in detail, and the provided cost analysis includes initial, and maintenance or replacement cost components of each retroreflective sheeting for a 15 ft × by 9 ft sign size per lifespan of each sheeting type. Based on cost analysis results shown in Table 6.4, The High Intensity (Type IV) is the most cost-effective sign sheeting, followed by Engineering Grade (Type I), and then by the Diamond Grade (Type XI).

Table 6.4: Cost Comparison of the Three Retroreflective Sheeting of a 15 ft × 9 ft Sign Size

	Details	Engineering Grade (Type I)	Diamond Grade (Type XI)	High Intensity (Type IV)
1	Initial cost ($\$/ft^2$)	0.80	3.93	1.45
2	Life (year)	7	12	10
3	Cost of (15 ft × 9 ft) sign sheeting ($)	108	530.55	195.75
4	Labor cost per each installment or replacement, ($)	200	200	200
5	Number of sign replacements in 50 years	7.14	4.17	5
6	Required sign sheeting cost ($/ 50 years)	771.12	2,212.40	957.50
7	Required labor cost ($/ 50 years)	1,428	834	1,000
8	Total cost ($/ 50 years)	2,199.12	3,046.40	1,957.50
9	Total cost excluding labor ($/year)	15.42	44.25	19.15
10	Total cost per year ($)	43.98	60.93	39.15

6.7 Combining Decision Criteria to find the Best Sign External Light Source

Based on light distribution of light sources evaluated in Chapter 4, HPS was the best light source, followed by MH, induction lighting, MV, and LED. In summary, the HPS light source is the best among traditional light sources, followed by MH and MV. Among the new generation light sources, induction lighting is recommended to be used by DOTs. Based on the Energy Independence and Security Act of 2007, the HPS, MH, and MV cannot be used in the United States after January 2012. Among those light sources that can be used in the United States, based on light distribution, the 85 W induction lighting is the best, followed by the 62 W LED. Based on cost analysis of the five light sources, excluding labor costs, the 85 W induction lighting source is the most cost-effective light source, followed by the 62 W LED, 250 W HPS, 250 W MV, and 250 W MH.

The combination of decision criteria, light distribution, and light source cost reveals that the 85 W induction lighting is the best light source being tested, followed by the 62 W LED.

6.8 Combining Decision Criteria to find the Best Sign Retroreflective Sheeting

Based on statistical analysis of the retroreflectivity experiment in Chapter 5, Diamond Grade (Type XI) sheeting provides the best sign visibility, followed by High Intensity (Type IV) sheeting and then Engineering Grade (Type I).

Based on cost analysis of retroreflective sheeting, the least expensive retroreflective sheeting material is High Intensity (Type IV), followed by Engineering Grade (Type I), and Diamond Grade (Type XI).

Combining decision criteria, sign visibility for drivers, and the cost of retroreflective sheeting, the best retroreflective sheeting type is High Intensity (Type IV), followed by Diamond Grade (Type XI).

6.9 Evaluating the Best Combination of Light Source and Retroreflective Sheeting

When combining the decision criteria (cost, light distribution, and usability in the US), the best light source for overhead guide sign illumination is the 85 W LED, followed by the 62 W LED. In addition, when combining the decision criteria (cost and visibility), the best retroreflective sign sheeting for providing high sign visibility to drivers at low cost is High Intensity (Type IV), followed by Diamond Grade (Type XI).

The yearly cost to operate the 85 W induction lighting is $45.37, and $67.91 for the 62 W LED, this cost is not including labor cost. The yearly cost when using High Intensity (Type IV) retroreflective sheeting is $39.15 including labor cost, meaning High Intensity (Type IV) retroreflective sheeting is more cost-effective than illuminating the guide sign.

Chapter 7: Conclusions

Based on a survey, states have two options for increasing overhead guide sign visibility during nighttime: either by illuminating signs, usually with newer, more efficient light sources, or using newer, brighter retroreflective sheeting materials. Approximately 57% of state DOTs illuminate their overhead guide signs, while 43% do not. Among those states which illuminate their overhead guide signs, the most common light sources used currently are MH, MV, HPS, induction lighting, and LED. In designing overhead guide sign lighting, states may refer to AASHTO standards, IES standards, both AASHTO and IES standards, historical practices and experiences, or to a state's own standards. States' future plans regarding improving overhead guide sign visibility include modifying existing lights into new, cost-efficient sources, or using new, brighter retroreflective sheeting for signs.

Based on a light distribution experiment, the HPS light source had the best light distribution among the conventional light sources followed by MH, and the induction lighting has the best light distribution among the new generation of light sources followed by the LED. According to the Energy Independence and Security Act (EISA) of 2007, HPS, MH, and MV are not allowed to be used on US roadways as of January 2012. The light sources cost analysis show that induction lighting is the most cost-effective light source, followed by LED. In conclusion, combining three decision criteria for light sources (light distribution, compliancy with the EISA of 2007, and cost-efficiency), the recommended light sources to be used by DOTs for overhead guide sign illumination is induction lighting, followed by LED.

According to statistical analysis of the field experiment, distance, sign retroreflective sheeting type, and sign-distance interaction are the resulting significant variables. Consequently, in order to improve driver safety on highways, careful consideration should be given to these important variables. Based on statistical analysis, the Diamond Grade (Type XI) sign sheeting enables drivers to read a sign's legend from a longer distance, followed by the High Intensity (Type IV). Engineering Grade (Type I) was the worst performing sign sheeting. The conclusion is made that when sign retroreflectivity values for legend and background are high, the sign's visibility will increase, and this leads to recommending Diamond Grade (Type XI) sign sheeting which has the highest retroreflectivity values for legend and background.

In addition, based on the frequency of human subjects at each headlight brightness level in the field experiment, the Diamond Grade (Type XI) sign was read by a majority of subjects at lower illuminance averages: 0.035 lux and 0.037 lux at 180 ft and 240 ft, respectively. In addition, all participating subjects were able to read the legend on the Diamond Grade (Type XI) sign, but not the High Intensity (Type IV) and Engineering Grade (Type I) sheeting. Therefore, it is concluded that the Diamond Grade sign has the best visibility compared to High Intensity (Type IV) and Engineering Grade (Type I) signs.

The cost analysis of the retroreflective sheeting showed that the most cost-effective retroreflective sheeting is the High Intensity (Type IV). In conclusion, combining the different decision criteria used for evaluating retroreflective sign sheeting: statistical analysis, minimum illuminance values based on frequency of human subjects at the different brightness levels, legend and background retroreflectivity values, and the cost analysis, the recommended retroreflective sheeting to be used by DOTs for guide signs is the High Intensity (Type IV), followed by the Diamond Grade (Type XI).

In comparing the best option of each method of increasing sign visibility: sign illumination, and sign retroreflectivity, the yearly cost to operate the 85 W induction lighting is $45.37, not including labor cost. The yearly cost when using High Intensity (Type IV) retroreflective sheeting is $39.15, including labor cost. Therefore, High Intensity (Type IV) retroreflective sheeting is the most cost-effective method which increases overhead guide sign visibility for drivers, and then increasing highway safety.

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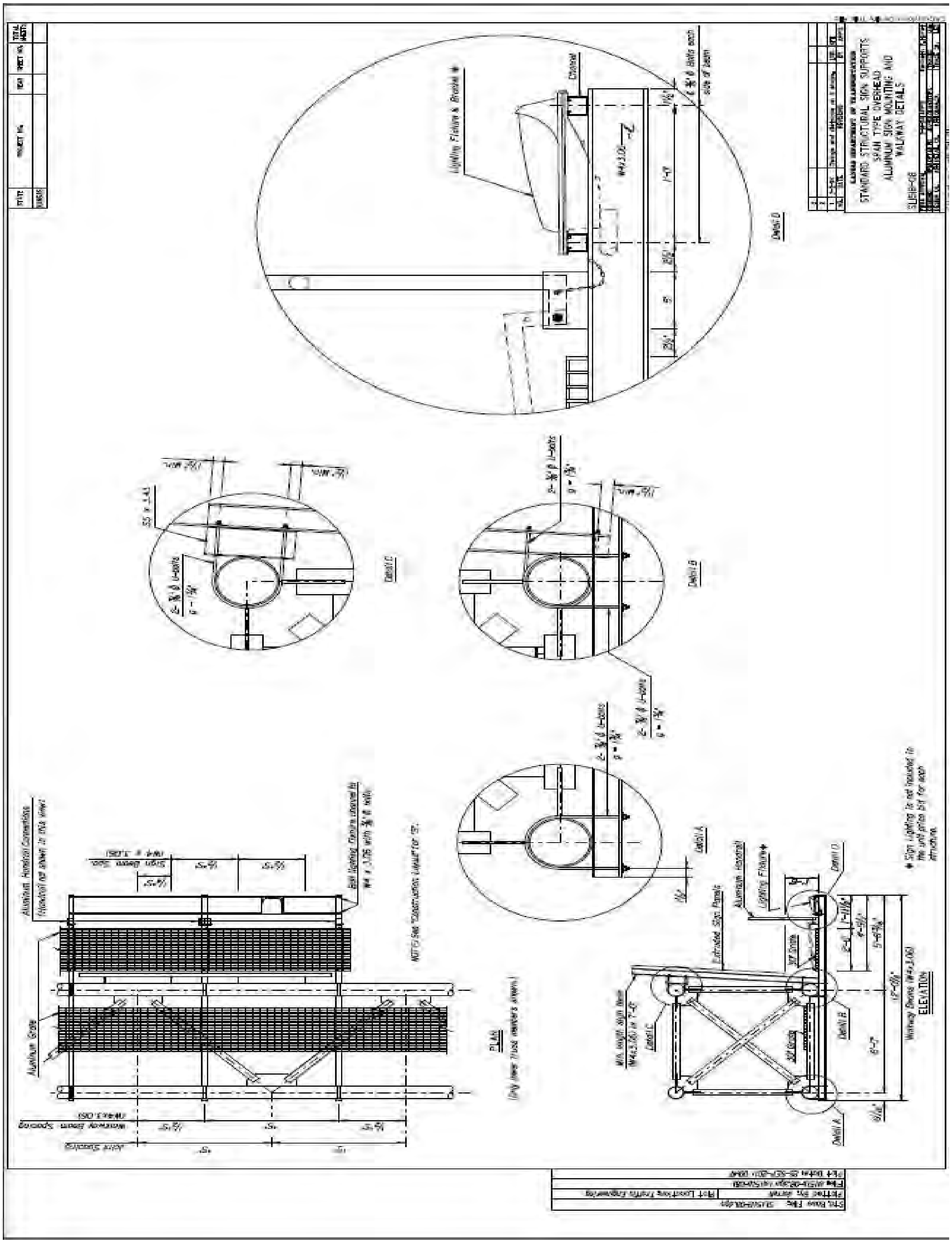
Appendix A - Standard Position of Light Unit Installed for Guide Sign Illumination



Appendix B - Field Experiment Approval Form

KANSAS STATE UNIVERSITY | University Research and Compliance Office

TO: Malgorzata Rys
IMSE
164 Rathbone

Proposal Number: 6766

FROM: Rick Scheidt, Chair
Committee on Research Involving Human Subjects

DATE: 08/02/2013

RE: Proposal Entitled, "Overhead Guide Sign Illumination and Retro reflectivity"

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §46.101, paragraph b, category: 2, subsection: ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

1863 2013 150

203 Fairchild Hall, Lower Mezzanine, Manhattan, KS 66506-1103 | (785) 532-3224 | fax: (785) 532-3278 | k-state.edu/research/comply

Appendix C - Field Experiment Consent Form

I verify that my signature below indicates that I have read and understand this consent form, and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.

(Remember that it is a requirement for the P.I. to maintain a signed and dated copy of the same consent form signed and kept by the participant

Participant Name:

Participant Signature:

Date:

Witness to Signature: (project staff)

Date:

Appendix D - SAS Codes

```
Libname Exp 'C:\Mohammed Obeidat\Dessertation\Statistic';
Proc Format;
Value Agegroup
                     20-<30 = '20-29'
                     30-<50 = '30-49'
                     50-High = '51 and above';
Run;
Data Exp.Data;
Input Subject Age Distance Sign Knob_pos Ill_Lux;
Datalines;
1     20    240   1     6     0.06
1     20    240   2     3     0.02
1     20    240   3     4     0.04
1     20    180   1     5     0.06
1     20    180   2     3     0.03
1     20    180   3     3     0.03
2     20    240   1     .     .
2     20    240   2     14    0.22
2     20    240   3     11    0.15
2     20    180   1     10    0.16
2     20    180   2     5     0.06
2     20    180   3     12    0.22
3     20    240   1     14    0.22
3     20    240   2     8     0.09
3     20    240   3     14    0.22
3     20    180   1     15    0.31
3     20    180   2     6     0.07
3     20    180   3     9     0.14
4     23    240   1     .     .
4     23    240   2     5     0.05
4     23    240   3     10    0.13
4     23    180   1     14    0.28
4     23    180   2     5     0.06
4     23    180   3     10    0.16
5     20    240   1     9     0.11
5     20    240   2     4     0.04
5     20    240   3     6     0.06
5     20    180   1     8     0.11
5     20    180   2     5     0.06
5     20    180   3     4     0.04
6     24    240   1     7     0.07
6     24    240   2     4     0.04
6     24    240   3     5     0.05
6     24    180   1     4     0.04
6     24    180   2     3     0.03
6     24    180   3     4     0.04
7     20    240   1     12    0.17
7     20    240   2     4     0.04
7     20    240   3     5     0.05
7     20    180   1     6     0.07
7     20    180   2     3     0.09
7     20    180   3     4     0.04
8     20    240   1     .     .
8     20    240   2     4     0.04
```

8	20	240	3	.	.
8	20	180	1	11	0.19
8	20	180	2	4	0.04
8	20	180	3	6	0.07
9	20	240	1	.	.
9	20	240	2	5	0.05
9	20	240	3	7	0.07
9	20	180	1	13	0.25
9	20	180	2	4	0.04
9	20	180	3	6	0.07
10	21	240	1	10	0.13
10	21	240	2	4	0.04
10	21	240	3	4	0.04
10	21	180	1	7	0.09
10	21	180	2	3	0.03
10	21	180	3	4	0.04
11	20	240	1	15	0.25
11	20	240	2	5	0.05
11	20	240	3	7	0.07
11	20	180	1	9	0.14
11	20	180	2	4	0.04
11	20	180	3	7	0.09
12	20	240	1	9	0.11
12	20	240	2	4	0.04
12	20	240	3	4	0.04
12	20	180	1	7	0.09
12	20	180	2	3	0.03
12	20	180	3	4	0.04
13	20	240	1	8	0.09
13	20	240	2	3	0.02
13	20	240	3	6	0.06
13	20	180	1	7	0.09
13	20	180	2	3	0.03
13	20	180	3	5	0.06
14	21	240	1	9	0.11
14	21	240	2	3	0.02
14	21	240	3	4	0.04
14	21	180	1	5	0.06
14	21	180	2	3	0.03
14	21	180	3	3	0.03
15	21	240	1	14	0.22
15	21	240	2	4	0.04
15	21	240	3	6	0.06
15	21	180	1	7	0.09
15	21	180	2	3	0.03
15	21	180	3	5	0.06
16	30	240	1	15	0.25
16	30	240	2	7	0.07
16	30	240	3	7	0.07
16	30	180	1	7	0.09
16	30	180	2	4	0.04
16	30	180	3	6	0.07
17	46	240	1	.	.
17	46	240	2	7	0.07
17	46	240	3	11	0.15
17	46	180	1	11	0.19
17	46	180	2	5	0.06

17	46	180	3	5	0.06
18	35	240	1	6	0.06
18	35	240	2	3	0.02
18	35	240	3	4	0.04
18	35	180	1	5	0.06
18	35	180	2	3	0.03
18	35	180	3	3	0.03
19	34	240	1	.	.
19	34	240	2	6	0.06
19	34	240	3	.	.
19	34	180	1	10	0.16
19	34	180	2	4	0.04
19	34	180	3	9	0.14
20	31	240	1	13	0.20
20	31	240	2	4	0.04
20	31	240	3	4	0.04
20	31	180	1	9	0.14
20	31	180	2	4	0.04
20	31	180	3	4	0.04
21	58	240	1	.	.
21	58	240	2	10	0.13
21	58	240	3	10	0.13
21	58	180	1	.	.
21	58	180	2	6	0.07
21	58	180	3	7	0.09
22	56	240	1	10	0.13
22	56	240	2	5	0.05
22	56	240	3	6	0.06
22	56	180	1	7	0.09
22	56	180	2	4	0.04
22	56	180	3	6	0.07
23	39	240	1	9	0.11
23	39	240	2	3	0.02
23	39	240	3	4	0.04
23	39	180	1	6	0.07
23	39	180	2	3	0.03
23	39	180	3	4	0.04
24	20	240	1	7	0.07
24	20	240	2	4	0.04
24	20	240	3	5	0.05
24	20	180	1	6	0.07
24	20	180	2	3	0.03
24	20	180	3	5	0.06
25	20	240	1	6	0.06
25	20	240	2	2	0.02
25	20	240	3	3	0.02
25	20	180	1	4	0.04
25	20	180	2	1	0.01
25	20	180	3	3	0.03
26	34	240	1	12	0.17
26	34	240	2	4	0.04
26	34	240	3	6	0.06
26	34	180	1	6	0.07
26	34	180	2	3	0.03
26	34	180	3	5	0.06
27	33	240	1	7	0.07
27	33	240	2	3	0.02

27	33	240	3	4	0.04
27	33	180	1	7	0.09
27	33	180	2	2	0.02
27	33	180	3	5	0.06
28	21	240	1	5	0.05
28	21	240	2	3	0.02
28	21	240	3	4	0.04
28	21	180	1	4	0.04
28	21	180	2	3	0.03
28	21	180	3	4	0.04
29	23	240	1	.	.
29	23	240	2	5	0.05
29	23	240	3	.	.
29	23	180	1	14	0.28
29	23	180	2	4	0.04
29	23	180	3	5	0.06
30	20	240	1	7	0.07
30	20	240	2	3	0.02
30	20	240	3	3	0.02
30	20	180	1	5	0.06
30	20	180	2	2	0.02
30	20	180	3	4	0.04
31	79	240	1	15	0.25
31	79	240	2	6	0.06
31	79	240	3	8	0.09
31	79	180	1	9	0.14
31	79	180	2	4	0.04
31	79	180	3	7	0.09
32	81	240	1	13	0.20
32	81	240	2	8	0.09
32	81	240	3	11	0.15
32	81	180	1	8	0.11
32	81	180	2	4	0.04
32	81	180	3	9	0.14
33	64	240	1	.	.
33	64	240	2	4	0.04
33	64	240	3	6	0.06
33	64	180	1	6	0.07
33	64	180	2	3	0.03
33	64	180	3	4	0.04
34	59	240	1	5	0.05
34	59	240	2	2	0.02
34	59	240	3	3	0.02
34	59	180	1	4	0.04
34	59	180	2	2	0.02
34	59	180	3	3	0.03
35	52	240	1	10	0.15
35	52	240	2	3	0.02
35	52	240	3	5	0.05
35	52	180	1	6	0.07
35	52	180	2	3	0.03
35	52	180	3	3	0.03
36	77	240	1	15	0.25
36	77	240	2	5	0.05
36	77	240	3	6	0.06
36	77	180	1	9	0.14
36	77	180	2	4	0.04

```
36     77     180    3      6      0.07
37     73     240    1      7      0.07
37     73     240    2      3      0.02
37     73     240    3      5      0.05
37     73     180    1      5      0.06
37     73     180    2      3      0.03
37     73     180    3      5      0.06
38     53     240    1      .      .
38     53     240    2      8      0.09
38     53     240    3      .      .
38     53     180    1      15     0.31
38     53     180    2      6      0.07
38     53     180    3      13     0.25
39     34     240    1      .      .
39     34     240    2      3      0.02
39     34     240    3      6      0.06
39     34     180    1      5      0.06
39     34     180    2      3      0.03
39     34     180    3      5      0.06
40     37     240    1      8      0.09
40     37     240    2      4      0.04
40     37     240    3      5      0.05
40     37     180    1      5      0.06
40     37     180    2      2      0.02
40     37     180    3      4      0.04
41     35     240    1      7      0.07
41     35     240    2      2      0.02
41     35     240    3      5      0.05
41     35     180    1      4      0.04
41     35     180    2      2      0.02
41     35     180    3      3      0.03
;
Run;
Data Exp.Data1;
      Set Exp.Data;
      Agegroup = Put(age, Agegroup.);
Run;
Proc Print Data=Exp.Data1 Label;
Title 'Retroreflectivity Experiment Formatted Data';
Label Agegroup ='Age Group'
        Knob_pos= 'Knob Position'
        Ill_Lux='Illuminance';
Run;
Title 'Repeated Measure Design';
Title 'Finding Significant Variables from Data';
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance|sign|Agegroup/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign Distance*Agegroup
sign*Agegroup/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
```

```
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign Distance*Agegroup
/ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign Agegroup;
Model Ill_lux= Distance sign Agegroup Distance*sign /ddfm=satterth;
Random Subject(Agegroup);
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign Distance*sign /ddfm=satterth;
Random Subject;
Run;
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign /ddfm=satterth;
Random Subject;
Run;
Title 'Keeping Significant Variables Only and/or Interactions';
Title1 ' Finding the Least Mean Square for Significant Variables';
Title2 'Difference of Least Square Mean';
Proc Mixed Data=Exp.Data1;
Class Subject Distance Sign;
Model Ill_lux= Distance sign /ddfm=satterth;
Random Subject;
Lsmeans Distance Sign /pdiff Adjust =Tukey;
Run;
```

Appendix E - SAS Output

Finding Significant Variables from Data

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3
Agegroup	3	20-29 30-49 51 and above

Dimensions	
Covariance Parameters	2
Columns in X	48
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History			
Iteration	**Evaluations**	**-2 Res Log Like**	**Criterion**
0	1	-602.48846101	
1	2	-679.37868901	0.00007950
2	1	-679.42357538	0.00000065
3	1	-679.42392682	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject(Agegroup)	0.001501
Residual	0.001351

Fit Statistics	
-2 Res Log Likelihood	-679.4
AIC (smaller is better)	-675.4
AICC (smaller is better)	-675.4
BIC (smaller is better)	-672.0

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	175	8.39	0.0043
Sign	2	174	93.17	<.0001
Distance*Sign	2	174	3.31	0.0387
Agegroup	2	37.3	0.76	0.4743
Distance*Agegroup	2	175	1.13	0.3249
Sign*Agegroup	4	174	0.29	0.8839
Distanc*Sign*Agegrou	4	174	0.95	0.4388

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3
Agegroup	3	20-29 30-49 51 and above

Dimensions	
Covariance Parameters	2
Columns in X	30
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-618.76769145	
1	2	-697.29662112	0.00007727
2	1	-697.34127172	0.00000063
3	1	-697.34161948	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject(Agegroup)	0.001513
Residual	0.001348

Fit Statistics	
-2 Res Log Likelihood	-697.3
AIC (smaller is better)	-693.3
AICC (smaller is better)	-693.3
BIC (smaller is better)	-689.9

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	179	8.03	0.0051
Sign	2	178	92.71	<.0001
Agegroup	2	37.3	0.76	0.4748
Distance*Sign	2	178	2.22	0.1112
Distance*Agegroup	2	178	0.92	0.3993
Sign*Agegroup	4	178	0.33	0.8609

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3
Agegroup	3	20-29 30-49 51 and above

Dimensions	
Covariance Parameters	2
Columns in X	21
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-642.93276478	
1	2	-723.28149573	0.00007417
2	1	-723.32564852	0.00000060
3	1	-723.32598875	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject(Agegroup)	0.001509
Residual	0.001329

Fit Statistics	
-2 Res Log Likelihood	-723.3
AIC (smaller is better)	-719.3
AICC (smaller is better)	-719.3
BIC (smaller is better)	-715.9

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	183	8.19	0.0047
Sign	2	182	104.70	<.0001
Agegroup	2	37.2	0.73	0.4893
Distance*Sign	2	182	2.27	0.1064
Distance*Agegroup	2	182	0.94	0.3911

Finding Significant Variables from Data

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3
Agegroup	3	20-29 30-49 51 and above

Dimensions	
Covariance Parameters	2
Columns in X	15
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-654.79979737	
1	2	-735.57812234	0.00007148
2	1	-735.62125459	0.00000057
3	1	-735.62157987	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject(Agegroup)	0.001508
Residual	0.001329

Fit Statistics	
-2 Res Log Likelihood	-735.6
AIC (smaller is better)	-731.6
AICC (smaller is better)	-731.6
BIC (smaller is better)	-728.2

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	185	6.58	0.0111
Sign	2	184	104.76	<.0001
Agegroup	2	37.2	0.73	0.4896
Distance*Sign	2	184	2.23	0.1099

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3

Dimensions	
Covariance Parameters	2
Columns in X	12
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion

Iteration History			
Iteration	**Evaluations**	**-2 Res Log Like**	**Criterion**
0	1	-666.01437757	
1	2	-747.11494482	0.00009470
2	1	-747.17319083	0.00000095
3	1	-747.17374225	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject	0.001481
Residual	0.001329

Fit Statistics	
-2 Res Log Likelihood	-747.2
AIC (smaller is better)	-743.2
AICC (smaller is better)	-743.1
BIC (smaller is better)	-739.7

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	185	6.57	0.0112
Sign	2	184	104.59	<.0001
Distance*Sign	2	184	2.24	0.1099

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3

Dimensions	
Covariance Parameters	2
Columns in X	6
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion

Iteration History			
Iteration	**Evaluations**	**-2 Res Log Like**	**Criterion**
0	1	-677.74127081	
1	2	-757.02297473	0.00007254
2	1	-757.06783520	0.00000057
3	1	-757.06817017	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject	0.001453
Residual	0.001351

Fit Statistics	
-2 Res Log Likelihood	-757.1
AIC (smaller is better)	-753.1
AICC (smaller is better)	-753.0
BIC (smaller is better)	-749.6

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Distance	1	186	5.75	0.0175
Sign	2	186	100.95	<.0001

Finding the Least Mean Square for Significant Variables
Difference of Least Square Mean

The Mixed Procedure

Model Information	
Data Set	EXP.DATA1
Dependent Variable	Ill_Lux
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
Subject	41	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
Distance	2	180 240
Sign	3	1 2 3

Dimensions	
Covariance Parameters	2
Columns in X	6
Columns in Z	41
Subjects	1
Max Obs Per Subject	246

Number of Observations	
Number of Observations Read	246
Number of Observations Used	230
Number of Observations Not Used	16

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	-677.74127081	
1	2	-757.02297473	0.00007254
2	1	-757.06783520	0.00000057
3	1	-757.06817017	0.00000000

Convergence criteria met.

Covariance Parameter Estimates	
Cov Parm	**Estimate**
Subject	0.001453
Residual	0.001351

Fit Statistics	
-2 Res Log Likelihood	-757.1
AIC (smaller is better)	-753.1
AICC (smaller is better)	-753.0
BIC (smaller is better)	-749.6

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Distance	1	186	5.75	0.0175
Sign	2	186	100.95	<.0001

Least Squares Means

Effect	Distance	Sign	Estimate	Standard Error	DF	t Value	Pr > |t|
Distance	180		0.07456	0.006822	49.2	10.93	<.0001
Distance	240		0.08632	0.006963	53.1	12.40	<.0001
Sign		1	0.1277	0.007446	68.3	17.15	<.0001
Sign		2	0.04280	0.007206	60.8	5.94	<.0001
Sign		3	0.07085	0.007277	62.9	9.74	<.0001

Differences of Least Squares Means											
Effect	Distance	Sign	_Distance	_Sign	Estimate	Standard Error	DF	t Value	Pr > |t|	Adjustment	Adj P
Distance	180		240		-0.01176	0.004906	186	-2.40	0.0175	Tukey-Kramer	0.0175
Sign		1		2	0.08487	0.006039	186	14.05	<.0001	Tukey-Kramer	<.0001
Sign		1		3	0.05683	0.006090	186	9.33	<.0001	Tukey-Kramer	<.0001
Sign		2		3	-0.02804	0.005829	186	-4.81	<.0001	Tukey-Kramer	<.0001

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KANSAS TRANSPORTATION RESEARCH AND NEW-DEVELOPMENT PROGRAM

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