A RETROREFLECTIVE SHEETING SELECTION TECHNIQUE FOR NIGHTTIME DRIVERS' NEEDS

A Thesis

by

SUSAN CHRISTINE PAULUS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Civil Engineering

A RETROREFLECTIVE SHEETING SELECTION TECHNIQUE FOR NIGHTTIME DRIVERS' NEEDS

A Thesis

by

SUSAN CHRISTINE PAULUS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee, H. Gene Hawkins, Jr.
Committee Members, Yunlong Zhang
Rodger Koppa
Paul J. Carlson
Head of Department, John Niedzwecki

May 2010

Major Subject: Civil Engineering

ABSTRACT

A Retroreflective Sheeting Selection Technique for Nighttime Drivers' Needs. (May 2010)

Susan Christine Paulus, B.S., University of Wisconsin at Milwaukee

Chair of Advisory Committee: Dr. H. Gene Hawkins, Jr.

In this thesis, the author developed a retroreflective sheeting selection technique for traffic signs. Previous research was used to determine the luminance needed by drivers (demand luminance). The author used roadways scenarios to determine the amount of luminance the retroreflective sheeting on a sign would produce (supply luminance). A spreadsheet was developed to determine the performance of different retroreflective sheeting types by comparing the demand and supply luminance for specific roadway scenarios.

Using the results of previous studies, three demand luminance levels were created: replacement, adequate, and desirable. The replacement level represents the level of luminance when a sign needs to be replaced and is 2.5 cd/m^2. The adequate level is the recommended amount of luminance when installing new traffic signs and is 10 cd/m^2. The desirable level is the approximate level when additional luminance has diminishing returns and is 30 cd/m^2.

Supply luminance on a specific traffic sign was determined by evaluating roadway geometries, sign placement, retroreflective sheeting type and vehicle data. The author reviewed roadway geometries in Texas to estimate typical number of lanes, shoulder widths and horizontal curvature in the US. Sign placement from the MUTCD determined the typical lateral placements, sign heights, and sign twists. Vehicle data included vehicle dimensions and headlamp type.

Both the supply and demand luminance were determined for a specific viewing distance for a given scenario. The viewing distance is the distance a driver needs to read or recognize a sign to respond properly. In addition, the type of sign, alphanumeric or symbol, determined how this distance was calculated. The author developed four sign groups to calculate the distance required to read and respond to a traffic sign, including 1) Stop required, 2) Reduction in speed required, 3) Read the message provided, and 4) Change of lane required.

For symbol signs, the minimum required visibility distance (MRVD) was determined for the sign group and for text signs, the viewing distance at a legibility index (LI) of 30 ft/in was found. At these distances, the author calculated the supply luminance and then compared it to the demand luminance levels to determine the performance level.

The author developed the Retroreflective Sheeting Selection Spreadsheet (RSSS) to allow others to use the methodology presented in this thesis. RSSS allows users to input the roadway data, vehicle data, and sign data. RSSS takes this information and looks up the supply luminance for the scenario. RSSS then compares the supply luminance to the demand luminance levels and outputs the retroreflective sheeting performance level for the scenario.

DEDICATION

To my Family

ACKNOWLEDGMENTS

I would like to take this time to thank the individuals who helped make this thesis possible. First, I would like to thank my advisor, Dr. H. Gene Hawkins, Jr., for guiding me through the process. Second, I would like to thank Dr. Paul Carlson who provided me the opportunity to work while competing my thesis. Third, I would like to thank all the other Texas Transportation Institute employees I worked with. Many encouraged me in times of doubt and gave me a boost of confidence when I needed it the most. I would also like to thank all the fellow graduate students for making this experience fun. Some of the friendships I have formed over the past two years will be ones I cherish for a lifetime. Finally, I would like to thank my family and friends in Wisconsin. Their support has gotten me to where I am today. They have taught me to never give up and to do my best. Being apart from them and their encouragement has been difficult but their support has helped me through my education and guided me to the path I have chosen.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
DEDICATION		v
ACKNOWLEDGMENTS		vi
TABLE OF CONTENTS		vii
LIST OF TABLES		ix
LIST OF FIGURES		xii
CHAPTER		
I	INTRODUCTION	1
	Problem Statement	3
	Research Objectives	4
	Research Activities	5
II	BACKGROUND	7
	Retroreflectivity	7
	Supply Luminance	10
	Demand Luminance	12
III	RETROREFLECTIVE SHEETING SELECTION DEVELOPMENT	25
	Viewing Distance	27
	Demand Luminance	31
	Supply Luminance	33
IV	RETROREFLECTIVE SHEETING SELECTION	45
	Overview	45
	User Inputs	54
	Calculations	56
	RSSS Examples	63
V	CONCLUSIONS AND RECOMMENDATIONS	76
	Recommendations	77
	Limitations of this Research	78
	Future Needs	81
REFERENCES		82

Page

APPENDIX A 87
APPENDIX B 91
APPENDIX C 92
APPENDIX D 96
APPENDIX E 99
APPENDIX F 103
APPENDIX G 104
APPENDIX H 111
VITA 122

LIST OF TABLES

TABLE Page

1 ASTM Sheeting Types 9
2 Accommodation Luminance Values 15
3 Threshold Luminance Values by Accommodation Level 16
4 Sign Luminance Required for Consistent Correct Identifications 17
5 Luminance Levels 18
6 Sign Groups 27
7 Demand Luminance Levels 31
8 Shoulder Widths for Urban Conditions 36
9 2-Lane Roads Sign Offsets 37
10 Multilane Urban Roads Sign Offsets 38
11 Sign Twist 39
12 Curve Radii Evaluated 40
13 2009 Market-Weighted Average Vehicle Dimensions 43
14 RSSS Sheets 46
15 RSSS Distances 50
16 Roadway Data Entry 54
17 Sign Data Entry 55
18 Vehicle Data Entry 55
19 MRVD Inputs 57
20 Reaction Time Excel Formulas 57
21 MRVD Excel Formulas 58
22 ETypeI Sheet Excel Formulas 59
23 Evaluation Sheet MRVD 60
24 Evaluation Sheet LI 60
25 Lookup Function for Luminance Supply of White Sheeting 61
26 Multiplier for Color Factor Excel Formulas 61

TABLE Page

27 Evaluation Sheet Demand Display 61
28 Excel Formulas for Performance Rank 62
29 Output Table 62
30 Output Table Excel Equations 63
31 Group 1 Sheeting Type Performance 65
32 Group 2 Sheeting Type Performance 67
33 Group 3 Sheeting Type Performance 69
34 Group 4 Sheeting Type Performance 71
35 Measured Vehicle Dimensions 96
36 Vehicle Sales as of July 2009 98
37 Market-Weighted Vehicle Dimensions 98
38 Luminous Intensity Values for 50 percent - model year 2004 US Headlamps 101
39 Luminance Provided by Different Sheeting Colors 103
40 Sign Group 1: Car – Curve to the Left, 573-Feet 111
41 Sign Group 1: Truck – Curve to the Left, 573-Feet 111
42 Sign Group 1: Car – Straight 112
43 Sign Group 1: Truck – Straight 112
44 Sign Group 1: Car – Curve to the Right, 573-Feet 112
45 Sign Group 1: Truck – Curve to the Right, 573-Feet 113
46 Sign Group 2: Car – Straight 113
47 Sign Group 2: Truck – Straight 114
48 Sign Group 2: Car – Curve to the Right, 11459-Feet 114
49 Sign Group 2: Truck – Curve to the Right, 11459-Feet 114
50 Sign Group 2: Car – Curve to the Right, 5730-Feet 115
51 Sign Group 2: Truck – Curve to the Right, 5730-Feet 115
52 Sign Group 2: Car – Curve to the Right, 2865-Feet 115
53 Sign Group 2: Truck – Curve to the Right, 2865-Feet 116
54 Sign Group 3: Car – Straight 116

TABLE Page

55 Sign Group 3: Truck – Straight 117
56 Sign Group 3: Car – Curve to the Left, 5730-Feet 117
57 Sign Group 3: Truck– Curve to the Left, 5730-Feet 117
58 Sign Group 3: Car – Curve to the Right, 5730-Feet 118
59 Sign Group 3: Truck– Curve to the Right, 5730-Feet 118
60 Sign Group 4: Car – Straight 119
61 Sign Group 4: Truck – Straight 119
62 Sign Group 4: Car – Curve to the Left, 11459-Feet 120
63 Sign Group 4: Truck – Curve to the Left, 11459-Feet 120
64 Sign Group 4: Car – Curve to the Left, 5730-Feet 120
65 Sign Group 4: Truck – Curve to the Left, 5730-Feet 121
66 Sign Group 4: Car – Curve to the Left, 2865-Feet 121
67 Sign Group 4: Truck – Curve to the Left, 2865-Feet 121

LIST OF FIGURES

FIGURE		Page
1	Entrance and Observation Angles	8
2	Luminance Required for a Legibility Index	14
3	Comparison of Carlson's Studies at 40 ft/in	17
4	Luminance Required for Drivers of Passenger Cars	19
5	Symbol Sign Recognition Distances	21
6	Critical Detail	22
7	Luminance Needed by Critical Detail Level	22
8	Two-Glance Model	23
9	Retroreflective Sheeting Selection Flowchart	26
10	Sign Placement for Two-Lane Roadways	35
11	Sign Placement for Four and Six-Lane Roadways	35
12	Longitudinal Sign Locations	39
13	Headlamp Aim on Sag and Crest Curves	41
14	Millions of Vehicle Sales	42
15	Input/Output Sheet	47
16	Sign Info Sheet	48
17	Evaluation Sheet	49
18	ETypeVIII Sheet	51
19	TypeVIII Sheet	53
20	Group 1 Example Inputs	64
21	Group 2 Example Inputs	66
22	Group 3 Example Inputs	68
23	Group 4 Example Inputs	70
24	Supply Luminance in a Curve	72
25	Number of Lanes	87

FIGURE Page

26 Shoulder Widths for Rural Two-Lane Conditions 88
27 Shoulder Widths for Urban Two-Lane Conditions 88
28 Shoulder Widths for Urban Four-Lane Conditions 89
29 Shoulder Widths for Urban Six-Lane Conditions 89
30 Cumulative Curve Radii for Radii Less than 15,000 Feet 90
31 Sign Placement on Paved Shoulders 91
32 Sign Placement with Curb and Gutter 91
33 Difference in Luminance from Sign Height for Passenger Cars 93
34 Luminance from Sign Twist for Passenger Cars 95
35 Low Beam Isocandela Plots 99
36 Low Beam Isoilluminance Plots 100
37 ERGO Geometry Input 104
38 ERGO Vehicle Inputs 105
39 ERGO Sign Inputs 106
40 EGRO Headlamp Input 107
41 ERGO Retroreflective Sheeting Input 108
42 ERGO Output Summary 109
43 ERGO Output Details 110

CHAPTER I

INTRODUCTION

Traffic control devices are an important part of our transportation system, as they provide vital information and help drivers navigate and respond to situations. Approximately 90 percent of the information drivers use is visual (1). Therefore, traffic control devices must be visible day and night, as the transportation system must function all the time. Daytime driving allows drivers to respond to various visual cues including traffic control devices, other road users and the surrounding environment. Nighttime driving is more challenging because fewer visual cues are available, as the only cues visible at a distance are those that are illuminated or retroreflective. Retroreflectivity is a material characteristic that reflects light back to the source and is widely used on traffic control devices.

The importance of visual cues at night arguably makes retroreflective traffic control devices one of the most important sources of information. Traffic control signs are particularly important because they notify users of regulations, allow users to guide themselves, and alert users of possible hazards or unexpected situations. The *Manual on Uniform Traffic Control Devices* (MUTCD) (2) addresses sign visibility and sign maintenance in many areas. Specifically, Section 2A.07 states, "Regulatory, warning, and guide signs and object markers shall be retroreflective or illuminated to show the same shape and similar color by both day and night, unless otherwise provided in the text discussion in this Manual of a particular sign or group of signs."

Retroreflective sheeting placed on a cutout provides retroreflectivity on signs. The development of retroreflective sheeting began in the 1930's. The tiny glass beads originally used in sheeting were developed for use on the cinema's "silver screens" to

---

This thesis follows the style of *Transportation Research Record: Journal of the Transportation Research Board.*

produce a brighter image. These glass beads led to experiments to reflectorize road markings by sprinkling them onto wet paint or adhesive; however after durability issues, the development was switched to reflectorize signs. Originally, the glass beads were sprinkled onto wet paint to create exposed bead signs. Rain and dirt buildup between the exposed beads created performance problems. A layer of plastic film was added over the glass beads to remedy the issues, creating the first retroreflective enclosed bead product in 1948. The market remained relatively stable until the 1970's when new companies entered the market and introduced encapsulated glass bead sheeting. In 1973, the first unmetalized microprismatic retroreflective sheeting entered the market. Again, the industry remained stable as manufacturers developed additional types of microprismatic retroreflective sheeting which became available in the 1980's. The most recent release of a new microprismatic retroreflective sheeting type was in 2006 (3, 4).

To define the different retroreflective sheeting types, retroreflectivity is measured by several angles. These angles define the relationships between the source of light, the retroreflective material and the observer. There are several standard angle combinations to measure retroreflectivity, which represent specific geometries. These geometries do not necessarily represent typical real-world conditions.

The ASTM International published the first specification for retroreflective sheeting in 1996. The specification was published to establish quality control of new sheeting types. ASTM groups the retroreflective materials into different "types" of sheeting based on the retroreflective properties at specific viewing geometries. Within these types, the retroreflectivity of individual sheeting can vary over other geometries not defined in the specification. Further, the same "type" of sheeting from different manufacturers may have different retroreflectivity levels outside of the required geometries. These differences can cause varying luminance levels as drivers view signs at more geometries than those specified. The luminance provided by retroreflective sheeting depends on the sheeting type, the vehicle characteristics, the location of the sign, and the relative position of the sign with respect to the vehicle.

Researchers, manufacturers and engineers have provided little guidance on how to select appropriate type of sheeting for a given sign. In 1978, 3M developed a slide rule tool to help make this decision (5). However, only three retroreflective sheeting types were available and for some situations, no retroreflectivity could meet the proposed needs of drivers. Since then, companies have invented other sheeting types and more manufacturers have entered the market.

With more retroreflective sheeting choices available, most agencies have resorted to a one-size-fits-all policy in regards to selecting retroreflective sheeting. With this policy, agencies apply the same retroreflective sheeting to all traffic signs regardless of the sign location or sign use. Usually, engineers determine the sheeting type from a specific scenario, such as overhead signs. Although this strategy can reduce costs for the agency, the sheeting can provide variable performance based on sign placements.

PROBLEM STATEMENT

This one-size-fits-all sheeting selection policy creates issues given the wide variety of roadway geometries found in the US. For some geometries, the resulting luminance may not be sufficient for the driver to properly read or recognize the sign at the appropriate distance. Retroreflective sheeting selection can be improved by considering drivers' needs while still trying to minimize cost to the agency.

This thesis develops a retroreflective sheeting selection technique to help select sheeting for different geometries. The technique will define the luminance needed by drivers (demand) and the luminance supplied by signs (supply). The luminance needed by drivers is determined by reviewing previous studies. The luminance supplied by traffic signs is based on real-world driving conditions including roadway geometries, sign placement and the current vehicle mix. After the luminance for supply and demand are determined, the performance of sheeting types can be determined by comparing the luminance supplied by a specific sign to the driver's demand luminance. The demand

and supply luminance will be put into a spreadsheet to allow for evaluation of different roadway geometries.

RESEARCH OBJECTIVES

The focus of this thesis is defining a retroreflective sheeting selection technique. Using the selection process, the author determined inputs from existing sources and developed a tool for sheeting selection. The objectives to complete this thesis included:

1. Determine the retroreflective sheeting selection technique.
2. Determine different viewing distances for traffic signs by reviewing previous research and determining a range of distances drivers need to read or recognize different types of traffic signs.
3. Determine demand luminance. Use published research results to determine luminance categories based on driver needs. The luminance categories represent different performance levels.
4. Determine supply luminance.
    a. Obtain geometric data from a database of Texas state highways to approximate the highways in the US. Develop roadway scenarios based on the geometric elements to represent the typical on-road viewing conditions for traffic signs.
    b. Choose vehicle and headlamp types representative of the vehicles in the US. Measure the top selling vehicles in the US to obtain recent trends in vehicle dimensions.
5. Determine the luminance supplied by the retroreflective sheeting types and develop a retroreflective sheeting selection tool.

RESEARCH ACTIVITIES

To complete the research objectives, the author divided this thesis into four additional chapters. Each chapter is a step towards the ultimate goal of creating a tool to determine retroreflective sheeting selection for the various geometries in the US.

Chapter II: Background

In this chapter, the author establishes the state-of-the-art retroreflectivity research. The author explains retroreflectivity basics, supply luminance, and demand luminance. Retroreflectivity basics include the measurement of retroreflectivity, the different types of retroreflective sheeting, and how contrast and deterioration affect the sheeting characteristics. Next, the author explains methods to determine supply luminance. Finally, the author describes previous studies about the luminance a driver needs to read or recognize a sign (demand luminance). Demand luminance includes how drivers view signs and how different sign types determine the luminance need, as well.

Chapter III: Retroreflective Sheeting Selection Development

In this chapter, the author presents the retroreflective sheeting selection technique. The technique ties together demand and supply luminance, which are explained after the general overview. First, the author discusses the viewing distance, which is needed for both supply and demand luminance. Next, the author develops the demand luminance levels from the research presented in the Chapter II. The author creates three performance levels to measure demand luminance. Finally, the author explains how supply luminance is determined using roadway geometries, sign placement and vehicle data.

Chapter IV: Retroreflective Sheeting Selection Spreadsheet

In this chapter, the author develops the Retroreflective Sheeting Selection Spreadsheet to apply the information presented in Chapter III. The author discusses each component of the Retroreflective Sheeting Selection Spreadsheet (RSSS). Each sheet is discussed with detailed information about the specific inputs and the Excel formulas. At the end of this chapter, the author presents four examples and general observations recognized while completing this research.

Chapter V: Conclusions and Recommendations

In this chapter, the author summarizes the work completed, presents recommendations for retroreflective sheeting selection, discusses the limitations of the study, and recommends additional research needed.

CHAPTER II

BACKGROUND

In this chapter, the author establishes the state-of-the-art research in retroreflectivity and retroreflective sheeting. The author describes the basics of retroreflectivity, discusses how the luminance provided by retroreflective sheeting can be calculated, and presents current research on drivers' luminance needs.

RETROREFLECTIVITY

Retroreflectivity is an important issue as the MUTCD requires regulatory, warning, and guide signs to be retroreflective or illuminated (2). The MUTCD also provides minimum retroreflectivity values for agencies to follow to ensure signs are visible. To understand retroreflectivity, it is important to know the components that describe it.

Three light components - luminous intensity, illuminance and luminance - determine how drivers perceive retroreflective signs. Luminous intensity is the amount of light emitted from a source (the headlamps). Illuminance is the light received by the viewing surface (the sign). The amount of illuminance reaching the surface depends on the distance between the light source and the surface (the headlamps and the sign) and the atmospheric conditions (fog, rain, snow, air pollution, etc.). Luminance, commonly referred to as the sign brightness, is the amount of light reflected off the surface (the sign) and viewed by the receptor (the driver) and is affected by the atmospheric conditions. Retroreflectivity is a measure of the material property to determine the amount of luminance reflected for a given illuminance. The luminance of traffic signs depends on the type of retroreflective sheeting and the viewing angles between the light source (headlamps), the viewing surface (sign) and the receptor (driver's eyes).

The four geometrical systems that describe the angles for viewing signs (6) are the International Commission on Illumination (CIE) goniometer system, intrinsic system, application system and road marking system. The application system is the most used system and includes four angles to define the retroreflective properties. The two most important angles are the entrance angle and the observation angle. The entrance angle (β) is the angle formed by the headlamp and the perpendicular to the sign face and the observation angle (α) is between the headlamp and the driver's eye, as shown in Figure 1. The other two angles are the orientation angle and the rotation angle (6). For each viewing scenario, the angles are measured for each headlamp to the driver's eyes.

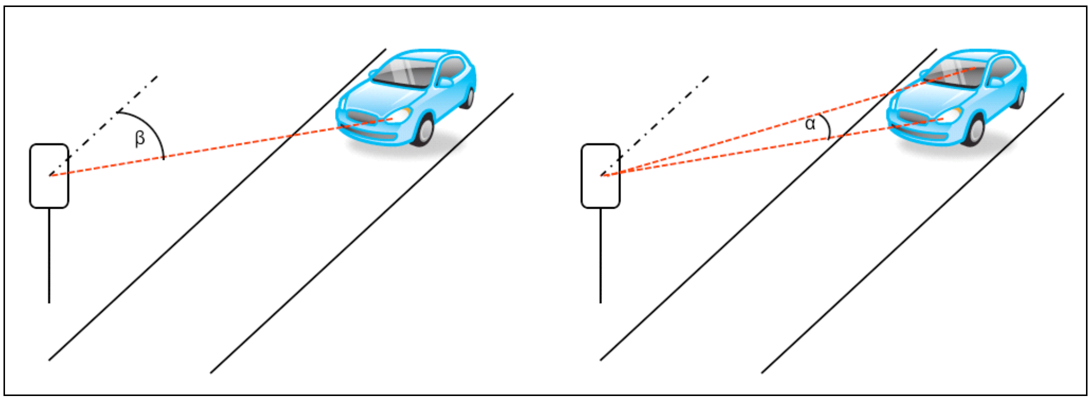

Figure 1 Entrance and Observation Angles

Currently, ASTM publishes the most used specifications for retroreflective sheeting. The specification defines seven retroreflective sheeting types for highway signing; see Table 1. Although, the sheeting types are numerically ordered, the higher the number does not mean greater performance; rather as manufacturers produce new materials, the material receives the next ASTM "Type." The ASTM D4656-09 grouped Types VII, VIII, and X into one type, Type VIII, and added Type XI (7).

Table 1 ASTM Sheeting Types

Type	Common Name	ASTM Description	Typical Construction
I	Engineering Grade	Medium-intensity	Enclosed Lens
II	Super Engineer Grade	Medium-high-intensity	Enclosed Lens
III	High Intensity	High-intensity	Encapsulated Glass Bead
IV	High Intensity	High-intensity	Microprismatic
VIII	Super High Intensity	Super-high-intensity	Microprismatic
IX	Very High Intensity	Very-high-intensity	Microprismatic
XI	Super High Intensity	Super-high-intensity	Microprismatic

The Coefficient of Retroreflection (R_A) is the material property to determine the portion of luminance returned for a given illuminance. ASTM D4656 (7) defines the Coefficient of Retroreflection for most sheeting types at four combinations of two observation angles and two entrance angles. For sheeting Types IX and XI, ASTM requires an additional observation angle. The minimum retroreflectivity levels in the MUTCD were specified at an observation angle and an entrance angle combination specified by ASTM (α=0.1, β=-4.0). However, many agree the ASTM angles do not represent on-road driving conditions (8).

It is important to consider other elements that affect how retroreflective sheeting types appear. The appearance of different sheeting types depends on the contrast of the sign and the deterioration of the retroreflective sheeting.

Contrast

The contrast of traffic signs can be positive or negative. For a negative contrast sign, the driver reads or recognizes a darker legend, such as a Speed Limit sign or warning sign. For a positive contrast sign, the driver reads or recognizes a brighter legend, such as a Stop sign or a guide sign.

A negative contrast sign usually has a black legend, which normally provides adequate contrast with a white, yellow, or orange background. For a positive contrast sign the legend is white and the background color can vary. Positive contrast signs are usually constructed of one or two retroreflective sheeting types and the contrast is more variable.

Some studies have looked at the comparison of different sheeting colors. Mace, Garvey, and Heckard (9) looked at the legibility of various sheeting colors and found white on green signs provide more legibility than negative contrast signs, and black on yellow signs are more legible than black on orange. Aoki, Battle, and Olson (10) determined how bright signs appeared when comparing different colors using Type III sheeting. In this study, subjects judged red, blue, and green brighter relative to white and yellow at the same luminance level.

Deterioration

Retroreflective sheeting gradually deteriorates over time, making signs less visible at night. Deterioration occurs from environmental effects and color fading. When the colors fade, the sign loses a distinguishing feature, and the contrast between legend and background decreases (11). This can create reduced legibility as shown by Schieber and Burns (12). The study found a 17 percent decrease in legibility distances for high speeds and 24 percent decrease in legibility for low speeds when comparing the Federal Highway Administration (FHWA) minimum retroreflectivity levels to newly installed sheeting.

SUPPLY LUMINANCE

There is on-going research to determine the luminance supplied by different sheeting types. There are a number of theoretical methods to estimate the supplied luminance including vector analysis, Exact Road Geometry Output (ERGO), and Target Visibility Predictor (TarVIP).

Johnson presented vector analysis to simplify the translation from road geometry to measurement and descriptive geometry during the 1999 Progress of Automotive

Lighting Conference (13). Johnson described the four angular systems to measure retroreflectance. Each system defines vectors, which can be used to calculate the luminance available.

The computer program ERGO (14) outputs the exact angles for a sign viewed by drivers. The program uses a simple mathematical vector structure to compute the angles needed to determine the exact retroreflectivity geometry. The inputs for ERGO include the distance to the sign, sign offset, height, twist, and tilt, vehicle dimensions, and headlamp type. ERGO also uses the angles to compute the luminance supplied by various retroreflective sheeting types. Finally, ERGO allows users to create their own input data, including vehicle dimensions, headlamp illuminance profiles, and retroreflective sheeting properties.

TarVIP is a computer program developed in Matlab by the Operator Performance Laboratory of the University of Iowa (15). Users can calculate detection distances for pavement markings, legibility distances of traffic signs, and visibility distances of pedestrians. TarVIP also considers variable fog and glare from oncoming vehicles, which other programs do not evaluate. TarVIP uses deterministic modeling of each component affecting visibility and legibility of nighttime roadway guidance.

Some researchers have used these programs in studies. Aktan and Burns (8) evaluated various retroreflective sheeting types based on the luminance provided by comparing in-field luminance levels to calculated values from TarVIP. Aktan and Burns found the performance ranking of the sheeting types (Types III, VII, IX, X, and XI) do not vary for different sign positions, only the absolute luminance output changes. Type III sheeting provided the least luminance while Type XI sheeting provided the most luminance. Types VIII, IX, and X performed between the two extremes, but individual performance varied depending on the distance between the driver and the sign. Further, the study showed a variation in the actual luminance of the retroreflective sheeting compared to the calculated luminance.

Bible and Johnson (16) evaluated the luminance provided by Types VII, VIII, and IX using a computer modeling program. Type VII was comparable to Type VIII at long distances with small entrance angles. Type VII provided more luminance than Type VIII and IX for large entrance angles. Type IX sheeting had higher luminance levels at shorter distances.

DEMAND LUMINANCE

There are many factors affecting the luminance a driver needs to read or recognize a sign. First, one must understand how luminance is viewed. Luminance is normally viewed as a log scale. This means when individuals view luminance at a low level, a small change in luminance has a larger effect then a small change at a higher luminance level. For example, in a dark room, a nightlight can greatly increase what an individual is able to see, whereas in the sunlight, the addition of a light has little impact.

The first and most important factor needed is the distance drivers need to read or recognize a sign, referred to the viewing distance in this thesis. Signs can be grouped into two categories, alphanumeric and symbol. Alphanumeric signs include those signs that have numbers or text, which drivers need to read directly, such as a guide sign. For symbol signs, a driver either needs to recognize a symbol on the sign, such as Intersection Ahead sign, or the sign itself, such as a Stop sign. The legibility index (LI) can describe alphanumeric signs and the minimum required visibility distance (MRVD) can describe symbol signs. Using LI and MRVD, the luminance drivers need to read or recognize a sign can be defined. Additional studies have evaluated driver sign viewing behavior, the effects sheeting types have on legibility, and the effects of font types.

Legibility Index

The legibility index is the proportion between the distance drivers can read a sign and the legend height. The legibly index is important as 2009 MUTCD (2) recommends a LI of 30 ft/in based on a Snellen visual acuity of 20/40. A concept derived from the legibility index is threshold legibility, which is the longest distance an individual reports the ability to read a sign. This distance may vary based on luminance, legend font and size, and color. Researchers can measure the threshold legibility distance in experiments; however, it may not represent the distance drivers actually read signs.

In general, older drivers have a lower legibility level when compared to younger drivers. Mace, Garvey, and Heckard (9) found younger drivers have a LI of 5 to 20 ft/in greater than older drivers at night and 20 to 30 ft/in greater during the day, while older drivers had a consistent LI. Another study by Graham, Fazal, and King (17) found older drivers need more luminance to read a sign then younger drivers at the same distance.

Since researchers easily quantify the LI, studies have shown the effects of the surround environment and the sign design on the LI of a sign. Schieber and Burns (12) found LIs ranged from 32 to 36 ft/in for rural settings and from 30 to 38 ft/in for suburban settings.

Minimum Required Visibility Distances

Although the recommended LI is 30 ft/in, drivers may need to view signs at a longer distance to be able to respond to the message provided. Further, the LI is not applicable to symbol signs. For these signs, the minimum required visibility distance (MRVD) is the distance required for perception, reaction, and response. A similar concept is decision sight distance, which includes the distances it would take a driver to 1) detect the object or situation, 2) recognize the object or situation, 3) decide an appropriate action, 4) initiate a control response, and 5) complete the required maneuver (18). McGee et al. considered these actions sequential and modified them into MRVDs by revising the detection and recognition phases. This differs from the LI, as the LI only considers the legend height to determine the distance.

Driver Luminance Needs

The author evaluated studies on drivers' luminance needs for alphanumeric and symbol signs. Some studies have looked at the critical detail of the sign to determine the amount of luminance needed by drivers. This approach can marry the alphanumeric and symbol signs into one grouping, however more information needs to be known about the sign and viewing situation to apply this concept.

Luminance Need for Alphanumeric Signs

In the 1970s, Forbes, et al. completed a number of landmark studies on luminance and contrast requirements for night legibility and color recognition (19, 20). For glance legibility, Figure 2 shows the LI as a function of the sign luminance from the brighter sign element.

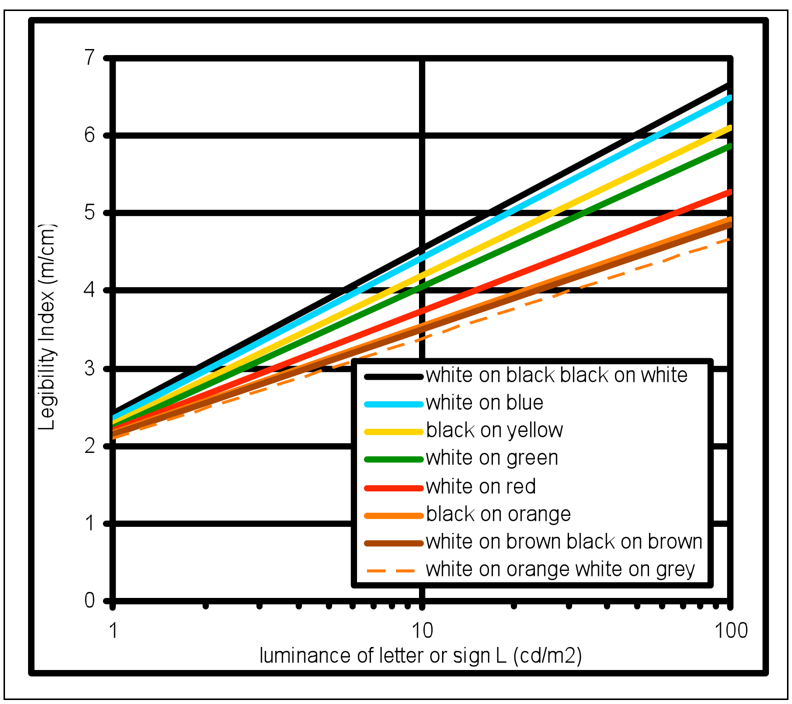

Figure 2 Luminance Required for a Legibility Index (20)

6 m/cm = 40 ft/in, 3 m/cm = 20 ft/in

The results show the LI increases with increasing luminance. Further, Forbes, et al. found the color of the sign effects legibility with black on white having the highest LI per luminance level. These trends are still apparent today, however researchers believe there is a point where the LI levels off with increasing luminance and may possibly decrease as a sign becomes too bright.

Carlson and Hawkins (21) evaluated the luminance needed for older drivers reading positive contrast street name signs and overhead guide signs. The luminance needed at a LI of 40 ft/in from this study is comparable to a study by Sivak and Olson (22) that conducted a review of 18 studies to determine optimal and minimum luminance levels. Table 2 shows the comparison. The accommodation percentile represents the percent of drivers able to read the sign at the measured luminance level. Older studies have referred to this level as the replacement percentile (22). Sivak and Olson identified the optimal luminance as 75 cd/m^2 for negative contrast signs and a minimum luminance of 2.4 cd/m^2 for the lighter component of positive and negative contrast signs. Sivak and Olson based their study on LIs of 50 ft/in and 40 ft/in for younger and older drivers, respectively. Table 2 also shows a third study by Graham, Fazal, and King (17).

Table 2 Accommodation Luminance Values

Accommodation Percentile	Sign Luminance (cd/m^2)			
	Carlson and Hawkins		Sivak and Olson	Graham, Fazal, and King*
	Guide Sign	Street Name Sign		
85	11.7	20.0	16.8	>15.9
75	5.7	14.1	7.2	N/A
50	2.3	3.9	2.4	4.5

* Luminance values at a LI of 38.8 ft/in

Table 3 shows Carlson and Hawkins's (21) results. The amount of luminance needed to properly read a sign varies with the LI more than the distance from the sign. This suggests that smaller legends are more difficult to read, possibly due to the reduced critical detail, and therefore drivers need more luminance. It is important to note, this study was in a static environment and the researchers increased luminance until the subject could correctly read the message on the sign.

Table 3 Threshold Luminance Values by Accommodation Level (cd/m²) (21)

Cumulative percentage of subjects in the sample	Overhead Signs *			Street Name Signs **		
	Legibility Index (ft/in)			Legibility Index (ft/in)		
	20	30	40	20	30	40
10	0.1	0.3	0.8	0.1	0.2	0.8
25	0.1	0.5	1.2	0.3	0.5	1.8
50	0.3	0.9	2.3	0.4	1.0	3.9
75	0.5	1.9	5.7	0.7	1.8	14.1
85	0.8	3.8	11.7	1.0	2.5	20.0
95	1.6	11.7	19.2	1.6	4.7	32.7
98	1.7	16.5	31.5	1.9	5.8	38.0
* For white Series E (Modified), 16/12-inch uppercase/lowercase (16" uppercase and 12" lowercase letters) words on a green background ** For white Series C, 6-inch uppercase words on a green background						

Carlson and Holick (23) expanded on the previous study by evaluating white on blue and white on brown signs. Carlson and Holick conducted the study with and without glare and roadway lighting, previously not considered. Figure 3 shows a comparison of this study and Carlson and Hawkins's (21) study.

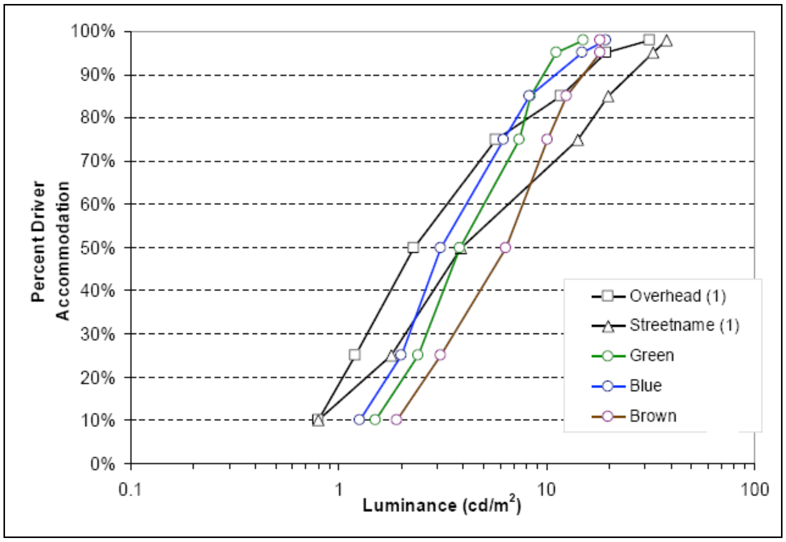

Figure 3 Comparison of Carlson Studies at 40 ft/in (23)

Graham, Fazal, and King (17) looked at how much luminance drivers need to read 6-inch black numerals on a yellow background for various distances. Materials with different retroreflectivity levels provided discrete luminance levels. Table 4 shows a summary of the results. The values in Table 4 do not represent the first time the respondents reached the percent correct, but when they reached consistent performance. Table 2 also shows the results of this study at a LI of 38.3 ft/in.

Table 4 Sign Luminance Required for Consistent Correct Identifications (cd/m^2) (17)

% Correct	Subject Group	Legibility Index (ft/in)						
		16.4	21.9	27.3	32.8	38.3	43.7	49.2
100	Younger	<0.23	<0.4	1.1	1.7	4.5	9.5	28.8
	Older	1.06	2.3	4.7	7.8	>15.9	>32.6	>40.2
>85	Younger	<0.23	<0.4	1.1	1.7	2.1	9.5	28.8
	Older	1.06	1.5	2.9	6.5	>15.9	>32.6	>40.2
>50	Younger	<0.23	<0.4	<0.8	<1.0	<2.0	<2.0	<2.7
	Older	<0.23	<0.4	<0.8	2.2	4.5	7.8	28.8

Values are in cd/m^2, < denotes the minimum luminance tested, > denotes the maximum luminance tested

A recent study (24) dynamically tested the effectiveness of nine luminance profiles for four different signing conditions. The study took place in three phases with phases two and three related to the luminance levels needed to read a sign. The second phase looked at six luminance profiles and the third phase looked at three additional profiles. Table 5 describes the luminance profiles for phase two. Between the different LIs, the luminance remained either constant or changed at a constant rate.

Table 5 Luminance Levels (24)

Condition	Luminance at LI				Significance
	50 ft/in	40 ft/in	20 ft/in	Sign	
Minimum Flat	1 cd/m^2 throughout the approach to the sign				Absolute minimum luminance that would be tested
Threshold flat	2.5 cd/m^2 throughout the approach to the sign				Threshold legibility luminance based on the FHWA minimum retroreflectivity levels
Medium flat	5 cd/m^2	30 cd/m^2	30 cd/m^2	5 cd/m^2	
High flat	5 cd/m^2	80 cd/m^2	80 cd/m^2	5 cd/m^2	½ log step above 30 cd/m^2
Peak early	5 cd/m^2	40 cd/m^2		5 cd/m^2	
Peak late	5 cd/m^2		40 cd/m^2	5 cd/m^2	

The cumulative distributions were determined for each sign type. The minimum and threshold profiles had the lowest performance and the high flat and peak early profiles had the best performance. Overall, these results suggest higher luminance improves the readability of a sign at longer distances regardless of legend size. Some conclusions based on the legibility results from the internally illuminated signs include (24):

- Luminance profiles of 30 cd/m^2 and 80 cd/m^2 were statistically the same.
- Luminance profiles of 1 cd/m^2 and 2.5 cd/m^2 were statistically the same.
- Luminance profiles of 30 cd/m^2 and 80 cd/m^2 were statistically different from luminance profiles of 1 cd/m^2 and 2.5 cd/m^2.

- Luminance profile of 10 cd/m^2 and 27 cd/m^2 were statistically different.

Currently, CIE Technical Committee 4-40 is developing a performance index to evaluate retroreflective sheeting by using the luminance levels shown in Table 3 (25). Figure 4 shows the method developed by CIE. The method uses average vehicle dimensions, market-weighted headlamp patterns, typical roadway cross-sections, and sign legend height to define reference scenarios. CIE uses the reference scenarios and six sign placements to calculate the supply luminance for different retroreflective sheeting.

The concept looks at five points in the last look region (LOOK3 in Figure 4) at distances based on LIs between 40 and 20 ft/in and the legend height. At each point, the CIE method calculates the supply luminance and using the luminance demand curves, the CIE method computes an interpolated performance metric. Finally, the CIE method takes an average of the five computations as the final performance metric.

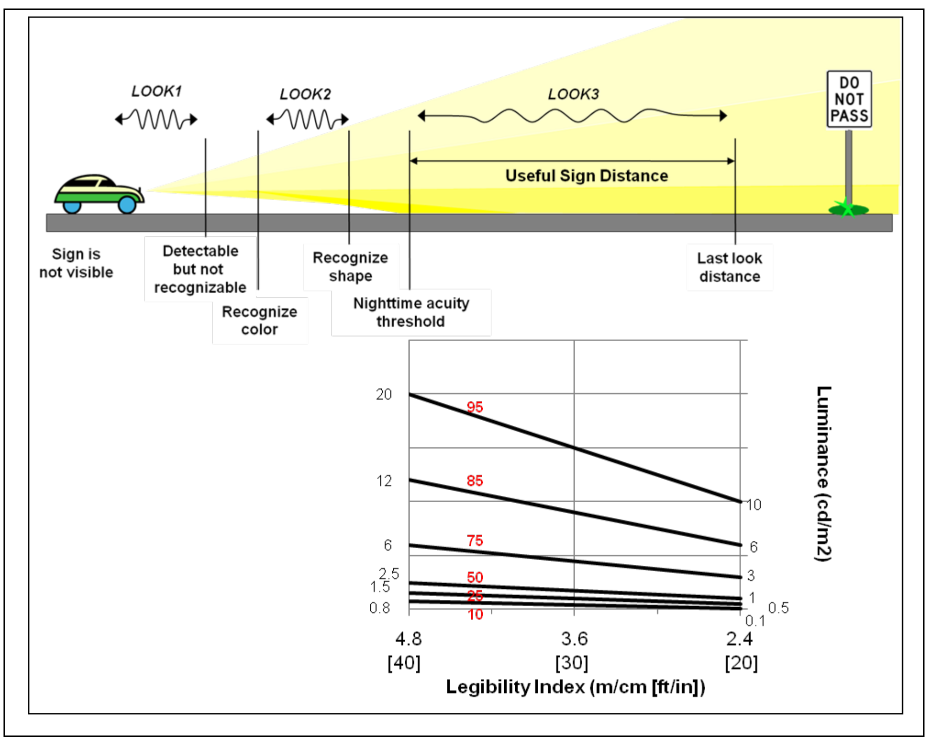

Figure 4 Luminance Required for Drivers of Passenger Cars (25)

Luminance Based on Recognition

There have been few studies evaluating the luminance required to recognize a sign. Various studies have found an increase in the recognition distances for a symbolic sign compared to the legibility distances for an equivalent alphanumeric sign.

Mercier, et al. (26, 27) determined the luminance needed to recognize various symbol and alphanumeric signs at the MRVD. The researchers compared the results to the Computer Analysis of the Retroreflectance of Traffic Signs (CARTS) model. The researchers did not analyze the data statistically, thus they only made general observations. The data showed with increasing age, drivers need more luminance to identify a sign and alphanumeric signs require more luminance to read.

Figure 5 shows the results from a study by Paniati (28). The recognition distance is the average distance the symbol was identifiable on a dark rural road. The study used a projector that produced sample images on a screen to simulate driving at 30 mph. The researcher used symbolic and text warning signs in the experiment. Paniati illuminated yellow signs at 3.4 cd/m^2 and orange signs at 1.7 cd/m^2. The study found symbol signs have longer recognition distances (up to four times) then the legibility distances of their text-based equivalents. Although this study did not look at the effects of luminance, the luminance levels used can provide a baseline of what to expect.

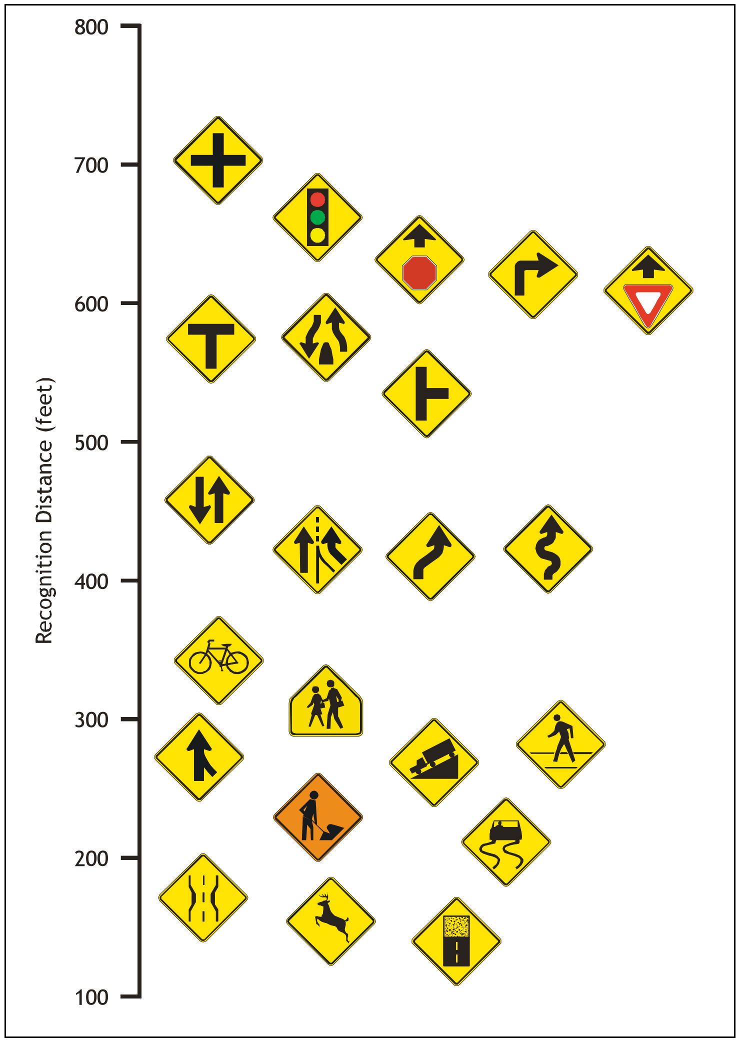

Figure 5 Symbol Sign Recognition Distances

Critical Detail

An additional way to approach the luminance needed is by looking at the critical detail of the sign. The critical detail is the angle extended (α) by the visual task of interest, as shown in Figure 6. The critical detail also is what defines normal vision. For normal vision (20/20), you need to correctly recognize an object with a critical detail of 1 min. of arc.

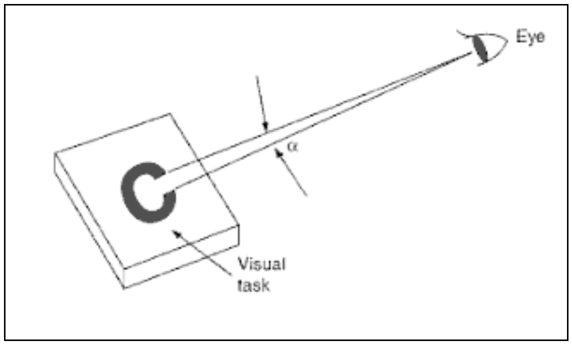

Figure 6 Critical Detail

α is the angular size of the critical detail

For a sign, the critical detail is the stroke width for an alphanumeric sign or the smallest detail of a symbol. As the legend of an alphanumeric sign decreases, so does the critical detail of the sign, making it more difficult to read. For symbol signs, an Intersection Ahead sign has a larger critical detail than a Road Narrows sign. Further, when a driver can recognize the entire sign, such as a Stop sign, the critical detail concept is hard to apply. The distance drivers view the sign affects the critical detail; the critical detail increases as drivers approach a sign.

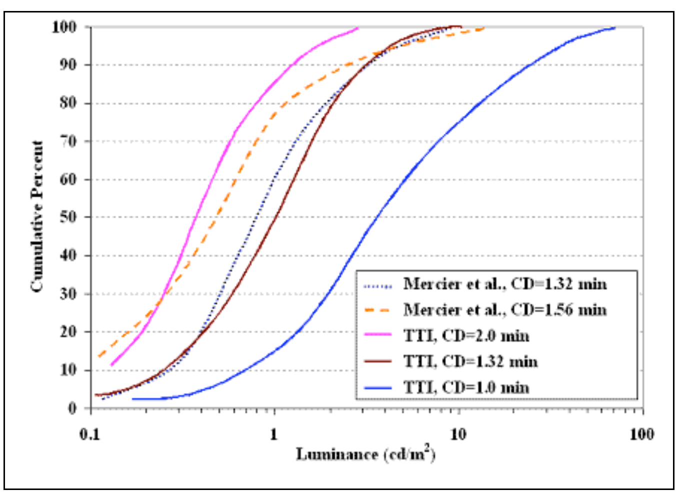

Figure 7 Luminance Needed by Critical Detail Level

Figure 7 shows the luminance needed by drivers based on the critical detail from two studies (29). As the critical detail decreases, more luminance is required to read a sign up to the point that deteriorates the contrast.

Sign Viewing Behavior

Zwhalen and Schnell (30) suggest drivers look at a sign multiple times during complete the viewing task. Zwhalen and Schnell's two-glance model describes the last glance and next-to-last glance while reading a sign. The model is shown in Figure 8. The first look distance is the distance measured from the sign to the driver when the driver begins to focus on the sign (Glance1). The last look distance is the distance between the sign and the driver the last time they look at the sign before reaching it (Glance0). Between Glance1 and Glance0, drivers fixate on the roadway.

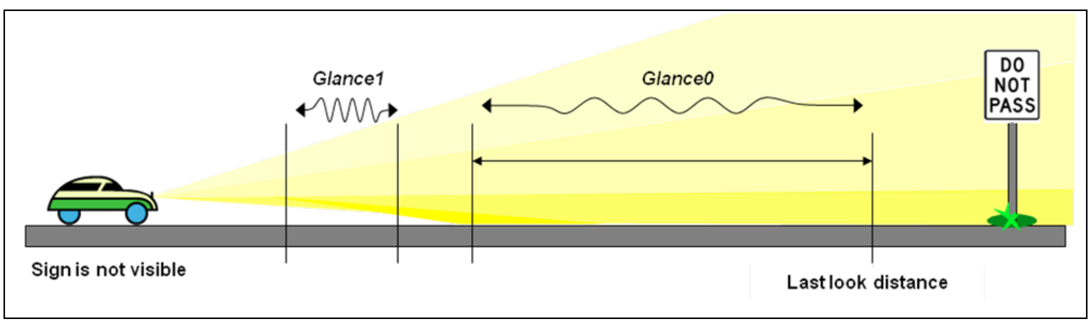

Figure 8 Two-Glance Model

Researchers have evaluated how the two-look model changes with different sheeting types. Schieber and Burns (12) modified the two-look model for the different viewing conditions. When comparing rural and suburban driving conditions, the driver's last glance occurs at a greater distance in suburban settings, and the next-to-last glance is short or missing in suburban settings especially for older drivers.

Legibility

The type of retroreflective sheeting applied to a sign can affect the legibility. Carlson and Hawkins (31) evaluated Type IX and Type III sheeting to determine the possible benefits to legibility by using microprismatic sheeting for overhead freeway guide signs. The study found a 9.5 percent increase in legibility distances when using microprismatic sheeting. Mace, Garvey, and Heckard (9) found positive contrast signs (Type I on Type VII) with a large contrast had poor legibility and Type VII is better than Type I for negative contrast signs.

Holick and Carlson (32) found that microprismatic traffic signs (Types VII, IX, and X) could produce an increase in legibility when compared to high intensity sheeting for shoulder mounted guide signs. Traffic signs with mixed sheeting (microprismatic legend on high intensity) also increased legibility. A study found the signs viewed at the closest distance had an increased legibility with Engineering Grade and High Intensity sheeting when compared to microprismatic sheeting and as the distance to the sign increased, an increase in legibility was seen with microprismatic sheeting (33).

Font Style

There are numerous fonts available for use on traffic signs; however, the legibility of each font differs. Carlson (34) evaluated the effects of the Clearview alphabet compared to the Series E (modified) alphabet for overhead guide signs and right shoulder signs and found the Clearview alphabet provides longer legibility distances especially for older drivers. Another study verified these results (35). Mace, Garvey, and Heckard (9) found Series D font provides 5 to 8 ft/in more legibility than Series C font.

CHAPTER III

RETROREFLECTIVE SHEETING SELECTION DEVELOPMENT

In this chapter, the author describes the retroreflective sheeting selection technique. First, the author presents a flowchart to demonstrate the complex decisions for sheeting selection. Next, each component of the flowchart is discussed.

Figure 9 shows the flowchart for retroreflective sheeting selection technique. The technique shows the demand and supply luminance. Demand luminance includes the surround environment, driver's needs, and the viewing distance. The author defined the demand luminance for three levels based on the studies presented in the Chapter II. The author calculated the supply luminance using the angles from geometric scenarios, the sheeting type and the headlamp profile. The angles from the geometric scenarios are determined from the design vehicle dimensions, the viewing distance, the sign placement, and the roadway geometry. One element shown, the viewing distance (outlined), is needed to determine both supply and demand luminance. The distance to the sign is determined by the speed and sign group.

This chapter is divided into three sections. First, the viewing distance is explained. Second, the demand luminance levels are presented. Finally, the elements to determine the supply luminance are discussed.

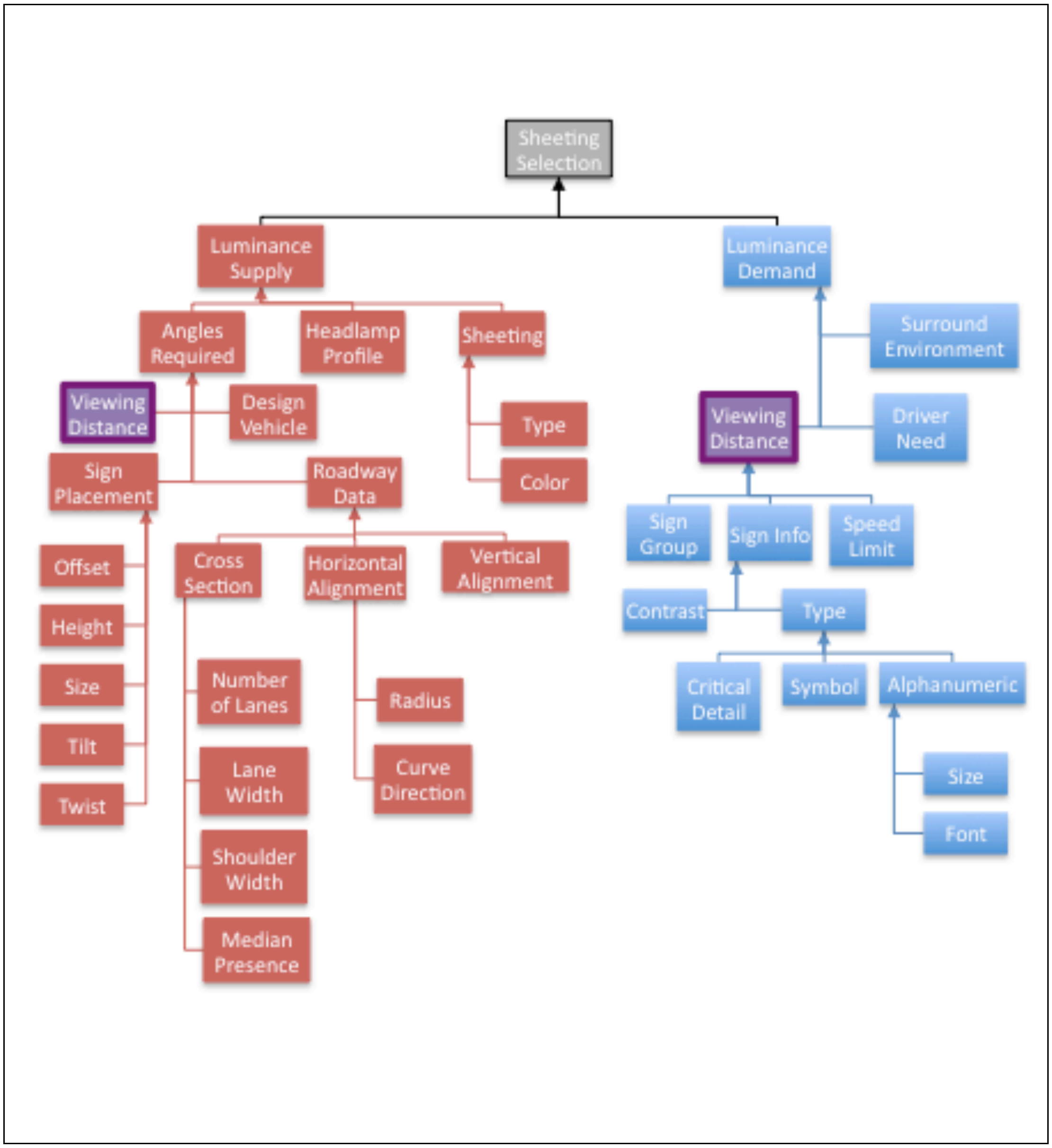

Figure 9 Retroreflective Sheeting Selection Flowchart

VIEWING DISTANCE

The sign viewing distance is needed to determine both demand and supply luminance; therefore, it is explained first. The viewing distance is the distance at which the driver needs to read or recognize the sign to be able to respond properly. The viewing distance can be applied to alphanumeric and symbol signs. With the variety of signs available, the viewing distance will vary depending on the action required by the sign, the speed, and the amount of information on the sign. The author grouped the signs from the MUTCD based on the action required and determined equations for the viewing distance based on the speed and amount of information on the sign. Table 6 shows the four groups developed.

Table 6 Sign Groups

Sign Group	MUTCD Type	Action Required	Factors Effecting Time to Read and React
1	Regulatory Warning	Stop	Time to Read Sign, Initial Speed, Deceleration Rate
2	Regulatory Warning Guidance	Speed Change	Time to Read Sign, Initial Speed, Final Speed, Deceleration Rate
3	Regulatory Warning Guidance	Advanced Warning, Informative	Time to Read Sign
4	Warning	Lane Change	Time to Read Sign, Time to Switch Lanes

For each sign group, the author determined the specific factors affecting the viewing distance. In addition to these factors, the sign placement is considered. If sign placement provides enough time after the sign location to make the appropriate action, the time needed to read or recognize the sign is the only factor affecting the distance. This is how Sign Group 3 is described. The chunks of information on the sign determine the time needed to read or recognize it. A common way to calculate the time to process the sign information is **Error! Reference source not found.** (36).

$$T = \frac{N}{3} + 2 \tag{1}$$

N = Number of chunks of information on the sign

T = Time required to process sign information (s)

For each sign group, a worst-case scenario was assumed to determine the amount of information on the sign. This, as well as the other factors affecting the viewing distance for each sign group, is explained next.

Sign Group 1

The first sign group requires a stop and includes regulatory and warning signs. These signs have three factors to determine the time needed to respond including, 1) the time to read or recognize the sign, 2) the initial speed, and 3) the deceleration rate. For this sign group, the author assumed the maximum chunks of information on the sign are two. The author used the deceleration rate from the AASHTO Green Book (37), 11.2 ft/s^2, which is the 90th percentile deceleration rate on wet pavement. With these values, calculates the total time and total distance if the sign placement is at the stopping point.

$$T_T = \left(\frac{N}{3} + 2\right) + \left(\frac{V_i}{a}\right) \qquad D_T = \left(\frac{N}{3} + 2\right)V_i + \left(\frac{V_i^2}{2a}\right) \tag{2}$$

T_T = Total time required (s)

D_T = Total distance required (ft)

N = Number of bits of information on the sign

V_i = Initial velocity (ft/s)

a = deceleration rate (ft/s^2)

Sign Group 2

The second sign group requires a speed change and includes regulatory, warning, and guide signs. These signs have four factors to determine the time needed to respond, including, 1) the time to read or recognize the sign, 2) the initial speed, 3) the final speed, and 4) the deceleration rate. For this sign group, the author assumed the maximum chunks of information on the sign are six. This accounts for guide signs with three destinations with directions. The final speed is 15 mph (22 fps), which is the estimated speed of a turn. The deceleration rate chosen for this sign group is 6.0 ft/s^2. The author calculated this value using the minimum deceleration lengths for exit terminals (37). The actual deceleration rate varied depending on the initial speed and final speed. For a final speed of 15 mph, the deceleration rate ranged from 3.2 ft/s^2 to 6.0 ft/s^2 depending on the initial speed. The author chose to use 6.0 ft/s^2 to represent a situation when the driver did not know about the speed reduction in advance and therefore applied the brakes quicker. With these values,
calculates the total time and total distance if the sign placement is at the point of the speed change.

$$T_T = \left(\frac{N}{3} + 2\right) + \left(\frac{V_i - 22}{a}\right) \qquad D_T = \left(\frac{N}{3} + 2\right)V_i + \left(\frac{V_i^2}{2a}\right) \qquad (3)$$

T_T = Total time required (s)
V_i = Initial velocity (ft/s)
D_T = Total distance required (ft)
a = deceleration rate (ft/s^2)
N = Number of bits of information on the sign

Sign Group 3

The third sign group requires information only to be read or recognized and includes regulatory, warning, and guide signs. These signs have one input to determine the time needed to respond, which is the time to read or recognize the sign. In addition, the speed determines the distance. For this sign group, the author assumed the maximum chunks of information on the sign are two. With these values, **Error! Reference source not found.** calculates the total time and total distance.

$$T_T = \left(\frac{N}{3} + 2\right) \qquad D_T = \left(\frac{N}{3} + 2\right)V_i \qquad (4)$$

T_T = Total time required (s)

D_T = Total distance required (ft)

N= Number of bits of information on the sign

V_i = Initial velocity (ft/s)

Sign Group 4

The last sign group requires a lane change and includes warning signs. These signs have two factors that determine the time needed to respond, including: 1) the time to read or recognize the sign and 2) time to make the maneuver. For this sign group, the author assumed the maximum bits of information on the sign are two. The author determined the time needed to change a lane using the decision sight distance for a rural road (37). The decision sight distance is "the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source… recognize the condition… select an appropriate speed and path, and initiate and complete the maneuver safely and efficiently." **Error! Reference source not found.** calculates this distance using time (t) equal to 11.2 seconds for a speed/path/direction change on a rural road.

$$d = 1.47Vt \qquad (5)\ (37)$$

Since the 11.2 seconds includes time for the driver to detect and recognize the situation, the time to read the sign is subtracted from the 11.2 seconds. **Error! Reference source not found.** calculates the total time and total distance if the sign placement is at the point of the lane change.

$$T_T = \left(\frac{N}{3} + 2\right) + \left(11.2 - \left(\frac{N}{3} + 2\right)\right) \qquad D_T = \left(\frac{N}{3} + 2\right)V_i + 1.47V_i\left(11.2 - \left(\frac{N}{3} + 2\right)\right) \tag{6}$$

T_T = Total time required (s) N = Number of bits of information on the sign

D_T = Total distance required (ft) V_i = Initial velocity (ft/s)

The viewing distance is needed to determine the supply luminance. The viewing distance is also the distance at which the demand luminance is needed, explained next.

DEMAND LUMINANCE

The author developed three luminance levels using the studies discussed in the Chapter II. The luminance levels were found for a LI of 30 ft/in, which represents the middle of the typical viewing range of nighttime drivers. Table 7 shows the proposed demand luminance levels. The author based the luminance levels on studies involving alphanumeric signs and used these levels for symbol signs at their MRVD. It is important to note, this thesis only evaluates the demand luminance at one viewing distance for each scenario, but how the luminance changes as a driver approaches a sign is important and should be considered.

Table 7 Demand Luminance Levels

Demand Luminance (cd/m^2)	
Replacement	2.5
Adequate	10
Desirable	30

The luminance levels were treated as a limiting factor. For example, a luminance level below 10 cd/m^2 is not sufficient and should not be used for initial installation, but does not need to be replaced if already installed. A luminance of 2.5 cd/m^2 and below indicates a need to replace. Therefore, a luminance below 10 cd/m^2 appears as replacement because it should not be used for initial installation. Next, the author describes each luminance level.

Replacement

The replacement level represents the amount of luminance a traffic sign should be replaced. The replacement level is 2.5 cd/m^2. This level is based the FHWA threshold legibility luminance of 2.5 cd/m^2 (24). Sivak and Olson found the minimum replacement luminance levels of 2.4 cd/m^2 (22). A luminance of 2.5 cd/m^2 would accommodate almost 85 percent of drivers for overhead signs and street name signs at 30 ft/in (21). A recent dynamic study tested luminance levels of 2.5 cd/m^2 and 1.0 cd/m^2 and found these luminance levels to be statistically the same (24). Further, Paniati's study measured the MRVD for symbol signs at luminance levels of 3.4 cd/m^2 and 1.7 cd/m^2 for yellow signs and orange signs, respectively (28). The replacement level is for not initial installation but should be considered if evaluating deteriorated retroreflective sheeting, as the luminance changes with the life cycle of the sheeting type.

Adequate

The adequate level is the amount of luminance recommended when installing new traffic signs. The adequate luminance level is 10 cd/m^2. This level will accommodate the majority of drivers at the appropriate distance. Sivak and Olson found the 85th percentile replacement level as 16.8 cd/m^2 (22). A luminance of 10 cd/m^2 would accommodate almost 95 percent of drivers for overhead signs and more than 98 percent of drivers for street name signs at 30 ft/in (21). A recent dynamic study found luminance levels of 10 cd/m^2 and 27 cd/m^2 were statistically different (24). The adequate level is suggested for installation in low complexity environments and where signs are located in typical locations.

Desirable

The desirable level is the approximate level at which additional luminance has diminishing returns. The desirable luminance level is 30 cd/m^2. The main study validating this level determined the luminance levels of 30 cd/m^2 and 80 cd/m^2 were statistically the same (24). Others suggested an optimal luminance between 34 cd/m^2 and 102 cd/m^2 (22). Sivak and Olson found the optimal luminance level of 75 cd/m^2 for negative contrast traffic signs (22). Carlson found luminance levels of 5.8 cd/m^2 for 98 percent recognition for street name signs at 30 ft/in, and the luminance level of 16.5 cd/m^2 for 98 percent recognition for overhead signs at 30 ft/in (21). The author chose the desirable level to be on the lower end of the ranges suggested. The desirable level is suggested for complex environments or non-typical sign placement, as the higher luminance may make the sign more conspicuous.

Other Factors

Other elements may affect the luminance a driver needs. These are not considered in this thesis, but are areas where additional research is needed. The surround environment can affect the demand luminance. The surround environment includes the ambient lighting and the complexity of the area. Other factors that can affect demand luminance are the age and experience of the driver. Further, sign specifics, such as the contrast of the sign, legend size, and font type can affect the amount of illuminance needed.

SUPPLY LUMINANCE

To determine the luminance supplied by retroreflective sheeting on a traffic sign, the author considered various factors, including roadway geometries, sign placement, retroreflective sheeting type, and vehicle type and headlamps.

The author used roadway geometries and sign placement to develop a typical highway cross-section in the US. The author used a database of Texas state highways to develop typical geometries. The author divided the database based on the population of the area, rural or urban, to determine typical geometric conditions for each subset. To determine sign placement, the author reviewed the MUTCD (2) and the Institute of Transportation Engineers (ITE) *Traffic Signing Handbook* (38).

Next, the author considered trends in vehicle types and headlamps. The headlamps provided the illuminance for the sign. The amount of illuminance the sign receives is based on the roadway geometries and the viewing distance. Once the illuminance reaches the sign, the retroreflective sheeting returns luminance to the driver. The luminance varies based on the sheeting type applied to the sign. The author explains the sheeting types considered in the last section of this chapter.

Roadway Geometries

Roadway geometries include the cross-section of the roadway, the longitudinal sign placement, and horizontal and vertical alignment. The author used geometric data from a database by Texas Department of Transportation (TxDOT) to describe the highways by different segments. The author used the database to determine the cross-section and the horizontal alignment.

Cross-Section

The author developed the typical cross-sections using the number of lanes and shoulder widths from the roadway geometries and sign placement. Figure 10 shows the two-lane scenario and Figure 11 shows the four and six-lane scenarios. For the cross-section, the author considered the number of lanes, the shoulder width, and the sign placement. Appendix A shows graphs of the geometric information.

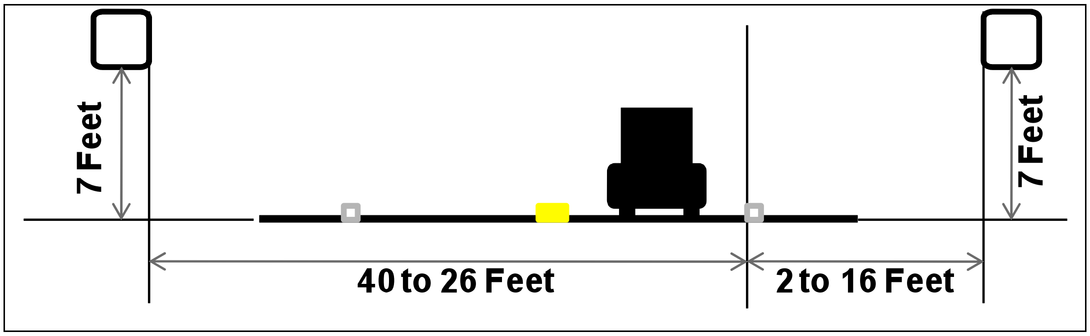

Figure 10 Sign Placement for Two-Lane Roadways

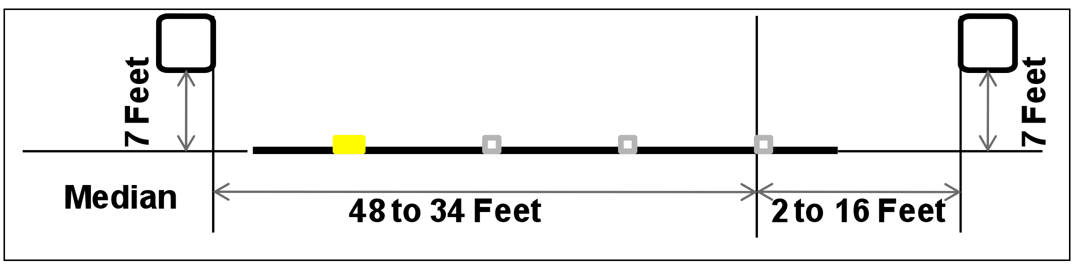

Figure 11 Sign Placement for Four and Six-Lane Roadways

First, the author determined the number of lanes for both rural and urban roadways. A graph is shown in Appendix A. There are 25 times more rural miles than urban miles. Over 90 percent of rural roadways are two-lane; while only 35 percent of urban highways are two-lane. Forty percent of urban highways are four-lane, about 16 percent are six-lane, and about 5 percent are eight-lane. This thesis evaluates two-lane rural roadways, and two, four, and six-lane urban roadways. The author considered this selection representative of the majority of roadways in the US.

After determining the number of lanes, shoulder widths were determined. Cumulative percentage graphs were developed for each classification and are located in Appendix A. For rural two-lane roads, there are 125 times more miles of roadways without curbs than with curbs; therefore, the author only considered roadways without curbs. Shoulders widths of 0 to 8 feet, excluding 7 feet, are considered for rural two-lane highways. These shoulder widths represent 93 percent of both the left and right shoulder widths without curb. This thesis does not consider the seven-foot width because it only comprises 1 percent of the all the widths present. Further evaluating shoulder widths of 6-feet and 8-feet will give an approximation of how a sign will perform at a 7-feet shoulder width.

There are more miles of curbed roadways in urban conditions; therefore, the author considers urban roadways with and without curb. Table 8 shows the shoulder widths chosen for the analysis. The number represents the percent of the total shoulder widths for a given category and the last row in Table 8 shows the percent of all the shoulders that are considered for analysis.

Table 8 Shoulder Widths for Urban Conditions

Shoulder Width (Feet)	Percentage of Total											
	2-Lane				4-Lane				6-Lane			
	Left Shoulder		Right Shoulder		Left Shoulder		Right Shoulder		Left Shoulder		Right Shoulder	
	Curb	No Curb	Curb	No Curb	Curb	No Curb	Curb	No Curb	Curb	No Curb	Curb	No Curb
0	30	12	31	12	65	13	56	9	84	18	74	14
1		9		9								
2		5		6		6		6				
3		7		7								
4	5	14	5	14		30				8		
6		9		9		21				8		
8	41	19	40	18	11	9	15	10				
9		6		7								
10	8	13	8	14	9	9	14	53		35	10	78
12										17		
Total Percent	84	96	84	96	85	88	86	80	84	86	84	92

The author considers this selection an approximation of the typical shoulder widths found within the US. Further, results can be interpolated for shoulder widths not considered. For four and six-lane roadways, 50 and 87 percent of the roadways have a median, respectively. Given the presence of a median, the author considered the signs located on the left shoulder in the median.

Sign Placement

The MUTCD (2) and the ITE *Traffic Signing Handbook* (38) provide general guidelines for sign placement. In addition to these general guidelines, many state and local agencies have additional guidance for sign installation based on their environment. Additional guidance in Texas includes the TxDOT standard detail drawings (39, 40). The TxDOT standard details are found in Appendix B. The author reviewed these sources to determine typical lateral offset, height, twist, and transverse location.

First, the author considered lateral offset. The MUTCD recommends small signs to be at least 12 feet from the edge of the travel lane where no curb is present and 2 feet from the travel lane when a curb is present. The MUTCD also recommends large signs to be at least 30 feet from the edge of the travel way and at least 7 feet from the edge of the shoulder (2). This thesis does not consider large guide signs as they are typically placed on freeways. Using the shoulder widths, the author calculated the typical lateral offsets from the edge of the right lane to the edge of the sign, shown in Table 9.

Table 9 2-Lane Roads Sign Offsets

Sign Offset* (Feet)		-40	-39	-38	-36	-34	-30	-26	2	6	10	12	14	15	16
Urban	Curb				X	X	X	X	X	X	X	X			
	No Curb	X	X	X	X							X	X	X	X
Rural	No Curb			X	X							X	X		

* Measured from the edge of the right lane to the edge of the traffic sign, negative values are to the left

For four and six-lane roadways, a median was assumed to restrict the placement of left shoulder signs. For example, on a divided highway with a concrete barrier, the sign placement can be on the concrete barrier, which is the edge of the left shoulder. The sign lateral offset is shown in Table 10. The actual offset to the sign varies depending on the location of the vehicle within the travel lanes.

Table 10 Multilane Urban Roads Sign Offsets

Sign Offset* (Feet)		-48	-34	2	4	10	12	14	16
4 Lane	Curb			X	X	X	X		
	No Curb		X				X	X	X
6 Lane	Curb			X			X		
	No Curb	X					X		X

* Measured from the edge of the right lane to the edge of the traffic sign, negative values are to the left and assumed to be in a median

Next, the author considered sign height. The MUTCD recommends sign heights of 7 feet to the bottom of a sign where pedestrians are present and 5 feet where pedestrians are not present or the sign is protected. The TxDOT standard details in Appendix B only show the 7-foot mounting height. For large guide signs, the recommended height to the bottom of the signs is 8.5 feet. This thesis evaluates the 7-foot mounting height, as the worst-case scenario. A comparison of the 5-foot and 7-foot sign heights can be found in Appendix C.

Finally, the author considered sign twist. The MUTCD advises signs should be orientated (twisted) at right angles to the direction of traffic. Further, to reduce mirror reflection, signs may be twisted. The ITE handbook specifies the exact orientation of signs. The handbook recommends rotating signs with Types I or II sheeting three degrees towards the approaching traffic. Signs with other sheeting types should be rotated 3 degrees away from traffic to prevent glare. For signs on curved roads, the

MUTCD recommends placing the sign based on the direction of approaching traffic and the ITE handbook recommends placing signs perpendicular to the driver when the driver is 250 feet from the sign. Table 11 shows the recommended sign twists using the 250 feet formula. Currently, it is unknown how sign twist varies on curved roads. Therefore, the author assumed all signs on curves are perpendicular to the travel lane. The authored compared how sign twist affects luminance; shown in Appendix C.

Table 11 Sign Twist

Radius	None	11459	5729	2865	1910	1432	1146	955	573
Sign Twist (degrees)	3	1.2	2.5	5	7.5	10	12.5	15	25

Alignment

Next, the author considered the longitudinal sign placement, horizontal alignment, and vertical alignment. The author determined the typical horizontal alignment from the TxDOT database. Vertical alignment was not considered for this thesis, but it is discussed.

This thesis evaluates two longitudinal sign locations: 1) tangent, where the sign is placed on a straight roadway and 2) end of curve, where the sign is placed at the end of the curve, so the entire sign viewing is within the curve. The placements are shown in Figure 12. Signs are located on both curves to the left and curves to the right.

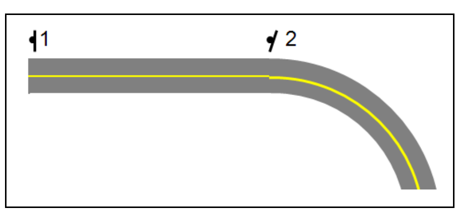

Figure 12 Longitudinal Sign Locations

The author evaluated horizontal curves separately for urban and rural roadways. The author calculated the curve radius (R) using the degree of curve (D) from the TxDOT database; see **Error! Reference source not found.**. The cumulative plot of the curve radii is in Appendix A.

$$R = \frac{5730}{D} \tag{7}$$

Table 12 shows the most frequent curve radii. This selection considers 80 percent of the curves radii on rural two-lane roads. For urban roadways, 75, 67, and 72 percent of the curve radii are considered for two, four, and six-lane roads, respectively. For other radii of interest, the results can be interpolated to give an approximate performance. The author considers radii larger than 11459 feet equivalent to a tangent section.

Table 12 Curve Radii Evaluated

Radius (feet)		11459	5730	2865	1910	1432	1146	955	573
Degree of Curve		0.5	1.0	2.0	3.0	4.0	5.0	6.0	10
Rural	**2 Lane**	X	X	X	X	X	X	X	X
Urban	**2 Lane**	X	X	X	X	X	X	X	X
	4 Lane	X	X	X	X	X	X		
	6 Lane	X	X	X	X	X	X		

Vertical curvature is an important issue as it influences the amount of luminance a sign will receive. With recent changes in headlamp patterns, this is becoming a more significant issue. Over the last 20 years, the amount of light a headlamp emits above the horizon has been decreasing, inadvertently providing less illuminance to traffic signs (41). Vertical curvature data is not part of the TxDOT database and the author did not analyze vertical curvature in this thesis; however, the author discusses the difference in luminance for vertical sag curves and vertical crest curves.

As a driver travels through a sag curve, the vehicle's headlamps are directed towards the pavement, as shown in Figure 13. This decreases the illuminance able to reach a sign and therefore, decreases the amount of luminance provided by the retroreflective sheeting. For situations on sag curves, a sheeting type with a higher retroreflectivity could improve the performance.

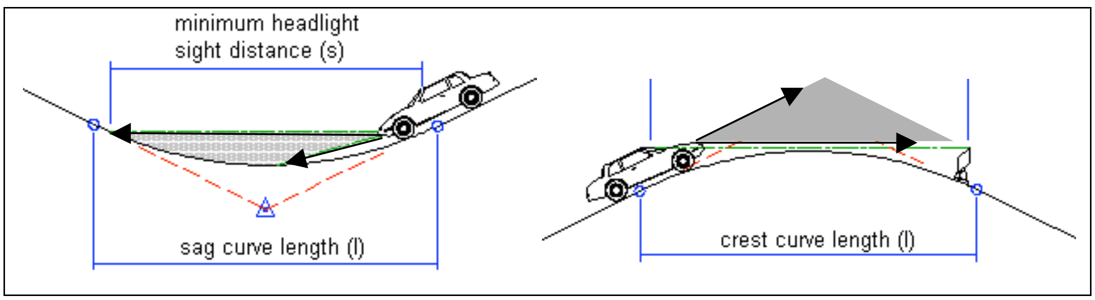

Figure 13 Headlamp Aim on Sag and Crest Curves

As a vehicle travels through a crest curve, the headlamps are directed towards the sky, as shown in Figure 13. This increases the illuminance able to reach a sign and therefore, increases the amount of luminance provided by the retroreflective sheeting. For situations on crest curves, a sheeting type with a lower retroreflectivity may provide the same performance when compared to a sign not in a crest curve.

Vehicle Trends

After considering roadway geometries, vehicle type is considered. With gasoline prices fluctuating and the auto industry struggling, the vehicle mix within the US is changing. The author used sales data to determine vehicle trends. Sales can determine the most prominent new cars on the roadways.

Beginning in the 1990's, the sales of new light trucks (including SUVs, pickups, and vans) increased steadily until about 2004 when sales began to drop. Since 2007, the sales of cars and trucks decreased and the sales of new cars have overtaken the sales of trucks, as shown in Figure 14. Most recently, the sales of cars increased in August 2009 with the Cash for Clunkers program. If these trends continue, the percentage of passenger cars in the US will continue to increase, while the percentage of light trucks will begin to decrease.

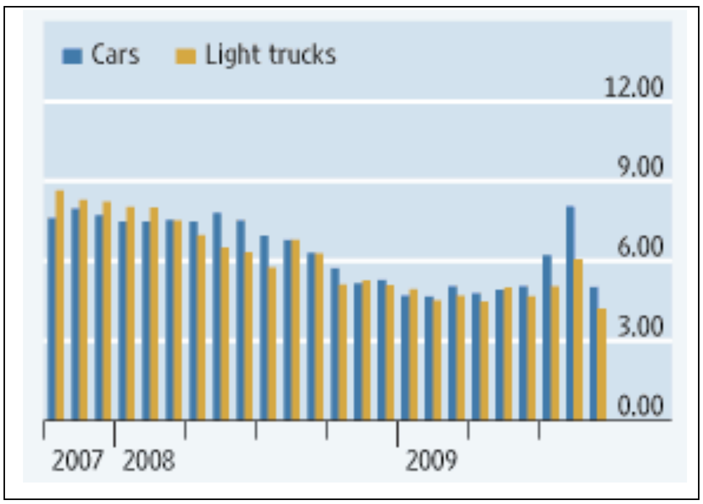

Figure 14 Millions of Vehicle Sales

Sept 2007 to Sept 2009 at Seasonally Adjusted Annual Rate (42)

With the recent changes in the vehicle fleet in the US, it is important to consider both passenger cars and light trucks in this analysis. Light trucks include pickups, SUVs, and vans. SUVs are considered equivalent to light trucks in terms of dimensions, which influence sign performance. This thesis does not make a distinction among the SUV sizes. Some SUVs such as "crossover" vehicles and compact (or mini) SUVs are more popular now and have dimensions different from light trucks, which could justify their own vehicle classification. While this could be a later improvement to the technique, it was not a priority for this thesis, as this thesis develops the process for sheeting selection. Therefore, for this thesis, the market-weighted average dimensions of passenger cars and light trucks (pickups and SUVs) are used.

Vehicle Dimensions

The author calculated the passenger car and light truck dimensions in Table 13 from the top 15 selling vehicles in the US for 2009; the calculations are in Appendix D. The commercial vehicle dimensions in Table 13 are from 2002 (43) and are shown as a comparison.

Table 13 2009 Market-Weighted Average Vehicle Dimensions

Vehicle Type	Vehicle Dimensions (inches)				
	Height of Headlamps above Road	Distance Between Headlamps	Height of Driver's Eye above Road	Transverse Distance of Eyes from Left Headlamp	Distance of Eyes Behind Headlamps
Passenger Car	27	53	47	13	82
Light Truck	36	60	60	13	84
Heavy Truck (43)	43	74	92	16	87

Headlamps

There have been many headlamp variations over the years and now, there is a large mix of headlamps on the roadways. The headlamps available include (44):

1. Incandescent: A tungsten filament creates light in an incandescent bulb. This is the oldest headlamp type.
2. Halogen: A thin tungsten filament surrounded by halogen gas creates light in a halogen bulb. The light is brighter and whiter than incandescent bulbs.

3. Xenon: An electrical charge traveling between two electrodes creates the light in this headlamp. This light is three times brighter than halogen. HID (high-intensity discharge) is a common type in new vehicles and has been available in the U.S. for over 10 years.

Sales data can determine the types of vehicle headlamps; however, this may not be representative of the headlamp types on the roadways at nighttime. Flannagan, et al. (45) found the proportion of HID headlamps varied from 1.5 percent to 20 percent. Although the HID headlamps do not appear to have a large proportion on the roadway at night, the headlamps provide less light to signs (41). For the vehicle types, the 2004 market-weighted average low-beam headlamp developed by University of Michigan Transportation Research Institute (UMTRI) is used (46). This is the most recent headlamp data available for the US. This market-weighted average represents the luminous intensity values for the tungsten-halogen headlamps from the 20 top-selling vehicles in 2003; Appendix E shows the headlamp data for the 2004 UMTRI headlamp.

Retroreflective Sheeting Types

This thesis evaluates seven different retroreflective types defined by ASTM, including: 1) Type I: Engineering Grade, 2) Type II: Super Engineer Grade, 3) Type III: High Intensity (Glass Bead), 4) Type IV: High Intensity (Microprismatic), 5) Type VIII: Super High Intensity, 6) Type IX: Very High Intensity, and 7) Type XI: Super High Intensity (7).

This thesis evaluates white retroreflective sheeting. A factor is applied for different color sheeting. For yellow, a factor of 0.74 is applied and for orange, a factor of 0.33 is applied. The factors were determined by comparing the luminance provided by each color of sheeting; see Appendix F. The sheeting color for luminance supply is the background on a negative contrast sign or the legend on a positive contrast sign.

CHAPTER IV

RETROREFLECTIVE SHEETING SELECTION SPREADSHEET

In this chapter, the author describes the retroreflective sheeting selection spreadsheet (RSSS) created using the information presented in Chapter III. RSSS is able to compute the retroreflective sheeting performance based on the demand luminance levels and supply luminance. The spreadsheet allows users to enter the roadway data, vehicle type, and sign data and determine the performance level of seven retroreflective sheeting types. The spreadsheet is available at https://ceprofs.civil.tamu.edu/ghawkins/Thesis_Final/RSSS_Tool.htm. In this chapter, an overview of RSSS is first presented with a discussion of each sheet in RSSS. Second, the author discusses the user inputs. Next, the computations and Excel formulas are discussed. Finally, the author discusses the outputs using four examples, one from each sign group.

OVERVIEW

The author developed RSSS to create an easy to use tool for determining retroreflective sheeting performance. Once users enter the roadway data, vehicle type, and sign data, the spreadsheet calculates the distance drivers need to read or recognize the sign and looks up the luminance supplied by each retroreflective sheeting type. The author used a computer program, ERGO, to calculate the luminance supplied for different geometries. Appendix G explains ERGO. The author created tables of the supply luminance calculated in ERGO for each sheeting type in RSSS. RSSS then compares luminance supplied by each sheeting type for the inputted scenario to the luminance demand levels to determine the performance. RSSS outputs these values in a table. RSSS includes 18 Excel sheets, shown in Table 14 and described next.

Table 14 RSSS Sheets

Sheet Number(s)	Label	Description
1	Input/Output	User input area and outputs results
2	Sign Info	MRVD and sign offset calculations
3	Evaluation	Luminance calculations
4-10	EType	Look up values for Evaluation sheet
11-17	Type	Look up values for EType sheets
18	Notes	Author contact information and references

Sheet 1: Input/Output

The Input/Output sheet is shown in Figure 15. At the top of this sheet, users can enter project information. The inputs are in the shaded boxes and include the roadway data (section A), the design vehicle (section B), and the sign data (section C).

The right side (section D) of the sheet shows the output data. The output displays a "R," "A," "D" or "N/A" for replacement, adequate, desirable, and below replacement level, respectively. N/A indicates a supply luminance below 2.5 cd/m^2. Replacement indicates a supply luminance value between 2.5 cd/m^2 and 10 cd/m^2. Adequate indicates a supply luminance value between 10 cd/m^2 and 30 cd/m^2. Desirable indicates a supply luminance value equal to or greater than 30 cd/m^2.

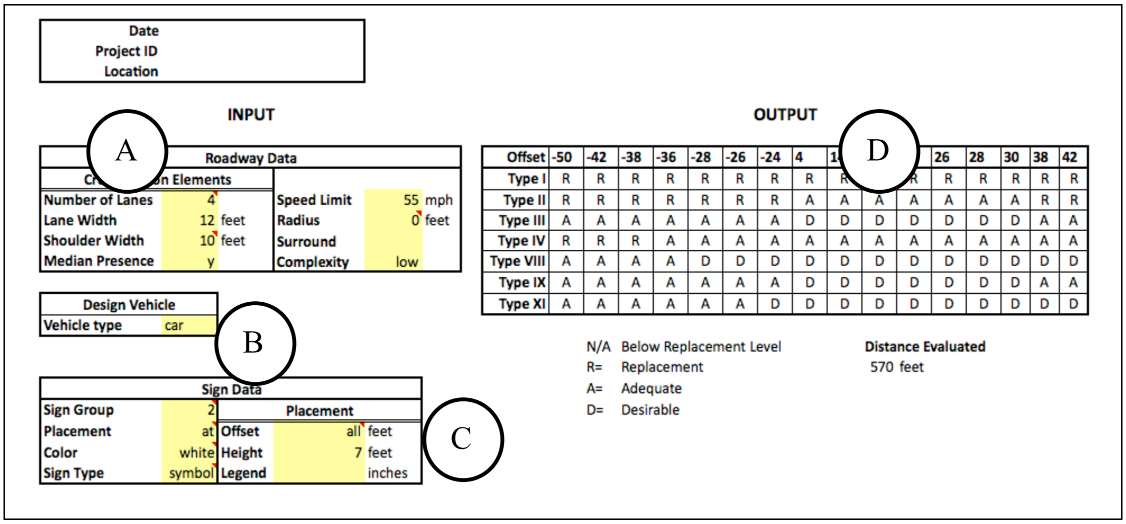

Figure 15 Input/Output Sheet

Sheet 2: Sign Info

Figure 16 shows the Sign Info sheet. This sheet calculates the minimum required visibility distance (MRVD) and the sign offset from each lane. Chapter III explains equations for the MRVD. The sheet also contains the color factors to apply to the luminance if the sheeting is not white. The sign and roadway information from the Input/Output sheet determines the offsets.

			Example Sign								
Sign Group	MUTCD Type	Sign Description	At Sign	Sign in Advance	Factors Effecting Distance	Read Time (s)*	Decel Rate (ft/s^2)**	Speed Change (mph)***	Reaction Time (s)	Total Time (s)	Distance (ft)
1	Regulatory Warning	Stop	Stop, Yield, Pedestrian Crossing	Deer Crossing	Initial Speed, Deceleration Rate, Time to Read Sign	2.67	11.20	NA	7.20	9.87	510
2	Regulatory Warning Guidance	Speed Change	Speed Limit	Reduced Speed Ahead, Curve, Guidance	Initial Speed, Adjusted Speed, Deceleration Rate, Time to Read Sign	4.00	6.00	40.00	9.78	13.78	610
3	Regulatory Warning Guidance	Advanced Warning, Informative	Do Not Pass, Mile Post	Narrow Bridge	Time to Read Sign	2.67	NA	NA	NA	2.67	220
4	Warning	Lane Change	Lane Ends	Lane Ends	Time to Read Sign, Time to Switch Lanes	2.67	NA	NA	8.53	11.20	910

* based on bits of information (N) on a sign Time (s) = 2 + N/3
** AASHTO Green Book
*** Assumes final speed of 15 mph if placed at location, assumes speed change of 15 mph if placed in advance

Luminance Adjustment		
White	Yellow	Orange
1	0.74	0.33

Number of Lanes	6			
Lane Width	12			
Shoulder Width	10			
Median	y			
Sign Offset	14	FALSE		
	Offset to sign from each lane			
Left Shoulder	3	2	1	Right Shoulder
no sign	38	26	14	sign

Figure 16 Sign Info Sheet

Sheet 3: Evaluation

Figure 17 shows the Evaluation sheet. This sheet calculates the performance of each retroreflective sheeting type. Section E of this sheet looks up values for each white retroreflective sheeting at the viewing distance. The luminance values are found from the EType Sheets. RSSS determines luminance values for three distances, shown in Table 15. The author determined the distances based on the sign type, alphanumeric or symbol. RSSS only uses the middle distance, the MRVD for symbol signs or the distance at a LI of 30 ft/in for text signs, to determine the performance level.

White Sheeting

Type	Distar	-50	-36	-26	4	14	26	38	42
Type I	660	2.5	3.1	3.5	8.2	8.5	9	6.2	5.4
	610	2.5	3.1	3.6	8.1	8.5	8.6	5.7	5.1
	560	2.6	3.2	3.7	7.8	8.4	7.7	5.1	4.7
Type II (E)	660	4.3	5.3	[illegible]	[illegible]	15	16	11	9.5
	610	4.3	5.4	6.1	14	15	15	10	8.9
	560	4.4	5.5	6.2	13	14	13	8.8	8.1
Type III	660	15	18	20	42	41	42	28	24
	610	15	19	21	42	42	41	26	23
	560	16	19	21	40	42	38	25	22
Type IV	660	7.9	9.7	11	26	27	29	20	18
	610	8	9.9	11	25	27	27	18	16
	560	8.1	10	11	24	26	24	16	15
Type VIII	660	23	29	33	77	79	84	59	51
	610	22	28	32	75	78	80	55	49
	560	21	27	31	70	77	73	50	46
Type IX	660	17	20	23	49	50	51	35	30
	610	17	21	23	47	49	48	31	28
	560	18	21	23	44	46	41	26	24
Type XI	660	19	25	29	75	76	80	55	47
	610	19	25	29	74	76	77	51	45
	560	19	25	29	71	76	70	46	42

White Sheeting

Type	-50	-36	-24	4	14	26	38	42
Type I	2.5	3	3.6	8.2	8.5	9	6.2	5.4
	2.5	3	3.7	8.1	8.5	9	5.7	5.1
	2.6	3	3.8	7.8	8.4	8	5.1	4.7
Type II (F)	4.3	5	[illegible]	[illegible]	[illegible]	16	11	9.5
	4.3	5	6.2	14	15	15	10	8.9
	4.4	5	6.4	13	14	13	8.8	8.1
Type III	15	18	21	42	41	42	28	24
	15	19	21	42	42	41	26	23
	16	19	21	40	42	38	25	22
Type IV	7.9	10	11	26	27	29	20	18
	8	10	12	25	27	27	18	16
	8.1	10	12	24	26	24	16	15
Type VIII	23	29	34	77	79	84	59	51
	22	28	33	75	78	80	55	49
	21	27	32	70	77	73	50	46
Type IX	17	20	23	49	50	51	35	30
	17	21	23	47	49	48	31	28
	18	21	24	44	46	41	26	24
Type XI	19	25	30	75	76	80	55	47
	19	25	30	74	76	77	51	45
	19	25	30	71	76	70	46	42

Performance @ Distance

Type	-50	-36	-26	4	14	26	38	42
Type I	0	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1
Type II (G)	1	1	[illegible]	[illegible]	[illegible]	2	2	1
	1	1	1	2	2	2	2	1
	1	1	1	2	2	2	1	1
Type III	2	2	2	3	3	3	2	2
	2	2	2	3	3	3	2	2
	2	2	2	3	3	3	2	2
Type IV	1	1	2	2	2	2	2	2
	1	1	2	2	2	2	2	2
	1	2	2	2	2	2	2	2
Type VIII	2	2	3	3	3	3	3	3
	2	2	3	3	3	3	3	3
	2	2	3	3	3	3	3	3
Type IX	2	2	2	3	3	3	3	3
	2	2	2	3	3	3	3	2
	2	2	2	3	3	3	2	2
Type XI	2	2	2	3	3	3	3	3
	2	2	2	3	3	3	3	3
	2	2	2	3	3	3	3	3

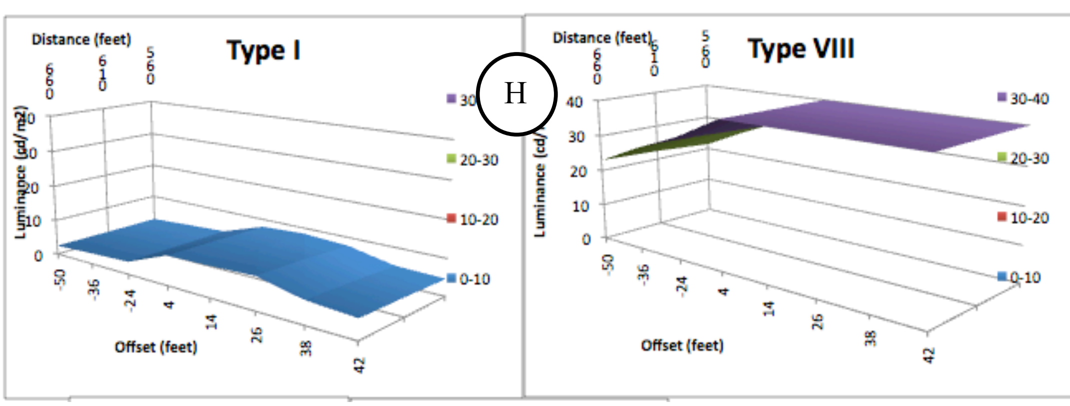

Figure 17 Evaluation Sheet

Table 15 RSSS Distances

Location from Sign	Alphanumeric Signs	Symbol Signs
Closest	@ LI = 20 ft/in	MRVD - 50 feet
	@ LI = 30 ft/in	MRVD
Furthest	@ LI = 40 ft/in	MRVD + 50 feet

Section F multiplies the values in section E by the color factor based on the color entered in the Input/Output sheet. Section G compares the values in section F to the demand luminance levels and assigns a number to represent each level. The sheet assigns 1 to the replacement level, 2 to the adequate level, and 3 to the desirable level. RSSS assigns a zero to luminance values below the replacement level. The values from section G are outputted as the appropriate letter to represent the performance level in the output section of the Input/Output sheet, Figure 15. The final portion, section H, of this sheet produces a graph for each sheeting type. The vertical axis is the luminance provided by the white sheeting, the horizontal axis is the range of sign offsets, and the depth axis is the three distances.

Sheets 4 – 10: EType

Sheets 4 though 10 provide the luminance levels for the scenarios entered in the Input/Output sheet. There are seven sheets, one for each sheeting type. The sheets are labeled ETypeI, ETypeII, ETypeIII, ETypeIV, ETypeVIII, ETypeIX and ETypeXI. Each of these sheets looks up the luminance values from the respective "Type" sheet, discussed in the next section. Figure 18 shows an example of this sheet.

Section A of this sheet looks up the values for the specific scenario which is defined in the first column. This column is a text chain that includes the vehicle type, radius, and distance. This thesis considers the luminance supply between viewing distances of 120 feet and 640 feet. Section B of this sheet displays the luminance values graphically.

The vertical axis is the luminance supplied, the horizontal axis is the offset, and the depth axis is the distance from the sign. The horizontal axis is not scaled.

TYPE VIII - White			Offset															
Vehicle,Radius, Distance	LI	Distance	-50	-42	-38	-36	-28	-26	-24	4	14	16	18	26	28	30	38	42
car,0,530	88.3	530	20.7	23.7	25.3	26.2	30.1	30.8	31.7	68.3	76.3	77.7	77.4	66.9	62.8	58.4	47.3	43.9
car,0,540	90.0	540	20.9	23.9	25.5	26.5	30.2	31.0	31.8	68.9	76.7	78.6	78.7	68.9	64.8	60.4	47.9	44.5
car,0,550	91.7	550	21.2	24.1	25.8	26.8	30.4	31.2	32.0	69.5	77.0	79.7	[illegible]	71.0	66.9	62.6	48.7	45.1
car,0,560	93.3	560	21.4	24.3	26.0	27.1	30.6	31.3	32.2	70.0	77.0	[illegible]	[illegible]	[illegible]	68.9	64.6	49.6	45.7
car,0,570	95.0	570	21.7	24.5	26.3	27.3	30.7	31.5	32.4	70.5	76.8	[illegible]	[illegible]	[illegible]	70.7	66.5	50.4	46.4
car,0,580	96.7	580	21.9	24.7	26.5	27.5	30.8	31.7	32.6	71.5	77.0	80.2	[illegible]	76.2	72.5	68.2	51.2	46.8
car,0,590	98.3	590	22.1	24.9	26.7	27.7	31.0	31.9	32.8	72.6	77.4	80.5	83.4	77.7	74.2	69.9	52.1	47.3
car,0,600	[illegible]	600	22.3	25.1	26.9	27.9	31.2	32.0	33.0	73.7	77.8	80.8	84.1	79.2	75.6	71.5	53.3	47.9
car,0,610	[illegible]	[illegible]	[illegible]	[illegible]	27.2	28.1	31.3	32.2	33.2	74.7	78.1	81.1	84.2	80.5	76.9	73.1	54.6	48.5
car,0,620	[illegible]	[illegible]	[illegible]	[illegible]	27.4	28.3	31.5	32.3	33.3	75.6	78.5	81.4	84.2	81.8	78.2	74.6	56.0	49.2
car,0,630	105.0	630	22.8	25.7	27.5	28.5	31.6	32.5	33.4	76.4	78.7	81.6	84.3	82.9	79.5	75.9	57.3	49.9
car,0,640	106.7	640	23.0	25.9	27.7	28.6	31.6	32.5	33.5	77.1	79.0	81.8	84.5	84.1	80.7	77.0	58.7	50.6

Car,0,560

A

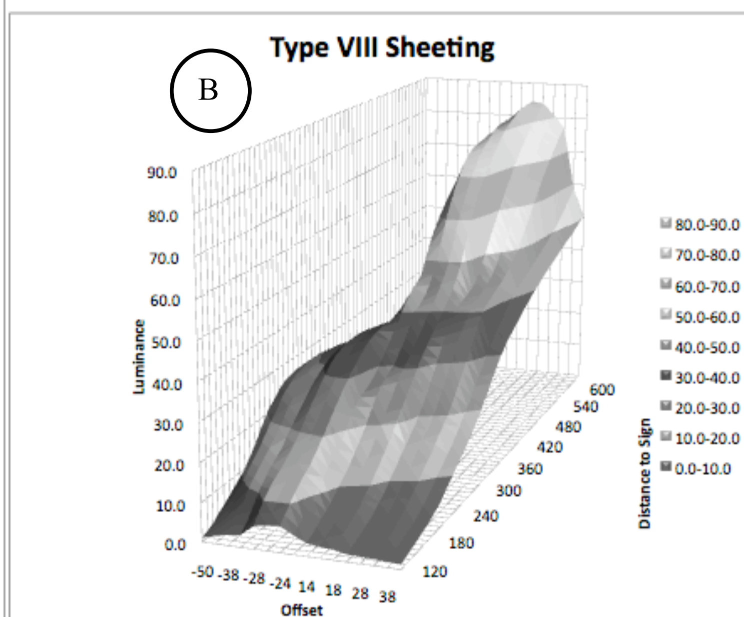

Figure 18 ETypeVIII Sheet

Sheets 11-17: Type

Sheets 11 though 17 provide the luminance levels for all of the possible geometries. The sheets must be sorted by the first column for RSSS to function properly. This is extremely important as different versions of Excel sort differently. RSSS was developed in Excel:mac 2008. There are seven sheets, one for each sheeting type. The sheets are labeled TypeI, TypeII, TypeIII, TypeIV, TypeVIII, TypeIX and TypeXI. The EType sheets look up the values from here. The author used ERGO to compute the luminance values in these sheets. These sheets include the luminance values for each vehicle, radius, distance, and offset considered.

Figure 19 shows an example of these sheets. The first column is a text chain that includes the vehicle type, radius, and distance. This column is the "lookup" values used to find the luminance for a specific scenario. The varying shades of the cells represent the luminance demand levels. The white cells represent luminance levels below the replacement level of 2.5 cd/m^2. The darkest shading represents luminance levels of 30 cd/m^2 and greater.

TYPE VIII					Offset															
Vehicle,Radius, Distance	LI	Vehicle	Distance	Radius	-50	-42	-38	-36	-28	-26	-24	4	14	16	18	26	28	30	38	42
Car,-11459,120	20	Car	120	-11459	1.3	2.4	3.3	3.8	6.3	6.7	6.9	4.9	3.3	3.0	2.8	2.2	2.0	2.0	1.7	1.5
Car,-11459,130	22	Car	130	-11459	2.0	3.6	4.8	5.7	8.4	8.4	8.4	5.5	3.8	3.6	3.2	2.7	2.6	2.4	2.1	2.1
Car,-11459,140	23	Car	140	-11459	3.0	5.2	6.9	8.3	10.2	10.0	10.1	6.4	4.5	4.3	4.0	3.4	3.2	3.1	2.7	2.6
Car,-11459,150	25	Car	150	-11459	4.5	7.1	9.6	10.4	11.8	11.7	11.8	7.6	5.5	5.0	4.8	4.0	3.9	3.7	3.3	3.2
Car,-11459,160	27	Car	160	-11459	5.7	9.0	11.4	12.1	13.0	13.1	13.1	8.8	6.5	5.9	5.4	4.7	4.5	4.4	4.0	3.8
Car,-11459,170	28	Car	170	-11459	7.3	11.2	12.8	13.3	14.1	14.3	14.3	10.5	7.4	6.9	6.3	5.3	5.2	5.1	4.6	4.4
Car,-11459,180	30	Car	180	-11459	8.7	13.0	14.0	14.5	15.4	15.4	15.5	12.3	8.5	8.0	7.5	6.1	6.0	5.8	5.3	5.0
Car,-11459,190	32	Car	190	-11459	10.5	14.4	15.4	15.7	17.0	17.0	17.3	13.8	9.8	9.1	8.6	7.0	6.8	6.6	6.0	5.6
Car,-11459,200	33	Car	200	-11459	12.5	15.6	16.5	17.4	18.5	18.8	19.3	15.0	11.1	10.4	10.0	8.1	7.8	7.7	6.8	6.5
Car,-11459,210	35	Car	210	-11459	14.9	17.5	18.6	19.0	20.2	20.6	20.7	16.1	12.6	11.8	11.3	9.4	9.1	8.8	7.8	7.3
Car,-11459,220	37	Car	220	-11459	17.4	19.3	20.5	20.6	22.1	22.6	22.3	17.2	14.0	13.3	12.5	10.6	10.3	10.0	8.9	8.2
Car,-11459,230	38	Car	230	-11459	19.5	21.3	22.2	22.4	24.2	24.6	24.2	19.3	15.3	14.7	13.8	11.9	11.4	11.1	10.0	9.3
Car,-11459,240	40	Car	240	-11459	21.1	23.5	23.8	24.4	26.4	26.4	26.3	21.6	17.1	16.2	15.2	13.0	12.6	12.1	11.0	10.5
Car,-11459,250	42	Car	250	-11459	22.7	25.1	25.7	25.9	28.4	28.2	28.3	23.6	19.4	18.0	17.1	14.0	13.6	13.1	12.0	11.6
Car,-11459,260	43	Car	260	-11459	24.4	26.3	27.1	27.5	30.0	30.0	30.2	25.1	21.6	19.9	19.0	15.5	14.7	14.3	12.9	12.7
Car,-11459,270	45	Car	270	-11459	25.5	27.5	28.4	29.5	31.4	31.7	32.1	25.8	23.3	21.8	20.6	17.1	16.2	15.6	14.0	13.8
Car,-11459,280	47	Car	280	-11459	26.7	28.8	29.9	31.1	32.8	33.3	33.8	26.6	25.0	23.7	22.2	18.4	17.9	17.1	15.3	14.9
Car,-11459,290	48	Car	290	-11459	27.5	29.7	31.3	32.1	34.1	34.9	35.0	27.5	26.8	25.9	24.2	19.8	19.4	18.8	16.6	16.2
Car,-11459,300	50	Car	300	-11459	27.8	30.1	32.1	32.8	35.3	36.3	36.1	28.5	28.7	27.9	26.4	21.6	21.0	20.7	18.0	17.4
Car,-11459,310	52	Car	310	-11459	27.9	30.5	32.5	33.3	36.4	37.5	36.8	29.6	30.4	29.9	28.8	23.7	22.8	22.4	19.5	18.5
Car,-11459,320	53	Car	320	-11459	28.0	31.0	32.8	33.6	37.1	37.7	37.2	30.7	32.2	31.9	31.2	25.8	24.8	24.1	21.1	19.9
Car,-11459,330	55	Car	330	-11459	28.1	31.2	32.9	33.7	37.7	37.8	37.7	32.2	34.0	34.0	33.4	27.9	26.7	25.8	23.1	21.6
Car,-11459,340	57	Car	340	-11459	27.9	31.2	32.9	33.6	38.0	37.6	38.2	34.0	35.5	35.7	35.4	29.9	28.7	27.6	24.9	23.3
Car,-11459,350	58	Car	350	-11459	27.6	31.0	32.6	33.3	37.6	37.4	38.4	35.9	37.0	37.1	37.1	31.9	30.6	29.4	26.8	25.0
Car,-11459,360	60	Car	360	-11459	27.2	30.7	32.2	33.0	37.2	37.3	38.5	37.7	38.3	38.5	38.7	33.9	32.4	31.3	28.5	26.9
Car,-11459,370	62	Car	370	-11459	26.7	30.2	31.7	32.6	36.6	37.3	38.5	39.4	39.6	39.6	40.1	36.0	34.3	33.0	30.2	28.6
Car,-11459,380	63	Car	380	-11459	26.3	29.6	31.2	32.2	36.0	37.2	38.5	40.9	40.9	40.7	41.2	38.0	36.2	34.8	31.6	30.2
Car,-11459,390	65	Car	390	-11459	25.7	29.0	30.7	31.8	35.8	37.0	38.2	42.6	42.0	41.4	41.9	39.6	37.8	36.2	32.6	31.3
Car,-11459,400	67	Car	400	-11459	25.2	28.6	30.4	31.6	35.5	36.6	37.7	45.0	43.3	42.2	42.3	40.6	39.0	37.2	33.3	32.2
Car,-11459,410	68	Car	410	-11459	24.9	28.3	30.2	31.7	35.2	36.2	37.3	47.7	44.8	43.3	43.0	41.4	39.9	38.3	33.9	33.0
Car,-11459,420	70	Car	420	-11459	24.8	28.1	30.1	31.7	35.0	35.8	36.9	51.5	46.4	44.7	43.7	42.2	40.8	39.2	34.5	33.5
Car,-11459,430	72	Car	430	-11459	24.6	28.0	30.3	31.7	34.7	35.4	36.6	55.8	48.5	46.3	44.7	43.0	41.6	40.0	35.0	33.8
Car,-11459,440	73	Car	440	-11459	24.4	27.9	30.4	31.7	34.5	35.2	36.8	59.6	50.8	48.2	45.8	43.6	42.3	40.8	35.5	34.0
Car,-11459,450	75	Car	450	-11459	24.3	27.8	30.4	31.4	34.3	35.2	37.4	62.9	53.4	50.4	47.5	44.1	43.0	41.4	36.0	34.3
Car,-11459,460	77	Car	460	-11459	24.1	27.8	30.5	31.2	34.3	35.4	38.3	65.8	55.8	52.5	49.4	44.7	43.5	42.0	36.6	34.6
Car,-11459,470	78	Car	470	-11459	24.1	27.9	30.4	31.1	34.4	35.7	39.3	68.4	58.0	54.4	51.0	45.2	44.0	42.5	37.1	34.9
Car,-11459,480	80	Car	480	-11459	24.1	28.2	30.4	31.0	34.5	36.6	40.3	70.7	59.9	56.1	52.4	45.8	44.5	43.0	37.5	35.1
Car,-11459,490	82	Car	490	-11459	24.3	28.5	30.4	31.1	34.8	37.6	41.5	72.7	61.6	57.6	53.8	46.3	44.9	43.4	37.8	35.3
Car,-11459,500	83	Car	500	-11459	24.5	28.7	30.4	31.2	35.1	38.6	42.8	74.4	63.2	59.0	55.0	46.7	45.3	43.7	37.9	35.4
Car,-11459,510	85	Car	510	-11459	24.8	29.1	30.6	31.4	36.1	39.9	44.3	76.0	64.6	60.3	56.1	47.1	45.6	44.0	38.0	35.5
Car,-11459,520	87	Car	520	-11459	25.1	29.3	30.8	31.6	37.2	41.2	46.0	77.3	65.9	61.7	57.3	47.4	45.8	44.2	38.0	35.5
Car,-11459,530	88	Car	530	-11459	25.5	29.5	31.1	31.9	38.5	42.6	47.8	78.4	67.1	62.9	58.4	47.8	46.1	44.4	37.9	35.5
Car,-11459,540	90	Car	540	-11459	26.0	29.9	31.4	32.3	39.8	44.2	49.8	79.4	68.1	63.9	59.4	48.0	46.3	44.5	37.9	35.4
Car,-11459,550	92	Car	550	-11459	26.5	30.2	31.8	32.7	41.3	46.2	51.8	80.7	69.3	65.0	60.4	48.3	46.6	44.7	37.8	35.4
Car,-11459,560	93	Car	560	-11459	27.0	30.5	32.2	33.0	42.9	48.3	54.0	81.8	70.2	66.0	61.2	48.5	46.8	44.8	37.6	35.3
Car,-11459,570	95	Car	570	-11459	27.5	30.8	32.6	33.5	44.7	50.5	56.3	82.7	71.1	66.8	61.9	48.7	46.9	44.9	37.5	35.1
Car,-11459,580	97	Car	580	-11459	27.9	31.2	33.0	34.0	47.0	52.8	58.6	83.6	71.8	67.4	62.6	48.8	47.0	44.9	37.3	34.9
Car,-11459,590	98	Car	590	-11459	28.4	31.6	33.4	34.5	49.3	55.2	61.0	84.6	72.4	68.0	63.1	48.9	47.0	44.9	37.0	34.7
Car,-11459,600	100	Car	600	-11459	28.8	32.0	33.9	35.2	51.5	57.5	63.2	85.4	73.0	68.5	63.5	49.0	46.9	44.9	36.8	34.4
Car,-11459,610	102	Car	610	-11459	29.2	32.4	34.4	35.8	53.8	59.8	65.2	86.2	73.4	68.9	63.9	49.0	46.8	44.8	36.5	34.0
Car,-11459,620	103	Car	620	-11459	29.5	32.8	34.9	36.5	56.0	62.0	66.9	87.0	73.7	69.2	64.2	49.0	46.7	44.7	36.3	33.7
Car,-11459,630	105	Car	630	-11459	29.8	33.2	35.5	37.7	58.2	64.1	68.6	87.7	74.0	69.5	64.5	49.0	46.6	44.6	36.0	33.3
Car,-11459,640	107	Car	640	-11459	30.0	33.5	36.1	39.0	60.4	66.0	70.3	88.3	74.2	69.7	64.7	48.9	46.5	44.4	35.8	32.9

Figure 19 TypeVIII Sheet

Sheet 18: Notes

This spreadsheet provides general notes and references for the spreadsheet. The author's and the university's contact information is also included.

USER INPUTS

In this section, the author describes each input box from the Input/Output sheet, Figure 15. The author displays each input table from RSSS with a number placed in each input box. The numbers below each table describe the input options. Table 16 shows the roadway data entry, Table 17 shows the sign data entry, and Table 18 shows the vehicle data entry.

Table 16 Roadway Data Entry

Roadway Data					
Cross Section Elements					
Number of Lanes	1		Speed Limit	5	mph
Lane Width	2	feet	Radius	6	feet
Shoulder Width	3	feet	Surround Complexity	7	
Median Presence	4				

1. Number of Lanes: Enter number of lanes in both directions, a value from 1 to 6. The spreadsheet can evaluate up to three lanes in one direction.
2. Lane Width: Enter Lane width, 12 feet is default.
3. Shoulder Width: Enter Shoulder Width.
4. Median Presence: Enter “y” or “n” if there is or is not a median.
5. Speed Limit: Enter speed limit or speed to evaluate if different from speed limit.
6. Radius: Enter the radius of the curve or “0” for a straight roadway. Enter negative values for curves to the right. Users can evaluate radii of 573, 716, 955, 1146, 1432, 1910, 2865, 5730, and 11459 feet for curves to the left and right.
7. Surround Complexity: Currently not functional; for more complex environments, driver may require more luminance to read or recognize a sign.

Table 17 Sign Data Entry

Sign Data				
Sign Group	8	Placement		
Placement	9	Offset	12	feet
Color	10	Height	13	feet
Sign Type	11	Legend	14	inches

8. Sign Group: Enter a number, 1 through 4 to represent the sign group.
9. Placement: Enter “at” or “advance” to signify the location of the sign. “At” refers to the point where the action must be completed, such as a Stop sign. “Advance” refers to a sign placed before the action needs to be completed, such as an advanced warning sign.
10. Color: Enter the color of the legend or background whichever is brighter. Choose from white, yellow, or orange.
11. Sign Type: Enter “symbol” or “text.” “Symbol” calculates the MRVD for the sign based on the sign group. “Text” uses a LI of 30 ft/in to determine the distance.
12. Offset: Enter the offset of the sign from the edge of the right lane to the center of the sign. Enter negative values for signs to the left. Enter “all” for all offsets to be displayed.
13. Height: Currently not functional. This additional feature would be able to evaluate various sign heights. The current default is 7-foot to the bottom of the sign.

Legend: Enter the legend if a text-based sign. If the legend is entered for a symbol sign, it is ignored.

Table 18 Vehicle Data Entry

Design Vehicle	
Vehicle type	15

14. Vehicle Type: Enter “car” or “truck.” “Car” evaluates the sign for the market-weighted average passenger car. “Truck” evaluates the sign for the market-weighted average light truck.

CALCULATIONS

This section contains the equations and Excel formulas used in RSSS. First, the author discusses the calculations and Excel formulas for the evaluation distance. Next, the author discusses the calculations and Excel formulas to determine the luminance supplied for the given geometries. Finally, the author explains the calculations and Excel formulas to display the output.

Viewing Distance

First, RSSS calculates the viewing distance. The inputs to determine the distance include speed, sign group, placement, sign type, and legend. RSSS determines if the distance is for a text or symbol sign from the sign type. For “text,” RSSS calculates the viewing distance for the sign based on the legibility index.

For “symbol,” RSSS calculates the MRVD in the Sign Info sheet. To simplify the calculations, RSSS calculates the MRVD for each sign group based on the sign placement. If sign placement is “at,” the calculation assumes the sign is at the point where the action must occur; whereas, if sign placement is “advance,” the calculation assumes the sign is in advance of the point where the action needs to occur. Table 19 shows the information used to calculate the reaction time and the MRVD. The equations for each sign group are in Chapter III. Table 20 shows the Excel formulas to calculate the reaction time.

Table 19 MRVD Inputs

Sign Group	MUTCD Type	Sign Description	Read Time (s)*	Deceleration Rate (ft/s^2)**	Speed Change (mph)***
1	Regulatory Warning	Stop	2.67	11.20	NA
2	Regulatory Warning Guidance	Speed Change	4.00	11.20	40.00
3	Regulatory Warning Guidance	Advanced Warning, Informative	2.67	NA	NA
4	Warning	Lane Change	2.67	NA	NA

* Based on bits of information (N) on a sign Time (s) = 2 + N/3 for each sign group in Chapter III

** AASHTO Green Book

*** Assumes final speed of 15 mph if placed at location

Table 20 Reaction Time Excel Formulas

Sign Group	Reaction Time (s)
1	=IF(Input_Output!C21="advance",0,Input_Output!F10/3600*5280/I4)
2	=IF(Input_Output!C21="advance",0,J5*5280/3600/I5)
3	NA
4	=IF(Input_Output!C21="advance",0,11.2-H7)

The first part of the formula for reaction time in Table 20 determines if the sign is in advance of the location. If the sign is in advance, the reaction time is equal to zero. If the location is not in advance, the reaction time needs to be computed. For sign groups 1 and 2, the reaction time is computed by dividing the change in speed by the deceleration rate. For sign group 4, the reaction time is 11.2 seconds minus the time to read the sign. For sign group 3, the reaction time is not applicable since these signs are information only. Using the factors in Table 19 and the reaction time, the MRVD is calculated. The Excel formulas are shown in Table 21.

Table 21 MRVD Excel Formulas

Sign Group	Distance (ft)
1	=ROUNDUP(H4*Input_Output!F10/3600*5280+(Input_Output!F$10)*K4/3600*5280-0.5*I4*K4^2,-1)
2	=ROUNDUP(H5*Input_Output!F10/3600*5280+(J5)*K5/3600*5280-0.5*I5*K5^2,-1)
3	=ROUNDUP(L6*Input_Output!F$10*5280/3600,-1)
4	=ROUNDUP(L7*Input_Output!F$10*5280/3600,-1)

The "roundup" function in Table 21 rounds the formula result up to a multiple of ten. Sign groups 1 and 2 have two components to determine the MRVD, including the distance traveled while reading or recognizing the sign and the distance while decelerating. Sign group 3 and 4 do not have a speed change, therefore the read and reaction time is multiplied by the speed.

Supply Luminance

Next, the author explains the calculations to determine the luminance supply. The author uses an example for Type I sheeting. First, the author explains how the values in the EType sheets are found. Second, the author explains the formulas to choose the viewing distance. Next, the author describes how the supply luminance is found for the viewing distance and geometries. Finally, the author elucidates how performance is found using supply and demand luminance.

First, the author discusses the values in the ETypeI sheet. The first column creates text chain of the vehicle type, radius, and distance. An example of this output is "car,11459,120." The vehicle type and radius are taken from the Input/Output sheet. The viewing distances evaluated range from 120 feet to 640 feet. Table 22 shows the Excel formulas. For each offset, this sheet looks up the luminance values from the TypeI sheet using the first column; this formula is shown in the fourth column. The LI is shown in the second column if a legend is entered on the Input/Output sheet.

Table 22 ETypeI Sheet Excel Formulas

Vehicle,Radius,Distance	LI	Distance	-50
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C3)	=C3/Input_Output!E$22	120	=LOOKUP($A3,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C4)	=C4/Input_Output!E$22	130	=LOOKUP($A4,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C5)	=C5/Input_Output!E$22	140	=LOOKUP($A5,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C6)	=C6/Input_Output!E$22	150	=LOOKUP($A6,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C7)	=C7/Input_Output!E$22	160	=LOOKUP($A7,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)
=CONCATENATE(Input_Output!C$15,",",Input_Output!F$10,",",ETypeI!C8)	=C8/Input_Output!E$22	170	=LOOKUP($A8,TypeI!$A$3:$A$2228,TypeI!F$3:F$2228)

The Evaluation sheet takes the information from the EType sheets and the Input/Output sheet to determine the sheeting performance. The Evaluation sheet summarizes the information needed to determine the supply luminance and to compare it to the demand luminance. On the right side of this sheet, the viewing distance, demand luminance levels and sign color factor are shown. To determine the viewing distance the sheet looks at the sign type on the Input/Output sheet.

For the MRVD distance, the formula looks at the sign group inputted from the Input/Output sheet and selects the appropriate MRVD from the Sign Info sheet. The Excel formulas in Table 23 display the distance calculated on the Sign Info sheet and the other two distances considered. The shortest distance is 50 feet less than the MRVD. The middle distance is the MRVD. The longest distance is 50 feet more then the MRVD. The part of the Excel formulas used to compute the distances are shaded in the table.

Table 23 Evaluation Sheet MRVD

Distance to Evaluate (feet)		Excel Formula
MRVD+50 feet	460	=IF(Input_Output!C22="symbol",Evaluation!B4-50,Input_Output!E22*40)
MRVD	510	=IF(Input_Output!C22="text",Input_Output!E22*30,IF(Input_Output!C19=1,'Sign Info'!L3,IF(Input_Output!C19=2,'Sign Info'!L4,IF(Input_Output!C19=3,'Sign Info'!L5,IF(Input_Output!C19=4,'Sign Info'!L6,"Error")))))
MRVD-50 feet	560	=IF(Input_Output!C22="symbol",Evaluation!B4+50,Input_Output!E22*20)

Table 24 shows the formulas to compute the viewing distances for the LI and legend height. The shortest distance is at a LI of 20 ft/in, the middle distance is at a LI of 30 ft/in, and the longest distance is at a LI of 40 ft/in. The part of the Excel formulas used to compute the distances are shaded in the table. For the LI distance, the formula uses the legend input from Input/Output sheet. RSSS only uses the middle distance, the MRVD for symbol signs or distance at a LI of 30 ft/in for text signs, to the determine the retroreflective sheeting performance.

Table 24 Evaluation Sheet LI

Distance to Evaluate (feet)		Excel Formula
LI=40 ft/in	320	=IF(Input_Output!C22="symbol",Evaluation!B4-50,Input_Output!E22*40)
LI=30 ft/in	240	=IF(Input_Output!C22="text",Input_Output!E22*30,IF(Input_Output!C19=1,'Sign Info'!L3,IF(Input_Output!C19=2,'Sign Info'!L4,IF(Input_Output!C19=3,'Sign Info'!L5,IF(Input_Output!C19=4,'Sign Info'!L6,"Error")))))
LI=20 ft/in	160	=IF(Input_Output!C22="symbol",Evaluation!B4+50,Input_Output!E22*20)

With the viewing distance, RSSS looks up the luminance supply values. Table 25 shows the Excel formulas at one offset. These formulas look up the supply luminance from the ETypeI sheet. RSSS then multiplies the supply luminance from Table 25 by the color factor, as shown in Table 26.

Table 25 Lookup Function for Luminance Supply of White Sheeting

White Sheeting			Cell
Type I	Distance	Offset = -50	
	=B5	=LOOKUP($F3,ETypeI!$C$3:$C$55,ETypeI!D$3:D$55)	H3
	=B4	=LOOKUP($F4,ETypeI!$C$3:$C$55,ETypeI!D$3:D$55)	H4
	=B3	=LOOKUP($F5,ETypeI!$C$3:$C$55,ETypeI!D$3:D$55)	H5

Table 26 Multiplier for Color Factor Excel Formulas

=CONCATENATE(PROPER(Input_Output!C21)," Sheeting")		
Type I	-50	Cell
	=G3*$B$16	Y3
	=G4*$B$16	Y4
	=G5*$B$16	Y5

After RSSS calculates the luminance for the specific color of sheeting, RSSS compares the supply luminance to the demand luminance levels. The demand luminance levels are shown in Table 27. The demand luminance levels are given a rank for easy output. RSSS assigns a ranking of 0, 1, 2 or 3 depending on the performance level. Zero is selected when the supply luminance is below the replacement level.

Table 27 Evaluation Sheet Demand Display

Luminance Demand (cd/m^2)		
Level	Rank	
Replacement	1	2.5
Adequate	2	10
Desirable	3	30

RSSS then compares the supply luminance values in Table 26 to the demand luminance in Table 27 and outputs the rank. Table 28 shows the Excel formulas for this procedure. RSSS uses this rank for the output portion of the Input/Output spreadsheet.

Table 28 Excel Formulas for Performance Rank

Performance @ Distance	
Type I	Offset = -50
	=IF(Y4>Evaluation!$D$12,IF(Y4>Evaluation!$D$13,IF(Y4>Evaluation!$D$14,3,2),1),0)
	=IF(Y5>Evaluation!$D$12,IF(Y5>Evaluation!$D$13,IF(Y5>Evaluation!$D$14,3,2),1),0)
	=IF(Y6>Evaluation!$D$12,IF(Y6>Evaluation!$D$13,IF(Y6>Evaluation!$D$14,3,2),1),0)

Output

RSSS uses the information from the Evaluation sheet to produce the output table on the Input/Output sheet. Table 29 shows the output table when the offset is "all." Table 30 shows the Excel formulas to display the performance level of each sheeting type. The top row in Table 30 displays the offset. If the user enters an actual offset, RSSS only displays the offsets for the specific scenario.

Table 29 Output Table

Offset	**-50**	**-42**	**-38**	**-36**	**-28**	**-26**	**-24**	**4**	**14**	**16**	**18**	**26**	**28**	**30**	**38**	**42**
I	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
II	R	R	R	R	R	R	R	A	A	A	A	A	A	A	A	R
III	A	A	A	A	A	A	A	D	D	D	D	D	D	D	A	A
IV	R	R	R	R	A	A	A	A	A	A	A	A	A	A	A	A
VIII	A	A	A	A	D	D	D	D	D	D	D	D	D	D	D	D
IX	A	A	A	A	A	A	A	D	D	D	D	D	D	D	D	A
XI	A	A	A	A	A	A	D	D	D	D	D	D	D	D	D	D

R = Replacement, A = Adequate, D= Desirable, N/A = Below Replacement Luminance

Table 30 Output Table Excel Equations

Offset	**=IF(E21="all","-50",IF('Sign Info'!$D27=-50,"-50",IF('Sign Info'!$E27=-50,"-50",IF('Sign Info'!$F27=-50,"-50",""))))**
Type I	=IF(J$8="","",IF(Evaluation!BH4<1,"N/A",IF(Evaluation!BH4<2,"R",IF(Evaluation!BH4<3,"A","D"))))
Type II	=IF(J$8="","",IF(Evaluation!BH5<1,"N/A",IF(Evaluation!BH5<2,"R",IF(Evaluation!BH5<3,"A","D"))))
Type III	=IF(J$8="","",IF(Evaluation!BH6<1,"N/A",IF(Evaluation!BH6<2,"R",IF(Evaluation!BH6<3,"A","D"))))
Type IV	=IF(J$8="","",IF(Evaluation!BH7<1,"N/A",IF(Evaluation!BH7<2,"R",IF(Evaluation!BH7<3,"A","D"))))
Type VIII	=IF(J$8="","",IF(Evaluation!BH8<1,"N/A",IF(Evaluation!BH8<2,"R",IF(Evaluation!BH8<3,"A","D"))))
Type IX	=IF(J$8="","",IF(Evaluation!BH9<1,"N/A",IF(Evaluation!BH9<2,"R",IF(Evaluation!BH9<3,"A","D"))))
Type XI	=IF(J$8="","",IF(Evaluation!BH10<1,"N/A",IF(Evaluation!BH10<2,"R",IF(Evaluation!BH10<3,"A","D"))))

RSSS EXAMPLES

The author evaluated an example from each sign group for the two vehicle types using RSSS. The examples cover a range of geometries and numerous geometries were considered for each sign group. For the purpose of this thesis, the author considered all sign offsets for the number of lanes specified.

Sign Group 1 Example

The first example looks at a sign located at the stopping point, such as a Stop sign (2009 MUTCD R1-1). The legend of this sign is white on a red background. Three two-lane scenarios are considered: a 573-foot (10˚) curve to the left, a 573-foot curve to the right, and a straight roadway. Figure 20 shows the inputs for this example.

Roadway Data					
Cross Section Elements					
Number of Lanes	2		Speed Limit	40	mph
Lane Width	12	feet	Radius	573	feet
Shoulder Width	10	feet	Surround		
Median Presence	n		Complexity	low	

Design Vehicle	
Vehicle type	car

Sign Data				
Sign Group	1	Placement		
Placement	at	Offset	all	feet
Color	white	Height	7	feet
Sign Type	symbol	Legend		inches

Figure 20 Group 1 Example Inputs

The spreadsheet calculates the MRVD as 320 feet and the time needed to recognize the sign and complete the maneuver as 7.90 seconds. The author created Table 31 from the spreadsheet results. The author used different colors to help distinguish the demand luminance levels. The warm or lighter colors represent a demand luminance level of replacement or less. Appendix H shows the supply luminance values.

Table 31 shows the luminance performance is better on a straight road than on a road with a 573-foot curve at 320 feet. The table shows Type VIII performs the best on 573-foot curves at 320 feet for the most sign placements. Further, for a 573-foot curve to the left, no sheeting types provide adequate or desirable luminance for left shoulder signs. For curves to the right, Type III sheeting performed adequately for all the scenarios investigated.

Table 31 Group 1 Sheeting Performance

Scenarios	Level	Offset (ft)* -38	-36	-28	4	14	18
573-ft Curve to the Left	NA	I_{CT} II_{CT}			I_{CT}		
	R	III_{CT} IV_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}			II_{CT} III_{CT} IV_{CT} $VIII_{T}$ IX_{CT} XI_{CT}	II_{CT} III_{CT} IV_{CT} $VIII_{T}$ XI_{CT}	
	A	none			$VIII_{C}$	$VIII_{C}$ IX_{CT}	
	D	none			none		
Straight	NA	none			none		
	R	I_{CT} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{T}		I_{CT} II_{CT}		
	A	III_{CT} $VIII_{T}$ IX_{CT} XI_{CT}	III_{CT} IV_{C} $VIII_{CT}$ IX_{CT} XI_{C}	III_{CT} IV_{C} $VIII_{T}$ IX_{CT}	IV_{CT} $VIII_{T}$		
	D	$VIII_{C}$	$VIII_{C}$ XI_{C}	$VIII_{C}$ XI_{CT}	III_{CT} $VIII_{C}$ IX_{CT} XI_{CT}		
573-ft Curve to the Right	NA	I_{T}		I_{CT}	I_{CT} II_{T}		I_{CT} II_{CT}
	R	I_{C} II_{CT} IV_{CT} $VIII_{T}$		II_{CT} IV_{CT} $VIII_{T}$	II_{C} IV_{CT} $VIII_{T}$ XI_{CT}		IV_{CT} $VIII_{T}$ XI_{CT} XI_{CT}
	A	III_{CT} $VIII_{C}$ IX_{CT} XI_{CT}			III_{CT} $VIII_{C}$ IX_{CT}		III_{CT} $VIII_{C}$
	D	none			none		

*The offset is from the right edge of the lane to the center of the sign; negative values are to the left.

Group 1: Signs requiring a stop

The subscripts for the sheeting type represent the vehicles, C=Car and T=Truck (Light).

Levels represent: NA=Below Replacement, R=Replacement, A=Adequate, and D=Desirable

Sign Group 2 Example

The second example looks at a street name sign located at the cross street. This sign has a white legend on a green background. Four four-lane scenarios are considered: an 11459-foot (0.5˚) curve to the right, a 5730-foot (1.0˚) curve to the right, a 2865-foot (2.0˚) curve to the right and a straight roadway. This example shows how the performance changes for curves to the right. Figure 21 shows the inputs for this example.

Roadway Data						
Cross Section Elements						
Number of Lanes	4		Speed Limit	55	mph
Lane Width	12	feet	Radius	0	feet
Shoulder Width	10	feet	Surround		
Median Presence	y		Complexity	low	

Design Vehicle	
Vehicle type	truck

Sign Data				
Sign Group	2	Placement		
Placement	at	Offset	all	feet
Color	white	Height	7	feet
Sign Type	text	Legend	6	inches

Figure 21 Group 2 Example Inputs

The viewing distance is calculated at a LI of 30 ft/in and equals 180 feet. The author created Table 32 from the spreadsheet results. The author used different colors to help distinguish the demand luminance levels. The warm or lighter colors represent a demand luminance level of replacement or less. Appendix H shows the supply luminance values.

Table 32 shows the luminance performance for most sheeting types on curves to the right is similar to a straight roadway at 180 feet. Type XI achieved the desirable luminance level for all curvature if the sign was close to the travel lanes. Further as the sign offset moves further to the left, the luminance provided by reaches the adequate level for more sheeting types, specifically Type VIII performs better on the signs located on the left shoulder than signs on the right shoulder.

Table 32 Group 2 Sheeting Performance

Scenario	Level	Offset (ft) -36	-24	4	14	16	26	30
Straight	NA	none		none				I_T II_C
	R	I_{CT} II_{CT} IV_{CT}		I_{CT} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$			I_C II_T IV_{CT} $VIII_{CT}$
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} $VIII_{CT}$ IX_{CT}	III_{CT} $VIII_{CT}$ IX_{CT}	III_{CT} IX_{CT} XI_{CT}			
	D	none	XI_{CT}	XI_{CT}	none			
11459-ft Curve to the Right	NA	none		none				I_T II_C
	R	I_{CT} II_{CT} IV_{CT}		I_{CT} II_{CT} IV_{CT} $VIII_T$	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$		I_C II_T IV_{CT} $VIII_{CT}$
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} $VIII_{CT}$ IX_{CT}	III_{CT} $VIII_C$ IX_{CT}	III_{CT} IX_{CT} XI_T	III_{CT} IX_{CT} XI_{CT}		
	D	none	XI_{CT}	XI_{CT}	XI_C	none		
5730-ft Curve to the Right	NA	none		I_T	none			I_T II_C
	R	I_{CT} II_{CT} IV_{CT}		I_C II_{CT} IV_{CT} $VIII_T$	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$		I_C II_T IV_{CT} $VIII_{CT}$
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} $VIII_{CT}$ IX_T	III_{CT} $VIII_C$ IX_{CT}	III_{CT} IX_{CT} XI_T	III_{CT} IX_{CT} XI_{CT}		
	D	none	IX_C XI_{CT}	XI_{CT}	XI_C	none		
2865-ft Curve to the Right	NA	none		none			I_T II_C	I_{CT} II_{CT} IV_T
	R	I_{CT} II_{CT} IV_{CT}		I_{CT} II_{CT} IV_{CT} $VIII_T$	I_{CT} II_{CT} IV_{CT} $VIII_{CT}$		I_C II_T IV_{CT} $VIII_{CT}$	IV_C $VIII_{CT}$
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} $VIII_{CT}$ IX_{CT}	$VIII_C$ IX_{CT}	III_{CT} IX_{CT} XI_{CT}			
	D	none	XI_{CT}	XI_{CT}	none			

*The offset is from the right edge of the lane to the center of the sign; negative values are to the left.

Group 2: Signs requiring a speed change

The subscripts for the sheeting type represent the vehicles, C=Car and T=Truck (Light).

Levels represent: NA=Below Replacement, R=Replacement, A=Adequate, and D=Desirable

Sign Group 3 Example

This third example looks at an informational warning sign, such as a Signal Ahead sign (2009 MUTCD W3-3). The background of this sign is yellow and the legend is black. Three six-lane scenarios are considered: a 5730-foot (1.0˚) curve to the left, 5730-foot curve to the right, and a straight roadway. This example shows how a curve compares to a straight roadway. Figure 22 shows the inputs for this example.

Roadway Data					
Cross Section Elements					
Number of Lanes	6		Speed Limit	70	mph
Lane Width	12	feet	Radius	-5730	feet
Shoulder Width	10	feet	Surround		
Median Presence	y		Complexity	low	

Design Vehicle	
Vehicle type	car

Sign Data				
Sign Group	3	Placement		
Placement	at	Offset	all	feet
Color	yellow	Height	7	feet
Sign Type	symbol	Legend		inches

Figure 22 Group 3 Example Inputs

The spreadsheet calculates the MRVD as 280 feet and the time needed to recognize the sign as 2.67 seconds. The author created Table 33 from the spreadsheet results. The author used different colors to help distinguish the demand luminance levels. The warm or lighter colors represent a demand luminance level of replacement or less. Appendix H shows the supply luminance. Table 33 shows the luminance provided on a 5730-foot curve is similar to the luminance provided on a straight road at 280 feet.

Table 33 Group 3 Sheeting Performance

<table>
<tr><th rowspan="2">Scenarios</th><th rowspan="2">Level</th><th colspan="9">Offset (ft)</th></tr>
<tr><th>-50</th><th>-38</th><th>-26</th><th>14</th><th>18</th><th>26</th><th>30</th><th>38</th><th>42</th></tr>
<tr><td rowspan="4">5730-ft Curve to the Left</td><td>NA</td><td>I_{CT}</td><td>I_{T}</td><td>none</td><td colspan="5">none</td><td>I_{T}</td></tr>
<tr><td>R</td><td>II_{CT} IV_{CT}</td><td>I_{C} II_{CT} IV_{CT}</td><td>I_{CT} II_{CT} IV_{CT}</td><td colspan="5">I_{CT} II_{CT} IV_{CT}</td><td>I_{C} II_{CT} IV_{CT} $VIII_{T}$</td></tr>
<tr><td>A</td><td colspan="3">III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}</td><td colspan="3">III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}</td><td colspan="2">III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}</td><td>III_{CT} $VIII_{C}$ IX_{CT} XI_{CT}</td></tr>
<tr><td>D</td><td colspan="3">none</td><td colspan="3">XI_{C}</td><td colspan="2">none</td><td>none</td></tr>
<tr><td rowspan="4">Straight</td><td>NA</td><td>I_{CT}</td><td>I_{T}</td><td>none</td><td colspan="4">none</td><td>I_{T}</td><td>I_{CT} II_{T}</td></tr>
<tr><td>R</td><td>II_{CT} IV_{CT}</td><td>I_{C} II_{CT} IV_{CT}</td><td>I_{CT} II_{CT} IV_{CT}</td><td colspan="4">I_{CT} II_{CT} IV_{CT}</td><td>I_{C} II_{CT} IV_{CT} $VIII_{T}$</td><td>II_{C} IV_{CT} $VIII_{T}$</td></tr>
<tr><td>A</td><td colspan="3">III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}</td><td>III_{CT} $VIII_{CT}$ IX_{CT}</td><td>III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}</td><td colspan="2">III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}</td><td colspan="2">III_{CT} $VIII_{C}$ IX_{CT} XI_{CT}</td></tr>
<tr><td>D</td><td colspan="3">none</td><td>XI_{CT}</td><td>XI_{C}</td><td colspan="4">none</td></tr>
<tr><td rowspan="4">5730-ft Curve to the Right</td><td>NA</td><td>I_{T}</td><td colspan="2">none</td><td colspan="2">none</td><td colspan="2">I_{T}</td><td colspan="2">I_{CT} II_{T}</td></tr>
<tr><td>R</td><td>I_{C} II_{CT} IV_{CT}</td><td colspan="2">I_{CT} II_{CT} IV_{CT}</td><td colspan="2">I_{CT} II_{CT} IV_{CT}</td><td colspan="2">I_{C} II_{CT} IV_{CT} $VIII_{T}$</td><td colspan="2">II_{C} IV_{CT} $VIII_{T}$</td></tr>
<tr><td>A</td><td colspan="2">III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}</td><td>III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}</td><td>III_{CT} $VIII_{CT}$ IX_{CT}</td><td>III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}</td><td colspan="4">$III_{CT}$$VIII_{C}$ IX_{CT} XI_{CT}</td></tr>
<tr><td>D</td><td colspan="2">none</td><td>XI_{C}</td><td>XI_{CT}</td><td>XI_{C}</td><td colspan="4">none</td></tr>
</table>

*The offset is from the right edge of the lane to the center of the sign; negative values are to the left.

Group 3: Signs for information only

The subscripts for the sheeting type represent the vehicles, C=Car and T=Truck (Light).

Levels represent: NA=Below Replacement, R=Replacement, A=Adequate, and D=Desirable

Sign Group 4 Example

This fourth example looks at Lane Ends sign placed ahead of the lane end taper (2009 MUTCD W4-2). This is a negative contrast sign with a yellow background. Three four-lane scenarios are considered: a 11459-foot (0.5˚) curve to the left, a 5730-foot (1.0˚) curve to the left, a 2865-foot (2.0˚) curve to the left, and a straight roadway. This example shows how the performance changes for curves to the left. Figure 23 shows the inputs for this example.

Roadway Data					
Cross Section Elements					
Number of Lanes	4		Speed Limit	70	mph
Lane Width	12	feet	Radius	5730	feet
Shoulder Width	10	feet	Surround		
Median Presence	y		Complexity	low	

Design Vehicle	
Vehicle type	car

Sign Data				
Sign Group	4	Placement		
Placement	advance	Offset	all	feet
Color	yellow	Height	7	feet
Sign Type	symbol	Legend		inches

Figure 23 Group 4 Example Inputs

The spreadsheet calculates the MRVD as 280 feet and the time needed to recognize the sign as 2.67 seconds. The author created Table 34 from the spreadsheet results. The author used different colors to help distinguish the demand luminance levels. The warm or lighter colors represent a demand luminance level of replacement or less. Appendix H shows the supply luminance values.

Table 34 Group 4 Sheeting Performance

Scenarios	Level	Offset (ft)						
		-36	-24	4	16	18	26	30
Straight	NA	none		none				
	R	I_{CT} II_{CT} IV_{CT}		I_{CT} II_{CT} IV_{CT}				
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}		III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} $VIII_{CT}$ IX_{CT}	III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	
	D	none		XI_{C}	XI_{CT}	XI_{C}	none	
11459-ft Curve to the Left	NA	none		none				
	R	I_{CT} II_{CT} IV_{CT}		I_{CT} II_{CT} IV_{CT}				
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} IV_{C} $VIII_{T}$ IX_{CT} XI_{T}	III_{CT} IV_{C} $VIII_{CT}$ IX_{CT}			III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}
	D	none	XI_{C}	XI_{CT}			XI_{C}	none
5730-ft Curve to the Left	NA	I_{T}	none	none				
	R	I_{C} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{CT}				
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} IV_{C} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} IV_{C} $VIII_{CT}$ IX_{CT}		III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}		III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}
	D	none	XI_{C}	XI_{CT}		XI_{C}		none
2865-ft Curve to the Left	NA	I_{T}	none	none				
	R	I_{T} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{CT}	I_{CT} II_{CT} IV_{CT}				
	A	III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}	III_{CT} $VIII_{CT}$ IX_{CT}	III_{CT} $VIII_{CT}$ IX_{CT} XI_{T}		III_{CT} $VIII_{CT}$ IX_{CT} XI_{CT}	
	D	none	XI_{C}	XI_{CT}	XI_{C}		none	

*The offset is from the right edge of the lane to the center of the sign; negative values are to the left.

Group 4: Signs requiring a lane change

The subscripts for the sheeting type represent the vehicles, C=Car and T=Truck (Light).

Levels represent: NA=Below Replacement, R=Replacement, A=Adequate, and D=Desirable

Table 34 shows the luminance performance for most sheeting types on curves to the left is similar to a straight road at 280 feet. There is a slight increase in the performance level for sheeting on the right shoulder when compared to the left shoulder.

General Observations

The author also evaluated other viewing distances for the geometries in the examples and additional radii. The author does not present the summary tables, but discusses general trends. First, trends based on the geometries are discussed. Next, the difference in vehicles is discussed. Finally, the author describes the performance of each sheeting type.

Geometries

For both the curves to the left and to the right, the luminance increases and then decreases as you approach sign. An example is shown in Figure 24.

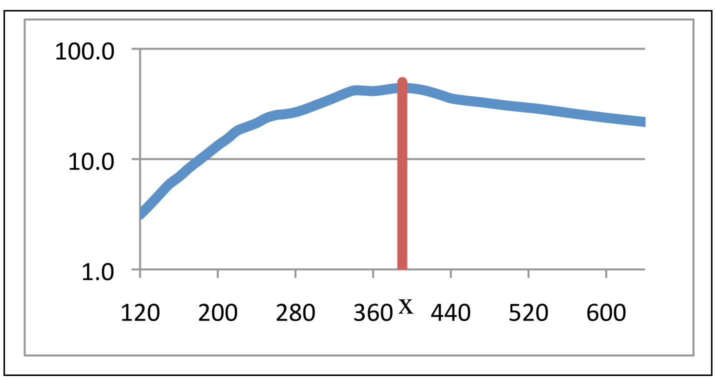

Figure 24 Supply Luminance in a Curve

As the distance from the signs decreases, the luminance increases for both the curves to the left and to the right (from 640 feet to x). Once you reach the point of maximum luminance (x), the luminance output begins to decrease (from x to 120 feet). The maximum (640 feet) and minimum (120 feet) distances represent the range of distances evaluated. These trends are apparent for all sheeting types. The maximum luminance may or may not be enough to produce an adequate performance level. For sheeting Types I and II, the adequate level is never reached. The location where the luminance reaches the maximum luminance changes based on the radius of the curve and the sign offset. As the curve radius increases, the maximum luminance level is met at a further distance from the sign. Luminance provided by sheeting on the right shoulder is higher for curves to the left, while the luminance provided by sheeting on the left shoulder is higher for curves to the right.

For straight roadways, luminance decreases from a maximum as you move closer to the sign. Although all sheeting types produce less luminance as you become closer to the sign, the trends are more apparent for sheeting Types III, VI, VIII, IX, and XI because they provide a larger range of luminance values. Further, for straight roadways, luminance provided by sheeting on the right shoulder is higher than the luminance provided by sheeting on the left shoulder.

Vehicle Choice

The difference in luminance performance from the two vehicles investigated is apparent. A passenger car usually outperforms a light truck. There are a few situations when a light truck performs slightly better for a large sign offset and on some curves. The author recommends identifying dimensions and headlamps for a tractor-trailer and determining the luminance supplied using this vehicle type. A tractor-trailer may present the worse case scenario.

Type I

Type I sheeting normally performs at the replacement luminance level. For a large number of geometries, Type I sheeting does not meet the replacement level. Overall, Type I sheeting does not provide enough luminance. Agencies should only install Type

I sheeting when there is additional lighting available. Further, agencies should ensure this additional illuminance allows enough luminance to be reflected to the driver.

Type II

Type II sheeting normally performs at the replacement luminance level. There are some situations on curves when Type II sheeting provides an adequate luminance level at viewing distances larger than 400 feet. However, on curves with smaller radii, Type II sheeting does not meet the replacement level for some viewing distances. Overall, Type II sheeting only provides enough luminance for a few situations. Agencies should only install Type II sheeting when there is additional lighting available. Further, agencies should ensure this additional illuminance allows enough luminance to be reflected to the driver.

Type III

Type III sheeting normally performs at the adequate demand luminance level. There are some situations on curves, where Type III sheeting does not meet the adequate level for long viewing distances. For small radius curves (573 and 716 feet), Type III sheeting does not meet the replacement level at long viewing distances (greater than 400 feet). Overall, Type III sheeting provides adequate or desirable luminance level at most geometries.

Type IV

Type IV sheeting normally performs at the replacement or adequate demand luminance level. There are situations on curves, where Type IV sheeting does not meet the replacement level for some viewing distances. Overall, Type IV sheeting provides replacement luminance levels at long distances. Agencies should only install Type IV sheeting when there is additional lighting available. Further, agencies should ensure this additional illuminance allows enough luminance to be reflected to the driver.

Types VIII, IX, and XI

Types VIII, IX, and XI have similar performance, so the author discusses them together. Types VIII, IX, and XI sheeting normally perform at the adequate or desirable demand luminance level. For Types VIII, IX, and XI, the amount of luminance decreases to the replacement level at the closest distances to the sign. For small radius curves (573 and 716 feet), Types VIII, IX, and XI do not meet the replacement level at long viewing distances (greater than 400 feet). Overall, Types VIII, IX, and XI provide adequate or desirable luminance for the majority of situations.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the author developed a retroreflective sheeting selection technique for traffic signs. The author used previous research to determine the luminance needed by drivers, demand luminance, and roadways scenarios to determine the amount of luminance the retroreflective sheeting on a sign would produce, supply luminance. The author developed a spreadsheet to create an easy to use tool to determine the performance of different retroreflective sheeting types by comparing the demand and supply luminance for specific roadway scenarios.

The demand luminance was determined by evaluating the results of previous studies. The author created three demand luminance levels: replacement, adequate, and desirable. The replacement level represents the level of luminance when a sign needs to be replaced and is 2.5 cd/m^2. The adequate level is the recommended amount of luminance when installing new traffic signs and is 10 cd/m^2. The desirable level is the approximate level when additional luminance has diminishing returns and is 30 cd/m^2.

The author determined supply luminance by evaluating roadway geometries, sign placement, sheeting type, and vehicle data. The author reviewed roadway geometries in Texas to estimate typical number of lanes, shoulder widths, and horizontal curvature in the US. Sign placement from the MUTCD determined the typical lateral placements, sign height, and sign twist. Vehicle data included vehicle dimensions and headlamp type.

Both the supply and demand luminance were determined for the specific viewing distance of a sign for a given scenario. In addition, the type of sign, alphanumeric or symbol, determines how this distance is calculated. The author developed four sign groups to calculate the distance required to read and respond to a traffic sign. The sign groups are:

1. Stop required,
2. Reduction in speed required,
3. Read the message provided, and
4. Change of lane required.

For symbol signs, the author determined the MRVD and for text signs, the author determined the distance at a LI of 30 ft/in. At these distances, the author calculated the supply luminance and then compared it to the demand luminance to determine the performance level.

The author developed the Retroreflective Sheeting Selection Spreadsheet (RSSS) to allow others to use the methodology presented in this thesis. RSSS allows users to input the roadway data, vehicle data, and sign data. RSSS takes this information and looks up the supply luminance for the scenario. RSSS then compares the supply luminance to the demand luminance levels and outputs the retroreflective sheeting performance.

RECOMMENDATIONS

Through the development and use of RSSS, the author gained an understanding of different retroreflective sheeting types. The author makes the following recommendations:

1. Sheeting Types I, II, and IV are not recommended on traffic signs in dark environments. These sheeting types may be used in environments where additional illuminance is available, however agencies should ensure this additional illuminance provides sufficient luminance for the driver.
2. Sheeting Types III, VIII, IX, and XI have similar performance and can be installed in most situations. When installing signs at a short or long viewing

distances or within a curve additional consideration should be given to the sheeting type.

3. For signs with a short viewing distance (less than 250 feet), Type VIII sheeting is not recommended. Type VIII sheeting has variable performance over the range of offsets evaluated, where as Type III, IX, and XI have consistent performance over the range of geometries. This is true for all curve radii and straight roadways.
4. For signs with a long viewing distance (more than 550 feet) and tight curvature to the right (less than 1146 feet), Type VIII sheeting is recommended. Type VIII sheeting has adequate performance over the range of offsets evaluated, where as Types III, IX, and XI have do not provide enough luminance for some offsets.
5. For signs with a long viewing distance (more than 550 feet) and tight curvature to the left (less than 1146 feet), Type IX sheeting is recommended, if it is not feasible to provide additional lighting. Type IX sheeting has less than adequate performance over the range of offsets evaluated, however Types III, VIII, and XI provide even less luminance for all offsets.

LIMITATIONS OF THIS RESEARCH

Since this thesis focused on developing the process for retroreflective sheeting selection, the author used currently available data for RSSS development. The use of available data caused many limitations in this thesis, including:

1. The author determined demand luminance levels from the results of previous research. Reviewing the results, although useful, can provide only so much information about luminance needed by drivers. The author recommends a more thorough review to validate the values presented in this thesis. Further, there are few studies investigating the luminance needed for symbol signs. In addition, there may be a luminance that is too bright for drivers, decreasing their ability to

read or recognize a sign. Additional research recommended to clarify drivers' luminance needs include:

- The effect of the environment complexity on the needs of drivers,
- The effects of the color and contrast of sheeting on drivers' needs,
- The luminance value when a sign becomes "too bright", and
- The luminance drivers need for symbol signs, both bold and fine detail.

2. The luminance demand was only determined at one location for each sign. This location was the MRVD for symbol signs or the distance at a LI of 30 ft/in for text signs. In actuality, drivers do not read signs instantly. The luminance profile a driver views can affect the ability to read a message.
3. The author evaluated only a passenger car and a light truck. The author calculated these dimensions based on the top 15 selling vehicle in 2009. Since the vehicle fleet is continually changing and there are a large number of older vehicles on the roadway, the dimensions used may not be representative of the average passenger car and light truck in the entire US vehicle fleet. Further, the geometries of a heavy vehicle can greatly affect the amount of luminance a sign receives and a heavy vehicle should be analyzed.
4. The author only evaluated the 2004 market-weighted headlamps. No recent headlamp data is available and updating this may have an impact on the results. Further, the 2004 market-weighted headlamp may not be appropriate to use on a heavy vehicle and no illuminance data exists for the headlamps of heavy vehicles. The author recommends:
   - Determining an illuminance profile for heavy vehicles, and
   - Updating the market-weighted headlamp metrics.
5. The retroreflective sheeting types evaluated present only a small portion of the sheeting available. The author evaluated only one brand of each sheeting type and other brands may have different performance. Further, some of the types evaluated represent sheeting manufactured over 10 years ago and the sheeting performance may have changed. The author recommends taking a samples of

new sheeting from multiple manufacturers, measuring the retroreflectivity values, and using the new sheeting types for the evaluation.

6. The author evaluated only new retroreflective sheeting and the results in the Chapter IV represent how new sheeting will perform. Since a sign installation lasts for a number of years before replacement, the author recommends evaluating deteriorated sheeting samples, as well. Results may find some sheeting types deteriorate at a fast rate and may need to be replaced at a shorter interval.
7. This thesis only evaluated small signs located on the shoulders. In addition, the author evaluated one sign height and one sign twist. In actually, sign height can vary and an analysis of other heights is recommended. Further, larger signs and signs placed overhead have a height greater than what this thesis presents. These signs receive less illuminance and may perform worse than the signs investigated in this thesis. Further, with a lower sign height, signs may perform better than the signs investigated in this thesis. The seven-foot mounting height represents the worst case for a small shoulder-mounted sign. Only one sign twist was evaluated, as no research exists about how sign twist varies with installation. A field study could show how sign twist varies on curves. This could help determine the appropriate sign twist to evaluate.
8. The author did not consider ambient lighting. The scenarios all assumed a dark roadway. The addition of ambient lighting may or may not improve the sheeting performance. For example, a smaller amount of luminance may be adequate in a dark, low complexity environment, whereas in a well-lit high-complexity area, more luminance may be needed to be able to read or recognize the sign.
9. This thesis does not consider vertical alignment. The effects of vertical alignment are apparent when traveling through a vertical curve. The author recommends additional research in this area.
10. Finally, this research did not consider environmental factors. These factors include weather, such as snow, rain and fog and sediment. Weather can effect

the amount of illuminance able to reach the sign and the amount of luminance able to reach the driver. Buildup of snow or dew on retroreflective sheeting can also affect its ability to reflect light. Other environmental factors include sediment and salt on the roadway. These materials can buildup on headlamps, signs, and reduce the illuminance and luminance provided.

FUTURE NEEDS

RSSS developed for this thesis shows how different sheeting types perform for a number of geometries. For a more comprehensive tool, the author believes the issues discussed in the Limitation of this Research Section should be addressed. Further, validation of the retroreflective sheeting selection technique is needed.

In additional to validation, RSSS can be expanded to provide more functionality. Some additional features RSSS could include are:

- Analysis for aged sheeting,
- Factors to apply to the demand luminance due to the effects of background complexity and contrast,
- Additional sign heights, and
- Additional vehicle choices.

REFERENCES

1. Hills, B. B. Visions, Visibility and Perception in Driving. In *Perception*, Vol. 9, 1980, pp.183-216.

2. *Manual on Uniform Traffic Control Devices (MUTCD)*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2009.

3. Sauter, G. Active Safety. *Proceeding of ERF Road Safety Engineering Seminar*, June 2009, Traffic Safety Systems Division, 3M, http://www.irfnet.eu/media/Road%20Safety%20Seminars_Prague%202009/Presentations/Sauter.pdf. Accessed September 16, 2009.

4. Lloyd, J. A Brief History of Retroreflective Sign Face Sheet Materials. *Understanding Retroreflectivity*, 2008, http://www.rema.org.uk/pdf/history-retroreflective-materials.pdf. Accessed September 16, 2009.

5. Signing for Safety Slide Rule. Traffic Control Materials Division, 3M, St. Paul, MN, 1978.

6. International Commission on Illumination. *Retroreflection: Definition and Measurement*, CIE 54.2 – 2001. CIE Central Bureau, Vienna, Austria, 2001.

7. ASTM International. *Standard Specification for Retroreflective Sheeting for Traffic Control,* ASTM D4956-09, West Conshohocken, PA, 2009.

8. Aktan, F. and D. M. Burns. In-the-Field and Modeled Luminance of Retroreflective Signs. In *2008 Transportation Research Board Annual Meeting* CDROM, Transportation Research Board of the National Academies, Washington, D.C., 2008.

9. Mace, D. J., P. M. Garvey, and R. F. Heckard. *Relative Visibility of Increased Legend Size vs. Brighter Materials*. Publication FHWA-RD-94-035, Office of Safety Research and Development, FHWA, U.S. Department of Transportation, 1994.

10. Aoki, T., D. S. Battle, and P. L. Olson. *The Subjective Brightness of Retroreflective Sign Colors*, UMRTI-89-22, Ann Arbor, MI, July 1989.

11. Opiela, K. S. and C. K. Anderson. Maintaining Traffic Sign Retroreflectivity: Impacts on State and Local Agencies. Publication FHWA-HRT-07-042, Office of Safety Research and Development, FHWA, U.S. Department of Transportation, 2007.

12. Schieber, F., D. M. Burns, J. Myers, N. Willan, and J. Gilland. Legibility and Eye Fixation Patterned while Reading Highways Signs under Dynamic Nighttime Driving Conditions: Effects of Age, Sign Luminance, and Environmental Demand. Presented at the 83rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2004.

13. Johnson, N. L. Reflective Sign Viewing Scenarios Using Vector Calculation Methods. *Volume 2, PAL '99, Proceedings of the Conference, Progress in Automotive Lighting*, Darmstadt: University of Technology, Department of Lighting Technology, 1999.

14. Uding, K. D. Exact Road Geometry Output Program for Retroreflective Road Sign Performance. In *Transportation Research Record 142.1,* Transportation Research Board of the National Academies, Washington, D.C., 1993, pp. 61-68.

15. Operator Performance Laboratory. *TarVIP*. The University of Iowa, September 2004, http://opl.ecn.uiowa.edu/Tarvip/. Accessed July 13, 2009.

16. Bible, R. C. and N. Johnson. Retroreflective Material Specifications and On-Road Sign Performance. *Transportation Research Record 1801*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 61-72.

17. Graham, J. R., A. Fazal, and L. E. King. Minimum Luminance of Highway Signs Required by Older Drivers. *Transportation Research Record 1573*, Transportation Research Board of the National Academies, Washington, D.C., 1997, pp. 91-98.

18. Awadallah, F. I. *Durability of Retroreflective Signs*, Ph.D. Dissertation, University of Maryland, College Park, 1987.

19. Forbes, T. W. Luminance and Contrast for Sign Legibility and Color Recognition. Highway Res. Record No. 611, Transportation Research Board of the National Academies, Washington, D.C, 1976.

20. Forbes, T. W. Luminance and Contrast Requirements for Legibility and Visibility of Highway Signs. Final Report, Part III "Interpretation and Application." Michigan State University, East Lansing. 1975.

21. Carlson, P. J. and H. G. Hawkins. *Minimum Retroreflectivity Levels for Overhead Guide Signs and Street-Name Signs*. FHWA-RD-03-082, United States Department of Transportation, Federal Highway Administration, Washington, D.C., December 2003.

22. Sivak, M., and P. L. Olson. *Optimal and Minimal Luminance Characteristics for Retroreflective Highway Signs*, Transportation Research Record No. 1027, Journal of the Transportation Research Board, 1985, p. 53-57.

23. Carlson, P. J. and A. Holick. Minimum Retroreflectivity Levels for Blue and Brown Signs with and without Glare and Roadway Lighting. In *2008 Transportation Research Board Annual Meeting* CDROM, Transportation Research Board of the National Academies, Washington, D.C., 2008.

24. Carlson, P. J., J. Miles, E. S. Park, S. Young, S. Chrysler, and J. Clark. *Development of a Model Performance-Based Sign Sheeting Specification Based on the Evaluation of Nighttime Traffic Signs Using Legibility and Eye-Tracker Data*, FHWA/TX-10/0-5235-1, Texas Transportation Institute, College Station, TX, September 2009.

25. Performance Evaluation of Retroreflective Traffic Signs. Commission Internationale De L'eclairage, Technical Committee 4-40, Draft Report No. 16, May 2009.

26. Mercier, C. R., C. Goodspeed, C. J. Simmons, and J. F. Paniati. Evaluation of Proposed Minimum Retroreflectivity Requirements for Traffic Signs. *Transportation Research Record 1495*, Transportation Research Board of the National Academies, Washington, D.C., 1995, pp. 57-67.

27. Goodspeed, C. Sign Visibility Performance: A Summary of the Mercier Experiment, Federal Highway Administration, 1993.

28. Paniati, J. F. *Legibility and Comprehension of Traffic Sign Symbols*. Thesis, University of Maryland, 1988.

29. Carlson, P. J. and H. G. Hawkins. *Updated Minimum Retroreflectivity Levels for Traffic Signs*. FHWA-RD-03-081, United States Department of Transportation, Federal Highway Administration, Washington, D.C., July 2003.

30. Zwahlen, H. T. and T. Schnell. Driver Eye Scanning Behavior When Reading Symbol Warning Signs. In *Vision in Vehicles – VI*, Elsevier Science Ltd, Kidlington, 1998, pp. 3-11.

31. Carlson, P. J. and H. G. Hawkins. Legibility of Overhead Guide Signs with Encapsulated versus Microprismatic Retroreflective Sheeting. *Transportation Research Record 1844*, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 59-66.

32. Holick, A. J. and P. J. Carlson. *Nighttime Guide Sign Legibility for Microprismatic Clearview Legend on High Intensity Background*, FHWA/TX-04/0-1796-4, College Station, TX, September 2003.

33. Meyer, E. and P. Atchley. *Assessment of Traffic Control Practices with respect to Older Drivers*, K-TRAN: KU-01-4, University of Kansas, Lawrence, KS, July 2007.

34. Carlson, P. J. *Evaluation of Clearview Alphabet with Microprismatic Retroreflective Sheetings*. FHWA/TX-02/4049-1, College Station, TX, October 2001.

35. Holick, A. J. and P. J. Carlson. *Nighttime Guide Sign Legibility for Microprismatic Clearview Legend on High Intensity Background*. FHWA/TX-04/0-1769-4, College Station, TX, September 2003.

36. International Commission on Illumination. *Roadsigns*, CIE 74 (1988). CIE Central Bureau, Vienna, Austria, 1988.

37. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highway and Streets*, Washington, D.C., 2004.

38. Institute of Transportation Engineers. *Traffic Signing Handbook.* Institute of Transportation Engineers, Washington, D.C., 1997.

39. Traffic Operations Division. Texas Department of Transportation. *Sign mounting Details Small Roadside Signs General Notes & Details*, SMD (GEN)-08, TX, 2002.

40. Traffic Operations Division. Texas Department of Transportation. *Sign mounting Details - Large Roadside Signs*, SMD (2-3)-08, TX, 1995.

41. Sivak, M., B. Schoettle, and M. J. Flannagan. *Recent Changes in Headlamp Illumination Directed Towards Traffic Signs*, UMRTI-2006-31, Ann Arbor, MI, September 2006.

42. Auto Sales. *The Wall Street Journal*, July 2009. http://online.wsj.com/mdc/public/page/2_3022-autosales.html. Accessed July 6, 2009.

43. Finley, M. D., P. J. Carlson, N. D. Trout, and D. L. Jasek. *Sign and Pavement Marking Visibility from the Perspective of Commercial Vehicle Drivers*. FHWA-TX-03-4269-1, United States Department of Transportation, Federal Highway Administration, Washington, D.C., September 2002.

44. Murphy, D. Headlight Types and Functions. *autoMedia.com*. http://www.automedia.com/Headlight_Types_and_Functions/ccr20040401al/1. Accessed July 7, 2009.

45. Flannagan, M. J., M. L. Buonarosa, and J. M. Devonshire. *Survey of HID Headlamps in Use in the U.S. by Region and Time of Night*, UMTRI-2008-56, Ann Arbor, MI, November 2008.

46. Schoettle, B., M. Sivak, M. J. Flannagan, and W. J. Kosmatka. *A Market-Weighted Description of Low-Beam Headlighting Patterns in the U.S.: 2004*, UMTRI-2004-23, Ann Arbor, MI, September 2004.

APPENDIX A

REVIEW OF ROADWAY GEOMETRIES FROM TXDOT

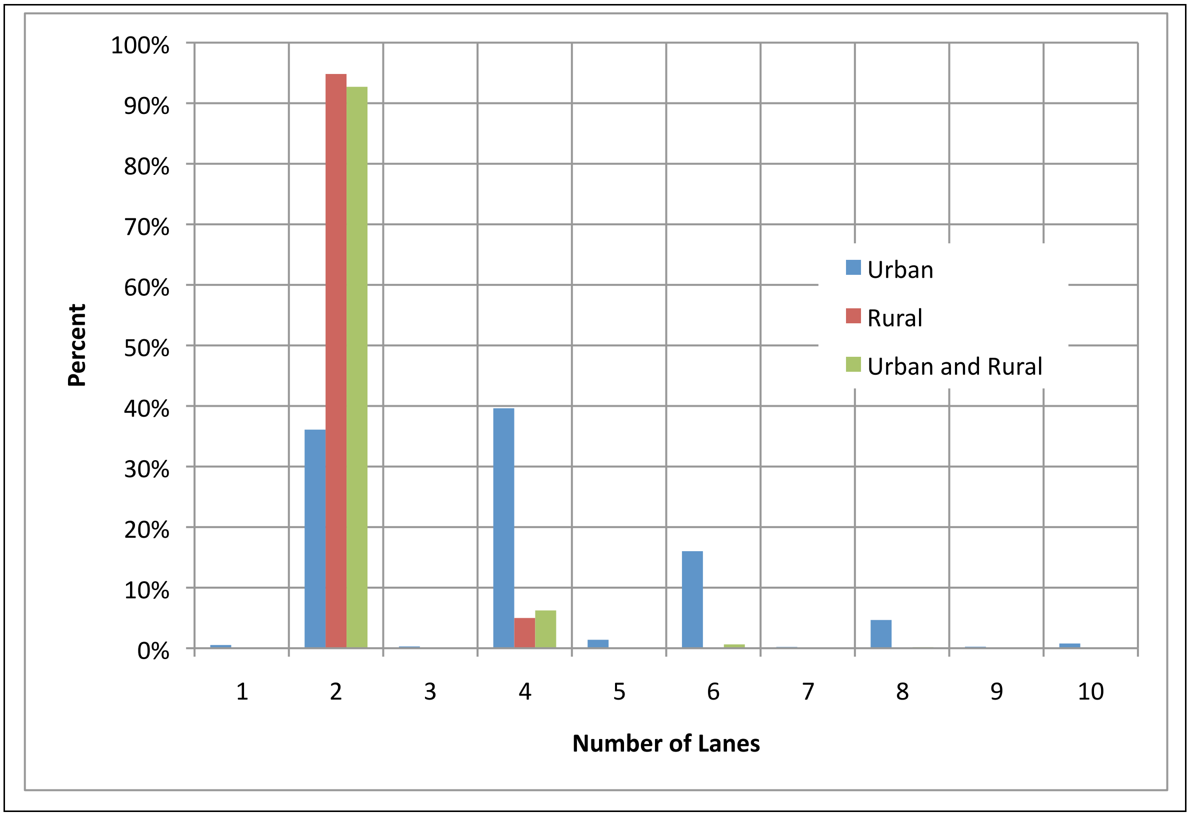

Figure 25 Number of Lanes

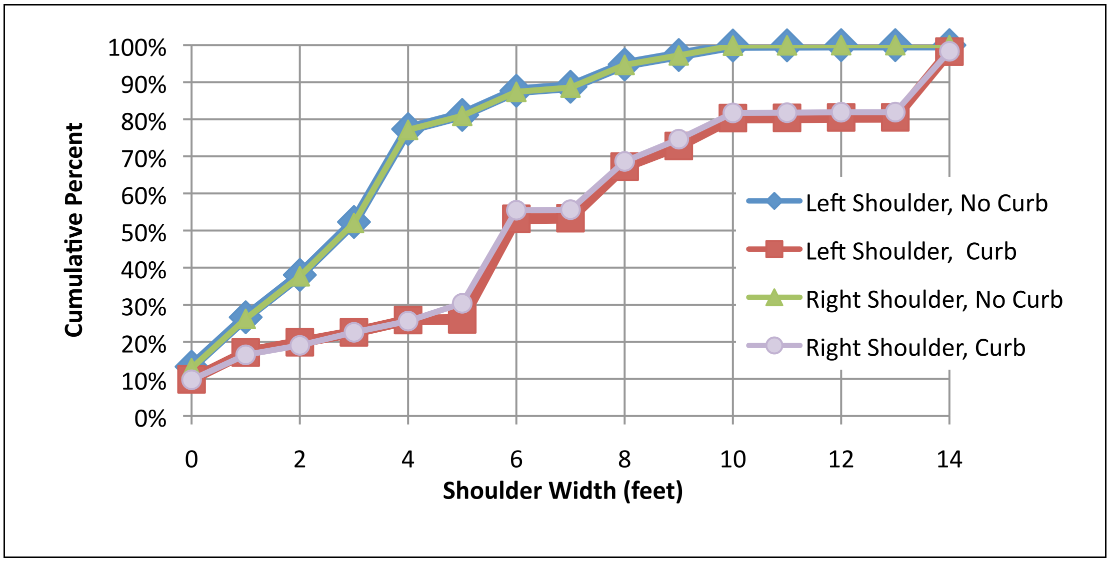

Figure 26 Shoulder Widths for Rural Two-Lane Conditions

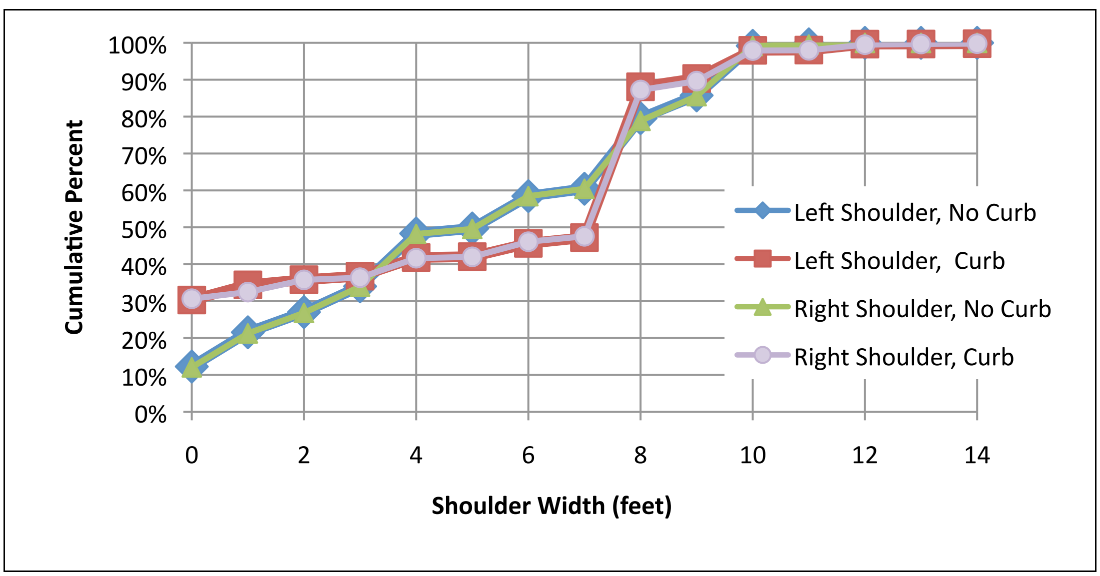

Figure 27 Shoulder Widths for Urban Two-Lane Conditions

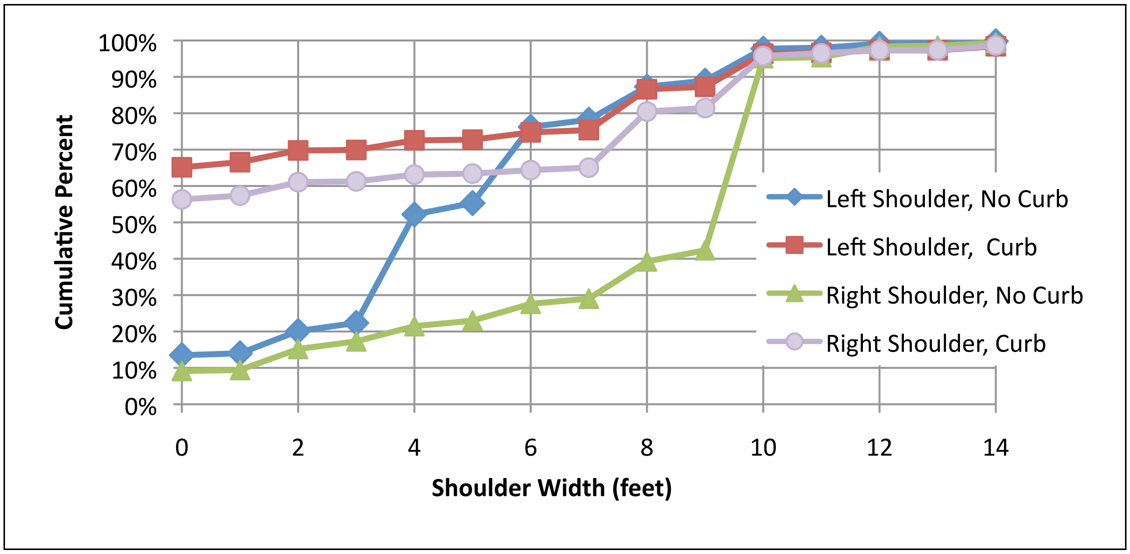

Figure 28 Shoulder Widths for Urban Four-Lane Conditions

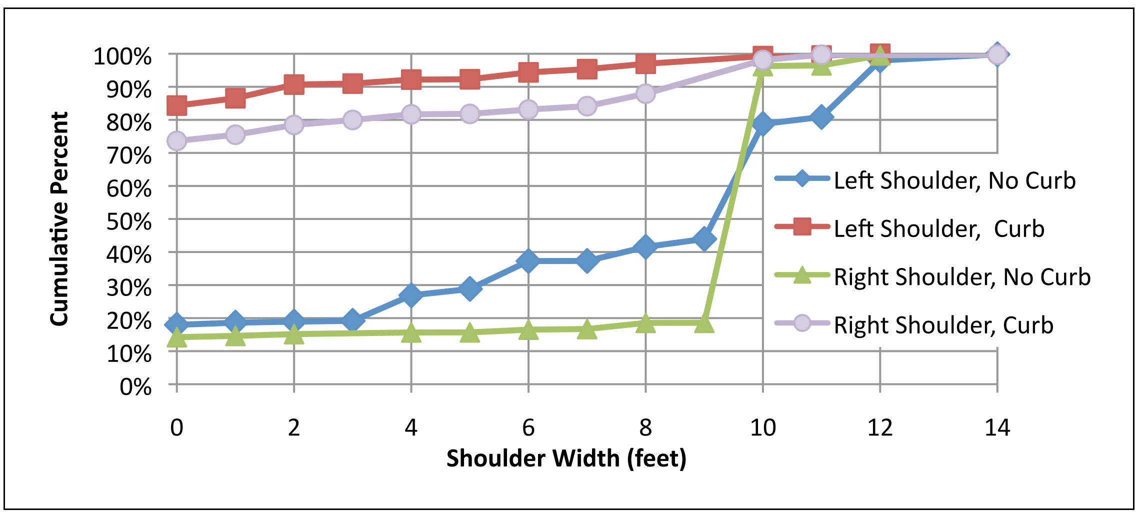

Figure 29 Shoulder Widths for Urban Six-Lane Conditions

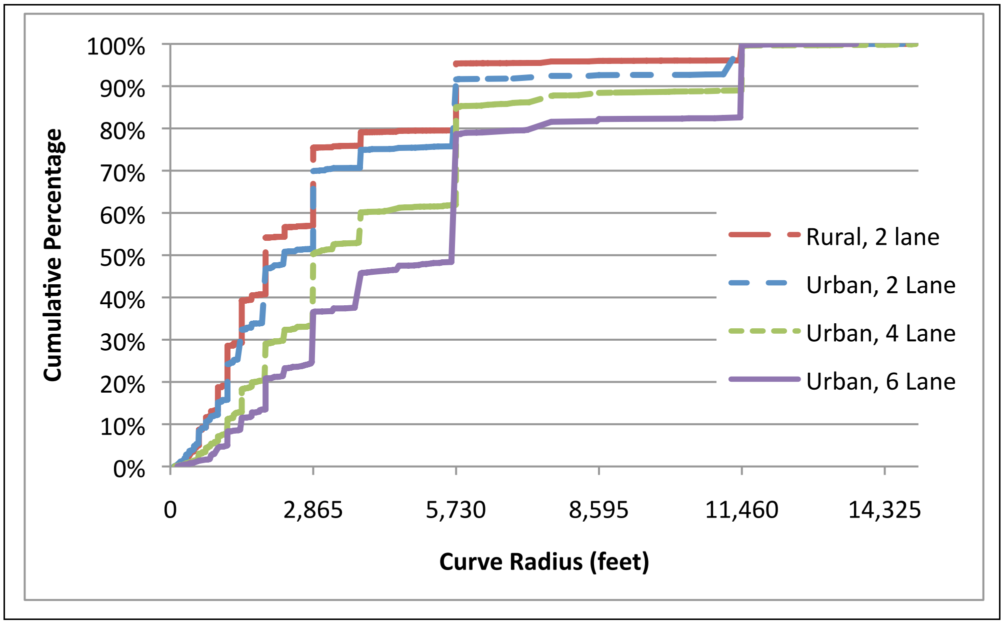

Figure 30 Cumulative Curve Radii for Radii Less than 15,000 Feet

APPENDIX B

TXDOT STANDARD DETAILS

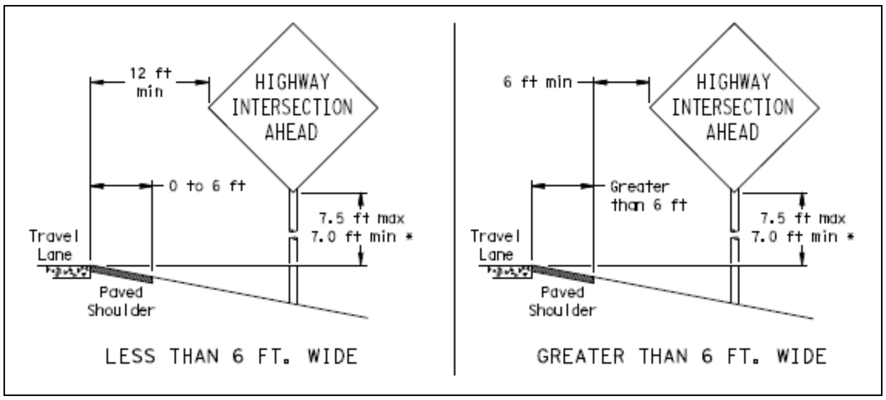

Figure 31 Sign Placement on Paved Shoulders (39)

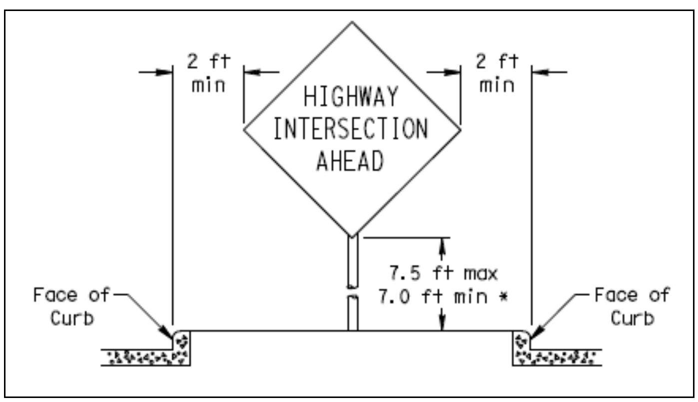

Figure 32 Sign Placement with Curb and Gutter (40)

APPENDIX C

COMPARISON OF SIGN MOUNTING HEIGHTS

A comparison of the luminance provided by a sign at the 5-foot and 7-foot mounting height shows the sheeting on a 5-foot sign provides more luminance. Figure 33 shows the luminance difference for the two mounting heights at four sign placements (two right shoulder offsets and two left shoulder offsets) using a passenger car with the market-weighted headlamps.

As shown, Types III, VIII, IX, and XI have the most variable performance between the different sign heights. The difference in luminance decreases between the two mounting heights as a vehicle approaches the sign. Types I, II, and IV have a smaller difference in luminance between the mounting heights, but they also provide less luminance overall.

For the left shoulder signs, there is only a small difference in luminance provided and the difference decreases as the sign moves further left. There is a larger difference for signs mounted on the right shoulder, especially those close to the edge of the roadway. Although there is only a two-foot difference in the two mounting heights, the luminance provided by Types VIII, IX, and XI for the lower sign is almost twice as much for distances greater than 250 feet. This represents luminance levels of 50 to 90 cd/m^2 for the 7-foot sign and 60 to 200 cd/m^2 for the 5-foot sign. Both of these levels are greater than the luminance provided by Types I, II, and IV. Again, as a right shoulder sign moves further to the right, there is a smaller difference in the luminance provided.

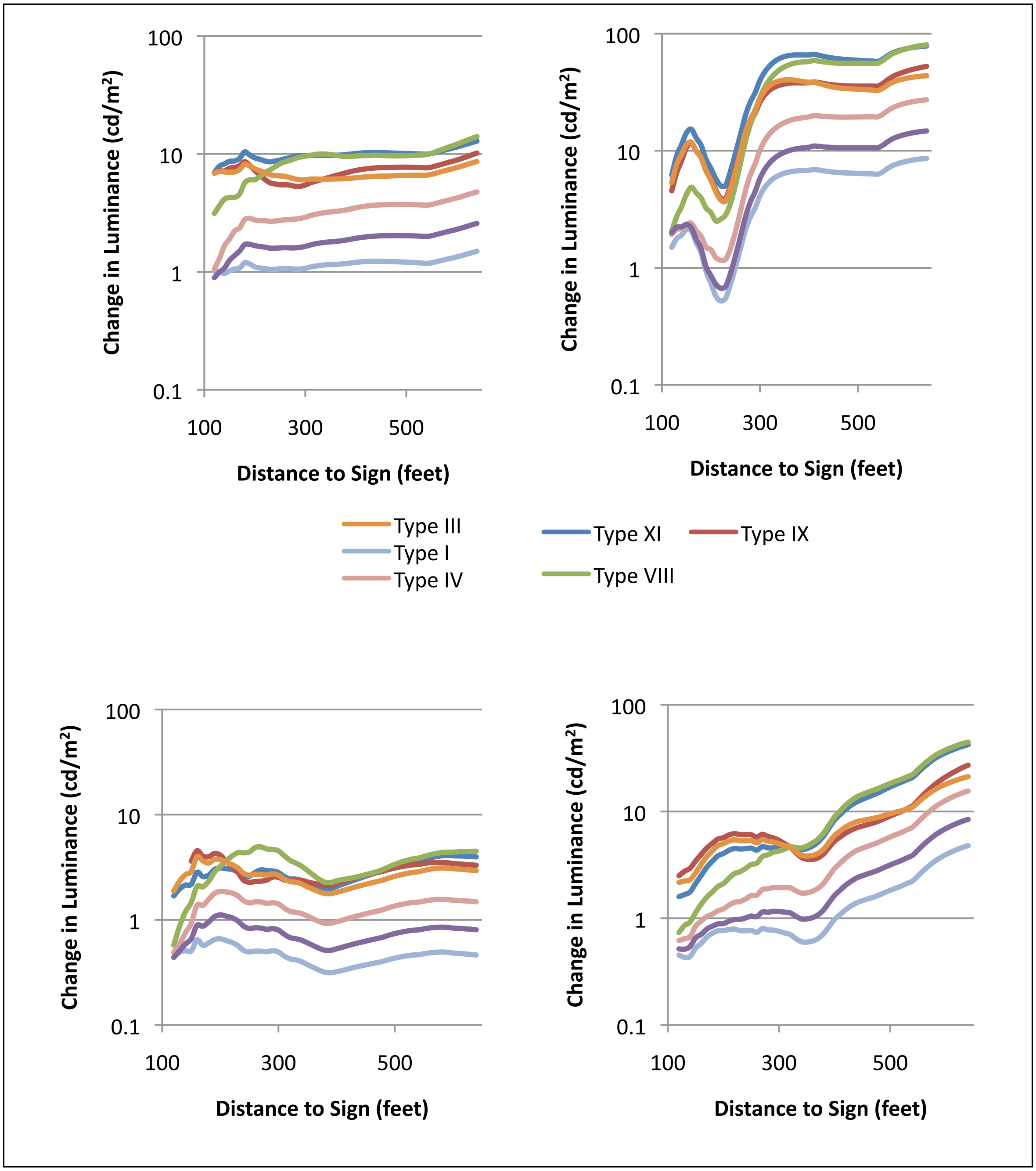

Figure 33 Difference in Luminance from Sign Height for Passenger Cars

Top left: sign offset of -24 feet   Top Right: sign offset of 4 feet

Bottom left: sign offset of -50 feet   Bottom right: sign offset of 42 feet

All offsets are measured from the edge of the right lane

COMPARISON OF SIGN TWIST ANGLES

The author evaluated the effects of twist for radii of 573 and 1146 feet. The sign is located on the right shoulder, 14 feet from the edge of the lane to the center of the sign. The author evaluated the effects of sign twist for passenger car with the market-weighted headlamps at 300 feet from the sign. Both the vehicle and the sign were within the curve. The author considered a curve to the left and a curve to the right. Figure 34 shows the results.

As shown, Type XI has a large variability in performance based on the sign twist. Types III, VIII, and VI have a small variability, which is more noticeable for curves to the left. Types I, II, and IV have similar performance over the twist investigated.

For this thesis, signs will be perpendicular to the curve at their placement (0˚ sign twist), for all materials. This twist provides a good approximation of the luminance over a range of twist angles. The author recommends further analysis of Type XI if placing this sheeting type in a curve.

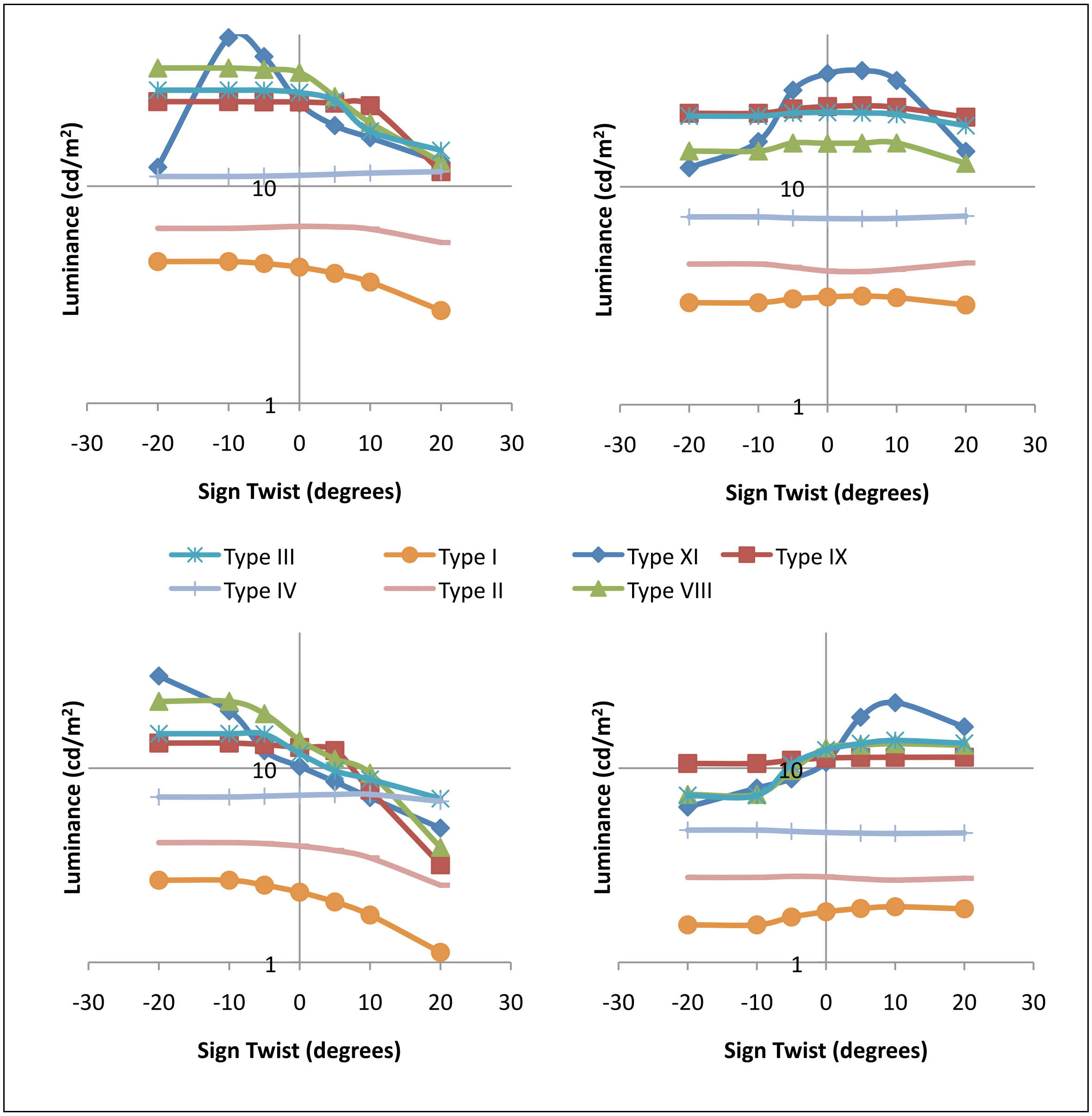

Figure 34 Luminance from Sign Twist for Passenger Cars

Sign location: 14 feet right from right edge of lane to center of sign

Car location: 300 feet from sign

Negative sign twist rotates the sign towards the roadway for a sign on the right shoulder

Top left: Curve to the left, Radius 1146 feet

Top Right: Curve to the right, Radius 1146 feet

Bottom left: Curve to the left, Radius 573 feet

Bottom right: Curve to the right, Radius 573 feet

APPENDIX D

Table 35 Measured Vehicle Dimensions

Type	Sales Rating*	Year	Vehicle	Year to Date (July 2009)	Height of Headlamps above Road (in)	Distance Between Headlamps (in)	Height of Driver's Eye above Road (in)	Transverse Distance of Eyes from Left Headlamp (in)	Distance of Eyes Behind Headlamps (in)	Weight	Weight per Vehicle Type
P	2	2009	Toyota Camry / Solara	184,216	27	45	48	10	86	0.096	0.162
P	4	2009	Honda Accord	160,817	28	58	45	10	82	0.084	0.141
P	5	2009	Toyota Corolla / Matrix	151,236	28	55	49	14	79	0.079	0.133
P	6	2009	Honda Civic	148,496	25	54	45	12	80	0.077	0.130
P	7	2009	Nissan Altima	115,680	27	61	46	17	83	0.060	0.102
P	9	2009	Ford Fusion	102,756	29	46	47	10	83	0.054	0.090
P	11	2009	Chevrolet Impala	93,336	28	57	49	16	87	0.049	0.082
P	13	2010	Chevrolet Malibu	91,168	28	56	47	18	77	0.048	0.080

Type	Sales Rating*	Year	Vehicle	Year to Date (July 2009)	Height of Headlamps above Road (in)	Distance Between Headlamps (in)	Height of Driver's Eye above Road (in)	Transverse Distance of Eyes from Left Headlamp (in)	Distance of Eyes Behind Headlamps (in)	Weight	Weight per Vehicle Type
P	14	2009	Ford Focus	91,184	28	50	48	10	82	0.048	0.080
S	10	2009	Honda CR-V	98,068	33	52	53	10	79	0.051	0.126
S	12	2009	Ford Escape	96,643	33	53	56	9	81	0.050	0.124
S	15	2009	Toyota RAV4	78,153	34	56	55	11	80	0.041	0.100
T	1	2009	Ford F – Series PU	215,959	37	62	61	15	86	0.113	0.277
T	3	2009	Chevrolet Silverado PU	177,566	37	65	63	17	86	0.093	0.228
T	8	2009	Dodge Ram PU	112,239	38	66	66	10	90	0.059	0.144

Table 36 Vehicle Sales as of July 2009

Total*	1,917,517
All Vehicles Sold*	7,432,596
Percentage of Total	25.8%

* As of July 2009

Table 37 Market-Weighted Vehicle Dimensions

		Year to Date (July 2009)	Height of Headlamps above Road (in)	Distance Between Headlamps (in)	Height of Driver's Eye above Road (in)	Transverse Distance of Eyes from Left Headlamp (in)	Distance of Eyes Behind Headlamps (in)
Weighted Average	P	1,138,889	27	53	47	13	82
	T, S	778,628	36	60	60	13	84

APPENDIX E

UMTRI 2004 Market-Weighted Headlamps

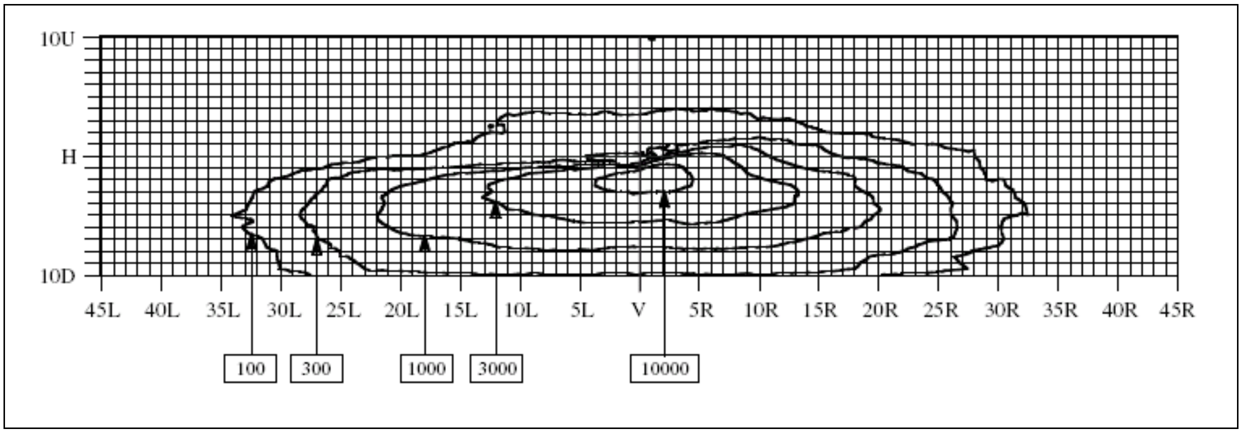

Figure 35 Low Beam Isocandela Plots (46)

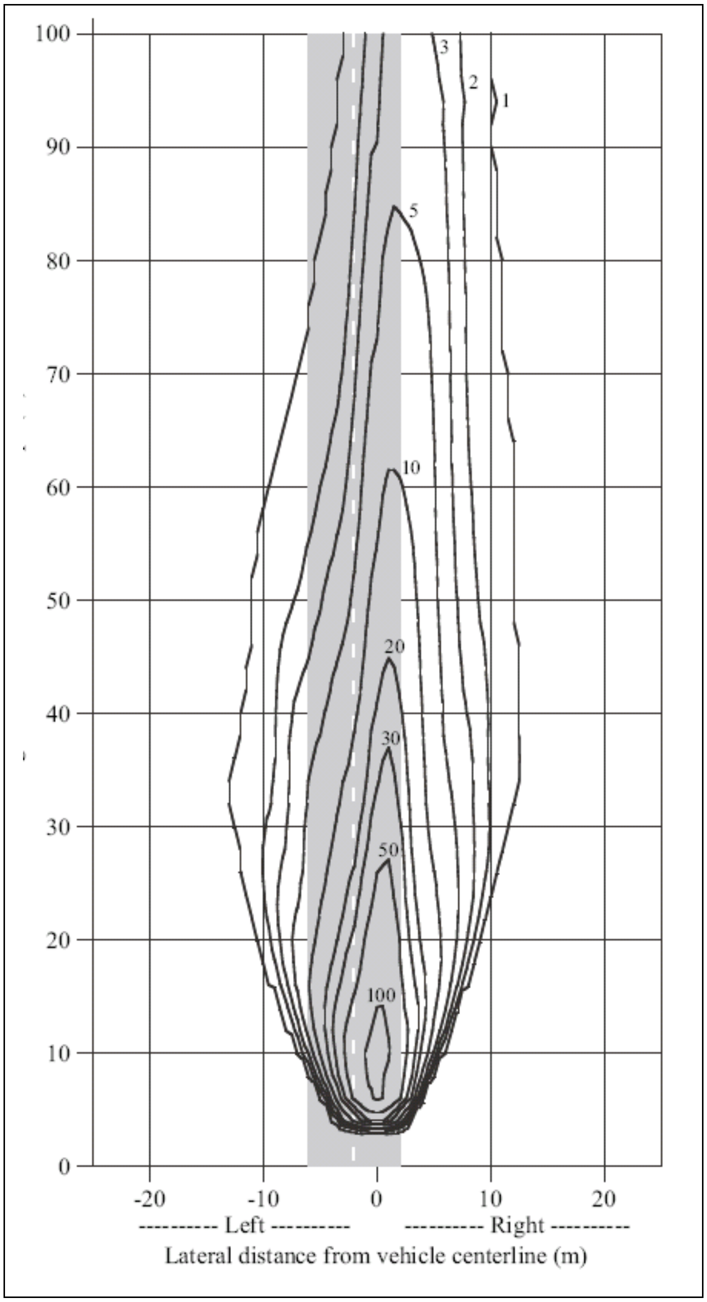

Figure 36 Low Beam Isoilluminance Plots (46)

Table 38 Luminous Intensity Values (cd) for 50 percent - model year 2004 US Headlamps (46)

	45L	40L	35L	30L	25L	20L	15L	10L	9L	8L	7L	6L	5L	4.5L	4L	3.5L	3L	2.5L	2L	1.5L	1L	0.5L	0
7U	15	20	24	25	27	42	51	71	71	70	70	72	76	75	75	75	77	79	80	81	82	81	81
	21	25	26	30	37	49	73	90	98	107	109	116	111	108	103	100	101	102	104	107	115	124	123
	35	34	33	33	45	56	79	105	116	119	128	141	147	151	148	143	143	146	145	141	136	134	135
6.5U	17	20	25	29	28	42	54	71	72	71	74	77	81	80	80	81	83	84	85	85	86	88	88
	25	28	29	32	38	51	75	97	104	112	118	119	114	112	110	111	112	114	117	122	126	137	136
	36	34	35	36	45	61	82	114	131	128	132	152	157	164	161	161	161	160	159	149	149	145	151
6U	17	21	26	30	29	44	59	74	76	78	81	84	86	87	87	84	89	91	91	91	92	96	99
	27	31	34	36	39	54	76	103	112	119	124	126	119	118	116	115	120	126	131	137	143	152	148
	37	37	37	38	47	66	87	127	133	140	153	163	183	188	188	191	194	179	169	164	164	163	168
5.5U	20	22	25	32	31	44	63	82	83	82	89	96	95	96	92	90	95	101	100	101	101	106	109
	28	31	34	39	42	57	79	112	119	127	132	133	139	131	131	134	142	150	159	163	159	158	169
	36	39	41	42	48	69	88	148	140	145	195	173	191	207	211	213	215	204	188	182	182	182	184
5U	18	22	26	34	33	45	67	90	90	93	99	104	106	108	105	101	102	107	113	113	113	115	116
	27	31	38	42	46	61	88	121	125	135	144	139	140	155	154	159	168	180	185	188	183	178	182
	36	40	45	46	53	77	102	153	158	152	204	188	210	218	221	211	212	229	210	204	204	202	204
4.5U	18	22	26	37	37	49	73	97	103	108	111	114	118	122	119	117	118	123	128	134	131	134	137
	27	32	42	46	50	63	90	135	144	152	156	155	159	163	176	181	187	203	210	211	208	203	199
	36	41	47	52	58	79	105	159	164	188	212	189	211	217	229	229	234	234	238	241	249	244	239
4U	17	22	26	39	43	57	81	104	113	116	128	129	138	143	139	137	138	141	146	144	145	148	146
	26	34	43	50	56	67	96	147	159	169	168	174	176	180	188	197	208	195	200	201	203	208	211
	36	42	49	55	61	82	114	177	185	200	190	201	225	236	245	253	245	250	261	263	284	298	292
3.5U	19	22	27	44	56	65	89	118	127	129	146	151	160	164	163	164	167	171	175	172	176	182	190
	26	35	43	56	59	75	102	158	169	181	185	194	200	202	204	215	217	223	229	230	233	239	250
	37	44	53	61	67	88	123	188	201	220	213	224	242	248	261	259	261	266	270	283	313	321	305
3U	20	23	30	48	63	71	102	137	146	146	163	164	176	177	179	183	183	197	196	197	197	197	189
	26	35	44	60	69	87	111	180	192	204	203	211	215	221	228	233	237	246	254	257	262	266	269
	36	46	55	66	73	99	130	193	205	226	230	237	258	271	283	305	307	317	330	353	345	353	349
2.5U	21	23	30	53	72	79	112	154	162	169	177	175	189	198	203	209	206	222	242	247	257	271	270
	26	36	46	64	79	108	127	198	215	225	225	233	242	250	257	256	261	269	270	274	291	296	317
	35	47	57	73	80	116	138	203	225	242	242	254	268	282	309	322	304	321	350	399	395	432	481
2U	23	24	34	58	81	91	130	175	183	197	196	198	204	208	211	214	218	234	257	269	275	273	247
	25	35	48	71	90	118	146	219	223	234	253	263	276	286	298	295	297	305	332	333	348	360	376
	35	43	59	75	92	134	152	229	242	256	271	297	306	336	372	407	417	421	428	444	455	516	572
1.5U	23	26	36	63	87	106	148	211	216	226	241	241	251	256	254	254	255	263	285	315	346	383	426
	25	37	51	78	101	141	176	251	255	272	288	301	330	335	351	356	365	372	370	392	425	453	446
	35	41	57	80	112	159	192	261	276	285	331	342	355	375	405	425	451	477	487	525	583	728	839
1U	23	30	43	74	103	135	190	268	278	296	298	282	290	298	306	326	344	362	372	411	461	499	490
	25	38	50	80	115	178	208	288	297	318	336	362	390	412	426	443	467	507	500	532	567	607	619
	38	40	56	86	125	204	272	336	353	387	405	438	458	458	494	524	555	606	642	700	761	887	952
0.5U	23	29	40	74	110	160	249	344	354	364	392	409	393	420	462	499	504	535	587	701	989	1148	1410
	23	36	54	84	143	226	276	414	415	421	426	446	496	561	597	647	708	774	835	932	1087	1633	2159
	41	41	59	103	153	278	316	449	493	555	645	719	759	781	806	807	904	939	1004	1110	1428	1975	2741
0	21	30	50	80	131	206	337	459	480	508	548	620	717	777	830	945	1071	1255	1706	2323	2576	3622	5758
	23	38	55	101	177	323	417	673	715	775	829	939	1093	1221	1213	1315	1486	1672	2080	2796	4352	6272	8830
	40	43	62	132	211	388	614	954	922	1078	1290	1469	1714	1960	2229	2380	2529	2741	3130	3799	5459	8273	11846
0.5D	21	30	52	88	158	339	583	1011	1273	1450	1577	1713	1868	1912	2062	2147	2235	2898	3713	5016	6435	9045	10401
	22	36	59	122	227	467	694	1307	1474	1699	2022	2338	2691	2921	3491	3663	4022	4541	5366	6760	8750	11788	14555
	36	45	66	182	298	679	1319	2022	2184	2531	2858	3549	4081	4243	4565	4915	5659	7015	7625	8841	11333	15013	19338
1D	19	30	52	89	223	489	938	1659	1907	2380	2600	2792	2937	3107	3319	3553	4205	6042	7292	8540	10782	13358	15520
	22	36	62	153	303	700	1090	3062	3285	3455	3946	4747	5306	5904	6338	6573	6960	7130	8823	10570	12513	15840	18902
	35	46	78	248	435	1074	2077	3245	3820	4350	5039	5979	6756	6951	7598	8353	8915	9524	10668	12525	15053	17885	20419
1.5D	19	30	49	101	322	637	1417	2385	2756	3137	3559	3725	4159	4395	4823	5481	6546	8022	8075	8842	10335	12772	15190
	23	35	67	170	384	934	1525	3357	3677	4248	4850	5774	6926	7601	8102	8274	8301	8813	11410	13309	14406	15957	17099
	39	51	97	332	562	1426	2532	4545	5018	5714	6769	7761	8134	8898	10126	11280	11950	12603	13476	16152	17175	18259	20271
2D	20	30	48	109	356	912	1922	3138	3347	3671	4153	4524	5065	5523	6139	7091	7670	7918	8111	8730	9804	11479	13349
	24	34	68	208	521	1368	2310	4438	4781	5089	6034	6835	7404	7875	7865	8268	9082	10333	11921	12191	13083	14222	14705
	43	49	101	357	740	1806	2932	5182	5872	6743	7647	8101	8695	9250	9730	10475	11278	11879	12911	13995	14646	15636	16603
2.5D	21	30	50	120	437	1111	2202	3556	4037	4548	5127	5018	6119	6415	6825	7122	7114	7111	7373	8115	8587	9495	10410
	23	33	72	213	596	1749	3004	4614	4909	5315	5809	6670	7101	7096	7430	8229	8957	8845	9678	10064	10458	11126	11790
	42	50	112	377	867	1939	3336	5775	6265	7398	8074	8259	8712	8997	9300	9502	9881	11203	11317	11490	11753	12124	13292
3D	20	31	49	123	494	1084	2289	3348	3598	4153	4484	4591	4748	4908	5157	5393	5748	6000	6325	6633	7017	7160	7411
	23	32	72	254	695	1771	3075	5080	5262	5599	6035	6444	6481	6551	7016	7382	7597	7765	7899	8403	8624	8762	8905
	42	48	121	393	926	2126	3648	5461	6023	6825	7091	6995	7653	7919	8145	8511	9375	9597	9564	9514	10294	10470	10472
3.5D	20	30	51	128	501	1065	2412	3202	3540	3625	3992	4385	4509	4309	4290	4305	4375	4511	4682	4887	5032	5158	5280
	23	32	71	258	775	1794	2585	4652	5100	5275	5622	5256	5449	5702	5842	6015	5949	5932	6472	6580	6505	6572	6773
	40	47	110	388	934	2155	3538	5072	5574	6094	6030	6575	7124	7349	7558	7843	8094	8214	7917	7734	7722	7827	7960
4D	19	30	49	158	481	962	2076	2683	2781	3023	3150	3273	3374	3485	3672	3828	3825	3883	3930	3961	3984	4056	4149
	24	32	72	257	795	1612	2454	4004	4324	4568	4516	4390	4448	4581	4730	4855	4855	4955	4964	5017	4993	5052	5157
	41	50	111	390	911	2091	3166	4324	4809	5070	5123	5508	5745	5889	5991	6030	6098	5972	5837	6005	6068	5945	6047
4.5D	19	29	47	159	438	854	1784	2187	2365	2439	2558	2718	2861	2803	2701	2641	2626	2649	2737	2748	2672	2686	2722
	23	30	68	239	791	1575	2314	3220	3377	3677	3641	3579	3637	3669	3729	3873	3951	4006	3999	3937	3950	3961	3939
	41	50	117	370	901	1856	2607	3826	3884	3868	3984	4199	4490	4596	4594	4623	4658	4624	4665	4657	4695	4669	4652
5D	21	25	46	143	368	758	1501	1755	1976	2063	2122	2132	1978	1990	1999	2008	2020	2060	2094	2024	1953	1956	1969
	23	31	60	205	685	1334	1905	2476	2679	2895	2909	2941	2963	2976	3002	3010	3031	3007	3035	3024	2991	2992	2965
	41	48	118	338	932	1634	2338	3180	3198	3052	3209	3334	3515	3570	3557	3486	3526	3581	3650	3696	3703	3842	3764

	0.5R	1R	1.5R	2R	2.5R	3R	3.5R	4R	4.5R	5R	6R	7R	8R	9R	10R	15R	20R	25R	30R	35R	40R	45R
7U	84 117 137	91 112 136	90 109 137	90 109 135	89 110 133	87 111 130	84 119 130	78 121 134	75 125 138	73 120 137	68 116 143	61 108 144	56 93 122	57 88 107	55 85 100	44 60 66	34 42 47	23 30 36	14 17 25	8 10 13	4 8 11	2 5 9
6.5U	90 132 153	94 128 155	94 131 156	94 130 159	92 127 158	91 130 155	88 135 152	86 137 153	85 138 149	81 138 151	74 134 154	67 129 159	63 101 133	60 94 121	56 91 111	46 66 71	37 47 51	25 33 36	14 18 28	8 10 14	4 8 11	3 5 8
6U	98 145 171	98 148 176	99 151 186	102 153 192	99 154 196	98 155 194	96 153 188	94 149 176	93 147 175	90 146 171	80 145 161	76 121 173	73 115 156	67 103 131	62 97 122	51 65 75	39 49 53	26 33 35	14 18 29	7 11 14	4 7 10	3 4 9
5.5U	111 169 186	111 174 203	109 176 201	106 175 207	105 173 213	102 181 212	105 187 207	104 192 195	100 185 194	97 169 191	91 149 181	87 157 185	81 122 172	76 114 143	71 105 128	54 69 82	42 50 58	30 35 40	16 20 30	8 11 14	4 7 11	3 4 9
5U	116 178 215	116 177 213	117 173 214	115 177 217	114 186 227	119 195 232	116 199 232	112 203 227	112 196 226	109 173 225	103 159 215	99 152 206	90 131 187	89 122 157	83 108 138	57 77 90	47 59 62	31 38 44	16 21 33	7 11 15	4 8 12	3 5 10
4.5U	136 200 244	138 198 240	136 198 238	137 198 239	137 207 248	135 196 249	134 214 249	128 215 251	124 202 250	119 192 250	115 165 243	112 162 217	100 143 196	101 136 169	96 115 156	67 86 96	48 65 68	32 39 50	15 21 35	8 12 17	4 8 13	3 5 10
4U	148 217 274	156 218 262	155 215 250	149 216 247	149 215 251	149 214 255	142 219 265	139 228 272	139 215 274	136 222 281	130 181 264	124 174 247	113 153 217	113 145 187	108 126 167	74 92 106	50 72 77	35 45 55	16 21 38	8 12 19	5 8 14	2 5 11
3.5U	188 253 286	185 244 287	186 236 283	191 234 277	188 233 280	182 234 274	180 236 263	171 240 261	161 246 259	156 223 261	154 215 264	139 191 278	128 182 236	127 172 209	124 152 175	80 102 121	53 78 86	38 50 57	17 23 39	8 13 20	4 8 14	3 5 12
3U	189 276 335	205 277 330	207 276 323	195 272 279	193 262 278	189 259 280	176 264 284	179 261 286	182 246 290	182 225 291	170 213 286	153 204 271	159 200 263	142 185 233	138 159 214	94 113 150	61 88 101	41 53 66	20 25 44	8 14 25	4 8 16	3 5 12
2.5U	270 329 510	250 330 525	251 314 487	250 300 424	244 296 398	246 295 371	256 298 350	236 291 322	223 274 331	194 276 326	192 271 319	188 264 332	180 231 313	167 207 274	160 185 244	104 129 168	71 97 126	47 63 81	21 27 47	8 16 28	4 7 19	3 4 12
2U	234 389 562	250 395 580	267 395 553	258 389 508	258 380 484	240 369 462	247 367 404	251 365 408	256 362 409	253 345 402	244 303 375	233 294 351	216 263 338	193 237 288	178 219 286	132 146 189	80 110 160	49 71 97	23 33 51	9 15 29	4 8 23	3 5 11
1.5U	389 452 840	407 448 837	391 419 826	387 432 744	389 435 713	413 440 805	311 440 786	306 424 683	323 479 624	334 423 566	302 370 486	283 342 419	261 332 368	233 294 348	216 282 322	161 188 241	105 127 193	57 75 101	23 38 60	9 14 28	4 8 22	3 4 12
1U	438 589 1033	494 662 987	473 620 1372	527 578 1270	426 577 1175	443 551 1159	458 600 1053	431 560 904	404 547 939	375 576 889	354 511 787	325 451 732	321 426 662	324 373 589	293 354 494	209 241 318	109 171 265	67 79 119	26 44 61	9 13 31	4 7 19	3 4 11
0.5U	1587 2393 3464	1772 2391 4032	1877 2387 4592	1808 2578 4437	1795 2815 4618	1531 2520 4562	1277 2206 4307	1158 1684 4094	906 1415 3449	850 1201 2776	720 875 1955	641 694 1328	560 582 1100	468 560 1000	449 519 967	283 340 620	130 224 355	76 97 162	24 52 60	8 13 30	3 7 15	3 4 10
0	6928 10124 14864	7419 11952 15369	7738 11972 15235	8033 12662 15814	7423 11838 15970	6556 10688 14869	5558 9678 13281	3920 7168 11026	3323 6261 9013	2226 4717 7011	1429 3092 4761	1133 2319 3467	941 1540 2855	702 1200 2155	596 1120 1706	412 514 1013	183 333 464	88 107 194	26 55 66	7 13 31	4 6 13	3 4 8
0.5D	12314 18927 21634	14520 18885 26203	15545 18564 27227	15293 17318 26806	14282 16958 25316	11186 15969 21204	8573 14287 18768	6891 12020 15194	5452 9411 12777	4285 7896 10831	2760 5457 8539	1873 3918 7096	1542 3290 4244	1175 2632 3345	933 2275 3464	680 859 1625	278 486 630	94 111 230	28 53 91	7 12 26	4 7 14	3 4 8
1D	17681 21929 22842	19353 22740 25640	19917 21595 25869	18788 20174 24478	16805 19033 23635	14120 16962 22360	12214 14921 20750	10531 13178 17065	8572 11174 14828	6854 9898 12662	4400 7295 9794	3206 5378 8753	2732 4221 7206	2615 3551 5310	2020 2801 4507	1202 1401 2015	421 691 814	113 140 260	25 50 101	6 15 28	4 7 13	2 4 7
1.5D	16911 19076 20835	17472 20241 24181	17127 19534 27177	16187 18785 25605	15185 18074 22788	14510 17209 19771	13330 16324 17922	10828 13592 16056	10003 11002 15223	8244 10257 13945	6322 8096 11359	5052 6429 9376	3756 5195 8797	3150 4632 6703	2956 4237 6229	1731 1968 2234	563 867 1116	140 191 303	25 50 125	6 14 31	4 6 13	3 4 7
2D	13339 16457 17316	12826 16273 19775	12447 16247 20658	12706 15821 20387	11982 15442 22282	11339 15130 18715	10618 14545 16310	9850 13626 14473	9072 11242 13539	8624 10498 12912	6121 8180 11073	4973 7105 9595	4389 5902 8770	3973 5122 7630	3635 4399 6456	1931 2516 2887	731 1089 1207	162 235 368	30 51 157	7 12 31	3 7 11	3 4 7
2.5D	10788 12335 14664	10398 12550 14656	10077 12603 15160	9633 12605 15914	9278 12491 15970	8736 12265 14488	7963 11860 13347	7365 11221 12159	7146 10115 11702	7137 9231 10863	6362 7600 9599	5368 6701 8615	4871 5599 7994	4147 5155 7357	3604 4932 6175	1875 3108 3332	871 1103 1450	176 290 453	29 50 149	6 13 31	4 6 12	2 4 8
3D	7020 9088 10925	6613 9294 10815	6425 9281 10682	6370 9208 11037	6256 9265 11134	6163 9314 11126	6077 9221 10502	5800 9025 9945	5508 8511 9338	5255 7795 8663	4971 6936 7744	4697 6186 7304	4329 5788 6930	3885 5457 6037	3313 4958 5856	1603 2969 3756	817 1184 1686	191 319 563	27 50 160	7 17 32	3 6 13	2 5 8
3.5D	5425 6660 8254	5423 6719 8358	5359 6748 8336	5343 6943 8341	5376 7303 8494	5302 7251 8106	5103 6920 8156	4701 6686 7918	4630 6471 7517	4620 6309 7067	4309 5957 6470	4012 5399 6171	3759 5084 5937	3493 4782 5736	3145 4342 5569	1495 2638 3828	755 1280 1729	179 337 608	22 48 161	6 15 33	3 7 13	2 4 7
4D	4154 4990 5968	4102 5025 6099	4041 5137 6083	4009 5152 6152	4076 5347 6175	4153 5237 6201	4014 5072 6360	3720 4964 6151	3408 4830 5880	3374 4708 5610	3371 4513 5212	3203 4306 4994	3011 4138 4826	2842 3880 4803	2705 3785 4550	1355 2301 3339	660 1276 1665	166 355 623	25 49 123	6 13 34	3 7 15	3 4 9
4.5D	2753 3962 4629	2715 3936 4583	2689 3911 4552	2692 3884 4512	2746 4107 4515	2838 4085 4591	2935 3899 4608	2894 3792 4600	2698 3658 4408	2481 3552 4232	2490 3564 4048	2541 3490 3968	2424 3287 3876	2310 3111 3826	2261 2978 3703	1182 2170 2876	558 1216 1526	148 368 562	22 50 116	6 12 32	3 7 14	2 4 8
5D	2046 2960 3740	2031 2930 3722	2014 2953 3643	2000 2973 3573	2004 3027 3507	2028 2993 3474	2048 2970 3563	2018 2929 3469	2072 2845 3397	2023 2813 3322	2038 2819 3217	2070 2662 3147	1946 2625 2982	1847 2582 3048	1822 2367 2910	945 1721 2463	422 1097 1406	112 319 493	20 57 108	6 13 33	4 6 12	2 4 8

APPENDIX F

Sheeting Color Factor

Table 39 Luminance Provided by Different Sheeting Colors

Luminance Provided (cd/m²) (10)					
White	Yellow	Orange	Green	Red	Blue
1.28	0.97	0.45	0.29	0.3	0.15
2.16	1.62	0.73	0.49	0.48	0.25
3.01	2.23	1.01	0.69	0.67	0.35
3.57	2.74	1.25	0.76	0.82	0.37
4.71	3.47	1.57	1.09	1.03	0.56
6.77	5.02	2.2	1.57	1.39	0.8
9.12	6.73	2.94	2.14	1.85	1.09
14.2	10.4	4.56	3.37	2.87	1.72
23	16.8	7.2	5.5	4.54	2.81
27.3	20	8.58	6.54	5.38	3.35
33.6	24	10.5	8.12	6.59	4.19
40.3	29.4	12.6	9.7	7.87	5.02
67.9	48.9	21.5	16.7	14.03	8.76

	Percent of White				
	Yellow	Orange	Green	Red	Blue
	75.8%	35.2%	22.7%	23.4%	11.7%
	75.0%	33.8%	22.7%	22.2%	11.6%
	74.1%	33.6%	22.9%	22.3%	11.6%
	76.8%	35.0%	21.3%	23.0%	10.4%
	73.7%	33.3%	23.1%	21.9%	11.9%
	74.2%	32.5%	23.2%	20.5%	11.8%
	73.8%	32.2%	23.5%	20.3%	12.0%
	73.2%	32.1%	23.7%	20.2%	12.1%
	73.0%	31.3%	23.9%	19.7%	12.2%
	73.3%	31.4%	24.0%	19.7%	12.3%
	71.4%	31.3%	24.2%	19.6%	12.5%
	73.0%	31.3%	24.1%	19.5%	12.5%
	72.0%	31.7%	24.6%	20.7%	12.9%
min	71.4%	31.3%	21.3%	19.5%	10.4%
max	76.8%	35.0%	24.6%	23.0%	12.9%
average	**73.8%**	**32.7%**	**23.4%**	**21.0%**	**12.0%**

APPENDIX G

EXACT ROAD GEOMETRY OUTPUT (ERGO) VERSION 1.0

Figure 37 displays the main screen of ERGO. On the left side, ERGO shows a pictorial representation of the entered scenario. On the right side, users can enter lane width and roadway geometry including the distance to the sign and curve information. Also there are buttons on the bottom left, where users can enter vehicle, headlamp, sign, and sheeting information. Each of these inputs is described next.

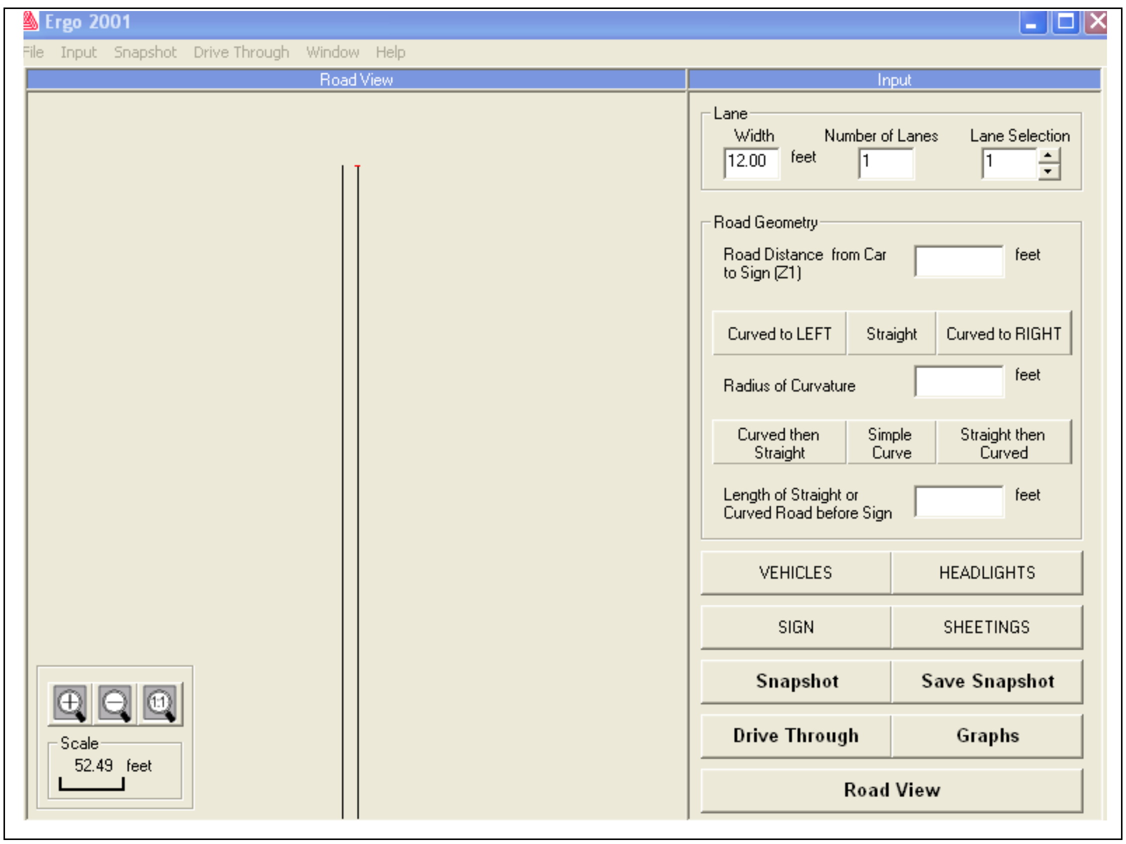

Figure 37 ERGO Geometry Input

Figure 38 shows the vehicle inputs. Here, the user can choose a vehicle from the drop down box or enter dimensions for their own vehicle type.

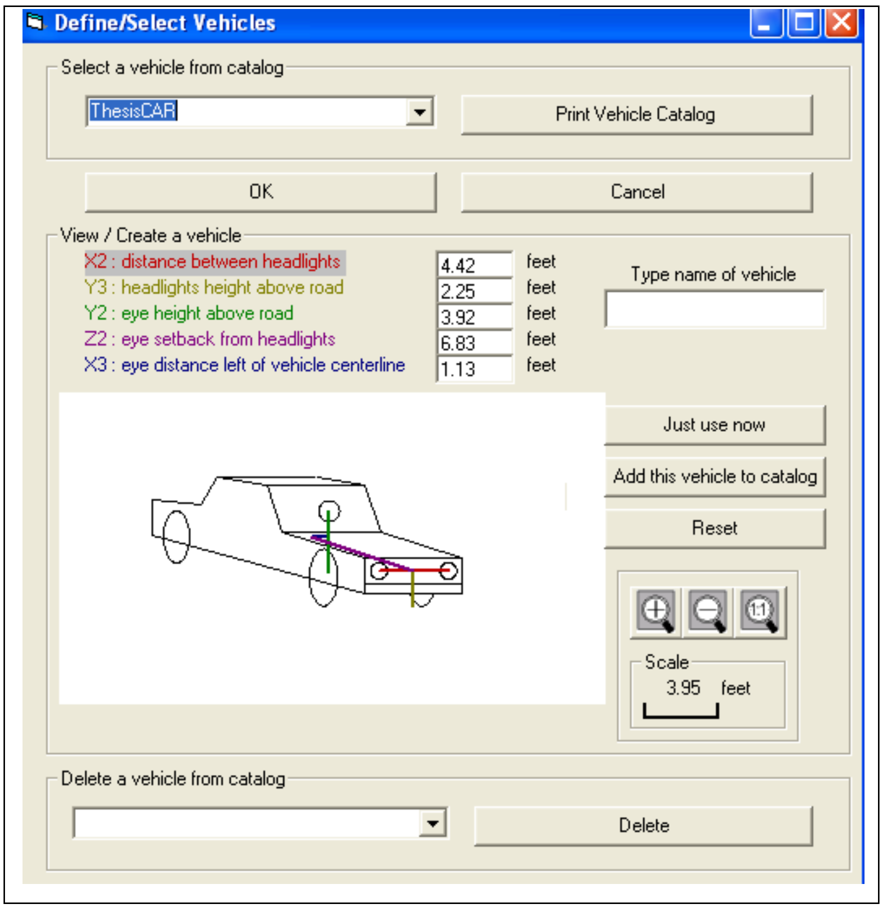

Figure 38 ERGO Vehicle Inputs

Figure 39 shows the sign inputs. In this window, the user can enter sign height, offset, twist and lean. The user can also enter the rotation of the sign and sheeting.

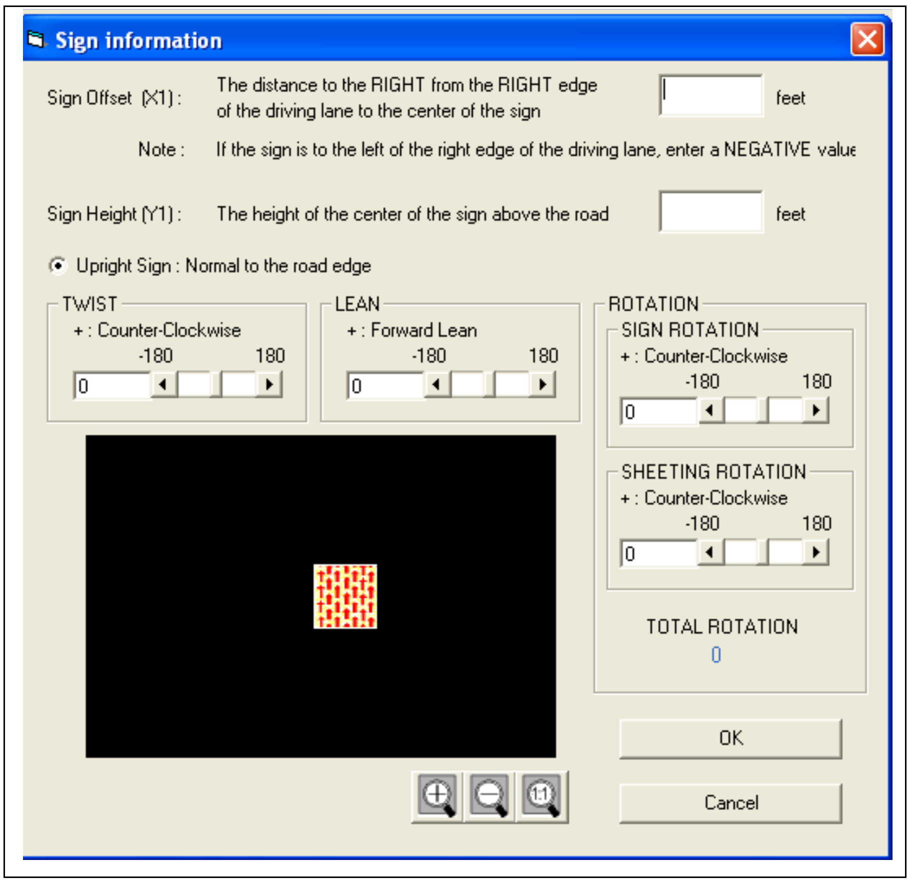

Figure 39 ERGO Sign Inputs

Figure 40 shows the headlamps input window. In this window, users can choose the headlamp from the dropdown list. Users can also upload their own headlamp file or download the headlamp files already present in ERGO.

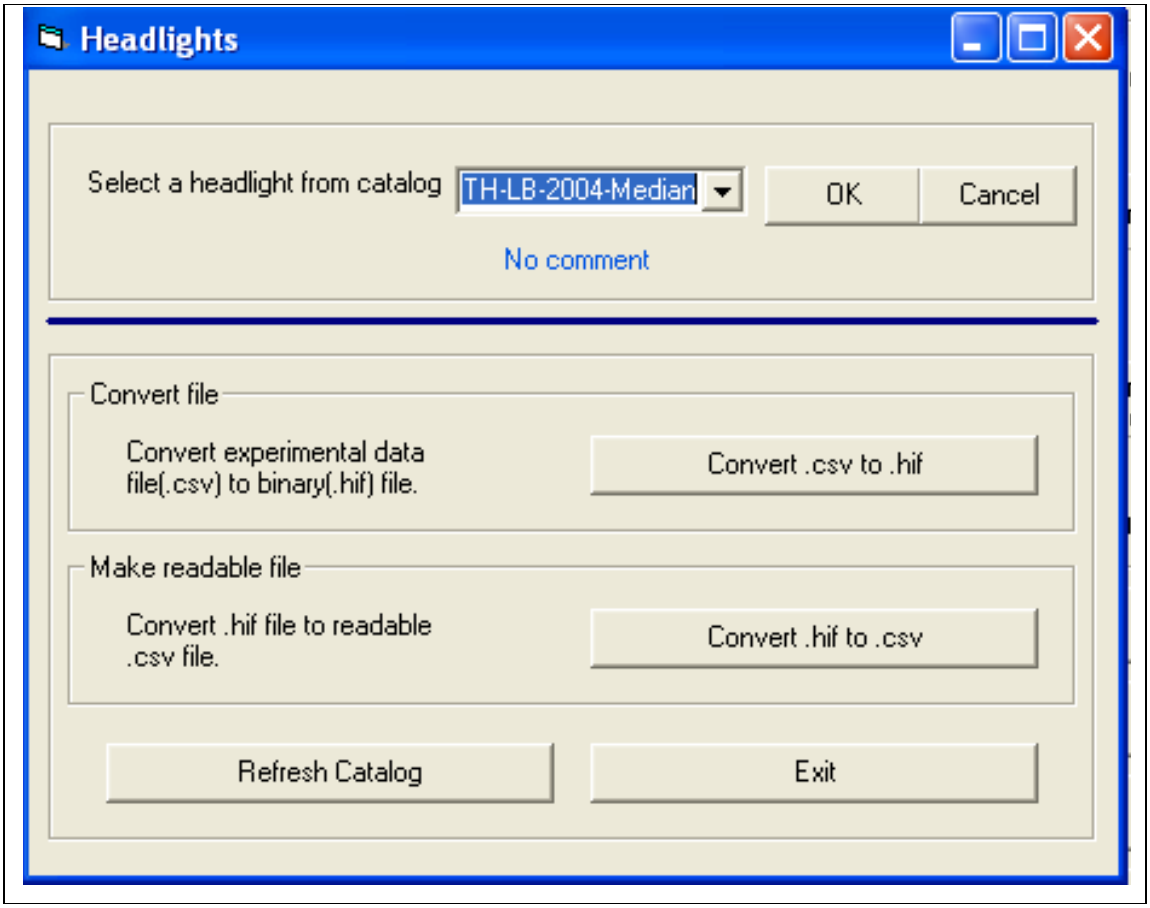

Figure 40 EGRO Headlamp Input

Figure 41 shows the retroreflective sheeting input. In this window, users can choose the sheeting type from the dropdown list. Users can also upload their own sheeting file or download the sheeting files already present in ERGO. Users can also enter specific angles to see the coefficient of Retroreflection for the sheeting types available.

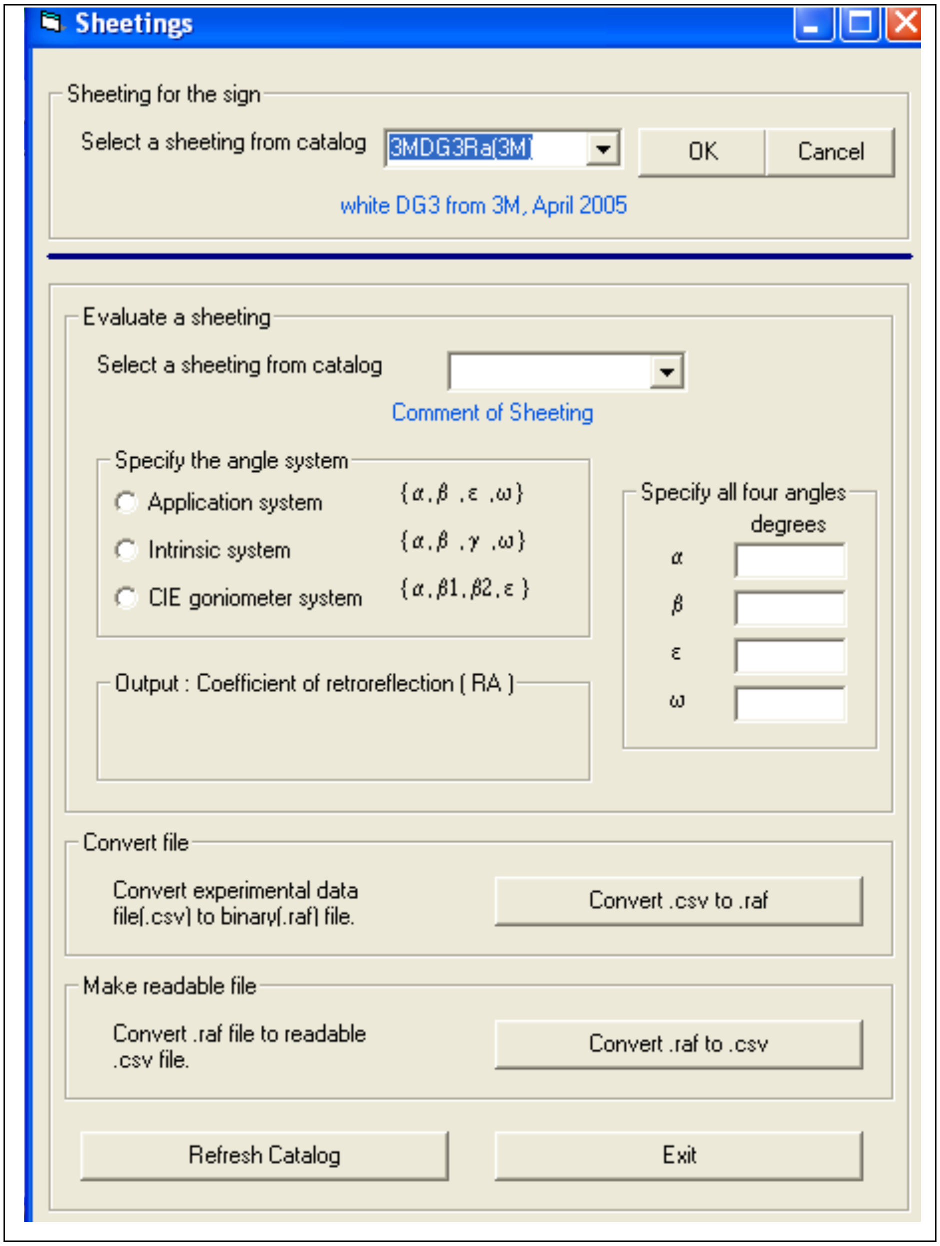

Figure 41 ERGO Retroreflective Sheeting Input

Figure 42 shows the output summary. The spreadsheet shows the input information, the calculated angles, and the values from the headlamp file selected by the user. This data can be saved as a file for use in a spreadsheet program.

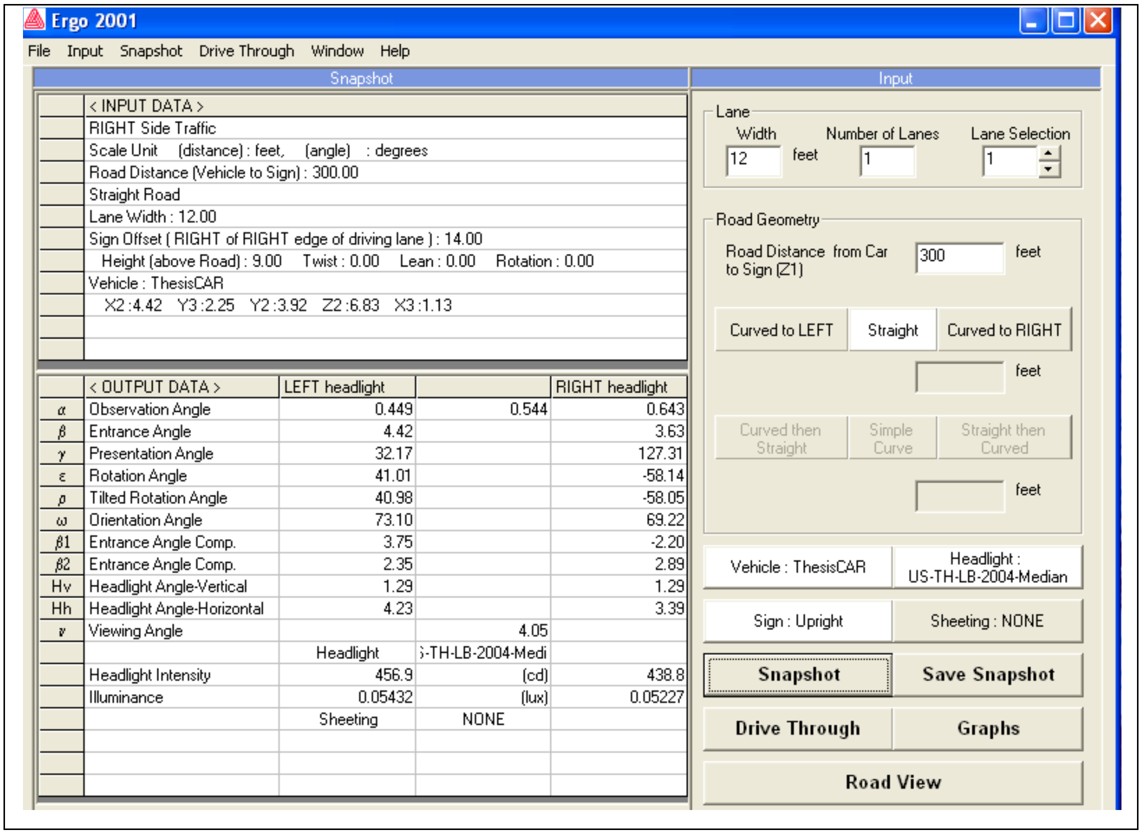

Figure 42 ERGO Output Summary

Figure 43 shows a graphical output summary. These graphs show how the angles and luminance change over a range of viewing distances. There are numerous output options available including a summary of the different angles, the headlamp intensity, and the illuminance reaching the sign. Further for each sheeting type, the retroreflection and sign luminance can be displayed. This output is also saved as a spreadsheet for use in a spreadsheet program.

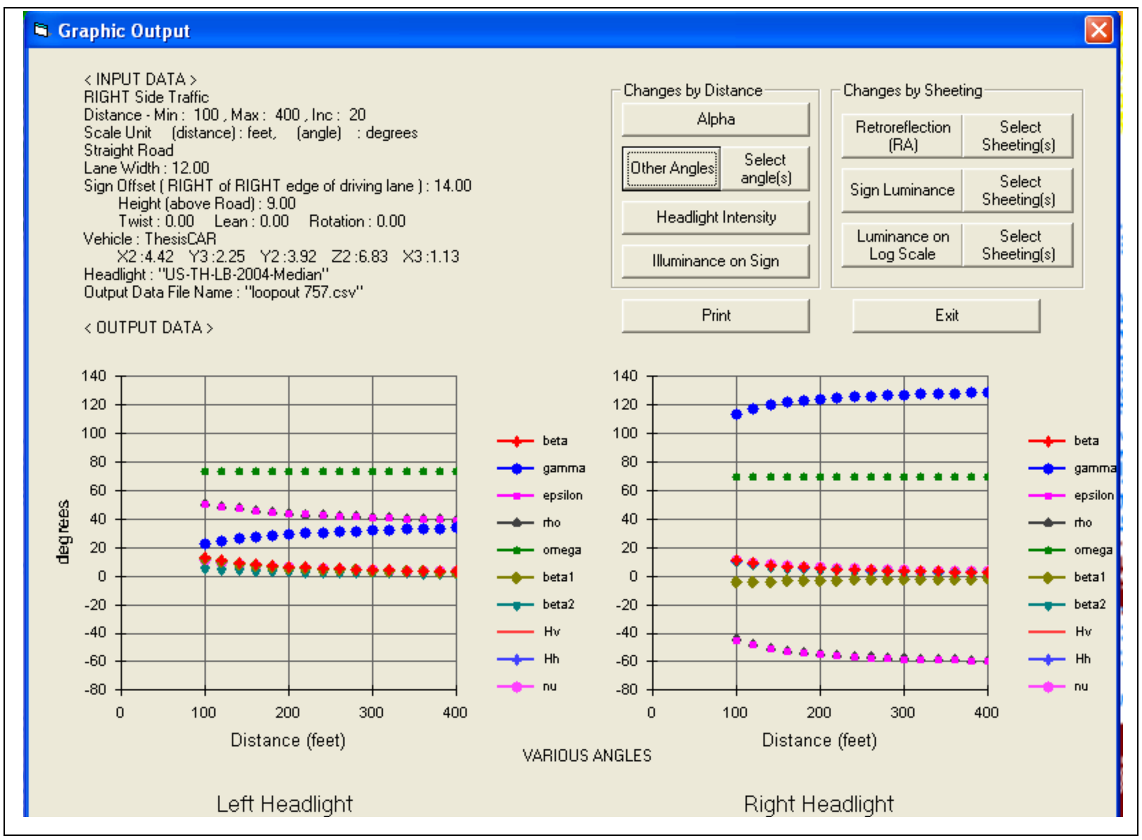

Figure 43 ERGO Output Details

APPENDIX H

Example 1: Sign Selection Calculations

Table 40 Sign Group 1: Car – Curve to the Left, 573-Feet

White Sheeting														
Luminance (cd/m²)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	0.9	1.1	1.2	1.4	1.5	1.8	2.0	2.0	2.2	2.2	2.3	2.3	2.4
	II	1.4	1.7	1.9	2.2	2.4	3.1	3.5	3.6	4.0	4.0	4.1	4.3	4.5
	III	5.8	7.1	7.4	7.6	8.9	9.0	9.1	9.8	9.5	9.5	9.6	10.1	10.3
	IV	2.2	2.8	3.1	3.8	4.0	5.7	6.4	6.7	7.5	7.7	7.8	8.4	8.7
	VIII	5.2	6.9	7.9	10.0	10.3	11.8	11.9	12.3	13.1	13.3	13.3	13.5	13.7
	IX	5.7	6.5	6.7	7.6	7.8	9.8	11.0	11.6	13.1	13.5	13.8	14.3	14.5
	XI	7.9	7.9	7.3	7.2	7.3	8.2	8.5	8.6	9.1	9.2	9.2	9.4	9.7

Table 41 Sign Group 1: Truck – Curve to the Left, 573-Feet

White Sheeting														
Luminance (cd/m²)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	0.9	1.0	1.1	1.3	1.4	1.7	1.8	1.9	2.0	2.0	2.1	2.1	2.2
	II	1.2	1.6	1.7	2.1	2.2	2.9	3.2	3.3	3.6	3.6	3.7	3.9	4.0
	III	5.4	6.7	7.1	7.3	8.6	8.8	9.0	9.5	9.2	9.2	9.3	9.8	9.9
	IV	1.9	2.4	2.7	3.3	3.6	5.1	5.7	6.0	6.7	6.8	6.9	7.3	7.6
	VIII	3.8	5.1	5.9	7.5	7.9	9.4	9.4	9.7	10.3	10.4	10.5	10.7	10.9
	IX	5.6	6.6	6.9	7.7	8.0	9.6	10.6	11.1	12.4	12.7	12.9	13.5	13.7
	XI	7.2	7.3	6.7	6.6	6.7	7.8	8.3	8.5	9.0	9.1	9.1	9.3	9.5

Table 42 Sign Group 1: Car – Straight

Luminance (cd/m²)	White Sheeting													
	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	3.1	3.4	3.8	4.2	4.5	4.7	4.7	5.0	4.7	4.5	4.3	3.8	3.6
	II	4.9	5.3	5.8	6.3	6.6	6.7	6.8	7.2	6.8	6.6	6.3	5.8	5.5
	III	17.2	19.1	20.3	21.2	24.4	25.5	26.5	31.7	31.8	33.1	33.3	31.1	29.8
	IV	8.5	9.3	10.1	11.0	11.6	11.7	11.8	12.4	11.7	11.2	10.8	9.8	9.3
	VIII	26.5	29.0	31.6	34.5	36.6	32.7	31.4	32.3	28.5	27.2	25.9	22.7	21.1
	IX	17.0	18.9	20.7	23.3	24.9	30.1	31.2	33.2	32.4	31.2	29.9	26.8	25.1
	XI	19.4	25.4	31.2	37.3	40.6	46.5	45.7	47.7	41.4	38.3	35.2	26.2	22.0

Table 43 Sign Group 1: Truck – Straight

Luminance (cd/m²)	White Sheeting													
	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.9	3.2	3.5	3.9	4.3	4.8	4.5	4.6	4.3	4.1	3.9	3.5	3.2
	II	4.4	4.8	5.1	5.6	6.0	6.3	6.0	6.1	5.5	5.2	5.0	4.5	4.2
	III	16.0	17.9	19.2	20.0	23.5	25.1	26.5	32.9	31.3	31.9	31.9	29.5	28.1
	IV	7.5	8.1	8.8	9.6	10.2	10.5	10.0	10.2	9.2	8.7	8.4	7.5	7.0
	VIII	22.3	24.0	25.8	28.1	30.2	28.1	25.5	25.3	21.9	20.5	19.5	16.7	15.3
	IX	15.5	17.4	19.2	22.1	24.1	31.7	31.5	32.9	32.0	30.7	29.6	26.5	24.9
	XI	24.5	23.7	28.6	33.6	39.1	45.8	42.8	43.6	42.1	39.9	38.1	33.0	29.5

Table 44 Sign Group 1: Car – Curve to the Right, 573-Feet

Luminance (cd/m²)	White Sheeting													
	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.9	2.7	2.7	2.4	2.3	1.8	1.7	1.6	1.3	1.2	1.2	1.0	0.9
	II	5.5	5.0	4.8	4.3	4.0	2.9	2.7	2.5	2.0	1.9	1.9	1.6	1.4
	III	14.8	14.1	13.8	13.7	12.9	12.8	12.8	11.6	11.0	10.7	10.0	8.0	7.7
	IV	9.7	8.8	8.3	7.5	7.0	5.0	4.7	4.3	3.5	3.3	3.2	2.8	2.5
	VIII	13.2	12.4	12.1	11.6	11.4	12.3	13.1	12.6	10.5	10.1	9.8	8.6	7.8
	IX	20.8	19.5	18.7	16.8	15.7	11.2	10.1	9.1	7.2	7.0	6.7	5.6	5.0
	XI	13.9	13.2	12.9	12.1	11.5	9.7	9.6	9.1	8.9	8.9	9.0	8.7	8.2

Table 45 Sign Group 1: Truck – Curve to the Right, 573-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	4.6	2.5	2.4	2.2	2.1	1.6	1.5	1.4	1.1	1.1	1.0	0.9	0.8
	II	4.6	4.2	4.0	3.5	3.2	2.4	2.2	2.1	1.6	1.6	1.5	1.3	1.2
	III	14.0	13.2	12.9	12.8	12.1	12.0	11.9	11.4	10.8	10.6	10.0	7.9	7.5
	IV	7.5	6.8	6.4	5.6	5.2	3.9	3.7	3.5	2.7	2.6	2.5	2.2	2.0
	VIII	9.9	9.3	8.9	8.2	7.8	7.9	8.5	8.4	7.0	6.8	6.7	6.0	5.6
	IX	19.9	18.9	18.2	16.5	15.6	11.6	10.4	9.4	7.1	6.8	6.5	5.4	4.8
	XI	13.0	12.3	11.9	10.9	10.4	8.8	8.6	8.3	7.9	7.9	7.9	7.8	7.3

Example 2: Sign Selection Calculations

Table 46 Sign Group 2: Car – Straight

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.2	2.9	3.5	4.0	4.3	5.1	4.1	3.7	2.9	2.7	2.6	2.1	2.0
	II	3.1	4.0	4.8	5.3	5.4	5.5	4.1	3.6	2.7	2.6	2.5	2.2	2.1
	III	13.7	18.0	20.2	21.3	25.2	26.2	27.1	29.5	24.2	22.9	22.1	17.8	17.3
	IV	4.6	6.1	7.1	7.7	7.8	6.3	4.4	3.8	2.9	2.9	2.8	2.7	2.7
	VIII	7.3	11.1	14.2	15.3	15.4	12.8	9.0	7.8	5.8	5.5	5.3	4.5	4.3
	IX	15.2	20.3	24.0	27.2	28.6	29.9	24.2	21.7	17.2	16.7	15.9	13.5	12.5
	XI	9.6	13.6	16.9	28.1	34.6	40.2	26.1	20.2	13.1	12.5	11.7	9.3	8.5

Table 47 Sign Group 2: Truck – Straight

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.0	2.5	2.9	3.4	3.8	4.6	3.7	3.3	2.7	2.6	2.5	2.0	1.8
	II	2.3	3.0	3.4	3.8	4.0	5.2	4.2	3.7	3.0	2.9	2.7	2.1	1.9
	III	12.7	15.8	17.5	18.3	21.2	22.3	23.0	24.0	18.7	17.6	16.7	13.8	13.5
	IV	3.1	4.1	4.6	5.1	5.3	5.5	4.3	3.8	3.0	2.9	2.7	2.2	2.1
	VIII	6.4	8.3	10.3	11.3	11.6	10.1	6.8	5.9	4.7	4.5	4.2	3.4	3.1
	IX	13.2	16.7	19.2	21.8	23.5	23.3	17.3	15.3	12.6	12.2	11.7	10.0	9.4
	XI	9.2	11.7	14.5	24.1	32.6	32.1	19.2	14.6	13.2	11.9	10.5	7.7	7.0

Table 48 Sign Group 2: Car – Curve to the Right, 11459-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.4	3.2	3.7	4.2	4.5	5.1	4.0	3.6	2.8	2.7	2.6	2.1	2.0
	II	3.2	4.3	4.8	5.3	5.5	5.3	4.0	3.5	2.7	2.6	2.4	2.2	2.1
	III	14.9	19.7	21.4	22.5	26.1	26.9	27.9	28.7	22.9	22.1	21.0	17.7	17.2
	IV	4.8	6.5	7.2	7.8	8.0	6.0	4.1	3.6	2.8	2.8	2.7	2.6	2.7
	VIII	8.7	13.0	14.5	15.4	15.5	12.3	8.5	7.5	6.1	6.0	5.8	5.3	5.0
	IX	16.2	22.2	25.2	28.4	29.8	29.1	23.2	21.0	17.0	16.5	15.7	13.3	12.5
	XI	11.0	17.7	25.8	36.0	39.4	43.0	31.4	27.2	18.2	16.5	14.6	10.2	9.3

Table 49 Sign Group 2: Truck – Curve to the Right, 11459-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.0	2.7	3.1	3.6	3.9	4.8	3.5	3.2	2.6	2.5	2.4	1.9	1.8
	II	2.4	3.1	3.5	3.9	4.1	5.3	4.2	3.7	3.0	2.8	2.6	2.0	1.9
	III	12.9	17.4	18.4	19.2	22.0	22.8	23.5	24.1	17.4	16.7	15.8	13.5	13.0
	IV	3.2	4.3	4.8	5.2	5.4	5.5	4.0	3.6	2.9	2.7	2.6	2.2	2.0
	VIII	6.6	9.7	10.5	11.4	11.8	9.9	6.4	5.6	4.5	4.3	4.1	3.4	3.1
	IX	13.5	18.3	20.2	22.7	23.9	23.4	16.5	14.7	12.3	11.8	11.3	9.8	9.3
	XI	9.3	15.3	21.9	30.2	33.2	36.2	23.5	20.3	13.6	12.2	10.8	7.6	7.0

Table 50 Sign Group 2: Car – Curve to the Right, 5730-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.5	3.3	3.7	4.3	4.6	5.0	3.9	3.4	2.8	2.6	2.5	2.1	1.9
	II	3.4	4.5	5.0	5.4	5.7	5.2	3.8	3.3	2.6	2.5	2.4	2.1	2.1
	III	15.3	20.2	22.2	22.9	26.8	27.6	28.9	27.9	22.3	21.3	19.9	17.4	16.7
	IV	5.1	6.8	7.4	7.9	8.1	5.7	3.9	3.3	2.8	2.7	2.7	2.6	2.6
	VIII	9.1	13.6	14.8	15.5	15.8	11.7	8.1	7.0	6.0	5.8	5.8	5.3	5.1
	IX	16.8	22.8	25.5	28.7	30.5	28.4	22.6	20.0	16.7	15.9	15.4	12.9	12.1
	XI	11.3	16.9	24.8	36.2	40.4	43.3	30.9	26.2	18.8	16.8	15.2	10.0	9.2

Table 51 Sign Group 2: Truck – Curve to the Right, 5730-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.1	2.8	3.2	3.7	4.0	2.3	3.5	3.1	2.5	2.4	2.3	1.9	1.7
	II	2.5	3.3	3.6	4.0	4.2	2.5	4.1	3.6	2.9	2.7	2.5	2.0	1.8
	III	13.5	17.7	19.0	19.7	22.5	23.2	24.3	23.0	17.0	16.0	15.1	13.1	12.6
	IV	3.5	4.5	4.9	5.3	5.6	5.3	3.9	3.4	2.8	2.6	2.5	2.1	2.0
	VIII	6.9	9.9	10.8	11.6	12.1	9.3	6.1	5.3	4.3	4.1	4.0	3.4	3.2
	IX	14.3	18.7	20.6	23.0	24.5	11.1	16.0	14.1	11.9	11.4	11.1	9.5	9.1
	XI	9.8	14.6	21.3	30.6	34.0	36.4	23.3	19.8	14.0	12.5	11.2	7.5	6.9

Table 52 Sign Group 2: Car – Curve to the Right, 2865-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.7	3.5	3.9	4.4	4.6	4.6	3.6	3.2	2.6	2.5	2.3	2.0	1.9
	II	3.9	4.8	5.3	5.7	5.6	4.8	3.5	3.1	2.5	2.4	2.3	2.1	2.1
	III	16.6	21.1	23.3	24.3	28.4	29.1	28.9	25.7	20.6	19.3	18.6	16.4	15.8
	IV	5.9	7.3	7.8	8.1	7.9	5.0	3.5	3.1	2.7	2.6	2.5	2.6	2.7
	VIII	9.9	14.1	15.5	15.9	15.3	10.3	7.2	6.4	5.8	5.6	5.5	5.4	5.3
	IX	18.8	23.8	26.6	29.6	29.8	26.4	20.8	18.6	15.7	14.9	14.2	12.4	11.8
	XI	12.2	16.5	23.0	36.0	39.3	39.8	29.8	25.1	19.5	17.6	15.8	10.6	9.2

Table 53 Sign Group 2: Truck – Curve to the Right, 2865-Feet

White Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.9	2.9	3.3	3.9	4.0	4.3	3.2	2.9	2.4	2.3	2.1	1.8	1.7
	II	2.9	3.5	3.8	4.2	4.3	4.9	3.8	3.4	2.7	2.5	2.4	1.9	1.8
	III	14.6	18.3	20.0	20.6	23.6	24.1	24.0	20.7	15.5	14.7	14.2	12.3	11.9
	IV	4.0	4.8	5.2	5.6	5.5	4.8	3.6	3.2	2.6	2.5	2.3	2.0	1.9
	VIII	7.5	10.3	11.4	12.1	11.8	8.0	5.5	4.9	4.0	3.9	3.7	3.4	3.3
	IX	15.7	19.4	21.5	23.9	23.9	19.9	14.5	13.1	11.2	10.8	10.2	9.2	8.8
	XI	10.6	14.0	19.8	31.0	33.1	32.6	22.2	19.1	14.4	13.1	11.6	7.8	6.8

Example 3: Sign Selection Calculations

Table 54 Sign Group 3: Car – Straight

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.4	2.6	2.8	3.2	3.4	3.5	3.8	3.7	3.1	3.0	2.9	2.5	2.4
	II	3.7	4.0	4.2	4.7	4.8	4.5	5.0	4.8	4.1	4.0	3.9	3.5	3.3
	III	13.0	14.5	15.5	16.0	19.4	20.1	20.8	24.0	26.0	25.0	25.0	21.0	20.4
	IV	6.4	6.8	7.2	8.0	8.2	7.7	8.3	7.9	6.7	6.4	6.3	5.6	5.4
	VIII	18.7	20.3	21.4	23.7	24.1	19.8	20.0	18.2	14.6	14.0	13.7	11.8	11.0
	IX	12.5	14.0	15.3	18.0	19.2	23.9	27.6	27.5	23.6	22.9	22.4	19.5	18.3
	XI	13.1	17.6	21.5	27.6	29.3	33.9	36.1	33.8	24.6	22.8	21.1	15.0	13.4

Table 55 Sign Group 3: Truck – Straight

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.2	2.3	2.5	2.9	3.1	3.1	3.4	3.3	2.8	2.7	2.6	2.3	2.1
	II	3.3	3.6	3.8	4.2	4.3	3.9	4.1	3.9	3.2	3.1	3.0	2.6	2.5
	III	12.0	13.4	14.5	15.0	18.0	18.8	19.6	20.9	23.0	22.7	22.6	19.5	18.8
	IV	5.4	5.9	6.2	6.9	7.1	6.1	6.3	6.1	4.9	4.7	4.6	3.9	3.7
	VIII	13.7	14.6	15.5	17.2	17.8	14.2	14.6	13.8	11.1	10.6	10.3	8.8	8.2
	IX	12.3	13.7	15.1	17.8	19.1	22.3	24.8	24.6	21.6	20.8	20.4	17.9	16.8
	XI	16.2	15.2	18.9	24.3	28.0	29.9	31.1	29.3	26.4	25.3	24.7	19.5	16.8

Table 56 Sign Group 3: Car – Curve to the Left, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.3	2.5	2.7	2.9	3.2	3.9	3.5	3.5	3.6	3.4	3.3	2.9	2.7
	II	3.5	3.7	4.0	4.2	4.5	5.1	4.6	4.6	4.7	4.5	4.4	3.9	3.7
	III	12.1	13.4	14.3	14.7	17.0	18.1	18.8	26.6	24.1	24.5	24.2	24.6	23.3
	IV	5.9	6.4	6.8	7.2	7.7	8.7	7.7	7.7	7.8	7.4	7.2	6.3	6.0
	VIII	17.8	19.4	20.7	21.9	23.3	23.5	19.5	19.0	17.9	16.7	16.0	13.7	12.7
	IX	11.6	12.9	14.0	15.7	17.1	25.2	24.5	25.3	27.1	25.9	25.1	22.2	20.8
	XI	19.1	21.7	24.1	27.6	30.7	39.1	33.9	33.9	33.3	30.9	28.8	21.1	17.7

Table 57 Sign Group 3: Truck– Curve to the Left, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.0	2.2	2.4	2.7	2.9	3.6	3.1	3.1	3.3	3.1	3.0	2.6	2.4
	II	3.1	3.3	3.5	3.8	4.0	4.5	3.8	3.8	3.9	3.7	3.5	3.1	2.8
	III	11.3	12.4	13.2	13.7	15.8	16.7	17.3	23.8	21.1	21.8	21.4	22.4	21.5
	IV	5.0	5.4	5.8	6.3	6.6	7.3	6.1	6.1	6.0	5.7	5.4	4.6	4.2
	VIII	12.7	13.8	14.8	15.9	16.8	17.3	14.1	14.0	13.6	12.9	12.2	10.4	9.4
	IX	11.4	12.7	13.8	15.7	17.1	24.6	22.6	23.0	24.4	23.6	22.7	19.9	18.5
	XI	16.3	18.5	20.7	24.4	27.4	35.6	29.8	29.6	29.1	27.2	25.2	18.4	15.3

Table 58 Sign Group 3: Car – Curve to the Right, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.6	2.8	3.2	3.5	3.6	3.6	3.5	3.2	2.8	2.7	2.7	2.4	2.3
	II	4.0	4.2	4.6	4.9	4.9	4.5	4.3	4.0	3.5	3.4	3.3	3.1	3.0
	III	14.3	16.3	18.0	18.8	22.1	22.5	23.2	24.9	24.0	23.2	22.1	19.5	19.0
	IV	6.8	7.2	7.9	8.4	8.4	7.7	7.3	6.7	5.9	5.8	5.6	5.1	5.0
	VIII	20.3	21.8	23.6	24.8	24.4	19.1	16.6	14.9	12.6	12.2	11.8	10.9	10.7
	IX	13.8	15.5	17.6	20.1	21.0	25.8	26.7	25.0	22.2	21.7	20.9	18.6	17.6
	XI	17.6	22.9	27.1	31.0	32.3	38.9	38.2	33.6	28.4	27.6	26.5	23.3	21.5

Table 59 Sign Group 3: Truck– Curve to the Right, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.3	2.6	2.9	3.3	3.3	2.3	3.2	2.9	2.5	2.4	2.3	2.1	2.0
	II	3.5	3.8	4.1	4.5	4.5	2.6	3.6	3.2	2.8	2.6	2.6	2.3	2.2
	III	13.2	15.3	16.8	17.6	20.9	21.1	21.7	22.0	22.0	21.2	20.3	17.8	17.3
	IV	5.8	6.3	6.8	7.4	7.4	6.0	5.6	5.0	4.3	4.1	3.9	3.5	3.4
	VIII	14.7	16.0	17.2	18.6	18.3	14.0	12.7	11.3	9.5	9.1	8.7	7.8	7.5
	IX	13.4	15.3	17.3	20.3	21.2	18.3	24.2	22.3	19.5	18.9	18.3	16.4	15.7
	XI	15.0	20.0	23.8	28.5	29.9	32.3	33.2	29.1	24.3	23.3	22.5	19.9	18.4

Example 4: Sign Selection Calculations

Table 60 Sign Group 4: Car – Straight

Yellow Sheeting														
		Offset												
Luminance (cd/m^2)	Type	-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.4	2.6	2.8	3.2	3.4	3.5	3.8	3.7	3.1	3.0	2.9	2.5	2.4
	II	3.7	4.0	4.2	4.7	4.8	4.5	5.0	4.8	4.1	4.0	3.9	3.5	3.3
	III	13.0	14.5	15.5	16.0	19.4	20.1	20.8	24.0	26.0	25.0	25.0	21.0	20.4
	IV	6.4	6.8	7.2	8.0	8.2	7.7	8.3	7.9	6.7	6.4	6.3	5.6	5.4
	VIII	18.7	20.3	21.4	23.7	24.1	19.8	20.0	18.2	14.6	14.0	13.7	11.8	11.0
	IX	12.5	14.0	15.3	18.0	19.2	23.9	27.6	27.5	23.6	22.9	22.4	19.5	18.3
	XI	13.1	17.6	21.5	27.6	29.3	33.9	36.1	33.8	24.6	22.8	21.1	15.0	13.4

Table 61 Sign Group 4: Truck – Straight

Yellow Sheeting														
		Offset												
Luminance (cd/m^2)	Type	-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.2	2.3	2.5	2.9	3.1	3.1	3.4	3.3	2.8	2.7	2.6	2.3	2.1
	II	3.3	3.6	3.8	4.2	4.3	3.9	4.1	3.9	3.2	3.1	3.0	2.6	2.5
	III	12.0	13.4	14.5	15.0	18.0	18.8	19.6	20.9	23.0	22.7	22.6	19.5	18.8
	IV	5.4	5.9	6.2	6.9	7.1	6.1	6.3	6.1	4.9	4.7	4.6	3.9	3.7
	VIII	13.7	14.6	15.5	17.2	17.8	14.2	14.6	13.8	11.1	10.6	10.3	8.8	8.2
	IX	12.3	13.7	15.1	17.8	19.1	22.3	24.8	24.6	21.6	20.8	20.4	17.9	16.8
	XI	16.2	15.2	18.9	24.3	28.0	29.9	31.1	29.3	26.4	25.3	24.7	19.5	16.8

Table 62 Sign Group 4: Car – Curve to the Left, 11459-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.3	2.6	2.8	3.1	3.3	3.7	3.6	3.8	3.4	3.2	3.1	2.7	2.5
	II	3.6	3.9	4.1	4.5	4.7	4.7	4.6	4.9	4.3	4.2	4.0	3.6	3.4
	III	12.4	14.1	14.9	15.4	18.4	19.3	20.2	25.3	24.4	25.4	25.9	22.9	22.0
	IV	6.0	6.6	6.9	7.7	8.0	8.0	7.7	8.2	7.2	6.9	6.6	5.9	5.6
	VIII	18.3	20.2	21.1	23.2	24.0	21.3	19.2	19.8	16.1	15.3	14.5	12.7	11.9
	IX	12.0	13.5	14.6	16.9	18.3	24.7	25.4	27.6	25.5	24.6	23.6	21.1	19.7
	XI	19.3	22.4	24.4	28.5	30.9	38.8	35.2	37.0	32.0	30.4	28.5	21.9	18.5

Table 63 Sign Group 4: Truck – Curve to the Left, 11459-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.1	2.3	2.5	2.8	3.0	3.3	3.2	3.4	3.1	2.9	2.8	2.4	2.3
	II	3.1	3.4	3.6	4.0	4.2	4.1	3.8	4.0	3.5	3.4	3.2	2.8	2.6
	III	11.5	13.0	13.9	14.4	17.0	17.7	18.4	22.2	21.5	22.3	23.0	21.0	20.1
	IV	5.2	5.7	6.0	6.6	6.9	6.5	6.1	6.3	5.4	5.2	4.9	4.2	3.9
	VIII	13.0	14.4	15.3	16.8	17.3	15.3	14.1	14.6	12.3	11.7	11.1	9.4	8.8
	IX	11.7	13.3	14.5	16.8	18.1	23.4	23.3	25.0	23.1	22.2	21.2	18.7	17.6
	XI	16.3	19.0	21.2	25.1	27.5	34.2	30.7	32.1	28.2	26.6	24.8	18.8	16.1

Table 64 Sign Group 4: Car – Curve to the Left, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.3	2.5	2.7	2.9	3.2	3.9	3.5	3.5	3.6	3.4	3.3	2.9	2.7
	II	3.5	3.7	4.0	4.2	4.5	5.1	4.6	4.6	4.7	4.5	4.4	3.9	3.7
	III	12.1	13.4	14.3	14.7	17.0	18.1	18.8	26.6	24.1	24.5	24.2	24.6	23.3
	IV	5.9	6.4	6.8	7.2	7.7	8.7	7.7	7.7	7.8	7.4	7.2	6.3	6.0
	VIII	17.8	19.4	20.7	21.9	23.3	23.5	19.5	19.0	17.9	16.7	16.0	13.7	12.7
	IX	11.6	12.9	14.0	15.7	17.1	25.2	24.5	25.3	27.1	25.9	25.1	22.2	20.8
	XI	19.1	21.7	24.1	27.6	30.7	39.1	33.9	33.9	33.3	30.9	28.8	21.1	17.7

Table 65 Sign Group 4: Truck – Curve to the Left, 5730-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.0	2.2	2.4	2.7	2.9	3.6	3.1	3.1	3.3	3.1	3.0	2.6	2.4
	II	3.1	3.3	3.5	3.8	4.0	4.5	3.8	3.8	3.9	3.7	3.5	3.1	2.8
	III	11.3	12.4	13.2	13.7	15.8	16.7	17.3	23.8	21.1	21.8	21.4	22.4	21.5
	IV	5.0	5.4	5.8	6.3	6.6	7.3	6.1	6.1	6.0	5.7	5.4	4.6	4.2
	VIII	12.7	13.8	14.8	15.9	16.8	17.3	14.1	14.0	13.6	12.9	12.2	10.4	9.4
	IX	11.4	12.7	13.8	15.7	17.1	24.6	22.6	23.0	24.4	23.6	22.7	19.9	18.5
	XI	16.3	18.5	20.7	24.4	27.4	35.6	29.8	29.6	29.1	27.2	25.2	18.4	15.3

Table 66 Sign Group 4: Car – Curve to the Left, 2865-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	2.0	2.3	2.5	2.8	2.9	4.0	3.6	3.4	3.6	3.7	3.6	3.2	2.9
	II	3.0	3.5	3.7	4.0	4.2	5.4	4.8	4.6	4.8	5.1	4.9	4.4	4.1
	III	10.9	12.5	12.9	13.4	15.3	15.8	16.4	27.1	24.8	24.3	23.6	24.4	25.5
	IV	5.2	6.0	6.3	6.8	7.1	9.2	8.1	7.7	8.0	8.4	8.1	7.2	6.6
	VIII	15.5	18.3	19.4	20.9	21.6	25.7	21.2	19.6	19.3	20.0	18.9	15.7	14.0
	IX	10.1	11.9	12.8	14.3	15.2	24.6	24.3	23.6	25.6	27.0	26.4	24.1	22.3
	XI	17.4	21.1	23.6	28.7	30.2	37.6	33.4	31.2	28.4	28.5	26.3	19.2	16.5

Table 67 Sign Group 4: Truck – Curve to the Left, 2865-Feet

Yellow Sheeting														
Luminance (cd/m^2)	Type	Offset												
		-50	-42	-36	-28	-24	4	14	18	26	28	30	38	42
	I	1.8	2.1	2.2	2.5	2.6	3.6	3.3	3.1	3.2	3.3	3.3	2.9	2.6
	II	2.7	3.1	3.3	3.6	3.7	4.8	4.2	3.9	4.0	4.1	4.1	3.6	3.3
	III	10.3	11.6	12.0	12.5	14.1	14.7	15.2	24.2	22.1	21.7	21.0	21.9	22.8
	IV	4.4	5.1	5.4	5.8	6.1	7.7	6.6	6.1	6.2	6.4	6.3	5.4	4.9
	VIII	11.1	12.9	13.7	14.9	15.6	18.7	15.5	14.2	14.2	14.6	14.3	12.0	10.7
	IX	10.1	11.7	12.7	14.2	15.2	24.1	23.0	22.0	23.3	24.3	24.1	21.9	20.2
	XI	15.2	18.1	20.3	25.5	26.9	34.2	30.1	27.6	24.7	24.5	23.1	16.9	14.6

VITA

Susan Christine Paulus

Education

B.S., Civil Engineering, University of Wisconsin - Milwaukee, May 2008.
M.S., Civil Engineering, Texas A&M University, May 2010.

Work Experience

Bloom Companies, LLC, January 2010 - Present
Texas Transportation Institute, August 2008 – December 2009.
Wisconsin Department of Transportation, June 2004 – August 2008.

Professional Affiliations and Societies

American Society of Civil Engineers
Institute of Transportation Engineers
National Association of Women in Constuction
Society of Women Engineers
Tau Beta Pi
Transportation Research Board

Contact Information

Bloom Companies, LLC
10501 W. Research Drive, Suite 100
Milwaukee, WI 53226

spaulus@bloomcos.com