NIGHTTIME DRIVER NEEDS:
AN ANALYSIS OF SIGN USAGE BASED ON LUMINANCE

A Thesis

by

JERREMY EUGENE CLARK

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 2007

Major Subject: Civil Engineering

NIGHTTIME DRIVER NEEDS:

AN ANALYSIS OF SIGN USAGE BASED ON LUMINANCE

A Thesis

by

JERREMY EUGENE CLARK

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,	David V. Rosowsky

May 2007

Major Subject: Civil Engineering

ABSTRACT

Nighttime Driver Needs:
An Analysis of Sign Usage Based on Luminance. (May 2007)
Jerremy Eugene Clark, B.S., Texas A&M University
Chair of Advisory Committee: Dr. H. Gene Hawkins, Jr.

The need to see traffic signs at night has led to the development of increasingly brighter retroreflective sign sheeting. The impact of this increased brightness has been shown to increase the legibility distance of the sign, but at what cost? With brighter signs being visible from farther away, there is an increased opportunity for the driver to look at the sign. This thesis assesses the impact of sign brightness on the nighttime driver's sign viewing behavior; such as the number of glances and the total glance duration directed at the sign.

Eye-tracking technology has been used to follow the nighttime driver's eye movements through tasks based on sign usage. The six signs used for the analysis are classified in three relative brightness categories of bright, medium, and dim on a closed course and on a public road. Data relating to the beginning and end of each glance were recorded as well as the distance at which the sign became legible to the driver.

Comparisons were made between the three brightness levels for the number of glances, total glance duration, and legibility distance of the sign. Further analysis was conducted to determine the effect of the testing environment on a driver's sign viewing behavior by comparing the results from the closed course with those from the open road.

The data for this thesis show varying results between the two courses with more defined differences based on luminance for the open road. The results of this thesis indicate that drivers do not consistently change the number of times they look at a sign or the amount of time dedicated to a sign based on its brightness. During real world driving scenarios, the brightest sign resulted in the longest legibility distance and the lowest total glance duration, indicating an increased efficiency reading the sign by the driver. Typically, a sign with a longer total glance duration had a shorter legibility distance. Comparisons between the closed and open courses revealed that open road driving resulted in a longer total glance duration and a shorter legibility distance.

DEDICATION

I dedicate this thesis and my education to my parents. Through your sacrifice, you have shown me the importance of having a solid foundation to build my life on. You have given me every opportunity to succeed and I will take every opportunity I have to show you my gratitude. I love you both very much. Thank you for everything.

ACKNOWLEDGMENTS

I would like to thank Dr. Paul Carlson for providing the means with which to conduct this research. His energy and excitement in this field are inspiring to someone new on the scene, and he has led me to a deeper understanding of the importance of transportation engineering. I would also like to thank Dillon Funkhouser for the manpower essential to complete the data collection for this thesis. There were several other researchers at the Texas Transportation Institute involved in this project, including Dr. Susan Chrysler and Jeff Miles, whose expertise and experience shed light onto many aspects of luminance and human factors research.

I want to personally acknowledge the dedication and patience of Nichole Leonard. Nichole has allowed me to explore many areas outside of school and has taught me as much about life as this thesis has about engineering. Also, her uncle Dr. Kevin Lunsford has proven to be both a valuable tool in the completion of my education and a great guy.

Finally, I would like to thank the members of my thesis committee. My committee chair, Dr. Gene Hawkins, has taught me many lessons beyond the writing process to prepare me for my career. Dr. Yunlong Zhang, Dr. Rodger Koppa, and Dr. Paul Carlson have been available for questions, concerns, and feedback throughout the progress of this research.

TABLE OF CONTENTS

Page

ABSTRACT ... iii

DEDICATION ... v

ACKNOWLEDGMENTS ... vi

TABLE OF CONTENTS ... vii

LIST OF TABLES ... x

LIST OF FIGURES ... xii

INTRODUCTION ... 1

- Nighttime Driving ... 2
- Driver Needs ... 4
- Eye-Tracking ... 6
- Problem Statement ... 7
- Objectives ... 8

BACKGROUND ... 11

- Retroreflectivity ... 12
- Light Transformation ... 14
- Sheeting Classification ... 17
- Sign Luminance and Legibility ... 19
    - Lab Studies ... 20
    - Field Studies ... 24
- Eye-tracking ... 28
    - Eye-Tracking Technology ... 29
    - Eye-Tracking Research ... 34

EXPERIMENTAL DESIGN ... 43

- Courses ... 43
    - Runway Course ... 43
    - Silver Hill Course ... 47
- Test Subjects ... 49

Page
Equipment 52
Data Collection 54
Calibration 60
Runway Course 63
Silver Hill Course 64
DATA ANALYSIS 65
Data Reduction 67
Data Analysis 69
Graphical Analysis 70
Descriptive Statistics 73
Hypothesis Testing 76
Closed Course versus Open Road Testing 88
Driver Glance Characteristics 93
Individual Glance Luminance 98
RESULTS 102
Driver Performance 102
Research Findings 103
Primary Measures 103
Closed Course versus Open Road 108
CONCLUSIONS AND RECOMMENDATIONS 110
Sign Luminance 111
Test Facility 111
Author Interpretation 112
Limitations of the Research 113
Recommendations 114
REFERENCES 116
APPENDIX A EXPERIMENTAL SCRIPT 122
APPENDIX B GRAPHS 128

Page

APPENDIX C DATA 140
VITA 161

LIST OF TABLES

Page
Table 1. Retroreflectivity Measurement Angles 19
Table 2. Sign Properties 46
Table 3. Subject Information 50
Table 4. Sample Data from Eye-Tracking Equipment 68
Table 5. Descriptive Statistics 75
Table 6. Effect of Sign Brightness on Legibility Distance 76
Table 7. Values for Paired *t*-Test 78
Table 8. Total Number of Glances: Closed Course 79
Table 9. Total Number of Glances Statistics 81
Table 10. Total Glance Duration Statistics 84
Table 11. Legibility Distance Statistics 87
Table 12. Last and Maximum Look Summary Statistics 94
Table 13. Last Looks versus Total Durations 95
Table 14. Maximum Looks versus Total Durations 97
Table 15. Summary of Analysis 104
Table 16. Means of Sign Viewing Characteristics 105
Table 17. Total Number of Glances 140
Table 18. Total Number of Glances Comparisons 141
Table 19. Total Glance Duration 144
Table 20. Total Glance Duration Comparisons 145
Table 21. Legibility Distance 148
Table 22. Legibility Distance Comparisons 149
Table 23. Reduction in Legibility Distance Caused by Decrease in Luminance 152
Table 24. Last Look Duration Ratios 153
Table 25. Last Look Duration Ratio Comparisons 154
Table 26. Maximum Look Duration Ratios 157

Page

Table 27. Maximum Look Duration Ratio Comparisons 158

LIST OF FIGURES

Page

Figure 1. Three Region Look Model 5
Figure 2. Three Types of Reflection 13
Figure 3. Retroreflectivity Angles 15
Figure 4. Entrance and Observation Angles 18
Figure 5. Richards Results 22
Figure 6. Forbes Color Combinations 25
Figure 7. Carlson and Hawkins Findings 26
Figure 8. Pupil Contrast Produced by Infrared Light 29
Figure 9. Head Mounted Eye-Tracking Systems 30
Figure 10. Remote Eye-Tracking System 32
Figure 11. EyeFrame™ Components 33
Figure 12. Rockwell Equipment and 7-Region Viewing Analysis 35
Figure 13. ASL 4000 Eye-Scanning Helmet Used by Zwahlen 37
Figure 14. Test Sign 38
Figure 15. Luminance for Rural and Suburban Viewing Conditions 39
Figure 16. Diem Eye Movements 41
Figure 17. Runway Course 44
Figure 18. Example of Sign along Runway Course 45
Figure 19. Experiment Signs 46
Figure 20. Example of Test Sign on Silver Hill Road 47
Figure 21. Silver Hill Course 48
Figure 22. Eye-Tracking Limitations 51
Figure 23. Test Subject 51
Figure 24. Data Collection System 53
Figure 25. Photometer Placement 56
Figure 26. Luminance Measurements 56
Figure 27. Speed Limit Luminance Curves 58

Page
Figure 28. Speed Limit Signs 58
Figure 29. Test Sign Luminance Curves 59
Figure 30. Silver Hill Test Signs 59
Figure 31. Calibration Grid-Day and Night 61
Figure 32. Calibration Grid-Installation 61
Figure 33. Calibration-Before (left) and After (right) 62
Figure 34. Typical Glance (left to right) 66
Figure 35. Fixation (left to right) 66
Figure 36. Data Extracted from Video 66
Figure 37. Variability in Location of Projected Gaze 69
Figure 38. Glance Plots by Sign 71
Figure 39. Glance Plots by Subject 72
Figure 40. Mean Total Number of Glances 82
Figure 41. Means of Total Glance Durations 86
Figure 42. Mean Legibility Distances 88
Figure 43. Lab versus Field Testing 91
Figure 44. Glance Duration versus Luminance-Dim Sign 99
Figure 45. Glance Duration versus Luminance-Medium Sign 99
Figure 46. Glance Duration versus Luminance-Bright Sign 100
Figure 47. Glance Duration versus Luminance-Three Signs 100
Figure 48. Legibility Distance and Luminance 107
Figure 49. Glance Plots by Sign 128
Figure 50. Glance Plots by Subject 132

INTRODUCTION

Taking on the night has forever been a precarious endeavor, especially in the transportation arena. Simple tasks such as reading a book or taking a walk become more difficult when the sun goes down. Imagine doing both at the same time in the dark. That is essentially what a nighttime driver does. Reading the signs along a highway would be virtually impossible without the advent of headlights or reflective material. Early retroreflective sign sheeting provided a limited amount of light to the driver. As the technology progressed, however, increasingly brighter signs have become the norm. This thesis is aimed at analyzing how the brightness of retroreflective traffic sign sheeting affects the nighttime driver. By optimizing the brightness of traffic signing to maximize the legibility, it is possible to simplify the driving task at night and consequently conquer the darkness.

Driving is a derived task, which means that most motorists travel to accomplish a separate objective such as commuting to work or going to the grocery store. Seldom do drivers drive without a goal. This nature of driving follows a hierarchy with three levels of performance: control, guidance, and navigation (*1*). As a driver progresses up this pyramid of responsibilities, information handling complexity increases. At the lower levels of control and guidance, the driver's main activities include interacting with the vehicle and maintaining the speed and path of that vehicle on the roadway. The information presented at these two levels is acquired by the driver's surroundings, including the vehicle and the highway system and its appurtenances. Regulatory speed limit signs, curve warning signs, and many other traffic control devices aid in these arenas.

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

Navigating a roadway requires the most information processing. Whereas the levels of control and guidance accomplish the movement of the vehicle, navigation leads the driver to his destination thereby completing his objective. Navigating consists of gathering information from directions or route guidance signs and using that information to reach a destination. As much as 90% of all information processed is gathered and received visually (*1*), thus emphasizing the importance of traffic signs in the driving process.

NIGHTTIME DRIVING

Traffic signs become even more important during nighttime driving. At night, the surrounding environmental features visible during daylight are lost in the shroud of darkness. As a result, nighttime drivers are more dependent on pavement markings and warning, regulatory, and guide signs for control, guidance, and navigation—all three levels of the driving task. The importance of signs at night has led to the development of products and procedures to aid the nighttime driver. Whether laying out a path using reflective pavement markings or guiding the driver with reflective traffic signs, these techniques have focused on harnessing the optical characteristics of reflective material to return light to the driver. Various types of sign sheeting have been developed to transform the light received from the headlights into light visible to the driver. There are four stages of light transformation for the nighttime driver: luminous intensity, illuminance, retroreflectivity, and luminance.

Luminous intensity is the amount of light emitted from a source, such as a vehicle headlight. *Illuminance* is the light received by the viewing surface (sign). Light dissipates with distance and therefore illuminance is dependent on the distance between the vehicle and the sign. *Retroreflectivity* is the ratio of light reflected back to the light source and is dependent on both the sign sheeting and the viewing angles between the light source (headlight), the viewing surface (sign), and the receptor (driver). *Luminance* is the amount light emitted from the viewing surface and is commonly referred to as the brightness of a sign; it is what the driver sees.

The evolution of sign sheeting has led to the American Society of Testing and Materials (ASTM) classification system that is now based on the order of production rather than the performance of the sign. Currently, sheeting is classified as Type I, II, III, IV, VII, VIII, IX, or X. When the first classification was published in 1989 the sheeting types were ranked numerically based on their performance. Type I and Type II denote the lower grades of beaded sheeting referred to as engineer grade and super engineer grade and Types III and IV are the beaded and microprismatic versions of high intensity sheeting and are brighter than Types I and II. Types V and VI represent retroreflective materials not used for rigid traffic signing. Since the introduction of the standard in 1989, the newly developed sign sheeting material has been added in chronological order without regard to its performance relative to the other sheeting types. As a result, the overall classification system does not indicate relative performance. For example, although Type IX sheeting would presumably be better than Type VII sheeting, it is less bright at longer distances but is better for short sight distances.

The ASTM classification system is a purchasing specification that defines the minimum performance for retroreflective sign sheeting based on the coefficient of retroreflection (R_A). The coefficient of retroreflection defines how much light is returned to the recipient in the form of luminance and is measured at specific viewing geometries. A classification system based on sheeting geometries does not account for the performance of the sign as seen by the driver. By evaluating sign sheeting based on what the driver actually sees, luminance, the specification process could be reversed. A specification based on the driver would establish a required luminance which could be transformed into characteristics measurable on the sign itself (R_A). This approach will require an analysis of how drivers look at signs.

DRIVER NEEDS

An alternative strategy for improving retroreflective sign sheeting performance is to use driver needs to develop a performance specification for sign materials based on nighttime driving. The effect of sign brightness on its visibility is without question: as an object gets brighter it becomes more conspicuous and can be detected from farther away. This longer distance gives the driver more time to view the sign. The increased viewing time may allow the driver to decipher parts of the sign such as the color and shape as he approaches thereby reducing or eliminating the time needed to read the sign when it becomes legible.

Using advanced eye-tracking technology, researchers are able to determine where a driver looks during the driving process. Earlier research has been conducted which has used this technology to assign multi-look models to generalize a driver's sign viewing behavior. The data presented by this thesis suggest an alternative method for analyzing driver viewing behavior that accounts for color recognition, shape recognition, and sign legibility.

Whereas previous "look models" have assigned specific numbers to the glances made to a sign, this thesis suggests that a sign attracts several regions of glances on each approach. As shown in Figure 1, this proposed model provides a relationship between the visibility characteristics of the sign, the visual capabilities of the driver, and the viewing behavior of the driver. The proposed model assumes that traffic signs follow similar trends of visibility as a driver moves toward them. As a driver travels, he or she systematically searches for features on the road ahead. Once a sign becomes visible, often referred to as conspicuity, the driver is able to detect that sign and begin trying to identify the type of sign, such as whether it is a guide sign or a route marker. Being able to identify the type of sign allows the driver to assess the importance of the sign for his or her driving task.

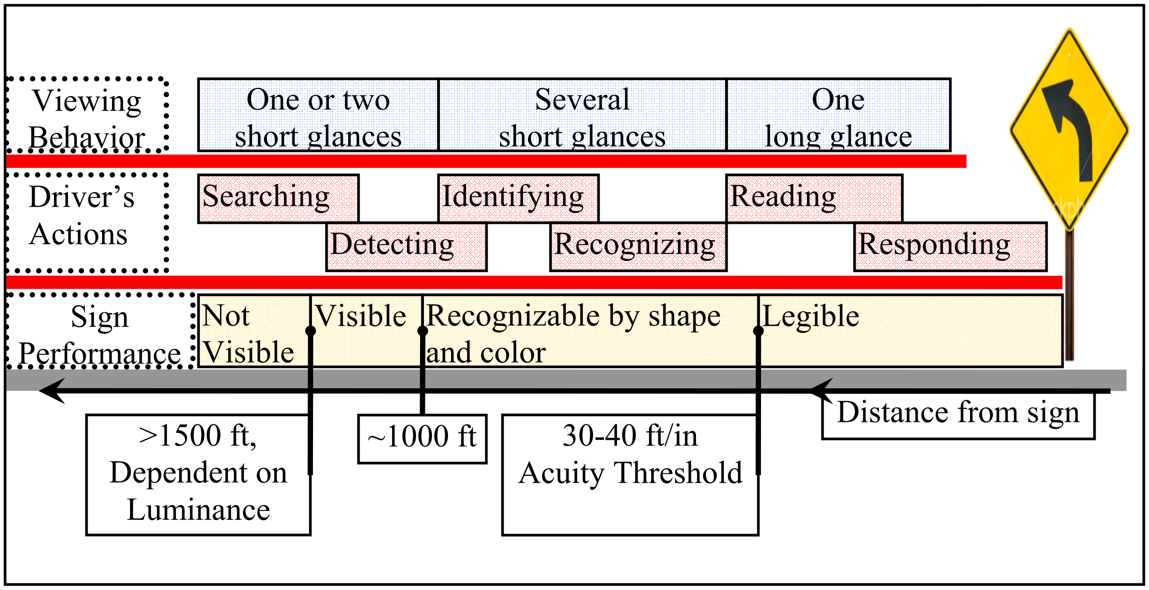


Figure 1. Three Region Look Model

Once the driver has established the importance of the sign, he or she will continue to check back to it with short glances until the sign provides another bit of information. Such information could consist of the number or length of the words on the sign. Many drivers are somewhat familiar with the roads on which they travel and are able to recognize an important sign before it becomes legible. As the driver continues to approach the sign, it is expected that the duration of the glances made to the sign will gradually increase. Once the legend becomes legible, the driver will typically devote a relatively long glance to the sign to read it. Once read, the driver is able to respond to the message. Typically the looks to the sign end after the driver has responded.

The proposed model in Figure 1 contains many generalized relationships between the driver's actions and the sign properties. The emphasis of this model is the depiction of how the driver views the sign during each of these regions. Shown at the bottom of the figure are estimates of key distances related to this model and this thesis. A commonly accepted legibility index is used as the threshold at which drivers will be able to read the sign. If a sign with 10 inch lettering is recognizable from 1,000 feet and it becomes legible from 400 feet, then there is a 600 foot distance within which the driver may look at the sign before it becomes legible. Also, depending on the size and luminance of the sign, its conspicuity could easily exceed the 1,500 feet listed in the figure giving even more time to view the sign before it becomes legible.

The two look regions in the figure after the sign becomes recognizable represent the approach zone of the sign referred to in this thesis. The approach zone is the area stretching from after the sign is recognizable to the distance where the sign becomes legible to the driver. This region is dependent on the capabilities of each driver and is expected to be centered around the commonly accepted acuity threshold of 40 ft/in. A deeper understanding of how drivers look at signs could provide insight to improve the design of sign sheeting. This thesis will evaluate how drivers acquire information from signs in the approach zone as a function of the sign's brightness.

EYE-TRACKING

Eye-tracking systems (also referred to as eye-scanning) have typically been used to evaluate the effectiveness of limited displays such as web-page layout. Eye-tracking systems trace the gaze of subjects by following the pupil as it focuses. By flooding the eye with infrared light, the pupil appears as a black hole within a lightened view of the iris. This image is captured by infrared cameras for processing by special software that uses the contrast of the pupil against the iris to locate it and project its point of gaze. To effectively map the driver's gaze, a calibration process is essential to orient the software with each subject. That point of gaze is then overlaid onto the forward facing scene as captured by another camera, which allows researchers to see where subjects are looking.

This research will push the limits of eye-tracking technology by requiring long distance looks, allowing free movement of the subject's head, and presenting moving targets in the form of approaching signs. Most eye-tracking systems are designed for both static subjects and targets. For this research, however, neither the subjects nor the targets will remain still. Subjects will be free to move their head and body just as they would during normal driving tasks. The “target” signs, although geographically static, will be moving across the subject’s field of view as the vehicle approaches them.

As eye-tracking technology has evolved, so has the quality of results obtained by associated research. This thesis will both build upon previous eye-tracking research and venture into new arenas. Much effort has been dedicated to analyzing how drivers look at existing signs and retroreflective sign sheeting. This research has used some of the methods employed by previous studies and their findings to develop an experiment capable of producing results that may be used to design new and more effective signs and sign sheeting based on what the nighttime driver needs.

PROBLEM STATEMENT

The effect of sign brightness on visibility and legibility has been studied and found to improve both. Its effect on the driver’s viewing characteristics, however, has received limited attention. This thesis will determine how sign brightness affects how a driver uses the sign to obtain information. Several possibilities are available to describe the effect of sign brightness on driver viewing characteristics. Brighter signs could either decrease or increase the total viewing time of the sign. Dimmer signs could have a similar affect. Another measure of the sign’s effect on driver usage is the number of looks within the approach zone; varying sign brightness may increase or decrease the total number of looks. Also of interest is how the increased or decreased viewing time affects the legibility distance of the sign. If the driver can see the sign further away and spends more time looking at the sign, does that affect the distance at which the driver reads the sign? This thesis will compare the performance as measured by these criteria for signs of varying brightness in a nighttime setting.

OBJECTIVES

The purpose of the parent Texas Transportation Institute (TTI) project is to quantify the nighttime driver's needs of retroreflective road signs as a function of their luminance. Ultimately, the TTI research is intended to develop a performance based sheeting specification based on nighttime driver's needs rather than current material based specifications given in ASTM D4956 (*2*). This thesis will provide a baseline from which to begin luminance research.

The results of this thesis will be based on two primary objectives: how often and how long subjects look at signs and how those looks correlate with the brightness level of the sign. The findings will be reached in the following steps:

1. Determine the luminance profiles of target signs.
2. Analyze the driver viewing behavior of target signs including the legibility distances and individual glances to the targets signs captured by the eye-tracking video.
3. Determine the total duration of glances made to the sign within the approach zone for each subject as the sum of the duration of each glance made to a sign.
4. Count the total number of glances made to the sign within the approach zone for each subject.
5. Using the known brightness levels of the signs, compare the look characteristics to sign luminance by answering questions such as the four below:
    a. Do drivers look more often at bright signs?
    b. Do drivers look more often at dim signs?
    c. Do drivers look longer at bright signs?
    d. Do drivers look longer at dim signs?
6. Establish the effect a sign's brightness level has on the legibility distance of the sign.

In order to accomplish these objectives, three basic hypotheses will be tested. The first null hypothesis (H_0) states that the mean number of glances (G) for the bright signs and the dim signs are the same; the alternative hypothesis (H_A) is dependent on the relationship between the two brightness levels. For a positive difference ($\mu_{G,B} - \mu_{G,D}$) the H_A states that the mean number of glances for the bright signs is greater than that for the dim signs, meaning the driver looks more often at brighter signs. Alternatively, for a negative difference, the test would be run to determine if the mean number of glances for the dim signs were greater than that for the bright signs. The medium brightness signs will also be compared with both the bright and dim signs. The null and alternative hypotheses for the positive differences are given below. The negative difference would be tested by: $\mu_{G,B} - \mu_{G,D} < 0$.

$H_{0,G}$: $\mu_{G,B} - \mu_{G,D} = 0$	$H_{0,G}$: $\mu_{G,B} - \mu_{G,M} = 0$	$H_{0,G}$: $\mu_{G,M} - \mu_{G,D} = 0$
$H_{A,G}$: $\mu_{G,B} - \mu_{G,D} > 0$	$H_{A,G}$: $\mu_{G,B} - \mu_{G,M} > 0$	$H_{A,G}$: $\mu_{G,M} - \mu_{G,D} > 0$

The second set of null hypotheses state that the total glance duration (D) within the approach zone for the bright , medium, and the dim signs are the same; the alternative hypotheses state that the mean glance duration for the brighter signs is either greater than or less than that for the dimmer ones depending on the sign of the difference between the signs, meaning the driver spends more or less time fixated on the brighter signs.

$H_{0,D}$: $\mu_{D,B} - \mu_{D,D} = 0$	$H_{0,D}$: $\mu_{D,B} - \mu_{D,M} = 0$	$H_{0,D}$: $\mu_{D,M} - \mu_{D,D} = 0$
$H_{A,D}$: $\mu_{D,B} - \mu_{D,D} > 0$	$H_{A,D}$: $\mu_{D,B} - \mu_{D,M} > 0$	$H_{A,D}$: $\mu_{D,M} - \mu_{D,D} > 0$

The final null hypotheses state that the mean legibility distances (*L*) for the bright, medium, and dim signs are the same whereas the alternative hypotheses state that the legibility distance of the brighter sign is greater than or less than that of the dim sign.

$H_{0,L}$: $\mu_{L,B} - \mu_{L,D} = 0$ $H_{0,L}$: $\mu_{L,B} - \mu_{L,M} = 0$ $H_{0,L}$: $\mu_{L,M} - \mu_{L,D} = 0$

$H_{A,L}$: $\mu_{L,B} - \mu_{L,D} > 0$ $H_{A,L}$: $\mu_{L,B} - \mu_{L,M} > 0$ $H_{A,L}$: $\mu_{L,M} - \mu_{L,D} > 0$

The dynamic nature of this research has incorporated human subjects in on-road driving situations. In order to minimize the variability of driving situations the author needed to standardize which signs the subjects encountered. As such, a 4-mile closed course was established at the Riverside Campus of Texas A&M University, a former U.S. Air Force Base. In addition to the closed course, the subjects navigated an open-road course near the Riverside Campus, which included additional test signs. The addition of an open-road portion of data collection was essential to compare data collected on the closed course with natural driving techniques on public roads.

The creation of test courses allowed the researcher to control the signs presented based on their luminance and legend. The three test signs on the closed course exhibit three distinct luminance profiles as do the three signs on the open road. The resulting luminance profiles accommodated their parsing into the three relative categories of bright, medium, and dim.

BACKGROUND

The topics addressed by this thesis, including sign luminance, sign legibility, and eye-tracking, have been the focus of many research endeavors. Each of these areas of transportation research addresses a variety of issues and methods critical to driver safety, highway safety, and transportation operations. These methods and their results have been reviewed to inform the reader and to increase the effectiveness of the experimental design for this thesis.

A great deal of prior research in the field of sign performance has revolved around two different yet related qualities: luminance and legibility. The luminance of a sign is a quantitative value describing the brightness of the sign. Luminance is the product of four stages of light transformation. A sign's legibility, on the other hand, quantifies how readable the sign is. Legibility varies with driver acuity, sign luminance, legend format, message content, and other factors and is a popular measure of effectiveness for evaluating sign luminance. The focus of this thesis is where these two qualities come together.

The following pages exhibit how previous research has analyzed the influence of luminance and legibility on the performance of traffic signs. The impact of laboratory studies versus field studies is also weighed with respect to the aforementioned characteristics. Finally, an exploration of the history of eye-tracking technology and associated research is included to provide a platform from which to base this research. First, however, a background of reflective properties is provided to give the reader a better understanding of the principles behind retroreflective sheeting.

RETROREFLECTIVITY

The nighttime driver is able to illuminate his surroundings by the headlights of his vehicle. This allows the driver to distinguish the presence of objects along the roadway. Traffic signs, however, require more than to be detected. To be effective, traffic signs must be read, understood, and responded to, which requires the light from the headlamps be returned to the driver. All surfaces reflect light in some manner. In order to maximize their visibility, the faces of traffic signs have been manufactured with an engineered retroreflective material to utilize the light provided by the vehicles headlamps.

To reflect light is to change its direction and/or composition. As shown in Figure 2, light can be redirected in three ways: diffuse reflection, retroreflection, and specular reflection. Diffuse reflection spreads the light across the surface of the receiver. When external illumination is used, such as a flood light, the viewing surface must spread the light so the entire sign is visible to the driver; diffuse reflection is used here. An example of specular reflection is a mirror, which bounces incoming light at an equal but opposite angle. Specular reflection only returns the light to the source when the surface is perpendicular to the source. Retroreflective signs are able to better utilize the light available to make signs brighter at night by directing the light back to its source.

Retroreflective signing began with using hemispherical glass reflectors, called cats eyes, to form the words of a legend. The reflection of light from these cats eyes effectively lit up the legend of traffic signs but left the background invisible to the nighttime driver. Eventually round retroreflective disks called buttons were used to form the legend. The next step in retroreflective technology was beaded sheeting. Initially, tiny glass beads were dropped onto a freshly painted surface. These beads adhered to the paint and reflected the light from the headlamps. Next, the tiny beads were fabricated on an adhesive surface to be installed on a sign face. Exposed lens sheeting, as it was called, was rough to the touch, much like sandpaper. Finally, the glass beads were impregnated into a membrane used to make a sign face, this method was referred to as enclosed lens sheeting. These beads were engineered to reflect light back to, or retroreflect, the nighttime driver. The early types of beaded sheeting are referred to as 'Engineering Grade' sheeting. Further development led to the grouping of the beads within the sheeting. This resulted in a higher performance product referred to as 'High Intensity'. The next step by the sheeting industry broke from the mold of beaded sheeting to develop prismatic sheeting. This technology used tiny prismatic reflective surfaces within the membrane to provide a more directional light pattern for the driver. Since the advent of microprismatic sheeting, the focus has been on manipulating the prisms to optimize the performance of the product.

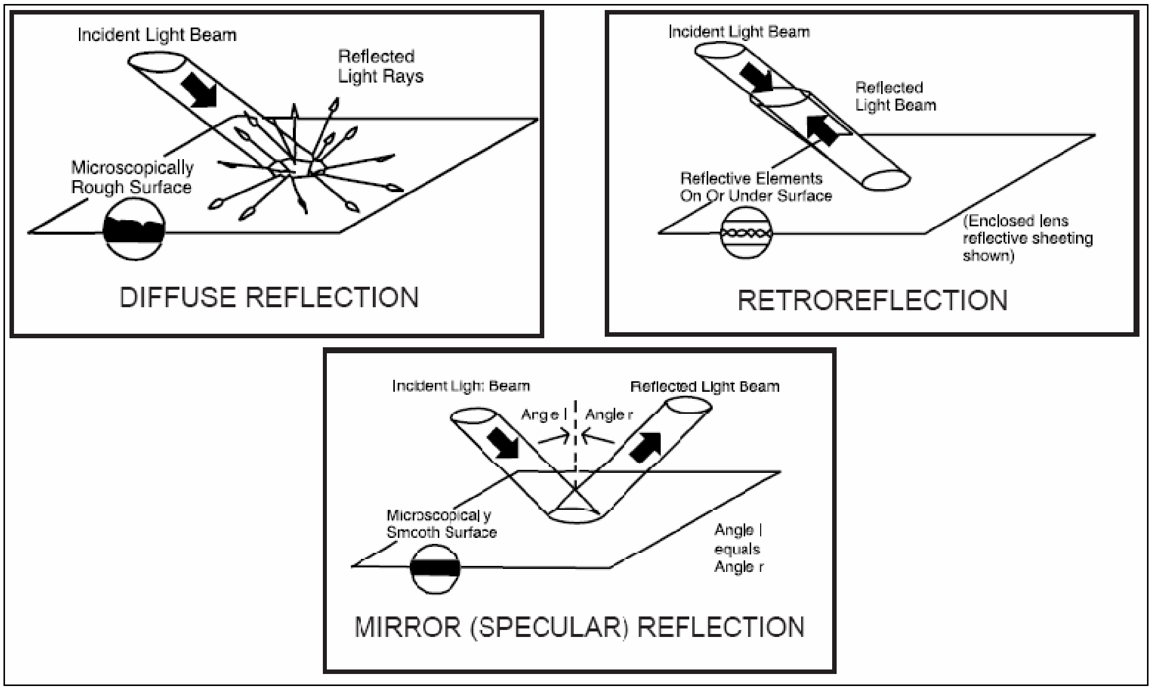


Figure 2. Three Types of Reflection (*3*)

The light produced by vehicle headlamps has changed with time, as well. The current trend is to minimize the amount of light above the horizontal and focus the light on the right side of the road, which reduces the amount of glare directed at opposing traffic. This redirecting of the light from the vehicle tends to decrease the amount of light that reaches traffic signs, which are typically above the level of the headlamps. Retroreflectance is a key feature of traffic signs that harnesses this light and returns it to the nighttime driver.

LIGHT TRANSFORMATION

The process through which the light from vehicle headlamps is transformed into light visible by the driver takes is accomplished in four steps. The four stages four stages of light transformation for the nighttime driver are:

1. Luminous Intensity
2. Illuminance
3. Retroreflectance
4. Luminance

During hours of daylight, the sun provides sufficient illumination for drivers to see traffic signs. During nighttime conditions, however, vehicle headlights or some other external illumination source such as floodlights are necessary. For self- or sun-illuminated signs, the light provided allows the driver to see the message presented. The majority of traffic signs, however, are dependent on vehicle headlights for illumination at night. *Luminous intensity* (*I*) is the amount of light emitted from a source, such as a vehicle headlight, measured in candelas (*cd*). *Illuminance* (*E*) is the light received by the viewing surface (sign) with units of lumens per meter squared which is also referred to as lux ($lm/m^2=lx$). Light dissipates with distance and is inversely proportional to the squared distance from the source, similar to gravity (Equation 1). The illuminance received by the sign is calculated for each headlight and is dependent on the relative position of the vehicle and the sign.

$$E = {}^{I}\!\!\diagup_{D^2} \qquad \textbf{Equation 1}$$

Retroreflectivity is the measure of how much light is reflected toward the light source and is dependent on both the sign sheeting being evaluated and the viewing angles between the light source (headlight), the viewing surface (sign), and the receptor (driver). The coefficient of retroreflection (R_A) is used to calculate how much of the light absorbed (illuminance) is returned (luminance).

The coefficient of retroreflection is dependent on the geometry of the viewing situation. The four angles used to determine the R_A value are the observation angle (α), the entrance angle (β), the rotation angle (ε), and the orientation angle (ω) (see Figure 3). The *observation angle* is that between the light source, the reflective surface (sign), and the receptor (driver). The *entrance angle* is the angle between the light source and the axis perpendicular to the viewing surface. The *rotation* angle is defined relative to the observation plane between the light source, the viewing surface, and the receptor (driver). The *orientation* angle is measured relative to the illumination plane, which is formed between the light source, the axis perpendicular to the viewing surface. Each of these angles can be shown to change with distance from the sign.

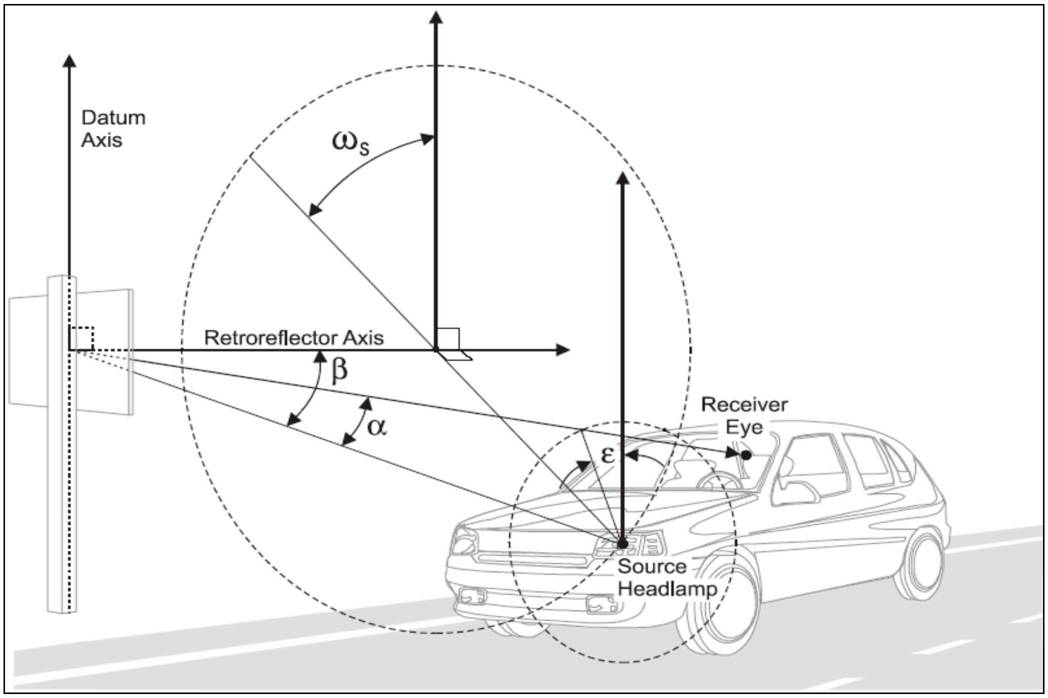


Figure 3. Retroreflectivity Angles

Observation (α), Entrance (β), Rotation (ε), Orientation (ω)

Luminance (L) is commonly referred to as the brightness of a sign; it is what the driver actually sees. Luminance can be calculated as a function of the illuminance (E), the coefficient of retroreflection (R_A) for each of the headlights, and the viewing angle (ν) as shown in Equation 2. The viewing angle is the angle between the receptor and the plane perpendicular to the viewing surface.

$$L = \left(R_{A,left} \times E_{\perp,left} + R_{A,right} \times E_{\perp,right}\right) \Big/ \cos(\nu) \qquad \textbf{Equation 2}$$

Another property of a traffic sign that can be derived from luminance is contrast. Contrast is a measure of the difference between the luminance of the legend and the luminance of the background of the sign as given by Schnell, et al. (*4*) in Equation 3. Signs are commonly referred to as either positive or negative contrast. Positive contrast signs refer to those with a light letter on a dark background, such as green Guide signs with white legends. When the luminance of the legend is greater than that of the background, the result of Equation 3 is positive. Negative contrast signs, on the other hand, include signs with bright backgrounds and dim or non-retroreflective legends such as Speed Limit signs.

$$\frac{L_{legend} - L_{background}}{L_{background}} \qquad \textbf{Equation 3}$$

SHEETING CLASSIFICATION

Retroreflectivity has become the primary method for categorizing sign sheeting by the American Society of Testing and Materials (ASTM). Currently, sheeting is classified as Type I, II, III, IV, VII, VIII, IX, or X. While the initial rankings were based on sheeting performance, the current trend has led to a classification system based on the order of production rather than how drivers use them or what drivers need. As a new sheeting product is developed with unique retroreflectivity characteristics, it is typically given its own designation. This classification method has led to an ascending numerical ranking that is not based on the performance of the sheeting. For example, recall that Type IX sheeting has been shown to be outperformed by Type VII sheeting at longer distances but is brighter at short distances.

The characteristics used to classify sign sheeting are the coefficients of retroreflection at certain viewing angles given by the entrance and observation angles (see Figure 4). The ASTM sign sheeting specifications are based on a combination of two entrance angles (-4°, 30°) and four observation angles (0.1°, 0.2°, 0.5°, 1.0°). The two most commonly used observation angles for measuring retroreflectivity are 0.2° and 0.5°. The other angles (0.1° and 1.0°) have been added to emphasize the performance of specific sheeting types. The 0.1° angle correlates with a very long viewing distance whereas the larger observation angle of 1.0° relates to a shorter viewing distance. The use of these angles is not entirely representative of real-world viewing characteristics.

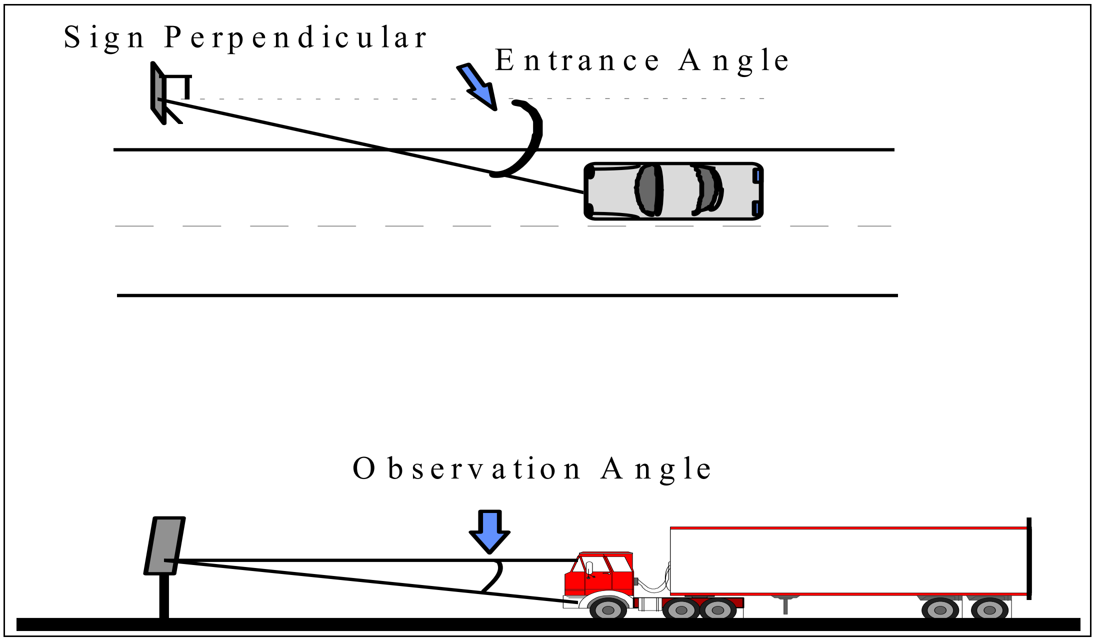


Figure 4. Entrance and Observation Angles

As an example, consider the viewing geometry evaluated for an entrance angle (β) of -4° and the two observation angles (α) of 0.2° and 0.5°. Assuming a sign offset of 12 feet from the edge of the lane to the edge of the sign and a sign height of 7 feet from the road surface to the bottom of the sign, Table 1 provides the observation and entrance angles. These values were calculated using a program produced by Avery Dennison called *ERGO* (Exact Road Geometry Output) (*5*). This program uses the vehicle headlamps and such measurements as driver eye height, headlamp height, etc specific to each vehicle to determine the geometry of the viewing situation as a driver approaches a sign. The vehicle measurements used to compile Table 1were gathered from a previous research project by TTI that measured several different types of vehicles.

As shown in Table 1, for a standard lateral offset and sign height, the values of the entrance and observation angles don't match up to the measurement angles at any distance. Neither the measurement geometry of (-4°, 0.5°) nor (-4°, 0.2°) occur at any distance along the approach to the sign. Further, these measurements only account for one point in space rather than the entire viewing interval used by the driver, which leads to the conclusion by Bible and Johnson that "*no single measurement geometry fully characterizes retroreflective material performance*" (*6*).

Table 1. Retroreflectivity Measurement Angles

Dist.	Left		Right		Average Observation Angle (α)	Average Entrance Angle (β)
	α	β	α	β		
100	1.579	12.755	1.286	10.731	1.433	11.743
200	0.635	6.458	0.778	5.413	0.706	5.935
282	0.416	4.590	0.585	3.840	0.500	4.215
298	0.391	4.360	0.559	3.650	0.475	4.000
300	0.386	4.315	0.555	3.615	0.471	3.965
400	0.276	3.239	0.430	2.712	0.353	2.976
500	0.214	2.592	0.351	2.171	0.283	2.381
600	0.175	2.161	0.297	1.809	0.236	1.985
700	0.148	1.852	0.257	1.551	0.202	1.701
702	0.147	1.850	0.256	1.550	0.200	1.700
800	0.128	1.621	0.226	1.357	0.177	1.489
900	0.112	1.441	0.202	1.206	0.157	1.324

The fact that classifying sign sheeting based on only the combinations of the two observation angles and four entrance angles is not entirely representative of real-world characteristics has led some researchers to use luminance rather than retroreflectivity to evaluate traffic signs. Because luminance is what the driver actually sees, it "*provides a means to match materials to roadway situations and driver needs* (*7*)".

SIGN LUMINANCE AND LEGIBILITY

Without the luminance provided by modern traffic control devices, highways and byways would be more difficult to travel. At night, retroreflective pavement markings and raised pavement markers (RPM) inform drivers of their position in the desired lane of travel. In addition, retroreflective sign sheeting alerts motorists to changes in speed, direction, and other roadway conditions. Further, route markers ranging from roadside mileage markers to freeway guide signs guide the way to a driver's destination. The Manual on Uniform Traffic Control Devices (MUTCD) requires that:

> *Regulatory, warning, and guide signs shall be retroreflective or illuminated to show the same shape and similar color by both day and night, unless specifically stated otherwise in the text discussion in this Manual of a particular sign or group of signs.(8)*

Several studies have looked at the impact of retroreflectivity and luminance on nighttime visibility with some focused on providing minimum values of retroreflectivity.

One of the earliest tests of retroreflective materials was conducted by Mill in a 1933 study that compared non-retroreflective signs with early retroreflective signs (*9*). Using retroreflective "buttons" was an early method for improving the nighttime visibility of traffic signs by placing circular reflectors in the legend of a sign. Without any retroreflective materials, the signs could not be seen at night from greater than 200 feet away. The addition of the reflectors, however, extended the nighttime visibility distance to beyond 500 feet.

As retroreflective materials evolved, so did the research conducted to analyze them and sign research began to diverge on to two paths: studies conducted in the field and studies conducted in a laboratory. Each of these alternatives exhibited their own strengths and weaknesses. Lab studies could test many aspects of traffic signs in any simulated environment desired. Field studies, on the other hand, were perceived as more realistic and therefore more representative of real-world sign performance.

Lab Studies

Early laboratory-based research was conducted using practices similar to a common eye exam. In 1977, Richards used a static vision testing method by seating subjects 20 feet from an eye chart (*10*). The chart was constructed of a rotating disk with letters printed on it to be seen through a slice taken out of the panel in the front of the disk. The letters decreased in size toward the center of the disk corresponding with increasing visual acuity levels. Four luminance levels were presented by supplying light from a projector calibrated to simulate a vehicle headlamp and filtering that light to 10, 1, 0.1, and 0.01 foot-lamberts (0.03 to 34 cd/m^2). Results were averaged for each decade of age collected (26-35, 36-45, etc). Richards found not only that acuity decreases with age, but also that the acuities at each luminance value followed similar curves as shown in Figure 5. The lines in the figure correspond to the age range of the subject. This finding could be used to provide for critical values of test letter contrast independent of age or acuity.

In 1995, Mercier, et al. modified Richards' approach by conducting a study using a projection system with signs on a rotating display device (*11*). There were five signs on the device that presented one at a time to the subject. Subjects viewed the scaled signs from two positions, 102 feet and 83 feet, corresponding to distances relating to visibility indices for 55 and 30 miles per hour, respectively. At these positions, the luminance of the display provided by a rear projector was incrementally adjusted until subjects were able to identify the messages.

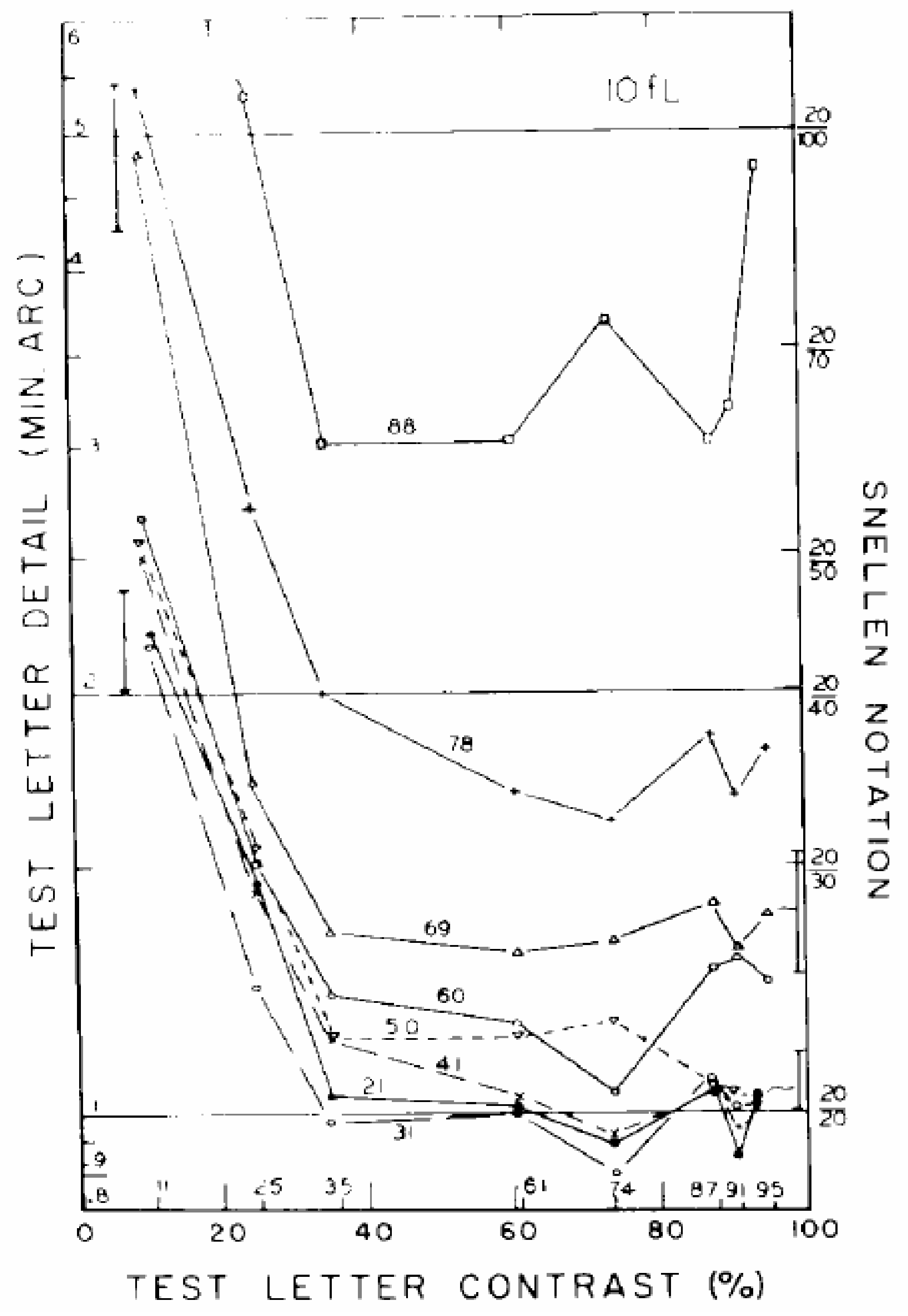


Figure 5. Richards Results (*10*)

Lines represent age groups, acuity increases with luminance contrast.

In 2004, Schnell, et al. further built upon this method of using projectors and screens (*12*). Schnell, et al. presented subjects with an image of a two-inch symbolic sign 64 feet away. To accomplish this, a mirror was set up to reflect the image from a high resolution projector onto a screen. The background of the scene was presented in a lower resolution to provide sufficient contrast between the sign and the scene. Luminance was measured by a color charge-coupled device (CCD) from the front of the screen. Subjects then walked toward the screen until the symbol was identifiable. This setup provided an efficient means for collecting data and adjusting the luminance of the image. Schnell, et al. found that the projector and mirror combination was a cheap, easy, and reliable method for adjusting the luminance of any sign presented. Further, the high resolution of the projector demonstrated that overglow was not a consequence for negative contrast signs for luminance levels up to 942 cd/m^2. Results from the 40 subjects who each completed 120 viewings of varying scenery conditions lead to the conclusion that 82 cd/m^2 was the maximum background luminance beyond which no improvement was witnessed.

Although Schnell's experiment accomplished its goal of effectively decoupling sign luminance requirements from specific sheeting materials and headlamps, the conditions of the procedure did not simulate real world driving conditions. Following the *Positive Guidance* approach, the dynamic task of driving involves more than walking in a darkened room. In fact, these subjects were permitted to pause at any time or distance to look at the sign. As such, values obtained from this and similar subsequent studies were considered as absolute minimum values.

While it is intuitive that lab studies would not produce identical results as those conducted in the field, it is often unclear just how different the findings could be. In 1979, Olsen and Bernstein conducted a two-tiered experiment to define the effects of luminance, contrast, color, and driver visual characteristics on sign legibility distance (*13*). The first phase was conducted using methods later employed by Mercier et al. and

Schnell et al. inside a laboratory using projectors to vary the luminance of legends. The second phase took place on a closed course at a private airport designed to simulate a freeway setting. With legibility distance as the measure of effectiveness, Olsen and Bernstein found that the 90th percentile laboratory data equated well with the mean field performance. This quantification of the difference between laboratory and field studies has driven many to take their research in to the real world.

Field Studies

There is an obvious benefit to research accomplished in a lab setting: control. The ability to control all aspects of the experiment is attractive to the researcher. Cost is also typically reduced by lab studies. Field studies, however, open up many possibilities for the type of research conducted. Running full scale experiments with near limitless space allows the researcher to study many aspects of traffic signing that labs cannot accommodate.

In 1976, Forbes analyzed many aspects including glance legibility and the effect of color combinations on the legibility of traffic signs (*14*). Forbes found that for lower luminance situations (low beam headlights) in the field, the resulting legibility distances were longer than any measurements in the lab, regardless of luminance. In addition, by limiting the observation time of subjects in the lab, Forbes found that situations requiring shorter glances the subject were accommodated by higher luminance signs. Another aspect of Forbes' study dealt with the color combination of traffic signs, a topic often overlooked by researchers. Forbes found that the interaction between the background and legend has a substantial impact on the legibility of the sign, regardless of the luminance. The signs used for the analysis in this thesis are all black on white signs which exhibit the longest legibility distances as shown in Figure 6.

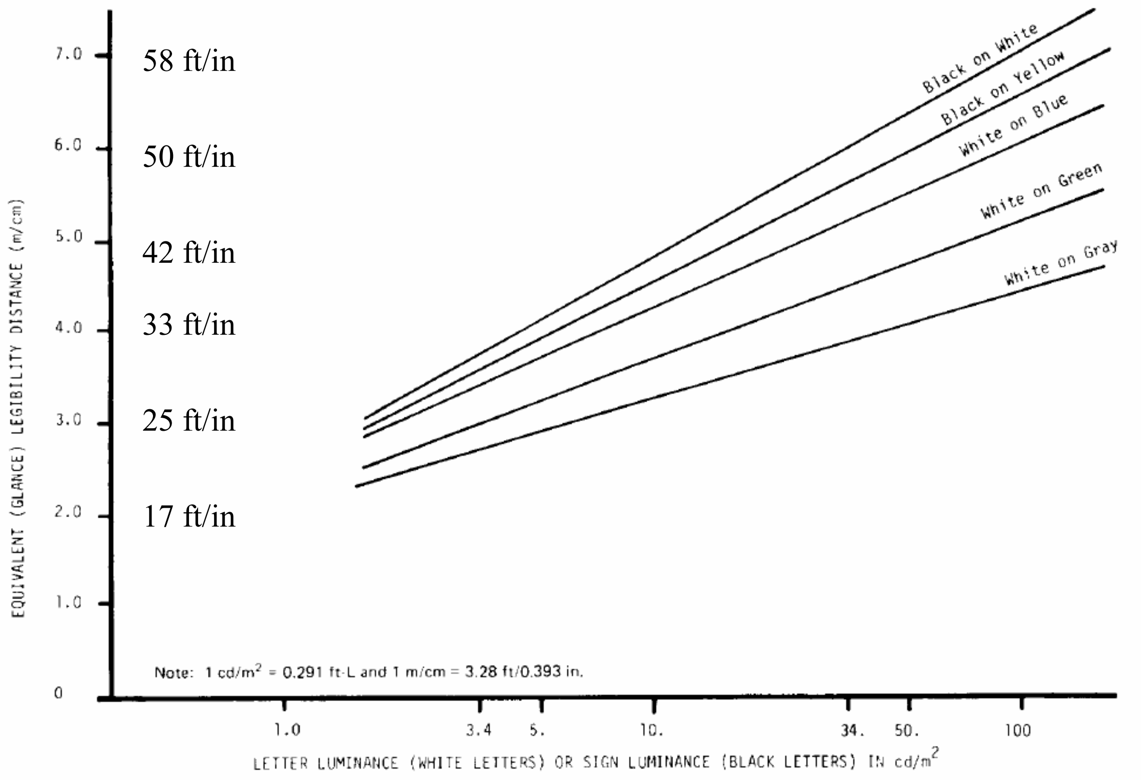


Figure 6. Forbes Color Combinations (*14*)

Black on white signs exhibit the highest legibility index.

Another factor relating to sign color was studied by Padmos in 2000. He found that the color recognition of a sign took place a much longer distance than that required for legibility (*15*). Padmos concluded that the standardization of colors used for highway signs allowed drivers to recognize those colors at lower luminance levels, which results in a longer recognition distance when higher luminance levels are required for legibility.

Padmos defined the lower limit of luminance as "*the lowest luminance that turns it sufficiently conspicuous for detection as such, and sufficiently legible in order to be identified at a safe distance*" (*15*). In 2001, Carlson and Hawkins completed a project aimed at identifying the minimum required luminance through minimum retroreflectivity requirements (*16*). The proposed minimum retroreflectivities were based on results obtained by a field study conducted at the same facility used for this thesis. Carlson and Hawkins used overhead signs with six letter common words and street name signs along with the driver's response to determine the legibility distance of the sign. The luminance was changed by varying the luminous intensity of the headlamp in the test vehicle through 32 settings. The results presented in Figure 7 illustrate the effect of increased luminance the percentage of correct responses for identifying street name signs. The three lines represent legibility indices according to the three positions used to read the signs.

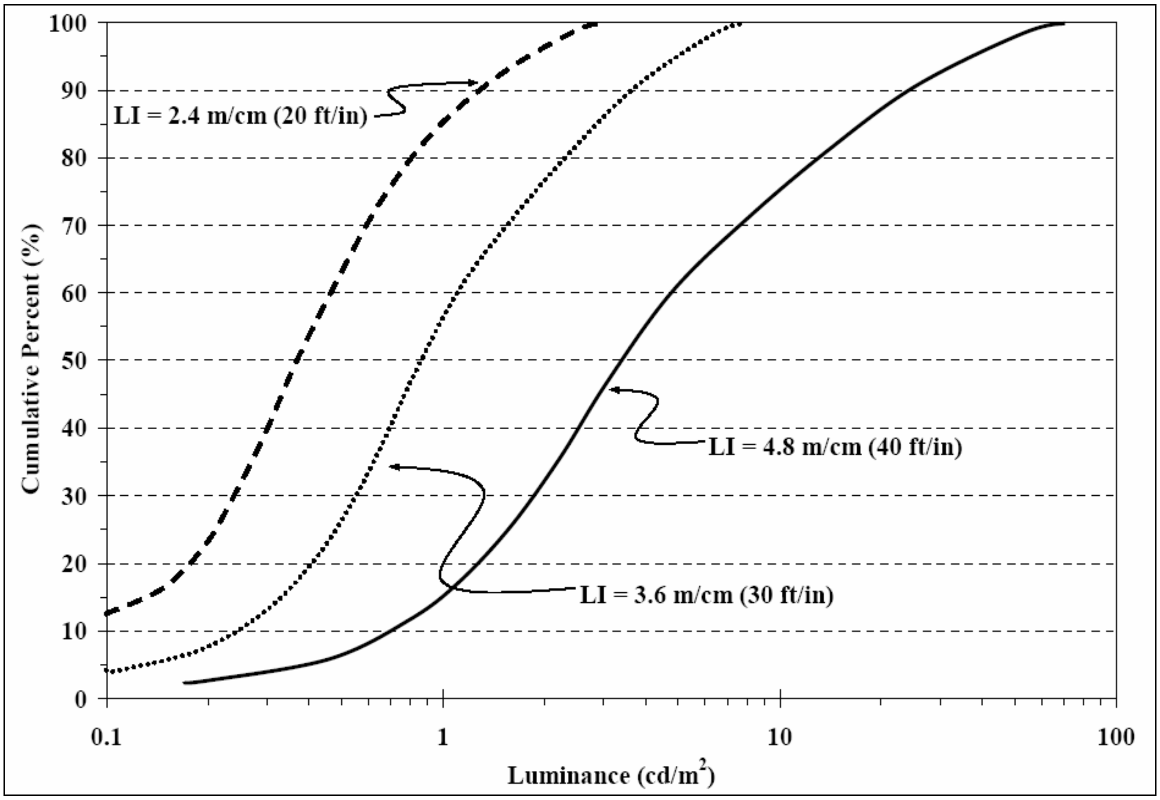


Figure 7. Carlson and Hawkins Findings (*16*)

Minimum luminance for street name signs.

Another influence of nighttime driver performance that is often overlooked is the effect of other drivers. Sivak and Olsen included this aspect in their 1982 report detailing the effect of disability glare on the legibility of traffic signs (*17*). Disability glare refers to the light from opposing vehicle headlamps. As more light enters the eye, the pupil contracts to regulate that light. While adjusting to this increased light level, the driver must still be able to read signs along the roadway. Sivak and Olsen found that glare only reduced the legibility distance of signs at small angles; whereas at larger angles of 0.6 and 1.5 the detrimental effect of the glare was countered by the performance of the eye. Sivak and Olsen concluded that larger glare angles may produce a "glare enhancement" effect on the performance of the driver and the human eye.

A brief explanation of the abilities of the human eye is necessary to better understand this phenomenon. The human eye is able to adapt its performance based on the amount of light present. The iris acts as a shutter that regulates how much light enters the eye. Past the iris is the retina. The retina contains two types of light sensitive cells called rods and cones. Cones are concentrated around the fovea (the area used for focusing) and rods are in the periphery. Aside from their position, these two types of cells accomplish different tasks: rods are specialized for low luminance vision whereas cones deal with color and detail. During daylight, the iris remains contracted allowing only enough light to stimulate cones, which explains the ability to see colors better during the day. The lower level of light available at night, however, places more dependence on the rods, which react slower than the cones. Objects at a higher luminance are readily detected as they stimulate the fovea (*18*).

Regardless of the goal of the variety of experiments conducted, a common measure of effectiveness is still the visibility or legibility of the sign. There are two methods commonly used to determine when signs become visible or legible in the field: driver response and eye tracking. The driver response method refers to the driver indicating when he or she can read a sign, most often by reciting the legend. This is traditionally the most common technique used to determine the visibility or legibility distance of a sign. Whereas the data collected with the driver response method is dependent on the driver to follow the experimental protocol, eye-tracking doesn't rely on the subject to collect data. Eye-tracking systems are used not only verify a driver's response with a glance to the sign but to monitor their behavior for previous glances as well. These two data collection methods are complimentary to each other. The eye-tracker captures looks to a sign that aren't necessarily used to read the sign. As such, the legibility of a sign cannot be determined using eye-tracking technology alone. The driver response method is essential to determine when the driver actually reads the sign. By using advanced technology to follow where the subject is looking, eye-tracking studies allow researchers to investigate many other aspects of driver behavior in addition to legibility.

EYE-TRACKING

Eye-scanning studies have been used for many years to evaluate where subjects look to improve the design and performance of many displays. In these studies, an eye-tracker is used to follow a subject's point of gaze as he or she views an image or scene. Most contemporary eye-trackers use a combination of infrared light and cameras to manipulate the eyes such that they can be easily followed. Typically, infrared lights are used to illuminate the subject's eye. This light reflects against the iris but not the open space of the pupil. The result is a very dark pupil within a "washed out", or very light, iris as shown in Figure 8. Infrared cameras use this contrast to follow the pupil as it moves across the visual range of the subject while another camera captures that visual range as the forward scene. A calibration process maps this movement of the pupil in x- and y-coordinates onto the forward scene. The calibration is essential to ensure the accuracy of eye-tracking movements. Typically stated in degrees, the accuracy is the closeness of the tracked point of gaze to the subject's actual point of gaze.

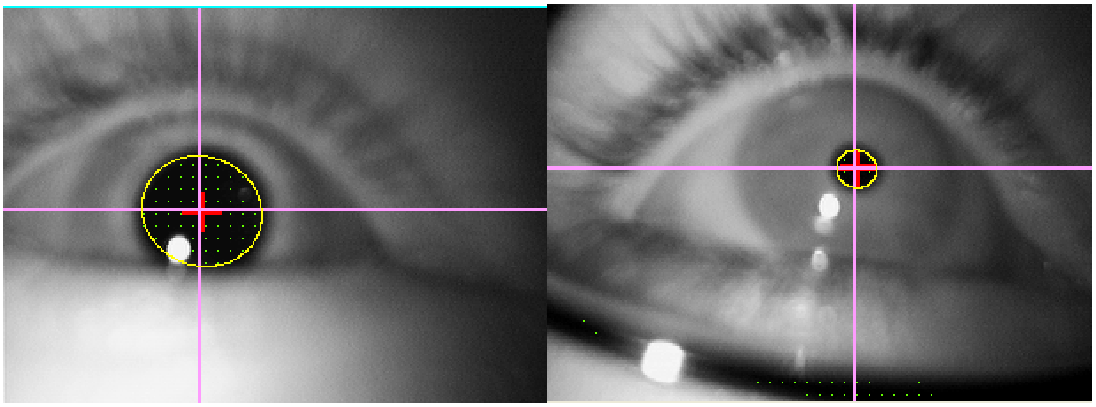


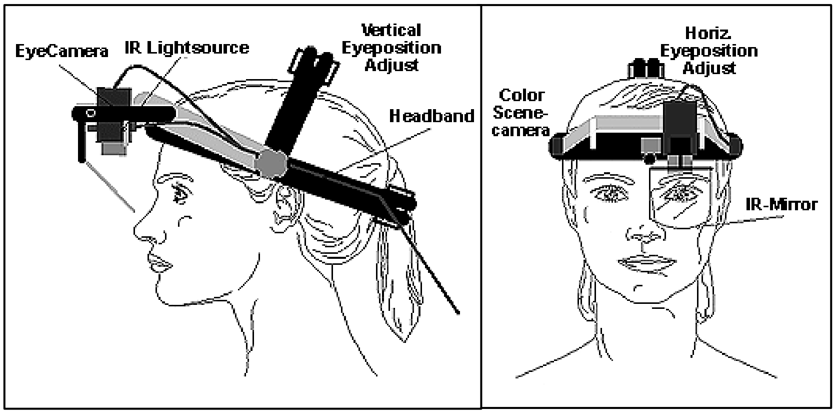
Figure 8. Pupil Contrast Produced by Infrared Light

Eye-Tracking Technology

A common use of eye-trackers in industry is in the development and design of effective web pages. This application presents a static display and evaluates how subjects look at the display; such as which feature draws more attention. Other functions of eye-trackers include evaluating other advertising media, human visual research, military systems, and transportation research. The wide variety of services provided by eye-trackers has led to the development of several different types of eye-tracking systems. Head mounted, remote, and muscular systems have all been used to map eye movement.

Head Mounted Systems

Early eye-tracking systems used equipment mounted on the subject's head to collect their data. Several apparatuses have been designed to support the lights, cameras, cables, and power supply necessary to operate the systems as shown in Figure 9. Systems used in laboratory settings often employ adjustable head-straps to accommodate the equipment. However, head straps alone sacrifice rigidity for ease of transference and lighter weight. More rigid applications involve the use of helmets on which to mount the system. These systems often clamp down onto the subject's head with chin straps to reduce the movement of the cameras relative to the subject. Also, mounting the cameras on the stiffer substrate of the helmet rather than the flexible strap eliminates the movement of each camera. Another method used to suppress movement is the use of a "bite bar" or chin rest which serves to keep the subject's head from moving. These types of setups are ideal for lab settings as opposed to real-world settings due to their imposing nature. The cumbersome equipment attached to the subject's head can be distracting, thereby reducing its effectiveness for studies requiring "naturalistic" responses, such as the transportation research included in this thesis. The benefit of head mounted systems, however, is their accuracy. In a survey conducted among the human factors profession, it was determined that most head mounted systems experience an in-use accuracy of 1°-2°. As related to this research, the ability to distinguish 1° correlates to a driver's lateral glance of 7 feet from 400 feet away.



http://www.mpi.nl/world/tg/eye-tracking/eye-tracking.html

http://www.a-s-l.com/ http://www.eyelinkinfo.com http://www.arringtonresearch.com

Figure 9. Head Mounted Eye-Tracking Systems (*19, 20, 21, 22*)

Remote Systems

Remote eye-tracking systems, on the other hand, sacrifice versatility for accuracy. Although most system manufacturers boast an accuracy of 1°, most users surveyed experienced an accuracy of 2°-6°. This correlates to the ability to distinguish a lateral glance of 14 to 42 feet at 400 feet. The reduced accuracy is largely due to the distance from the cameras to the eyes and the angle between the cameras and the eyes. For in-car studies (see Figure 10), one or two eye cameras are mounted in the dash of the vehicle (two dashed circles) and trained on the head of the driver while a forward facing camera (solid oval) captures the scene through the windshield. For highest accuracy, the eye cameras should be on a level plane with the eye; but vehicle dashboards are much lower than that plane and raising the cameras above the dashboard would affect a driver's field of vision.

In addition to the reduced accuracy, these systems often lose sight of the eye, which greatly reduces the amount of reliable data collected. Natural driving tendencies require the subjects to move their heads, which often takes them out of the range of the cameras. Remote systems are designed to recapture the subject's gaze but the change in the position of the eye affects calibration.

Remote systems excel by eliminating interaction with subjects. Other than the knowledge of the presence of an eye-tracking system and undergoing a calibration procedure, drivers are not limited in movement, restricted in sight, or weighed down with equipment. This makes remote systems ideal for transportation studies. In transportation research it is important for subjects to perform naturally rather than skew the results such as those shown by experiments in lab settings as opposed to field settings. However, the requirements of this research call for a much greater accuracy than either remote systems or even traditional head mounted systems can produce. As a result, another innovative eye-tracking design has been sought out for this research.

Figure 10. Remote Eye-Tracking System (*23*)

The EyeFrame and MobileEYE

The research presented in this thesis has been conducted using the *ViewPoint EyeTracker*® with *EyeFrame*™ hardware by Arrington Research, Inc. The *EyeFrame*™ is essentially a modified pair of safety goggles design to support miniature lights and cameras as shown in Figure 11. The *EyeFrame*™ works like other head mounted systems by using the contrast between the pupil and the iris provided by the infrared light. Two cameras follow the pupil while a third camera, positioned at the bridge of the glasses, captures the forward scene. The difference between this system and other head mounted systems is the lightweight equipment. First, by mounting all three cameras on one rigid frame, the geometry between the cameras stays constant for each subject. This rigid geometry, in addition to the proximity of the cameras to the eyes (2-3 inches), is able to capture smaller movements in the eyes than do most other systems; resulting in resolution as low as 0.25° (lateral glance of 2 feet at 400 feet). Also, the *EyeFrame*™ fits just like a pair of glasses, which most subjects are familiar with, as opposed to a head strap or helmet. The cameras mounted on the *EyeFrame*™ are less imposing than other systems due to their position below the line of sight and the concealment of the wires down the nose of the subject. Finally, with the addition of a power supply, this system is entirely mobile, which releases the reliance on laboratory studies for accurate eye-tracking results. There is a similar eye-tracking system called the Mobile Eye that is available from Applied Science Laboratories with slightly different capabilities.

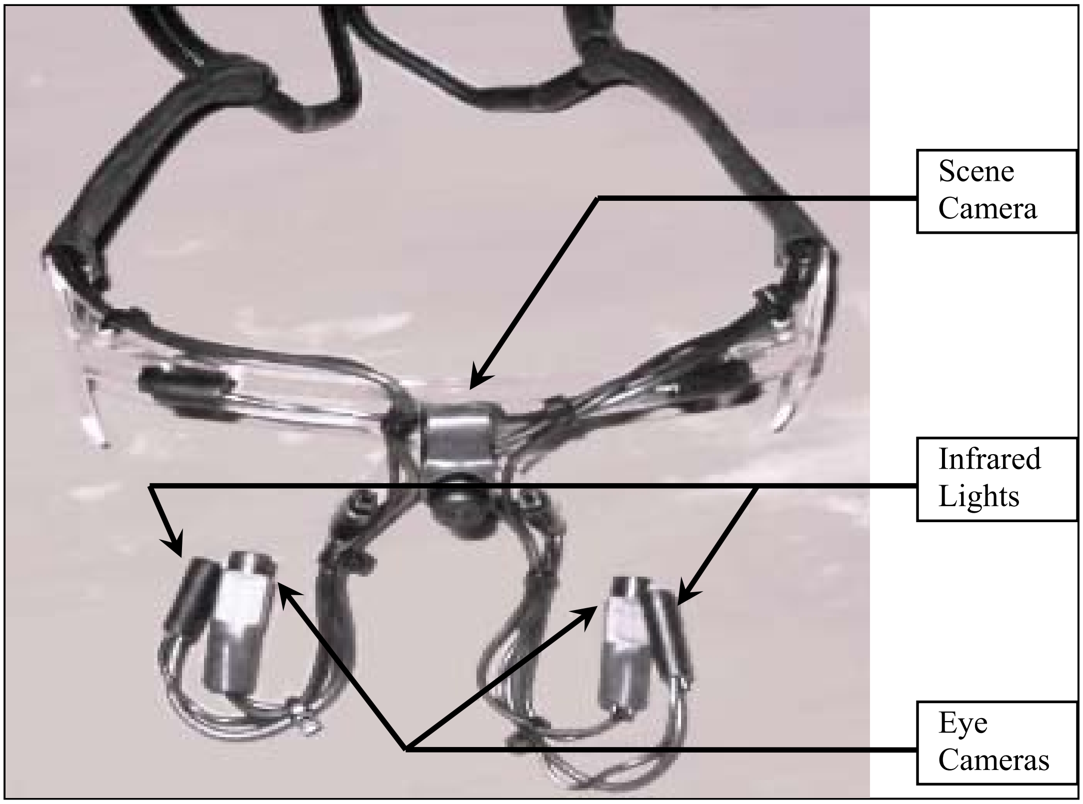


Figure 11. EyeFrame™ Components

Another method used to track eye movements has been through the muscular system surrounding the eye called Electro-Oculography (EOG) (*24*). By monitoring the muscles around the eye socket with three to four electrodes and undergoing a similar calibration procedure, the point of gaze may be determined. The wide variety of equipment, methods, and applications of eye-trackers has led to their widespread use in many arenas. Within the transportation field, research began as early as the 1960s with Rockwell, et al.

Eye-Tracking Research

Some of the earliest research by Rockwell, et al. (*25*) in 1968 assembled a head mounted system comprised of lights, cameras, and fiber optic cables as shown in Figure 12. Although once considered state-of-the-art, the camera was limited to a 20° field of view and the cables lost 80% of the light captured. Further, the sheer size of the unit attached to the subject's head was daunting. Despite this, Rockwell, et al. was able to extrude useful results from their study and achieve an accuracy of less than 0.5°. By dividing the forward viewing area into seven regions as shown in Figure 12, Rockwell et al. established that drivers looked at the road differently at night than during the day. Nighttime drivers tended to concentrate more on the road 0 to 75 feet in front of the vehicle than daytime drivers.

Further study by Mourant and Rockwell (*26*) in 1970 revealed that as drivers become more familiar with a route, their eyes become more focused on the road ahead rather than observing the local environment. By sending subjects down the same open road several times, Mourant and Rockwell were able to address the effects of familiarity on eye movements. In addition, when subjects were in car-following situations, it was found that the fixations were 1° lower (closer to the vehicle) for all subjects.

These early studies quickly grew to long term wide ranging research on sign reading behavior. In 1973 Bhise and Rockwell (*27*) ascertained that drivers do not steadily concentrate on a sign to obtain its information. Their data showed several glances on the approach to the sign as it became legible. The amount of time dedicated to viewing the sign was shown to be dependent on how soon the sign was visible, how much traffic was present, or how relevant the sign was. Other factors such as sign complexity and type of information were also shown to affect a driver's sign viewing behavior. Subsequent studies by Rackoff and Rockwell (*28*) and Shinar, et al. (*29*) analyzed varying aspects of driver eye-movement behavior such as daytime versus nighttime driving, age, and roadway geometry. The discovery that drivers use several glances to obtain information from signs opened the door to much of the research conducted today; including this thesis. As technology advanced and eye-tracking capabilities increased, new research was undertaken to build on Rockwell, et al.'s groundbreaking studies.

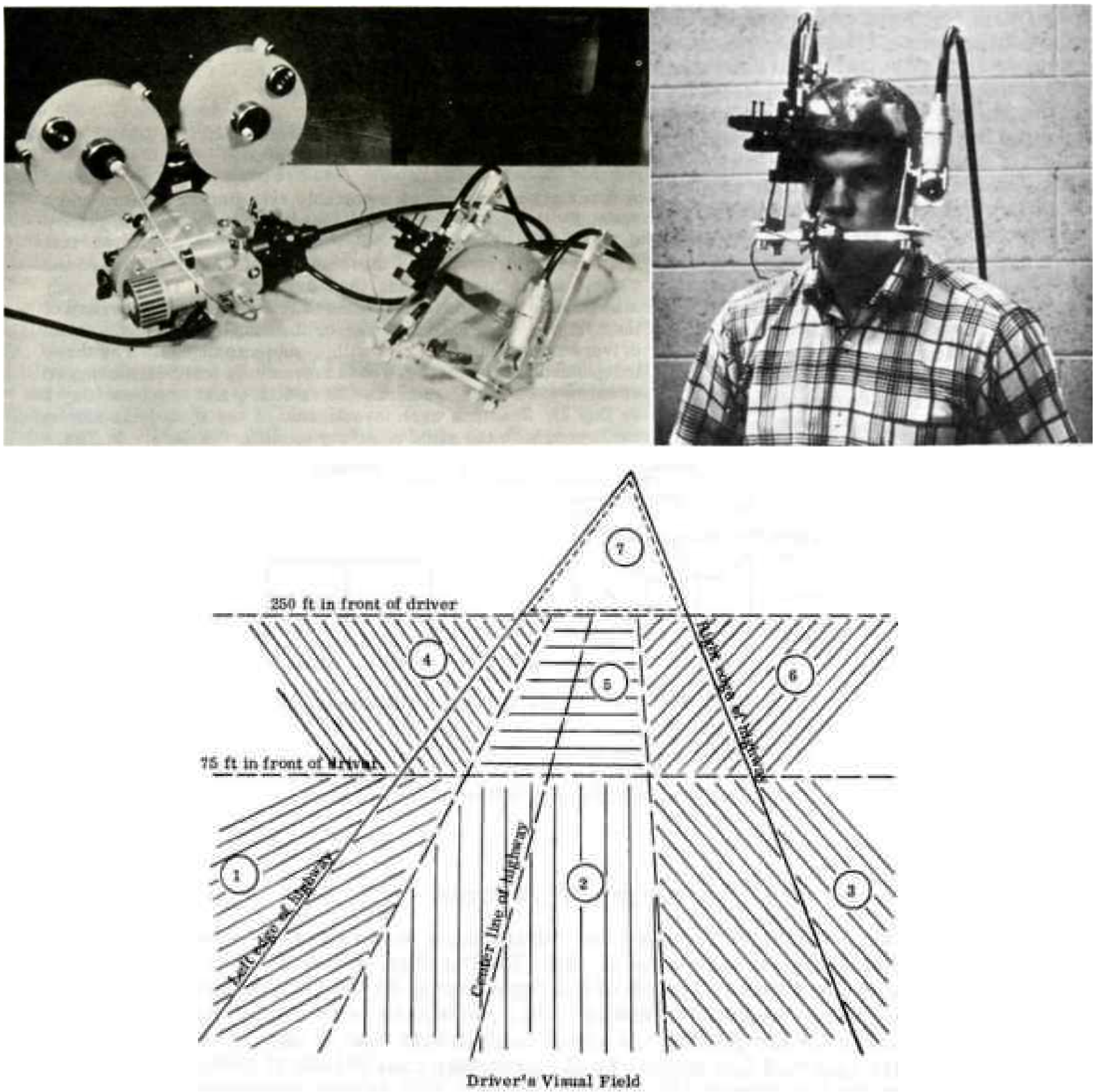


Figure 12. Rockwell Equipment and 7-Region Viewing Analysis

The next key player in eye-tracking research began investigating specific signs along roadways. In 1987, Zwahlen used a head mounted system and a 1973 Volkswagen to analyze the effectiveness of advisory speed signs with curve warning signs in Ohio (*30*). Zwahlen's results verified the separate looks and durations as discovered by Bhise and Rockwell. Zwahlen, however, dug deeper by including vehicular data such as speed, lateral acceleration, gas pedal deflection, and braking from the more than 30 instruments in the test vehicle. This experiment also included a later report documenting Stop Ahead and Stop signs and their effect on eye-scanning behavior (*31*). Zwahlen not only confirmed Bhise and Rockwell's findings that signs with more text took longer to read but added that the last look distance is shorter for signs with more content. That is, drivers are closer to the sign when reading signs with more content when those with fewer words. Zwahlen also found the addition of advisory speed signs did not influence drivers to slow when approaching a curve and that Stop Ahead signs did not "*give drivers adequate visual stimulus to prepare them to stop when approaching an unexpected, partially concealed intersection*"(*31*). Zwahlen also began dividing the subject's glances into "First Look" and "Last Look" glances.

> *Because of the much lower sign luminance values found at night, the legibility or recognition of the message on a warning or similar sign such as a regulatory sign during nighttime is more important than the legibility or recognition during daytime.(32)*

Zwahlen continued his eye-tracking research in 1995 by concentrating on legibility during nighttime driving using short word or symbol signs. This study also shifted focus from a minimum required visibility distance (MRVD) to a minimum required legibility distance (MRLD). The minimum required visibility distance referred to the distance previously used to develop a minimum retroreflectivity requirement for traffic signs. Zwahlen developed a minimum required legibility distance model that was based on actual driver eye scanning behavior and found the MRLD to be longer than the MRVD in most cases. Another nighttime study by Zwahlen, et al. (*33*) evaluated the effectiveness of ground-mounted diagrammatic signs at freeway interchanges by determining if they elicited excessive eye fixations. The more recent studies conducted by Zwahlen were accomplished by a more advanced eye-tracking system. Figure 13 illustrates this advancement in the technology of head mounted systems.

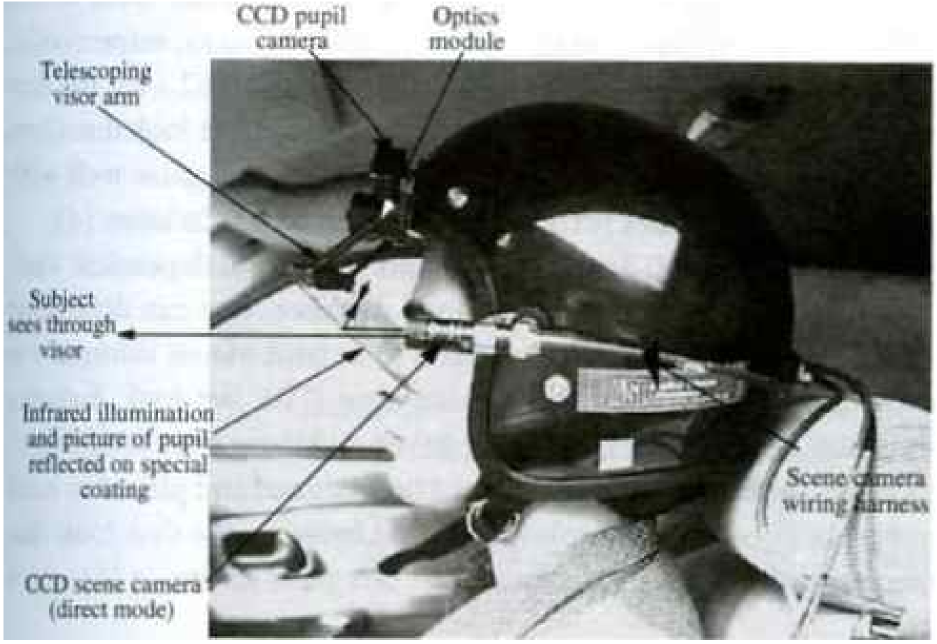


Figure 13. ASL 4000 Eye-Scanning Helmet Used by Zwahlen

Remote eye-tracking systems have also been used in research. In their study evaluating the effects of age, sign luminance, and environmental demand, Frank Schieber, et al. used an ETS-PC system from Applied Science Laboratories to follow their subjects' gaze as they drove on public roadways (*34*). Subjects completed a 30-minute test drive with the task of locating several test signs as shown in Figure 14. Schieber, et al. studied several factors relevant to this thesis. First, it was established that decreasing sign retroreflectivity from 100 to 15 percent resulted in a 17 to 24 percent decrease in legibility. Further, the authors found that the average fixation while reading (the last look) exceeded three seconds and the total viewing time surpassed six seconds, given unrestricted sight distance. Schieber et al.'s results, however, were limited by the reported capabilities of the remote eye tracking system, only allowing detection as far away as 984 feet (300 meters). Perhaps their most significant conclusion dealt with the comparison between suburban and rural conditions shown in Figure 15. The numbers in parenthesis represent the lateral offset of the sign from the roadway and the two vertical lines denote the 197 and 249 foot (60 and 76 meter) mean legibility distances observed for the rural and suburban environments, respectively.

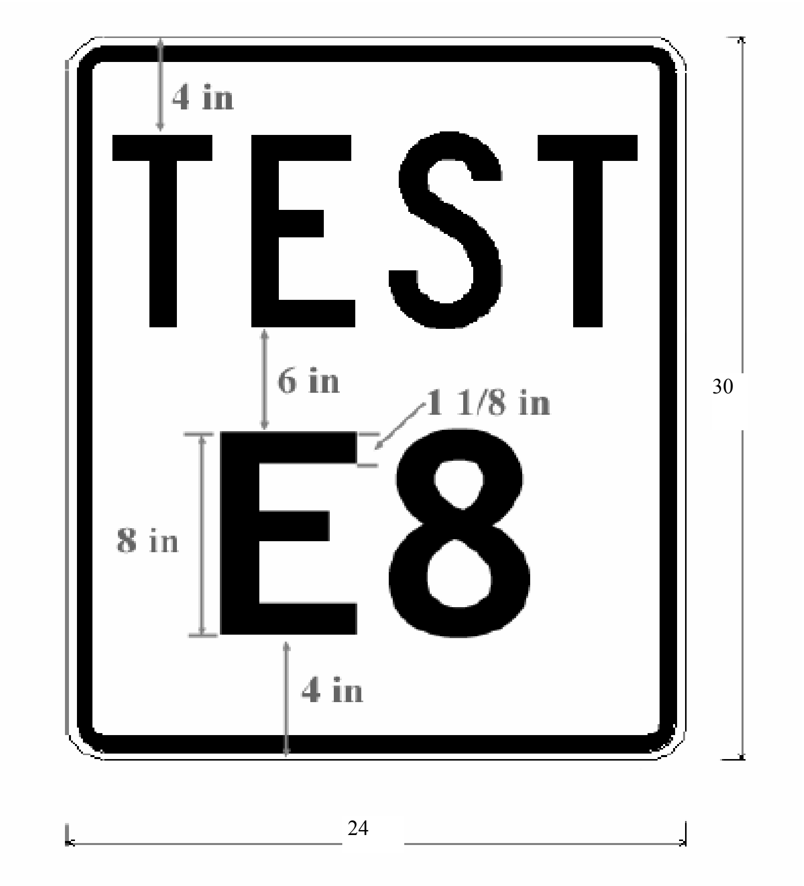


Figure 14. Test Sign (*34*)

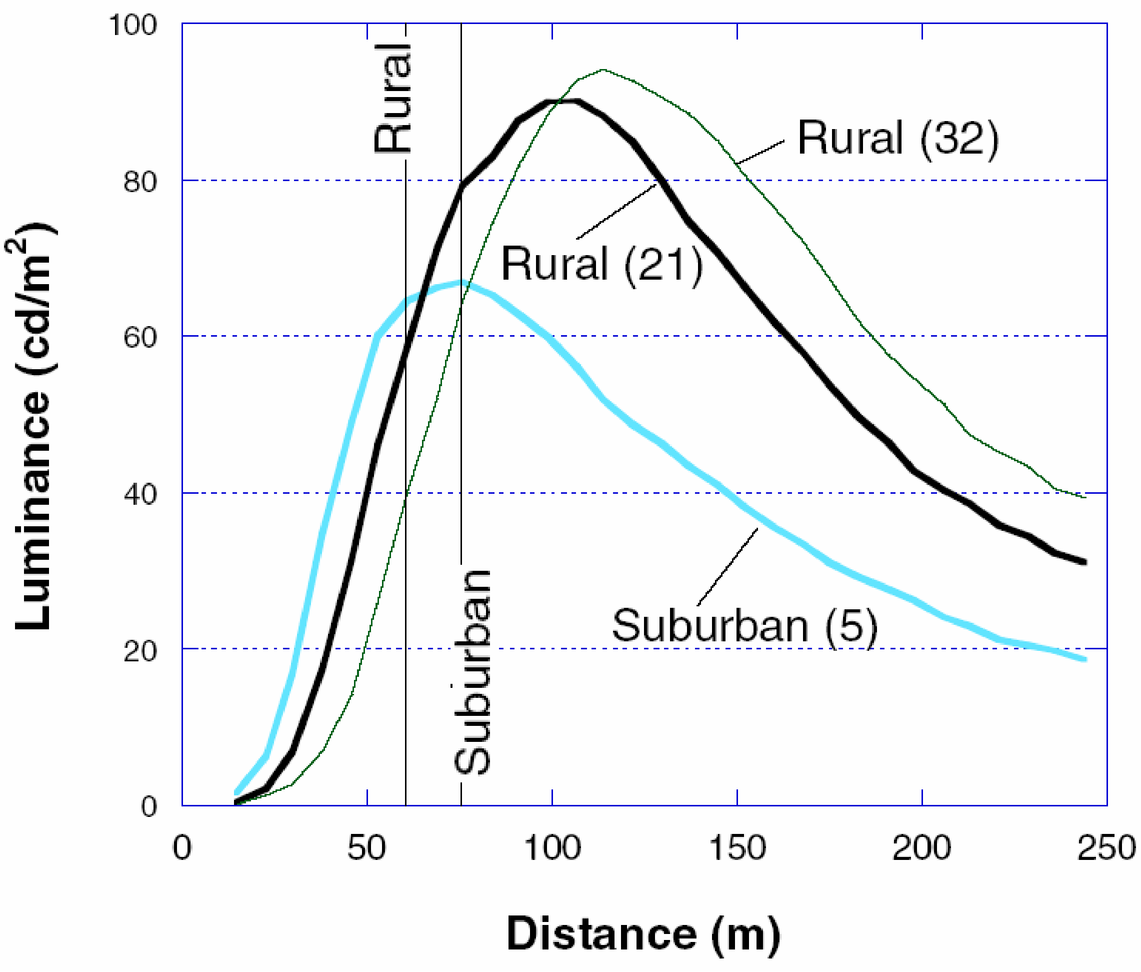


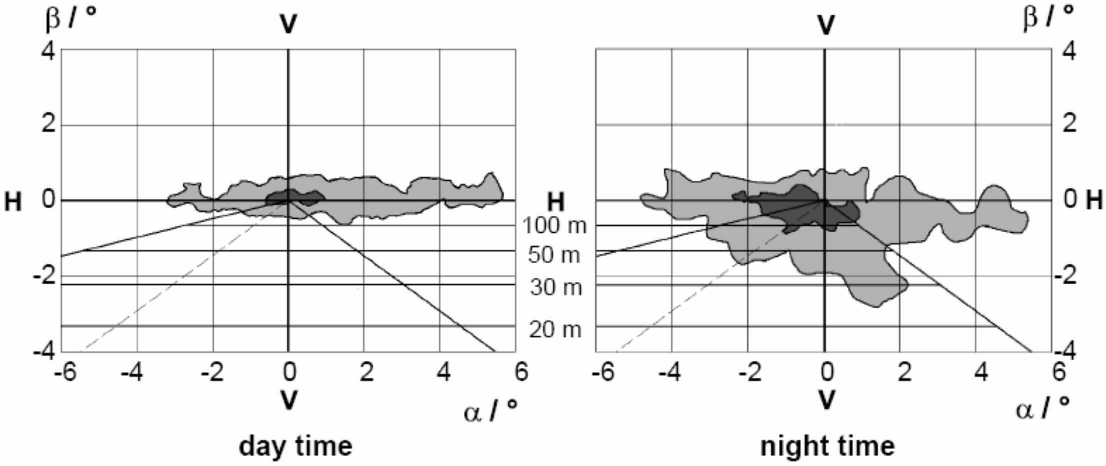
Figure 15. Luminance for Rural and Suburban Viewing Conditions (*34*)

The importance of this comparison relates directly to the research presented in this thesis. The peak of the 'suburban' luminance curve for their brightest sign occurs at the mean reading distance for the suburban signs. As written by Schieber et, al.:

> *It is interesting to note that the peak level of the luminance distribution is considerably reduced in the case of the Suburban environment (mostly due to increased sign mounting height). However, this apparent disadvantage seems to have been offset by the fact that the peak of the luminance distribution occurred at an optimal distance from the target stimulus signs.(34)*

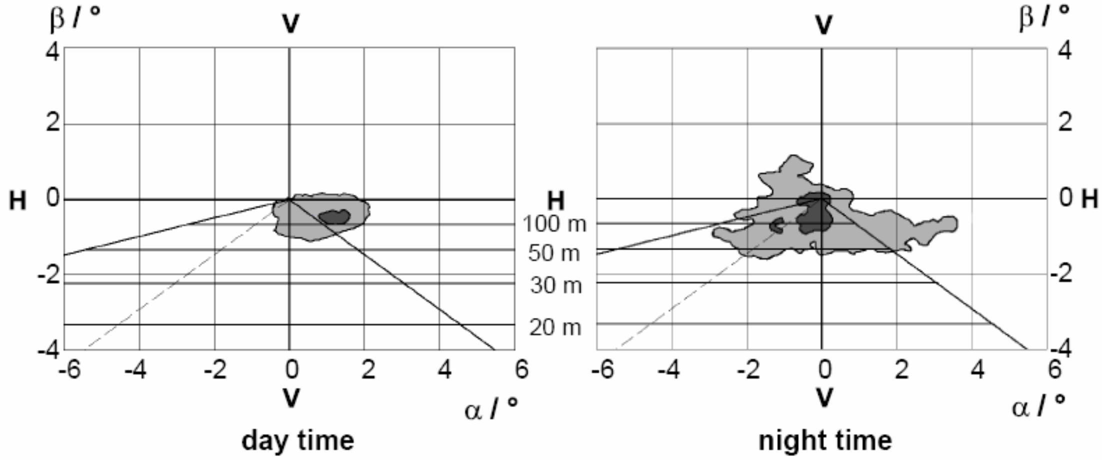
The authors continue to note that the peaks of the luminance curves for the rural environments are located at nearly twice the distance the sign is being recognized, suggesting that the luminance distribution was nearly optimal for the suburban environment but highly suboptimal for the rural conditions.

Another eye-tracking study with a remote system was conducted by Diem in 2005 to study how driver's eyes move while driving (*35*). Comparisons were made between eye movements during the daytime and nighttime as well as between built up areas and country roads. Several conclusions can be drawn from Diem's research and are aptly illustrated by the charts in Figure 16. In the graphs, the dark area represents the 10th percentile location of the eye while the grey area depicts the 50th percentile. The comparisons between daytime and nighttime driving in both Graph 1 and Graph 2 reveal that the driver searches more during nighttime driving. The area scanned by the nighttime driver is considerably larger that that analyzed by the daytime driver. Diem attributes this to the "*decrease of absorption of information via the peripheral"* due to the decreased light. This leads to longer and more accurate fixations at night in order to receive the same information as the daytime driver. Another comparison is made between the driver's viewing behavior in urban areas (Graph 1) and rural areas (Graph 2). Rural drivers tend to concentrate more on the road further ahead than drivers in built up areas.



Graph 1: graphical representation of the distribution of fixations driving in a built-up area

■: *10% - area* □: *50% - area*



Graph 2: graphical representation of the fixation distributions on straight route sections on country roads

■: *10% - area* □: *50% - area*

Figure 16. Diem Eye Movements (*35*)

Eye-tracking systems are still in use to serve several transportation research interests. Many studies have been undertaken to evaluate the effectiveness of specific signs and sign sheeting while others have presented models of how often drivers look at certain signs. Some studies have even focused on verifying or disproving the empirical rules taught to drivers about how to scan the road ahead. Still more research deals with the driver inside of the vehicle and possible distractions created by the ever increasing presence of communication in the form of cellular phones, in-vehicle DVD systems, and other features.

Whereas much of the previous research has evaluated driver performance based on existing materials, this research provides another perspective by basing the results on how the driver uses those materials. By using information related to how often and for how long a driver looks at signs of varying brightness, this thesis has transferred the focus on nighttime visibility characteristics from evaluating industry's products to understanding what the nighttime driver needs based on how he uses signs at night. Although varying types of sign sheeting were utilized, only the resulting luminance of those signs was used to assess the impact of sign brightness on driver behavior, thereby eliminating the dependence on existing products. Through the use of both emerging and established technology, the research presented in this thesis provides a comparison between how drivers look at signs based on how bright those signs are.

EXPERIMENTAL DESIGN

The research presented in the literature review was intended to emphasize the importance of field testing and varying the luminance of tested signs. This experiment, designed to evaluate the effect of sign brightness on driver viewing behavior, employs both of these aspects of sign research. The experimental design was accomplished through three primary stages: driving course layout, sign luminance design, and equipment assembly. The data collected for this thesis was part of an exploratory task of a larger research project conducted by the Texas Transportation Institute for the Texas Department of Transportation (TxDOT) to develop a performance based sheeting specification. The data collected for this thesis was accomplished in conjunction with the TTI project which incorporated a total of 15 signs. The analysis completed in this thesis deals with all signs of a common format and color, which account for six of the signs presented to the subjects.

COURSES

This experiment was divided into two segments: a closed runway course and a route on public roads. The runway course consisted of a four-mile path on the runways at Texas A&M University's Riverside Campus, a former Army Air Corps installation. The open road course is referred to as the Silver Hill course due to its loop around Silver Hill Road, a Brazos County, TX facility.

Runway Course

The four mile closed course began and ended on the runways of the Riverside Campus as shown in Figure 17. In order to vary the presentation of the signs, subjects began at one of two locations. Figure 17 illustrates the first starting location on the taxiway and the alternative starting position is the turnaround on runway 35L (at the top of the map). The starting position was changed rather than moving the signs to ensure the signs remained in the same orientation to maintain similar luminance characteristics for each subject. An example of a test sign on the runway course is provided in Figure 18.

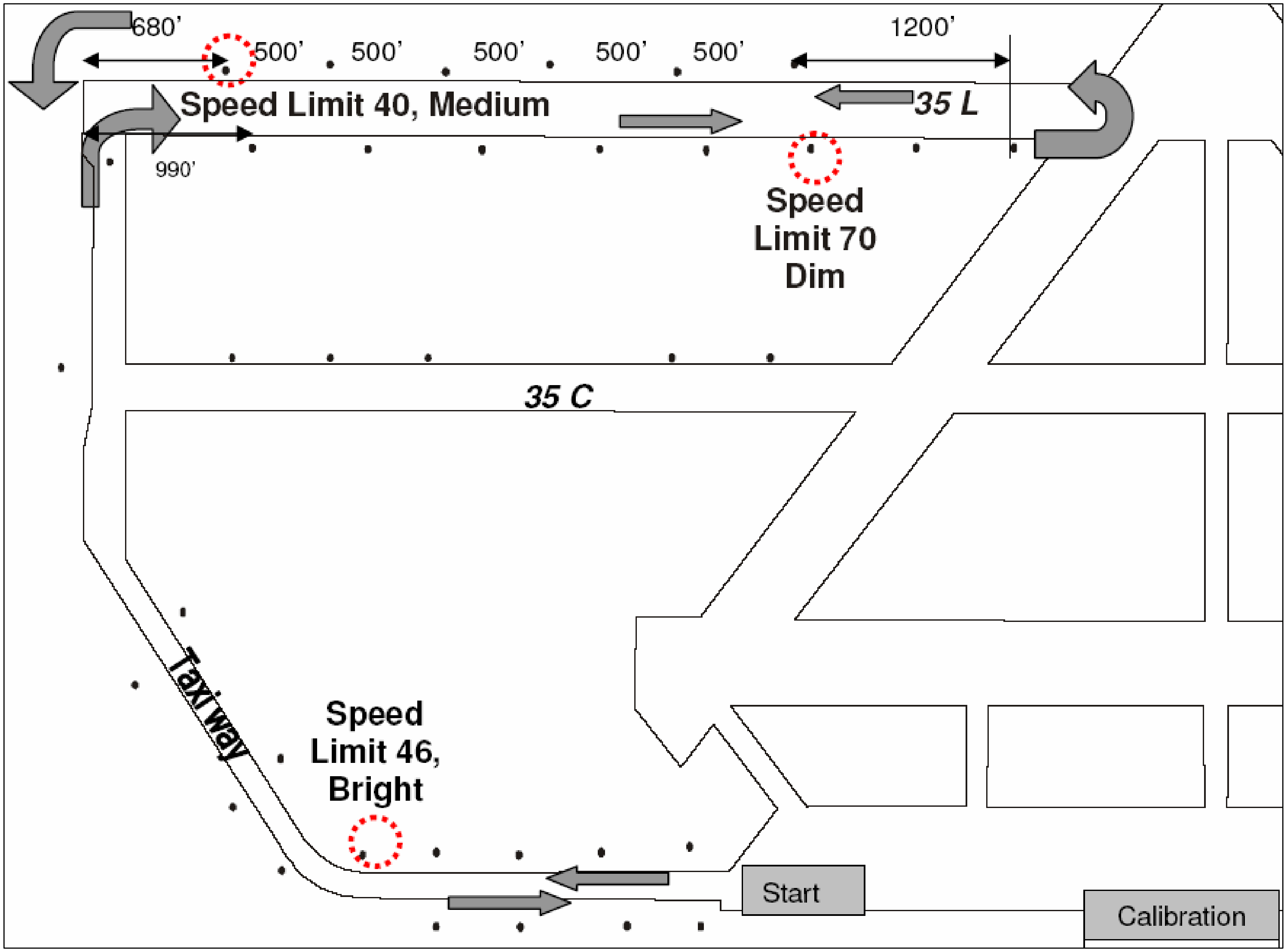


Figure 17. Runway Course

Figure 18. Example of Sign along Runway Course

The positions of the three signs presented on the runway course are shown in Figure 17. The location of each sign was measured in reference to a common stopping point for each subject. The stopping points on the runway course are located at the start line, at the beginning of the runway before the dim Speed Limit sign, and at the beginning of the runway before the medium brightness Speed Limit sign. The target signs were selected to provide three levels of brightness to the nighttime driver on each course. Descriptions of the runway signs and the Silver Hill signs and the distances from the stopping points are listed in Table 2 and images of the signs are given in Figure 19.

Table 2. Sign Properties

Name	Legend	Sheeting Type	R_A $\alpha=0.2°,\beta=-4°$ cd/m^2	Brightness Level	Dist. from stop (ft)	Loc.
SL-46	Speed Limit 46	AD T-7500	850	Bright	2004	Closed Course
SL-40	Speed Limit 40	HI	245	Medium	3792	
SL-70	Speed Limit 70	EG	98	Dim	3246	
TS-Y2	Test Sign Y2	3M DG[3]	545	Bright	19036	Open Course
TS-F5	Test Sign F5	HI	267	Medium	14101	
TS-X7	Test Sign X7	EG	118	Dim	9308	

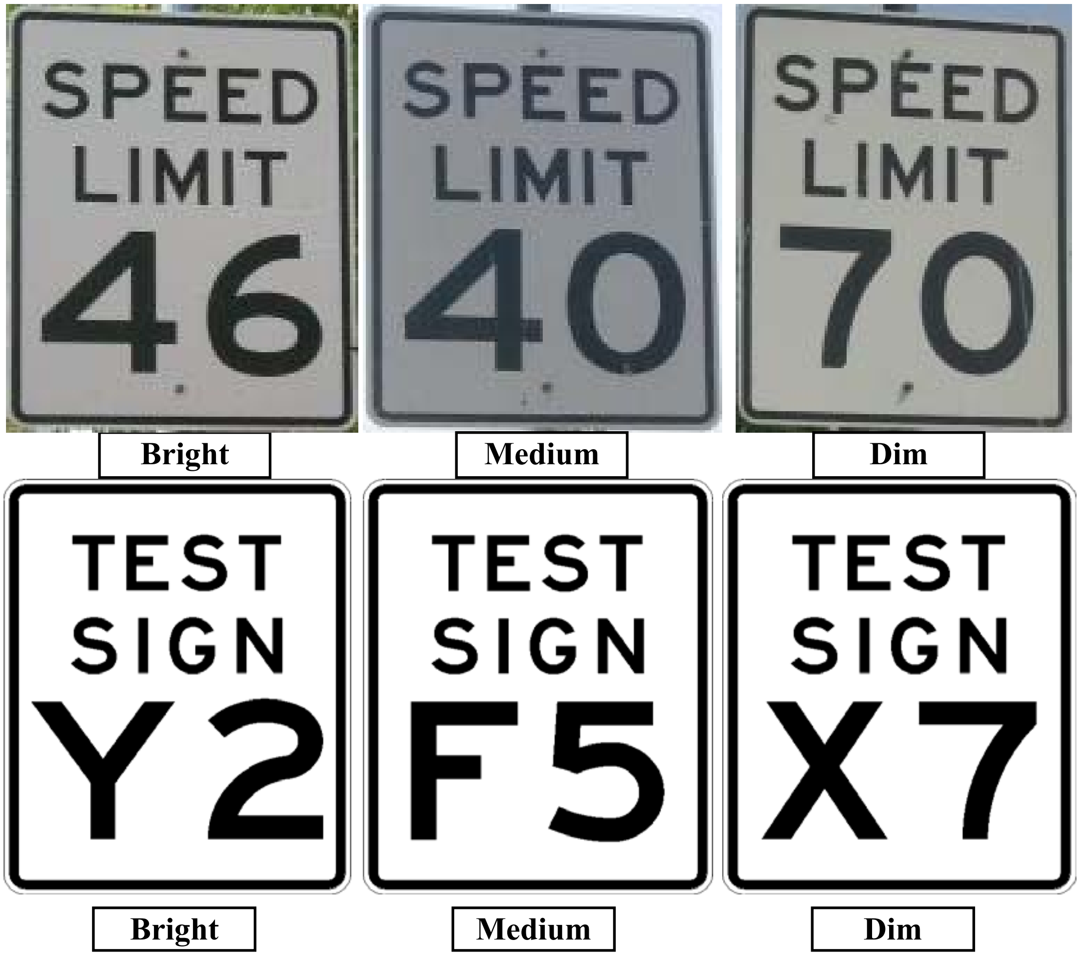


Figure 19. Experiment Signs

Silver Hill Course

The open road course consists of a six mile loop with three test signs installed as shown in Figure 20. The course began and ended at the entrance to the Riverside Campus as shown in Figure 21. Although the subjects traveled across a section of State Highway 47, data were only collected along a two mile section of Silver Hill Road. Silver Hill Road is maintained by Brazos County, Texas. The author coordinated with the county engineer to install the three test signs. The open road course was chosen for several reasons. First, Silver Hill is a seldom traveled road which ensured that our subjects would not be familiar with their surroundings or the presence of the test signs. Also, the low traffic volume meant that the test signs were less likely to be struck or stolen during the data collection. Finally, its proximity to the Riverside Campus and easy access via State Highway 47 made the Silver Hill route an obvious choice.

Figure 20. Example of Test Sign on Silver Hill Road

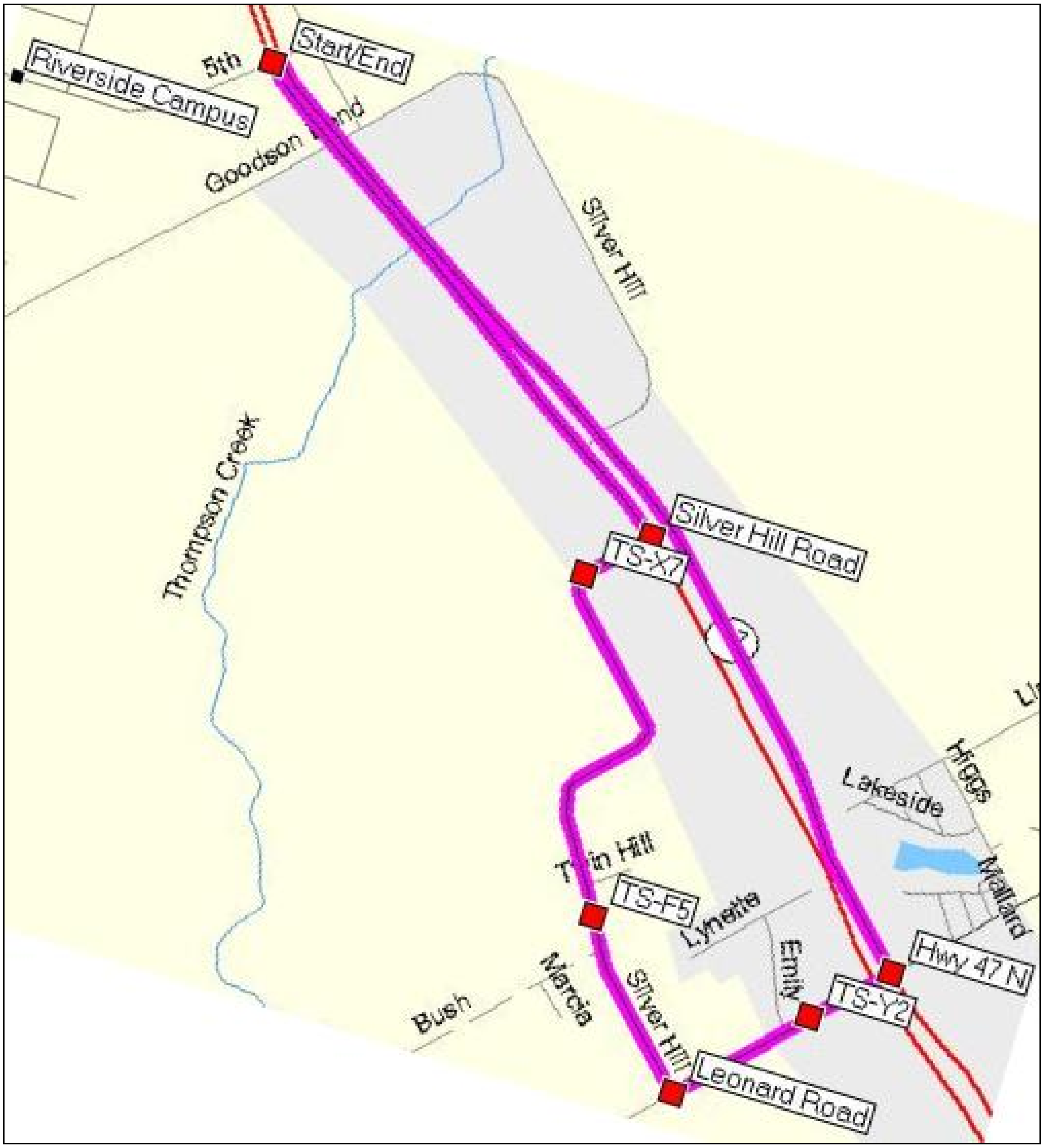


Figure 21. Silver Hill Course

TEST SUBJECTS

The use of human subjects for this project required special approval. As such, a proposal was submitted and approved by the Institutional Review Board (IRB) at Texas A&M University. This process ensures that researchers do not expose human subjects to any unnecessary hazards.

A variety of subjects were selected based on their age, eye color, and visual correction. Each of the subjects were licensed drivers familiar with the local driving habits and none of them were familiar with the setting for the open road course. Table 3 includes all of the subject information including their visual acuity as measured by a Snellen acuity chart, gender, and starting point on the closed course. All subjects were evaluated based on their eye-scanning behavior while being given additional tasks such as maintaining position in a narrow lane, searching for requested information on signs, and other road-based functions. As a requirement of the Texas A&M University risk management office, any subject participating in an experiment leaving University property must be covered by the agency's insurance. To satisfy this requirement, all test subjects were employees of the Texas Transportation Institute. The author received valuable input from each of the student workers, clerical staff, and researchers that participated in the experiment. Also of note is that two of the subjects have been omitted from the table. A total of 18 subjects were recruited for the experiment of which 17 participated and 16 produced usable data. One of the original subjects was unable to participate and the eye-tracker was unable to collect data for another. The remaining subjects have been renumbered for simplicity. The original data files list the subjects according to their initial number. Any reference to the original data should account for this.

The flaw in the eye-tracking system was due to the combination of very light colored eyes and the dark eye make-up used by the subject. As shown in Figure 22, when the subject looked away from the camera, the *ViewPoint*® software mistook the dark mascara for the pupil and tried to track it. The image on the left shows a correct tracking while the right image shows the software tracking the eyelashes. Several other subject characteristics that warranted consideration such as the size of glasses worn, the amount of hair, and the acceptable comfort level had to be addressed during the data collection. The three subjects wearing glasses were able to fit their glasses under the *EyeFrame* apparatus. Subjects with long hair had more difficulty keeping the apparatus immobile on their head and required the head strap to be tighter, which caused some eventual discomfort. None of the aforementioned challenges appear to have adversely affected the subjects or influence their driving behavior. Figure 23 shows a subject wearing the *ViewPoint EyeTracker* ®.

Table 3. Subject Information

No.	Age	Eye Color	Visual Correction	Starting Point	Corrected Visual Acuity 20/X
1	30	green	none	Taxiway	20
2	34	brown	none	35L	20
3	21	blue	none	Taxiway	20
4	28	hazel	contacts	35L	13
5	52	blue	glasses	Taxiway	20
6	31	hazel	none	Taxiway	13
7	45	brown	none	35L	20
8	28	blue	contacts	35L	25
9	45	blue	glasses	Taxiway	25
10	20	blue	contacts	35L	13
11	55	hazel	none	Taxiway	20
12	41	blue	contacts	35L	20
13	29	brown	none	Taxiway	20
14	28	brown	none	35L	13
15	32	brown	contacts	Taxiway	20
16	31	blue	glasses	35L	13
Average Age		34	Correction:	# with	8
Average Acuity		20/18		# without	8

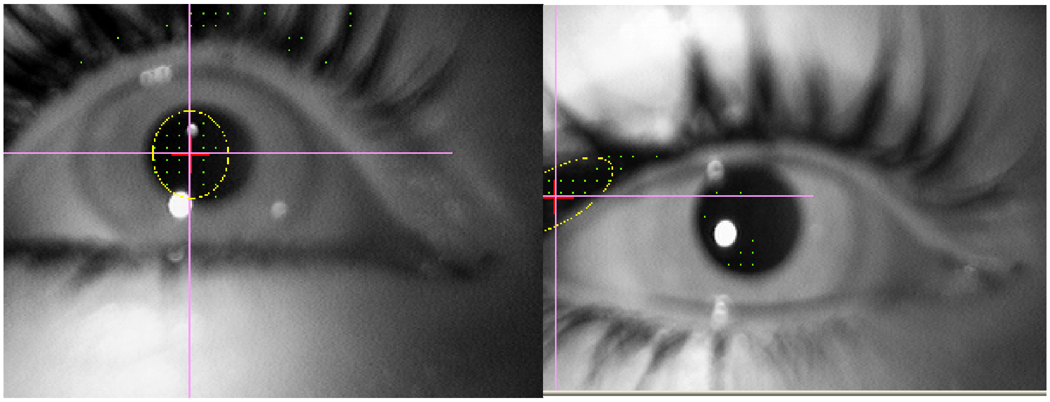


Figure 22. Eye-Tracking Limitations

Image on right shows tracking of dark eye-lashes.

Figure 23. Test Subject

EQUIPMENT

The primary piece of equipment used in this study is the *ViewPoint EyeTracker*® by Arrington Research, Inc. This modern technology has allowed the author to determine where a driver is looking throughout the experiment. Several other devices were required to collect the information vital to this research. A distance measuring instrument (DMI) along with video titling equipment, a customized DMI control box, and a specialized laptop computer have been coupled inside the largest piece of equipment—the vehicle.

A description of the equipment used for this research is best accomplished in the same process as the components are connected and is illustrated by the flowchart in Figure 24. The vehicle used for this research was a 2003 Ford Taurus owned by TTI. The backseat of the test vehicle was transformed into a workstation during the data collection. The power for the necessary equipment came directly from the vehicle through a power inverter. This power was then conveyed to the eye-tracker, the laptop, the video titler, and the DMI control box. A video capture card included with the eye-tracker was installed into the laptop docking station to collect and route all of the video data to the *ViewPoint*® software. Between the *EyeFrame*™ and the computer, however, an additional step has been added. Although the software adds its own timestamp to the video, which allows the author to assess the glances chronologically, this research required a distance element as well. The DMI has been manipulated to be input into the eye-tracker video to allow for a distance display to complete the system.

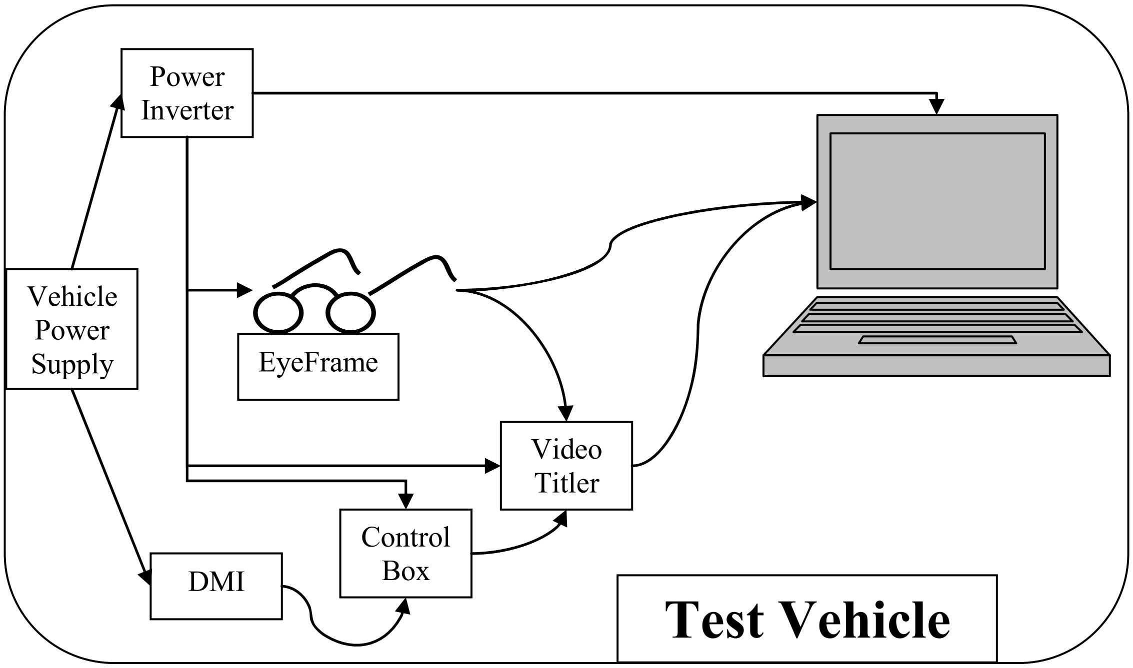


Figure 24. Data Collection System

A distance measuring instrument uses electrical impulses generated by sensors in the vehicle to determine the distance traveled. Transmission sensors, for instance, provide six pulses for each revolution of the internal disk according to the NITESTAR® operation manual from Nu-Metrics® (*36*). The DMI is calibrated by traveling a known distance and correlating that distance with the number of pulses recorded. The stated error of the NITESTAR® distance measuring instrument is 1 foot for every 1,000 feet traveled but previous use has witnessed an error of 1 foot for every mile traveled.

The distance measuring instrument includes a smaller subsystem of its own before reaching the central computer. First, the DMI receives its power and distance input from the vehicles transmission. The transmission sends a signal to the DMI six times for every revolution it makes relating to the distance traveled, which is unique for every vehicle. From the DMI, distance data was sent through a custom control box that refreshed the display on the DMI. This control box implanted the data from the DMI into the video titling device every 0.1 seconds (10 Hz). Next, the data stream from the control box was sent to a video titling device that overlaid an image onto the video.

The scene video from the *EyeFrame*™ was also routed through the video titling device to add the DMI output to the display. Finally, the two eye-camera video cables and the video titling cable along with the scene video were connected to the video capture card in the laptop docking station. From here the data were interpreted by the *ViewPoint*® software 30 times per second (30 Hz) and displayed on the laptop screen.

The use of a single computing system is essential for post-processing efforts. This allowed the researcher to assess when the subject glances at a sign and the distance to the sign from one interface. A final element critical to data processing was an external back up hard drive to store the large data files. Even though the eye-tracker video was collected in short three to five minute segments, an approximate file size of one gigabyte per minute required that the files be transferred after each session. This system was designed to be highly portable and capable of a wide range of scenarios.

The collection of sign luminance data required an additional piece of equipment. Sign luminance measurements were taken with a charge coupled device (CCD) photometer made by ProMetric and borrowed from the Federal Highway Administration (FHWA). The photometer captures an image of the sign which is later analyzed to assess luminance. Essentially an intricate camera, the photometer saves an image of the scene with luminance data included in the file. This image can then be used to determine the luminance, illuminance, or color of a point of interest as well as to provide a visual representation of the captured scene.

DATA COLLECTION

Prior to running the first subject, luminance data were collected for each of the signs presented. Sign luminance was measured at distances based on legibility indices according to the size of the lettering on the sign. The closest measurement was taken at a distance equivalent to 20 ft/in then incrementally increased by 50 feet to an index of 40 ft/in followed by two readings, each 100 feet further. The Speed Limit format signs used for this thesis have a 10 inch legend. Luminance measurements for the signs were taken at 200, 250, 300, 350, 400, 500, and 600 feet.

The effective luminance of a retroreflective sign is highly dependent on the unique viewing geometry and the orientation of the car relative to the sign. Such factors as the amount of fuel in the tank can change the angle of the headlights while the use of accessories such as air conditioning can decrease the power sent to the headlights. Drivers on the road represent the full range of possible vehicular modifications which results in each driver observing a slightly different luminance for the same sign. In order to account for these variations the signs on the driving courses were measured three times to assess the luminance characteristics.

Sign luminance measurements were collected with the CCD photometer from the driver's point of view as shown in Figure 25. Sign luminance was then measured by selecting "points of interest" on the sign from which the ProMetric software returned the average luminance over the selected area as shown in Figure 26. The analysis of the sign images collected with the photometer revealed a variation in luminance across the face of the sign. Figure 26 illustrates this characteristic of retroreflective sheeting. To compensate for this, common regions of the sign face for each type of sign were measured and averaged to obtain the overall sign luminance at a particular distance. Such measurements were conducted for each sign at each of the distances previously listed.

Figure 25. Photometer Placement

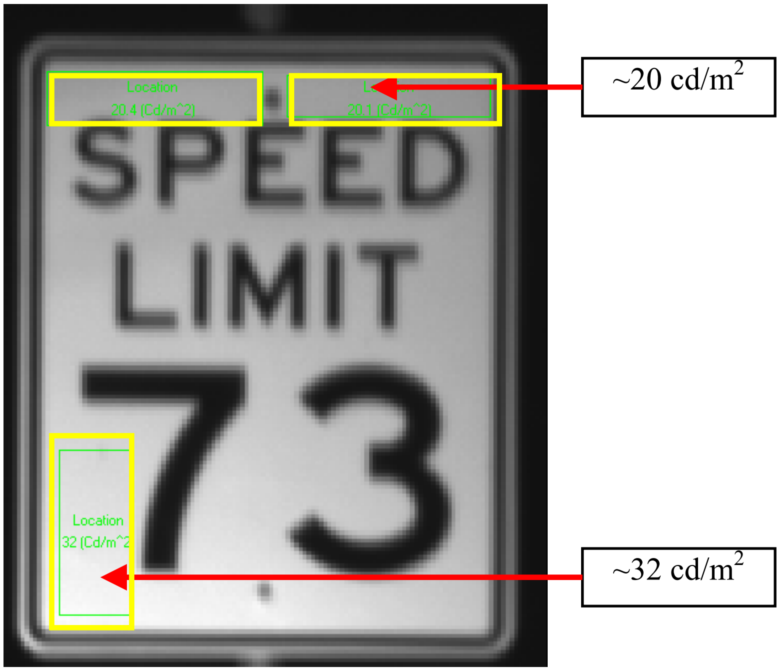


Figure 26. Luminance Measurements

These measurements were then used to construct unique luminance curves for each sign based on its retroreflective characteristics and approach geometry as shown in Figure 27 through Figure 30. Due to the variability of luminance measurements caused by vehicle orientation and headlamp power, a simple linear regression was completed to fit a line for the multiple measurements of each sign. While the accessories such as the air conditioner were common for each measurement, a change in the vehicle orientation or lane position could have affected the luminance measurements. Further, the fuel level of the vehicle was not constant throughout the three measurements, which could have added to the variability.. The best fit lines emphasize the relative brightness of each sign. The linear regression, however, does not produce a precise representation of the luminance data. The R^2 values for the Silver Hill signs, in fact, are extremely low, too low to be considered for analysis relating to specific luminance values. The relative increase in unexplained variation quantified by the R^2 value for the open course compared to the closed course can be attributed to several factors. The most likely explanation is the approaching roadway. Runways, by design, are straight and flat. The Silver Hill course, on the other hand, adheres to much less stringent standards. The roadway approaching the signs on Silver Hill road was often uneven with small depressions or swells close to the edge of the road associated with the road base settling beneath the pavement. Despite these variations in the readings, the three signs do have an increasing relative brightness from dim to bright.

Also included in the plots are luminance values calculated provided by the ERGO software. These values are intended to compare the field measurements with theoretical luminance data. As shown in the figures, the relative measured brightness between the bright, medium, and dim signs is consistent with the ERGO data. Also, the ERGO data extend the distance of the measurements made with the photometer. By extending the luminance profiles to 900 feet from the sign, the relative brightness of the signs are shown to be consistent.

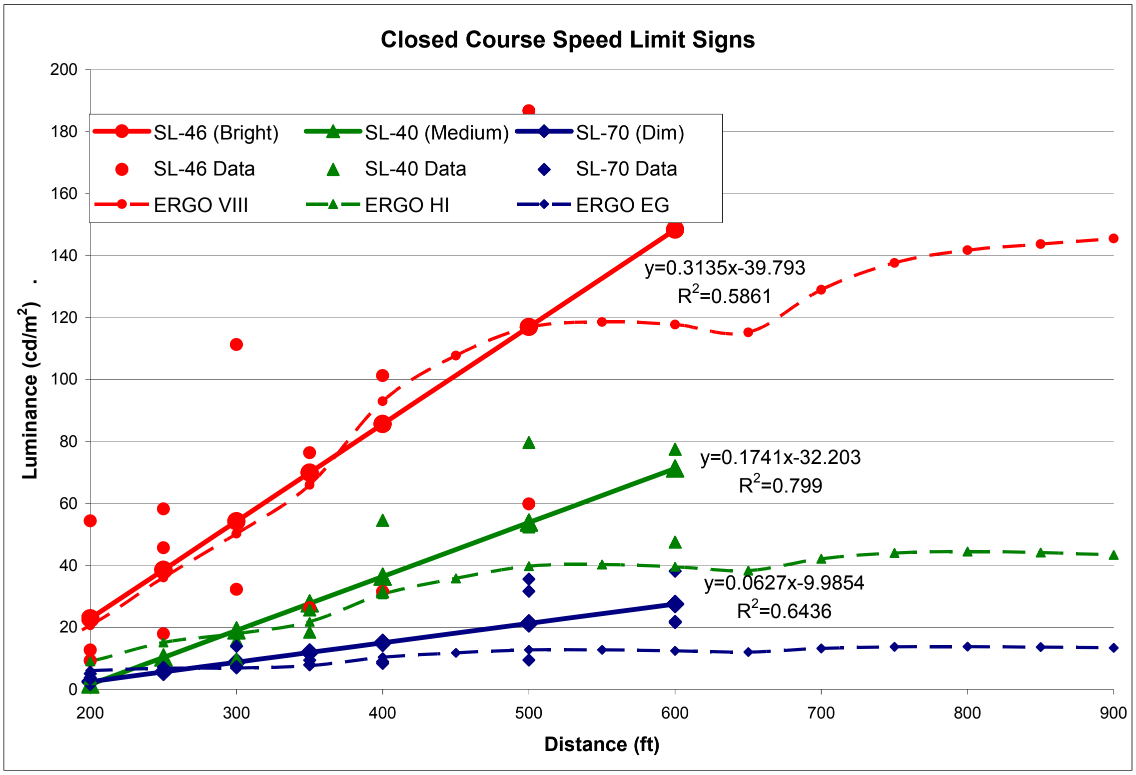


Figure 27. Speed Limit Luminance Curves

Figure 28. Speed Limit Signs

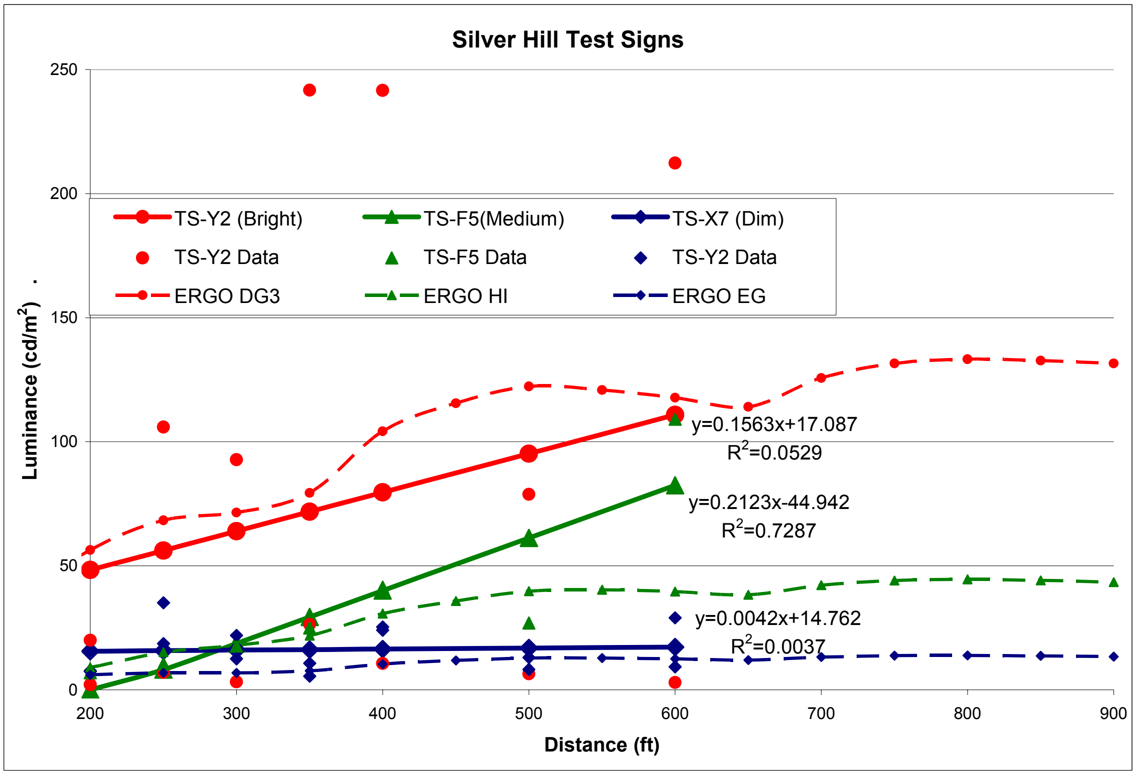


Figure 29. Test Sign Luminance Curves

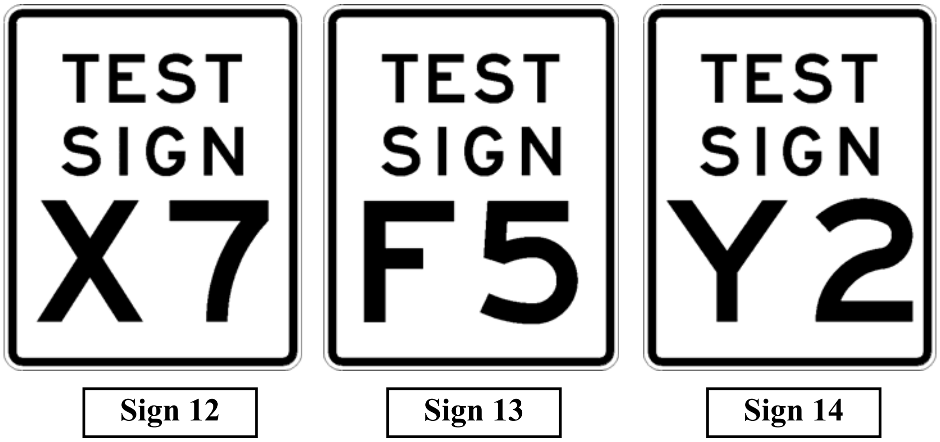


Figure 30. Silver Hill Test Signs

Calibration

Data collection for the subject began with a calibration process. The first step in calibrating the eye-tracker was to fit the apparatus to the subject's face. Once the *EyeFrame*™ was secured to the subject's head by the adjustable strap, each of the cameras had to be adjusted such that the subject's eye was at the center of the viewing area (see Figure 8). Although there was little variation between each subject's facial geometry, the flexibility of the mounting wires supporting the cameras resulted in movement when the apparatus was transferred and therefore required adjustment for each subject. Finally, the scene camera was adjusted to capture the same view the subject saw.

Typically, eye-tracker calibration consists of a subject viewing targets on a screen. The accuracy obtained by such a process is adequate for the short distance viewing of static objects. The *ViewPoint EyeTracker*® presents a grid of 16 points across the field of view of the scene camera as shown on the left of Figure 31. The subject fixated on each of those points while keeping their head immobile and the position of the eye was recorded. To increase the accuracy of the eye-tracking system, the author created a 40-foot tall calibration grid on a building at the Riverside Campus (Figure 32) which allowed calibration at a longer distance than typical eye-trackers. The increased calibration distance increased the accuracy for long distance sign viewing.

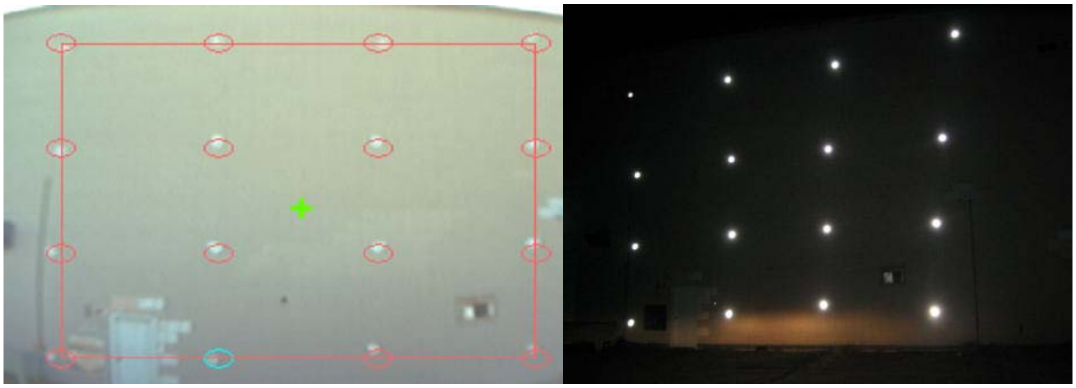


Figure 31. Calibration Grid-Day and Night

Figure 32. Calibration Grid-Installation

The test subject viewed the calibration grid from a tripod modified with a chinrest set up approximately 55 feet from the grid. The chinrest helped orient the subject's head and resist head movement. As a number corresponding to a calibration target was announced, the subject fixated on that target and the position of their pupil was recorded by the *ViewPoint*® software. The transformation of the 16 point grid during the calibration process is presented in Figure 33. The left side of the figure shows the default grid before calibration. As the location of the pupil is captured for each target, the corresponding point in the calibration grid is adjusted. According to the *ViewPoint EyeTracker*® PC-60 Scene Camera Users Guide:

> *Successful calibration will be indicated by a rectilinear and well-separated configuration of green dots corresponding to the locations of the pupil at the time of calibration point capture. Uniform curvature of the field of dots is acceptable*. (*37*)

The calibration of the eye-tracker was checked and corrected as necessary throughout the three courses as well as at the end of the experiment to ensure the quality of the data. After a successful calibration, the subject began the driving portion of the study on the runway course.

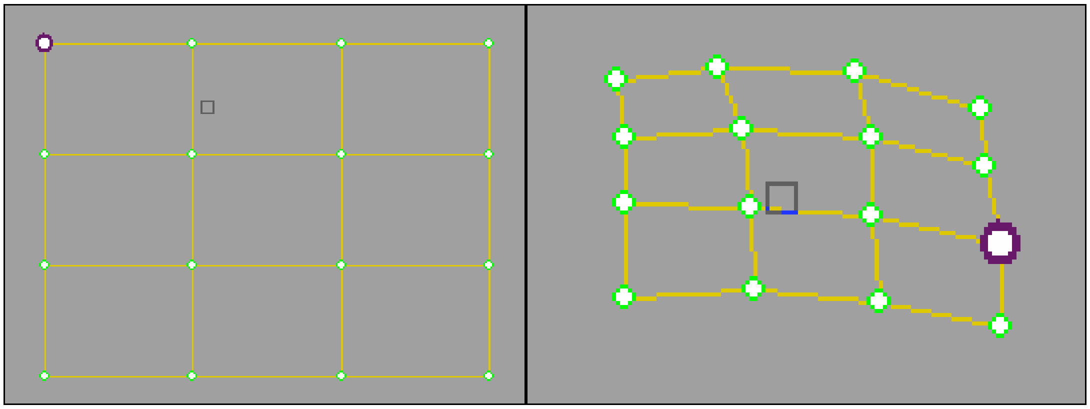


Figure 33. Calibration-Before (left) and After (right)

Runway Course

To begin the experiment the subject drove the test vehicle to one of the two starting points on the runways where a standard set of instructions was read and the DMI reset to zero. The researcher and the data collection system remained in the back seat of the vehicle throughout the data collection. The subjects were given the premise that they were helping to evaluate the new eye-tracking system to promote naturalistic driving rather than focusing on the test signs. A complete script of subject instructions is provided in Appendix A and they are summarized below.

Throughout the experiment, the subject was instructed to drive the vehicle at 30 miles per hour along the marked course while completing tasks that required the use of the installed signs. The signage along the closed course had been laid out to maximize viewing distance on the approach to each sign. The author reset the DMI to zero and created a new eye-tracking video file for each section of the closed course. In addition to the tasks required by the TTI project, the subject was directed to search for Speed Limit signs located in each section of the course. To accomplish this task the driver read the posted speed aloud to the researcher. The Speed Limit signs each contained a unique legend, some of which were not conventionally used for real-world speed limits. This variability in the legends ensured that the subjects had to read the sign and could not respond based on the recognition of a common Speed Limit sign. The researcher then recorded the distance at which the speed was read. This distance was used to determine the legibility distance and provided a starting point from which to begin the video data reduction. Upon completion of the closed course, the subject was instructed to exit the runways and exit the Riverside Campus to begin the open road portion of the experiment.

Silver Hill Course

The instructions for the Silver Hill course were given outside of the main gate of the Riverside Campus and the DMI reset to zero. Throughout the Silver Hill course, subjects were instructed to look for the test signs and read aloud the alpha-numeric combination on each sign. The distance at which the legend was read was again recorded to determine the legibility distance. Additionally, subjects were asked to indicate when they believed they saw a test sign as opposed to a normal traffic sign. After the three signs were observed, the subjects completed the 6.6 mile loop and returned to the Riverside Campus for the completion of the data collection. The open-road loop was intended to provide a comparison between real world driving and the closed course performance.

Following the final task the subjects returned to the staging area to complete the experiment. The calibration was checked once again and the system removed. At this time subjects were debriefed with the actual purpose of the study. Subjects were also asked to complete a brief evaluation of the eye-tracker and sign a waiver to be included in this and future publications and presentations. The eye-tracking and distance measurement information for each subject was saved in electronic format for subsequent analysis.

DATA ANALYSIS

The eye tracking system assigns x-y coordinates to the point of gaze depending on the position of the pupil. The *ViewPoint*® software integrates these two dimensional positions with the video captured by the forward facing scene camera. The calibration process uses 16 points spaced across the forward scene to attune the individual eye to the *EyeFrame*™ geometry. The typical use of eye-tracking equipment is used to measure gaze against a constant or premeditated background, whereas driving provides a completely dynamic scene. Even for long sections of straight roads, the scene changes as the driver approaches objects along the road. For this reason, tools built in to the eye-tracker to indicate when a subject looks into a certain region of the scene cannot be utilized. Instead, the reduction of the video to usable data required the researcher to review the video to establish several aspects unique to each subject.

The two examples of the video data illustrate how the glances were assessed. In Figure 34, a subject is looking from a sign on the right to a sign on the left. The image of the video shows the location of the DMI distance in the upper left hand corner of each frame and the vehicle's speed in the upper right hand corner. Figure 35 illustrates a feature of the software that detects a fixation of the eye. As can be seen by the DMI readings, the frames progress from left to right. The light colored circle surrounds the point of gaze of the driver and grows as the length of the fixation increases.

The video produced by the *ViewPoint EyeTracker*® and the video titler with the DMI data contain all of the information necessary to conduct the analysis. First, however, that data must be extracted from the video. Each unique eye-tracking file begins at a zero time and progresses as the file grows. The time is displayed in the title bar of the analysis program as shown in the box at the top right of Figure 36. Similarly, the distance for each file is reset externally on the DMI and is seen on the video through the titler as shown circled in Figure 36. Other information provided by the DMI through the titler includes a timer output from the DMI (left) and the vehicle speed (right).

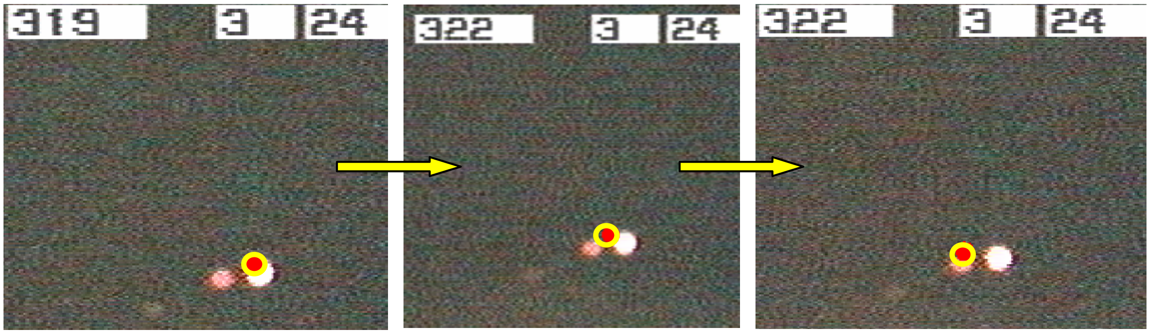


Figure 34. Typical Glance (left to right)

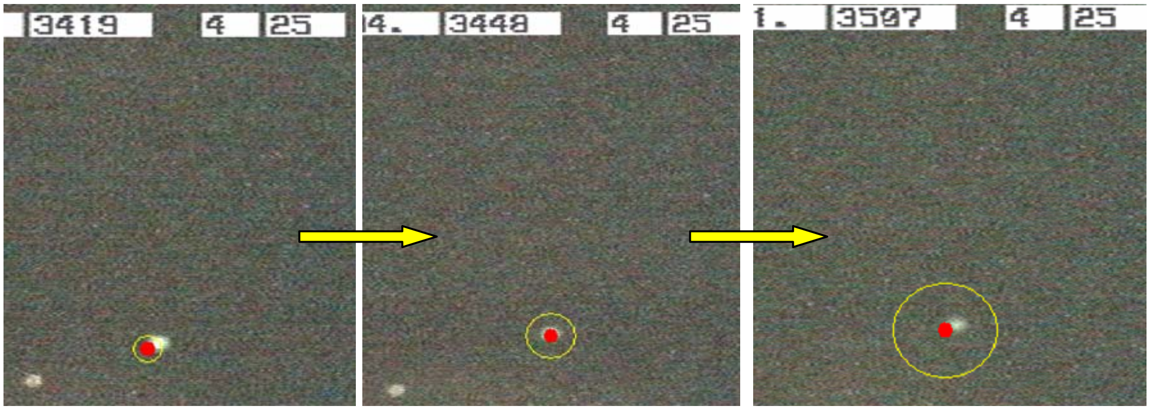


Figure 35. Fixation (left to right)

Figure 36. Data Extracted from Video

DATA REDUCTION

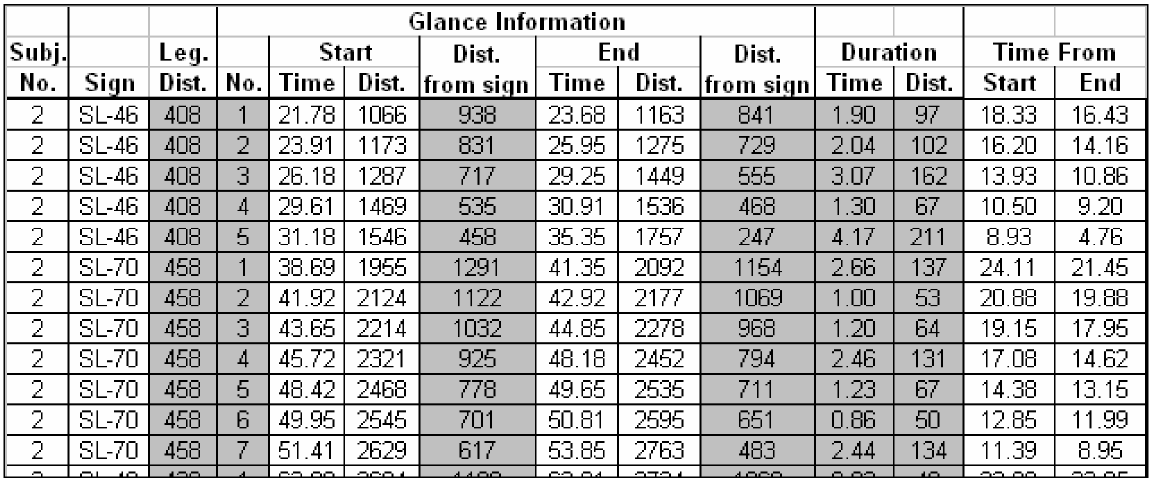
Several data points were collected, not only for each driver and each sign, but for each glance directed at that sign. The video was reduced to data for the glance time, location, and duration. Such data consist of recorded information including the time the subject looked at a sign, the distance at which the subject looked at the sign, and the time and distance at which the subject looked away from the sign.

The video reduction is the most tedious step in the analysis due to the variability of each subject's calibration and viewing habits. Furthermore, a limitation of the eye-tracker was most pronounced during this step. The resolution of the scene video is 640 × 480 pixels. This low resolution combined with nighttime conditions results in difficulty viewing the signs from a long distance. Although the distance varied with the brightness of the sign, the white signs were visible through the scene camera from at least 1,000 feet. It is interesting to note that there were possible glances detected by the eye-tracker before the sign was distinguishable in the scene video. An improvement in the quality of the video could facilitate an analysis of the earlier looks.

The data reduction began for each sign based on the distance the reading task was completed. From that distance, the video was backed up to begin video analysis. This provided a starting point from which to begin the video reduction. From this point, the video was reversed frame by frame until the sign was not visible by the scene camera. From there, the video is advanced frame by frame to record glance characteristics. At the beginning and end of each glance, two values were recorded: time and distance. Within the analysis distance, the video was advanced frame by frame as the subject approached the reported legibility point, recording the time and distance of the beginning and end of each glance. The glance locations and duration were then compiled for further analysis. An example of the data are provided in Table 4. For most of the signs, the longest detectable glance was over 1,000 feet from the sign. However, for the first two signs on the open course, the first detected glance for any driver was only over 900.

The analysis conducted by this thesis compares the sign viewing behavior for each driver within 900 feet of the sign.

Table 4. Sample Data from Eye-Tracking Equipment



			Glance Information										
Subj. No.	Sign	Leg. Dist.	No.	Start Time	Start Dist.	Dist. from sign	End Time	End Dist.	Dist. from sign	Duration Time	Duration Dist.	Time From Start	Time From End
2	SL-46	408	1	21.78	1066	938	23.68	1163	841	1.90	97	18.33	16.43
2	SL-46	408	2	23.91	1173	831	25.95	1275	729	2.04	102	16.20	14.16
2	SL-46	408	3	26.18	1287	717	29.25	1449	555	3.07	162	13.93	10.86
2	SL-46	408	4	29.61	1469	535	30.91	1536	468	1.30	67	10.50	9.20
2	SL-46	408	5	31.18	1546	458	35.35	1757	247	4.17	211	8.93	4.76
2	SL-70	458	1	38.69	1955	1291	41.35	2092	1154	2.66	137	24.11	21.45
2	SL-70	458	2	41.92	2124	1122	42.92	2177	1069	1.00	53	20.88	19.88
2	SL-70	458	3	43.65	2214	1032	44.85	2278	968	1.20	64	19.15	17.95
2	SL-70	458	4	45.72	2321	925	48.18	2452	794	2.46	131	17.08	14.62
2	SL-70	458	5	48.42	2468	778	49.65	2535	711	1.23	67	14.38	13.15
2	SL-70	458	6	49.95	2545	701	50.81	2595	651	0.86	50	12.85	11.99
2	SL-70	458	7	51.41	2629	617	53.85	2763	483	2.44	134	11.39	8.95

The interpretation of the glances made by each subject required multiple viewings of the video and was independent of other subjects. Although the accuracy of the calibration for each of the subjects was comparable, the precision of all subjects varied. As shown in Figure 37, the projected gaze at a given sign is not consistent for the three subjects. The light blur on the right side of each of the images is the sign and the circle represents the subject’s projected gaze. For the image on the right, gaze is very near the location of the sign. However, images on the middle and left show offsets above and to the right, respectively, from the location of the sign. The three projected gaze offsets illustrated by the images in Figure 37 are similar for each of the signs viewed and for all of the subjects.

Prior to reduction, the video for each subject was viewed to assess the location of their gaze relative to the sign. The location at which the subject read the sign (recorded as the legibility distance) provided a common viewing point for each subject. The position of the projected gaze relative to the sign was noted for several signs. Most subjects’ glances were offset just below or to the right of each sign. For each subject, this offset was constant throughout the eye-tracker video. Also, the horizontal accuracy of the eye-tracker exceeded the vertical accuracy. As a result, more weight was given to the driver's lateral glance than any vertical deviation in their point of gaze. Once the offset between their projected gaze and their actual point of gaze was assessed, the video was reduced to the glance data provided in Table 4. The author is working with Arrington Research, Inc. to add the option for a constant offset to the eye-tracker video analysis program.

Figure 37. Variability in Location of Projected Gaze

DATA ANALYSIS

The video reduction effort recorded over 400 data points for analysis. The first step in the data analysis was to segment the data into smaller datasets for each sign and each subject. With the data in a more manageable format, several plots were created to initiate a graphical analysis and allow the author to search for trends. Next, two of the primary measures of effectiveness, total number of glances and total glance duration, were extracted from each sign's dataset for comparison. A preliminary analysis was performed to establish the independence of these two measures. Finally, a statistical analysis of the data was performed using a series of paired *t*-tests.

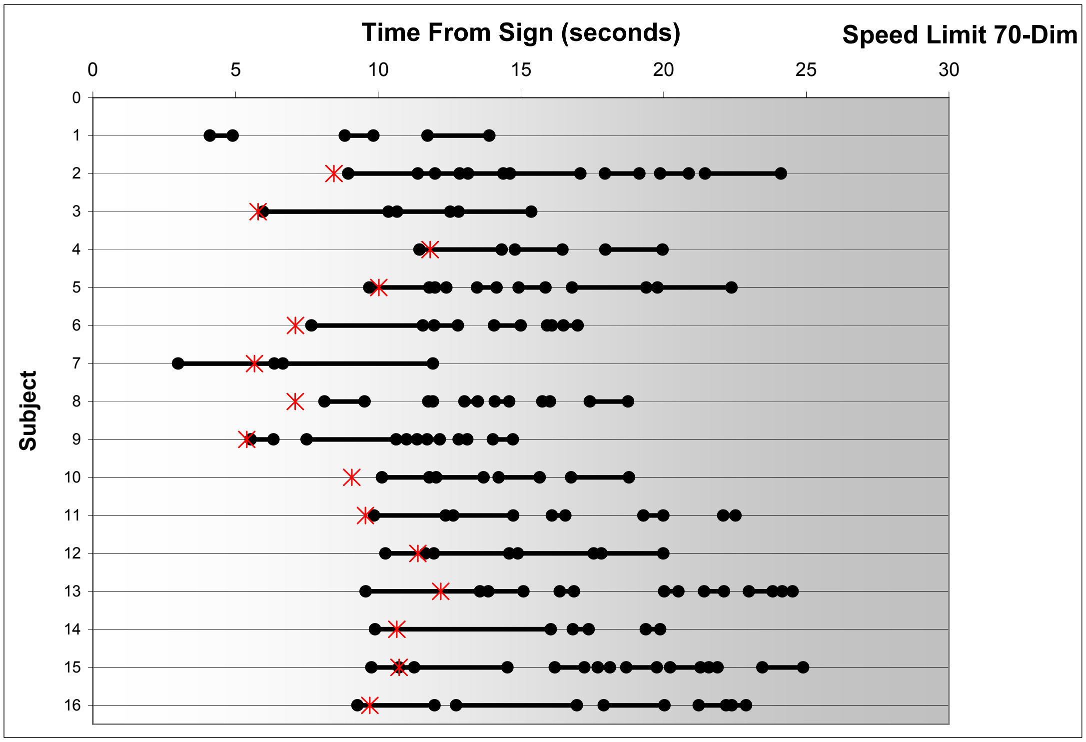
Graphical Analysis

The need to “see” the data presents a challenge in any analysis. By preparing a series of graphs, the author was able to uncover several trends and reach the next step in the analysis. Two types of graphs were prepared: all subjects glances for a particular sign and all signs for a single subject.

Four sample graphs are presented in Figure 38 and Figure 39 and a complete collection of all graphs is included in Appendix B. The horizontal scale in the plots relate to seconds from the sign, with zero being the location of the sign. The vertical axis represents either the subject or sign number depending on the type of graph. The heavy circles on the graphs symbolize the beginning or end of a glance while the heavy line connecting two dots is the duration of the glance. Gaps between dots indicate the subject was not looking at the sign. Finally, the asterisks in the graphs represent the location at which the sign became legible as reported by the subject. A more detailed description of the information included and conclusions extracted from each plot follows.

By Sign

The first of the plots created were those for each sign on the two courses. As shown by the two plots in Figure 38, all subjects tend to follow a similar trend in viewing the signs. Typically, a driver makes several short glances to a sign followed by at least one relatively long glance near the reported legibility distance. The top graph in Figure 38 is for sign SL-70 (the dim Speed Limit sign) and the bottom for TS-X7 (the dim Test Sign). The viewing behavior of the individual subjects is interesting to note. For both the dim sign on the closed course and that on the open road course, subject 7 stops looking at the sign substantially closer than most of the other subjects. Trends such as this justify the paired testing procedure used during the statistical analysis. By pairing the glance data by subject for each sign, the bias introduced by individual subject tendencies will be minimized.



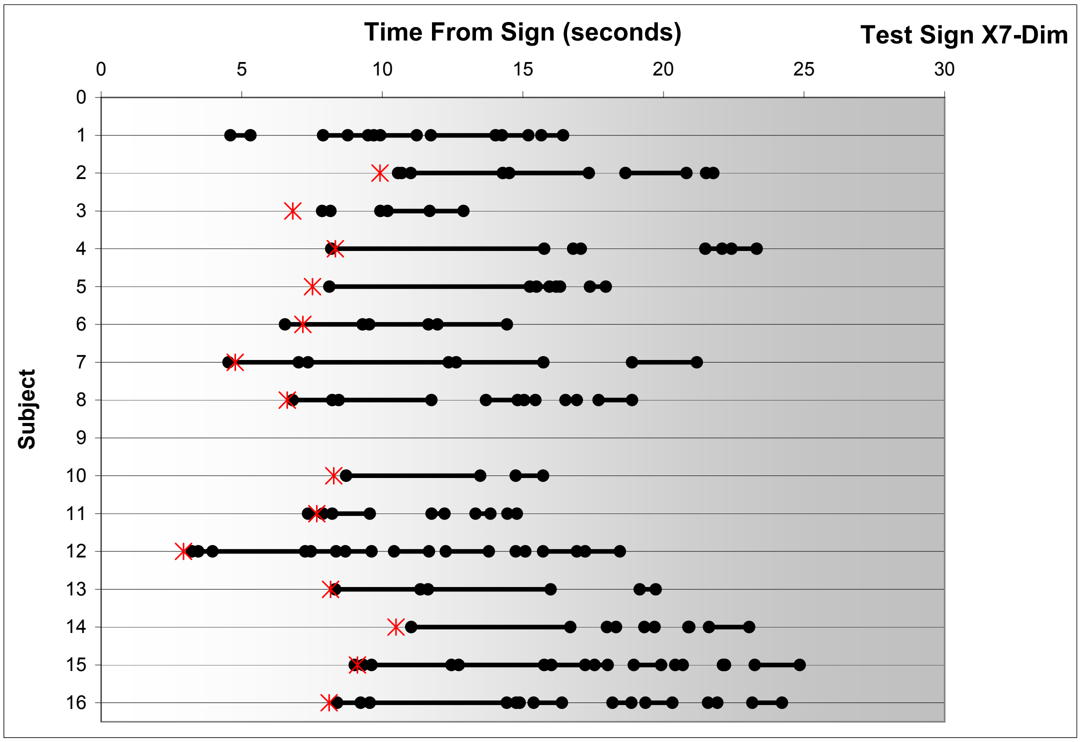


Figure 38. Glance Plots by Sign

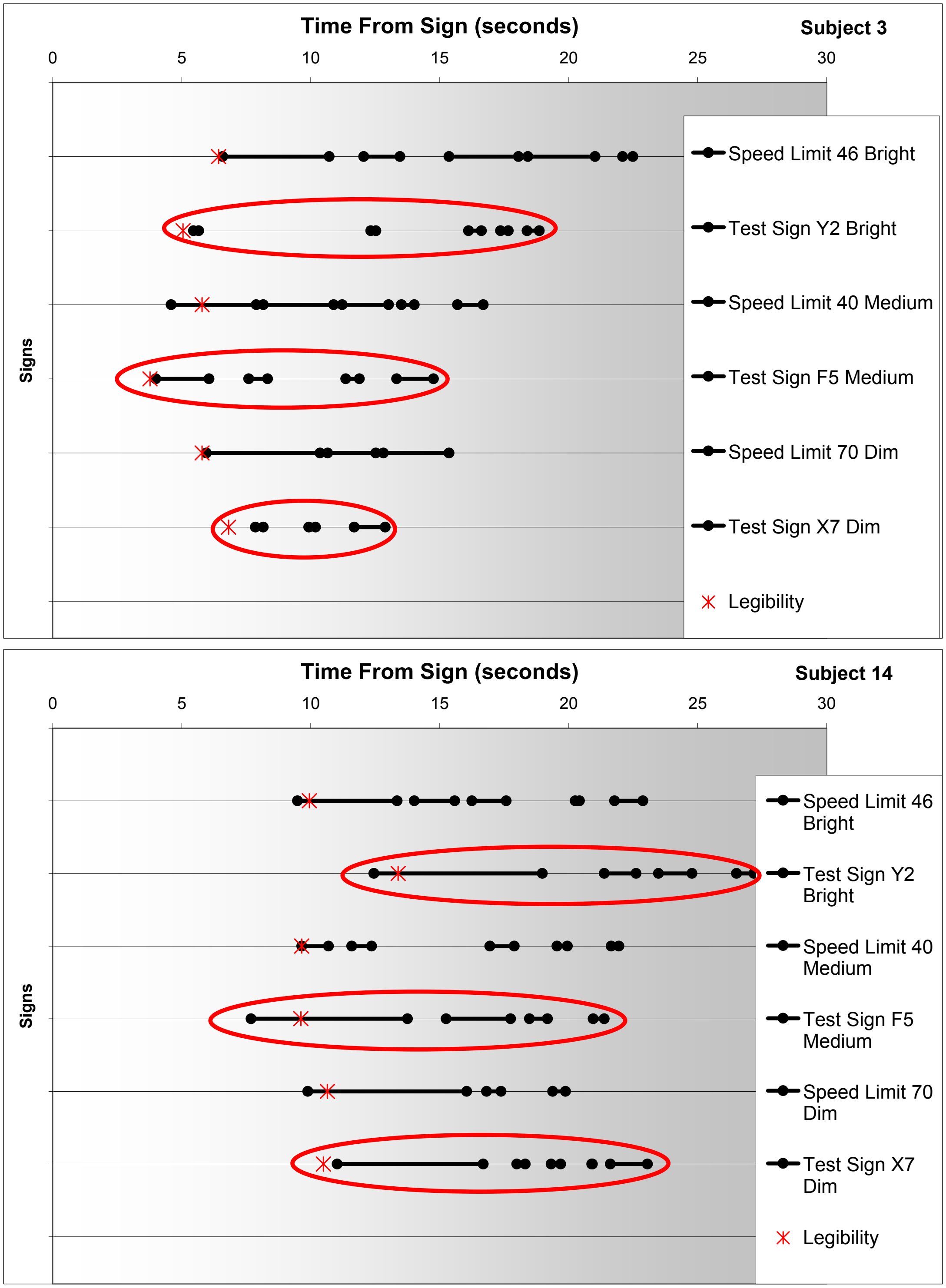


Figure 39. Glance Plots by Subject

By Subject

Another way of visualizing the data is through each subject's eyes. Figure 39 presents the viewing behavior for subjects 3 and 14 and illustrates several key aspects of this analysis. First, by comparing the two subjects' graphs, it is apparent that each driver views the signs differently. The glances for subject 3 all appear to shift closer to the sign compared to those for subject 14. Both subjects have 20/20 vision or better which leads the author to attribute the difference to the tendencies of each driver. If the author were to group all of the data together rather than to pair it by subject, this unique viewing behavior would be ignored.

In addition to the inconsistencies between different subjects, the subject's viewing behavior for each sign presents considerable variability. The data for subject 3 reveal a particularly interesting trend. For the brighter signs, the glances start earlier than for the dimmer signs, most likely due to the increased conspicuity of the signs. However, for the signs on the Silver Hill course (circled on the plots) not only do the glances start later, but the glances are much shorter than for the closed course signs. Although not all subjects follow this trend, these graphs show promise in leading to the confirmation of several beliefs about sign viewing behavior.

Descriptive Statistics

The next step was to calculate several parameters from the glance data for each sign to justify the normality assumption for using a paired *t*-test. Table 5 provides the mean and standard deviation for the total number of glances, total glance durations, and legibility distances for the six Speed Limit format. The minimum and maximum values for individual glances are also given with a calculated average length of glance. Tables including all of the data are included in Appendix C.

Several observations arise from these macroscopic parameters of the data. First, the range of mean values for the number of glances was one glance (4.13-5.13). Such a narrow range limits the possibility of significant variation in the number of looks based on sign luminance. Also, this many glances does not support previous research describing two- or three-look models. Also, the endpoints of the range correlate with the dim signs on the closed and open courses, respectively, which shows the lack of consistency between sign luminance and the number of glances. The parameters for the number of glances do not present any trends based on the brightness of the signs. The values for total glance duration, on the other hand, do present a trend. For each of the courses, one sign attracts the highest duration while the other two attract similar durations. For the closed course, the mean total glance duration for bright sign was over eight seconds whereas the mean durations for the medium and dim signs were 6.45 and 6.43 seconds, respectively. The open course mean durations, however, favored the medium brightness sign with over nine seconds while the other signs' durations were just below eight seconds. These results predict that drivers look at brighter signs longer. Joining the data for the total number of glances and total duration reveals that the individual glance durations for drivers on the open course were consistently greater than or equal to those on the closed course. Also, the brighter signs required a longer average individual glance duration. The amount of time a driver looks away from the road ahead should be minimized. These generalized results would advocate using dim sign sheeting to minimize glance duration. The paired testing used for the hypothesis tests accounts for each driver's unique viewing behavior.

Table 5. Descriptive Statistics

Number of Glances

	bright **SL-46**	bright **TS-Y2**	medium **SL-40**	medium **TS-F5**	dim **SL-70**	dim **TS-X7**
mean	4.73	4.13	5.06	4.31	4.13	5.13
median	5	4	5	4	4	4
st dev	2.05	1.41	1.61	1.14	1.36	2.33
n	15	15	16	16	16	15

Total Glance Duration (s)

	bright **SL-46**	bright **TS-Y2**	medium **SL-40**	medium **TS-F5**	dim **SL-70**	dim **TS-X7**
mean	8.37	7.89	6.45	9.19	6.43	7.98
median	8.90	7.76	6.20	9.46	6.51	7.96
st dev	2.43	2.81	2.35	1.78	1.66	2.85
n	15	15	16	16	16	15

Minimum, Maximum, and Average Length of Glance (s)

	bright **SL-46**	bright **TS-Y2**	medium **SL-40**	medium **TS-F5**	dim **SL-70**	dim **TS-X7**
Minimum	0.04	0.06	0.13	0.17	0.16	0.03
Maximum	5.80	9.82	5.13	8.50	6.16	7.57
Average	1.77	1.91	1.27	2.13	1.56	1.56

Legibility Distance (ft)

	bright **SL-46**	bright **TS-Y2**	medium **SL-40**	medium **TS-F5**	dim **SL-70**	dim **TS-X7**
mean	368	357	406	309	409	291
median	390	383	441	327	431	298
st dev	80	99	116	90	99	77
n	15	15	15	15	15	15

The parameters for the legibility distance data produced the most defined trends. On the closed course, legibility distance increased as luminance decreased. This trend is counterintuitive as one would expect legibility distance to decrease as a sign becomes less bright as shown by Schieber, et al. (*34*). However, beyond some level, an increased brightness tends to wash out the legend making it more difficult to read. It is possible that the brightest sign on the closed course presented such a situation, thereby decreasing its legibility distance. Conversely, on the open course, legibility distance increased with luminance. Schieber, et al. reported a 17 to 24 percent reduction in the legibility distance as the retroreflectivity of the sign was decreased from 100 to 15 percent. The data presented in Table 6 show a decrease in luminance from the brightest sign reduced the average legibility distance of each subject by 13 to 16 percent. The complete tabulated calculations are provided in Table 23 in Appendix C. There is a sharp change in the legibility distance between the bright sign and the medium and dim signs. The reduction in luminance from the medium brightness sign to the dim sign resulted in only a one percent decrease in legibility distance. A closer look and trends or lack of trends for the glance data follows.

Table 6. Effect of Sign Brightness on Legibility Distance

Average Reduction in Legibility Distance		
	Course	
Comparison	Closed	Open
Bright to Medium	-16%	13%
Bright to Dim	-16%	16%
Medium to Dim	-4%	1%

Hypothesis Testing

As stated in the objectives, the author tested three sets of hypotheses to evaluate the effect of sign brightness on driver viewing behavior. The tests assess whether a brighter sign changes the number of times a driver glances at a sign, changes the amount of time a driver fixates on a sign, or changes the distance at which the sign can be read. Within each of those three main hypotheses are three specific tests comparing the three brightness levels of the signs: bright, medium, and dim. The signs used for the testing are SL-46, SL-70, SL-40, TS-X7, TS-F5, and TS-Y2. Within these six signs there are three different comparisons that can be made. Not only can the three brightnesses be compared for both the closed and open courses, but the driver's viewing behavior can be evaluated for each brightness between the closed and open courses. A series of paired *t*-tests was carried out analyzing each of these scenarios.

Paired data are those with which a third variable "pairs" the data into units. In addition to the experimental variables of the signs and their brightness levels, the experimental units themselves represent the third variable as illustrated by the graphs in Figure 38. Pairing the data serves to reduce the effects of variability between the experimental units.

$$D_i = x_{ij} - x_{ik}$$ **Equation 4**

$$H_o : \mu_D = \Delta_0$$

$$H_a : \mu_D > \Delta_0 \text{ or } H_a : \mu_D < \Delta_0$$

$$\text{where } \Delta_0 = 0$$

$$\text{Rejection region: } t \geq t_{\alpha,n-1}$$

$$t = \frac{\bar{d} - \Delta_0}{s_D / \sqrt{n}}$$ **Equation 5**

For each comparison between two signs, the author has tested the difference (D_i, Equation 4) between the two observations in a pair (x_{ij}, x_{ik}). For example, the difference in total glances for each subject (*i*) between a bright and a dim sign (*j, k*) will be calculated. The average of these values (μ_D) became the parameter being tested. If the average of the differences is zero ($\Delta_0=0$), there is no difference between the observations. The generic null and alternative hypotheses used for each of the analyses are stated above. The test statistic was calculated as shown in Equation 5 where $\overline{d}$ is the mean difference over all of the subjects, s_D is the standard deviation of the differences, and n is the number of observations. Table 7 provides several common $t_{\alpha,n-1}$ values used during this analysis. A probability of error (α) of 0.05 was chosen for the analyses conducted. The symmetric nature of the t-distribution results in similar t-values whether the alternative hypothesis is stated as greater than or less than. For example, if a negative value is calculated as the test statistic and its absolute value is greater than the t-value, the opposite of the alternative hypothesis is true, or dim is greater than bright. An example of the calculations is provided in Table 8.

Table 7. Values for Paired *t*-Test

$t_{\alpha,n-1}$ Values	
$t_{0.05,15}$	1.753
$t_{0.05,14}$	1.761
$t_{0.05,13}$	1.771

Number of Glances

The first set of tests compares the total number of glances by a subject to a test sign. Table 8 shows an example of the data used to calculate the test statistic for the closed course signs. The top row of the table defines the two signs being compared. For each test, the null hypothesis states that drivers look at the brighter sign the same number of times as the dimmer sign, or H_0: $\mu_B - \mu_D = 0$, and the alternative hypothesis for a positive difference states that subjects look at the brighter signs more often than the dimmer ones, or H_A: $\mu_B - \mu_D > 0$. Table 9 provides the parameters and test statistics for the closed and open road signs and the comparison between the two courses.

Table 8. Total Number of Glances: Closed Course

	bright-dim SL46 - SL70	bright-medium SL46 - SL40	medium-dim SL40 - SL70
Subj.	D_i	D_i	D_i
1			2
2	1	1	0
3	1	-1	2
4	1	-1	2
5	-4	-4	0
6	0	1	-1
7	0	-3	3
8	-1	3	-4
9	0	-1	1
10	0	-3	3
11	0	-2	2
12	4	4	0
13	1	1	0
14	0	0	0
15	-1	-1	0
16	6	1	5
μ_D=	0.53	-0.33	0.94
s_D=	2.23	2.23	2.05
n=	15	15	16

The number of times a driver looks at a sign can relate to any number of factors. A driver may use a distant sign to gauge their speed or rate of approach, to check the sign for applicability (such as looking for a route marker and disregarding a mile marker), or to actually read the sign. As a result, the author did not expect the number of glances to a sign to change significantly due to the brightness of the sign. Although the medium brightness sign on the closed course attracted a statistically significant greater number of glances than the dim sign ($\alpha = 0.05$), the same wasn't true between the other brightness comparisons. Further, the *P*-value of the test between the medium and dim signs is 0.0435, indicating a narrow margin of significance. These factors lead the author to believe the number of looks does not consistently differ as a function of sign luminance within the region of interest of 900 feet.

However, the differences for the signs on the Silver Hill Course are more defined. The dim sign on Silver Hill Road attracted a significantly higher number of glances than both the medium sign (*P*-value of 0.0442) and the bright sign (*P* -value of 0.0247). During real-world driving scenarios, drivers look more often at dim signs than bright ones to gather the same information. This increase in the number of glances to the dim signs is expected to be caused by the driver's inability to see the sign sufficiently to read the legend and therefore continually "checking back" to the sign. Also of note is that the comparison between the medium and dim sign is reversed between the closed and open courses. On the runway course, the medium signs were shown to attract more looks at an α of 0.05; however, on the Silver Hill course, the dim sign attracted more glances at the same level.

Table 9. Total Number of Glances Statistics

	Closed Course		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	SL46=SL70	SL46=SL40	SL40=SL70
μ_D=	0.53	-0.33	0.94
s_D=	2.23	2.23	2.05
n=	15	15	16
	T-STAT	**T-STAT**	**T-STAT**
	0.926	-0.580	1.831
$t_{\alpha,n-1}$	1.761	1.761	1.753
Rej H_0:	No	No	Yes
	Open Road		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	TSY2=TSX7	TSY2=TSF5	TSF5=TSX7
μ_D=	-1.15	-0.20	-0.87
s_D=	1.99	1.21	1.81
n=	14	15	15
	T-STAT	**T-STAT**	**T-STAT**
	-2.166	-0.642	-1.857
$t_{\alpha,n-1}$	1.771	1.761	1.761
Rej H_0:	Yes	No	Yes
	$\bar{d}$: Closed Course – Open Road		
	bright	medium	dim
H_0:	SL46=TSY2	SL40=TSF5	SL70=TSX7
μ_D=	0.71	0.75	-1.13
s_D=	1.68	1.61	2.36
n=	14	16	15
	T-STAT	**T-STAT**	**T-STAT**
	1.587	1.861	-1.863
$t_{\alpha,n-1}$	1.771	1.753	1.761
Rej H_0:	No	Yes	Yes

The glance data also provide another excellent example of the importance of paired testing. As shown in Figure 40, the mean number of glances for each sign does not differ by very much, particularly for the open road signs. With average looks between the three signs confined to a range of one look (4.13-5.13) as shown by the diamonds within each of the box plots, the difference between the bright and dim sign would be nearly impossible to prove without accounting for the behavior of each driver with paired testing. According to Table 9, the dim signs attract a greater number of looks than both the bright and medium signs on the open road. A comparison based on the means and variation shown in Figure 40 would not reach this same conclusion. It is interesting to note that the range illustrated in the box plots decreases with sign brightness on the closed course but increases as the brightness decreases on the open course. At lower luminance levels, there is more variability in the number of looks directed at a sign for the open road course. A decrease in sign luminance does not consistently alter the number of looks made by the driver.

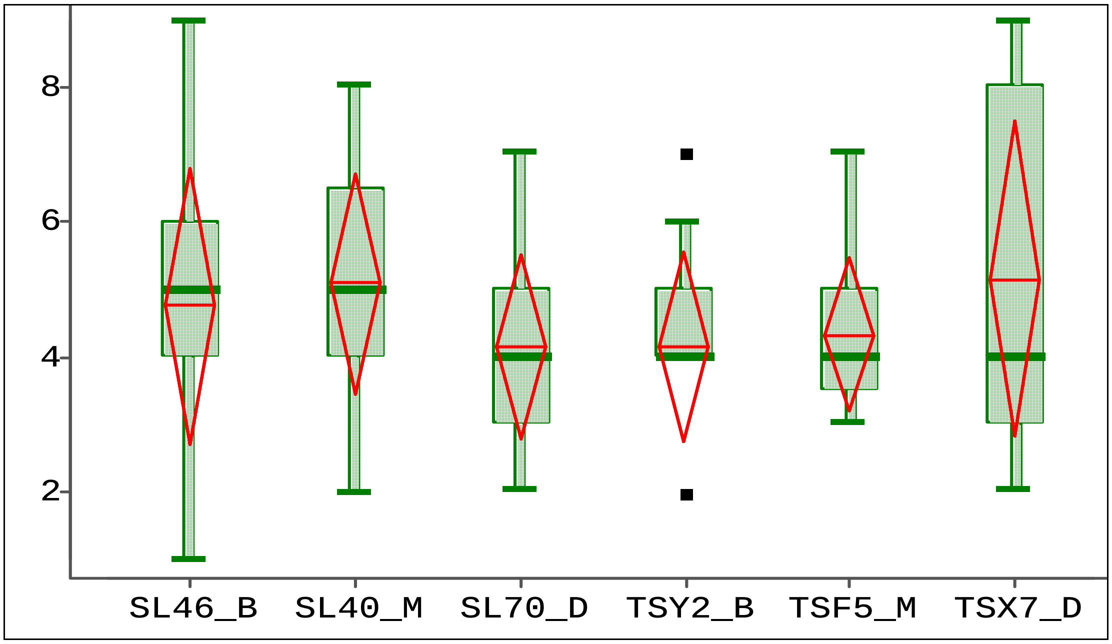


Figure 40. Mean Total Number of Glances

Total Glance Duration

The results presented in the previous section become even more interesting when combined with the total glance duration. The second set of null hypotheses state that the total glance duration for the bright, medium, and the dim signs are the same. Accordingly, the alternative hypotheses state that the total glance duration for the brighter signs is greater than or less than that for the dimmer signs. This relates to the driver spending more or less time fixated on the brighter signs. Table 10 provides the statistics for the total glance duration for each of the closed course, open road, and closed versus open course comparisons.

The total glance duration dedicated to a sign is perhaps one of the most critical measures of the sign's efficiency. If a driver must concentrate on a sign for a relatively long period of time to identify its legend, he may become distracted from the primary task of driving. A recent news article cited research that found a driver's likelihood of being involved in a crash doubled when he or she looked away from the road for two seconds or longer (*38*). The optimum performance of a sign, therefore, would be a lower total glance duration. Recall from the previous section that the bright sign on the closed course did not attract any more looks than either the medium or dim signs. Although the difference in the number of looks were not statistically significant, the total glance duration for the bright sign is significantly greater than both the medium and dim signs with *P*-values approaching 0.01. It should be noted that the medium sign also tended to require a longer duration than the dim sign, though not statistically significant with a *P* -value of only 0.48. The combination of these two measures (equal looks but greater duration) suggests that the individual looks by the driver were longer for the bright sign than for the medium and dim signs on the closed course. This implies that the dimmer signs perform better on the closed course. The open road signs, however, produce different results.

Table 10. Total Glance Duration Statistics

	Closed Course		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	SL46=SL70	SL46=SL40	SL40=SL70
μ_D=	1.78	1.88	0.03
s_D=	2.79	2.86	2.49
n=	15	15	16
	T-STAT	**T-STAT**	**T-STAT**
	2.470	2.547	0.044
$t_{\alpha,n-1}$	1.761	1.761	1.753
Rej H_0:	Yes	Yes	No
	Open Road		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	TSY2=TSX7	TSY2=TSF5	TSF5=TSX7
μ_D=	-0.10	-1.23	1.07
s_D=	2.84	2.11	2.24
n=	14	15	15
	T-STAT	**T-STAT**	**T-STAT**
	-0.137	-2.255	1.848
$t_{\alpha,n-1}$	1.771	1.761	1.761
Rej H_0:	No	Yes	Yes
	$\bar{d}$: Closed Course – Open Road		
	bright	medium	dim
H_0:	SL46=TSY2	SL40=TSF5	SL70=TSX7
μ_D=	0.02	-2.74	-1.56
s_D=	3.99	2.76	2.92
n=	14	16	15
	T-STAT	**T-STAT**	**T-STAT**
	0.022	-3.973	-2.059
$t_{\alpha,n-1}$	1.771	1.753	1.761
Rej H_0:	No	Yes	Yes

Once again, the Silver Hill signs produced conflicting results to those on the runways. On the open road, the medium sign collected the highest total glance duration exceeding both the bright and dim signs. Perhaps even more interesting than the shift in focus to the medium brightness sign is the relationship between the bright and dim signs on the Silver Hill course. As listed in Table 10, the null hypothesis stating the bright and dim signs have the same total glance duration cannot be rejected at an α of 0.05. The difference between the two durations is not large enough to be significant. The author expected the relative glance durations from the closed course to match those from the open road course. Further, on average, the total glance duration for the medium and dim signs on the open road course are both higher than those on the closed course as illustrated in Figure 41. This could be attributed to two factors. First, it may mean that drivers do look longer at signs in real world scenarios than on a closed course. Alternatively, the design of the test signs may have affected the driver's total glance duration. The driver's inability to read an alphanumeric legend rather than a typical speed limit could have increased the driver's total glance duration. These differences have spurred a comparison between the two courses that will be discussed later in this section.

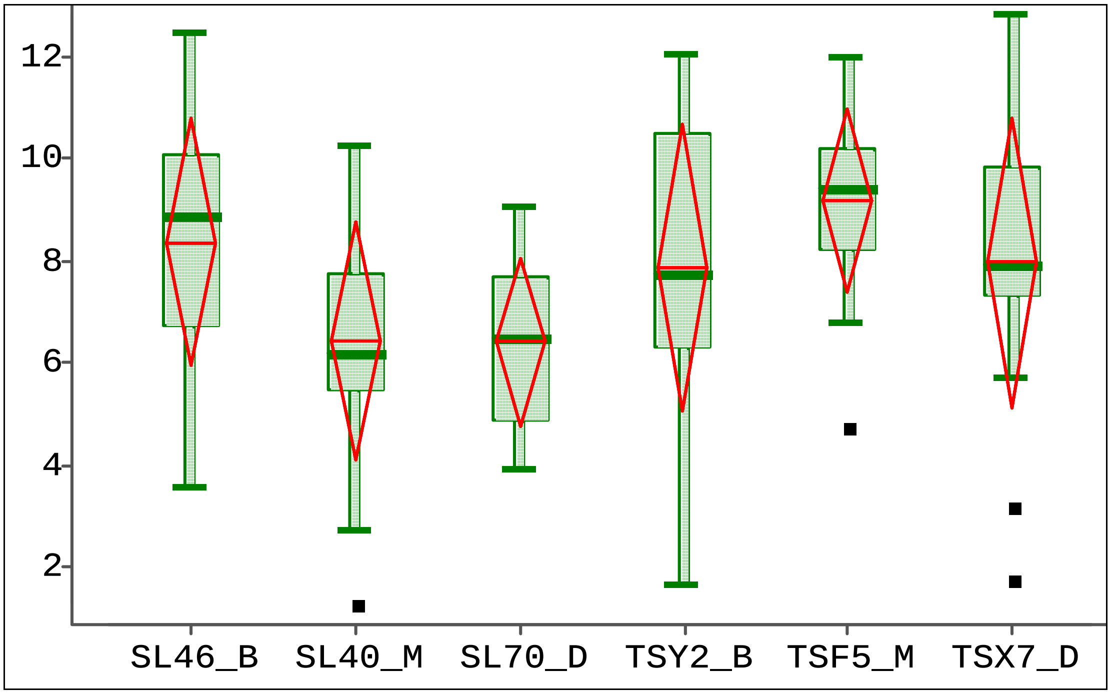


Figure 41. Means of Total Glance Durations

Legibility Distance

The final objective of this thesis was to compare the mean legibility distances for the bright, medium, and dim signs. The goal of these tests was to determine what affect, if any, the change in sign brightness and driver viewing behavior had on the legibility of the sign. By combining the results of the number of glances and glance duration tests with the legibility tests, the author can compare whether a sign with longer viewing time or more frequent glances has an increased legibility distance. Table 11 lists the parameters and test statistics for the three comparisons.

The previous results have shown that as the number of glances increases, the total glance duration typically tends to increase. How do these two measures affect the legibility of the sign? For the signs on the runway course, there is not a statistically significant difference in the legibility distance of the bright, medium, and dim signs. Despite the medium signs having more glances and the bright signs drawing a longer duration, none of the signs had a significantly longer or shorter legibility distance. Figure 42 shows the

Table 11. Legibility Distance Statistics

	Closed Course		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	SL46=SL70	SL46=SL40	SL40=SL70
μ_D=	-40.87	-37.60	-3.27
s_D=	110.64	130.29	44.36
n=	15	15	15
	T-STAT	**T-STAT**	**T-STAT**
	-1.431	-1.118	-0.285
$t_{\alpha,n-1}$	1.761	1.761	1.761
Rej H_0:	No	No	No
	Open Road		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	TSY2=TSX7	TSY2=TSF5	TSF5=TSX7
μ_D=	66.07	47.87	18.20
s_D=	67.93	46.11	64.77
n=	15	15	15
	T-STAT	**T-STAT**	**T-STAT**
	3.767	4.021	1.088
$t_{\alpha,n-1}$	1.761	1.761	1.761
Rej H_0:	Yes	Yes	No
	$\bar{d}$: Closed Course – Open Road		
	bright	medium	dim
H_0:	SL46=TSY2	SL40=TSF5	SL70=TSX7
μ_D=	11.60	97.07	118.53
s_D=	56.01	113.96	116.33
n=	15	15	15
	T-STAT	**T-STAT**	**T-STAT**
	0.802	3.299	3.946
$t_{\alpha,n-1}$	1.761	1.761	1.761
Rej H_0:	No	Yes	Yes

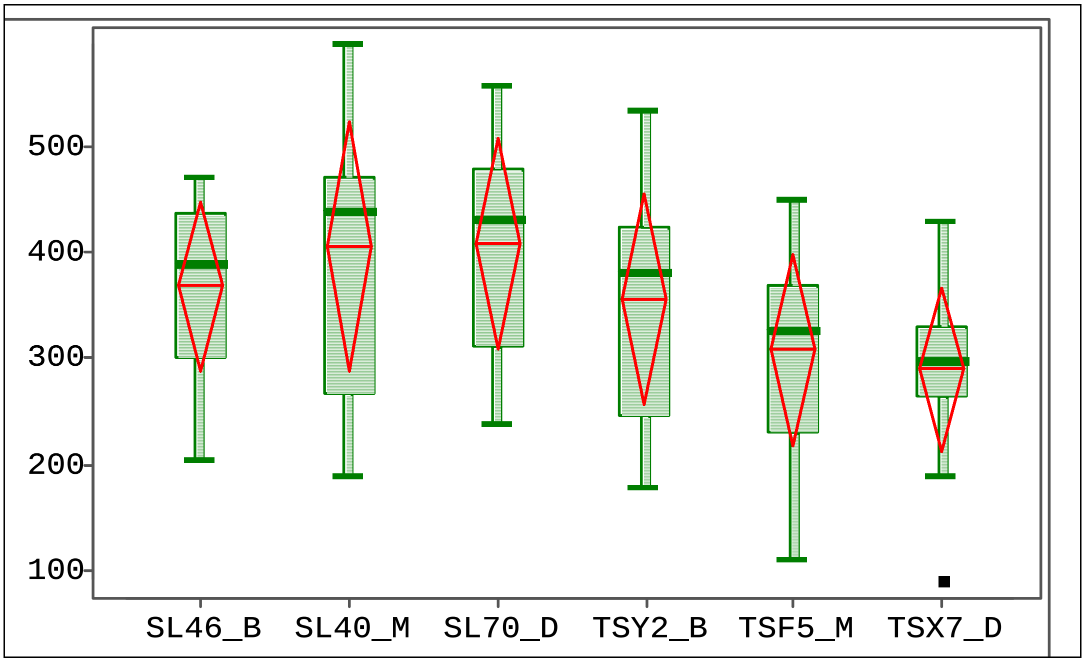


Figure 42. Mean Legibility Distances

similarities between the mean legibility distances. This figure illustrates an interesting trend. As luminance decreases on the closed course, the mean legibility distance increases whereas it decreases on the open road course.

On the Silver Hill course, the bright sign clearly had the greatest legibility. The bright sign had a longer legibility distance than both the medium and dim signs with highly significant *P* -values of less than 0.005. Recalling that the bright sign attracted the least number of glances and the lowest total glance duration, it was unexpected for the bright sign to have a longer legibility distance. The disparity between these results may suggest an optimum viewing situation: one in which the looks and duration are minimized for a longer legibility distance. This theory, however, cannot be proven by the data presented in this thesis.

Closed Course versus Open Road Testing

Throughout this section, implicit comparisons have been made between the runway course and the Silver Hill course. Now an explicit comparison is made between each of the bright, medium, and dim signs on the closed course with their counterparts on the open road for each of the three measures of effectiveness. A comparison between laboratory and real-world testing serves to assess the impact of on-road driving techniques and behavior on the results of this thesis.

The difference that leaps to the front of this discussion is actually the lack of a difference. A comparison between the two brightest signs for each of the measures of number of glances, total glance duration, and legibility distance reveals no statistically significant difference at an α of 0.05. Although the total number of glances for the bright sign on the closed course can be considered greater than the number of looks on the open road at a lower confidence level (p-value of 0.068), the author cannot reject the hypothesis that the two values are the same. This finding is most intriguing because of the apparent differences observed in the earlier tests.

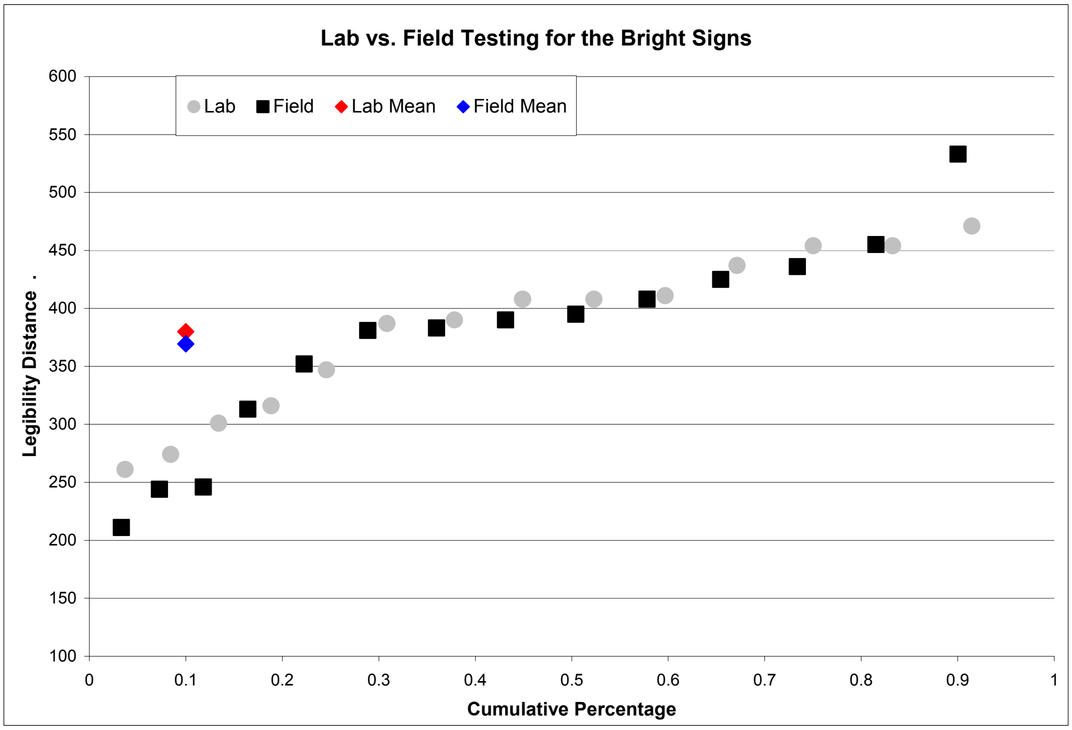
For the other signs, however, the differences aren't so slight. For the total number of glances, for instance, the medium sign for the closed course attracted a greater number of looks than did the corresponding sign on Silver Hill Road. In contrast, the Silver Hill dim sign garnered more looks than the runway sign. Despite drawing fewer looks, the medium Silver Hill sign brought a longer total glance duration than the runway sign with a P -value of less than 0.001. Fewer looks with a longer duration may result in longer individual glances for the medium open road sign. The dim sign, on the other hand, follows its trend with the Silver Hill sign by drawing a longer total glance duration than the runway sign.

Even though the results varied for the glance statistics, both the medium and dim runway signs had significantly longer legibility distances than the open road signs. With average differences of 97 and 118 feet and P -values of 0.002 and 0.0007 for the medium and dim signs, respectively, the effect of the open road on driving behavior and performance is convincing. The significance of these differences can be linked with some of the research discussed earlier.

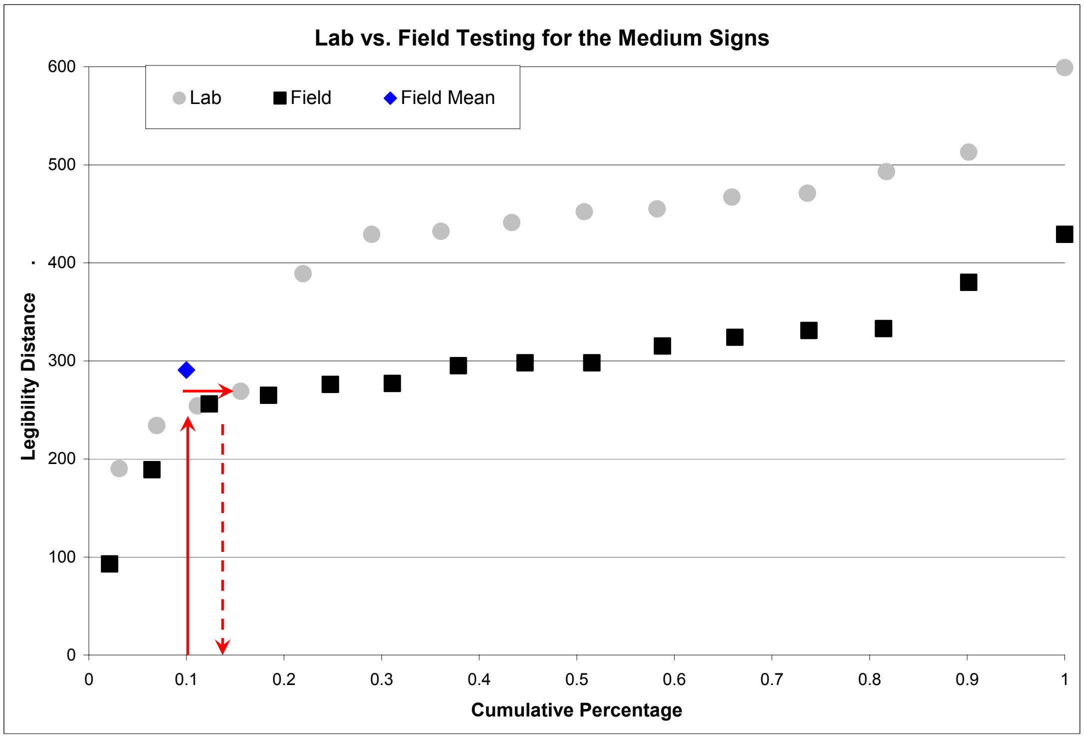
As stated in the literature review, Olsen and Bernstein found that their 90th percentile performance for the laboratory data equated well with the mean field performance, meaning subjects performed better in the lab setting than in the field (*13*). A similar comparison is performed here. As shown in Figure 43, the 90th percentile of performance equates to the 10th percentile of legibility distance (90% of the drivers had a shorter legibility distance). Assuming the runway acts as a laboratory setting, the 90th percentile runway legibility distance is well below the mean of the open road data for both the medium and dim signs. For the medium brightness sign, in fact, the 90th percentiles are nearly equal at 255 feet.

The plots in Figure 43 show the similarities between the testing done on the Riverside Test Facility and that accomplished on public roads. The bright signs, for example, have similar legibility distances on both courses. For the medium and dim signs, on the other hand, the legibility distance for a given percentile driver is greater on the closed course than on the open road. The arrows on graphs represent the relationship of the 90th percentile legibility distance on the closed course with the open road results.

The interpretation of the data provided in this section was intended to shed light on several aspects of nighttime driving. Sign luminance has been shown to have an effect on the number of glances a driver makes to the sign, the total amount of time a driver fixates on a sign, and the distance at which the driver is able to read that sign. Further, introducing real-world driving scenarios has been shown to impact sign viewing behavior, as well.

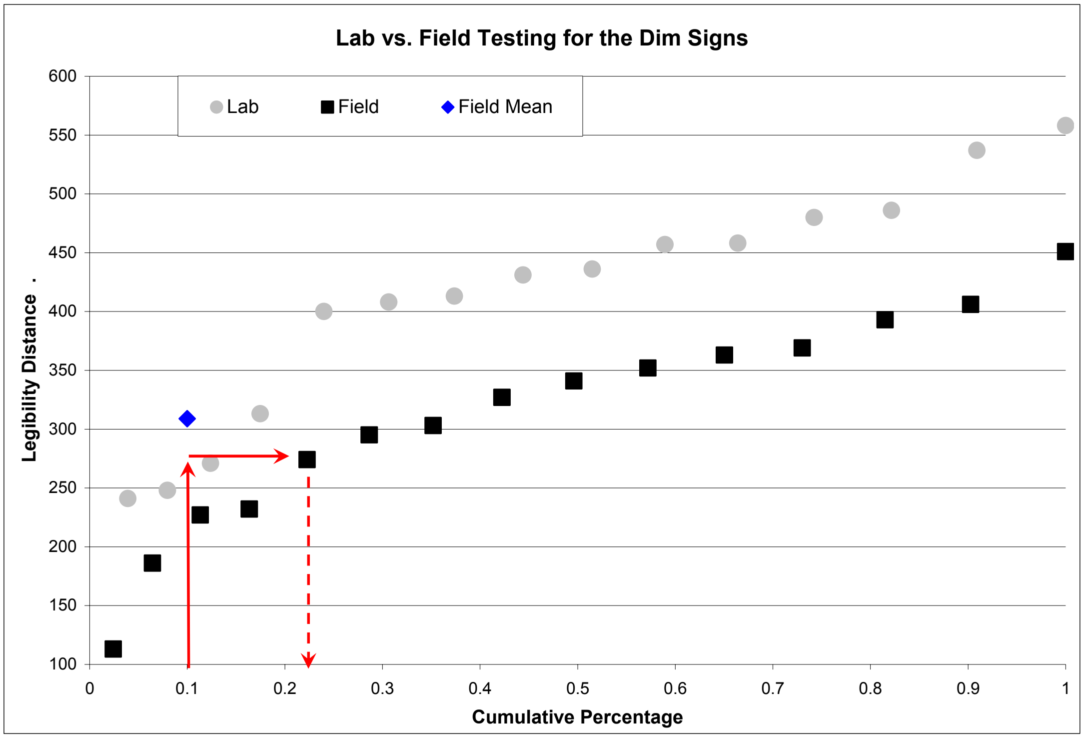


(a)



(b)

Figure 43. Lab versus Field Testing



(c)
Figure 43. Continued

Driver Glance Characteristics

Another aspect of driver sign viewing behavior that may be affected by the brightness of a sign is the effect of that brightness on the individual glances made by the driver. As shown by the glance plots in Figure 39 and in Appendix B, the subject typically made several initial glances to a sign followed by at least one relatively long glance. In theory, these glances were attempts to determine the type of sign or to check the legibility of the message. Once the sign legend became legible, a longer glance was necessary to read the message. How was this long glance affected by the luminance of the sign?

The author developed two methods to quantify the amount of time dedicated to the sign during this longer glance. The first test uses the last glance made by the subject at each of the Speed Limit format signs and the other uses the longest glance made by the subject. Table 12 provides a summary of the last and longest looks made. The average values presented in the table tend to favor the medium brightness sign on both the closed and open courses based on the length of individual glances. With the exception of the maximum look duration on the open road, the medium brightness signs have the lowest values, indicating a shorter glance to the sign and therefore more attention to the road ahead. The performance of the medium brightness signs could be a result of contrast of the sign. The bright sign may produce too much contrast and the dim sign too little, which leads to an ideal contrast presented by the medium brightness signs. This contrast makes the legend easier to distinguish and therefore require a relatively shorter glance to read.

Recalling that the number of glances made by each subject to a particular sign was unique for each subject, an attempt is made to normalize the glance data. As a result, a ratio of the “last look” glance duration and the total glance duration for each subject has been calculated. A comparison of these values using the paired t-test is provided in Table 13. A complete tabulation of the ratios are provided in Appendix C.

Table 12. Last and Maximum Look Summary Statistics

	bright	bright	medium	medium	dim	dim	
	SL-46	**TS-Y2**	**SL-40**	**TS-F5**	**SL-70**	**TS-X7**	
mean	2.89	2.59	2.16	2.49	3.70	3.49	Last Look Duration (s)
median	2.60	2.47	2.02	1.40	3.15	3.70	
st dev	1.48	1.49	1.26	2.62	2.32	2.59	
n	16	16	16	15	16	15	
mean	38%	41%	36%	32%	39%	42%	Last Look / Total Duration
median	36%	37%	35%	18%	37%	35%	
st dev	24%	21%	21%	32%	22%	29%	
n	15	16	16	15	16	15	
mean	3.52	3.33	2.70	3.99	4.40	4.10	Maximum Look Duration (s)
median	3.59	3.08	2.92	3.30	3.64	4.00	
st dev	1.27	1.29	1.15	1.88	1.86	2.27	
n	15	16	16	15	16	15	
mean	45%	51%	44%	52%	48%	51%	Maximum Look / Total Duration
median	39%	50%	42%	42%	43%	50%	
st dev	21%	14%	16%	21%	16%	21%	
n	15	16	16	15	16	15	

Table 13. Last Looks versus Total Durations

	Closed Course		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	SL46=SL70	SL46=SL40	SL40=SL70
μ_D=	-0.04	0.00	-0.04
s_D=	0.29	0.24	0.27
n=	15	15	16
	T-STAT -0.512	**T-STAT** -0.024	**T-STAT** -0.603
$t_{\alpha,n-1}$	1.761	1.761	1.753
Rej H_0:	No	No	No
	Open Road		
$\bar{d}$	bright-dim	bright-medium	medium-dim
H_0:	TSY2=TSX7	TSY2=TSF5	TSF5=TSX7
μ_D=	0.11	0.04	0.05
s_D=	0.38	0.35	0.26
n=	14	15	15
	T-STAT 1.106	**T-STAT** 0.428	**T-STAT** 0.751
$t_{\alpha,n-1}$	1.771	1.761	1.761
Rej H_0:	No	No	No
	$\bar{d}$: Closed Course – Open Road		
	bright	medium	dim
H_0:	SL46=TSY2	SL40=TSF5	SL70=TSX7
μ_D=	-0.05	-0.03	0.10
s_D=	0.33	0.29	0.31
n=	14	16	15
	T-STAT -0.548	**T-STAT** -0.434	**T-STAT** 1.224
$t_{\alpha,n-1}$	1.771	1.753	1.761
Rej H_0:	No	No	No

The comparisons of last look ratios between the bright, medium, and dim signs on the closed and open courses reveal no statistical significance of the effect of luminance on last look duration. An interesting trend is present, however, for the two courses. The last look ratios for the medium and dim signs are greater than those for the bright and medium signs, respectively. That is, on the closed course, the driver's glances toward the bright and medium signs tend to draw a shorter last look relative to the total duration than their dimmer counterpart. The opposite is true for the signs on the Silver Hill course. On the open road, the last look ratios for the brighter signs (bright and medium) are typically greater than those for the dimmer signs (medium and dim, respectively). This indicates that drivers on the open road use a relatively longer last look for brighter signs than for dimmer ones.

Despite the consistent trends for each of the closed and open courses, there are no obvious differences in a comparison between the two. For bright and medium signs, the subjects had a relatively longer last look on the open road than on the closed course. However, the opposite is true for the dim signs. Based on the increased workload of on-road driving, the author expected all of the on-road last look ratios to be greater than the closed course ratios. With an increased workload, drivers were expected to only look at the signs as necessary, rather than dedicating extra time to view them.

An alternative method for evaluating the driver's glance behavior uses a different individual glance in the ratio. A closer look at the aforementioned glance plots reveals that many drivers' last look is a relatively short glance. For example, subject nine in the 70 mph Speed Limit plot (Figure 38) uses a short glance to read the sign only after a longer glance is completed. This short look may be all that is required to read the sign or could be a confirmation glance to verify a sign that was already read. Regardless of the reason, there may have been a glance other than the "last look" with a longer duration. The following comparisons form a ratio between the maximum individual glance duration and the total glance duration for each subject and are included in Table 14.

Table 14. Maximum Looks versus Total Durations

	Closed Course		
$\bar{d}$	bright-dim SL46 - SL70	bright-medium SL46 - SL40	medium-dim SL40 - SL70
$\mu_D=$	-0.06	0.01	-0.07
$s_D=$	0.25	0.21	0.23
n=	15	15	16
	T-STAT -0.963	**T-STAT** 0.262	**T-STAT** -1.291
	Open Road		
$\bar{d}$	bright-dim TSY2 - TSX7	bright-medium TSY2 - TSF5	medium-dim TSF5 - TSX7
$\mu_D=$	0.00	0.04	-0.06
$s_D=$	0.29	0.25	0.19
n=	14	15	15
	T-STAT -0.039	**T-STAT** 0.690	**T-STAT** -1.250
	$\bar{d}$: Closed Course – Open Road		
	bright SL46 - TSY2	medium SL40 - TSF5	dim SL70 - TSX7
$\mu_D=$	-0.07	-0.03	-0.01
$s_D=$	0.22	0.22	0.25
n=	14	16	15
	T-STAT -1.147	**T-STAT** -0.629	**T-STAT** -0.193

While these tests also did not reveal any statistically significant effects of luminance on driver sign viewing characteristics, the maximum look method produces different results than those reached by the last look ratio. For both the closed and open courses, the maximum look ratio for the dim signs was higher than those for both the bright and medium signs. Conversely, the bright signs exhibited relatively longer maximum look duration than the medium signs for both courses.

The expected results stated for the comparison between the closed and open courses in the last look analysis were achieved using the maximum look method. For each of the comparisons between the maximum look ratios for the bright, medium, and dim signs, the open course setting resulted in a greater ratio than that of the closed course. This means that drivers on the open road tend to make an individual longer glance that is a relatively large portion of the overall time dedicated to the sign. For example, assuming a driver requires a two second glance to effectively evaluate a sign and that glance is the longest made by the driver, a greater maximum look ratio refers to the open road driver having a lower total glance duration than the closed course driver and therefore spending less time fixated on the sign.

INDIVIDUAL GLANCE LUMINANCE

Building on the preceding analysis of evaluating the subjects' individual glance characteristics, an attempt was made to determine the relationship between the length of an individual glance and the luminance of the sign. The data compiled for this analysis consist of the duration of the individual glances for each of the three runway Speed Limit signs. The corresponding luminance of the glance was calculated using the regression equations, given in Figure 27, at the distance corresponding to the beginning of each glance. The first three graphs (Figure 44-Figure 46) represent the dim, medium, and bright Speed Limit signs on the closed course and Figure 47 is a compilation of the data for all three signs.

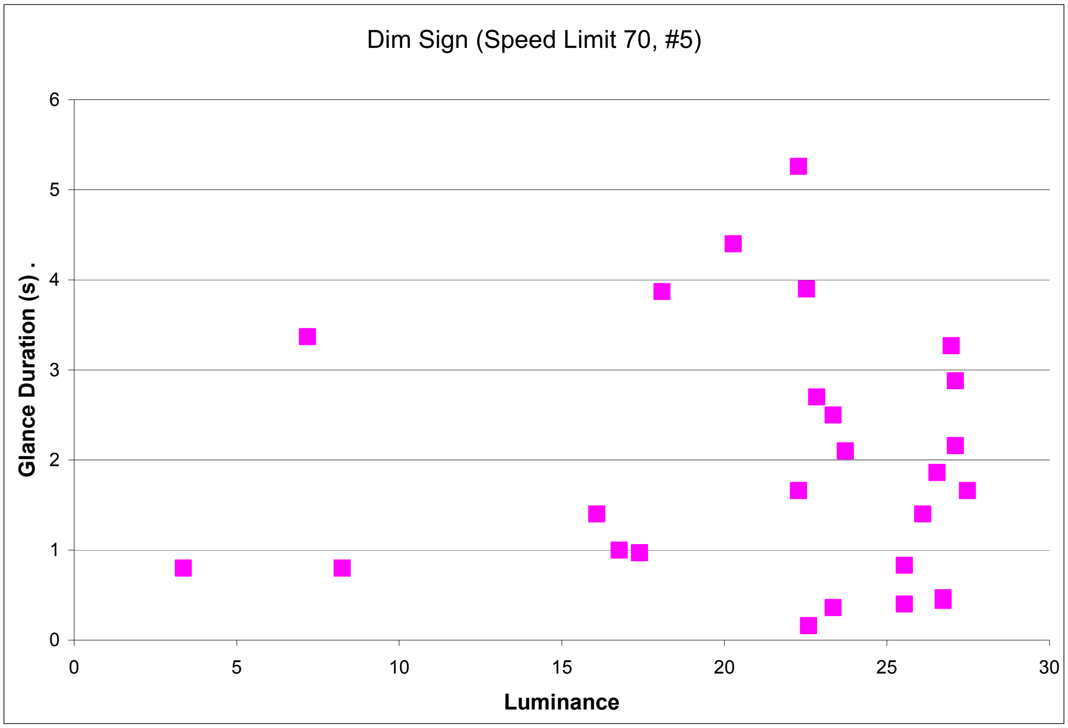


Figure 44. Glance Duration versus Luminance-Dim Sign

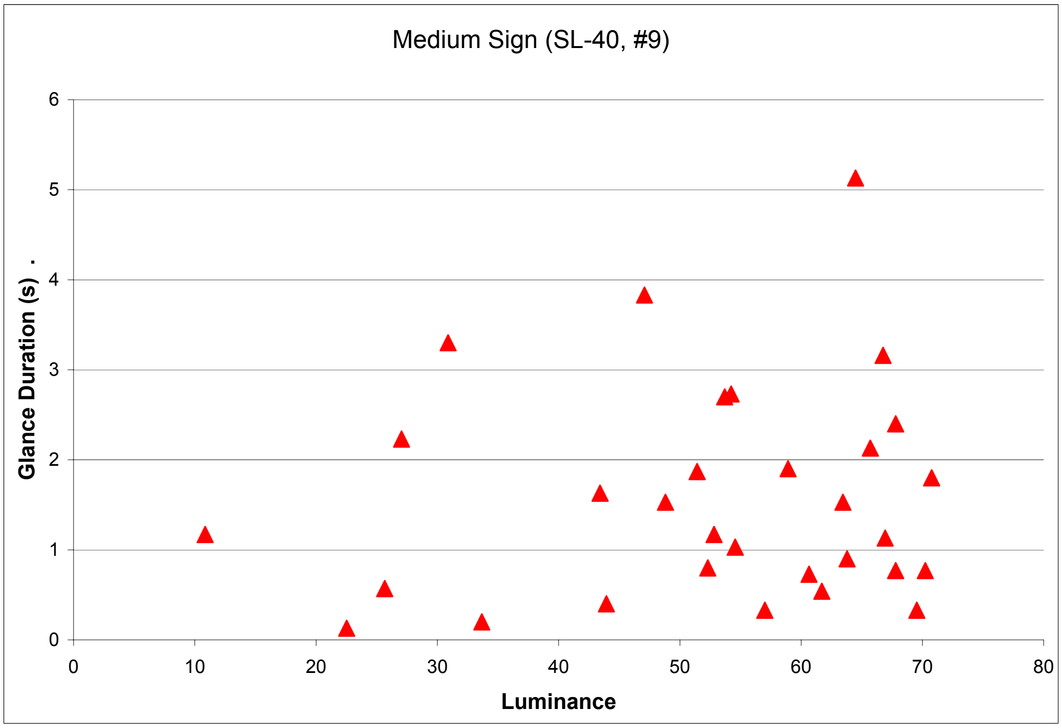


Figure 45. Glance Duration versus Luminance-Medium Sign

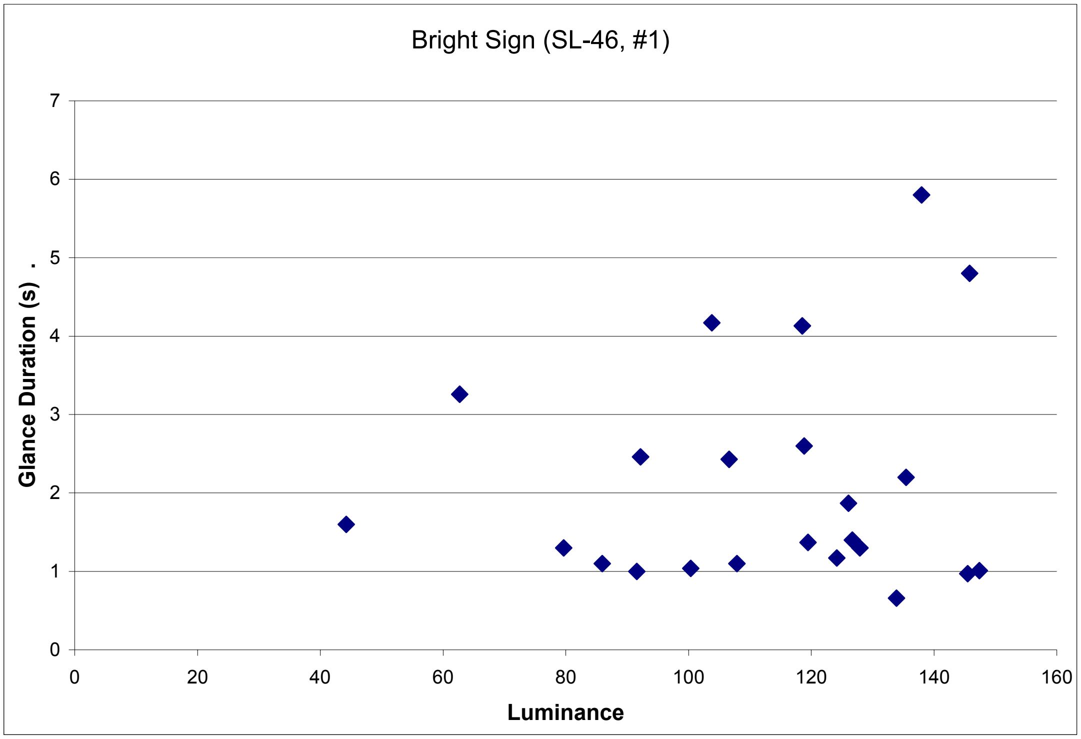


Figure 46. Glance Duration versus Luminance-Bright Sign

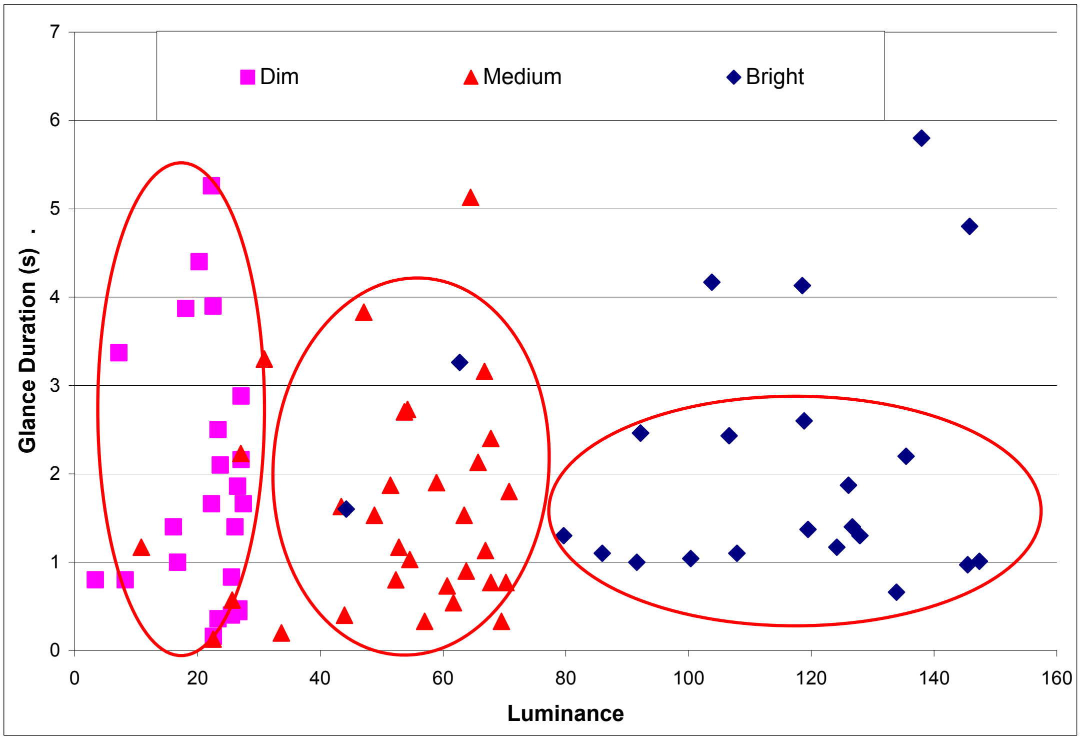


Figure 47. Glance Duration versus Luminance-Three Signs

At first glance, the individual scatter plots for the dim, medium, and bright signs appear very similar. Each of the datasets tend to exhibit lower glance durations for lower luminance levels then and higher durations begin to occur as the luminance increases. All of the glance durations do not increase with luminance, however. Despite several longer glances at higher luminance levels, the shorter glances continue regardless of the sign brightness. Although the individual scatter plots appear similar, a closer inspection reveals that they are plotted for different ranges. Each of the signs results in similar tendencies by the drivers but on a different scale.

Combining all of the data to one graph brings to light an interesting feature of the glance durations. For the most part, the data associated with each of the signs is segregated from those of the other signs. It is important to note that the graph including all three signs does not correspond to any distance scale. The dim sign, for example, reaches a luminance of 30 cd/m^2 at when viewed from 600 feet away. The same luminance level for the bright sign, on the other hand, occurs at a distance of approximately 225 feet due to the higher performance retroreflective sheeting. As the luminance scale climbs, however, the data seem to "flatten". The circles encompassing the bulk of each of the datasets are intended to aid the reader in visualizing this trend. The effect of luminance on the duration of individual glances offers another measure one could use to analyze nighttime driver needs but is out of the scope of this thesis.

Many of the findings presented in this section follow the assumptions made regarding the way drivers look at signs. Several of the results, however, stray from the commonly accepted assumptions of driver viewing behavior. The next section provides an explanation of the findings produced by the data used in this thesis.

RESULTS

This thesis has examined how drivers acquire information from traffic signs as a function of their brightness. Eye-tracking technology was used to follow the nighttime driver's eye movements during assigned tasks designed to replicate viewing situations with varying brightness levels. The six signs used for the analysis, three on a closed course and three on a public road, were classified in three relative brightness categories of bright, medium, and dim. Data relating to the beginning and end of each glance were recorded as well as the distance at which the sign became legible to the driver. Comparisons were made between the three brightness levels for the number of glances, total glance duration, and legibility distance of the sign. Further analyses were conducted to determine the effect of the testing environment on a driver's sign viewing behavior by comparing the results from the closed course with those from the open road.

The statistics presented in the previous section were subsequently interpreted to increase their usability. The following pages serve to translate the numbers presented earlier into relevant findings necessary to draw conclusions. Beginning with a discussion about the driver behavior recorded by the eye-tracker, this section relates what the data suggest to their role in sheeting selection.

DRIVER PERFORMANCE

The human eye is the primary sensory device for nighttime driving. In addition to analyzing the driver's sign viewing behavior, the author noticed several interesting trends among the test subjects. First, nearly all of the subjects' eyes began to drift as they fixated on the signs. At the beginning of the glance, the eyes maintain position on the sign. As the glance duration grows, however, the eyes start to float around the sign. The environmental conditions of this study made it apparent that the driver was still looking at the sign, but for studies with complex scenes (such as urban streets) this may make the video reduction more problematic.

Another noteworthy aspect of the drivers' viewing behavior is their individual tendency to look around. Several of the subjects' eyes were extremely active, keeping their glances very short throughout the experiment. Others tended to make fewer glances and fixate on each glance for as much as a half second or more. The contrast between these two types of subjects made the video reduction a perpetually shifting process. This contrast also impacts any recommendation made for sheeting design. Any decision made based solely on the number of glances made to a sign or the glance duration would fail to account for one of these types of drivers. As a result, recommendations will be derived from the interaction of following results rather the performance of a single measure of effectiveness.

RESEARCH FINDINGS

The variation in the results achieved between the closed and open road courses are remarkable. On the runway course, only three of the nine primary tests comparing the number of glances, total glance duration, and legibility distance of the bright, medium, and dim signs attained statistical significance as shown in Table 15. Further, the significant differences that were attained were counterintuitive to many expected outcomes. On the open course, on the other hand, six of nine tests produced statistically significant results, some of which required further inquiry into their basis.

Primary Measures

A common assumption made in sheeting selection is that brighter is better. One goal of this thesis was to provide evidence to support or refute this assumption. The author expected the data to follow a distinct pattern for each of the three measures of effectiveness. Table 16 provides the mean values for each of these measures.

Table 15. Summary of Analysis

		H_o	H_a	Statistic	$t_{0.05,n-1}$	Reject H_0?	Inference
Runway Course	Number of Glances	b = d	b > d	0.926	1.761	No	
		b = m	b < m	-0.580	1.761	No	
		m = d	m > d	1.831	1.753	Yes	m > d
	Total Glance Duration	b = d	b > d	2.470	1.761	Yes	b > d
		b = m	b > m	2.547	1.761	Yes	b > m
		m = d	m > d	0.044	1.753	No	
	Legibility Distance	b = d	b < d	-1.431	1.761	No	
		b = m	b < m	-1.118	1.761	No	
		m = d	m < d	-0.285	1.761	No	
Silver Hill Course		H_o	H_a	Statistic	$t_{0.05,n-1}$	Reject H_0?	Inference
	Number of Glances	b = d	b < d	-2.166	1.771	Yes	b < d
		b = m	b < m	-0.642	1.761	No	
		m = d	m < d	-1.857	1.761	Yes	m < d
	Total Glance Duration	b = d	b < d	-0.137	1.771	No	
		b = m	b < m	-2.255	1.761	Yes	b < m
		m = d	m > d	1.848	1.761	Yes	m > d
	Legibility Distance	b = d	b > d	3.767	1.761	Yes	b > d
		b = m	b > m	4.021	1.761	Yes	b > m
		m = d	m > d	1.088	1.761	No	
Closed Course vs. Open Course		H_o	H_a	Statistic	$t_{0.05,n-1}$	Reject H_0?	Inference
	Number of Glances	$b_c = b_o$	$b_c > b_o$	1.587	1.771	No	
		$m_c = m_o$	$m_c > m_o$	1.861	1.753	Yes	$m_c > m_o$
		$d_c = d_o$	$d_c < d_o$	-1.863	1.761	Yes	$d_c < d_o$
	Total Glance Duration	$b_c = b_o$	$b_c > b_o$	0.022	1.771	No	
		$m_c = m_o$	$m_c < m_o$	-3.973	1.753	Yes	$m_c < m_o$
		$d_c = d_o$	$d_c < d_o$	-2.059	1.761	Yes	$d_c < d_o$
	Legibility Distance	$b_c = b_o$	$b_c > b_o$	0.802	1.761	No	
		$m_c = m_o$	$m_c > m_o$	3.299	1.761	Yes	$m_c > m_o$
		$d_c = d_o$	$d_c > d_o$	3.946	1.761	Yes	$d_c > d_o$
	🟩	bright > dim		🟦	dim > bright		

Table 16. Means of Sign Viewing Characteristics

Sign Descriptions		Number of Glances	Total Glance Duration (s)	Individual Glances (s)	Legibility Distance (ft)
bright	**SL-46**	4.73	8.37	1.77	368
bright	**TS-Y2**	4.13	7.89	1.91	357
medium	**SL-40**	5.06	6.45	1.27	406
medium	**TS-F5**	4.31	9.19	2.13	309
dim	**SL-70**	4.13	6.43	1.56	409
dim	**TS-X7**	5.13	7.98	1.56	291

The data for each of these measures is representative of driver viewing behavior within 900 feet of a sign. Recall the model introduced in the introduction section of this thesis. According to this model, the region of interest analyzed encompasses two regions of driver viewing behavior. Signs are assumed to become identifiable by shape and/or color from as far away as 1,000 feet but aren't legible until a distance of 300 to 400 feet. The driver's viewing behavior is likely different during these two regions. The analysis conducted for this thesis does not separate the data into two regions and evaluates the driver's entire approach to the sign from 900 feet. A separation of the data into these two regions may reveal trends not presented in this thesis.

Number of Glances

The number of glances made by a driver to a sign did not consistently follow any consistent trend related to the brightness level of the sign. The dim sign attracted the highest number of looks on the open course and the fewest number of looks on the closed course. The only consistency between the two courses for the number of glances is the relationship between the bright and medium signs. For both courses, the average number of looks dedicated to the medium sign garnered exceeded those made to the bright sign. In fact, an increase in sign brightness on the open course was shown to result in a decrease in the number of looks. It was expected for brighter signs to attract more glances. If a sign was distinguishable from farther away, the driver was expected to look at that sign from farther away, and therefore more often. The data collected for this thesis do not consistently assert any relationship between the brightness of a sign and the number of looks dedicated to it.

Total Glance Duration

The results for the measure of total glance duration, while more similar, are not consistent for both courses. On the closed course, the brightest sign had the longest total duration. This trend followed for the other signs as the total duration for the medium sign exceeded the dim sign. Although the relationship between the medium and dim sign held for the open course signs, the bright sign shifted to the least duration. As luminance decreased, the total glance duration was expected to increase as the driver strained to read the sign. This trend would have resulted in the dim signs having the longest glance duration. The data presented by this thesis show that the assumption of longer glance duration for decreased luminance is not correct.

Legibility Distance

An increased legibility distance allows the driver more time to respond to the message presented. On the open road course, the brighter signs (bright over medium, medium over dim, etc) had longer legibility distances. The most significant differences are those comparing the bright signs to the other two levels as was shown in Table 6 on page 73. On the open road course, a reduction in the luminance provided by the brightest sign to the medium and dim levels resulted in a decrease in the legibility distance from 13 to 16 percent, respectively. The reduction in legibility distance is only one percent as a result of the decreased luminance from the medium brightness level to the dim level.

A similar contrast was present on the closed course as well, but with a negative relationship. While there is still a marked difference between the performance of the bright sign and that of the lower luminance level signs, the closed course results show a negative relationship between luminance and legibility distance. On the closed course, these data show a decrease in the legibility distance as the luminance of the sign is increased.

The discussion revolving around the graph in Figure 15 alluded to an average legibility distance occurring at the peak of the luminance curve. The corresponding data collected for this thesis is presented in Figure 48 with the calculated luminance profiles from the ERGO software. These data present no such trend. The average legibility distances for signs on the open road course appear to occur as the luminance profile increases from a plateau. More evident for the medium and bright signs, the luminance curves are shown be increasing at the legibility distances shown by the vertical lines. The peaks of the luminance profiles, in fact, occur well beyond the legibility threshold of 400 feet (40 ft/in).

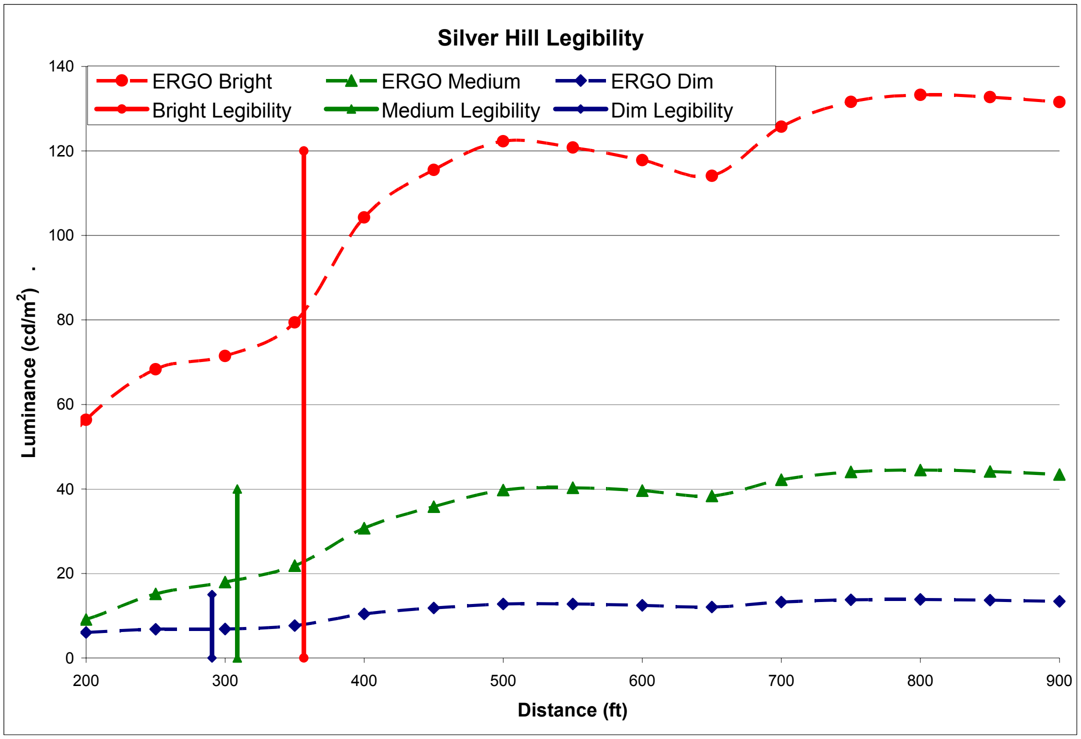


Figure 48. Legibility Distance and Luminance

The relatively low significance and inconsistency of the findings reached for the signs on the runway course could indicate a number of factors. First, drivers may feel more comfortable on a closed course and therefore relax their driving habits. It is also possible that the subjects subconsciously focused on all of the signs as much as possible to accomplish their given tasks. Finally, the drivers may have even been curious about the experimental setup. As previously stated, all subjects were employees of the Texas Transportation Institute and have been witness to or conducted some type of research before. Their prior knowledge of transportation research could have influenced their behavior on the closed course. Regardless of why driver behavior may have been altered, it appears that driving on the closed course tends to normalize the driver's sign viewing behavior. The contrast between the significance of the results from the closed and open courses shows more pronounced variations for driver behavior on the open course.

Closed Course versus Open Road

Perhaps the most convincing results obtained by this thesis are those comparing the driver's viewing behavior on the closed course with that on the open road. First and foremost, the statistics show that drivers view bright signs the same regardless of the testing environment. None of the comparisons between the two courses for the bright sign viewing behavior are statistically different.

For the medium, and dim signs, however, the differences for each of the measures are significant. Although the results vary for the number of glances, the total glance duration is consistently greater for the open road signs than for those on the closed course. This implies that drivers on the open road look at signs longer than on the closed course. One would expect drivers to look longer at signs on the closed course due to the decreased workload. An increased workload was present on the open road course due to an additional task. Whereas subjects on the closed course needed only to respond to the signs presented, subjects on the open road had to determine relevant signs from irrelevant signs and respond to those. The addition of this task illustrates just one difference between closed course and open road driving. The legibility distance, on the other hand, exhibits the opposite relationship from the total glance duration data: the medium and dim signs on the open road have a shorter legibility distance than those on the closed course. That is, the drivers on the open road need to be closer to the signs in order to read them. This finding follows that by Olsen and Bernstein relating laboratory results to field results (*13*). It is likely that the decreased legibility distance contributed to the increased total glance duration due to the subjects' increased efforts to read the sign.

CONCLUSIONS AND RECOMMENDATIONS

The use of an eye-tracking device to follow a subject’s gaze through both closed and open road courses provided several measures of effectiveness to determine the relative performance of signs with three brightness levels. The driver’s viewing behavior within 900 feet of a sign with a 10-inch legend was quantified and analyzed based on the brightness of that sign. The results obtained by the primary analyses lead to several conclusions presented by this thesis. The comparisons between signs with bright, medium, and dim luminance levels serve as the beginning effort to further studies relating driver needs to an optimum luminance. Additional scrutiny into the data revealed a significant difference between driver viewing behavior on closed courses verses that on the open road. Finally, a deeper look into the individual glances made by a driver uncovered promising trends with potential relevance to future research. The conclusions reached by this thesis are provided below, and the recommendations for the treatment of those conclusions follow.

- In real world driving scenarios, an increase in sign luminance increases the legibility distance.
- On the open road, medium and dim signs attract a longer total glance duration which results in a shorter legibility distance.
- With the exception of signs with high luminance levels, drivers view signs on the open road with a longer total glance duration and have a shorter legibility distance than when viewing signs on a closed course.
- During real-world driving scenarios, drivers look more often at dim signs than bright ones to gather the same information.
- Drivers tend to normalize their sign viewing behavior on a closed course.
- Increased sign brightness does not consistently decrease the viewing time required.
- The number of glances directed at a sign is not a consistent predictor of sign performance.

SIGN LUMINANCE

The primary measures used to interpret the luminance results obtained by this thesis are the results obtained from the open road course. The inconsistencies of the drivers' sign viewing behavior on the closed course performance do not provide sufficient statistical evidence from which to draw conclusions. In real world driving scenarios, the data show that drivers are able to read signs with higher luminance levels from farther away. The amount of time required to read the sign is effectively decreased by an increased legibility distance as shown by the typical increase in total glance duration for signs with lower luminance levels. Further, the increase in total viewing time for medium and dim signs is accompanied by more glances to the sign. An ideal sign viewing situation would result in multiple short glances to a sign with a long legibility distance. Signs with higher luminance levels analyzed by this thesis adhere to this theory.

TEST FACILITY

Another significant conclusion of this thesis is the nature of the testing environment. Besides comparing signs of the three brightness levels in the same setting, a contrast was made between the closed course and open road situations. The data show that regardless of how realistic the test facility is, drivers on a closed course do not act like those on the open road. The drivers tend to normalize their viewing behavior on the closed course due to their decreased workload, which seems to put all signs on an equal footing regardless of their luminance level.

In analyzing the performance of signs on both of the courses, only the brightest luminance level signs were found to be independent of the testing environment. For the less bright signs, however, the findings of this thesis follow previous research relating real world results to those achieved in a laboratory setting. The legibility distances for signs on the open course were less than those for the signs on the closed course while the total glance durations were higher on the open course. While this result points out the drawback of studies conducted on closed courses, it also emphasizes the benefit of the TTI Riverside Test Facility for transportation research by producing comparable results to those on the open road. The results of the study by Olsen and Bernstein have often been referred to throughout this thesis (*13*). Whereas Olsen and Bernstein found that the 90th percentile of their laboratory results equated well with the mean of their field results, the two sets of results obtained by this thesis are much closer. For the medium and dim signs, the 90th percentile closed course results correspond to approximately the 85th and 75th percentile open road results, respectively. As shown by Figure 43a, the legibility distances for bright signs are similar regardless of the testing environment. While the Riverside Test Facility does not match real world driving scenarios, the driver performance recorded by this thesis suggests that the facility more closely mimics real world driving than do laboratory studies.

AUTHOR INTERPRETATION

The statistical evidence provides one set of conclusions to be presented. The observations of the author, though not statistically proven, offer another perspective on the results reached by this thesis. It is apparent that the number of glances made by the nighttime driver is not consistently affected by the luminance of a sign within the 900-foot region of interest. The results of this thesis show that inconsistency to extend to the total glance duration as well. Statistically, the driver's viewing behavior, quantified by number of looks and total duration, does not change based on sign luminance within the region of interest. The author believes, however, that either the total glance duration measured in this thesis or the driver's individual glance durations do change with luminance. The limited amount of data collected for this thesis, though apparently bountiful, restricted the power of several of the findings such that they were not statistically significant. Future research that the author will take part in takes this aspect of the experimental design into account in an effort to collect more relevant and meaningful data.

LIMITATIONS OF THE RESEARCH

The exploratory nature of this research and the wide focus of the experimental design have resulted in several limitations of the quantity and quality of the results presented. First, the lack of repeatability of the subjects' viewing behavior presents doubt as to how drivers look at signs. Each subject in this study viewed a sign of a particular luminance and legend only once. This design did not allow the author to evaluate each driver's consistency in viewing similar signs of a particular luminance.

Further limitations of the experimental design include the selection and placement of the signs themselves. After looking at the data, there is typically a large gap between those for the bright sign and the medium and dim signs. Reading the medium and dim signs on the closed course could have been considered recognition tasks based on their common legend. The brightest sign, on the other hand, had an abstract legend that required subjects to actually read it, just as they did for the alphanumeric legends on the open road. This feature may have contributed to the similarity of the data for the bright signs on the closed and open courses. On the open road course, the dim sign may present some bias. The approach to this sign is approximately 1,000 feet. This relatively short distance compared to the other signs in addition to the task of transitioning from a major highway onto a county road may have affected the driver's sign viewing behavior as much as the sign brightness did.

The luminance values themselves present a limitation, as well. The variability present in the luminance measurements taken from the test signs was too great to base specific luminance recommendations on. Any recommendations made relating to luminance and sign sheeting will be given in a relatively wide range of values rather than specific threshold luminance levels. Future research into this arena should account for these limitations to reach more conclusive results.

RECOMMENDATIONS

Based on the data collected, analysis conducted, and results concluded, several recommendations based on the findings in this thesis are provided. The first is the manner in which the data were collected. Each of the six signs analyzed were viewed only once by each subject. As a result, it is unknown how much variability is present within each subject's viewing behavior toward a particular sign. To counter this, it would benefit future studies to present subjects with similar signs more than once. It is possible that a driver could change his or her viewing behavior based on factors other than luminance such as the order stimuli were presented or the position of the sign along the course. The repeatability of measurements would strengthen results such as those obtained by this thesis considerably.

The author recommends further study aimed at quantifying the optimum luminance to satisfy driver needs and therefore improve nighttime sign performance. Such research would benefit from a larger number of subjects and a more targeted selection of test signs to maximize the effectiveness of the experiment. The construction of internally illuminated variable luminance test signs would allow researchers to evaluate several luminance levels completely independent of any sheeting type. The results presented in this thesis provide a baseline to begin this research. The change in legibility distance with luminance was the greatest between the bright and medium signs at 16 percent. At a distance of 400 feet from the signs (relating to an acuity threshold of 40 ft/in), these two brightness levels equate to 80 cd/m^2 for the bright sign and 40 cd/m^2 for the medium sign. It is unclear whether an increase above the brightest level of luminance tested would further improve the legibility of the sign or if the optimum level is between the medium and bright levels. Future research should be focused on this range to optimize the luminance for the nighttime driver. The optimum luminance values found should then be connected to retroreflective sheeting at realistic viewing angles for performance based product development and specification.

The effect of field testing is also of high significance for research such as that conducted for this thesis. Studies evaluating or developing products utilized in real world driving scenarios should be conducted in real world scenarios. Given the task of driving on public roads is proven infeasible, the effective design and implementation of a closed course was found to closely mimic the viewing behavior exhibited by on-road driving.

The potential for future research relating to individual glance has been introduced as well. It is possible that a single glance at an optimum luminance could be used to read traffic signs. Given that the sign luminance at a legibility distance from the sign is derived from driver needs, the viewing behavior could change drastically to adapt to this improved scenario. By developing retroreflective sheeting to match driver needs, these optimum conditions may be attained.

REFERENCES

1. Lunenfeld, H. and G.J. Alexander. *A Users' Guide to Positive Guidance, 3rd Ed.* Publication FHWA-SA-90-017. FHWA, U.S. Department of Transportation, 1990.

2. American Society for Testing and Materials. *Standard Specification for Retroreflective Sheeting for Traffic Control,* ASTM D4956-05, West Conshohocken, PA, 2004.

3. 3M Sales Brochures and Flyers. Reflectivity. http://multimedia.mmm.com/mws/mediawebserver.dyn?6666660Zjcf6lVs6EVs66SVxACOrrrrQ-. Accessed October 19, 2006.

4. Schnell, T., F. Aktan, and C. Li. Traffic Sign Luminance Requirements of Nighttime Drivers for Symbolic Signs. In *Transportation Research Record: Journal of the Transportation Research Board, No.1862*, TRB, National Research Council, Washington, D.C., 2004, pp. 24-35.

5. *ERGO™2001 User's Guide*, Version 1.0.2, Avery Dennison Reflective Products Division, Niles, IL, January, 2002.

6. Bible, R.C. and N. Johnson. Retroreflective Material Specifications and On-Road Sign Performance. In *Transportation Research Record: Journal of the Transportation Research Board*, No.1801, TRB, National Research Council, Washington, D.C., 2002, pp. 61-72.

7. Woltman, H.L. and T.J. Szczech. Sign Luminance as a Methodology for Matching Driver Needs, Roadway Variables, and Signing Materials. *In Transportation Research Record No. 1213*, TRB, National Research Council, Washington, D.C., 1989, pp. 21-26.

8. US-DOT/FHWA. *Manual on Uniform Traffic Control Devices*. Washington, D.C., U.S. Department of Transportation, Federal Highway Administration, 2003.

9. Mills, F.W. Comparative Visibility of Standard Luminous and Non-Luminous Highway Signs. *Public Roads*, Vol. 14, No.7, September, 1933, pp. 109-128.

10. Richards, O.W. Effects of Luminance and Contrast on Visual Acuity, Ages 16 to 90 Years. *American Journal of Optometry & Physiological Optics*, Vol.54, No.3, 1977, pp.178-184.

11. Mercier, C.R., C. Goodspeed, C.J. Simmons, and J.F. Paniati. Evaluation of Proposed Minimum Retroreflectivity Requirements for Traffic Signs. In *Transportation Research Record: Journal of the Transportation Research Board, No.1862,* TRB, National Research Council, Washington, D.C., 2004, pp.57-67.

12. Schnell, T., F. Aktan, and C. Li. Traffic Sign Luminance Requirements of Nighttime Drivers for Symbolic Signs. In *Transportation Research Record: Journal of the Transportation Research Board, No.1862*, TRB, National Research Council, Washington, D.C., 2004, pp. 24-35.

13. Olson, P.L. and A. Bernstein. The Nighttime Legibility of Highway Signs as a Function of Their Luminance Characteristics. *Human Factors*, Vol. 21, No. 2, 1979, pp. 145-160.

14. Forbes, T.W. Luminance and Contrast for Sign Legibility and Color Recognition. *In Transportation Research Record No. 611*, TRB, National Research Council, Washington, D.C., 1976, pp. 17-24

15. Padmos, P. *Minimum Required Night-time Luminance of Retroreflective Traffic Signs*. Report TM-00-C029, TNO Human Factors, Netherlands Organization for Applied Scientific Research, 2002.

16. Carlson, P.J. and H.G. Hawkins. *Minimum Retroreflectivity Levels for Overhead Guide Signs and Street-Name Signs*. Publication FHWA-RD-08-082, Office of Safety Research and Development, FHWA, U.S. Department of Transportation, 2001.

17. Sivak, M. and P.L. Olson. Nighttime Legibility of Traffic Signs: Conditions Eliminating the Effects of Driver Age and Disability Glare. *Accident Analysis and Prevention*, Vol. 14, No. 2, 1982, pp. 87-93.

18. Plainis, S., K. Chauhan, I.J. Murray, and W.N. Charman. Retinal Adaptation under Night-time Driving Conditions. In *Vision in Vehicles VII*. Edited by A.G. Gale, I.D. Brown, C.M. Haslegrave, and S.P. Taylor, Elsevier, Amsterdam, 1999.

19. Eye Tracking Labs at the MPI. Max Planck Institute for Psycholinguistics. http://www.mpi.nl/world/tg/eye-tracking/eye-tracking.html. Accessed September 14, 2006.

20. H6 Binocular High Speed. Applied Science Laboratories. http://www.a-s-l.com. Accessed September 14, 2006.

21. EyeLink II. SR Research EyeLink. http://www.eyelinkinfo.com/mount_main.php. Accessed September 14, 2006.

22. Precision Head Positioner. Arrington Research, http://www.arringtonresearch.com/precision.html. Accessed September 14, 2006.

23. ETS-PC II. Engineering Systems Technologies GmbH & Co. KG. http://www.est-kl.com/hardware/eyetracking/asl/etspcii.html. Accessed September 14, 2006.

24. Green, P. *Review of Eye Fixation Recording Methods and Equipment*, Intelligent Vehicle-Highway Systems, University of Michigan, Ann Arbor, MI, 1992.

25. Rockwell, T.H., C. Overby, and R.R. Mourant. Drivers' Eye Movements: An Apparatus and Calibration. In *Highway Research Record No. 247*, HRB, National Research Council, Washington, D.C., 1968, pp. 29-41.

26. Mourant, R.R. and T.H. Rockwell. Mapping Eye-Movement Patterns to the Visual Scene in Driving: An Exploratory Study. *Human Factors*, Vol. 12, No. 1, 1970, pp. 81-87.

27. Bhise, V.D., T.H. Rockwell. Toward the Development of a Methodology for Evaluating Highway Signs Based on Driver Information Acquisition. In *Highway Research Record No. 440*, HRB, National Research Council, Washington, D.C., 1973, pp. 38-56.

28. Rackoff, N.J. and T.H. Rockwell. Driver Search and Scan Patterns in Night Driving. *Transportation Research Board Special Report, No. 156*, TRB, National Research Council, Washington, D.C., 1975, pp. 53-63.

29. Shinar, D., E.D. McDowell, N.J. Rackoff, T.H. Rockwell. Field Dependence and Driver Visual Search Behavior. *Human Factors*, Vol. 20, No. 5, October, 1978, pp. 553-559.

30. Zwahlen, H.T. Advisory Speed Signs and Curve Signs and Their Effect on Driver Eye Scanning and Driving Performance. In *Transportation Research Record No. 1111*, TRB, National Research Council, Washington, D.C., 1987, pp. 110-120.

31. Zwahlen, H.T. Stop Ahead and Stop Signs and Their Effect on Driver Eye Scanning and Driving Performance. In *Transportation Research Record No. 1168* TRB, National Research Council, Washington, D.C., 1988, pp. 16-24.

32. Zwahlen, H.T. Traffic Sign Reading Distances and Times During Night Driving. In *Transportation Research Record No. 1495*, TRB, National Research Council, Washington, D.C., 1995, pp. 140-146.

33. Zwahlen, H.T., A. Russ, and T. Schnell. Viewing Ground-Mounted Diagrammatic Guide Signs Before Entrance Ramps at Night, Driver Eye-Scanning Behavior. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1843*, TRB, National Research Council, Washington, D.C., 2003, pp. 61-69.

34. Schieber, F., D.M. Burns, J. Myers, N. Willan, and J. Gilland. Driver Eye Fixation and Reading Patterns while Using Highway Signs under Dynamic Nighttime Driving Conditions: Effects of Age, Sign Luminance, and Environmental Demand. *Proceedings of the 83rd Annual Meeting of the Transportation Research Boar*d, Washington, D.C., 2004.

35. Diem, C. Eye Movement Behaviour of Car Drivers. *Proceedings of the International Symposium on Automotive Lighting*, Darmstadt, Germany, 2005.

36. *Nu-metrics®. NITESTAR® Model No. NS-50/NS-60 Operation Manual*, Uniontown, PA, 1999.

37. *ViewPoint EyeTracker*® PC-60 Scene Camera Option Users Guide, Scottsdale, AZ, 2005.

38. Copeland, L. Distracted Driving Big Cause of Crashes. *USA Today*, posted December 11, 2006, http://www.usatoday.com/news/nation/2006-12-11-distracted-driving_x.htm, Accessed Dec. 20, 2006.

APPENDIX A

EXPERIMENTAL SCRIPT

PRIOR TO STUDY - VERBAL INSTRUCTIONS TO SUBJECTS

My name is ______________________________; I work for the Texas Transportation Institute, which is part of the Texas A&M University System. I would first like to thank you for volunteering to participate in this study. The study is being sponsored by the Texas Department of Transportation. The purpose of this study is evaluate a new eye tracking system.

First, we need to confirm that you are over the age of 18, and you currently have a Texas driver's license without nighttime or special equipment restrictions, and you are not color blind.
NOTE: The above questions should have been asked when they were recruited. They are repeated at this time for added assurance.

You will have 2 simple visual screening tests. The tests are:

Snellen acuity "eye chart" (visual acuity screening test)

Binocular only. Record acuity (e.g., 20/20, 20/50) based on last line of which participant reads all letters correctly. If participant misses only one or two letters, have them try to read the next larger line. If they get all the letters correct, continue to the next line down. If they can't read it, go back to the previous line. If they still make errors, use last all correct line to determine acuity.

Color Blindness screening

Now, let me tell you a little about your task.

INTRO
Tonight we're going to ask you to help us evaluate our new eye-tracking system. First we will calibrate the eye-tracking system to your face and eyes. The eye-tracker works by mapping your pupil to a forward facing scene provided by a camera. The calibration process remembers where your pupil is as you look at a grid of 16 points covering the forward facing scene. After the system is calibrated we're going to take about a 10 minute drive around our test course. During this drive we will ask you a few questions about information presented on road signs that you will pass. After the test track portion, we will take a short drive on public roads, and again we will be asking you a few questions about information presented on road signs that you will pass. First,

however, we will let you familiarize yourself with the test vehicle. Take this opportunity to adjust the seats, mirrors, and controls.

(Show subjects the car and point out the equipment in the back seat. Have 2nd researcher put on eye-tracker to show subject how it follows eyes. Allow subjects to adjust vehicle controls. Measure the subjects eye-height inside the vehicle. Accompany subjects as they drive to building 7072. Arrive at Building 7072 for calibration of the eye-tracker)

PUTTING ON EYE-TRACKER

First attach this bag to your waist. You will only wear this for the calibration process. Now put the eye-glasses on just as you would normal glasses, and then tighten the strap in the back so that the glasses won't move on your face.
(Before tightening the strap, solicit questions from the subject. Explain that infrared light will be shone into their eyes to enhance the presence of the pupil. Explain that this is completely safe.)

Next I will attach the clips on the cables to your shirt collar. This will allow you to freely move your head without moving the tracking equipment. Finally, we will attach a small bag to your waist. This bag will be removed when you re-enter the test vehicle.

Now that you have the eye-tracker on, we need to adjust the cameras and infrared lights so that your pupils are visible to the software. You will not be able to see any light coming from the infrared LED's but the cameras are specially designed to "see" this kind of light.
(Subject will approach the rear driver's side window of the test vehicle as a researcher from within the vehicle adjusts the cameras and lights.)

CALIBRATION

(One researcher will remain outside of the vehicle next to the subject to provide direction during the calibration process. Show the subject the calibration grid on building 7072. Show the subject a picture of how the grid will line up on the wall. Provide calibration grid numbering guide).

Now we will begin the calibration. First you will place your chin in the rest on the tri-pod. Make yourself comfortable because this process takes approximately 5 minutes. You may use the stool to provide support. Then I will give several short instructions such as "Up, Down, Left, Right" to align the on-camera calibration grid to the targets on the wall. Throughout the calibration I may call out these instructions to realign the two grids.

The calibration process will work like this: First, I will call out a number. This number will correspond to a target on the wall as listed on the calibration grid numbering guide.

At this time a researcher will shine a flashlight at the target corresponding with that number on the wall. I would like you to stare at the black dot in the center of this target. When you are looking at the dot, give the researcher a verbal indication such as "Ready." The researcher will then indicate to me that you are ready. After this response, focus on the center of the target for 3 seconds while I capture the location of your pupil. You may then relax your eyes until the next target is illuminated. We will do this for each of the 16 targets. Remember, from time to time I may instruct you to move your head slightly in a specific direction.

RIVERSIDE PRE-DRIVE SET-UP—Taxiway start

(Assist the subject in getting into the vehicle, ensure that they are comfortable driving with the equipment.)

Now I will ask you to drive out to the two reflective cones in the middle of the runway…

(Reset DMI at 2500)

During this first test-track portion of our drive tonight, I will ask you to try to maintain a speed of 30 mph. The entire course can be safely traveled at 30 mph, but you may want to go slower through the curves.

The entire route is marked with white raised pavement markers. These pavement markers are used to mark the "Center line" of our road tonight. Therefore we would like you to stay within a few feet to the right of the center line at all times to simulate a car staying in its lane on a public road. The raised pavement markers should stay on the left side of the vehicle.

While I will ask you to maintain a speed of 30 mph during this first driving portion, I will also ask you to pay attention to any road signs indicating a speed limit along our route. If at any time you see a speed limit sign, as soon as you are confident you can correctly read the posted speed, read the speed out loud to me. Do not accelerate to the posted speed; maintain 30 mph.

Also, from time to time I may ask you in what direction a given destination is located. The answer to these questions will appear on upcoming signs. In these cases I would simply like you to respond either up, down, right or left when you determine the correct direction to the given destination. Cardinal directions do not need to be given.

Finally, there will be a couple other questions you will be asked, but those will be explained to you later.

For now remember:
Try to drive about 30 mph

Try to stay "in your lane"
If you see a posted speed limit, read it to me
If you're asked about a direction to a destination, please reply either up, down, right or left…(*which direction is Mapleton/Lansing?)*

(Start Recording Eye-tracker Video; filename=subject#_a)

Okay, you can go ahead and get it up to 30 mph.

AT FIRST STOP (before orange/yellow signs)

(reset DMI)

This question is about the next two signs you will pass, the first sign is yellow and the second sign is orange. As you drive, I would like you to tell me which sign has more words on it. As soon as you can which of those two signs has the most words say the color of that sign. Also, as you approach each sign read the word on the top line as soon as you are confident you can correctly read it.

(Pause, confirm understanding of task)

After we pass these signs I would like you to remember:

Try to drive about 30 mph
Try to stay "in your lane"
If you see a posted speed limit, read it to me
If you're asked about a direction to a destination, please reply either up, down, right or left…

AT SECOND STOP (before return trip on back runway)

(reset DMI)

This question is about the next three signs you will pass. This time, I would like you to tell me which of the next three signs you will pass has the fewest words on it by saying one, two, or three. Also, as you are able to read each sign, I would like you to read the top word on each sign out loud. Again, please wait until you are confident you can correctly read the word before answering.

(Pause, confirm understanding of task)

After we pass these signs I would like you to remember:

Try to drive about 30 mph

Try to stay "in your lane"
If you see a posted speed limit, read it to me
If you're asked about a direction to a destination, up, down, right or left is what we are looking for…

(Lead subject around curve to next stop between cones)

AT THIRD STOP (before final pass on taxiway)

(reset DMI)

For this portion of the study I will ask you to continue driving along the marked route. Also at this time I will ask you to tell me which direction (Lakewood, Paterson) is?

(Pause, confirm understanding of task)

During this portion I would like you to remember:

Try to drive about 30 mph
Try to stay "in your lane"
If you see a posted speed limit, read it to me
If you're asked about a direction to a destination, up, down, right or left is what we are looking for…(*which direction is Lakewood/Paterson?)*

(Stop recording the eye-tracker video after the last speed limit sign)

SILVER HILL DRIVE

(Have them stop after passing through the gate and reset DMI with mirror at 2nd post)

Now we're going to take a short drive on some public roads. After we exit the riverside campus, we will be heading south on a state highway with a speed limit of 65 mph after dark. We will be on this road approximately 5 minutes before we will make a right turn onto a smaller country road. It is important that you obey the speed and warning signs posted along this road. Once on this country road, I would like you to be looking for some custom made signs we have installed. These signs look similar to a speed limit sign, but instead say "Test Sign" and also display a letter and a number instead of a speed. As you drive, when you are confident that you can correctly read the number and letter on one of the test signs, please read it out loud.

In addition, we would also like to know when you believe we are approaching one of the test signs. Upon your first instinct that we are approaching one of these signs, indicate this to me.

(Start Recording Eye-tracker Video; filename=subject#_b)

FIFTH STREET

(Have them stop at the gate and reset DMI with mirror at 1st post)

As we complete this experiment there is one more task I'd like you to perform. As we drive down this street, I would like you to turn onto the street named after a U.S. state.

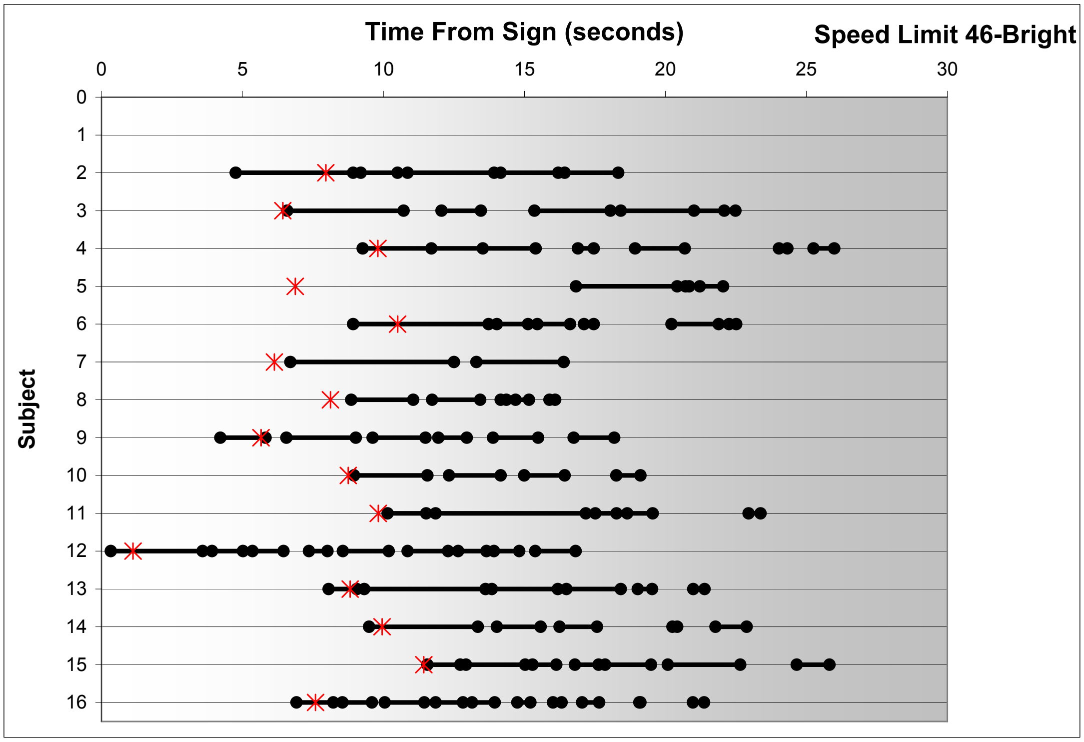
(Stop recording data after turn)

(DO NOT let participant turn off ignition)

(make sure eye-tracker is completely unhooked before allowing participant to exit the vehicle.)

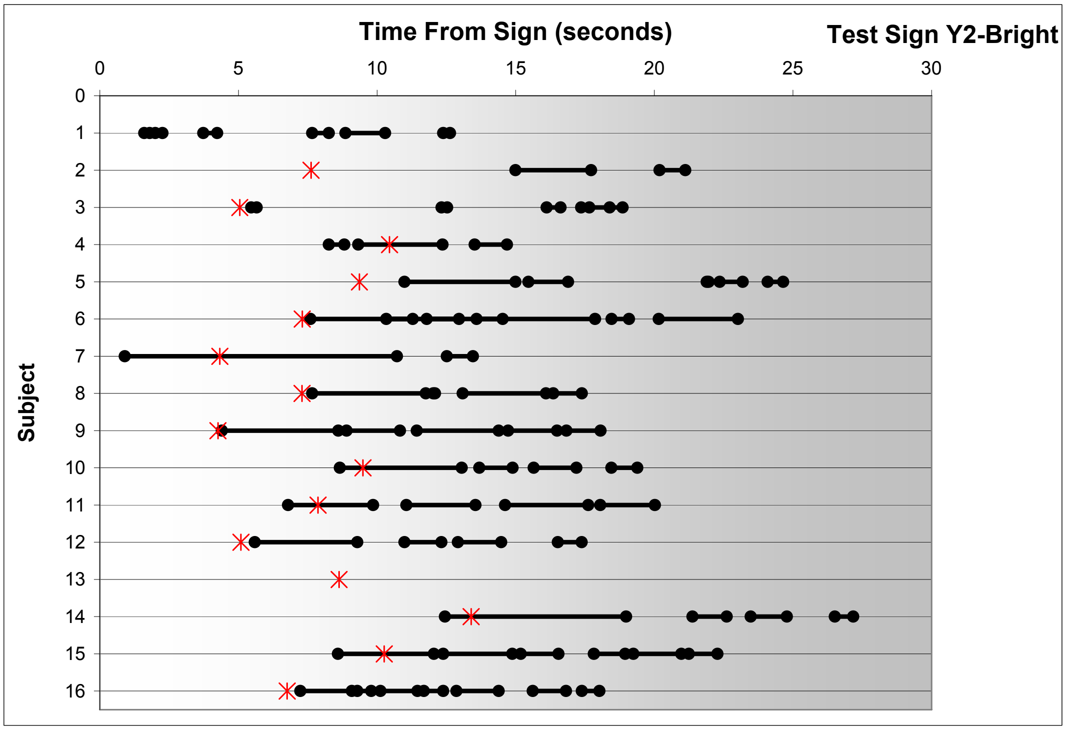
APPENDIX B

GRAPHS

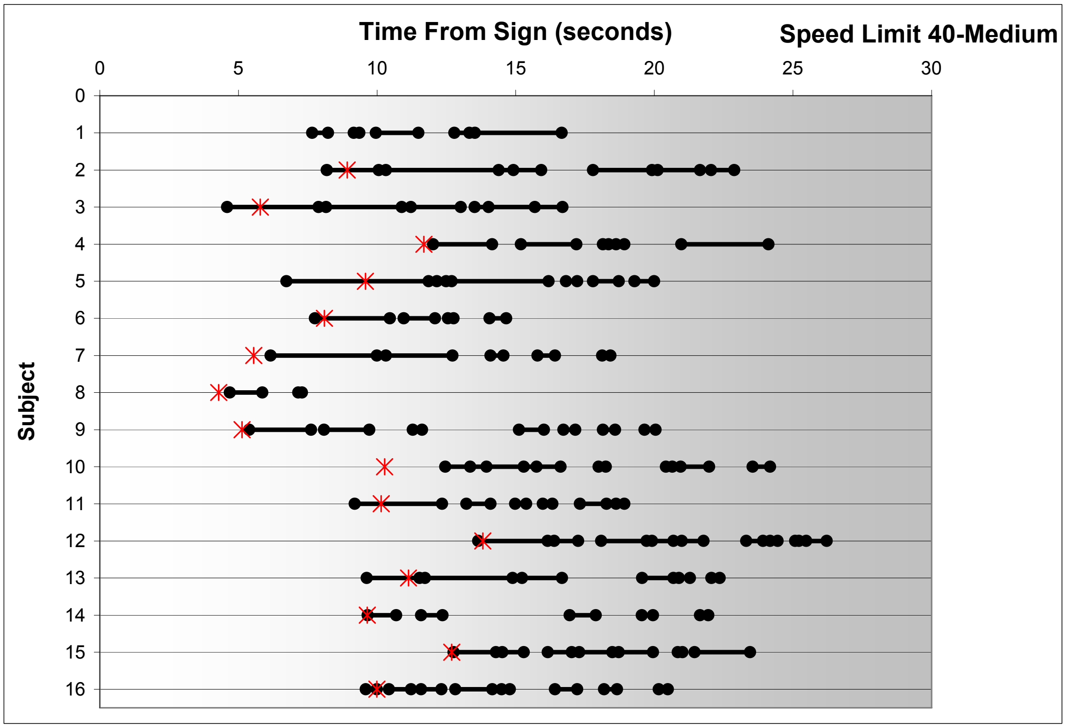


(a)

Figure 49. Glance Plots by Sign

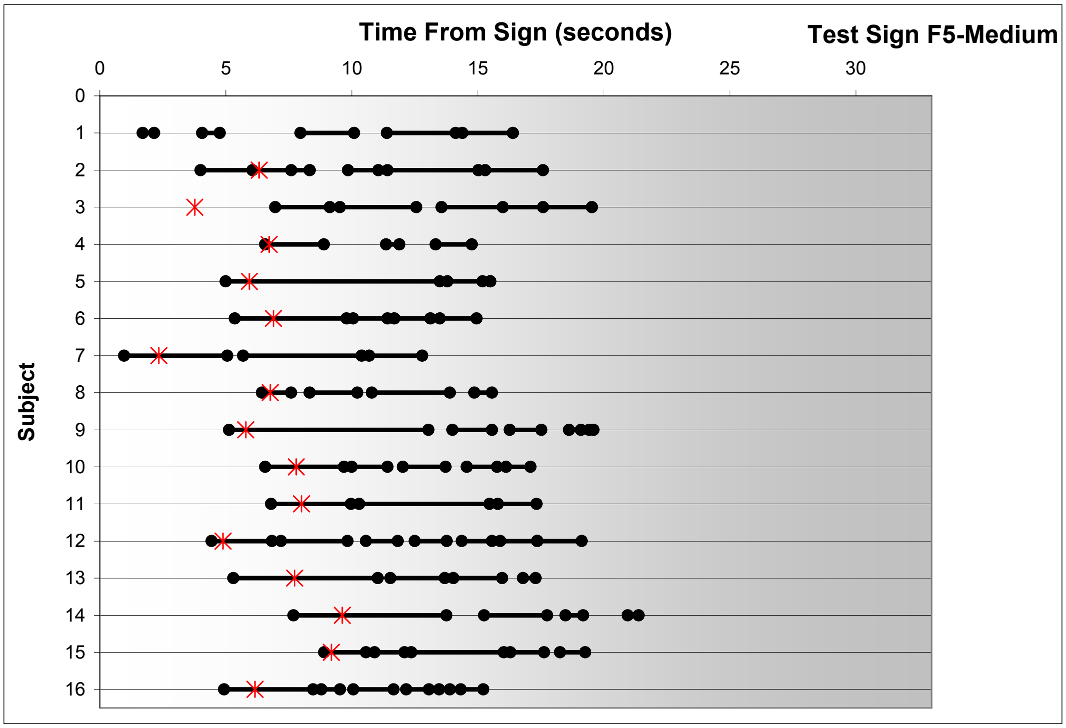


(b)

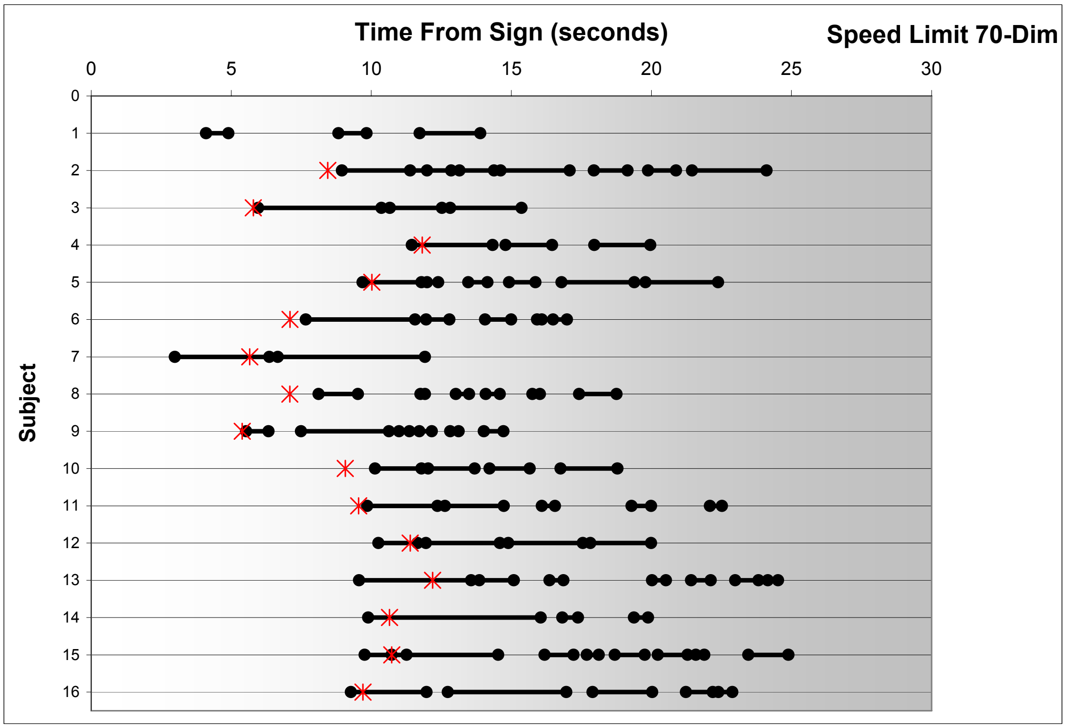


(c)

Figure 49. Continued

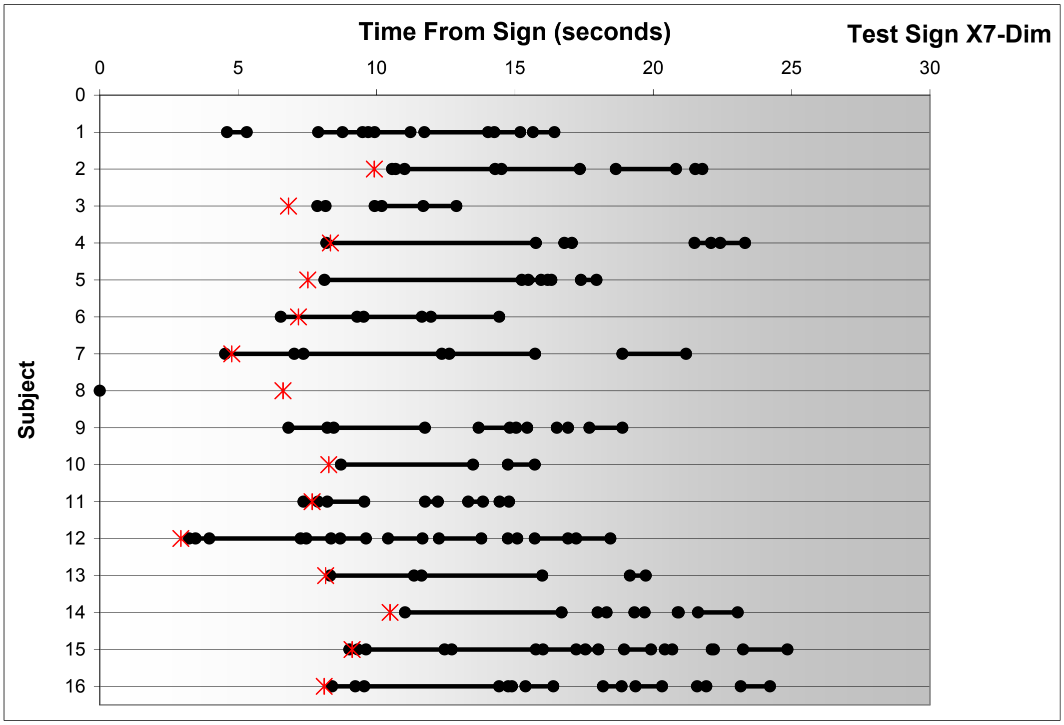


(d)

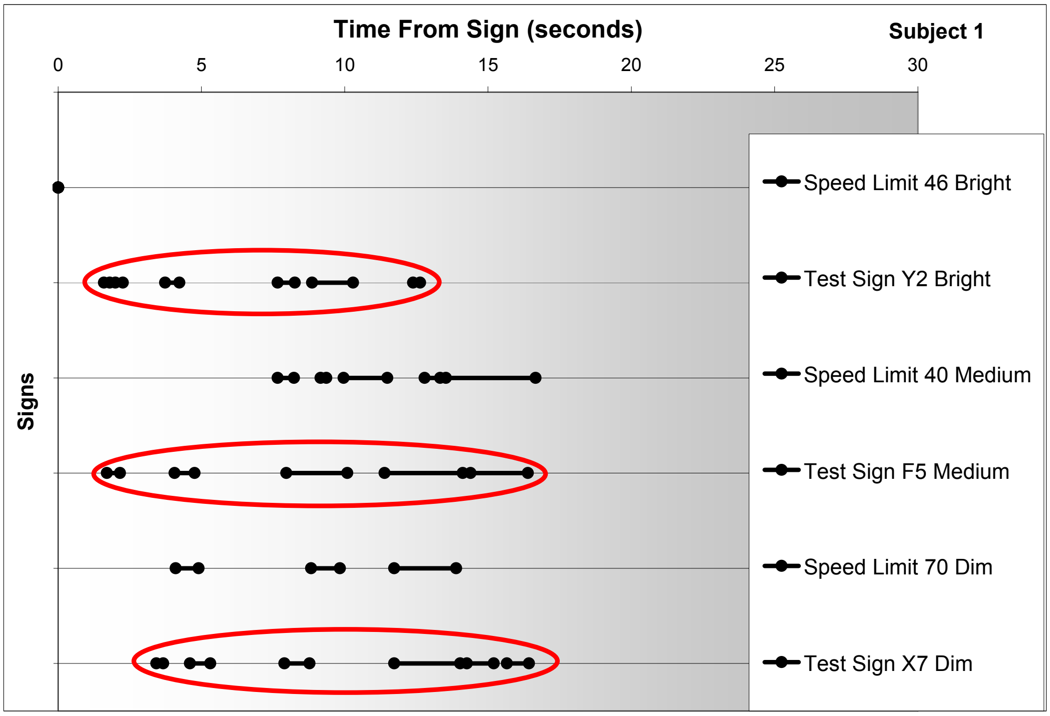


(e)

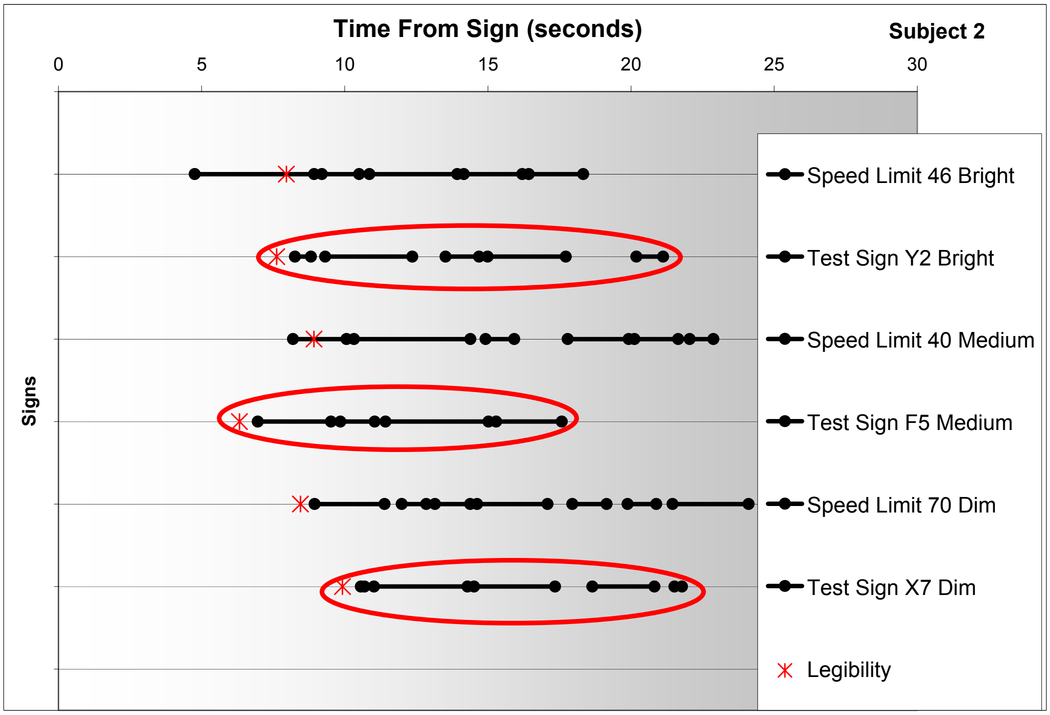
Figure 49. Continued



(f)
Figure 49. Continued



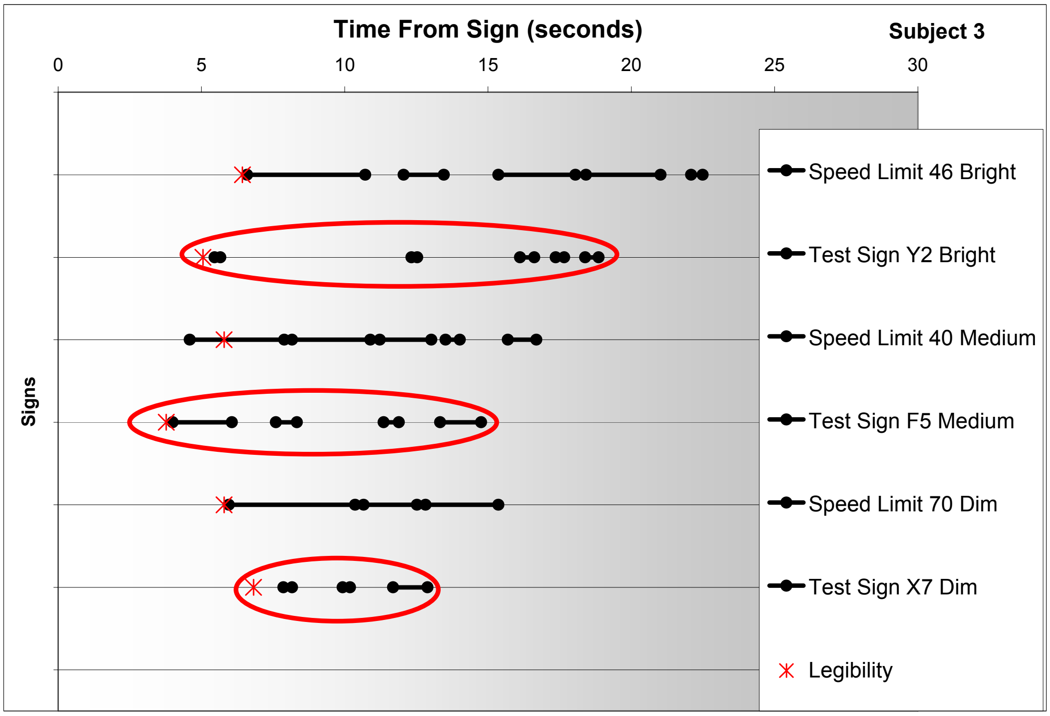
(a)



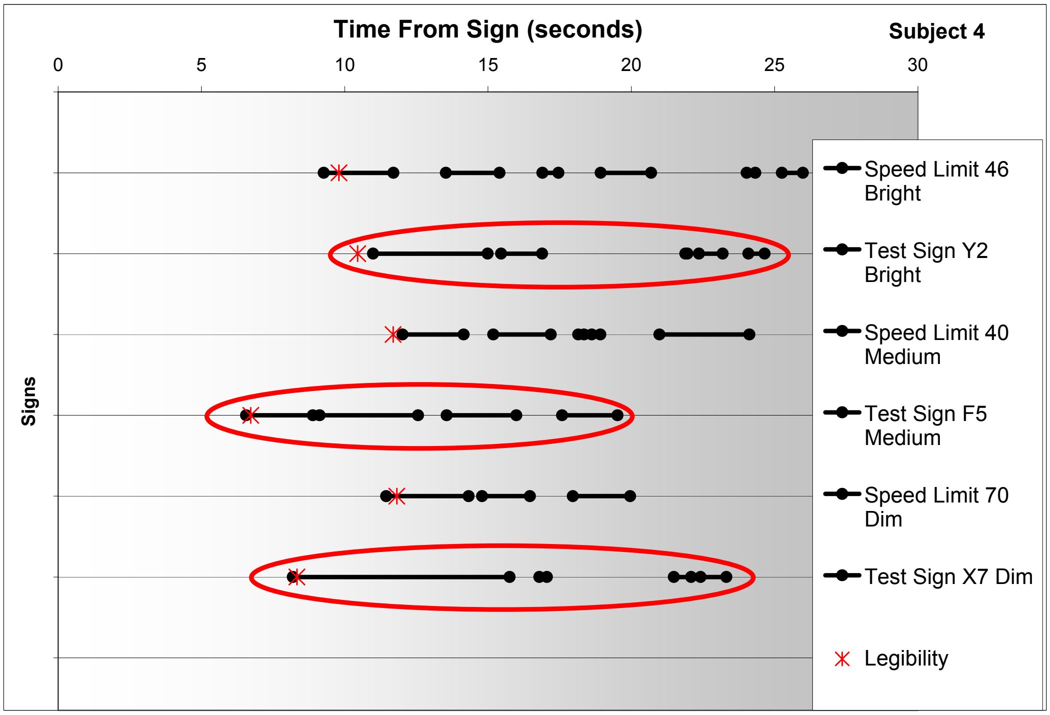
(b)

Figure 50. Glance Plots by Subject

(circled data indicate signs on the open road course)



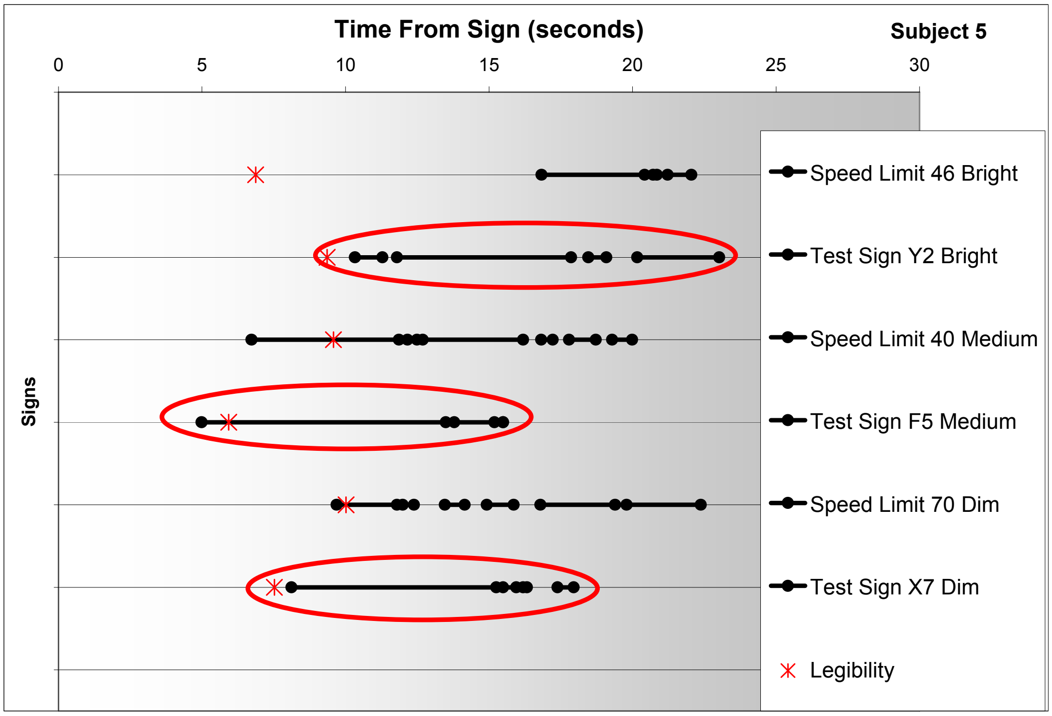
(c)



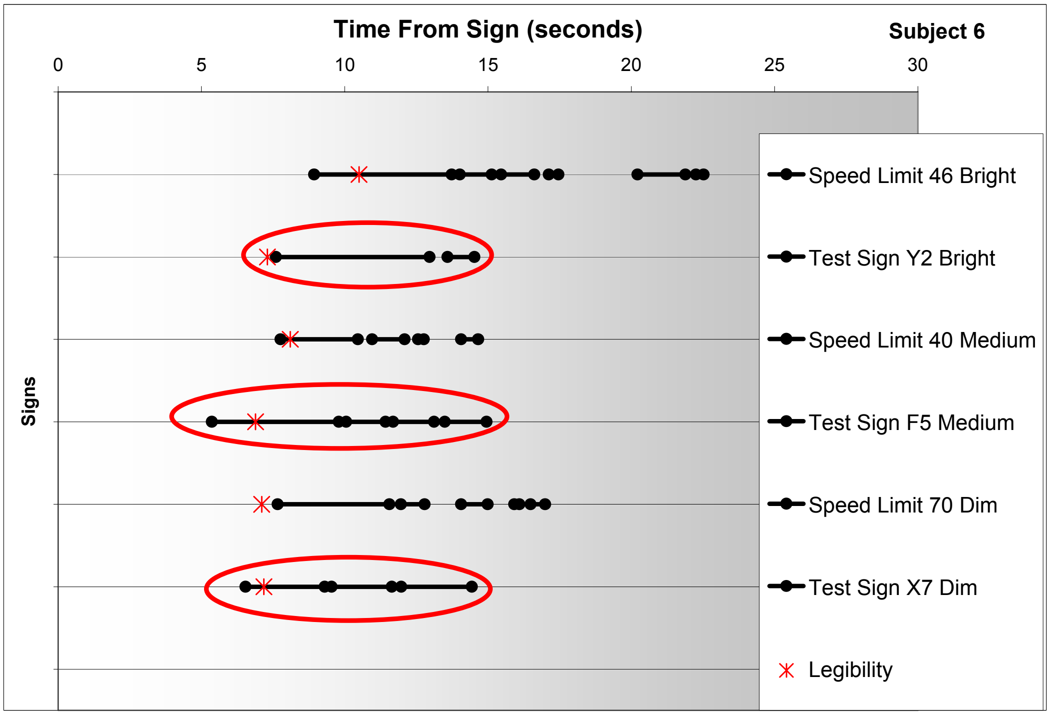
(d)

Figure 50. Continued

(circled data indicate signs on the open road course)



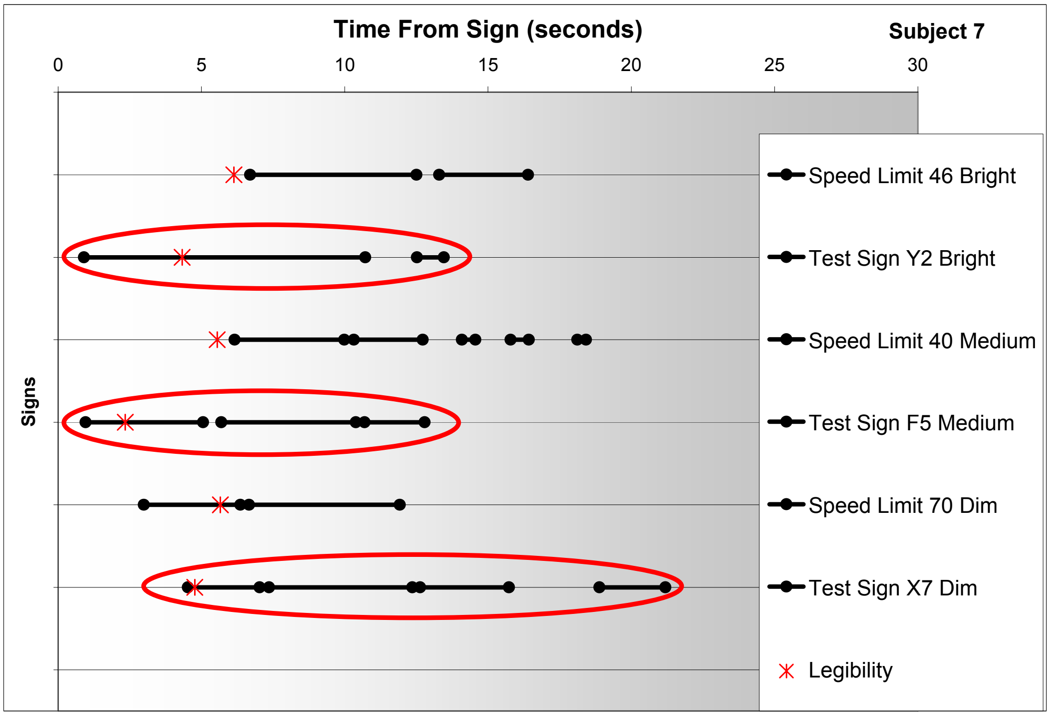
(e)



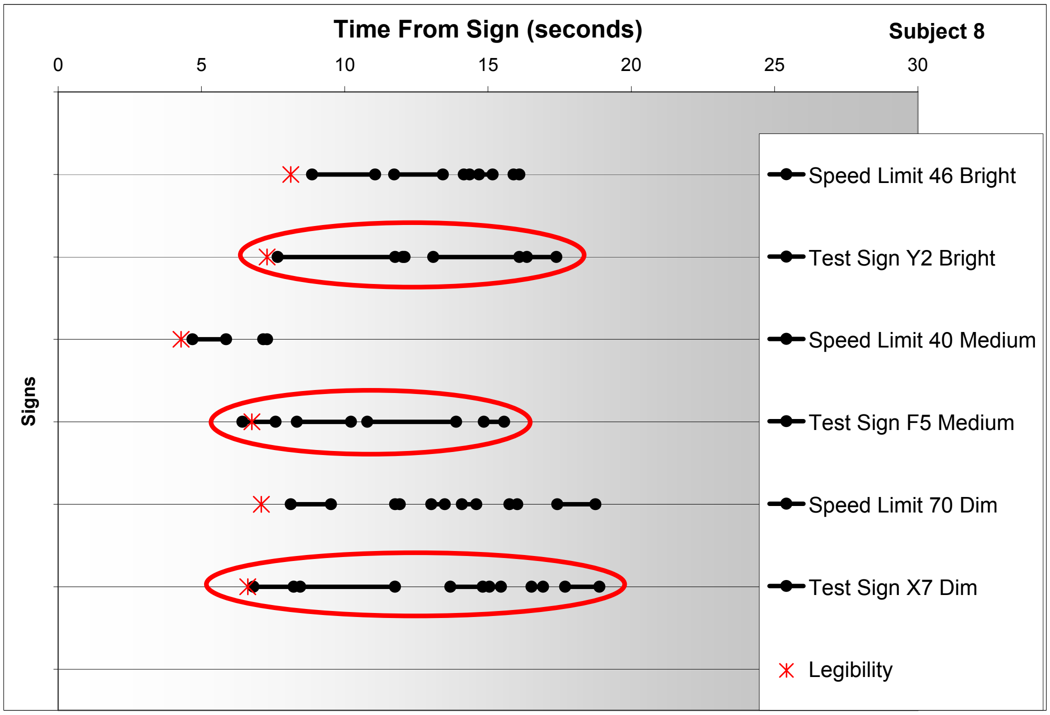
(f)

Figure 50. Continued

(circled data indicate signs on the open road course)



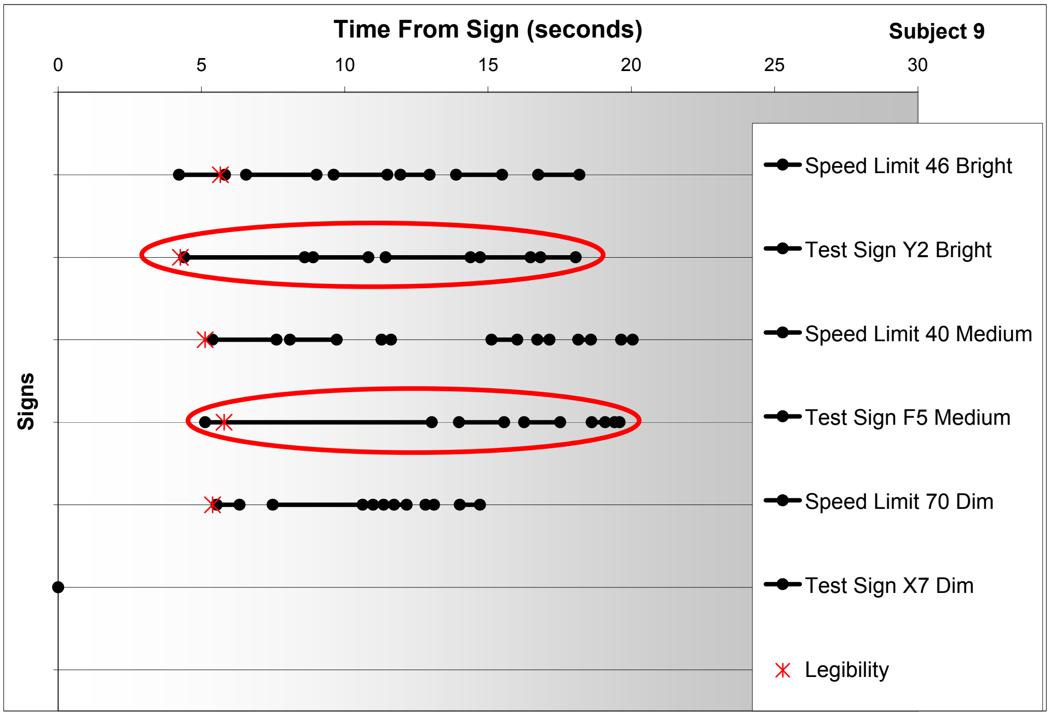
(g)



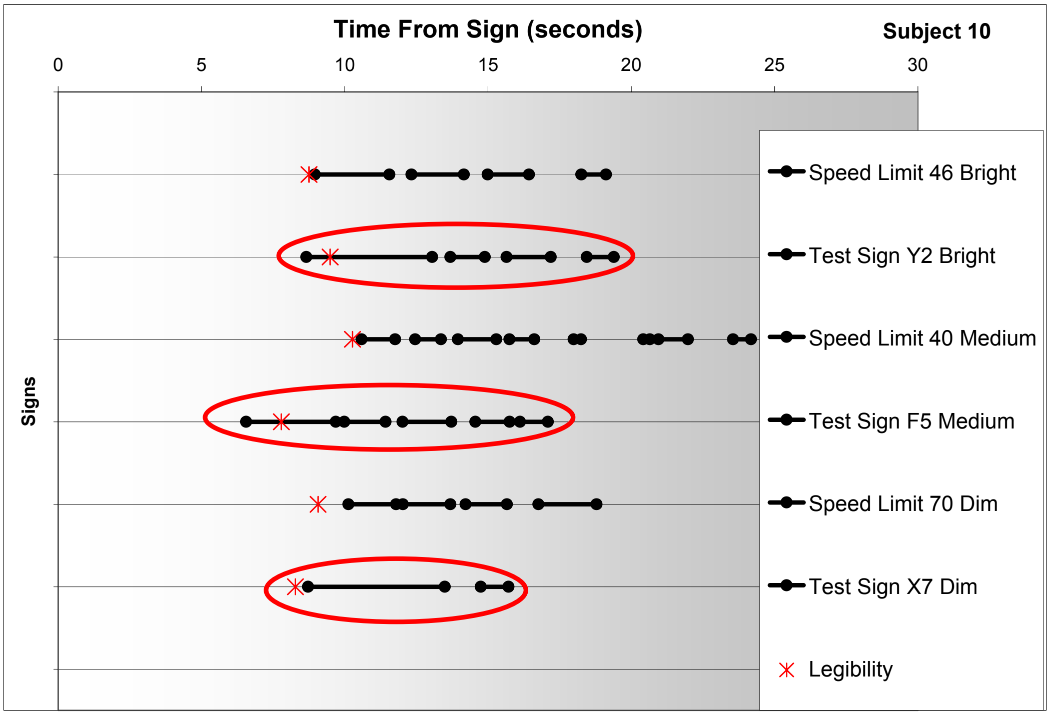
(h)

Figure 50. Continued

(circled data indicate signs on the open road course)



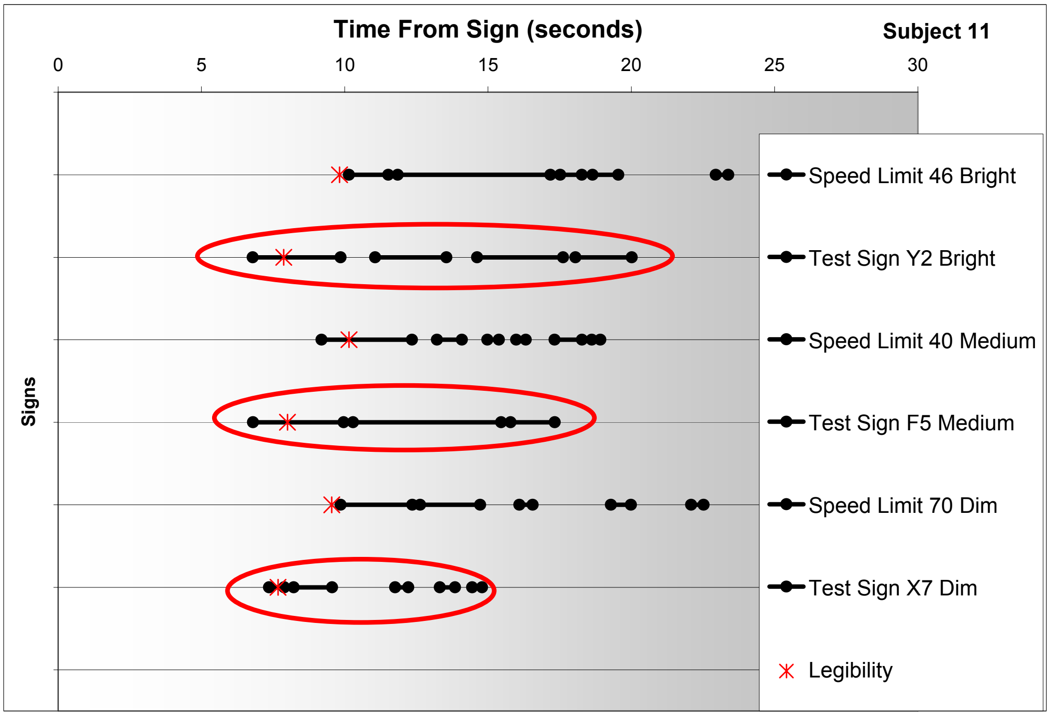
(i)



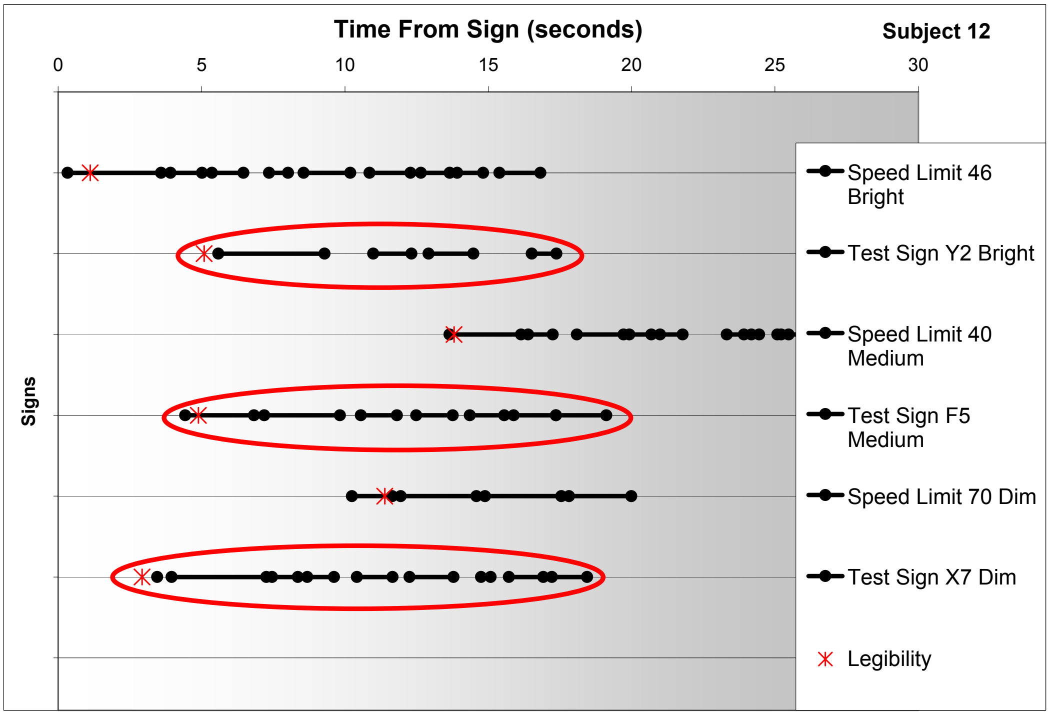
(j)

Figure 50. Continued

(circled data indicate signs on the open road course)



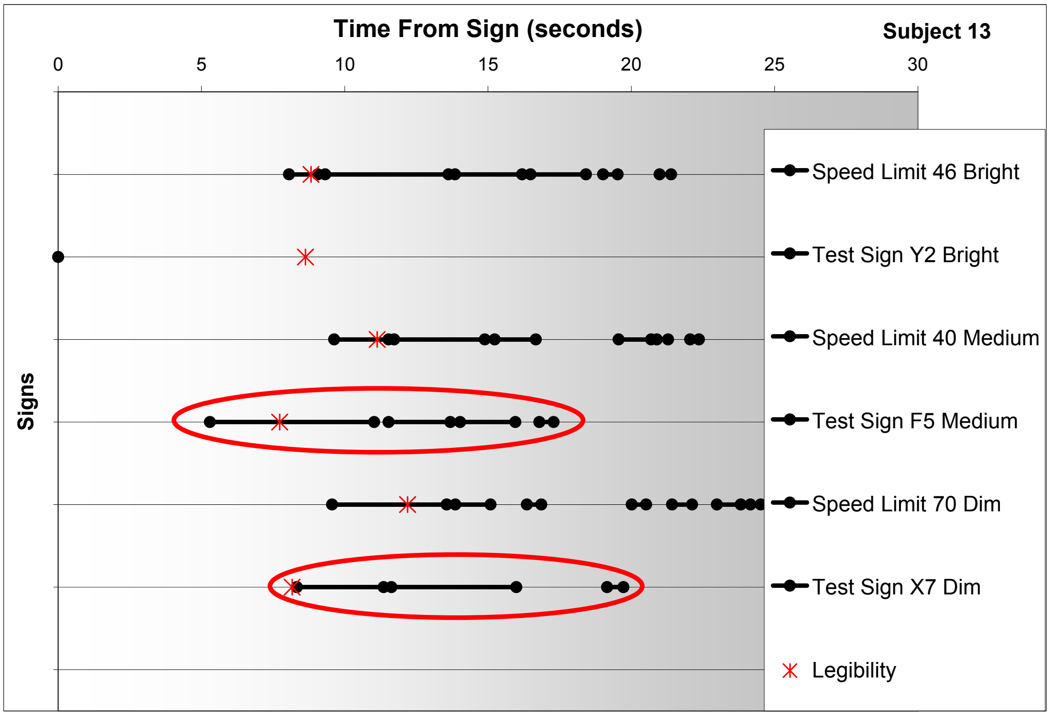
(k)



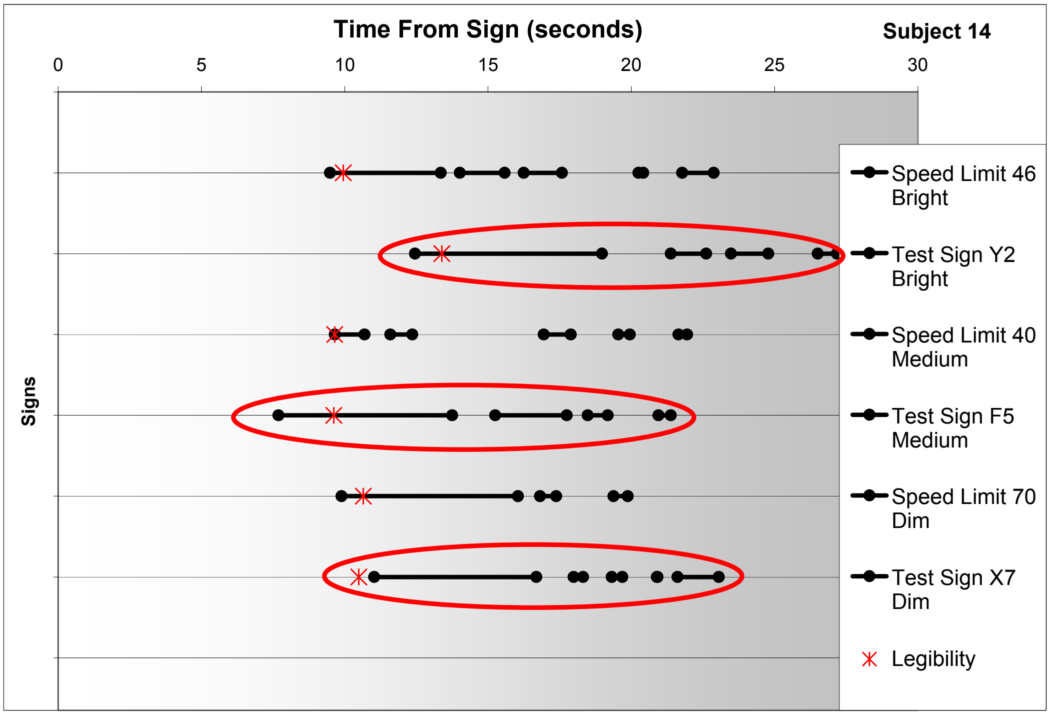
(l)

Figure 50. Continued

(circled data indicate signs on the open road course)



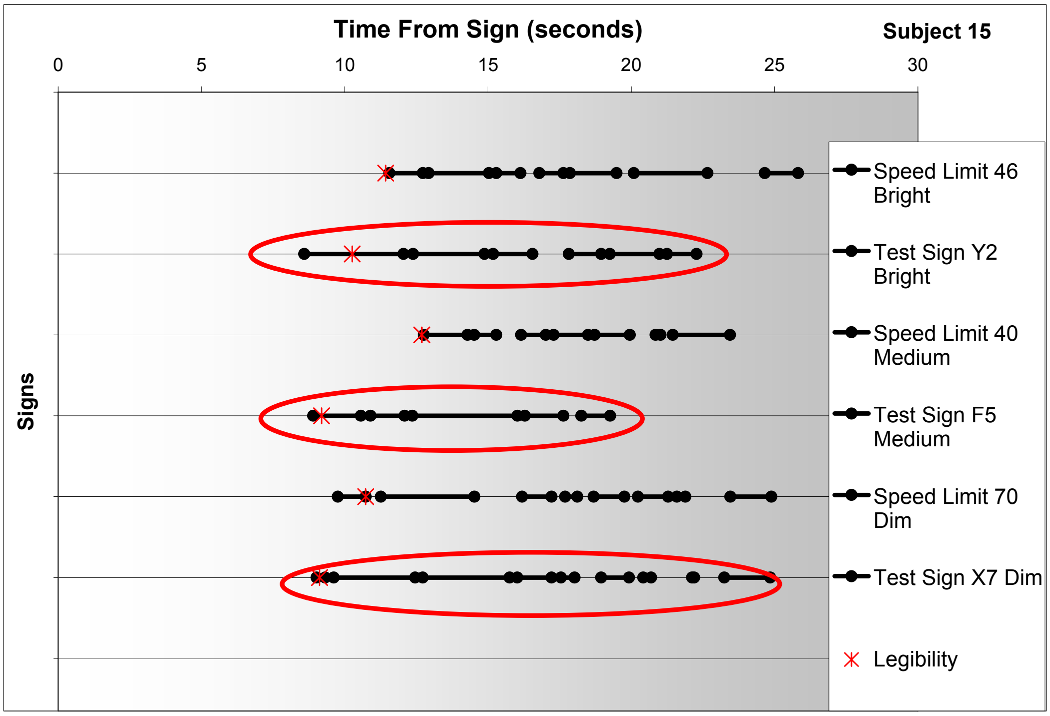
(m)



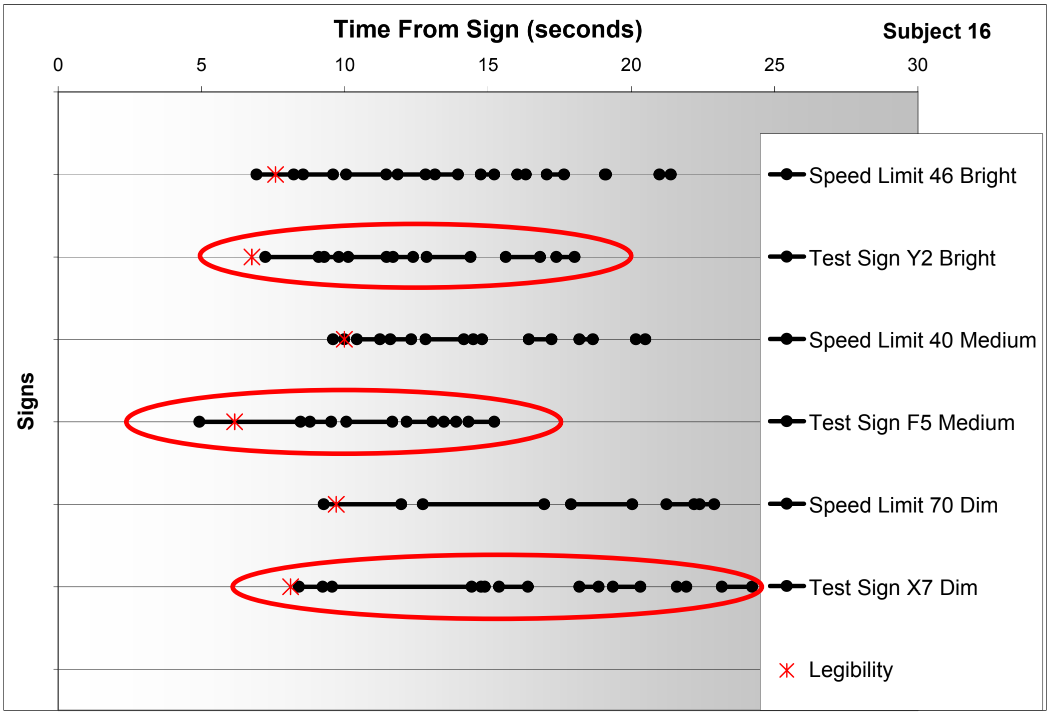
(n)

Figure 50. Continued

(circled data indicate signs on the open road course)



(o)



(p)

Figure 50. Continued

(circled data indicate signs on the open road course)

APPENDIX C

DATA

Table 17. Total Number of Glances

	Speed Limit Signs					
	bright	dim	medium	dim	medium	bright
Subject	**SL-46**	**SL-70**	**SL-40**	**TS-X7**	**TS-F5**	**TS-Y2**
1		3	5	8	5	6
2	5	4	4	5	4	4
3	4	3	5	3	4	5
4	4	3	5	4	4	4
5	1	5	5	4	3	4
6	5	5	4	3	4	2
7	2	2	5	4	3	2
8	5	6	2	6	4	4
9	6	6	7		5	5
10	4	4	7	2	5	4
11	4	4	6	5	3	4
12	8	4	4	9	7	4
13	5	4	4	3	4	
14	3	3	3	4	3	2
15	6	7	7	9	5	5
16	9	3	8	8	6	7
mean	4.73	4.13	5.06	5.13	4.31	4.13
median	5	4	5	4	4	4
st dev	2.05	1.36	1.61	2.33	1.14	1.41
n	15	16	16	15	16	15

Table 18. Total Number of Glances Comparisons

(a)

Closed Course			
	bright-dim	bright-medium	medium-dim
	SL46 - SL70	SL46 - SL40	SL40 - SL70
Subj.	D_i	D_i	D_i
1			2
2	1	1	0
3	1	-1	2
4	1	-1	2
5	-4	-4	0
6	0	1	-1
7	0	-3	3
8	-1	3	-4
9	0	-1	1
10	0	-3	3
11	0	-2	2
12	4	4	0
13	1	1	0
14	0	0	0
15	-1	-1	0
16	6	1	5
μ_D=	0.53	-0.33	0.94
s_D=	2.23	2.23	2.05
n=	15	15	16
	T-STAT	**T-STAT**	**T-STAT**
	0.926	-0.580	1.831

Table 18. Continued

(b)

Open Road			
	bright-dim	bright-medium	medium-dim
	TSY2 - TSX7	TSY2 - TSF5	TSF5 - TSX7
Subj.	D_i	D_i	D_i
1	-2	1	-3
2	-1	0	-1
3	2	1	1
4	0	0	0
5	0	1	-1
6	-1	-2	1
7	-2	-1	-1
8	-2	0	-2
9		0	
10	2	-1	3
11	-1	1	-2
12	-5	-3	-2
13			1
14	-2	-1	-1
15	-4	0	-4
16	-1	1	-2
μ_D=	-1.15	-0.20	-0.87
s_D=	1.99	1.21	1.81
n=	14	15	15
	T-STAT -2.166	**T-STAT** -0.642	**T-STAT** -1.857

Table 18. Continued

(c)

Closed Course vs. Open Road					
	bright		medium		dim
	SL46 - TSY2		SL40 - TSF5		SL70 - TSX7
Subj.	D_i		D_i		D_i
1			0		-5
2	1		0		-1
3	-1		1		0
4	0		1		-1
5	-3		2		1
6	3		0		2
7	0		2		-2
8	1		-2		0
9	1		2		
10	0		2		2
11	0		3		-1
12	4		-3		-5
13			0		1
14	1		0		-1
15	1		2		-2
16	2		2		-5
μ_D=	0.71		0.75		-1.13
s_D=	1.68		1.61		2.36
n=	14		16		15
	T-STAT 1.587		**T-STAT** 1.861		**T-STAT** -1.863

Table 19. Total Glance Duration

	Speed Limit Signs					
	bright	dim	medium	dim	medium	bright
Subject	**SL-46**	**SL-70**	**SL-40**	**TS-X7**	**TS-F5**	**TS-Y2**
1		3.96	5.97	7.33	8.02	3.23
2	12.48	4.53	9.07	8.66	9.65	7.50
3	10.82	8.80	9.33	1.76	4.75	1.67
4	6.82	6.55	7.77	9.34	10.12	6.33
5	3.59	6.73	10.29	8.28	9.90	10.52
6	9.08	6.33	4.63	7.33	8.69	6.30
7	8.90	8.63	7.63	12.90	10.90	10.76
8	4.77	4.13	1.30	7.83	6.85	8.19
9	9.98	6.47	6.36		11.38	12.08
10	6.73	4.76	5.80	5.74	8.43	8.07
11	8.35	5.07	6.03	3.20	9.87	10.53
12	11.09	6.70	5.76	10.90	12.00	7.45
13	10.08	5.73	7.63	7.96	10.32	
14	6.75	7.22	2.74	7.82	9.26	7.76
15	9.15	8.13	7.76	10.76	8.86	10.18
16	6.92	9.06	5.17	9.85	8.10	7.76
mean	8.37	6.43	6.45	7.98	9.19	7.89
median	8.90	6.51	6.20	7.96	9.46	7.76
st dev	2.43	1.66	2.35	2.85	1.78	2.81
n	15	16	16	15	16	15

Table 20. Total Glance Duration Comparisons

(a)

Closed Course			
	bright-dim	bright-medium	medium-dim
	SL46 - SL70	SL46 - SL40	SL40 - SL70
Subj.	D_i	D_i	D_i
1			2.01
2	7.95	3.41	4.54
3	2.02	1.49	0.53
4	0.27	-0.95	1.22
5	-3.14	-6.7	3.56
6	2.75	4.45	-1.7
7	0.27	1.27	-1
8	0.64	3.47	-2.83
9	3.51	3.62	-0.11
10	1.97	0.93	1.04
11	3.28	2.32	0.96
12	4.39	5.33	-0.94
13	4.35	2.45	1.9
14	-0.47	4.01	-4.48
15	1.02	1.39	-0.37
16	-2.14	1.75	-3.89
μ_D=	1.78	1.88	0.03
s_D=	2.79	2.86	2.49
n=	15	15	16
	T-STAT	**T-STAT**	**T-STAT**
	2.470	2.547	0.044

Table 20. Continued

(b)

Open Road Course			
	bright-dim	bright-medium	medium-dim
	TSY2 - TSX7	TSY2 - TSF5	TSF5 - TSX7
Subj.	D_i	D_i	D_i
1	-4.1	-4.79	0.69
2	-1.16	-2.15	0.99
3	-0.09	-3.08	2.99
4	-3.01	-3.79	0.78
5	2.24	0.62	1.62
6	-1.03	-2.39	1.36
7	-2.14	-0.14	-2
8	0.36	1.34	-0.98
9		0.7	
10	2.33	-0.36	2.69
11	7.33	0.66	6.67
12	-3.45	-4.55	1.1
13			2.36
14	-0.06	-1.5	1.44
15	-0.58	1.32	-1.9
16	-2.09	-0.34	-1.75
μ_D=	-0.10	-1.23	1.07
s_D=	2.84	2.11	2.24
n=	14	15	15
	T-STAT -0.137	**T-STAT** -2.255	**T-STAT** 1.848

Table 20. Continued

(c)

Closed Course versus Open Road Course			
	bright	medium	dim
	SL46 - TSY2	SL40 - TSF5	SL70 - TSX7
Subj.	D_i	D_i	D_i
1		-2.05	-3.37
2	4.98	-0.58	-4.13
3	9.15	4.58	7.04
4	0.49	-2.35	-2.79
5	-6.93	0.39	-1.55
6	2.78	-4.06	-1
7	-1.86	-3.27	-4.27
8	-3.42	-5.55	-3.7
9	-2.1	-5.02	
10	-1.34	-2.63	-0.98
11	-2.18	-3.84	1.87
12	3.64	-6.24	-4.2
13		-2.69	-2.23
14	-1.01	-6.52	-0.6
15	-1.03	-1.1	-2.63
16	-0.84	-2.93	-0.79
μ_D=	0.02	-2.74	-1.56
s_D=	3.99	2.76	2.92
n=	14	16	15
	T-STAT 0.022	**T-STAT** -3.973	**T-STAT** -2.059

Table 21. Legibility Distance

	Speed Limit Signs					
	bright	dim	medium	dim	medium	bright
Subject	**SL-46**	**SL-70**	**SL-40**	**TS-X7**	**TS-F5**	**TS-Y2**
2	408	458	429	380	327	383
3	301	271	269	277	186	246
4	390	486	467	298	274	408
5	316	457	452	265	295	395
6	454	408	389	295	369	381
7	274	241	254	189	113	211
8	411	313	190	276	352	390
9	261	248	234	256	227	178
10	387	400	432	333	363	436
11	437	413	471	298	341	352
12	205	558	599	93	232	244
13	408	537	513	331	393	425
14	454	480	455	429	451	533
15	471	436	493	324	406	455
16	347	431	441	315	303	313
mean	368.27	409.13	405.87	290.60	308.80	356.67
median	390	431	441	298	327	383
st dev	80.42	99.27	116.36	77.48	90.24	99.37
n	15	15	15	15	15	15

Table 22. Legibility Distance Comparisons

(a)

Closed Course			
	bright-dim	bright-medium	medium-dim
	SL46 - SL70	SL46 - SL40	SL40 - SL70
Subj.	D_i	D_i	D_i
2	-50	-21	-29
3	30	32	-2
4	-96	-77	-19
5	-141	-136	-5
6	46	65	-19
7	33	20	13
8	98	221	-123
9	13	27	-14
10	-13	-45	32
11	24	-34	58
12	-353	-394	41
13	-129	-105	-24
14	-26	-1	-25
15	35	-22	57
16	-84	-94	10
μ_D=	-40.87	-37.60	-3.27
s_D=	110.64	130.29	44.36
n=	15	15	15
	T-STAT	**T-STAT**	**T-STAT**
	-1.431	-1.118	-0.285

Table 22. Continued

(b)

Open Road Course					
	bright-dim		bright-medium		medium-dim
	TSY2 - TSX7		TSY2 - TSF5		TSF5 - TSX7
Subj.	D_i		D_i		D_i
2	3		56		-53
3	-31		60		-91
4	110		134		-24
5	130		100		30
6	86		12		74
7	22		98		-76
8	114		38		76
9	-78		-49		-29
10	103		73		30
11	54		11		43
12	151		12		139
13	94		32		62
14	104		82		22
15	131		49		82
16	-2		10		-12
μ_D=	66.07		47.87		18.20
s_D=	67.93		46.11		64.77
n=	15		15		15
	T-STAT 3.767		**T-STAT** 4.021		**T-STAT** 1.088

Table 22. Continued

(c)

Closed Course versus Open Road Course			
	bright	medium	dim
	SL46 - TSY2	SL40 - TSF5	SL70 - TSX7
Subj.	D_i	D_i	D_i
2	25	102	78
3	55	83	-6
4	-18	193	188
5	-79	157	192
6	73	20	113
7	63	141	52
8	21	-162	37
9	83	7	-8
10	-49	69	67
11	85	130	115
12	-39	367	465
13	-17	120	206
14	-79	4	51
15	16	87	112
16	34	138	116
μ_D=	11.60	97.07	118.53
s_D=	56.01	113.96	116.33
n=	15	15	15
	T-STAT	**T-STAT**	**T-STAT**
	0.802	3.299	3.946

Table 23. Reduction in Legibility Distance Caused by Decrease in Luminance

	Closed Course		Open Course	
	Luminance reduction from bright sign to X			
Subj.	medium	dim	medium	dim
2	-5%	-12%	15%	1%
3	11%	10%	24%	-13%
4	-20%	-25%	33%	27%
5	-43%	-45%	25%	33%
6	14%	10%	3%	23%
7	7%	12%	46%	10%
8	54%	24%	10%	29%
9	10%	5%	-28%	-44%
10	-12%	-3%	17%	24%
11	-8%	5%	3%	15%
12	-192%	-172%	5%	62%
13	-26%	-32%	8%	22%
14	0%	-6%	15%	20%
15	-5%	7%	11%	29%
16	-27%	-24%	3%	-1%
Avg.	**-16%**	**-16%**	**13%**	**16%**
	Luminance reduction from medium sign to X			
Subj.		dim	dim	
2		-7%	-16%	
3		-1%	-49%	
4		-4%	-9%	
5		-1%	10%	
6		-5%	20%	
7		5%	-67%	
8		-65%	22%	
9		-6%	-13%	
10		7%	8%	
11		12%	13%	
12		7%	60%	
13		-5%	16%	
14		-5%	5%	
15		12%	20%	
16		2%	-4%	
Avg.		**-4%**	**1%**	

Table 24. Last Look Duration Ratios

	Speed Limit Signs					
	bright	dim	medium	dim	medium	bright
Subject	**1**	**5**	**9**	**12**	**13**	**14**
1		20%	10%	3%	6%	6%
2	33%	54%	21%	2%	27%	7%
3	38%	50%	35%	17%	43%	12%
4	36%	44%	27%	81%	23%	63%
5	100%	31%	50%	86%	86%	9%
6	53%	62%	58%	38%	51%	85%
7	65%	39%	50%	19%	38%	91%
9	46%	34%	90%	18%	17%	50%
10	16%	12%	35%		70%	35%
11	39%	35%	20%	83%	37%	54%
13	16%	49%	52%	17%	32%	29%
14	29%	21%	43%	2%	20%	50%
15	10%	70%	25%	38%	56%	
16	57%	85%	38%	72%	65%	84%
17	13%	12%	20%	3%	19%	34%
18	19%	30%	8%	8%	44%	24%
mean	38%	41%	0.36	0.32	0.39	0.42
median	36%	37%	0.35216	0.1788	0.37372	0.34768
st dev	0.24	0.21	0.21	0.32	0.22	0.29
n	15	16	16	15	16	15

Table 25. Last Look Duration Ratio Comparisons

(a)

Closed Course			
	bright-dim	bright-medium	medium-dim
	SL46 - SL70	SL46 - SL40	SL40 - SL70
Subj.	D_i	D_i	D_i
1			-0.11
2	-0.20	0.13	-0.33
3	-0.12	0.03	-0.15
4	-0.08	0.08	-0.17
5	0.69	0.50	0.19
6	-0.09	-0.05	-0.03
7	0.26	0.15	0.11
8	0.12	-0.44	0.56
9	0.04	-0.19	0.23
10	0.04	0.18	-0.15
11	-0.33	-0.36	0.03
12	0.09	-0.14	0.23
13	-0.60	-0.15	-0.45
14	-0.28	0.20	-0.48
15	0.01	-0.07	0.08
16	-0.11	0.11	-0.22
μ_D=	-0.04	0.00	-0.04
s_D=	0.29	0.24	0.27
n=	15	15	16
	T-STAT -0.512	**T-STAT** -0.024	**T-STAT** -0.603

Table 25. Continued

(b)

	Open Road Course		
	bright-dim	bright-medium	medium-dim
	TSY2 - TSX7	TSY2 - TSF5	TSF5 - TSX7
Subj.	D_i	D_i	D_i
1	0.03	0.00	0.02
2	0.06	-0.19	0.25
3	-0.05	-0.31	0.26
4	-0.18	0.40	-0.58
5	-0.77	-0.77	0.00
6	0.47	0.34	0.13
7	0.72	0.54	0.18
8	0.32	0.33	-0.01
9		-0.35	
10	-0.29	0.17	-0.46
11	0.13	-0.03	0.15
12	0.48	0.30	0.18
13			0.17
14	0.12	0.19	-0.07
15	0.31	0.15	0.16
16	0.16	-0.20	0.35
μ_D=	0.11	0.04	0.05
s_D=	0.38	0.35	0.26
n=	14	15	15
	T-STAT	**T-STAT**	**T-STAT**
	1.106	0.428	0.751

Table 25. Continued

(c)

Closed Course versus Open Road Course			
	bright	medium	dim
	SL46 - TSY2	SL40 - TSF5	SL70 - TSX7
Subj.	D_i	D_i	D_i
1		0.04	0.17
2	0.26	-0.06	0.52
3	0.26	-0.08	0.33
4	-0.28	0.04	-0.37
5	0.91	-0.36	-0.55
6	-0.32	0.07	0.24
7	-0.26	0.13	0.20
8	-0.04	0.73	0.16
9	-0.19	-0.34	
10	-0.16	-0.17	-0.48
11	-0.13	0.20	0.33
12	-0.20	0.23	0.19
13		-0.31	0.32
14	-0.27	-0.28	0.13
15	-0.21	0.01	0.09
16	-0.05	-0.36	0.21
μ_D=	-0.05	-0.03	0.10
s_D=	0.33	0.29	0.31
n=	14	16	15
	T-STAT	**T-STAT**	**T-STAT**
	-0.548	-0.434	1.224

Table 26. Maximum Look Duration Ratios

	Speed Limit Signs					
	bright	dim	medium	dim	medium	bright
Subject	**1**	**5**	**9**	**12**	**13**	**14**
1		55%	52%	31%	34%	44%
2	33%	54%	45%	38%	37%	41%
3	38%	50%	35%	68%	43%	30%
4	36%	44%	40%	81%	34%	63%
5	100%	31%	50%	86%	86%	58%
6	53%	62%	58%	38%	51%	85%
7	65%	61%	50%	39%	43%	91%
9	46%	34%	90%	42%	45%	50%
10	25%	60%	35%		70%	35%
11	39%	43%	23%	83%	37%	54%
13	64%	49%	52%	42%	52%	29%
14	29%	40%	43%	30%	22%	50%
15	43%	70%	41%	55%	56%	
16	57%	85%	38%	72%	65%	84%
17	28%	40%	26%	28%	41%	34%
18	19%	47%	26%	49%	44%	24%
mean	45%	51%	44%	52%	48%	51%
median	39%	50%	42%	42%	43%	50%
st dev	21%	14%	16%	21%	16%	21%
n	15	16	16	15	16	15

Table 27. Maximum Look Duration Ratio Comparisons

(a)

Closed Course					
	bright-dim		bright-medium		medium-dim
	SL46 - SL70		SL46 - SL40		SL40 - SL70
Subj.	D_i		D_i		D_i
1					-0.02
2	-0.21		-0.11		-0.09
3	-0.12		0.03		-0.15
4	-0.08		-0.05		-0.04
5	0.69		0.50		0.19
6	-0.09		-0.05		-0.03
7	0.04		0.15		-0.11
8	0.12		-0.44		0.56
9	-0.35		-0.10		-0.25
10	-0.04		0.16		-0.20
11	0.15		0.11		0.03
12	-0.10		-0.14		0.04
13	-0.27		0.01		-0.28
14	-0.28		0.20		-0.48
15	-0.12		0.02		-0.14
16	-0.28		-0.07		-0.21
μ_D=	-0.06		0.01		-0.07
s_D=	0.25		0.21		0.23
n=	15		15		16
	T-STAT		**T-STAT**		**T-STAT**
	-0.963		0.262		-1.291

Table 27. Continued

(b)

Open Road Course			
	bright-dim	bright-medium	medium-dim
	TSY2 - TSX7	TSY2 - TSF5	TSF5 - TSX7
Subj.	D_i	D_i	D_i
1	0.13	0.10	0.03
2	0.03	0.03	0.00
3	-0.38	-0.13	-0.25
4	-0.18	0.29	-0.47
5	-0.28	-0.28	0.00
6	0.47	0.34	0.13
7	0.53	0.48	0.04
8	0.08	0.05	0.03
9		-0.35	
10	-0.29	0.17	-0.46
11	-0.13	-0.23	0.11
12	0.19	0.28	-0.08
13			0.01
14	0.12	0.19	-0.07
15	0.06	-0.07	0.13
16	-0.25	-0.20	-0.06
μ_D=	0.00	0.04	-0.06
s_D=	0.29	0.25	0.19
n=	14	15	15
	T-STAT	**T-STAT**	**T-STAT**
	-0.039	0.690	-1.250

Table 27. Continued

(c)

Closed Course versus Open Road Course					
	bright		medium		dim
	SL46 - TSY2		SL40 - TSF5		SL70 - TSX7
Subj.	D_i		D_i		D_i
1			0.18		0.23
2	-0.07		0.08		0.17
3	0.08		-0.08		-0.18
4	-0.28		0.07		-0.37
5	0.42		-0.36		-0.55
6	-0.32		0.07		0.24
7	-0.26		0.07		0.22
8	-0.04		0.45		-0.08
9	-0.10		-0.34		
10	-0.16		-0.14		-0.40
11	0.35		0.00		0.07
12	-0.20		0.21		0.09
13			-0.14		0.15
14	-0.27		-0.28		0.13
15	-0.06		-0.16		0.12
16	-0.05		-0.18		-0.03
μ_D=	-0.07		-0.03		-0.01
s_D=	0.22		0.22		0.25
n=	14		16		15
	T-STAT -1.147		**T-STAT** -0.629		**T-STAT** -0.193

VITA

Jerremy Eugene Clark

Education

B.S., Civil Engineering, Texas A&M University, August, 2005.
M.S., Civil engineering, Texas A&M University, May 2007.

Work Experience

Texas Transportation Institute, September 2005 – May 2007.
Garrett Engineering, January 2005 – August, 2005
United States Air Force, January 2003 – January 2005

Professional Affiliations and Societies

Institute of Transportation Engineers
Transportation Research Board
American Society of Civil Engineers

Areas of Interest

Transportation operations and design
Traffic operations analysis
Traffic signal design
Traffic signal operations and control
Human factors

Contact Information

Engineering Research Associate
Texas Transportation Institute
3135 TAMU
College Station, TX 77843-3135

jerremyclark@hotmail.com