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16. Abstract

This project focused on the evaluation of traffic sign sheeting performance in terms of meeting the nighttime driver needs. The goal was to develop a nighttime driver needs specification for traffic signs. The researchers used nighttime sign legibility and eye-tracker data to assess the performance needs of nighttime drivers on a closed-course facility as well as on the open road. The researchers also used internally illuminated signs during the research to control the sign luminance (rather than being constrained to the luminance curves provided by the retroreflective sheeting materials on the market). Using the results of the nighttime legibility and eye-tracker studies, the researchers developed a classification scheme for retroreflective sheeting materials based on luminance requirements derived from the study. Then the researchers modeled the retroreflective geometries resulting from common roadway scenarios (sign position, roadway type and cross-section, vehicle size, etc). Using the luminance requirements derived from the study and market-weighted headlamp flux matrices, the researchers developed an approach to sign sheeting specification that is based on nighttime driver needs.

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Paul J. Carlson, P.E., (Texas, # 85402).

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Many agencies are looking for ways to determine which kind of retroreflective sheeting material they should use on their signs. While most agencies prefer to use one kind of material, others use different materials for different applications. Undoubtedly, a one-size-fits-all approach is particularly challenging from both management and economic perspectives. In addition, the ability to manufacture prismatic retroreflective sheeting materials allows the industry to select or design how the retroreflected light is distributed or made available to drivers.

One of the reasons that agencies are beginning to take a serious look at their policies regarding retroreflective sheeting materials is that, at least in the United States, the Federal Highway Administration (FHWA) has implemented revisions to the *Manual on Uniform Traffic Control Devices* (MUTCD), which include minimum maintenance levels for traffic sign retroreflectivity (*1*). The rule-making activities, marketing, and outreach, as well as upcoming compliance dates, have raised the awareness of sign retroreflectivity among agencies responsible for maintaining traffic control devices.

As agencies begin updating their policies regarding retroreflective sheeting materials, they are finding that there are more materials available today than ever before. One of the things they are also learning is that there is very little guidance concerning strategies or recommendations for when to use certain kinds of materials for certain applications, or whether one particular kind of material is adequate for all conditions within an agency's jurisdiction. This makes the job of the specification developer or writer particularly challenging.

Most, if not all, agencies look to the American Society for Testing and Materials (ASTM) specification D4956, *Standard Specification for Retroreflective Sheeting for Traffic Control*, for help (*2*). To their disappointment, however, they learn that ASTM D4956 does not provide useful information concerning the most applicable use of certain kinds of materials. Instead, ASTM D4956 provides very general descriptions of the materials, almost arbitrarily grouped into types. Table 1 provides the descriptions of the types of materials listed in ASTM D4956.

Table 1. ASTM Retroreflective Sheeting Type Descriptions.

ASTM Type	ASTM Description	Typical Construction	Suggested Use	Typical Applications
I	Medium intensity	enclosed lens	none provided	permanent highway signing, construction zone devices, & delineators
II	Medium high-intensity	enclosed lens	none provided	permanent highway signing, construction zone devices, & delineators
III	High-intensity	encapsulated glass beads	none provided	permanent highway signing, construction zone devices, & delineators
IV	High-intensity	microprismatic	none provided	permanent highway signing, construction zone devices, & delineators
V	High-intensity	metallized microprismatic	none provided	delineators
VI	Elastomeric high-intensity	vinyl microprismatic	none provided	orange temporary roll-up warning signs, traffic cone collars, & post bands
VII	Super-high-intensity	microprismatic	medium and long road distances	permanent highway signing, construction zone devices, & delineators
VIII	Super-high-intensity	microprismatic	medium and long road distances	permanent highway signing, construction zone devices, & delineators
IX	Very-high-intensity	microprismatic	short road distances	permanent highway signing, construction zone devices, & delineators
X	Super-high-intensity	microprismatic	medium road distances	permanent highway signing, construction zone devices, & delineators
XI*	Super-high-intensity	microprismatic	medium and short road distances	permanent highway signing, construction zone devices, & delineators

* Proposed ASTM type under consideration

Although the ASTM specification defines these descriptions as "functional performance," the reality is that driver performance or driver needs were not considered when developing the categories represented by ASTM as types. The ASTM types are based on product availability and marketing strategies cloaked as type proposals that the ASTM committee members discuss and debate. Originally, ASTM D4956 was a quality control specification rather than a material selection specification. While the ASTM committee members are experts in their field, there are different opinions and positions concerning how the materials are categorized or even how the materials should be categorized. The D4956 specification is now more a catalog of retroreflective materials than a document that can or should be used to understand sheeting applications or issues thereof with respect to specification development.

In fact, research studies have shown that the performance of various types of sheeting are not statistically different when measured against a metric related to driving, such as legibility (instead of using a metric such as retroreflectivity measured at only a few geometries—and unrealistic or at least unimportant roadway scenario geometries at that) (*3, 4*). The primary criterion that makes each ASTM type different is the measurement of retroreflectivity conducted at geometries that do not necessarily correlate with roadway conditions where motorists need to acquire critical mission information.

Instead of categorizing materials based on what they are and how they measure, a much more useful concept would be to categorize materials based on how they are needed or used by the road users. In this case, retroreflective sheeting materials are needed to make traffic signs visible at night. This means that the traffic signs are conspicuous enough for detection against competing eye-attracting sources such as advertising signs and legible enough at the appropriate distances so they function in the intended manner.

Therefore, a new specification for traffic signs is needed that is based on the needs of the nighttime drivers. While it is likely that a new specification will include retroreflective measurements, perhaps the measurements are made at geometries more realistic of the driving environment and maybe the retroreflective measurements compliment other possible techniques to quantify sign performance, such as luminance or fractional retroreflectance. It is also reasonable to expect a new specification to offer agencies more guidance in terms of what type of sheeting to specify or at least provide a method that agencies can use to better determine the performance differences between various sheeting materials as the nighttime driver would observe the differences while driving at night. These concepts and the potential benefits that could be gained through their realization led to research that is described in this report. The overall objective of the research was to assess the nighttime driver needs for signing and develop a recommended specification based on those needs.

PROJECT SCOPE

Instead of evaluating retroreflective sheeting materials as they enter the market, this project measures how nighttime drivers use traffic signs at night and then using these data, recommend a specification based on the needs of nighttime drivers. A needs-based specification will provide the industry with a benchmark to compare the performance of their current retroreflective sign sheeting materials against the needs of nighttime drivers. Furthermore, it will better enable the industry to refine and/or redesign their product line to better serve the nighttime driving population, which hopefully will decrease their costs, and those cost savings could be passed onto already cash-strapped Departments of Transportation (DOTs).

The research was carried out in three phases. In the first phase, the researchers tested new equipment and the general experimental design to validate the proposed equipment usefulness and to explore possible metrics that could be used to help establish a needs-based specification. The researchers focused on nighttime driver legibility and eye-tracking data as the metrics in Phase I. In Phase II, the researchers focused on closed-course testing using internally illuminated signs to investigate the impact of different luminance profiles on driver legibility and eye-tracking. The study design for Phase III was developed from the findings of Phase I and Phase II, and this last effort focused on both closed-course and open-course efforts.

The remainder of this report is divided into the following chapters:

- Chapter 2: Background and Significance of Work,
- Chapter 3: Phase I Research Summary,
- Chapter 4: Phase II Research Summary,
- Chapter 5: Phase III Research Summary, and
- Chapter 6: Conclusions and Basis for Proposed Specification.

CHAPTER 2:
BACKGROUND AND SIGNIFICANCE OF WORK

Driving tasks follow a hierarchy with three levels of performance, which include control, guidance, and navigation (*5*). Control is the most important task, and navigation is a lesser significant task. A driver's main activities include interacting with the vehicle and maintaining proper speed and alignment. As much as 90 percent of all information is gathered and received visually (*5*), thus emphasizing the importance of traffic signs in the driving process. When a driver confronts excessive information or roadway complexity, then he or she will focus more on vehicle control and guidance and less on navigating to the final destination. The information presented at these two levels is acquired from the drivers' roadway and in-vehicle environments. Regulatory speed limit signs, curve warning signs, and many other traffic control devices aid in all three tasks.

NIGHTTIME DRIVING

Traffic control devices and signs become even more important during nighttime driving. During the day, surrounding features (e.g., large building, shopping area, or geographic feature) are used by drivers to indicate the direction of travel and serve as common reference points in the navigation task. These features cannot be seen be the human eye during nighttime conditions. The capabilities of the human eye are dependent on the amount of available light. The eye's retina contains two types of light sensitive cells: rods and cones (*6*). Cones are concentrated around the fovea (the area used for focusing), and rods are in the periphery. Cones operate at higher levels of illumination and are color sensitive. Rods function at lower levels of illumination and are not color sensitive. The low lighting levels at night places a greater dependence on the rod vision where objects are not as easily detected (*6*). As a result, nighttime drivers are more reliant on the traffic control devices for safe and efficient travel.

Traffic control devices must be either internally or externally illuminated to be viewed during low lighting conditions. Internally illuminated signs provide luminance via an internally lighting source to be seen. Externally illuminated signs are viewed with the aid of an externally light source, as such vehicle headlights. The light from the headlight redirects from the externally illuminated sign back to the viewer by way of retroreflectivity. Retroreflectivity is an optical property of a material that enables incoming light to be reflected back to a driver. Various sign sheeting types have been developed with differing retroreflective capabilities.

A sign sheeting's capabilities are determined by three light components, which are luminous intensity, illuminance, 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 (e.g., sign face). Light dissipates with distance and illuminance depends on the distance between the vehicle and the sign. Luminance is the amount light that is viewed by the driver and is commonly referred to as the brightness of a sign; it is what the driver sees. Retroreflectivity is the ratio of light reflected back to the receptor compared to the amount that is emitted by the source. The ratio depends on the sign sheeting, the viewing angles between the light source (headlight), the viewing surface (e.g., sign face), and the receptor (e.g., driver's eyes).

Retroreflective Sheeting Specifications

The American Society of Testing and Materials developed a specification for all retroreflective sign sheeting types, referred to as ASTM specification D4956. In the late 1980s, American Association of State Highway and Transportation Officials (AASHTO) and FHWA adopted the ASTM specification as the national specification for traffic signs.

As of June 2009, the ASTM D4956 sign sheeting classifications for rigid signs are Types I, II, III, IV, VII, VIII, IX, and X. ASTM established the initial classification from numerically-based performance and retroreflective capabilities. For instance, Type III High Intensity sheeting outperforms Type II Super Engineering Grade. The original performance-based classification was intended to simplify sign sheeting selection. After 1989, newly developed sign sheeting materials were added in chronological order of development as opposed to the original numerically-based performance. As a result, the current classification system does not indicate relative performance. For example, Type IX sheeting is less bright at longer distances than Type VII, but Type IX is brighter at shorter distances.

Most state agencies developed their own state specification based on the ASTM specification and some states employ the ASTM D4956 specification without any modifications (*2*). Texas uses a modified version of the ASTM specification, which is specification DMS-8300. One modification is that the TxDOT specification groups five different ASTM microprismatic retroreflective sheeting types into one classification. The reasoning for the single classification was based on research findings that showed no performance-based differences between each of the microprismatic sign sheeting types (*3, 4*).

LUMINANCE RESEARCH

Mills conducted one of the earliest tests of retroreflective materials in 1933 (*7*). The study compared non-retroreflective signs with early retroreflective signs that utilized retroreflective "buttons" placed in the legend of a sign as the experimental treatment. The non-retroreflective signs at night could not be seen at a distance of greater than 200 ft away. The addition of the retroreflective buttons, however, extended the nighttime visibility distance to beyond 500 ft. As retroreflective materials evolved, so did the research conducted to analyze them. Sign research began to diverge into two paths: studies conducted in the field and studies conducted in a laboratory. Both lab and fields have their advantages and disadvantages, and researchers must consider all aspects when creating an experimental design.

Laboratory Studies

Early laboratory-based research employed practices similar to a common eye exam. In 1977, Richards (*8*) used a static vision testing method by seating subjects 20 ft from an eye chart. The chart was constructed of a rotating disk with letters printed on it to be seen through a slice taken out of the panel in the front of the disk. The letters decreased in size toward the center of the disk. Four luminance levels were presented by supplying light from a projector calibrated to simulate a vehicle's headlamp. The light source was adjusted to filter light at 10, 1, 0.1, and 0.01 foot-lamberts (0.03 to 34 cd/m^2). Results were averaged for each decade of age collected (26–35, 36–45, etc). Richards found not only that acuity decreases with age, but also that the acuities at each luminance value exponentially decreased with test letter contrast.

In 1995, Mercier et al. (*9*) modified Richards' approach by conducting a study using a projection system with signs on a rotating display device. There were five signs on the device that presented one at a time to the subject. Subjects viewed the scaled signs from distances of 83 and 102 ft, which corresponded to the visibility indices for speeds of 30 and 55 mph, respectively. At these positions, the luminance of the display was incrementally adjusted until the subjects were able to identify the messages.

In 2004, Schnell et al. (*10*) further built upon this method of using projectors and screens. Schnell et al. presented subjects with an image of a 2-inch symbolic sign 64 ft away. To accomplish this, a mirror was set up to reflect the image from a high resolution projector onto a screen. The background of the scene was presented in a lower resolution to provide sufficient contrast between the sign and the scene. Luminance was measured by a color Charge-Coupled Device (CCD) from the front of the screen. Subjects then walked toward the screen until the symbol was identifiable. This setup provided an efficient means for collecting data and adjusting the luminance of the image. Schnell et al. found that the projector and mirror combination was a cheap, easy, and reliable method for adjusting the luminance of any sign presented. Further, the high resolution of the projector demonstrated that overglow was not a consequence for negative contrast signs for luminance levels up to 942 cd/m^2. Results lead to the conclusion that 82 cd/m^2 was the maximum background luminance beyond which no improvement was witnessed.

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

In 1979, Olsen and Bernstein (*11*) conducted a two-tiered experiment to evaluate the effects of luminance, contrast, color, and driver visual characteristics on sign legibility distance in both a lab and field setting. The first phase utilized laboratory projectors to vary the luminance of sign legends similar to methods employed by Mercier et al. and Schnell et al. The second phase took place on a closed-course track at a private airport that was designed to simulate a freeway setting. Legibility distance was the analyzed measure of effectiveness. Olsen and Bernstein found that the field performance data equated well with the 90th percentile laboratory data. This proved that field studies could be just as accurate as controlled laboratory studies, which persuaded many researchers to take their experiment into the field.

Field Studies

In 1976, Forbes (*12*) analyzed the effects of color combinations as a function of legibility distance. Forbes found that low beam headlights in the field resulted in longer legibility distances than previous lab measurements. The study also determined that signs with higher luminance levels produced shorter subject glance durations. The color combination analysis identified that the interaction between the background and legend produced a substantial impact on sign legibility, regardless of the luminance. The color combinations of black on white and black on yellow achieved the longest legibility distances and white on gray performed the worst.

Padmos (*13*) in 2000 found that the color recognition of a sign took place at a much greater distance than sign legibility. The results showed that the standardization of highway signs allowed drivers to recognize those colors at lower luminance levels. Padmos defined the lower limit of luminance as "the lowest luminance that turns it sufficiently conspicuous for detection as such and sufficiently legible in order to be identified at a safe distance."

In 2001, Carlson and Hawkins (*14*) completed a project aimed at identifying the minimum required luminance through minimum retroreflectivity requirements. The proposed minimum requirements were based on field data that were obtained at the Riverside test facility. The study analyzed subject legibility distances as a function of varying luminous intensity. The luminous intensity of a test vehicle's headlamps was adjusted to produce 32 different levels. In the study, subjects viewed overhead and guide signs and were asked to read the sign content. Signs were viewed under different luminance levels. Figure 1 illustrates the effect of increased luminance on the percentage of correct responses of sign content. The three lines in the figure represent legibility indices according to the three positions used to read the signs.

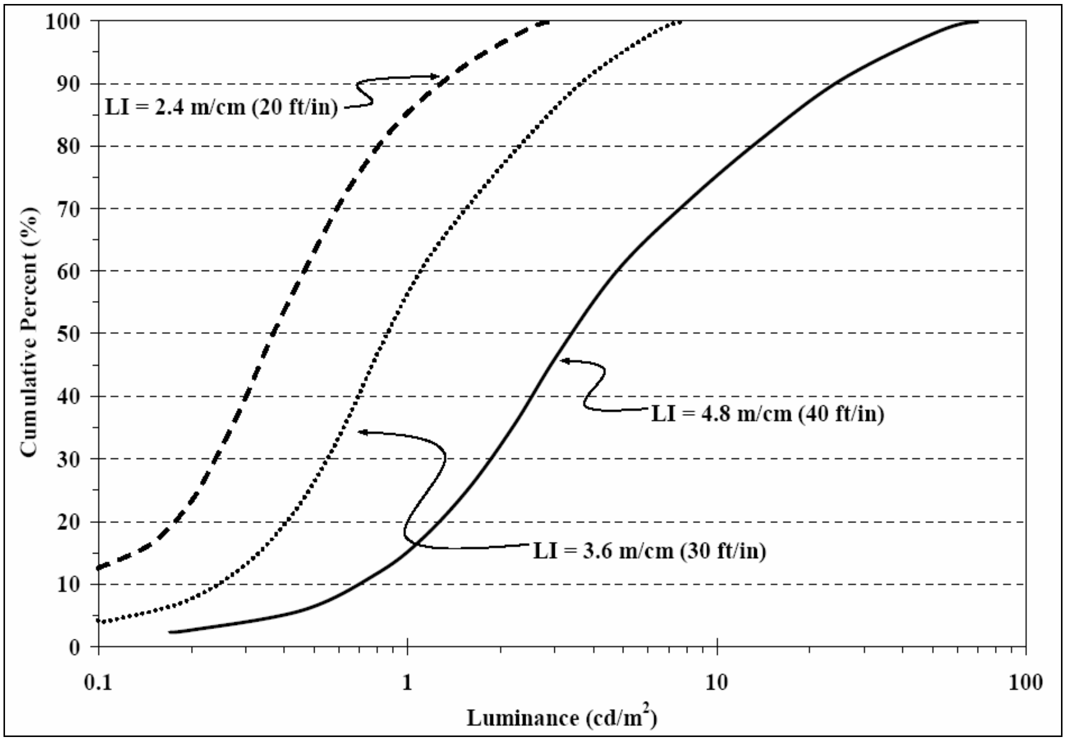


Figure 1. Minimum Sign Luminance (*14*).

EYE-TRACKING RESEARCH

Two methods commonly used to study sign visibility and legibility are driver response and eye-tracking. The driver response method relies on the driver to indicate when he or she can read a sign's content. Eye-tracking devices monitor the fovea view of the driver. The eye-tracker captures eye movements and glances at a sign. Advanced eye-tracking technology has allowed researchers to investigate many other aspects of driver behavior in addition to legibility. Both driver response and eye-tracking methods have been employed effectively in past research.

Eye-tracking studies have been used for many years to evaluate subject eye movements to improve the design and performance of signs. Most contemporary eye-trackers use a combination of infrared light and cameras to record fovea view. Infrared light projected on the eye will reflect against the dark part of the iris but not the white space of the pupil. Infrared cameras use the reflected light to follow the pupil. An additional camera captures the forward view to determine where the fovea view is focusing. Figure 2 shows examples of an eye-tracking device following the dark pupil area.

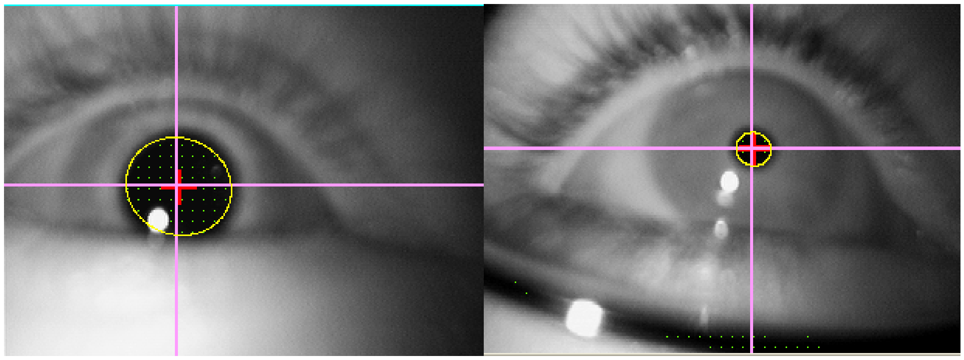


Figure 2. Pupil Contrast as Seen by Infrared Camera.

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, which include remote, muscular, and head-mounted systems.

Remote Systems

Remote eye-tracking systems are the least invasive system of the eye-tracking devices. Remote systems place inconspicuous and discreet cameras near the subject to monitor and record eye movements. Figure 3 depicts an example of a remote eye-tracking system where two eye cameras are mounted in the dash of the vehicle (two dashed circles) while a forward facing camera (solid oval) captures the scene through the windshield. Remote systems excel by eliminating subject interaction. Drivers' movements are not restricted or constrained by the equipment. This makes remote systems ideal for transportation studies. In transportation research, it is important for subjects to react naturally and unaffected to the data collection equipment.

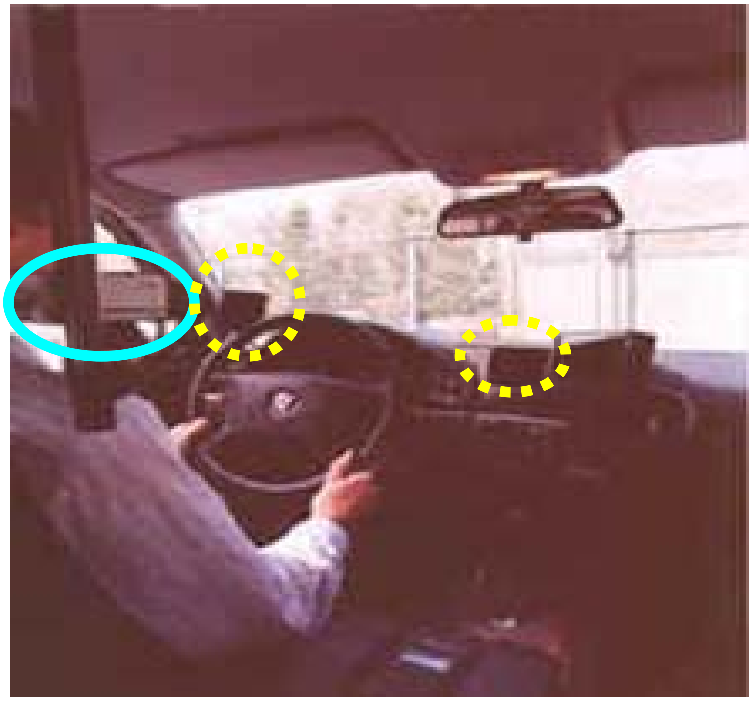


Figure 3. Remote Eye-Tracking System (*15*).

Remote systems often sacrifice accuracy for discretion. For highest accuracy the eye cameras should be on a level plane with the eye. Although most system manufacturers boast an accuracy of 1 degree, most users surveyed experienced an accuracy of 2 to 6 degrees. This correlates to the ability to distinguish a lateral glance of 14 to 42 ft at 400 ft. The reduced accuracy is largely due to the distance between the cameras to the eyes. Remote systems are prone to lose focus and sight of the eye. Natural driving tendencies require the subjects to move their heads, which often takes them out of the range of the cameras.

Muscular Systems

The muscular system is one of the least commonly used eye-tracking systems. One muscular system is called the Electro-Oculography (EOG) (*16*). The system uses three to four electrodes placed around the eye socket to monitor eye movements of a subject. There is an extensive calibration process and the system does not provide video for review. The muscular system is typically not employed in transportation or field studies.

Head-Mounted Systems

Early eye-tracking systems used equipment mounted on the subject's head. Several apparatuses have been designed to support the lights, cameras, cables, and power supply necessary to operate the systems. Figure 4 depicts a head-mounted system and the important device components. The equipment secured to the subject's head can be distracting, thereby reducing its effectiveness for studies requiring "naturalistic" responses. 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 degree to 2 degrees. As related to this research, the ability to distinguish 1 degree correlates to a driver's lateral glance of 7 ft from 400 ft away.

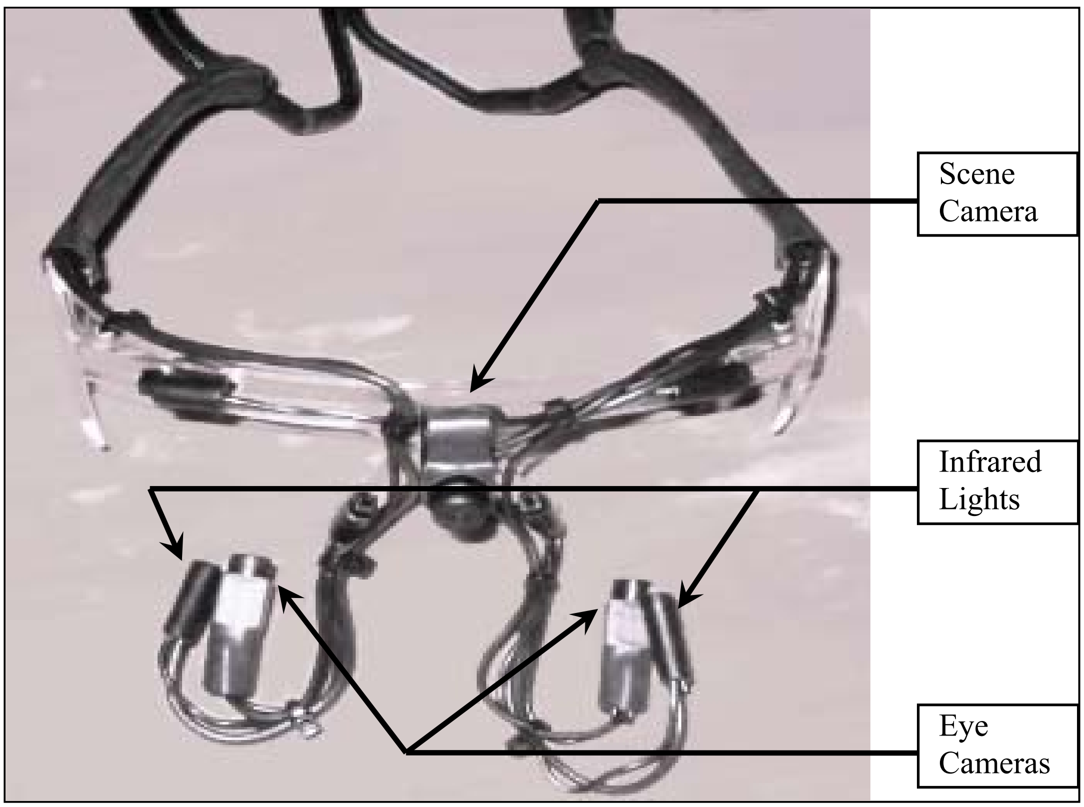


Figure 4. Head Mounted Eye-Tracking System.

One of the effective head-mounted systems is the ViewPoint EyeTracker® with EyeFrame™ hardware by Arrington Research, Inc. The EyeFrame™ is essentially a modified pair of safety goggles designed to support miniature lights and cameras. Two cameras follow the pupil while a third camera, positioned at the bridge of the glasses, captures the forward scene.

The advantage of this system over other head-mounted systems is the lightweight apparatus. The EyeFrame™ is also less imposing than other systems due to its position below the line of sight and the concealment of the wires down the nose of the subject. First, by mounting all three cameras on one rigid frame, the geometry between the cameras stays constant for each subject. The close proximity of the cameras makes it possible to capture small and detailed eye movements, resulting in resolution as low as 0.25 degree (lateral glance of 2 ft at 400 ft). This system is very mobile and versatile in field applications, which releases the reliance on laboratory studies for accurate eye-tracking results.

Eye-Tracker Studies

In a study in 1968, Rockwell et al. (*17*) used a head-mounted system comprised of lights, cameras, and fiber optic cables attached to a helmet. Although once considered state-of-the-art, the camera was limited to a 20-degree field of view and the cables lost 80 percent 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 degrees. By dividing the forward viewing area into seven regions, 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 ft in front of the vehicle than daytime drivers.

Further study by Mourant and Rockwell (*18*) in 1970 revealed that as drivers become more familiar with a route, eye fixations become more focused on the road ahead rather than observing the 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 degree lower (closer to the vehicle) for all subjects.

These early studies quickly grew to long-term research on sign reading behavior. In 1973, Bhise and Rockwell (*19*) ascertained that drivers do not steadily concentrate on a sign to obtain its information. Their data showed that subjects performed several glances on the approach to the sign before 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 (*20*) and Shinar et al. (*21*) analyzed varying aspects of driver eye-movement behavior such as daytime versus nighttime driving, age, and roadway geometry. The studies discovered that drivers use several glances to obtain information from signs (*20, 21*). This revelation opened the door to much of the research conducted today, including this project. As technology and eye-tracking capabilities advanced, new research was undertaken to build on Rockwell et al.'s groundbreaking studies.

The next key player in eye-tracking research began investigating specific signs along roadways. In 1987, Zwahlen (*22*) used a head-mounted system and a 1973 Volkswagen to analyze the effectiveness of Advisory Speed plaques on Curve Warning signs in Ohio. 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 (*23*). Zwahlen confirmed Bhise and Rockwell's findings that signs with more text took longer to read. This meant that driver legibility occurred closer to the sign when there are more words and content to comprehend (*23*). Zwahlen also found the addition of Advisory Speed plaques 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 (*23*)." Zwahlen also began dividing the subject's glances into "First Look" and "Last Look" glances.

Zwahlen (*24*) continued his eye-tracking research in 1995 by concentrating on legibility of short words or symbol signs during nighttime driving. This study shifted focus from a Minimum Required Visibility Distance (MRVD) to an Minimum Required Legibility Distance (MRLD). The MRVD was the distance previously used to develop a minimum retroreflectivity requirement for traffic signs. Zwahlen developed an MRLD model based on actual driver eye scanning behavior and found that the MRLD was longer than the MRVD in most cases. Another nighttime study by Zwahlen et al. (*25*) in 2003 evaluated the effectiveness of ground-mounted diagrammatic signs at freeway interchanges by determining if they attracted excessive eye fixations. The more recent studies conducted by Zwahlen were accomplished by a more advanced eye-tracking system.

Schieber et al. (*26*) evaluated the effects of age, sign luminance, and environmental demand with a remote eye-tracking system. Subjects completed a 30-minute test drive with the task of locating several test signs. Schieber et al. studied several factors relevant to this project. First, it was established that decreasing sign retroreflectivity from 100 to 15 percent resulted in a 17 to 24 percent decrease in legibility (*26*). Further, the authors found that the average fixation while reading (the last look) exceeded three seconds and the total viewing time surpassed six seconds during unrestricted sight distance conditions. Schieber et al.'s results were hindered by the reported capabilities of the remote eye-tracking system. The system was limited to a viewing distance of 984 ft (300 m). Perhaps their most significant conclusion dealt with the comparison between suburban and rural conditions. Figure 5 depicts a graph of the luminance results for the rural and suburban environments. The numbers in parenthesis represent the lateral offset of the sign from the roadway, and the two vertical lines denote the 197 and 249 ft (60 and 76 m) mean legibility distances observed for the rural and suburban environments, respectively.

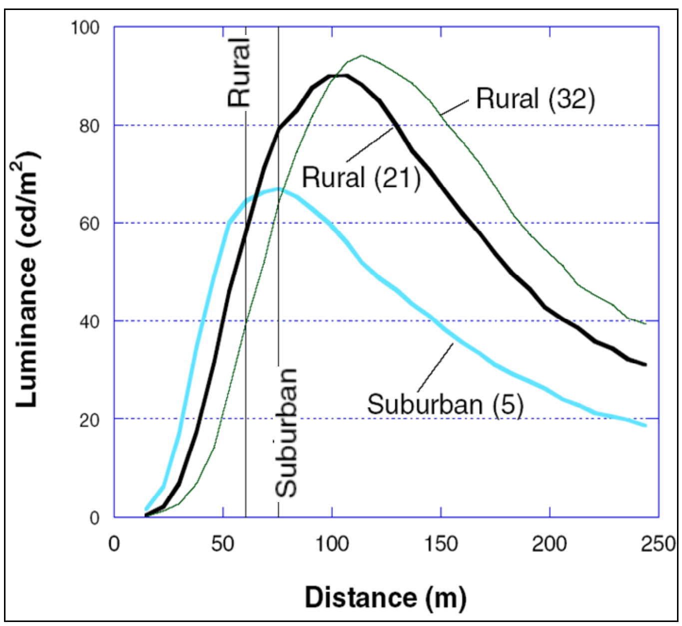


Figure 5. Luminance for Rural and Suburban Viewing Conditions (*26*).

The importance of this comparison relates directly to the goal of this research. 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.

The authors noted that the peaks of the luminance curves for the rural environments were located at nearly twice the recognition distance, suggesting that the luminance distribution was nearly optimal for the suburban environment but highly suboptimal for the rural conditions (*26*).

Another eye-tracking study with a remote system was conducted by Diem (*27*) in 2005 to study driver eye movements under differing conditions. Comparisons were made between eye movements during the daytime and nighttime as well as between built up areas and country roads. The comparisons between daytime and nighttime revealed that the driver searches more during nighttime driving. The area scanned by the nighttime driver was considerably larger than 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 eye fixations at night in order to receive the same information during daytime conditions. It was also determined that drivers in rural areas tend to concentrate more on the road further ahead than drivers in built up areas.

Driver Needs

Roadway signs must be detected, recognized, and comprehended in a timely manner for a driver to react accordingly to downstream situations. Sign detection is directly related to a sign's conspicuity with respect to its size, color contrast, and luminance capabilities. As the degree of conspicuity increases, then theoretically so does the detection and legibility distances. A longer detection and legibility may provide a driver with more time to react accordingly to the sign's message. In this study the detection, recognition, and comprehension process is referred to as the Three-Look Model. The model was shaped by previous research from influential researchers such as Zwahlen, Schieber, Rockwell, etc. The Three-Look Model is explained in additional detail below.

A vast majority of published sign studies have been conducted in a static environment, including the FHWA minimum performance level efforts described above. Unfortunately, drivers use signs while driving, not while parked. This is a simple but fundamental concept, as studies have shown that dynamic testing, compared to static testing, is more difficult for the research participant, and therefore the measured metrics, such as legibility distance, decrease when the participants have to drive a vehicle and read signs (*26, 29*).

In a recent paper that reported on a combination of metrics including legibility distance and eye movements, a two-glance look model was used to describe how drivers acquire information from signs in a dynamic fashion (*26*). Figure 6 shows a version of the two-glance look model.

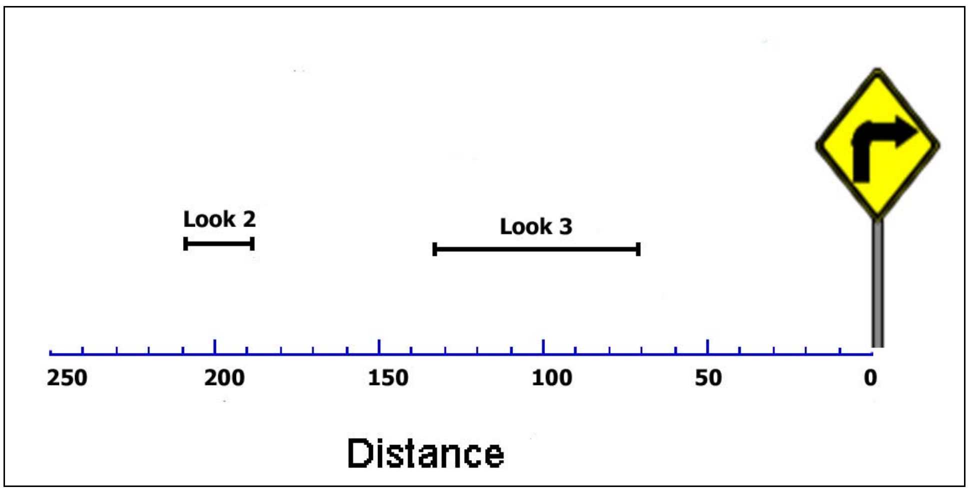


Figure 6. A Two-Glance Look Model.

In Figure 6, the first look, or LOOK1, is somewhere to the left of the diagram. It is not shown because it cannot be confidently tied to a distance with today's research tools such as the eye-tracking technology that can be used to locate LOOK2 and LOOK3. The resolution of eye-tracking equipment is not great enough to discern when drivers are looking at signs or the roadway when the distances are relatively long. But, from previous eye-tracking work, we know that a two-glance look model, ignoring the first look, reasonably explains drivers' traffic sign information acquisition process when they are attempting to read signs in a mission-critical manner (i.e., when they are trying to read unfamiliar signs as quickly as they can, not when they are casually driving and incidentally searching the roadside for certain sign types or shapes).

The first look, or LOOK1, is not a critical element of the seeing model. LOOK1 can be eliminated or missed as a result of sight line obstructions or driver distraction. In this case, LOOK1 and LOOK2 would be shown consecutively as one look. There are a number of other cases that deviate from the three-look model as proposed herein. It is not within the scope of this paper to cover all possible situations. The purpose of the proposed seeing model described in this paper is used to tie distances to luminance curves representing nighttime driver needs so that the performance of retroreflective sheeting materials can be assessed and categorized.

In the model shown in Figure 6, LOOK2 occurs sometime after LOOK1. LOOK1 is simply the recognition of a target possibly related to the driving task. The target could be a traffic sign, a light on the side of a building, or a set of headlamps far enough in the distance that they appear as a point source of light. LOOK1 could be anything that might be remotely related to the driving task.

LOOK2 occurs at a closer distance and can be considered an assessment or verification look. During this look, the driver assesses the target to determine if it is related to the driving task. If not, then the target is dismissed and likely not viewed again. However, if during LOOK2 the driver decides that the target is related to the driving task at hand, then another look will occur, but not before a quick look to the roadway for lane keeping and other obviously important driving tasks.

During the third look, or LOOK3, the driver actually acquires the information on the sign. This look and the sign's design are often the most studied aspect of traffic signing as it relates to sign warning distances and the intended maneuvers conveyed by the sign design. However, without the previous elements of the model as described above, the true sign acquisition process is oversimplified and cannot be adequately modeled or used to assess signing needs such as desired nighttime performance (*28*).

Using a key figure from a International Commission on Illumination (CIE) draft report, a three-look model is proposed graphically in Figure 7 (*30*). In Figure 7, the three looks described above are superimposed with critical but traditionally qualitative distances corresponding to an approach to a traffic sign. The relationship between driver sign looks (using the proposed model) and critical distances related to sign visibility is now evident. The next concern is linking the three looks with distances or times.

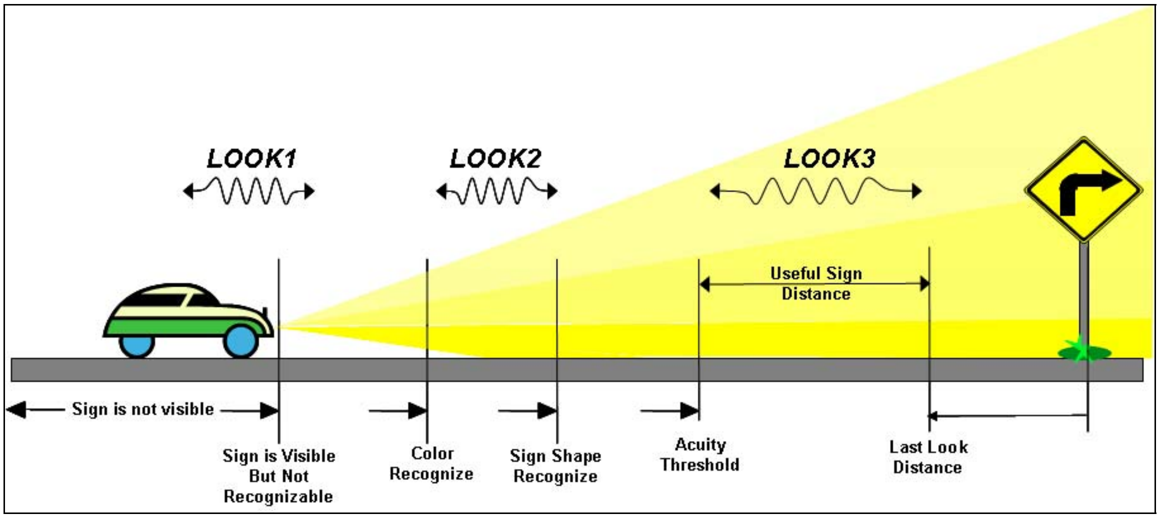


Figure 7. A Three-Look Model.

Recent research has provided new information concerning how drivers use signs while driving on real highways with real traffic and at real operating speeds (*26*). The findings of this recent work provide new and interesting insight into the information acquisition process as drivers look for and decipher traffic sign messages (as opposed to static testing, simulator testing, or closed-course testing).

This recent work also focused on a "mission-critical" sign reading task rather than monitoring incidental interaction with unexpected warning sign stimuli (which has been the focus of previous eye-tracking research [*31*]). The study design required drivers to read a text sign from as far away as possible without compromising the safety of the driving task. Although this paradigm is not "naturalistic" since the drivers knew that their sign reading and eye movement data were being recorded, the task itself remains realistic insofar as the need to read signs from far away is commonly required when navigating a vehicle in unfamiliar environments.

Two conditions were used for this research. One was a suburban condition that comprised a four-lane roadway in a commercial area with moderate traffic volumes, overhead illumination, constrained sight distances, and a 35 mph posted speed limit. The second was a rural condition that included a divided highway in a rural setting with low traffic volumes, straight and flat roadway sections, and a 65 mph posted speed limit.

One of the key findings related to this study that is particularly relevant here is that the time of LOOK3 remained relatively constant, with averages ranging from 3.1 to 3.5 seconds. In addition, LOOK3 ended at nearly the same location regardless of speed. For high-speed conditions, LOOK3 ended at a distance associated with a legibility index of 20 ft/in (2.4 m/cm). For low-speed conditions, LOOK3 ended with at slightly larger average legibility index of 22 ft/in (2.64 m/cm).

The end of LOOK3 distances appear to correlate well with a long-standing rule-of-thumb concerning last look distances, and that is 10 degrees out of view. On average, the rural signs were offset about 32 ft from the middle of the lane. Using the 10 degree rule-of-thumb, one calculates a last look distance of 180 ft, or 22 ft/in.

Using the last look distances to calculate when LOOK3 starts, it becomes evident that depending on the letter size of the sign, LOOK3 starts near the legibility index of 40 ft/in (4.8 m/cm) of letter height. For 25 mph speeds, LOOK3 start corresponds to 4.5-inch letter heights using a legibility index of 40 ft/in as suggested in the MUTCD. Assuming that the visual acuity threshold is near 40 ft/in, then 4-inch letter heights on streets with 25 mph speeds do not meet driver need. For 70 mph speeds, letter heights of at least 12 inches are needed to ensure that LOOK3 start times occur after the visual acuity threshold has been realized (assuming that visual acuity thresholds can be based on the legibility index of 40 ft/in).

This means that once drivers verify they need to acquire the information on the sign they identified during LOOK2, they may or may not begin trying to acquire the information when it is legible, depending on the letter height. Assuming that adequate letter height is used, LOOK3 occurs at a distance closer to the sign than most drivers' visual acuity threshold (based on a legibility index of 40 ft/in). Once LOOK3 begins, it is from this point forward on the approach to a sign that information from the sign is acquired and where the emphasis of performance levels should be placed. In this range, it would be desirable that signs perform for as many conditions as possible.

One more thought on LOOK3 is that it is reasonable to think of LOOK3 as being either a relatively short look or a longer look as presented above. For the shorter time of LOOK3, drivers begin to look at the sign in an acquisitional mode at the onset of legibility acuity. It is also reasonable to assume that LOOK3 first involves a recognition scan so that drivers can acquire the sign information as soon as possible. If the sign does not contain information related to the critical mission, in other words, if it was a false alarm, the driver terminates LOOK3 early and redirects their attention. It is important to note that it is the longer look of LOOK3 that is of interest here. During this look, the driver goes through the same steps as just described but rather than terminating the look early because of a false alarm, the driver continues to acquire and process the sign information. Again, the total time for LOOK3 can range from 3.0 to 3.5 seconds.

The same work also was used to generate time intervals prior to LOOK3. The time interval between LOOK3 and LOOK2 ranged from about 0.33 to 0.66 seconds. The time for LOOK2 was close to 1 second. The resolution of today's eye-scanning equipment is limited to about the LOOK2 position. Therefore, time or distances associated with LOOK1 are not empirically available. In this paper, the time between LOOK2 and LOOK1 is assumed to be 1 second, and LOOK1 is assumed to be 0.5 seconds. Using the times associated with each look as just described, and the out-of-view distances (OVDs) determined in the NCHRP 4-29 work, a set of distances were derived as shown in the Table 2.

Table 2. LOOK Distances (ft).

SPEED (mph)	LOOK1		LOOK2		LOOK3	
	Start	End	Start	End	Start	OVD
25	290	271	235	198	179	60
40	458	428	369	311	281	90
55	625	585	504	423	383	120
70	793	742	639	536	484	150
Time (sec)	0.5	1.0	1.0	0.5	3.25	

The LOOK distances shown in Table 2 were derived from the best information available in terms of describing how drivers use signs. The distances are not meant to indicate how far signs need to be read in order to provide adequate driver reaction times. Preferably, the LOOK3 start distances in Table 2 are shorter than the distances that signs are placed based on driver needs and assumed reaction times. Although it is not within the scope of this investigation, it would be interesting to compare sign placement and legend size recommendations contained in the MUTCD and agency policies with the criteria summarized in Table 2. In other words, are the guidelines used for sign design and sign placement consistent with the way drivers use signs?

With the spatial components of the three-look model defined as shown in Table 2, the next issue to tackle is assigning luminance needs or performance needs to the three looks and their distances. Although one could define performance needs with various descriptors such as optimum or ideal, this paper focuses on *minimum* and *desired* performance levels. The next section of this paper describes the meaning of these performance levels and includes examples of luminance levels associated with each. Figure 8 shows the order and details for the Three-Look Model.

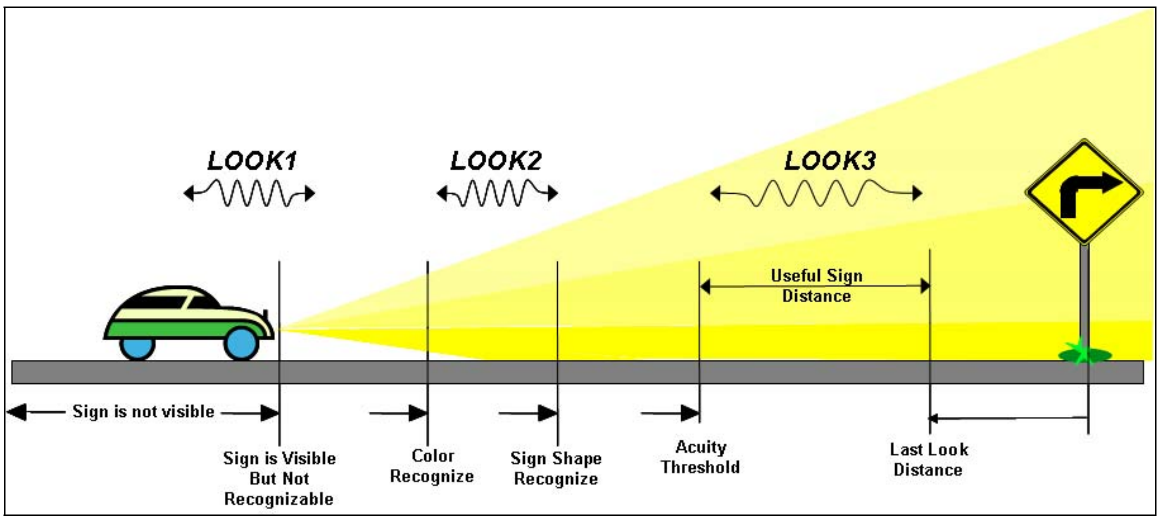


Figure 8. Three-Look Model.

The Three-Look Model shows many generalized relationships between the drivers' actions and viewing behavior as it relates to the sign's performance. The model classifies eye glances and glance duration into categories of detection, recognition, and comprehension. The first classification is detection where the driver searches the roadway environment for pertinent information. The driver is essentially mapping out the surroundings and searching for critical information with saccadic eye movements. The roadway searching and object detection is performed with both peripheral and fovea view (*18*). If the driver detects something of interest, then he or she will decide whether to devote more time in examining the detected object.

The driver should be able to determine that the detected object is a roadway sign at a distance of approximately 1,000 ft. The shape and color of the sign will be recognizable and the driver will begin to anticipate the sign's content from previous experiences and surrounding roadway clues. During the recognition period, the sign is still too far for the driver to identify the actual content. The driver will divert several short glances from the roadway to assess if the sign's words or symbols are legible.

The driver can comprehend the sign's content once it is within the driver's acuity threshold, which is typically around 30 to 40 ft/in. The driver will then typically devote one long glance around 3 sec (*19, 25, 26*). Once the sign's message is comprehended, then the driver will respond or react to the presented information. The legibility glance is critical since the driver will divert fovea view from downstream traffic to the sign for a substantial amount of time.

Establishing Performance Levels

Making decisions regarding the performance needs of traffic control devices can be a difficult task. On one hand, it is desirable to provide traffic control devices with performance levels that satisfy the needs of all road users under all conditions. On the other hand, the technology might not exist or even if it does it could be cost prohibitive. Therefore, tough decisions need to be made that provide a reasonable balance between all factors at play.

For overhead sign legends the ultimate solution might be fixed sign lighting. However, capital and maintenance costs can make fixed sign lighting on all overhead signs cost prohibitive. The situation is not one-sided, however. Legislation in many parts of the U.S. restricts lighting to maintain dark skies. In some areas of the U.S., summertime power consumption levels reach and exceed capacity. In these areas, removing sign lighting can be seen as an easy target to conserve power, especially when retroreflective sheeting materials exist to provide at least some nighttime sign performance.

While advancements in retroreflective sheeting materials help mitigate the need for lighting overhead signs, retroreflectivity alone does not provide a solution for all conditions. Urban conditions and areas with complex backgrounds may require fixed sign lighting. In addition, there are combinations of certain factors that make retroreflective overhead signs inadequate, even in rural conditions or areas with no glare from background sources.

In this research, the primary metrics will be based on luminance and its effect on legibility and nighttime driver eye behavior. It is expected that performance levels can be derived from the luminance of the traffic sign, particularly the luminance available to the nighttime driver in the LOOK3 regions of the Three-Look Model explained above.

CHAPTER 3:
PHASE I SUMMARY

This project was segmented into three phases, where each phase progressively increased in complexity. This chapter details the first phase in this study. The first phase focused on assessing the use of a head-mounted eye-tracking system and exploring possible measures of effectiveness resulting from recorded eye-tracking video. The procedure and methods for using the eye-tracking system were tested and validated during this task. This chapter includes a description of Phase I as well as the findings that carry over to the subsequent phases of the research.

OBJECTIVES

Phase I was designed to test the usefulness of the equipment and identify a methodology that could be utilized successfully in the latter phases. The objectives of the research conducted in Phase I were to:

- test the usefulness of the eye-tracker data in terms of accuracy, resolution, and reliability,
- explore testing methodologies that could be utilized successfully in the later phases, and
- investigate changes in driver glance behavior as it relates to differing sign luminance levels.

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 evaluated the effect of sign brightness on driver eye behavior with various sign luminance levels. The experimental design was accomplished through three primary stages of course layout, sign luminance design, and equipment assembly.

Course Layout

The course layout was divided into three sections including a closed-course testing facility, rural county roads open to public travel, and a segment on a residential street. The closed-course testing facility consisted of a 4-mile path at Texas A&M University's Riverside Campus. Riverside campus was a former Army Air Corps installation that is used for various research projects and testing applications. The open-road course is referred to as the Silver Hill course due to its loop around Silver Hill Road, a rural two-lane roadway in Brazos County, Texas. The final segment was along 5th Street within the Riverside Campus. Different test signs were presented on each course. Table 3 describes the test signs. Report 0-5235-1 Volume 2 shows the three courses as well as all test signs and their measured luminance.

Table 3. Phase I Test Sign Information.

Sign		Sign Legend	Sign Color	Viewing Order from Start Point	
No.	Name			Taxiway	35L
1	SL-46	Speed Limit 46	white	1	7
2	G-ML	Mapleton/Lansing	green	2	8
3	Y-2ln	Always/Animal	yellow	3	9
4	O-3ln	Twenty/Thrown/Public	orange	4	10
5	SL-70	Speed Limit 70	white	5	11
6	W-3a	Hungry/Famous/School	white	6	1
7	W-2	Magnet/Listen	white	7	2
8	W-3b	Couple/Reason/Strike	white	8	3
9	SL-40	Speed Limit 40	white	9	4
10	G-LP	Lakewood/Pleasanton	green	10	5
11	SL-73	Speed Limit 73	white	11	6
12	TS-X7	Test Sign X7	white	12	12
13	TS-F5	Test Sign F5	white	13	13
14	TS-Y2	Test Sign Y2	white	14	14
15	SN-AZ	Arizona	green	15	15

Note: Signs 1-11 were located on the Runway Course, signs 12-14 were on Silver Hill Road, and sign 15 was on 5th Street.

Closed-Course Testing

The 4-mile closed-course began and ended on the runways of the Riverside Campus. The course consisted of two different starting points, which allowed the signs to be viewed in two randomized blocks. Half of the subjects started at one point and the second half started at the alternate point. Subjects saw test signs 1 through 11 within the 4-mile closed-course. Each subject observed each test sign in a constant position and orientation.

Test signs on the closed course consisted of regulatory signs, overhead guide signs, and yellow and orange warning signs. Test signs 1 through 10 were externally illuminated by the test vehicle's headlights, and sign 11 was illuminated with a 1200 watt flood light. The flood light provided a more uniform luminance level for the driver regardless of vehicle headlights and viewing distance. Figure 9 shows images of test sign 11 and flood light illumination. While the subject was driving on the course, the floodlight was turned on and then turned off once the driver passed the sign to avoid glare. The flood light was powered by a generator and shielded to eliminate detection by the driver.

Figure 9. Floodlight on Sign 11 at Day and Night.

Open-Road Testing – Silver Hill Course

The open-road course consisted of a 6-mile loop that began and ended at the entrance to the Riverside Campus. Although the subjects traveled across a section of State Highway 47, data were only collected along a 2-mile section of Silver Hill Road. Silver Hill Road is maintained by

Brazos County, Texas. The Silver Hill Course offered several advantages over other nearby roadways. 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. This road was in close proximity to the Riverside Campus and easy access via State Highway 47.

Figure 10. Silver Hill Road Test Sign.

Residential Street Testing – 5th Street Segment

Subjects drove through the final 5th Street segment on their way back into the Riverside Campus. The intersecting roads along 5th Street are named sequentially Avenue A through Avenue D. This portion of the experiment required a researcher to replace one of the street name signs on 5th Street with a test sign. Subjects saw test sign 15, which contained "Arizona" in the legend.

Figure 11. 5th Street Test Sign.

Test Subjects

The Institutional Review Board at Texas A&M University approved and sanctioned the experimental procedure. This approval process ensured that no subjects were exposed to any unnecessary hazard or harm. Due to a Texas A&M University insurance issue, all subjects in Phase I were employed by the Texas Transportation Institute (TTI).

Subjects in this phase differed in age, driving experience, visual acuity, visual correction, eye color, gender, and road network familiarity. The data collection measured the number of eye glances and glance duration for each. 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. The additional tasks were meant to occupy the subjects' attention with something other than just focusing on sign legibility. A total of 17 subjects participated in Phase I but data from only 16 participants were usable. Table 4 includes pertinent information for the 16 subjects.

Table 4. Subject Information.

No.	Start Point	Age	Eye Color	Visual Correction	Visual Acuity[1] (20/XX)
1	Taxiway	30	green	none	20
2	35L	34	brown	none	20
3	Taxiway	21	blue	none	20
4	35L	28	hazel	contacts	13
5	Taxiway	52	blue	glasses	20
6	Taxiway	31	hazel	none	13
7	35L	45	brown	none	20
8	35L	28	blue	contacts	25
9	Taxiway	45	blue	glasses	25
10	35L	20	blue	contacts	13
11	Taxiway	55	hazel	none	20
12	35L	41	blue	contacts	20
13	Taxiway	29	brown	none	20
14	35L	28	brown	none	13
15	Taxiway	32	brown	contacts	20
16	35L	31	blue	glasses	13
Average Age		34	**Corrective Lenses**	Needed	8
Average Acuity		20/18		Not Needed	8

[1] This is the visual acuity with corrective lenses, assuming the lenses were necessary.

Researchers identified and corrected eye-tracking system difficulties at the onset of Phase I. The eye-tracker infrared cameras target dark areas that reflect light. This created a problem with participants with light blue colored eyes and dark eye make-up. Figure 12 shows a picture where the ViewPoint® software targeted the dark eyelash mascara instead of the pupil. This problem was quickly remedied by having subjects remove any eye makeup. In general, there was nothing identified with the eye-tracking system or participant use that was detrimental to the data collection.

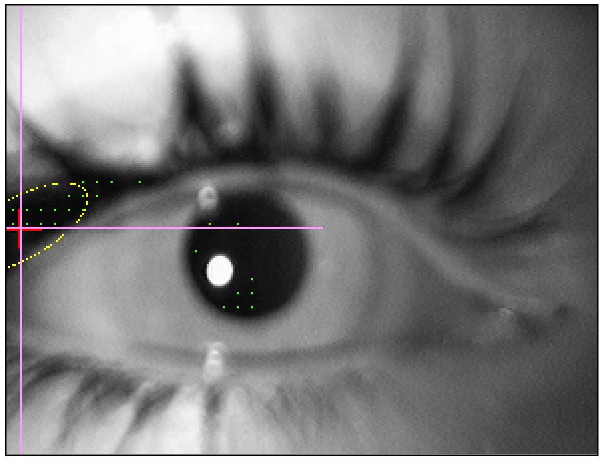


Figure 12. Example of Eye-Tracking Error.

Equipment

The primary piece of equipment used in this study was the ViewPoint EyeTracker® by Arrington Research, Inc. This evolving technology allowed eye movements and glance data to be accurately collected. Subjects drove a test vehicle that was retrofitted with equipment to accommodate the eye-tracking system and a Distance Measuring Instrument (DMI). A specialized laptop computer was placed in the back of the test vehicle to execute the eye-tracking software and to control the data collect equipment. Figure 13 shows a subject wearing the eye-tracking system in the test vehicle.


Figure 13. Test Subject.

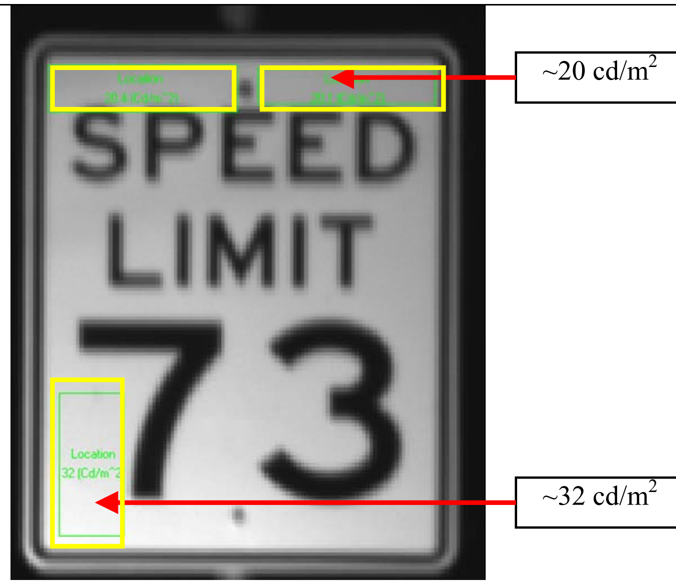
This phase employed a 2003 Ford Taurus as the test vehicle. A data collector positioned in the backseat managed and operated the data collection equipment. The test vehicle directly supplied the power to the eye-tracker system and data collection equipment through a power inverter. The eye-tracker relayed data to the laptop in the backseat. The laptop contained a specialized video card and eye-tracker software so the video data could be acquired and processed. The eye-tracking software imprinted a timestamp and a DMI measurement on the video. DMI distances were recorded at a rate of one measurement per 0.1 seconds (10Hz) and eye-tracking data was interpreted at a rate of 30 times per second (30 Hz). Eye-tracker video was collected in short three to five minute segments, which was backed-up on an external hard drive.

Data Collection

Researchers measured the luminance for each of the 16 signs presented. A Charge Coupled Device photometer measured sign luminance. The CCD photometer captures an image of the sign to analyze luminance. Figure 14 depicts an image of the CCD photometer and a figure of luminance readings on a sign. All sign images were collected from a driver's point of view. Figure 14 shows that one sign could produce fairly different luminance measurements at different locations on the sign. Overall sign luminance was generated by averaging the luminance at several points of interest on the sign. The average luminance ensured a more representative luminance as opposed to measuring just one location.

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 ft or less until an index of 40 ft/in. The measurements created a luminance profile for each sign. Report 0-5235-1 Volume 2 shows the measured luminance of the signs used in Phase I.

CCD Photometer



Points of Interest for Measurement

Figure 14. Luminance Measurements.

Calibration

Data collection for the participant began with a calibration process. The first step in the calibrating process was to ensure that the eye-tracker apparatus fit comfortably and securely on the participant's head. The data collector focused the eye-cameras directly on the eyes' pupils and positioned the forward camera to capture the same view as the subject.

The eye-tracking system was calibrated with a 16-point grid. The grid consisted of reflective targets placed on the side of a building. Subjects viewed the reflective targets from a tripod positioned approximately 55 ft back from the grid. The data collector asked the subjects to fixate on a specific target while keeping their head immobile. The eye-tracker software recorded each target fixation to create a personalized eye-mapping grid. Finally, the eye mapping grid was used to calibrate the equipment. The eye-tracker calibration 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 participant began the driving portion of the study on the runway course.

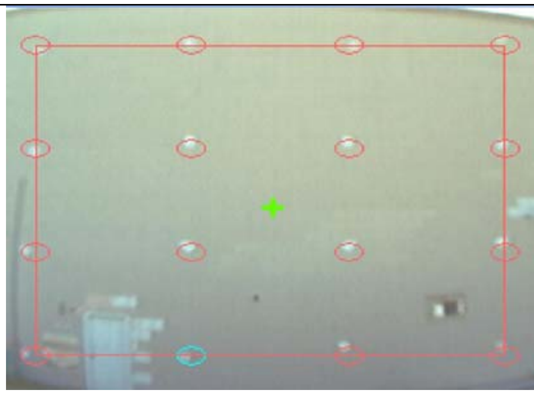
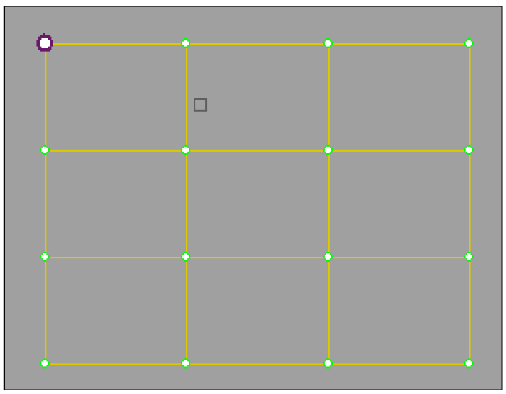
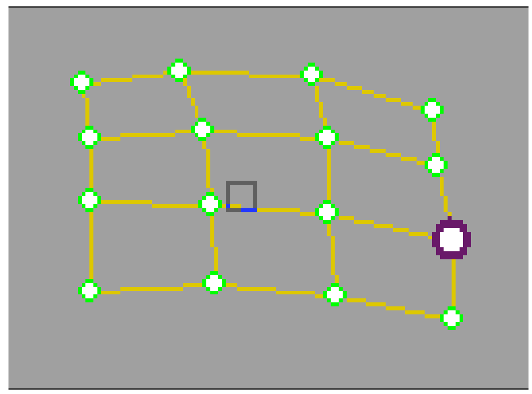
	
a.) Software/Physical Grid Alignment	**b.) Night Shot of Retroreflective Grid**
	
c.) Eye-Mapping Grid Before Calibration	**d.) Eye-Mapping Grid After Calibration**

Figure 15. Calibration Grid and Eye-Mapping.

Runway Course

Participants drove the test vehicle to one of the two starting points on the runway course where a standard set of instructions was read and the DMI was reset to zero. The data collector informed the subjects that they were helping to evaluate the new eye-tracking system and that they should drive as naturally as possible. The data collector instructed subjects to maintain a vehicle speed around 30 mph throughout the runway course. The signage along the closed runaway course had been laid out to maximize the usable data. Each of the four sections of the closed runaway course had a unique task relating to the signs in that section. The data collector reset the DMI to zero and created a new eye-tracking video file for each of the four sections. The first section contained regulatory speed limit signs. Subjects were directed to search for speed limit signs and to immediately read aloud the speed limit sign's content. The speed limit signs contained a mixture of conventional and non-conventional messages. For instance, a conventional message contained a speed limit of "40" and a non-conventional sign displayed "46." The non-conventional signs allowed researchers to obtain true legibility distances as opposed to recognition distance where a subject may read an expected speed limit number. Figure 16 depicts the runaway course speed limit signs. The data collector recorded the DMI distance where the sign content was correctly read aloud. This distance was used to determine the legibility distance and provided a starting point for the video data reduction.

			
a.) Sign 1	**b.) Sign 5**	**c.) Sign 9**	**d.) Sign 11**

Figure 16. Runaway Course Speed Limit Signs.

The second section contained guide signs. Each guide sign displayed the name of a destination along with a diagrammatical directional arrow, which either pointed up, down, right, or left. Subjects were instructed to read aloud the name of the destination and the direction of the arrow. For example, a subject would read "Mapleton is ahead." Again, the data collector would record the legibility distance for the correct response. Figure 17 depicts the four guide signs that were used in this phase.

	
a.) Sign 2	**b.) Sign 10**

Figure 17. Runaway Course Guide Signs.

The third section displayed a warning sign and a construction sign placed side by side at one location. These signs were arranged such that glances could be detected between two relatively close signs. The warning sign displayed two lines of text on a yellow background and the construction sign displayed three lines of text on an orange background. Each line of the text contained one word with a black legend. Figure 18 depicts both signs. The data collector directed the subject to note which of the two signs contained more lines of text by indicating the color of that sign. The correct response was always the orange construction sign. In addition, subjects were instructed to either read the top or bottom word of one of the signs. The legibility distance was recorded when there was a correct response.

a.) Sign 3

b.) Sign 4

Figure 18. Runaway Course Warning Sign and Construction Sign.

A similar set of tasks was in the fourth section. This section employed three rectangular regulatory signs that were placed next to each other. The regulatory signs contained either two or three lines of black text. Figure 19 shows the three regulatory text signs. The subject indicated which sign contained the least number of words by stating the order of the sign: one, two, or three. The second sign always contained the fewest words. Finally, the subject was asked to read either the top or bottom word on each sign. After completing the course, subjects were instructed to exit the Riverside Campus and to begin the open-road portion of the experiment.

c.) Sign 6	d.) Sign 7	e.) Sign 8

Figure 19. Runaway Course Regulatory Text Signs.

Silver Hill Course

The instructions for the Silver Hill course were given outside of the main gate of the Riverside Campus, and the DMI was reset to zero. Throughout the Silver Hill course, subjects were instructed to look for regulatory test signs and read aloud the alpha-numeric combination for each sign. Figure 20 shows the three regulatory test signs. The legibility distance was recorded for correct responses. Additionally, subjects were asked to indicate when they first detected the test sign as opposed to a normal traffic sign. Subjects returned to the Riverside Campus after viewing the third test sign on Silver Hill Road. The open-road loop provided a comparison between real-world driving and the closed-course performance.

a.) Sign 12	b.) Sign 13	c.) Sign 14

Figure 20. Silver Hill Road Regulatory Signs.

5th Street Course

Subjects reentered the Riverside Campus for the final task. The instructions were given and the DMI was reset to zero at the Riverside entrance gates. The data collector instructed subjects to search for a street name sign named after a U.S. state. Subjects passed several intersections before reaching the target intersection that displayed the state name "Arizona" in the place of the street name. This section did not require a verbal response from the subject but instead required them to turn right at the target intersection.

Following the final task, subjects returned to the staging area to complete the experiment. The calibration was checked once again, and the system was removed. The data collector debriefed the subjects with the actual purpose of the study. Subjects were also asked to complete a short evaluation of the eye-tracker system and sign a waiver. The eye-tracking data and distance measurements for each subject were saved in electronic format for subsequent analysis.

Data Reduction

The eye-tracking data required extensive reduction and screening before any data analysis. Researchers reduced video data for all 16 subjects and for 14 of the test signs. The legibility distance served as a reference point for the start of a sign's data reduction. Glances were measured when subjects first fixated their eyes on the sign and when they looked away. Researchers recorded the time and the DMI distance for the start and end of each sign glance. The recorded data produced the eye glance duration and the distance traveled during that glance. The total number of glances and total glance duration were calculated for each time a subject viewed sign. Figure 21 shows a typically recorded eye glance. The frames in Figure 21 progress from left to right in sequential order. The light colored circle surrounds the point of gaze of the driver and grows as the length of the fixation increases.

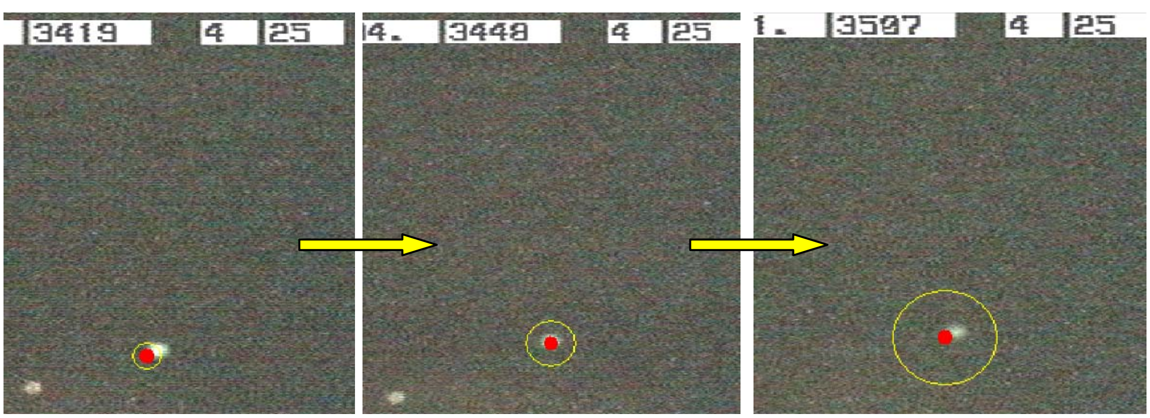


Figure 21. Recorded Eye Glance.

The video reduction recorded over 1,100 data points for the Phase I analysis. The reduction segmented the data into smaller datasets for each sign and each subject. Smaller datasets allowed researchers to create graphical figures and extract meaningful trends.

RESULTS

Researchers arranged the results accordingly to the eye-tracker and legibility task. The results of the eye-tracker data focused on five measurements of effectiveness: total number of glances, total glance duration, minimum glance duration, maximum glance duration, and average glance duration. The legibility distance data set was the single measure of effectiveness for the legibility task. Descriptive statistics, as such the mean, median, and standard deviation, were generated for all of the measures of effectiveness.

Legibility Task

The text sign legibility distance analysis produced mixed and inconclusive results. Table 5 contains the descriptive data for the text sign analysis. Signs in Table 5 were arranged in sequential viewing order. High luminance sign 2 achieved the longest mean legibility distance and high luminance sign 7 exhibited the shortest. Medium luminance sign 3 outperformed high luminance signs 7 and 8. The average legibility distance for all of the high luminance signs was 164.5 ft, which was approximately equal to the distance of low luminance sign 4.

Table 5. Text Sign Legibility Distance Data.

Sign Number	6	7	8	3	4	2
Sign Name	W-3a	W-2	W-3b	Y-2ln	O-3ln	G-ML
Luminance Level	High	High	High	Medium	Low	High
Mean (ft)	179	135	149	173	164	194
Median (ft)	179	153	142	186	158	191
St. Dev. (ft)	68	55	63	76	70	90

Table 6 contains descriptive legibility distance data for the speed limit test signs. Low luminance sign 5 achieved the longest mean legibility distance and medium luminance sign 13 exhibited the shortest. The low luminance sign 5 and medium luminance sign 9 surpassed all of the high luminance sign legibility distances by approximately 50 ft. The legibility distances for the high luminance were all approximately 360 ft. Overall, the signs that achieved the longest legibility distance were the signs with conventional numeric speed limits.

Table 6. Speed Limit Sign Legibility Distance Data.

Sign Number	1	11	14	9	13	5
Sign Name	SL-46	SL-73	TS-Y2	SL-40	TS-F5	SL-70
Luminance Level	High	High	High	Medium	Medium	Low
Mean (ft)	368	358	357	406	309	409
Median (ft)	390	336	383	441	327	431
St. Dev. (ft)	80	78	99	116	90	99

Eye-Tracker

In order to first investigate the eye-tracking data, each participant's glances were investigated using simple graphs such as that shown in Figure 22. Participants typically made several initial glances at 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. One of the questions to be explored in this study during the later phases is how the legibility glance might be affected by the brightness of the sign.

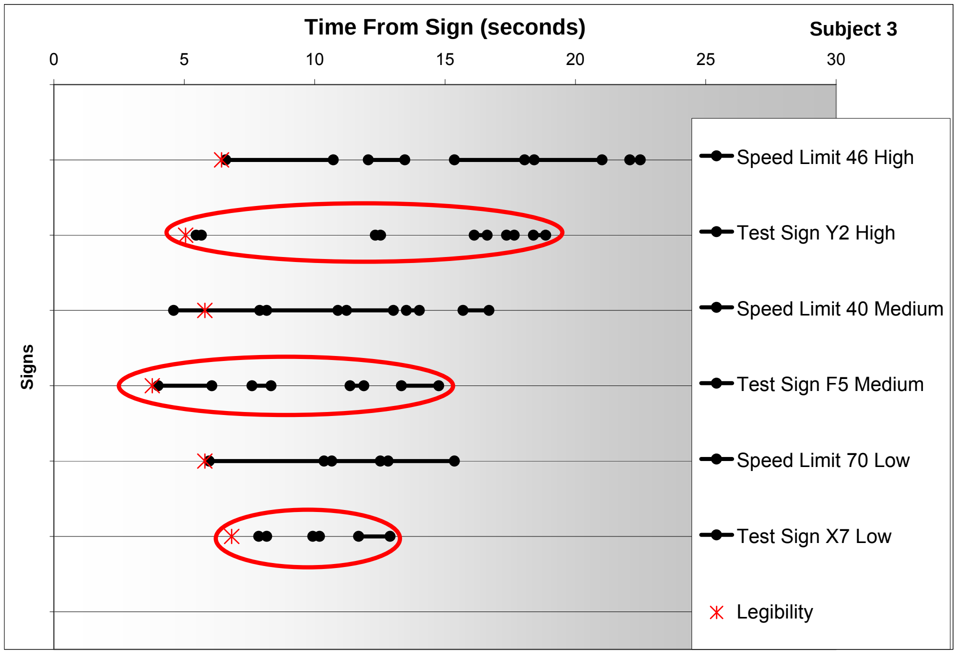


Figure 22. Example of a Glance Plot (Circled Data Represents Open-Course Data).

The analysis of the eye-tracker data generated the mean, median, and standard deviation for the number of eye glances and the total glance duration. Table 7 and Table 8 provide the descriptive statistics for the total number of glances. Table 9 and Table 10 present the descriptive statistics for the glance duration data.

Table 7 shows that each guide and text sign received approximately the same number of glances, which were around 5 glances. There was very little variation among all of the means glances, and the lowest number was 4.43 and highest was 5.40. All of the standard deviations were around 1.6 glances and ranged from 1.44 to 1.91 glances. There was also a negligible difference between the text signs with three words compared to the signs with two words. There was very little variation in the table and the high, medium, and low signs produced similar results.

Table 7. Number of Glances at Guide and Text Signs.

Sign Number	6	7	8	2	3	4	10
Sign Name	W-3a	W-2	W-3b	G-ML	Y-2ln	O-3ln	G-LP
Lum. Level	High	High	High	High	Medium	Low	Low
Course Type	Runway	Runway	Runway	Runway	Runway	Runway	Runway
Mean	5.19	5.27	5.19	4.43	4.94	5.40	4.81
Median	5	5	5	4	4	5	5
St. Dev.	1.66	1.71	1.38	1.45	1.91	1.44	1.76

Table 8 contains the glance data for the speed limit signs on the Runway Course and on Silver Hill Road. The results in Table 8 were similar to the guide and text sign results in Table 7. The low luminance sign 5 achieved the lowest number of glances at 4.07, and low luminance sign 12 received the highest mean glances at 5.20. The lower number of glances at sign 5 may be attributed to the conventional numeric message of "70." Some of the non-conventional and alpha-numeric signs exhibited a high number of glances. Despite sign 5, the number of glances on the Runaway course was quite similar and subjects may be normalizing their glance behavior. There was more of a difference for the Silver Hill road signs. On the open road, the high luminance sign achieved the fewest glances, and the low luminance sign received the highest glances.

The analysis compared the Runaway Course and the Silver Hill Road values. The high and medium luminance signs on the Runaway Course received more glances than the high and medium luminance signs on Silver Hill Road. The higher number of glances may be attributed to fewer roadway stimuli on the closed-course Roadway Course. Subjects devoted more glances and normalized their viewing behavior when there were fewer distractions and less roadway complexity in the closed-course setting.

Table 8. Number of Glances at Speed Limit Signs.

Sign Number	1	11	14	9	13	5	12
Sign Name	SL-46	SL-73	TS-Y2	SL-40	TS-F5	SL-70	TS-X7
Lum. Level	High	High	High	Medium	Medium	Low	Low
Course Type	Runway	Runway	Silver Hill	Runway	Silver Hill	Runway	Silver Hill
Mean	5.00	4.63	4.14	5.06	4.31	4.07	5.20
Median	5	4	4	5	4	4	5
St. Dev.	1.84	1.86	1.41	1.61	1.14	1.41	2.31

Table 9 contains the glance duration data for the guide and text signs. The glance duration ranged from approximately 6.72 to 9.47 seconds. High luminance sign 2 exhibited the shortest glance duration at 6.42 seconds, and low luminance sign 4 had the longest glance duration at 9.47 seconds. On average, the high luminance signs achieved the shortest glance durations and the low luminance signs received the longest duration. Subjects were able to devote less time to viewing the high luminance signs. There was a 0.5 second difference between the averages for the text signs with two and three words. The glance duration was less for the text signs with two words, which reconfirms earlier findings described in Chapter 2.

Table 9. Glance Duration for Guide and Text Signs.

Sign Number	6	7	8	2	3	4	10
Sign Name	W-3a	W-2	W-3b	G-ML	Y-2ln	O-3ln	G-LP
Lum. Level	High	High	High	High	Medium	Low	Low
Course Type	Runway	Runway	Runway	Runway	Runway	Runway	Runway
Mean (s)	7.61	7.32	8.01	6.72	8.22	9.47	8.22
Median (s)	7	8	8	6	8	9	8
St. Dev. (s)	2.57	1.93	1.52	2.67	1.43	1.49	2.28

Table 10 shows the glance duration data for the speed limit signs. The glance duration for all of the signs ranged from approximately 6.45 to 9.33 seconds, which was similar to the range in Table 9. The shortest glance duration was achieved by low luminance sign 5, and the longest was high luminance sign 11. Again, the two signs with the shortest glance duration also contained the conventional numeric speed limits. Despite sign 5 and sign 9, the duration values for both high luminance signs on the Runaway Course were similar and were longer than the low luminance sign 12 on Silver Hill Road. Again, subjects devoted more viewing time and normalized their glance duration for the high luminance signs in the closed-course setting.

Table 10. Glance Duration for Speed Limit Signs.

Sign Number	1	11	14	9	13	5	12
Sign Name	SL-46	SL-73	TS-Y2	SL-40	TS-F5	SL-70	TS-X7
Lum. Level	High	High	High	Medium	Medium	Low	Low
Course Type	Runway	Runway	Silver Hill	Runway	Silver Hill	Runway	Silver Hill
Mean (s)	8.71	9.33	7.7	6.45	9.19	6.4	7.98
Median (s)	9	9	8	6	9	6	8
St. Dev. (s)	2.12	2.72	2.82	2.35	1.78	1.71	2.85

SUMMARY

The overall goal in Phase I was to refine the experimental procedure that would be employed for Phase II and Phase III. Researchers investigated the operational performance of eye-tracker system and identified several promising measures of effectiveness. The procedure and design methodology created a strong foundation and provided guidance for later phases.

Eye-Tracker Procedure

Researchers developed procedures and techniques to utilize the eye-tracker system in an effective manner to produce reliable and accurate data for evaluation of traffic signs. The eye-tracker system was a relatively new system that required some troubleshooting and practice. An investigation into the data determined that eye color, contacts, and eye-glasses do not affect the system or influence the data. The combination of light blue eyes and dark eye makeup may hinder the data collection, but this can be easily remedied by removing the eye makeup. It was further determined that the eye-tracker had the resolution needed to evaluate eye fixations at distances associated with nighttime driving.

Properly adjusting and calibrating the equipment was a critical step in acquiring reliable data. Movement of the equipment while driving would diminish the accuracy of the data. The system needed to fit securely to the subject's head, without causing discomfort or unnecessary distractions. Negligence or rushing the calibration process produced inaccurate data. It was important to allow the subject to feel comfortable when viewing the calibration grid. Researchers verified from an adjacent computer monitor that the subject's fovea view was looking directly at the calibration targets. Over time, researchers developed techniques that minimized calibration time while ensuring accurate and reliable data.

Researchers gained experience with coding the eye-tracker video and developed proficiency with extracting the valuable glance data. Phase I utilized the total number of glances, glance duration, and legibility distances as the primary measures of effectiveness. These measures of effectiveness provided insight into subject viewing behavior and proved to be adequate indicators for sign performance. Simple descriptive statistics of the measures of effectiveness were used effectively and allowed researchers to gain a comprehensive understanding of subject and sign viewing patterns. Additional evaluation techniques were explored in a Texas A&M University thesis (*32*).

Preliminary Phase I Findings

Preliminary findings indicate that:

- high luminance signs provided a longer detection distance but do not necessarily result in a longer legibility distance,
- increased sign brightness did not consistently decrease the viewing time required,
- legend content had a considerable effect on glance data, and
- differences exist between open-road and closed-course glance data.

The data revealed that drivers on a closed course do not view signs the same way as those on the open road. The drivers tended to normalize their viewing behavior on the closed course due to their decreased workload. The Runway Course was very isolated and subjects were able to concentrate on sign legibility without interference or distraction from other vehicles or roadway stimuli. This may justify why high luminance signs on the closed course exhibited longer glance durations than signs on the open road.

Content in the sign legend greatly influenced the subjects' glance patterns. The conventional speed limit signs that displayed "40" and "70" in the legend achieved the longest legibility distance, the fewest number of glances, and the shortest glance duration regardless of luminance level. Drivers anticipate numeric speed limit signs that are in increments of 5 mph. Correctly identifying sign content of "46" or "Y2" was more of a legibility task as opposed to anticipating and recognizing "40." The researchers concluded that non-conventional or alpha-numeric sign content was more beneficial in identifying true sign legibility.

CHAPTER 4:
PHASE II SUMMARY

This phase utilized the lessons learned from Phase I to develop a study design that could test the effectiveness of various luminance profiles without having to be tied to the luminance profiles resulting from the characteristics of retroreflective sheeting materials. Six luminance profiles were generated for each of four different signing conditions:

- an overhead-mounted guide sign with a 12-inch white legend on green background,
- a shoulder-mounted warning sign with a 7-inch black legend on yellow background,
- a shoulder-mounted speed limit regulatory sign with a 14-inch black legend on white background, and
- a shoulder-mounted regulatory sign with a 7-inch legend on white background.

The purpose of the multiple signing conditions and luminance profiles was to assess nighttime driver needs with respect to signing with the plan to generate results that could be used to develop performance-based sign sheeting requirements.

OBJECTIVES

The objective of this phase was to determine how different sign luminance profiles free of retroreflective sheeting material characteristics impact driver performance as measured using threshold legibility distance and other metrics derived from recorded video of the drivers' eye movement.

EXPERIMENTAL DESIGN

The researchers conducted a nighttime legibility and eye-tracking study at the Texas A&M University Riverside Campus in Phase II (see Figure 23). The legibility data were collected when test participants responded with the correct legend content of various signs. As in Phase I, the eye-tracking data were collected simultaneously with the legibility data.

Figure 23. Aerial View of Riverside Campus.

Equipment

Several different state-of-the-art pieces of equipment were brought together for this research effort. One of the pieces of equipment referred to is the eye-tracker that was also used in Phase I and is described in Chapter 3. Other equipment included the TTI instrumented vehicle and three internally illuminated signs that were designed by TTI to simulate different sign luminance profiles.

Instrumented Vehicle

The TTI instrumented vehicle is a 2006 Toyota Highlander that has been upgraded with several different state-of-the-art sensors. The heart of the instrumented vehicle is a Dewetron DEWE5000 data acquisition system that has several different sensor inputs that can be programmed for different devices. One device is the Trimble DSM 232 DGPS system that uses a single frequency antenna to gather global positioning system data at a rate of 10 readings per second, or 10 Hertz. This device also has sub-meter accuracy.

Three switches were also added to the Dewetron for various tasks during data collection. The first switch was used to mark when test participant correctly identified the text for each test sign. The other two switches operated two single yellow light emitting diodes (LEDs). One LED was positioned by the driver side mirror and the other LED was positioned in the center of the rear window. These LEDs were turned on randomly to keep the test participant from staring at the test signs while approaching each sign.

Signs

Three different internally illuminated signs were designed and constructed by TTI. There was a guide sign, a warning sign, and a regulatory sign. Each sign was constructed out of aluminum sheet metal, and the lighting source was dimmable fluorescent lighting. A laptop was used to control each sign, and a Honda EU2000i generator was used at each sign to power the various pieces of equipment. Figure 24 shows each of these devices. The driving course was set such that the driver was approximately 12 ft left of the near or inside edge of each sign.

For illumination of the signs, incandescent, fluorescent, and LED lighting were all considered. Eventually, the researchers used fluorescent lighting to provide the internal illumination needed. The fluorescent lighting required the least amount of electronic complexity; fluorescent tube lighting provided a relatively uniform lighting source that required the least amount of lighting, and it decreased the complexity of the design with regard to minimizing sign face lighting uniformity. The researchers were able to design a parallel gradient dot matrix system that reduced the light output directly in front of the bulbs so that the sign faces provided uniform luminance to the nighttime drivers (verified with CCD luminance measurements). The fluorescent lighting also provided stable color temperatures throughout the range of luminance (verified using a PR-650 SpectraScan colorimeter).

Using fluorescent light sources has one potential caveat in that the spectral distribution of the emitted light is not representative of the spectral distribution of the retroreflected light that a nighttime driver would encounter. During pilot studies, the researchers viewed the internally illuminated warning sign next to a warning sign made with typical retroreflective sheeting material. The test was conducted from the same perspective as the study participants saw the signs. The side-by-side comparison was intended to test, among other things, the appearance of the internally illuminated sign. The researchers concluded that the internally illuminated sign appeared to be nearly identical in appearance to the adjacent sign made with typical retroreflective sheeting material.

a) Guide Sign

b) Warning Sign

c) Regulatory Sign

d) Generator and Controller

Figure 24. Internally Illuminated Signs.

The heart of the signs was the wireless lighting zone controller by Lutron®. This device allowed researchers to create luminance profiles with 100 different levels. These profiles were then run through a controller program written by TTI staff that communicated with the Lutron® lighting zone controller. The researchers were able to update the lighting profile at each sign three times a second, or at 3 Hertz. Each luminance profile was queued by a member of the field crew, and the luminance profiles were started when the instrumented vehicle crossed an upstream tapeswitch sensor. The tapeswitch sensors were placed at the 80 Legibility Index (LI) point from each sign.

The guide sign was 8 ft tall by 10 ft wide and included a state route shield with two rows of text below it. The route shield was a standard state highway route shield. The two rows below the route shield contained the test words and consisted of four removable panels with one four-letter word with a 12-inch letter height on each panel. With 12-inch tall test words, the tapeswitch sensor to initiate the start of each luminance profile was set at 960 ft from this sign. The test words consisted of a white legend on green background, a positive contrast legend.

There were six unique four-letter beginning and ending words that were interchanged to create different words to avoid a heuristic response. The first letter of each word was capitalized followed by lower case letters. The words were specifically chosen to have lower case ascenders and descenders and also to be realistic four-letter words for destination names while not being common. Table 11 lists these words.

As seen in Figure 24, the sign was designed to be an overhead mounted sign, and it was raised and lowered using a winch. When hoisted into position for data collection, the bottom of the sign was 18.5 ft in the air.

Table 11. Guide Sign Words.

Beginning Words	Ending Words
Lake	Camp
Long	Port
Gray	Cape
Bear	Road
Owen	Park
East	Bend

The warning sign contained two lines of black text with 7-inch letter height on a yellow background, a negative contrast legend. With 7-inch tall test words, the tapeswitch sensor to initiate the start of each luminance profile was set at 560 ft from this sign. The sign was a 4-ft by 4-ft diamond shape sign and was mounted with the bottom of the sign 7 ft above the ground. As seen in Figure 24, a platform was built in front of the sign, but it was painted black to mask it from being observed at night. This structure aided the field crew with replacing the sign faces containing the different legends. There were six different sign faces with two six-letter words, depicted in Figure 25. Unlike the guide sign, the entire sign face was replaced for the warning sign.

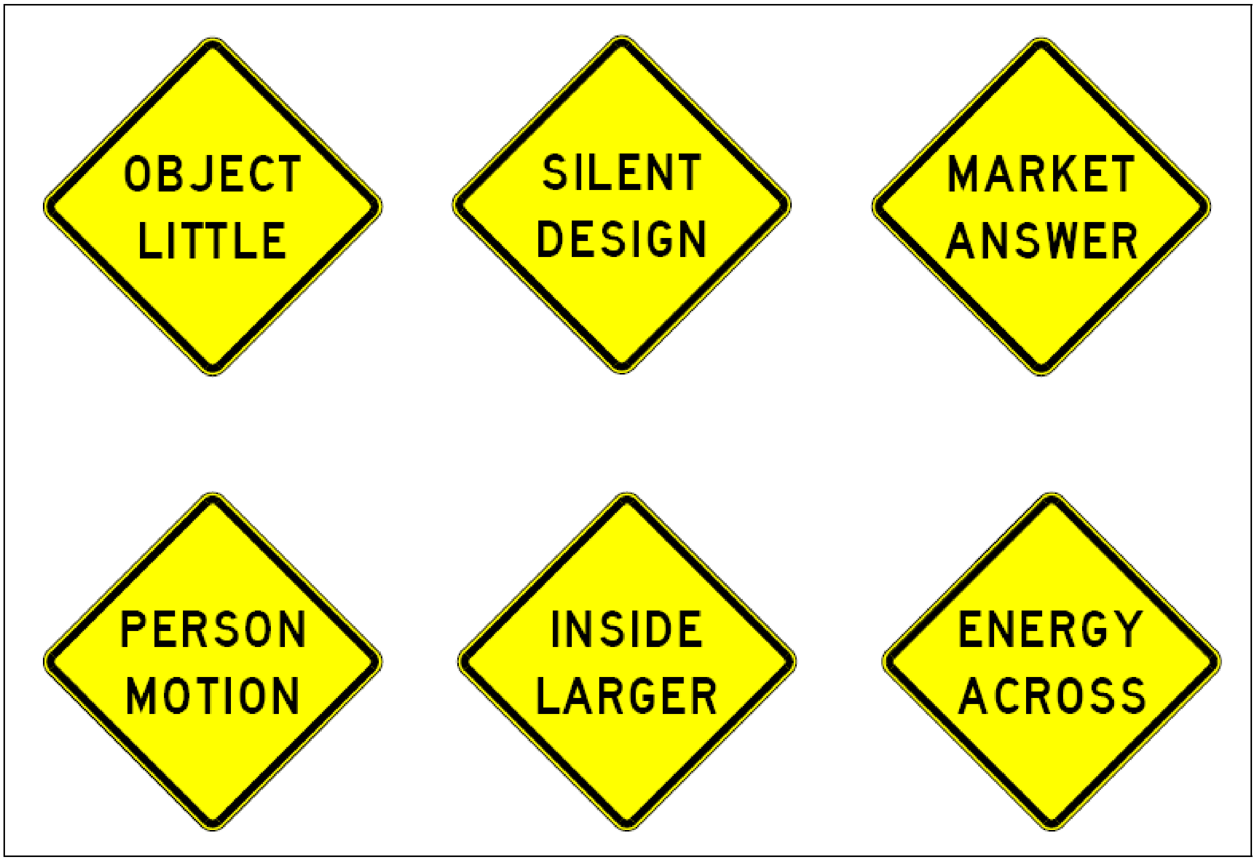


Figure 25. Warning Sign 7-Inch Test Legends.

The setup for the regulatory sign was similar to that of the warning sign. A platform was placed in front of the sign to aid the field crew with the replacement of the various different legends. The sign legends were negative contrast with a black legend on a white background. The size of the sign was 4-ft tall by 3-ft wide and was mounted with the bottom 7 ft above the ground. Similar to the warning sign, the entire sign face was replaced.

This sign had two different types of sign faces. The first type emulated a speed limit sign with the test, "SPEED LIMIT," at the top and the normal two-digit speed was supplemented with an alpha-numeric combination. This combination had a 14-inch letter height, and there were 9 different alpha-numeric combinations. They are listed in Figure 26. A second type of sign face consisted of two to three lines of 7-inch tall six-letter words (see Figure 27). Since there were two different legend heights, the tapeswitch sensor was set for the larger text legend at 1120 ft from the sign, and for the 7-inch legends, the profiles were set at a constant luminance until the test vehicle was within 560 ft of the regulatory sign.

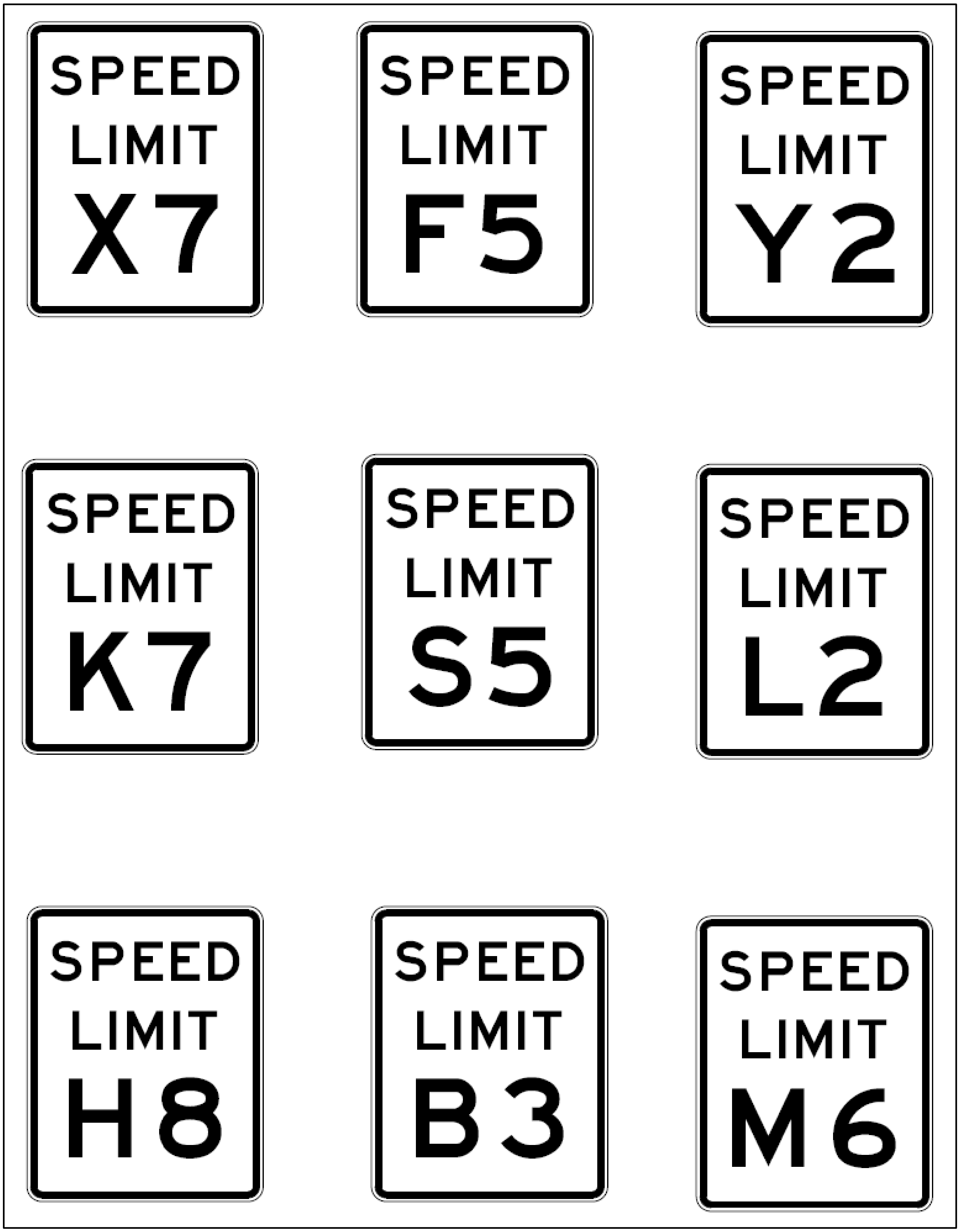


Figure 26. Regulatory Alpha-Numeric 14-Inch Test Legends.

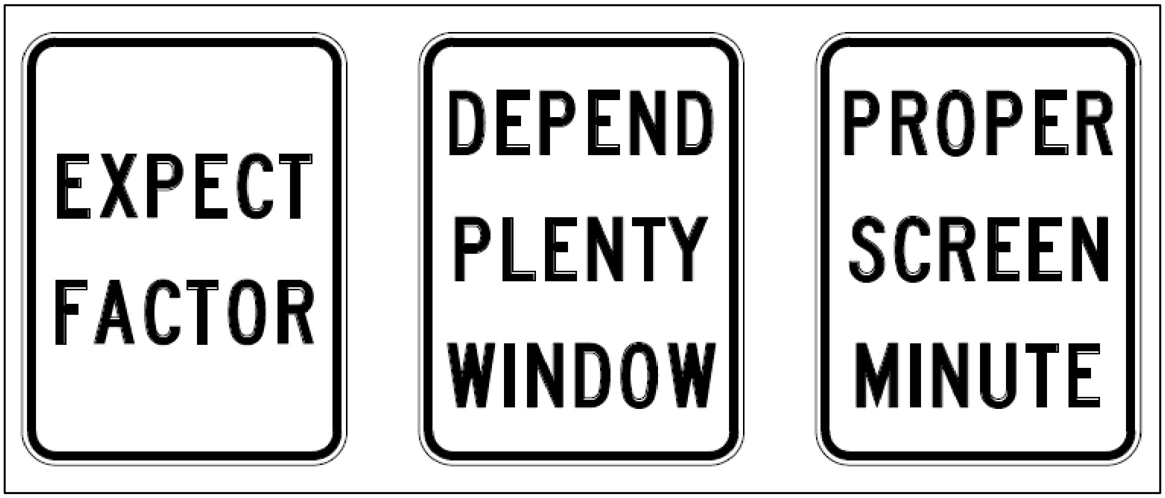


Figure 27. Regulatory Six Letter 7-Inch Test Legends.

Luminance Profiles

Six luminance profiles were designed for each of the three sign types. The profiles were triggered by a trip wire located at a distance corresponding to a legibility index of 80 ft/in of letter height. The profiles were shown in a counterbalanced fashion to eliminate order bias. They were timed to run at a rate corresponding to the approaching test vehicle speed. The profiles are described below and shown in Figure 28.

- Minimum flat – this luminance profile remained at 1 cd/m^2 throughout the approach to the sign. This was set as the absolute minimum luminance that would be tested (the testing conditions were dark and rural with no glare or background complexity).
- Threshold flat – this luminance profile remained at 2.5 cd/m^2 throughout the approach to the sign. This was set as the threshold legibility luminance based on the FHWA minimum retroreflectivity levels (*14*).
- Medium flat – at a distance corresponding to an LI of 50 ft/in depending on the size of the legend, this profile ramped up from 5 cd/m^2 and reached 30 cd/m^2 at a distance corresponding to an LI of 40 ft/in. The profile remained at 30 cd/m^2 through the LOOK3 region and then dropped to 5 cd/m^2 at a constant rate by the time driver reached the sign.
- High flat – at a distance corresponding to an LI of 50 ft/in depending on the size of the legend, this profile ramped up from 5 cd/m^2 and reached 80 cd/m^2 at a distance corresponding to an LI of 40 ft/in. The profile remained at 80 cd/m^2 through the

LOOK3 region and then dropped to 5 cd/m^2 at a constant rate by the time driver reached the sign.

- Peak early – this profile ramped up to 40 cd/m^2 by the beginning of the LOOK3 region. It then dropped at a constant rate throughout the LOOK3 region. The profile was designed to have approximately the same cumulative luminance throughout the LOOK3 region as the medium flat profile.
- Peak late – this profile started at approximately 5 cd/m^2 and ramped up to 40 cd/m^2 by the end of the LOOK3 region. It then dropped at a constant rate until the driver reached the sign. The profile was designed to be the opposite of Peak early. It also had approximately the same cumulative luminance throughout the LOOK3 region as the medium flat profile.

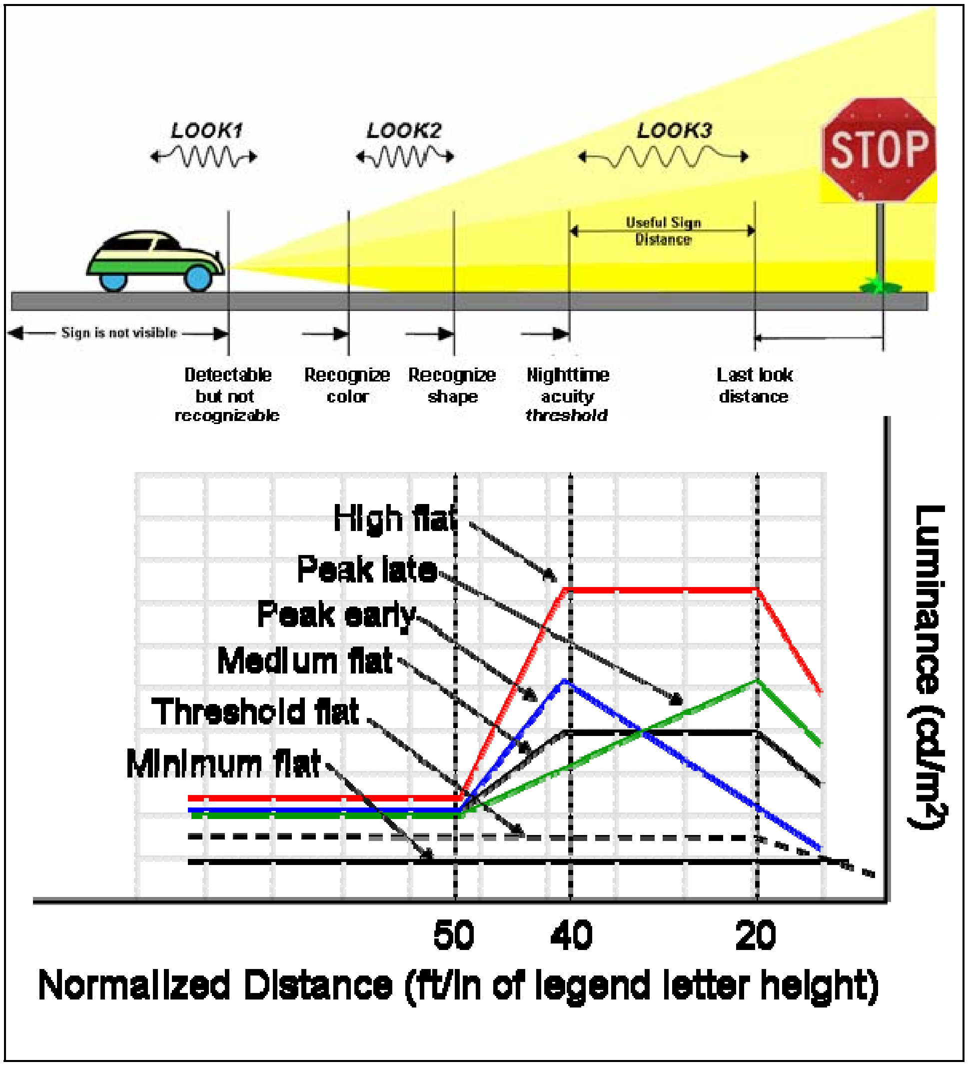


Figure 28. Luminance Profiles.

Data Reduction

Using the process described for the Phase I effort, legibility data and eye-tracker data were reduced. The data reduction was completed in several stages. In the first stage, the legibility data were combined with the subject and sign data. The legibility data were converted from travel distances, measured from a starting point as the study vehicle approached a sign, into the distance remaining between the study vehicle and the sign face, as shown in Figure 29. This would be the legibility distance (d_L). Specific starting points were set for each sign. Then, the revised legibility distances were used to calculate LI.

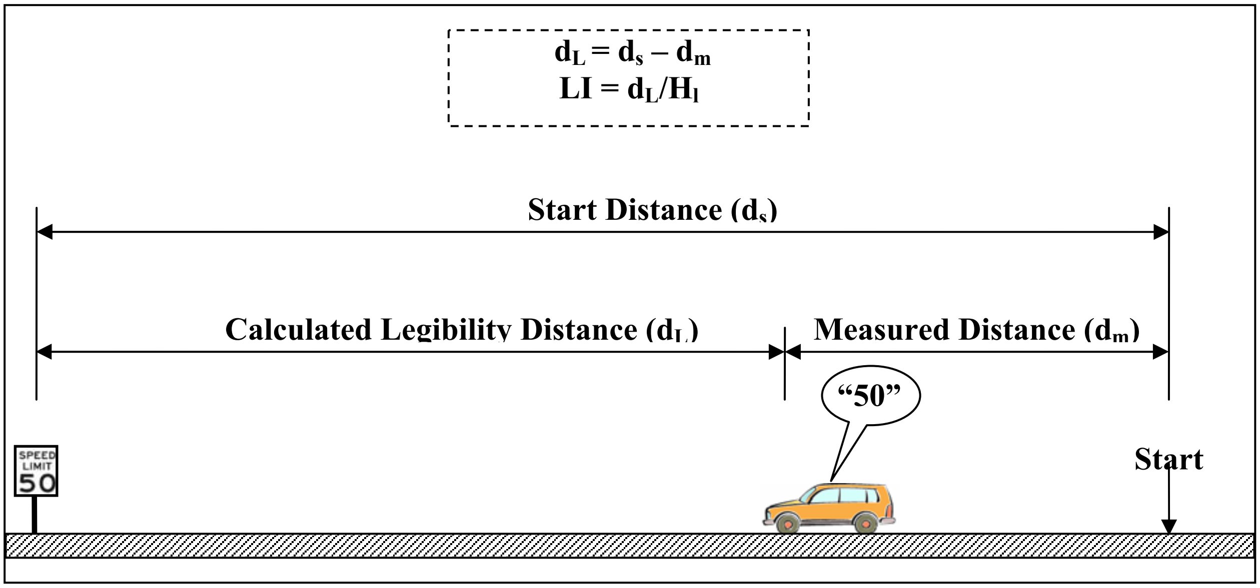


Figure 29. Legibility Distance Calculation.

The data set was then cleaned. Any data that contained questionable or missing input values for the sign information or legibility data were removed first. The LI data were also used to find suspect errors in the sign information. There was one case where the LI was as low as 9 and another as high as 108, when it was expected to find the majority of the LI values between 20 and 40. In all, only five errors of this type were recorded out of 625 entries.

In the second stage, the eye-tracker data were reduced in a similar manner as in Phase I. The primary difference was that additional personnel were used to speed the reduction process. Some of the data were reduced by at least two different individuals to investigate any data reduction bias. The general procedure for the reduction of the eye-tracker procedure is bulleted below:

- advance the eye-tracker footage to the point at which each subject was about to pass the sign;
- backup the video to the first time that it appears the subject looked at the sign (since the data reducer started at the point where the subject was about to pass the sign; this equates to the end of the last glance the subject takes of the sign);
- record the distance and the time for the end of the glance;

- backup the video to the point at which the subject looks away from the sign (this equates to the beginning of the last glance the subject of the sign);
- record the distance and the time for the start of the glance;
- repeat these steps until the video footage reaches the beginning of the footage, or until it is no longer possible to differentiate between when the subject is glancing at the sign or the surrounding environment (the latter case was always beyond the 80 LI range); and
- determine for each glance for each sign for each participant, the distance and duration data.

Once these data were tabulated, the data were further reduced and reorganized for the later analysis phase. In this effort, the individual glances for each sign were combined with the demographic information for the associated subject, the sign information, and the legibility data. While glance data were collected beyond the 80 LI threshold, it was decided to trim the data of any glances outside of the 80 LI threshold.

This was done for several reasons. First and foremost, the sign profiles did not differ beyond the 80 LI range. Second, no subject was able to read the sign beyond the 80 LI range. Another reason was that the data were far more difficult to accurately access glances at the sign versus the surrounding environment beyond the 80 LI range.

At this point, several calculations were completed on the data to generate additional independent variables for analysis. During the initial data reduction effort, the sign profiles were simply recorded as ordinal values. Using the glance data and the structure of the sign profiles, an exposure, or dosage, was calculated for each sign and each subject. The dosage for each glance was calculated by multiplying the luminance provided to the subject during a particular glance times the exposure time. This was calculated using a basic numerical integration with the trapezoid rule. Each glance dosage was then summed into three cumulative dosages: one for 40 LI to 20 LI, one for 50 LI to 20 LI, and one for 80 LI to 20 LI. It was also believed that the cumulative dosage regardless of whether the subject was glancing at a sign could be a factor, so the total dosages for each of the ranges were also calculated for each sign. It should be noted that this is similar to the original ordinal values except the magnitudes are representative of the luminance exposure for each subject.

The individual glance data were also reduced for analysis. The total number of glances and the total duration were summed, and these values were used to calculate the average duration for each sign a subject viewed. The individual duration for the legibility glance was also singled out for analysis.

The final data reduction step prior to analysis was to split the data sets. As stated previously, the data for multiple test subjects were reduced by more than one person. This was to test for interrelated reliability, and this would require the entire data set. However, a subset of the data that only included data reduced by a single person was generated. This data set was generated using the following criteria:

- remove data reduced by one data reducer when the glance durations were disproportionately longer than that of another data reducer for the same subject's data (extreme outliers [greater than 3 times the inner quartile range—1.3 seconds—away from the third quartile] for non-legibility glances); and
- remove data reduced by one data reducer when their data have been disproportionately incorrect with respect to the first criterion when compared to other data reducers' efforts (out of six different data reducers, there was only one data reducer that fit the second criterion).

Study Participants

There were 36 study participants in this phase. Two subject age categories were selected for this study: a young group aged 18 to 54 (sample size = 25, mean = 37 years) and an older group aged 55 and up (sample size = 11, mean = 65 years). The gender split was approximately 50/50 for both age groups. Vision screening showed visual acuity scores of the subjects to be no worse than 20/30 with 22 subjects having 20/20 or better vision.

Analysis

A total of 1,170 observations were available for the analyses. The researchers completed an analysis using legibility as the dependent variable. They also completed analyses of the eye-tracker data. Exploratory analyses were also completed by characterizing the luminance profiles in various manners to predict legibility. The following sections describe the analyses that were performed.

Legibility Data

The cumulative distribution results are shown for each sign type in Figures 30 through 33. Initial inspection of these data reveals some interesting findings as described below.

- In general, the minimum and threshold profiles had the lowest performance.
- In general, the high flat and peak early profiles had the best performance. The medium flat profile had similar performance to the high flat and peak early profiles.
- The peak late profile had lower performance at the longer distances but throughout the approach the sign, increased performance to be among the top performing profiles at the shortest legibility distances.
- The differences between the medium flat profile and high flat profile are small and not nearly as evident as the differences between the threshold flat profile and medium flat profile, even though the jump in luminance levels from the threshold flat profile to the medium flat profile to the high flat profile are similar.

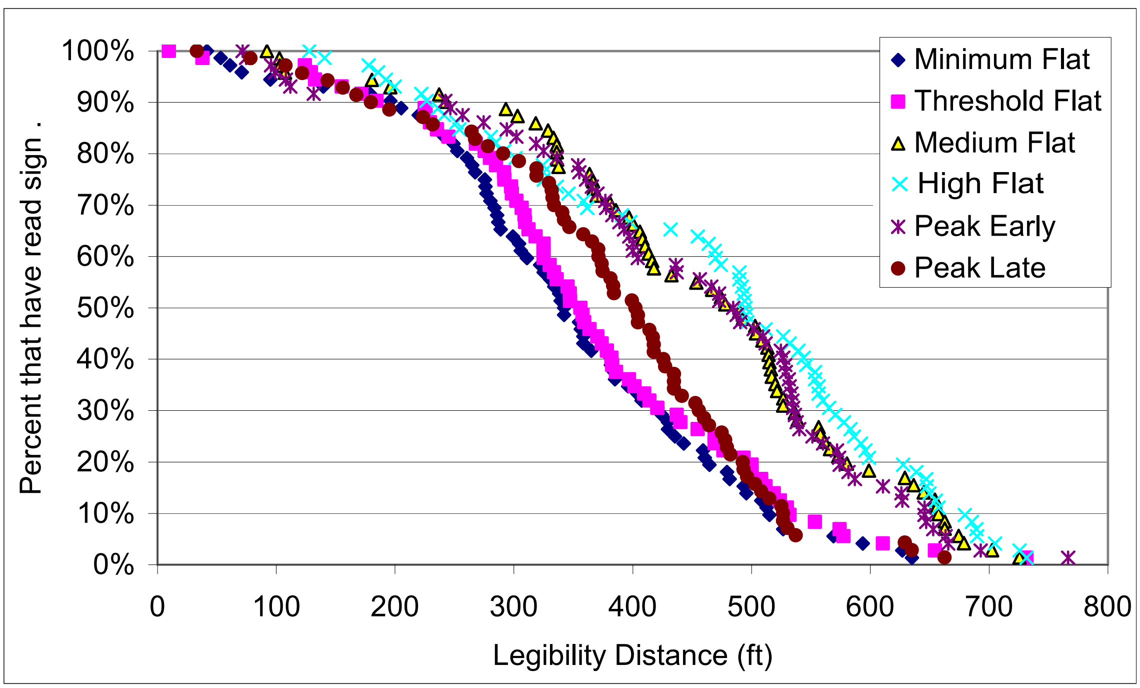


Figure 30. Guide Sign Results.

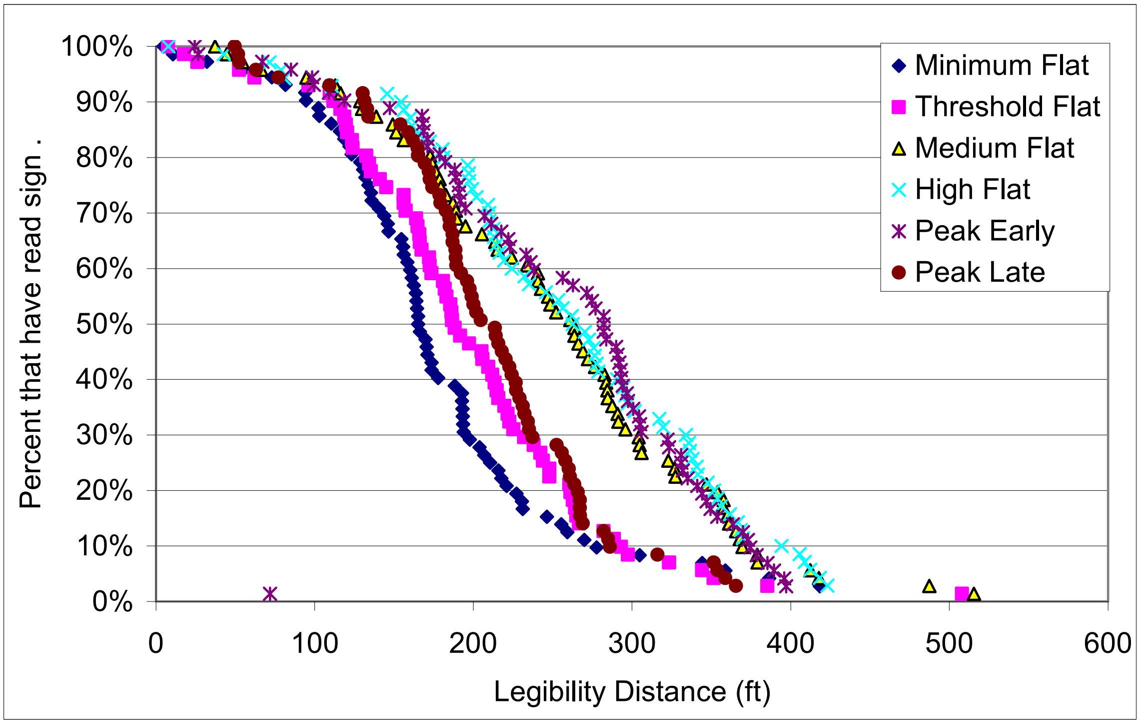


Figure 31. Warning Sign Results.

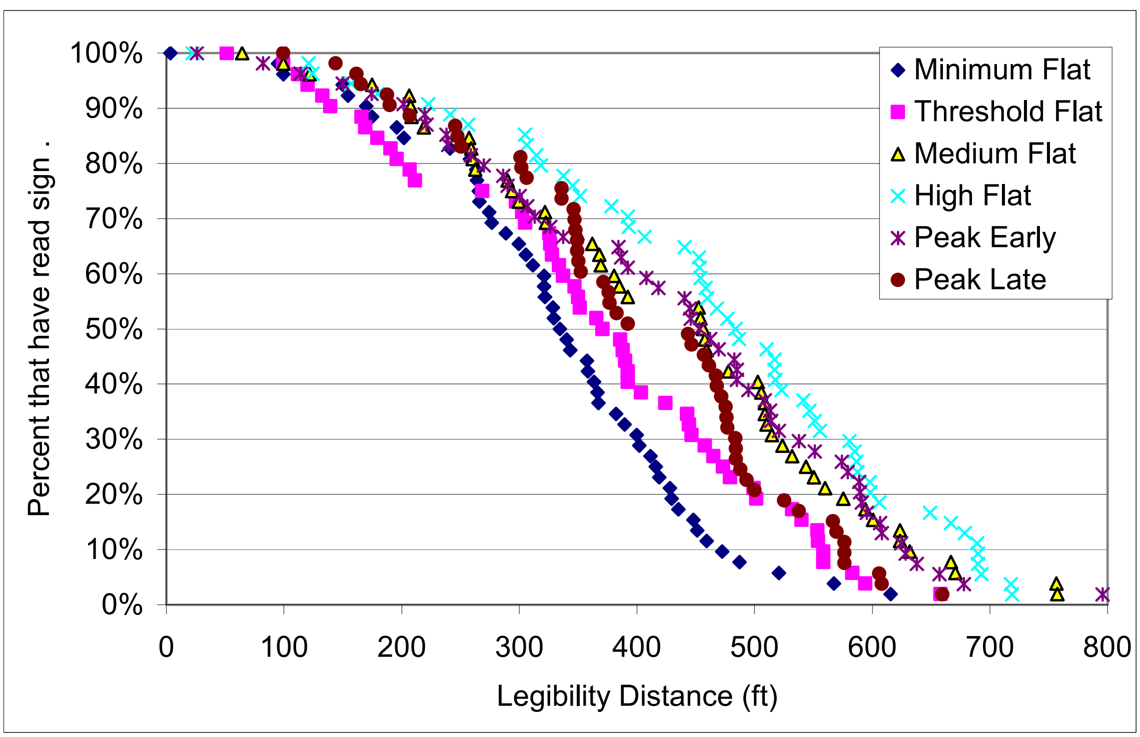


Figure 32. Regulatory Sign Results - Speed Limit Signs.

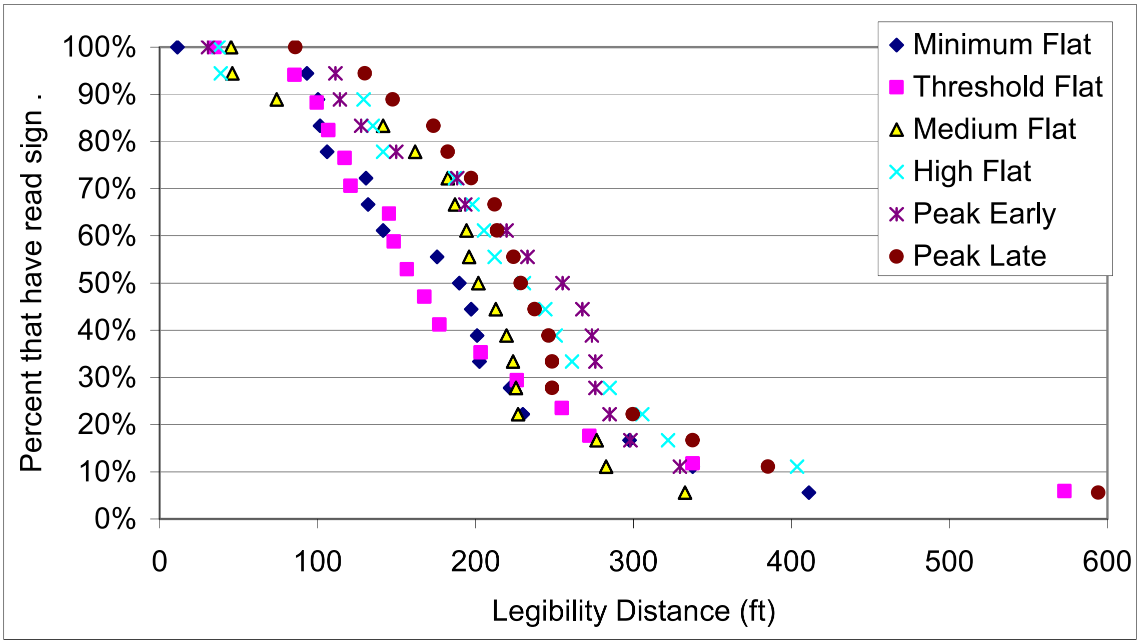


Figure 33. Regulatory Signs Results - Legend Signs.

The study was designed such that the regulatory sign showed two different sign types, and therefore the amount of data from the regulatory sign, while in aggregate, was the same as the warning and guide signs and was shared between signs that looked like speed limit signs and signs that were more textual in nature. There was an unequal balance between these two regulatory signs types as well. The speed limit sign was shown more often than the textual sign. These results are evident in Figure 32 and Figure 33. Table 12 shows the average legibility and standard deviation results. These results are collapsed across age of participants.

Table 12. Descriptive Statistics.

Profile	Statistic	Guide Sign 12-inch Legend	Warning Sign 7-inch Legend	Regulatory Sign 14-inch Legend	Regulatory Sign 7-inch Legend
Minimum	Average Legibility (ft)	344	168	317	182
	Standard Deviation (ft)	125	85	112	96
	Sample (n)	72	72	50	18
Threshold Flat	Average Legibility (ft)	381	182	358	190
	Standard Deviation (ft)	137	80	143	124
	Sample (n)	72	71	52	17
Medium Flat	Average Legibility (ft)	454	246	418	190
	Standard Deviation (ft)	138	100	180	76
	Sample (n)	72	72	52	18
High Flat	Average Legibility (ft)	467	252	482	241
	Standard Deviation (ft)	157	95	153	159
	Sample (n)	71	72	54	18
Peak Early	Average Legibility (ft)	446	234	422	246
	Standard Deviation (ft)	153	100	180	159
	Sample (n)	72	72	54	18
Peak Late	Average Legibility (ft)	383	207	400	244
	Standard Deviation (ft)	137	70	130	113
	Sample (n)	72	71	53	18

The data were analyzed in a split-plot design with the dependent variable being Legibility Distance and the factors of interest were Gender, Age Group (≤ 55 years, > 55 years), Visual Acuity, Legend, Profile, and Order. After examining the distribution of Visual Acuity, it was decided to group Visual Acuity into two categories (≤ 20/20, > 20/20) because some of the original Visual Acuity values have very few subjects. The experiment was conducted for four different signs with different levels of Legend and Profile. Subject, Gender, Age Group, and Visual Acuity Group were treated as whole plot factors while Legend and Profile served as split-plot factors and were nested within each of the four signs. The definitions of each of the factors are detailed below.

- Subject – the individual test subject, and the term was used to serve as a random effects variable to account for subject specific effects not associated with gender, age, and visual acuity.
- Gender – whether the subject was male or female.
- Age Group – whether the subject was 55 years old or younger, or older than 55 years of age.
- Visual Acuity Group – whether the subject had corrected vision of 20/20 or better, or worse than 20/20 vision.
- Sign – there were 4 different types:
  - overhead guide sign (8.5 ft x 10 ft with 12-inch white legend on green background),
  - warning sign (4 ft x 4 ft with 7-inch black legend on yellow background),
  - regulatory speed sign (4 ft x 3 ft with 14-inch black legend on white background), and
  - regulatory legend sign (4 ft x 3 ft with 7-inch black legend on white background).
- Legend – this term refers to the different words or alpha-numeric combinations that were presented to the various subjects, and they were different for each sign.
- Profile – this term refers to the different luminance profiles for each sign, and there were six profiles for each sign.

An initial model of all of the data was analyzed, and it was found that the signs should be analyzed individually. Sign was a statistically significant factor (see Table 13). From the table, it is also apparent that there is a significant Sign*Acuity Group and Sign*Age Group interaction. This suggests that Acuity Group and Age Group behave differently for different signs and therefore the analysis should be conducted separately for each of the four signs.

Table 13. Model of All Data, Main Effects, and Two-Way Interactions.

Source	Nparm	DF	DFDen	Sum of Squares	F Ratio	Prob > F	
Subject[Gender,AcuityGroup,AgeGroup]&Random	36	35	916	6956088.3	.	.	Shrunk
Gender	1	1	35	381.9	0.0670	0.7972	
sign	3	3	916	5748388.3	336.3265	<.0001	
legend[sign]	32	32	916	136524.4	0.7489	0.8429	
profile[sign]	20	20	916	1013778.8	8.8971	<.0001	
AcuityGroup	1	1	35	26030.1	4.5689	0.0396	
AgeGroup	1	1	35	6219.7	1.0917	0.3033	
AgeGroup*legend[sign]	32	32	916	107208.4	0.5881	0.9674	
AgeGroup*profile[sign]	20	20	916	199763.7	1.7532	0.0215	
legend*profile[sign]	160	160	916	964146.1	1.0577	0.3107	
profile*AcuityGroup[sign]	20	20	916	91083.9	0.7994	0.7163	
legend*AcuityGroup[sign]	32	32	916	148858.0	0.8165	0.7555	
sign*AcuityGroup	3	3	916	80828.4	4.7291	0.0028	
sign*AgeGroup	3	3	916	177007.8	10.3564	<.0001	

SS for Tests on Random effects refer to shrunken predictors rather than traditional estimates.

Before the individual analyses for each sign are discussed, it should be pointed out that several possible interactions were considered, but only a few were found to be significant and some were not even able to be tested. The three-way interactions Legend*Profile*Age Group and Legend*Profile*Acuity Group could not be included in the models without resulting in singularity problems. When analyzing the data for each sign separately, all main effects (including Order) and the Legend*Profile, Legend*Age Group, Profile*Age Group, Profile*Acuity Group, and Legend*Acuity Group interactions were included. Including Order in the model did not cause singularity problems as it did in the case of the combined model. However, the Order main effect turned out to be insignificant for all the signs and so will not be included in any models presented below. The effect of Legend*Acuity interaction was also insignificant for all the signs and will not be presented either. The effect of Profile*Acuity Group interaction was significant only for Sign 3, and so it will be included only in Sign 3 analysis. The two-way interactions, Legend*Profile, Legend*Age Group, and Profile*Age Group are the terms that were included regardless of whether they are significant or not.

Guide Sign. For the guide sign, it was found that the main factors profile, Age Group and Visual Acuity Group and the interaction between Profile and Age Group were significant (see Table 14). With respect to the effect of visual acuity, it was found that as visual acuity improves, so does detection distance. A Tukey's HSD test was completed to see which profiles were statistically significantly different from each other with respect to Age Group. Table 15 contains the results of the Tukey Test, and Figure 34 is a plot of the least square mean values. For the drivers 55 years old and younger, the medium flat, high flat, and peak early all outperformed the other luminance profiles tested. For the drivers over the age of 55, the results show that there is no difference between the different profiles. It should also be noted that younger drivers had better legibility distance than older drivers.

Table 14. ANOVA of Guide Sign.

Source	Nparm	DF	DFDen	Sum of Squares	F Ratio	Prob > F	
Subject[Gender,AcuityGroup,AgeGroup]&Random	36	35	303	3213092.8	.	.	Shrunk
Gender	1	1	35	875.4	0.1781	0.6756	
legend	11	11	303	58093.7	1.0746	0.3815	
profile	5	5	303	499992.3	20.3464	<.0001	
AcuityGroup	1	1	35	23013.1	4.6824	0.0374	
AgeGroup	1	1	35	22930.4	4.6656	0.0377	
legend*profile	55	55	303	220184.0	0.8145	0.8203	
legend*AgeGroup	11	11	303	36550.6	0.6761	0.7611	
profile*AgeGroup	5	5	303	110576.3	4.4997	0.0006	

SS for Tests on Random effects refer to shrunken predictors rather than traditional estimates.

Table 15. Guide Sign Tukey HSD Results.

Age Group	Luminance Profile	Tukey Level Statistic[1]		Least Square Mean (ft)
≤ 55	Low Flat		B	355.8584
	Minimum		B	383.42076
	Medium Flat	A		478.38628
	High Flat	A		499.79629
	Peak Early	A		488.0845
	Peak Late		B	386.71044
> 55	Low Flat		B	287.19009
	Minimum		B	293.54433
	Medium Flat	A	B	361.1087
	High Flat	A	B	351.21133
	Peak Early	A	B	338.22353
	Peak Late	A	B	339.80772

[1]Levels not connected by same letter are significantly different.

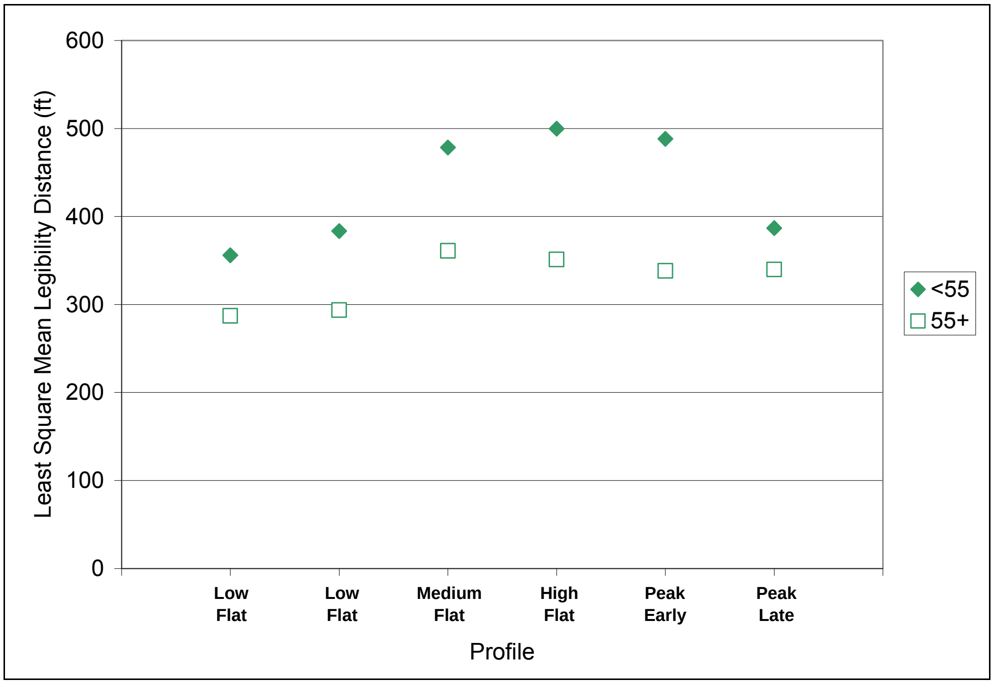


Figure 34. Guide Sign Least Square Mean Results by Profile and Age Group.

Warning Sign. The results for the split-plot analysis of the warning are presented in Table 16 below. Profile was the only factor that had a statistically significant effect. A Tukey Honest Significant Difference (HSD) test was conducted to investigate the differences between the profiles. Table 17 presents the results. The medium flat, high flat, and peak early luminance profiles provided significantly better legibility distance than the other three profiles.

Table 16. ANOVA of Warning Sign.

Source	Nparm	DF	DFDen	Sum of Squares	F Ratio	Prob > F	
Subject[Gender,AcuityGroup,AgeGroup]&Random	36	35	301	1712238.9	.	.	Shrunk
Gender	1	1	35	22.5	0.0082	0.9284	
legend	11	11	301	25371.0	0.8418	0.5983	
profile	5	5	301	242366.3	17.6913	<.0001	
AcuityGroup	1	1	35	8149.3	2.9743	0.0934	
AgeGroup	1	1	35	2067.6	0.7546	0.3909	
legend*profile	55	55	301	131538.4	0.8729	0.7245	
legend*AgeGroup	11	11	301	23026.0	0.7640	0.6760	
profile*AgeGroup	5	5	301	23458.1	1.7123	0.1315	

SS for Tests on Random effects refer to shrunken predictors rather than traditional estimates.

Table 17. Warning Sign Tukey HSD Results.

Luminance Profile	Tukey Level Statistic[1]		Least Square Mean (ft)
Low Flat		B	178.81669
Minimum		B	184.05466
Medium Flat	A		239.0534
High Flat	A		253.81498
Peak Early	A		244.01757
Peak Late		B	207.22876

[1]Levels not connected by same letter are significantly different.

Regulatory Signs with 14-Inch Legends. Table 18 presents the results for the split-plot analysis of regulatory speed sign. Only the interaction of visual acuity and profile were found to have a statistically significant effect on legibility distance. A Tukey HSD test was completed with respect to visual acuity and profile, and the drivers with better vision outperformed the drivers with poorer vision (see Table 19 and Figure 35). With respect to profile, the drivers in the 20/25 to 20/40 visual acuity group had similar performance regardless of the luminance profiles presented. The better vision group only showed improved legibility detection distance performance for the high flat and peak early luminance profiles.

Table 18. ANOVA for Regulatory Speed Sign.

Source	Nparm	DF	DFDen	Sum of Squares	F Ratio	Prob > F	
Subject[Gender,AcuityGroup,AgeGroup]&Random	36	35	207	2778937.0	.	.	Shrunk
Gender	1	1	35	40.7	0.0081	0.9287	
AcuityGroup	1	1	35	7328.7	1.4606	0.2349	
AgeGroup	1	1	35	3782.9	0.7539	0.3912	
legend	8	8	207	21430.5	0.5339	0.8302	
profile	5	5	207	40633.5	1.6197	0.1562	
legend*profile	40	40	207	196662.6	0.9799	0.5110	
AgeGroup*legend	8	8	207	22916.3	0.5709	0.8011	
AgeGroup*profile	5	5	207	30902.5	1.2318	0.2954	
AcuityGroup*profile	5	5	207	86027.7	3.4291	0.0053	

SS for Tests on Random effects refer to shrunken predictors rather than traditional estimates.

Table 19. Regulatory Speed Sign Tukey HSD Results.

Acuity Group	Luminance Profile	Tukey Level Statistic[1]			Least Square Mean (ft)
20/10 to 20/20	Low Flat			C	357.36326
	Minimum	A	B	C	404.86184
	Medium Flat	A	B		487.16016
	High Flat	A			496.29116
	Peak Early	A			491.42218
	Peak Late	A	B	C	401.59957
20/25 to 20/40	Low Flat			C	285.3842
	Minimum			C	284.57249
	Medium Flat		B	C	291.58847
	High Flat	A	B	C	350.18749
	Peak Early	A	B	C	328.53309
	Peak Late	A	B	C	350.73408

[1]Levels not connected by same letter are significantly different.

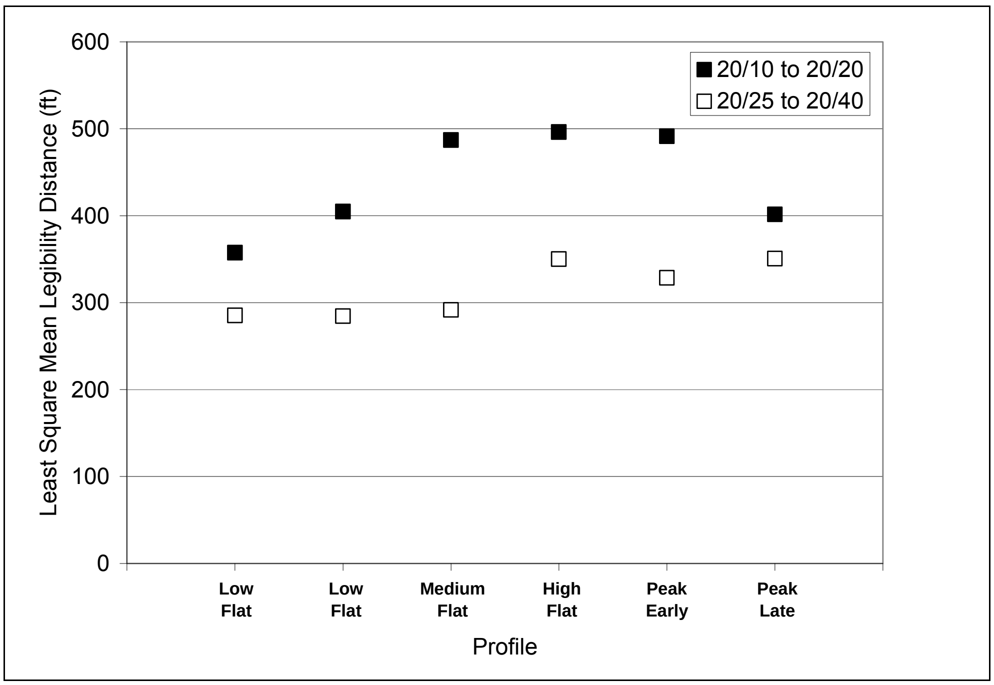


Figure 35. Regulatory Speed Limit Sign Least Square Means Results by Profile and Visual Acuity.

Regulatory Sign with 7-Inch Legends. This sign type was not evaluated as frequently as the other signs. The results are not consistent with the other signs either. One of the main reasons is probably that the sample size (18 observations per profile) was too small to overcome the variability in the data.

Table 20 presents the results for the split-plot analysis of the regulatory legend sign. Unlike for the previous signs, there are not any statistically significant effects at α=0.05 in this model. Even though profile did not have a statistically significant effect on legibility distance, a Tukey HSD test was completed with the results shown in Table 21.

Table 20. ANOVA of Regulatory Legend Sign.

Source	Nparm	DF	DFDen	Sum of Squares	F Ratio	Prob > F	
Subject[Gender,AcuityGroup,AgeGroup]&Random	36	35	44	937756.38	.	.	Shrunk
Gender	1	1	35	140.16	0.0739	0.7874	
legend	2	2	44	1185.86	0.3125	0.7332	
profile	5	5	44	16729.57	1.7636	0.1403	
AcuityGroup	1	1	35	5544.67	2.9226	0.0962	
AgeGroup	1	1	35	920.91	0.4854	0.4906	
legend*profile	10	10	44	13480.44	0.7105	0.7097	
legend*AgeGroup	2	2	44	1758.26	0.4634	0.6322	
profile*AgeGroup	5	5	44	15214.20	1.6039	0.1790	

SS for Tests on Random effects refer to shrunken predictors rather than traditional estimates.

Table 21. Regulatory Legend Sign Tukey HSD Results.

Luminance Profile	Tukey Level Statistic[1]	Least Square Mean (ft)
Low Flat	A	191.130616
Minimum	A	205.584701
Medium Flat	A	210.775096
High Flat	A	243.780624
Peak Early	A	242.534603
Peak Late	A	221.16517

[1]Levels not connected by same letter are significantly different.

Legibility Summary

In general, the findings are consistent with previous research regarding nighttime visibility. In other words, increasing the legend letter size results in an increased legibility distance, younger drivers have longer legibility distances than older drivers, and drivers with visual acuity levels ≤ 20/20 have longer legibility distances than those with worse visual acuity.

The luminance-distance profiles used in this study led to the following preliminary findings. Overall, the results show that increasing sign luminance will lead to increased legibility distances but there appears to be a point of diminishing returns. While the profiles were significant in all statistical testing, the relationships were somewhat different for each sign type. In general the medium-flat, high-flat, and peak early profiles provided the longest legibility distances but the three were also found to be statistically similar. What is interesting is that the level of luminance provided by these profiles was quite different. The high flat profile provided more than twice the luminance than the medium flat and the peak early profiles but they were generally not deemed statistically significantly different from each other. This information may be useful in leading to a ceiling on the amount of luminance needed from traffic signs for nighttime driving. However, the conditions tested in this study are only applicable to rural areas as the background complexity of the testing area was dark with no ambient lighting.

It should be pointed out that the distance-luminance profiles used in this study do not represent any particular type of retroreflective sheeting material. Therefore, signs viewed at nighttime with retroreflective sheeting materials will have different distance-luminance profiles. The signs tested in this study are more akin to internally illuminated signs, except the brightness was varied in the study as a function of the distance of the approach vehicle. The complementary analyses provided below and based on the eye-tracker data may provide additional insight.

Eye-Tracker Data

This section includes the analyses and findings from the eye-tracker data from Phase II. For a variety of reasons, the number of participants with recorded and usable eye-tracker data varies by sign type and is different than the legibility data, which are much more reliable data to obtain. Therefore, the sample size for each sign is shown along with the descriptive statistics in Table 22 to Table 25.

Table 22. Descriptive Statistics for Phase II Guide Sign Eye-Tracker Data.

Profile	Sample Size	Avg Legibility Distance (ft)	Avg LI	Avg Legibility Look (sec)	Avg Total Looks (sec)	Avg Num Glances
Low	36	344	29	4.5	8.7	4.7
Min	36	381	32	5.1	9.2	4.1
Med	33	454	38	4.4	8.3	3.9
High	33	467	39	4.6	8.4	3.9
Early	34	446	37	5.4	8.9	3.9
Late	33	383	32	3.8	8.1	3.9

Table 23. Descriptive Statistics for Phase II Warning Sign Eye-Tracker Data.

Profile	Sample Size	Avg Legibility Distance (ft)	Avg LI	Avg Legibility Look (sec)	Avg Total Looks (sec)	Avg Num Glances
Low	34	168	24	2.4	4.9	3.3
Min	35	182	26	2.7	5.4	3.2
Med	35	246	35	3.0	5.0	2.5
High	33	252	36	3.3	5.6	2.9
Early	36	234	33	3.5	5.5	2.6
Late	36	207	30	2.9	5.3	2.9

Table 24. Descriptive Statistics for Phase II Regulatory Speed Limit Sign Eye-Tracker Data.

Profile	Sample Size	Avg Legibility Distance (ft)	Avg LI	Avg Legibility Look (sec)	Avg Total Looks (sec)	Avg Num Glances
Low	25	317	23	2.8	9.6	7.1
Min	26	358	26	2.8	8.8	6.7
Med	24	418	30	3.9	9.8	6.2
High	24	482	34	3.3	8.9	5.6
Early	25	422	30	4.0	9.5	5.7
Late	29	400	29	3.2	9.4	6.0

Table 25. Descriptive Statistics for Phase II Regulatory Sign Eye-Tracker Data.

Profile	Sample Size	Avg Legibility Distance (ft)	Avg LI	Avg Legibility Look (sec)	Avg Total Looks (sec)	Avg Num Glances
Low	11	174	25	3.6	5.7	3.1
Min	7	122	17	4.0	6.7	3.7
Med	9	171	24	3.8	6.6	3.4
High	7	188	27	3.2	5.7	3.0
Early	9	194	28	5.0	6.5	2.6
Late	9	199	28	2.8	5.1	2.8

These descriptive statistics begin to show how the eye-tracker results are less a function of the luminance profile than the legibility results. There is no consistent trend in the luminance profiles and any of the three eye-tracker data metrics shown above. In order to further investigate the eye-tracker findings, cumulative distribution profiles were also generated as a way to understand the eye-tracking data. Figure 36 through Figure 39 show cumulative distribution profiles by sign type and profile for the percent of drivers spending the majority of their time (over 50 percent) looking at the sign within half second intervals.

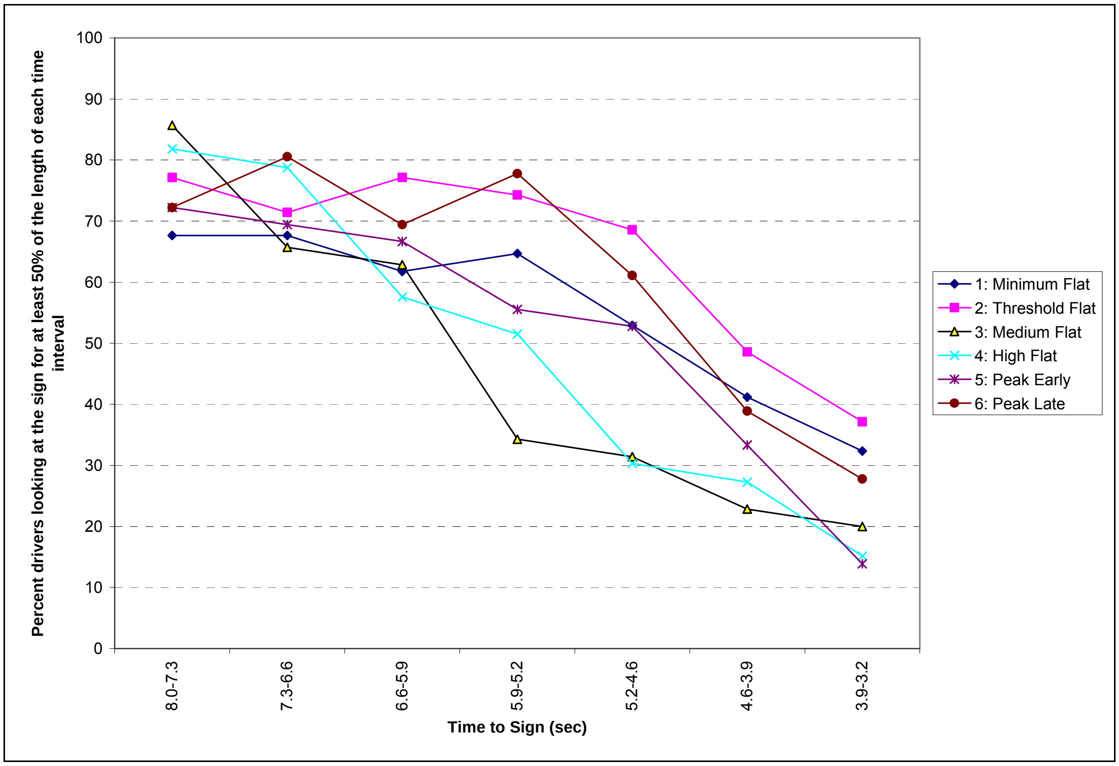


Figure 36. Driver Focus on the Warning Sign.

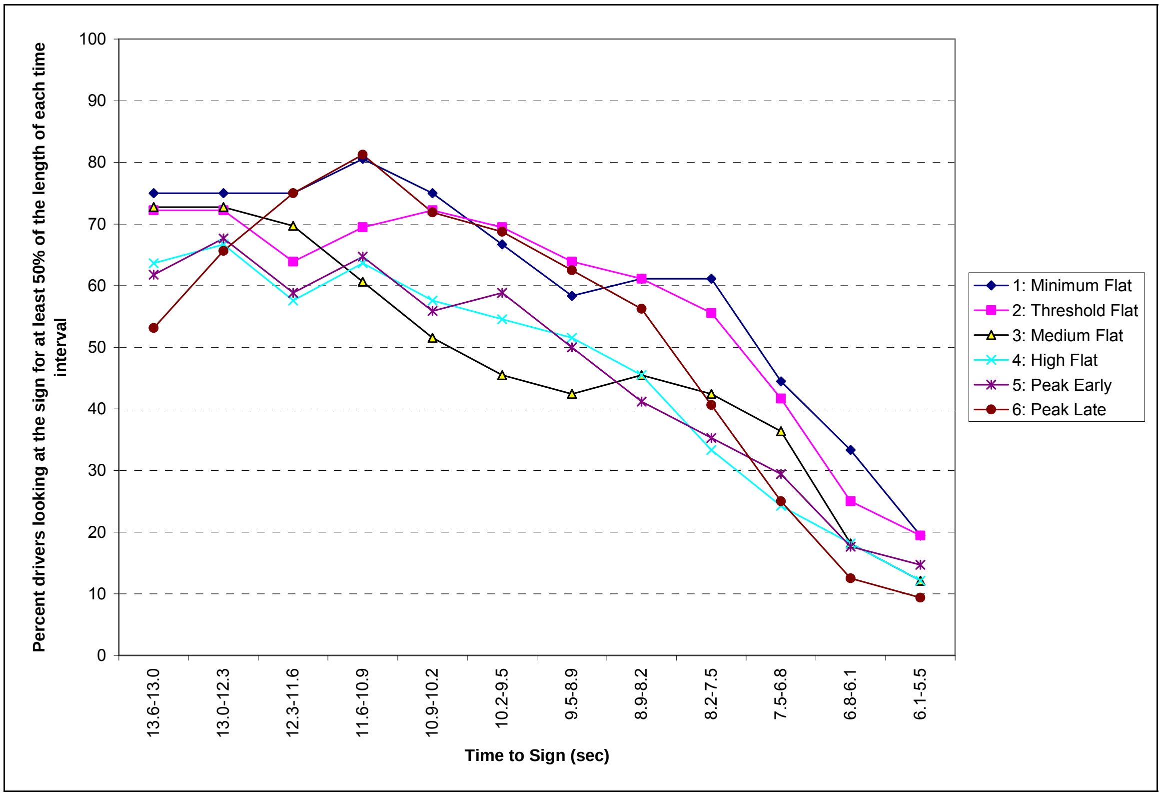


Figure 37. Driver Focus on the Guide Sign.

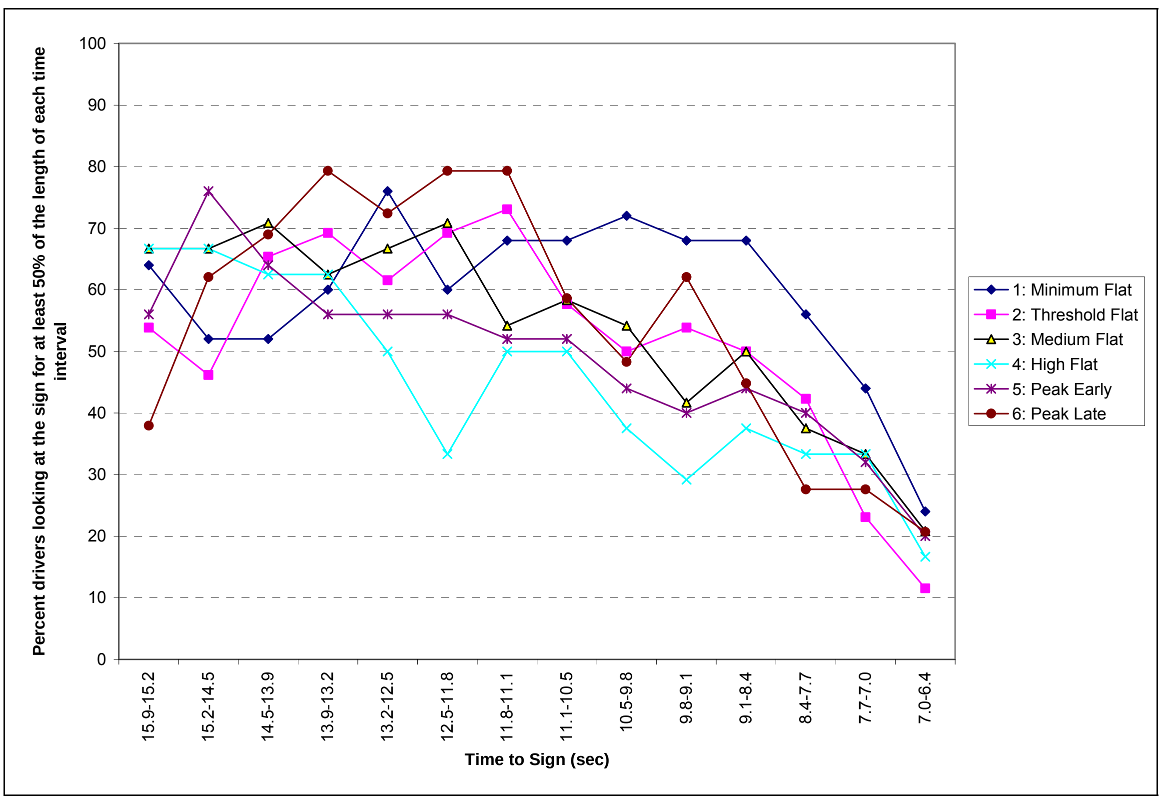


Figure 38. Driver Focus on the Speed Limit Sign.

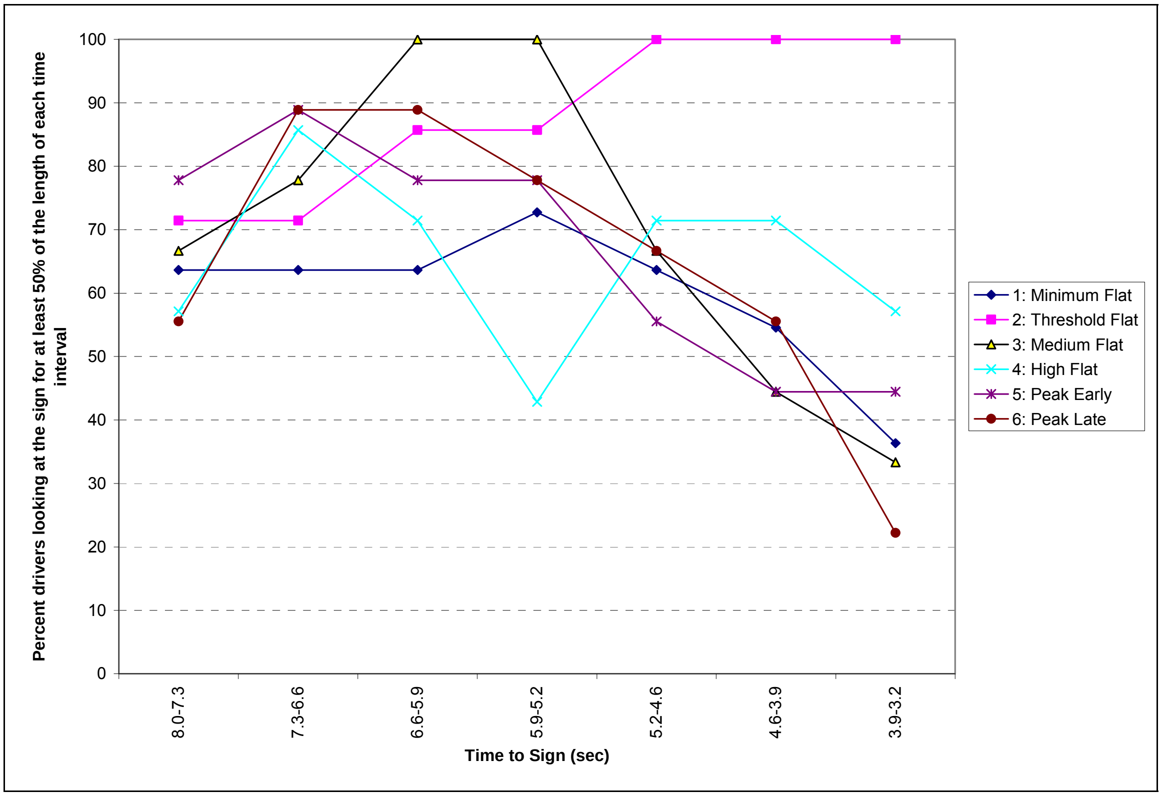


Figure 39. Driver Focus on the Regulatory Sign.

The cumulative distribution profiles reveal more interesting findings than the descriptive statistics alone. Particularly for the guide sign, the results are similar to the legibility data (see Figure 30) where the medium flat, high flat, and peak early profiles generate results that can be interpreted as being better than the results generated from the remaining three profiles. However, the variability shown in these graphs was thought, at least in part, to be caused by the testing conditions that were on a closed course in a rural setting with very little visual clutter other than the target of interest. Detailed statistical analyses were not conducted for these data in order to save time and move more quickly to an on-the-road test, which was thought to have more potential to eventually discern eye behavior differences as a function of luminance and environmental surrounds.

Exploratory Analysis Using Luminance Metrics

The objective of this effort was to explore how various techniques of quantifying the luminance profiles affect the measured legibility distance. This effort was investigative in nature and conducted in order to determine if results from earlier studies could be further enhanced using different techniques to quantify sheeting performance rather than retroreflectivity. For instance, in a previous TxDOT-sponsored study (FHWA/TX-04/1796-4), the results shown in Figure 40 were presented. The intent of the current analysis was to explore various techniques that could be used to quantify the material performance to more clearly differentiate the performance of retroreflective sheeting materials in terms of nighttime driving. It was anticipated that these exploratory analyses, if deemed useful, could lead to the basis for a new criteria to support a performance-based retroreflective sheeting specification based on nighttime driver needs.

Table 17. Duncan Multiple Range Test for Sheeting.

Retroreflective Sheeting Combination	Mean Legibility (ft)	Duncan Grouping (α=0.05)	
VIII on IX	626.4	■	
IX on III	602.4	■	
IX on IX	595.4	■	■
VIII on III	591.5	■	■
III on III	549.9		■

Table 20. Duncan Multiple Range Test for Sheeting Combination.

Retroreflective Sheeting Combination	Mean Legibility (ft)	Duncan Grouping (α=0.05)	
VIII on VIII	216.4	■	
VIII on III	215.2	■	
IX on III	208.4	■	
III on III	169.9		■

Figure 40. Results from TxDOT Study 1796-4.

For these analyses, the dependent variable was Legibility Distance and the factors of interest are Aspect of Profile (see new variables described in Table 1), Age Group (0:≤ 55 years, 1:> 55 years), Visual Acuity Group (0:≤ 20, 1:> 20), and Legend.

The data were analyzed utilizing the split-plot design with Subject (driver) as a whole-plot and each treatment combination as a split-plot. Recall that the experiment was conducted for four different signs with different levels of Legend and Aspect of Profile. The variables Age

Group and Visual Acuity Group are treated as whole plot factors while Legend and Aspect of Profile serve as split-plot factors and are nested within each of the four signs. The data were analyzed separately by Sign as in previous analyses.

Table 26. Variables Quantifying Different Aspects of Profile.

Variables	Description
CLum_CTime 40LI	Total amount of light available to the study subject as they approach the sign from the 40 to the 20 LI region
Log 40 LI	Log transform of CLum_CTime 40LI
CLum_CTime 50LI	Total amount of light available to the study subject as they approach the sign from the 50 to the 20 LI region
Log 50 LI	Log transform of CLum_CTime 50LI
CLum_CTime 80LI	Total amount of light available to the study subject as they approach the sign from the 80 to the 20 LI region
Log 80 LI	Log transform of CLum_CTime 80LI

The variables in Table 26 cannot be simultaneously included in an analysis due to a strong linear relationship (colinearity) among the variables. As a result each of the six variables in Table 26 was analyzed separately.

For the guide sign, the results under the final model with CLum_CTime 40LI in place of Aspect of Profile for Sign 2 are presented in Table 27. The effect of CLum_CTime 40LI on the legibility distance is positive, i.e., as CLum_CTime 40LI increases, the legibility distance increases. Table 27 contains the model with statistically significant (at $\alpha=0.05$) effects as well as the main effect variables that are part of two-way interaction effects. It can be seen that the overall model fit stays almost the same (especially in terms of the adjusted R-square) as the initial model(s).

Table 27. JMP Output for the Final Model with CLum_CTime 40LI.

Summary of Fit

RSquare	0.761892
RSquare Adj	0.759646
Root Mean Square Error	78.53739
Mean of Response	408.7219
Observations (or Sum Wgts)	429

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	360.78866	18.89517	35.91	19.09	<.0001
Age Grp[0]	34.074443	24.66653	33	1.38	0.1764
Acuity Grp[0]	59.975283	23.40114	33	2.56	0.0151
CLum_CTime 40LI	0.2153271	0.027899	391	7.72	<.0001
Age Grp[0]*(CLum_CTime 40LI-137.675)	0.0758134	0.027899	391	2.72	0.0069

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age Grp	1	1	33	1.9083	0.1764
Acuity Grp	1	1	33	6.5686	0.0151
CLum_CTime 40LI	1	1	391	59.5670	<.0001
Age Grp*CLum_CTime 40LI	1	1	391	7.3841	0.0069

Table 27 also shows the estimated model coefficients in the Parameter Estimates table. A prediction equation for Legibility distance (Y) for sign 2 can be written using those coefficients (if desired) as follows:

Y=360.78866+34.074443 Age Grp[0] + 59.975283 Acuity Grp[0] +0.2153271 CLum_CTime 40LI

+0.0758134 Age Grp[0]*(CLum_CTime 40LI-82.1944)

where Age Grp[0] and Acuity Grp[0] are indicator functions as defined previously.

This equation can be simplified by replacing the indicator function by either 0 or 1 depending on whether the condition is satisfied. For example, when Age Group = 0 and Acuity Group = 0, the previous equation can be rewritten as:

Y=360.78866+34.074443 + 59.975283 +0.2153271 CLum_CTime 40LI

+0.0758134 *(CLum_CTime 40LI-82.1944) = 448.6069+ 0.2911 CLum_CTime 40LI

and when Age Group = 1 and Acuity Group = 1, Equation (1) can be rewritten as:

Y=360.78866+0.2153271 CLum_CTime 40LI

These results indicate that the rate of increase (slope for CLum_CTime 40LI) of legibility distance (as CLum_CTime 40LI increases) is larger for young drivers than for old drivers as the significant interaction effect Age Grp*CLum_CTime 40LI suggests. Using the log of the variable CLum_CTime 40LI resulted in similar findings as shown in Report 0-5235-1 Volume 2.

As noted, additional versions of this analysis were completed with the guide sign data but using more luminance data (out to 50 LI and 80 LI, respectively). The results were similar to that above for both the 50 Li and 80 LI analyses, and for both the cumulative luminance as well as the log transformation. Table 28 shows the overall fit of all the models for the guide signs.

Table 28. Overall Model Fit with Visual Acuity.

Variables	R-square Adjusted
CLum_CTime 40LI	76.0
Log 40 LI	77.8
CLum_CTime 50LI	77.1
Log 50 LI	79.0
CLum_CTime 80LI	77.8
Log 80 LI	80.0

These results demonstrate that the log transformation of the cumulative luminance over the specified distance has a slight improvement in each of the three cases. In addition, each extension of the analysis from 40 LI to 50 LI to 80 LI had a slightly positive impact in the model fit. Overall, however, the practical difference between the models remains questionable. These analyses were also completed for the warning sign as well as the two different regulatory signs. The detailed results are shown in Report 0-5235-1 Volume 2.

In a follow-up analysis, visual acuity was removed from consideration since it is not a design parameter that a specifier can use. In addition, the researchers also re-evaluated the data using newly created variables as shown in Table 29. This was completed in order to capture the log transformation of the luminance data more appropriately.

Table 29. Variables Quantifying Different Aspects of Profile.

Previous Variables	New Variables	Description
CLum_CTime 40LI	LOG(CLum)_Ctime 40LI	Total amount of light available to the study subject as they approach the sign from the 40 to the 20 LI region
CLum_CTime 50LI	LOG(CLum)_Ctime 50LI	Total amount of light available to the study subject as they approach the sign from the 50 to the 20 LI region

Overall, there was not a large difference between the current analysis (without Acuity) and the previous analysis (with Acuity) for the effects of the aspect of profile variables. Table 30 provides a side-by-side comparison of the results with and without visual acuity included in the model. There is practically no loss in the predictive power of the modeling. The results appear promising and additional profiles were tested in Phase III.

Table 30. Comparison of Overall Model Fit with and without Visual Acuity.

Variables	R-square Adjusted	
	Previous Analysis	Without Visual Acuity
CLum_CTime 40LI	76.0	77.5
Log 40 LI	77.8	77.9
CLum_CTime 50LI	77.1	77.1
Log 50 LI	79.0	79.0
CLum_CTime 80LI	77.8	n/a
Log 80 LI	80.0	n/a
LOG(CLum)_Ctime 40LI	n/a	77.5
LOG(CLum)_Ctime 50LI	n/a	79.0

Eye-Tracker Summary

The results of the eye-tracker data were less revealing than hoped. One of the reasons could be that the testing for this phase was all conducted on a closed course where the participants have a clutter-free visual environment and perhaps a sense of extreme comfort as there were no vehicles, pedestrians, or other potential hazards that would be evident during typical on-the-road conditions. There was a strong belief among the researchers and project advisory panel members that on-the-road testing would lead to more revealing results.

The one item that did appear to be useful was using the integrated luminance within LOOK3 to predict nighttime performance as a function of legibility. Additional details are provided in the next section.

DISCUSSION OF RESULTS

The findings from Phase II demonstrate several important aspects. The legibility results from the internally illuminated signs were as expected in terms of the effect of brightness on legibility. This finding is important to note because of the differences between these internally illuminated signs and signs made with retroreflective sheeting materials. Knowing that the legibility results were as expected provided faith in that additional analysis can be conducted on the legibility data without being concerned that the signs were so different that the results may not be transferrable.

One of the additional analyses was to compare the luminance dosage concept to the legibility results. While the luminance dosage concept provided promising results above, additional graphs were generated to compare the luminance dosage concept to legibility, using the legibility index to normalize the legibility results. Figure 41 shows the results for the three sign types tested (only the speed limit data were used for the regulatory sign).

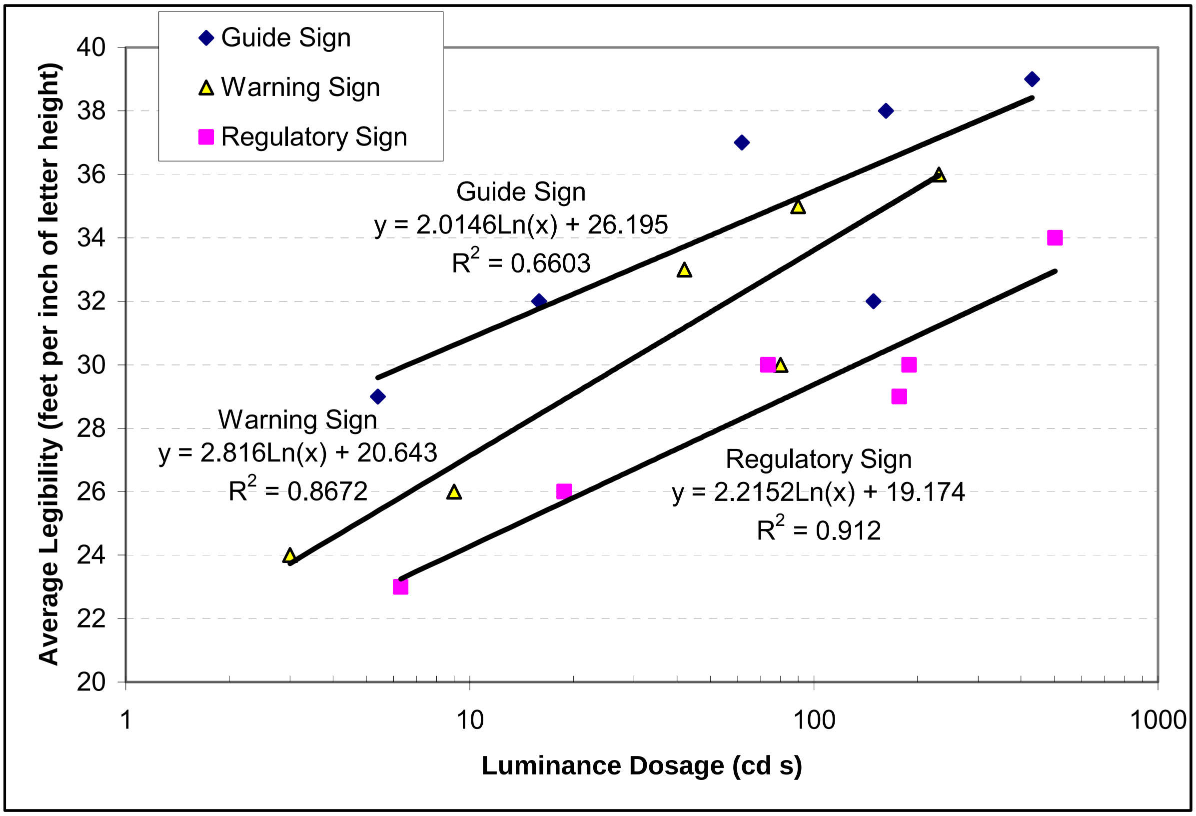


Figure 41. Luminance Dosage from LOOK3 by Average Legibility for All Profiles.

While the results in Figure 41 look promising, the researchers removed the Peak Early and Peak Late profiles because of their uniqueness. Figure 42 shows the results for the four flat profiles.

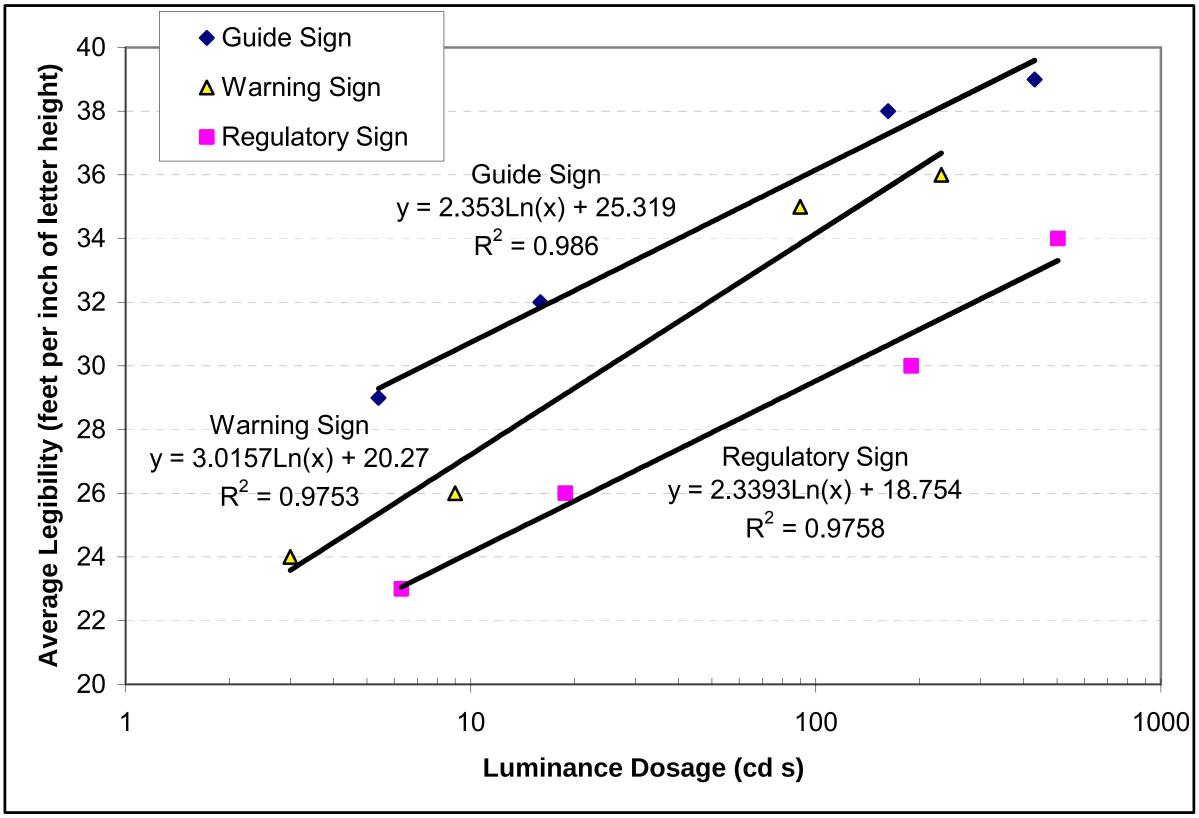


Figure 42. Luminance Dosage from LOOK3 by Average Legibility for Flat Profiles.

The data summarized in Figure 42 are surprisingly well behaved. The goodness of fit is above 97 percent for all three sign types. The slopes of the curves are near parallel. The results here prompted the researchers to continue to use the internally illuminated signs in Phase III to further explore this potential promising method to quantify nighttime sign performance.

CHAPTER 5:
PHASE III SUMMARY

Phase III builds from the findings of Phase I and II while also introducing rural and urban on-the-road testing to the closed-course testing. The on-the-road was conducted to produce more representative eye-tracker data (compared to the closed-course testing carried out in Phase II). The closed-course testing was continued for two reasons. First, additional luminance profiles were in need of testing to further investigate the luminance dosage concept described in the previous chapter. In addition, adding retroreflective signs of the same shape and legend style to the closed-course setting allowed the researchers to further explore the differences between closed-course testing and on-the-road testing, an issue that was discovered in Phase I but not fully investigated.

EXPERIMENTAL DESIGN

The experimental procedure for Phase III was developed from the procedures used in Phase I and Phase II. Test participants drove through several different signing scenarios on a circuitous closed course at the Texas A&M Riverside Campus for approximately 20 to 30 minutes before driving along a single loop course laid out on the open road for approximately 30 to 40 minutes. While traversing the closed- and open-road course, the study participants viewed 29 different study signs. Various details with respect to the driving environment and the design of the signs are detailed in Table 31 below. The luminance columns indicate whether the viewed luminance from a particular sign resulted from an internal source, or retroreflected light from the study vehicle's headlights, and how many different levels were viewed by each test participant. From this point forward, luminance level will be used to indicate a particular sign's brightness.

Table 31. Phase III Sign Summary.

Course	Environment	Sign Design						
		Luminance[1]		Type[2]	Quantity	Dimensions (inches)		
		Source	Level			Width	Height	Legend Height
Closed	Rural	Internal	2	W	2	48	48	7
		Internal	2	R	2	36	48	7
		Retroreflective	3	W	3	48	48	7
		Retroreflective	3	R	3	36	48	7
		Retroreflective	2	R[3]	8	36	48	10
Open	Rural	Retroreflective	3	W	2	48	48	7
		Retroreflective	3	R	3	36	48	7
		Retroreflective	3	G	2	102	66	8
		Retroreflective	3	S	1	40	12	6
	Urban	Retroreflective	3	W	1	48	48	7
		Retroreflective	3	G	1	102	66	8
		Retroreflective	3	S	1	57	13	6

[1] This category describes the possible differences with respect to the measureable luminance that may be available to each study participant. Source describes how the luminance was achieved through either an internal light source from fluorescent lighting or from retroreflected light by means of a retroreflective sheeting.
[2] There were four possible sign types: warning (W) sign with black legend on yellow background, regulatory (R) sign with black legend on white background, guide (G) sign with white legend on green background, and street name (S) sign with while legend on green background.
[3] These signs were added to the study but were not a part of the original scope. Two commonly used sheeting products were tested for discomfort glare associated with the use of high beam headlights. One product was a high intensity beaded and one was a high intensity prismatic.

The research team believed that the viewing of the different signs under the different conditions would better enable the researchers to develop a performance-based sheeting specification. The closed-course versus open-course condition was included in the study design to document and quantify any differences between these two different testing conditions. The rural and urban conditions included on the open-road portion of the study was added to assess any differences between the rural and urban driving environments, such as did the increase in the ambient lighting in the urban condition increase legibility distances or did the more complex driving environment decrease legibility distances or the number of glances at a sign. The use of internally illuminated signs in Phase III was to further investigate specific luminance profiles for the development of a performance-based sheeting specification that uses luminance rather than retroreflectivity. The use of retroreflective sheeting products was to study some commonly available sheeting products that are on the qualified products list that cover a wide range of retroreflectivity levels (100 to 700 mcd/m^2/lx for 0.2 degree observation and -4.0 degree entrance angles). The luminance levels associated with these sheeting products were also quantified, so the results could be compared with the results associated with the internally illuminated signs. Eight of the closed-course signs were used to specifically investigate whether there was discomfort glare associated with the use of two commonly used high intensity grade sheeting products when drivers used their high beams. There is a note in Table 31 indicating which products were viewed using high beams. All other signs listed in Table 31 were viewed with low beams only.

The order in which the various signs and luminance levels were set in a pseudo-randomized order. For instance, the order with respect to sign type for the open-road course signs was fixed because they were placed in a manner to blend in with the surrounding environment. Furthermore, the size of the guide signs necessitated the use of concrete slip bases and made the likelihood of randomizing their location cost prohibitive, unsafe, and inefficient. The street name sizes were tied to existing roadways as to not confuse the driving public, and so, their locations could not be randomized either. While the locations of the open-road courses signs could not be randomized, the luminance levels and the contents of the legends on each sign were randomized where possible.

The closed course was also pseudo-randomized. While it was possible to change the order in which the sign types were presented for the retroreflective signs at the closed-course facility, it was not possible to randomize the location of the internally illuminated signs because the large bulky signs could not be easily moved. As a result, it was decided to keep the sign order with respect to sign type constant for the closed-course portion of Phase III as well. For all of the closed-course signs with the exception of the regulatory signs tested with high beam headlight illumination, the luminance level and legend were randomized where possible. It was desired to randomize the order of these eight signs, a miscommunication with some of the field staff led to this unfortunate flaw in the study design. That said the researchers always intended to include sign order as a random covariate in the analysis to test for any unanticipated variable associated with sign order.

With all of the different conditions being tested, three overall different mixed model analyses were conducted. One model would investigate the two luminance profiles associated with the internally illuminated signs. Another model would describe the relationship between closed-course and open-road course studies with respect to three different commonly available retroreflective sheeting products. The final model was intended to quantify whether discomfort glare was associated with two different high intensity sheeting products when viewed under high beam illumination. Within the first two models, individual models were developed within sign type.

Measures of Effectiveness

As with the previous two phases, the primary measure of effectiveness (MOE) was legibility distance, and the secondary MOEs were associated with eye-glance behavior. To minimize the likelihood that legibility data were based off of recognition and not off of legibility, the research team selected legends for each condition that were not considered typical for the particular signing application, such as the use of the word "magnet" on the warning and regulatory signs. For secondary MOEs, the research team found little support from the review of literature for any one method of assessing eye-glance behavior that would directly correlate with safety. Hence, they chose to investigate several different factors that the researchers believed could be associated with an impact on safety, and they were:

- total number of glances for a sign,
- total percent time looking at a sign,
- average glance duration prior to the legibility look,
- glance duration associated with the legibility look, and
- distance from the sign at the start of the glance associate with the legibility look.

Independent Variables

Phase III was a balanced study design with respect to age and gender groups. The age groups were under 55 years of age and 55 years of age and older. All study participants viewed the signs from the driver seat position set at his/her specific comfort level. Road course, environment, luminance type and level, and sign type were additional independent variables. With respect to sign dimensions, only the legend height was listed among the independent variables to be included in the analysis. The background and legend colors were encompassed in sign type, so they were not included in the analysis. The vehicle type was constant for all subjects, so it was not included. While there were signs viewed under low and high beam headlight illumination, this was not included as a factor because only a subset of the data was viewed under high beam, and no sign was viewed under both headlight illumination conditions. Furthermore, this could be assessed using the luminance level factor. Luminance type was only considered for the closed-course data because only the closed course had more than one type. The list of independent variables to be considered in the analysis is detailed below.

- Age Group (two levels):
  - under 55 years of age,
  - 55 years of age and older;
- Gender (two levels):
  - male,
  - female;
- Course Type (two levels):
  - closed-road,
  - open-road;
- Sign Type (one to four levels):
  - warning,
  - regulatory,
  - guide,
  - street name;
- Luminance Type (two levels):
  - internally illuminated,
  - retroreflective; and
- Luminance Level (two to three levels):
  - low,
  - medium, and
  - high.

Data Collection

Each night of data collection, the study participants were met at the entrance to the Texas A&M University Riverside Campus and escorted to an office building for prescreening. During the prescreening, they completed an Informed Consent form and a demographics questionnaire. Next, the subjects underwent the Snellen Eye Chart test for visual acuity and the Ishihara Color Test. Participants all scored 20/40 or better on the acuity test and had normal color vision.

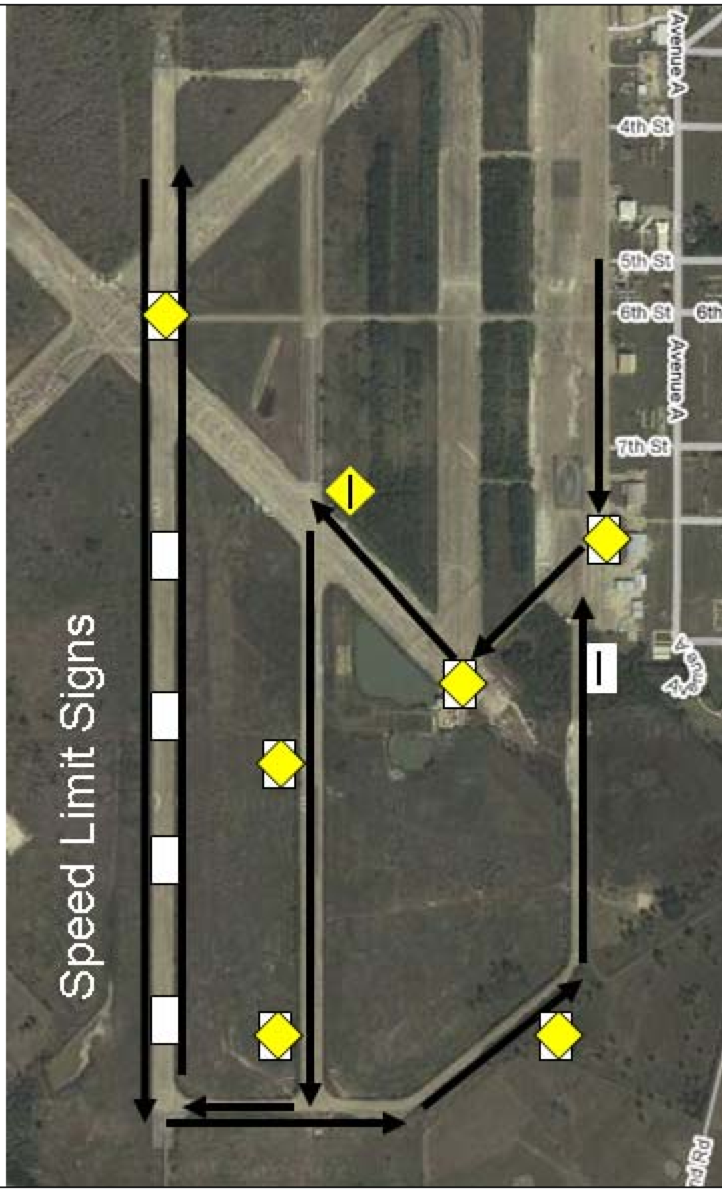
Upon completion of the prescreening, each participant was taken to the instrumented vehicle. Only one test participant could be tested at a time, but each test participant was accompanied by two researchers. One researcher operated the data collection equipment, while the second researcher acted as a safety observer for when the test participant drove the open-road course. The safety observer would watch of potential safety concerns and alert the driver when appropriate. The researcher operating the data collection equipment also served as the primary instructor for the test participant who would guide the test participant by directing him/her of when and where to turn. This better enabled the safety observer to keep his/her focus on potential safety risks within the study environment. The test participant was provided with ample time to familiarize him/herself with the vehicle and make adjustments for comfort, such as adjusting the seat, mirrors, and air conditioning system. Once comfortable and any questions posed by the test participant with respect to the vehicle and the study were addressed, the test participant was guided to a calibration course.

At the calibration course, one of the researchers affixed an eye-tracker device to the face of each test participant. Then the researcher operating the data collection equipment gave instructions to the test participant in order to calibrate the eye-tracker to the test participant. If minor adjustments were needed for comfort or to improve the calibration, the test participant was recalibrated. The entire calibration procedure took approximately 10 minutes, and once complete, one of the researchers directed the test participant to the start of the closed course.

Closed Course

The closed course consisted of a total of 18 test signs. Four of the signs were internally illuminated, and the other 14 signs were covered with retroreflective sheeting products. All of the signs were either black legend on yellow background warning signs, or black legend on white background regulatory signs. While driving the closed course, the test participants were instructed to try and maintain 30 miles per hour. The layout of the course is depicted in Figure 43 below. Each participant viewed two signs at each location. There were two courses within the closed course. The course was set up so there were two distinct orders of sign presentation in order to remove possible biases from a learning effect.

Each test participant was directed to state aloud each test word from each study sign as soon as they could. If they misread the word, they were instructed to state the word “Wrong,” and then proceed to tell the researcher the correct word. At each instance that the study participant read a word aloud, the researcher operating the data collection equipment coded an “Event” in the data stream that would be used later for data reduction purposes. Any incorrect responses were logged by the researcher for use during the data reduction phase. Once the closed-course route was complete, the study participant was guided to the open-road course.



- The yellow diamond with "I" and white rectangle with "I" show the locations of the internally illuminated signs.
- The yellow diamonds superimposed on the white rectangles represent the retroreflective signs (see Figure 40).
- The white rectangles show where the speed limit signs were tested with high beam illumination.

Figure 43. Phase III Closed-Course Layout.

Figure 44. Retroreflective Sign (Regulatory Sign Showing with Warning Sign on Back Side).

Open-Road Course

The open-road course consisted of an additional 11 signs using retroreflective sheeting. It was originally intended to have 12 signs on the open-road course with an additional street name sign; however, the manner in which the original street name sign was mounted prohibited the sign from being able to be replaced on a daily basis. There were a few similarities and a few differences between the open-road and closed courses.

The primary difference entailed the change in environments. The open-road course allowed the test participant to interact in both a roadway environment and with other motorists. In addition, the closed course solely included a rural test setting, while the open-road course had both rural and urban conditions. Several of the key differences between rural and urban environments are that urban environments have increased intersection densities per mile, increased ambient lighting, increased traffic volumes, signalization, and lower speeds. As a result of these differences, the urban environment was considered more visually complex, and it was believed the increased visual complexity could impact sign legibility and eye-glance behavior. Both the rural and urban portions of the open-road course were viewed using low beam headlight illumination.

With respect to sign types, there were identical warning and regulatory signs on the open-road course that would be compared back to their closed-course counterparts; however, there were two additional sign types added to the open-road course. Unlike the closed course, white legend on green background guide signs and street name signs were included on the open course. All four sign types were viewed under rural conditions on the open-road course, but only the warning, guide, and street name signs were viewed under the urban conditions.

The layout of the open-road course is in Figure 45 below. The star in the figure indicates the start of the open-road course where the study participant would leave the Riverside Campus. Table 32 lists the background complexity at each of the signs. Prior to starting the open-road course, the study participants were reminded that the testing protocol was the same as with the closed course, and he/she was given an opportunity to ask any questions.

Figure 45. Phase III Open-Road Course Layout.

Table 32. Sign Surround Descriptions.

Sign Area	Type	Speed Limit (mph)	Length (mi)	Visual Complexity (1=Lo, 2=Med, 3=Hi)			Score
				Light	Sign	Other	
1, 11	Rural	70/65	2.7	1	1	1	3
2	Rural	70/65	2.1	1	1	1	3
3	Rural/Urban	60	1.1	2	1	2	5
4-5	Urban	45	1.4	3	2	3	8
6	Urban	50	1.2	3	1	2	6
7	Rural/Urban	60	1.3	2	1	2	5
8-10	Rural	50	2.9	2	1	2	5

Equipment

The same equipment used in Phase II, the instrumented vehicle, the eye-tracker, and the internally illuminated signs, were used in Phase III with the addition of 14 signs for the closed course and 11 signs added for the open-road course. The instrumented vehicle remained unchanged, but the eye-tracker was modified by the manufacturer to improve the nighttime resolution of the forward seeing camera.

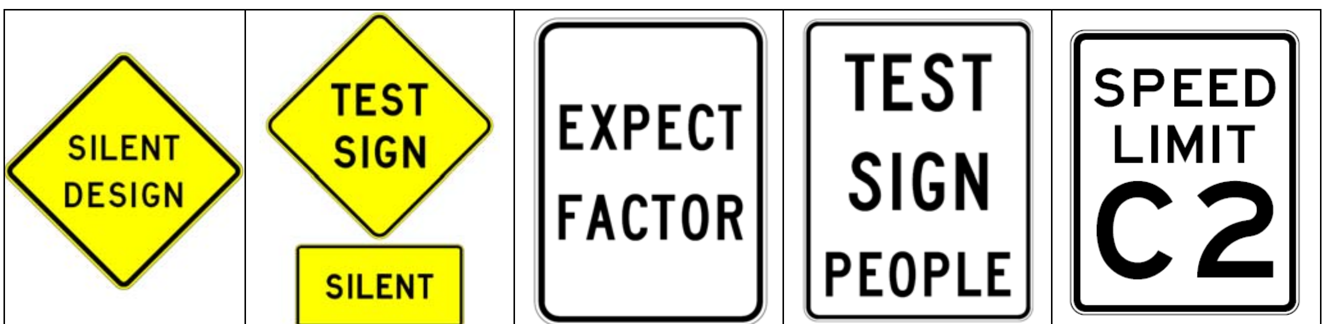
Closed Course

The only changes to the internally illuminated signs between Phase II and Phase III were within the luminance levels. Both the legends and the fonts remained unchanged between the two phases. There were only two luminance levels in Phase III, and they were created using the results of Phase II. The data from Phase II suggested that there was not a statistically significant difference between a constant luminance level set at 30 cd/m^2 (referred to as the medium flat profile in Phase II) or a constant luminance level set 80 cd/m^2 (referred to as the high flat profile in Phase II). Therefore, luminance levels of 30 cd/m^2 were set as the maximum in Phase III. It was also decided to introduce a new flat luminance profile that was in between the "minimum flat" at 3 cd/m^2 and the medium flat at 30 cd/m^2 from Phase II in the hopes to better establish a lower limit with respect to luminance.

For Phase III, the luminance of the warning sign was driven to levels of 6 cd/m^2 and 10 cd/m^2. For the regulatory sign, the luminance levels were measured at 10 and 27 cd/m^2. The other 14 signs for the closed course used retroreflective sheeting, and there were three different sign conditions represented within the additional 14 signs. All of the signs were negative contrast signs (black legend on a lighter colored background) tested under rural-closed course conditions. Two groups consisted of warning signs and regulatory signs viewed under low beam headlight illumination, and the other group consisted of regulatory signs viewed under high beam headlight illumination.

The signs tested under the low beam headlight illumination utilized three different types of retroreflective sheetings. These signs differed slightly in their design from their internally illuminated counterpart in that the words "TEST SIGN" were included in the text. Figure 46 depicts the differences between the internally illuminated and the retroreflective test signs. The internally illuminated warning signs contained two test words centered in a diamond sign versus the single test word placed on a plaque beneath a yellow diamond for the retroreflective signs. The regulatory signs followed a similar format except all of the legend was kept to one sign.

The different format for the retroreflective signs was so that these signs would match their open-road course counterparts. It was believed that the open-road signs needed some way of guaranteeing that the driving public did not misinterpret their content to pertain to the driving task. To minimize the likelihood that the words "TEST SIGN" would negatively impact the legibility distances associated with the test word: 1) the TEST SIGN legend had a 9-inch legend height versus a 7-inch legend height for the test word; 2) the TEST SIGN legend was written in all capital letters; and 3) the study participants were shown examples of the all the possible test signs that could be seen during the course of the study. The difference in the legend height theoretically provided a viewing buffer of approximately 80 ft prior to seeing the test word, assuming a 40 ft/in LI. No test words were included in the examples. Highway C font was used on the warning signs, but Highway D font was used for the regulatory signs. The three different sheeting types tested were engineering grade, high-intensity beaded, and high-intensity prismatic.



a.) Internally Illuminated Warning	b.) Retroreflective Warning	c.) Internally Illuminated Warning	d.) Retroreflective Regulatory	e.) Retroreflective Regulatory (Hi-Beam)

Figure 46. Closed-Course Signs.

The signs tested under the high beam headlight illumination consisted of black legend on white high-intensity beaded or high-intensity prismatic retroreflective sheetings. These signs were designed to represent speed limit signs, but the numbers were replaced with alpha-numeric combinations to make the task a legibility task rather than a recognition task. The alpha-numeric combinations had a 10-inch legend height.

Open-Road Course

The 11 signs for the open-road course were set throughout the length of the open-road course, and they were designed to blend into the natural driving environment while allowing for ease of replacement. The need for ease of replacement came from the need to replace sign faces between study participants. There were three different sign faces for each sign location, so there were a total of 33 different sign faces.

The 11 different sign locations and the specific signs for the open-road course were selected to investigate a broad range of sign types and driving environments with respect to how drivers use them. The 11 sign types and the roadway environment that they were placed in are listed in Table 33 below. Negative contrast and positive contrast signs were both selected for this phase. The negative contrast signs were previously depicted in Figure 46b and d. The positive contrast signs are shown in Figure 47. As in Phase II, there was black on yellow warning signs, black on white regulatory signs, and white on green guide signs. Also included in Phase III was a black on white guide sign for providing route destination and distances (see Figure 46d).

Table 33. Open-Road Signs.

Roadway Environment	Black 7-inch Legend on White	Black 8-inch Legend on Yellow	White Legend on Green	
			Guide Sign (8-inch Legend)	Street Name Sign (6-inch Legend)
Rural	3	2	2	1
Urban	0	1	1	1
Total	3	3	3	1

The two green and white signs in Figure 47 are a destination and a street name guide signs, respectively from top to bottom. The destination guide sign differs from a standard guide sign in that the text, “TEST SIGN,” is at the top, and that the numeral representing the distance was two inches shorter than the destination name. This was done to provide the test participant with two separate legibility tasks buffered by approximately 80 ft, assuming a 40 ft/in LI. The street name signs differed from their real-world counterparts in that the retroreflective sheeting was different and the words were not written in all capital letters.

a) Destination | b) Street Name

Figure 47. Open-Road Course Phase III Test Guide Signs.

While the street name signs could be completely replaced, the destination signs could not. The destination signs were 8.5-ft wide by 5.5-ft tall, so it would be extremely difficult to change out the entire sign face each day. Hence, the researchers only replaced the test words by covering the original words with a separate rectangular sign plaque. For instance, a separate sign plaque with the words "Long Bend 4" could be placed over the words "East Park 2." The background legend for the original signs and the additional sign plaques consisted of high-intensity beaded sheeting, and then, only the test word sheeting differed between the different sign plaques.

Data Reduction

The data reduction technique was slightly different from Phase I and II because the study design was slightly modified. One of the main changes was that the larger course format that included both closed- and open-road testing required the use of global positioning system (GPS) data to locate signs and legibility glance distances. Previously in Phase I and II, the researchers were able to set consistent reset points to utilize data collected with a distance measuring instrument. The Phase III course was over 40 miles in length with over 30 miles on the open road with study participants interacting with the rural and urban traffic.

Another key difference is that the researchers decided to only reduce the eye-tracker data for the legibility glance and up to eight glances prior to the legibility glance. This was decided because the data reduction for Phase II only yielded 2 instances out of 620 where a study participant glanced at a sign more than 8 times prior to the legibility glance.

Analysis

A total of 23 drivers participated in Phase III, 14 drivers aged 18 to 54 with an average age of 39 years. There were 9 drivers aged 55 and older with an average age of 67 years. The researchers completed analyses using legibility as the dependent variable. They also completed a separate set of analyses using the eye-tracker data. The following sections describe the analyses that were performed.

Legibility Data

Descriptive statistics such as the average and standard deviation are shown in Table 34 and Figure 48 through Figure 51.

Table 34. Descriptive Legibility Statistics (ft).

Scenario				Legibility Distance Mean	Legibility Distance Stdev.	Legibility Index Mean	Legibility Index Stdev.
Riverside	Internally Illuminated	Warning	Low	209	72	30	10
			High	238	109	34	16
		Regulatory	Low	174	66	25	9
			High	212	71	30	10
	Reflective	Warning	Low	210	103	30	15
			Medium	253	116	36	17
			High	248	94	35	13
		Regulatory	Low	194	90	28	13
			Medium	182	88	26	13
			High	225	92	32	13
Open Road	Rural	Warning	Low	178	84	25	12
			Medium	187	105	27	15
			High	199	84	28	12
		Regulatory	Low	144	68	21	10
			Medium	143	73	20	10
			High	177	82	25	12
		Guide	Low	224	93	28	12
			Medium	263	116	33	15
			High	283	107	35	13
		Street Name	Low	101	66	17	11
			Medium	132	66	22	11
			High	129	63	21	11
	Urban	Warning	Low	173	96	26	14
			Medium	236	38	34	5
			High	186	65	27	9
		Guide	Low	296	136	37	17
			Medium	238	106	30	13
			High	269	113	34	14
		Street Name	Low	154	70	26	12
			Medium	155	78	26	13
			High	166	63	28	10

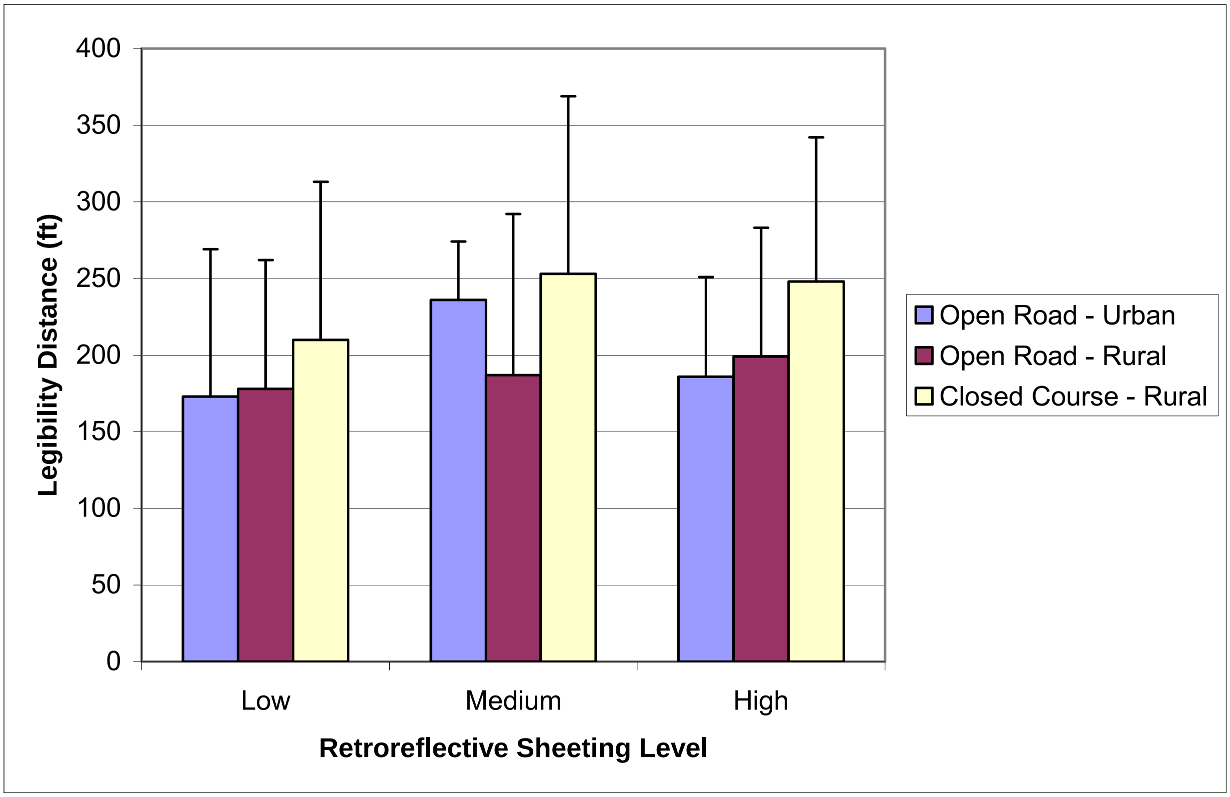


Figure 48. Warning Sign Legibility Results.

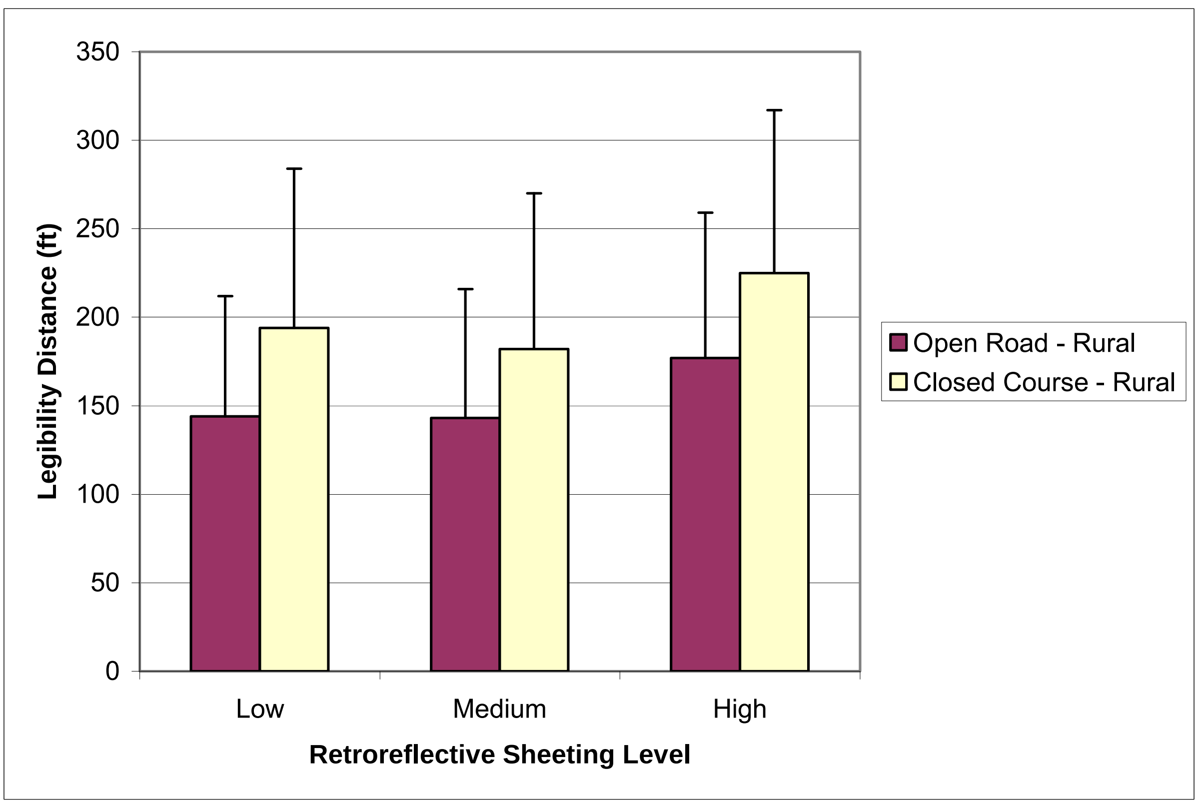


Figure 49. Regulatory Sign Results.

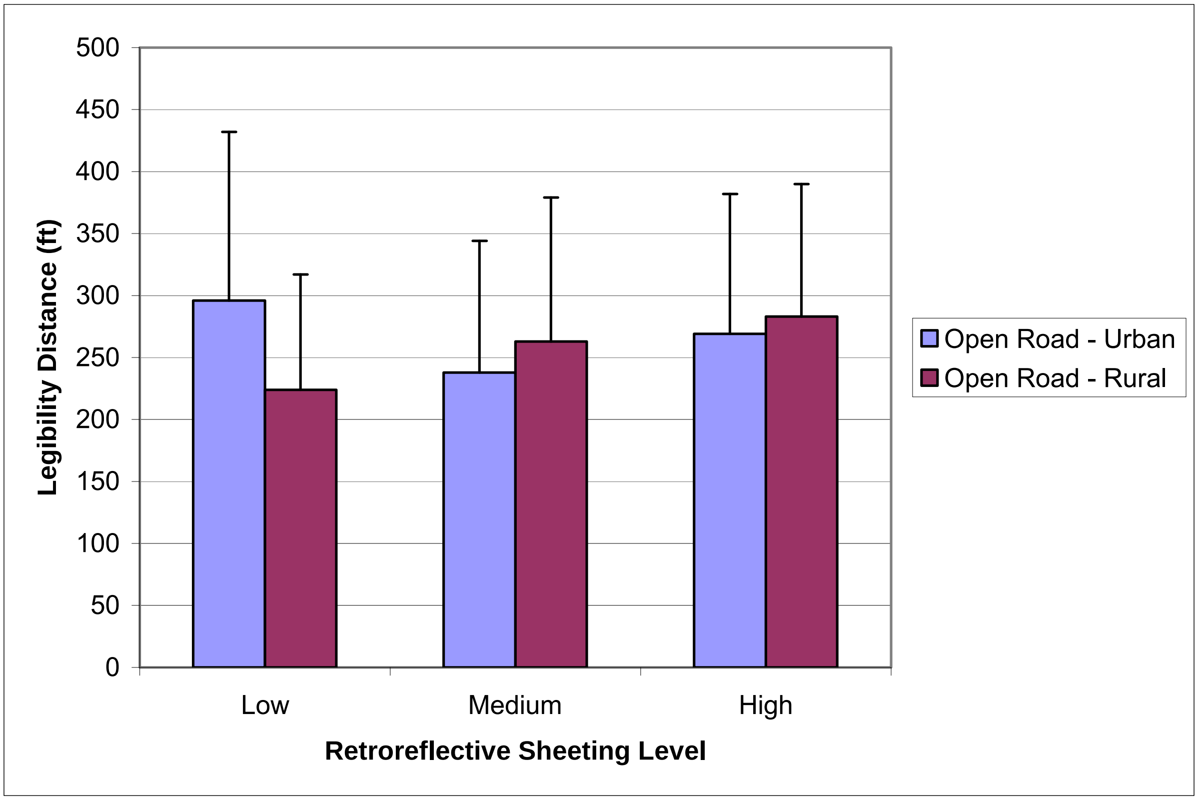


Figure 50. Guide Sign Results.

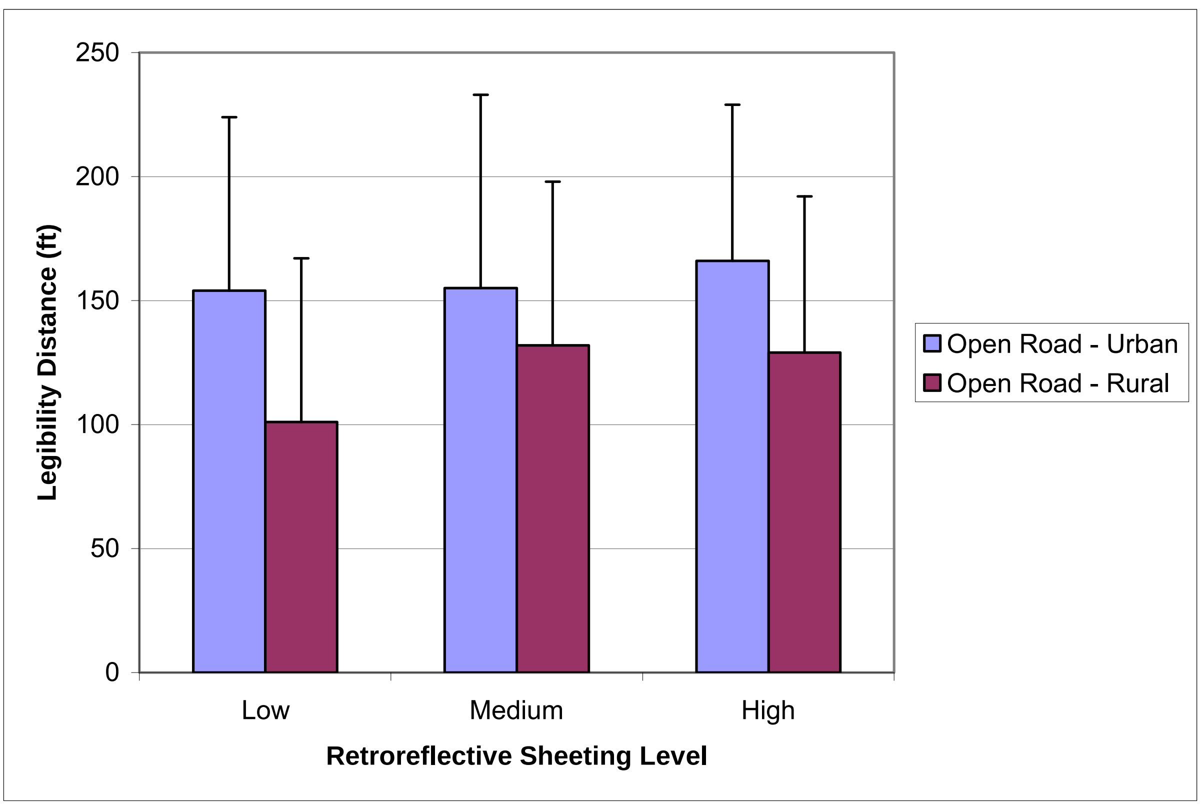


Figure 51. Street Name Sign Results.

The descriptive statistics show some of the same general findings as seen in the pilot efforts described in Phase I. More specifically, legibility results appear longer under the closed-course testing conditions than the open-road testing conditions, even the rural-open road testing conditions. During open-road testing, there appears to be little difference in the legibility of the signs as a function of the level of retroreflective sheeting. Finally, the differences between urban and rural legibility results were dependent on sign type.

In order to account for the differences between sign types, the statistical analyses were conducted separately by each sign type. For each sign type, the data were analyzed utilizing the split-plot design with subject (driver) as a whole-plot and each treatment combination as a split-plot. Table 35 shows the levels of factors/variables for each sign type.

Table 35. Levels of Factors/Variables for Each Sign Type.

Sign Type	Warning	Regulatory	Guide	Street Name
Reflective Level	Low, Medium, High	Low, Medium, High	Low, Medium, High	Low, Medium, High
Age	Old, Young	Old, Young	Old, Young	Old, Young
Reflectivity Type	II (Low or High, Closed, Rural), RS	II (Low or High), RS	RS	RS
Course Type	Closed (Rural), Open (RS)	Closed (Rural), Open (RS)	Open	Open
Course Setting	Rural, Urban (Open)	Rural	Rural, Urban	Rural, Urban
Letter Height	7	7, 10	8	6
Headlight Beam Type	Low	Low (7), High (10, RS, Closed, Low or Medium)	Low	Low

Note: A(B) represents that level A exists only for level B (of another factor).

The statistical analyses for the Phase III legibility data that are included in the report are listed below.

1. Evaluation of three retroreflective levels of warning signs, regulatory signs, guide signs, and street name signs tested on the closed course and open course (in rural and urban conditions).

2. Evaluation of luminance profiles from the internally illuminated warning signs and regulatory signs tested on the closed course.
3. Evaluation of two retroreflective levels of regulatory speed limit signs tested on the closed course under high beam illumination.

Additional analyses were performed but not reported in the body of the report. For additional details, see Report 0-5235-1 Volume 2.

Evaluation of Retroreflective Levels for Warning Signs. For Reflectivity Type RS (Reflective Sheeting), there are two levels for each of Course Type and Course Setting (Course Type = Closed, Course Setting = Urban). To get a better understanding of the effects of Course Type and Course Setting as well as their joint effect on legibility distance, factors 'Course Type' and 'Course Setting' are combined into a new factor 'Course' with three levels (Closed-Rural, Open-Rural, Open-Urban) for Reflective Sheeting Warning signs. A split-plot model with Age, Reflective Level, and Course as main effects, and Age*Reflective Level and Course*Reflective Level as two-way interactions, and Driver nested within Age as a random effect is used as an initial model. Table 36 contains the results under the initial model, which shows that Reflective Level, Course, and Age are significant at $\alpha=0.05$ (see Fixed Effect Tests table). It can be observed from the Effect Details table that a higher reflective level, closed course, and/or Young age group correspond to longer legibility distance. Figure 52 contains the plots of least squares means, which illustrates the effects of each factor. Note that the interaction plots (Figures 52d and e) are for informational purposes only (interactions were not statistically significant).

Table 36. JMP Output for the Initial Model for Reflective Sheeting Warning Signs.

Response Legibility Distance (ft) Reflectivity Type=RS
Summary of Fit

RSquare	0.777223
RSquare Adj	0.75697
Root Mean Square Error	52.24978
Mean of Response	215.2654
Observations (or Sum Wgts)	133

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	2	2	100.2	3.4159	0.0367
Course	2	2	99.85	12.8530	<.0001
Age	1	1	20.49	7.1768	0.0142
Reflective Level*Course	4	4	102.4	1.0283	0.3964
Age*Reflective Level	2	2	99.93	1.0907	0.3399

Effect Details

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	178.35461	17.755516
Medium	202.52642	17.821863
High	210.04256	17.782204

Course
Least Squares Means Table

Level	Least Sq Mean	Std Error
Closed-Rural	226.62970	16.653618
Open-Rural	176.76648	17.345381
Open-Urban	187.52741	19.060651

Age
Least Squares Means Table

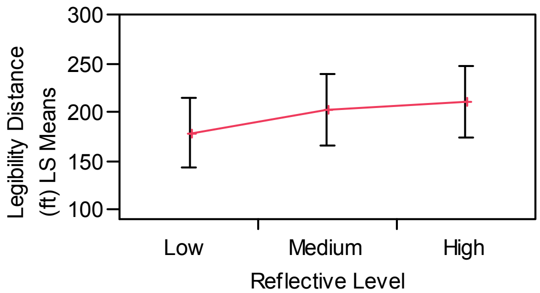
Level	Least Sq Mean	Std Error
Old	153.96643	25.093399
Young	239.98262	20.241365

Reflective Level*Course
Least Squares Means Table

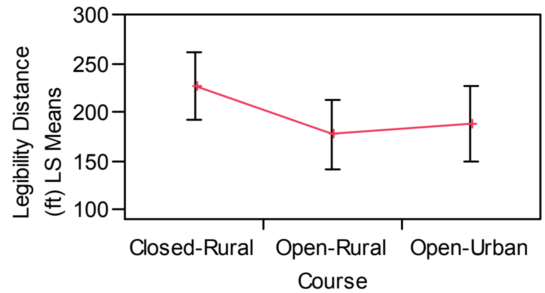
Level	Least Sq Mean	Std Error
Low, Closed-Rural	208.75494	18.900326
Low, Open-Rural	169.05650	20.806286
Low, Open-Urban	157.25237	26.123883
Medium, Closed-Rural	230.84389	19.497096
Medium, Open-Rural	193.43780	21.095366
Medium, Open-Urban	183.29756	25.389502
High, Closed-Rural	240.29026	18.888694
High, Open-Rural	167.80513	21.253938
High, Open-Urban	222.03229	26.082801

Age*Reflective Level
Least Squares Means Table

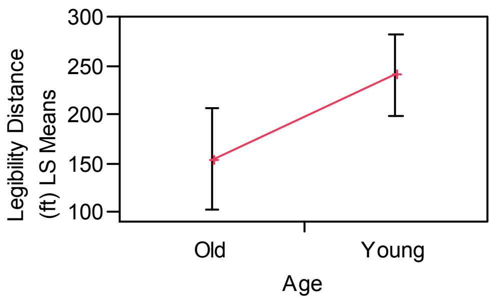
Level	Least Sq Mean	Std Error
Old, Low	133.90253	27.013726
Old, Medium	151.66036	27.906935
Old, High	176.33640	27.073468
Young, Low	222.80668	22.307561
Young, Medium	253.39247	21.815570
Young, High	243.74871	22.403431



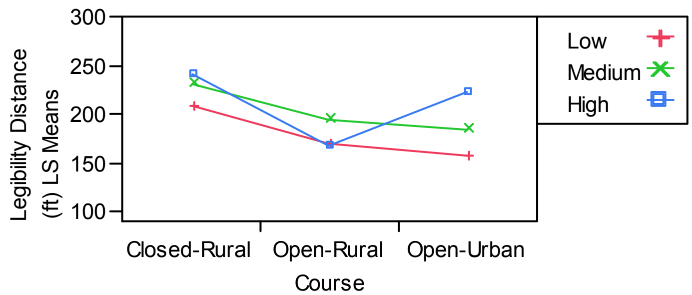
(a) LS Means Plot for Reflective Level



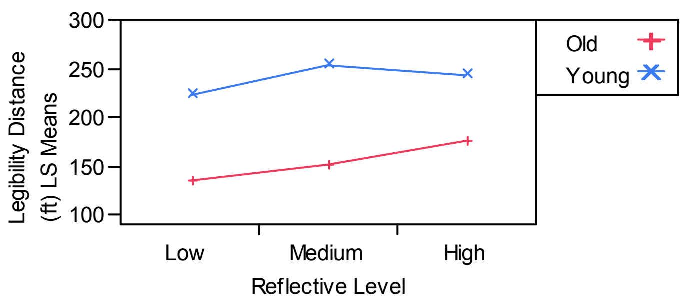
(b) LS Means Plot for Course



(c) LS Means Plot for Age



(d) LS Means Plot for Reflective Level*Course



(e) LS Means Plot for Age*Reflective Level

Figure 52. Least Squares Means Plots of Factor Effects for Reflective Sheeting Warning Signs.

Table 37 contains the reduced model with Reflective Level, Course, and Age (which were statistically significant at α=0.05 in the initial model) as main effects and Drivers (nested within Age) as random effects, which leads to basically the same conclusions on the effects of Reflective Level, Course, and Age as above. Multiple comparison tests (Fisher's Protected LSD) indicate that for Reflective Level, High and Medium are significantly different from Low although High and Medium are not significantly different. For Course, Closed-Rural is significantly different from Open-Rural and Open-Urban although Open-Rural and Open-Urban are not significantly different.

Table 37. JMP Output for the Reduced Model for Reflective Sheeting Warning Signs.

Response Legibility Distance (ft) Reflectivity Type=RS

Summary of Fit

RSquare	0.760281
RSquare Adj	0.750843
Root Mean Square Error	52.65369
Mean of Response	215.2654
Observations (or Sum Wgts)	133

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	2	2	106	3.3861	0.0375
Course	2	2	105.9	13.1292	<.0001
Age	1	1	20.52	7.1767	0.0142

Effect Details

Reflective Level

Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	180.74256	17.051621
Medium	206.91272	17.062720
High	205.48860	17.058360

Course

Least Squares Means Table

Level	Least Sq Mean	Std Error
Closed-Rural	227.42789	16.231528
Open-Rural	176.55043	16.966591
Open-Urban	189.16557	18.693632

Age

Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	155.90032	24.410465
Young	239.52894	19.700164

The key findings from this work are that the high and medium retroreflective levels provided statistically longer legibility distances than low retroreflective level, but there was not practical or significant difference between high and medium. The closed-course testing provided significantly longer legibility than the open-course testing. The young participants had significantly longer legibility distances than the older participants.

Evaluation of Retroreflective Levels for Regulatory Signs. For Reflectivity Type RS, there are two levels for Course Type and three levels for Reflective Level. A split-plot model with Age, Reflective Level, and Course Type as main effects, Age*Reflective Level and Course Type*Reflective Level as two-way interactions, and Driver nested within Age as a random effect is used as an initial model. Table 38 contains the results under the initial model, which shows that Reflective Level, Course Type, and Age are statistically significant (see Fixed Effect Tests table). It can be observed from the Effect Details table that High reflective level, Closed-course type, and/or Young age correspond to longer legibility distance.

Table 38. JMP Output for the Initial Model for Reflective Sheeting Regulatory Signs.

Response Legibility Distance (ft) Reflectivity Type=RS
Summary of Fit

RSquare	0.765772
RSquare Adj	0.750286
Root Mean Square Error	46.99962
Mean of Response	177.78
Observations (or Sum Wgts)	130

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	2	2	99.74	6.2584	0.0028
Course Type	1	1	100.3	31.1791	<.0001
Age	1	1	20.57	4.3183	0.0504
Course Type*Reflective Level	2	2	99.86	0.2181	0.8044
Age*Reflective Level	2	2	99.76	1.0973	0.3378

Effect Details
Analysis ID[Age]

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	160.22450	15.597883
Medium	158.27378	15.626930
High	191.25972	15.764667

Course Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Closed	193.30804	15.034800
Open	146.53063	15.127167

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	139.80636	22.565109
Young	200.03231	18.181824

Course Type*Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Closed, Low	187.12958	17.041099
Closed, Medium	181.34947	17.172540
Closed, High	211.44507	17.252387
Open, Low	133.31942	17.177897
Open, Medium	135.19809	17.179205
Open, High	171.07438	17.659201

Age*Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old, Low	126.55208	24.290479
Old, Medium	136.91325	24.290479
Old, High	155.95376	24.469566
Young, Low	193.89693	19.574179
Young, Medium	179.63431	19.666632
Young, High	226.56568	19.921188

Table 39 contains the reduced model with Reflective Level, Course Type, and Age as main effects and Drivers (nested within Age) as random effects, which leads to basically the same conclusions on the effects of Reflective Level, Course Type, and Age as above.

Table 39. JMP Output for the Reduced Model for Reflective Sheeting Regulatory Signs.

Response Legibility Distance (ft) Reflectivity Type=RS
Summary of Fit

RSquare	0.759947
RSquare Adj	0.752265
Root Mean Square Error	46.67855
Mean of Response	177.78
Observations (or Sum Wgts)	130

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	2	2	103.8	7.0411	0.0014
Course Type	1	1	104.3	32.7597	<.0001
Age	1	1	20.56	4.2565	0.0520

Effect Details
Analysis ID[Age]

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	161.04702	15.536355
Medium	156.72537	15.572574
High	191.89908	15.706098

Course Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Closed	193.63378	15.021122
Open	146.14719	15.108651

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	140.01070	22.557525
Young	199.77028	18.170004

Table 40 contains the Tukey's multiple comparison test results, suggesting that for Reflective Level, High is significantly different from Low and Medium, while Low and Medium are not significantly different.

Table 40. Tukey's Multiple Comparison Test for Reflective Level for Reflective Sheeting Regulatory Signs.

Level			Least Sq Mean
High	A		191.89908
Low		B	161.04702
Medium		B	156.72537

Levels not connected by same letter are significantly different.

The key findings from this effort on regulatory signs shows that the high retroreflectivity levels provided statistically longer legibility distances than low and medium retroreflective levels, and there was no practical or significant difference between low and medium. Again, the closed-course testing provided significantly longer legibility than the open-course testing, and the young participants had significantly longer legibility distances than the older participants.

Evaluation of Retroreflective Levels for Guide Signs. A split-plot model with Age, Reflective Level, and Course Setting as main effects, Age*Reflective Level and Course Setting *Reflective Level as two-way interactions, and Driver nested within Age as a random effect is employed for guide signs. Table 41 contains the results of running the model by JMP. It can be observed from the Fixed Effect Tests table that the effect of Course Setting *Reflective Level is significant at α=0.05, and the effect of Age*Reflective Level is significant at α=0.1.

Table 41. JMP Output for the Model for Guide Signs.

Response Legibility Distance (ft)
Summary of Fit

RSquare	0.901249
RSquare Adj	0.886343
Root Mean Square Error	45.06829
Mean of Response	260.059
Observations (or Sum Wgts)	62

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	20.03	8.3228	0.0091
Reflective Level	2	2	34.38	1.3617	0.2697
Course Setting	1	1	32.98	1.4839	0.2318
Age*Reflective Level	2	2	33.67	3.2714	0.0503
Course Setting*Reflective Level	2	2	39.52	5.7090	0.0066

Effect Details
Analysis ID[Age]

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	188.59086	30.304170
Young	301.88137	24.954696

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	235.25082	22.064835
Medium	239.44966	21.197345
High	261.00786	22.011683

Course Setting
Least Squares Means Table

Level	Least Sq Mean	Std Error
Rural	237.75478	20.045620
Urban	252.71744	21.062463

Age*Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old, Low	167.47999	34.326215
Old, Medium	204.99990	32.309224
Old, High	193.29269	34.221725
Young, Low	303.02164	27.036752
Young, Medium	273.89942	27.859677
Young, High	328.72304	27.034888

Course Setting*Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Rural, Low	193.38629	23.398269
Rural, Medium	268.92484	23.625073
Rural, High	250.95322	23.414677
Urban, Low	277.11534	28.262683
Urban, Medium	209.97448	26.843192
Urban, High	271.06251	28.098771

Figure 53 contains the Age*Reflective Level interaction plot, which shows that the effect of Reflective Level on legibility distance is somewhat different for different Age groups. Table 42 presents the Fisher's Protected LSD multiple comparison test results.

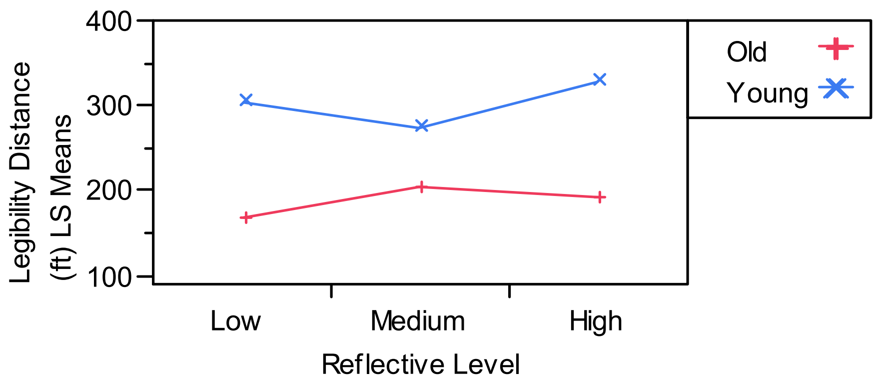


Figure 53. Interaction Plot of Age*Reflective Level for Guide Signs.

Table 42. Multiple Comparison Test (Fisher's Protected LSD) for Age*Reflective Level.

Level					Least Sq Mean
Young, High	A				328.72304
Young, Low	A	B			303.02164
Young, Medium		B	C		273.89942
Old, Medium			C	D	204.99990
Old, High			C	D	193.29269
Old, Low				D	167.47999

Levels not connected by same letter are significantly different.

Figure 54 contains the Course Setting*Reflective Level interaction plot, which shows that the effect of Reflective Level on legibility distance is different for Rural and Urban. Table 43 presents the Fisher's Protected LSD multiple comparison test results. It can be concluded that for Rural Course Setting, Medium and High Reflective Level lead to longer legibility distances than Low Reflective Level while there is no significant difference between Medium and High. Also, Low Reflective Level seems to work better under the urban-course setting than under the rural-course setting.

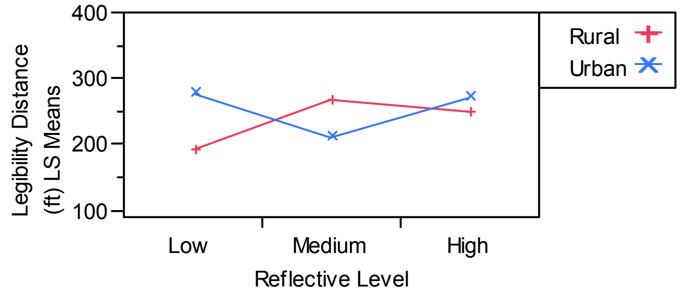


Figure 54. Interaction Plot of Course Setting*Reflective Level for Guide Signs.

Table 43. Multiple Comparison Test (Fisher's Protected LSD) for Course Setting*Reflective Level.

Level				Least Sq Mean
Urban, Low	A			277.11534
Urban, High	A	B		271.06251
Rural, Medium	A			268.92484
Rural, High	A	B		250.95322
Urban, Medium		B	C	209.97448
Rural, Low			C	193.38629

Levels not connected by same letter are significantly different.

The key findings from work on guide signs shows that retroreflective level by itself is not statistically significant although it is significant when considering the interaction with the course setting (open-road testing in rural versus urban conditions in this case). The implication, however, is difficult to determine. There seems to be more difference between the urban and rural settings (as measured using legibility) when the retroreflective level is low compared to when it is high. There were no retroreflective guide signs installed on the closed course so a direct comparison between closed course and open course could not be made with the guide signs. As in the cases of the warning signs and regulatory signs, the young participants had significantly longer legibility distances than the older participants.

Evaluation of Retroreflective Levels for Street Name Signs. Like the guide sign experiment, there were no retroreflective street name signs installed on the closed course so a direct comparison between closed course and open course could not be made with the guide signs. A split-plot model with Age, Reflective Level, and Course Setting as main effects, and Age*Reflective Level and Course Setting *Reflective Level as two-way interactions, and Driver nested within Age as a random effect is employed for street name signs. Table 44 contains the final results without the statistically insignificant two-way interactions. For street name signs, it appears that signs can be seen better (i.e., have longer legibility distance) under Urban setting than under Rural setting. Also, Reflective Level does not seem to matter.

Table 44. JMP Output for the Reduced Model for Street Name Signs.

Response Legibility Distance (ft)
Summary of Fit

RSquare	0.705517
RSquare Adj	0.685552
Root Mean Square Error	44.99042
Mean of Response	144.476
Observations (or Sum Wgts)	64

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	19.91	7.3154	0.0137
Reflective Level	2	2	39.29	0.6777	0.5136
Course Setting	1	1	39.09	9.8135	0.0033

Effect Details

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	102.79730	16.856868
Young	161.73475	14.047083

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	123.77400	13.407187
Medium	133.33002	13.911187
High	139.69406	13.686420

Course Setting
Least Squares Means Table

Level	Least Sq Mean	Std Error
Rural	113.44124	13.425691
Urban	151.09081	11.663161

The key findings from work on street name signs shows that retroreflective level was not statistically significant. There were no retroreflective street name signs installed on the closed course, so a direct comparison between closed course and open course could not be made with the guide signs. As in the cases of the warning signs, regulatory signs, and the guide signs, the young participants had significantly longer legibility distances than the older participants.

An interesting finding here is that the aggregated street name signs in the urban environment had statistically longer legibility distances than those in the rural environment (this finding was repeated with the guide signs although not at a statistically significant level). It could be that the added sign and ambient luminance in the urban condition (supplemented with the fixed roadway lighting and roadside development) contributed to this finding by first providing more sign luminance but also by providing more ambient luminance thereby allowing the nighttime driver's eyes to perhaps be more accommodated near the photopic side of the mesopic visual response function.

Evaluation of Warning Sign Luminance Profiles. A split-plot model with Age and Reflective Level as main effects, Age*Reflective Level as a two-way interaction, and Driver nested within Age as a random effect is used as an initial model for internally illuminated warning signs. Table 45 contains the final model obtained by JMP. It can be observed from the Fixed Effect Tests table that the effect of Reflective Level is significant at α=0.05.

Table 45. JMP Output for the Reduced Model for Internally Illuminated Warning Signs.

Response Legibility Distance (ft) Reflectivity Type=II
Summary of Fit

RSquare	0.909942
RSquare Adj	0.907798
Root Mean Square Error	38.57236
Mean of Response	223.2039
Observations (or Sum Wgts)	44

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	1	1	20.52	5.3840	0.0307

Effect Details
Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	211.50967	19.251607
High	239.05053	19.251607

The findings here show that the differences between the profiles results in significantly different legibility results. The high luminance profile of 10 cd/m^2 provided statistically longer legibility distances than the lower luminance profile of 6 cd/m^2. The fixed effect variable age was not statistically significant for these sign types (p value = 0.1420). However, there is a substantial difference between the age-related legibility where younger drivers reported nearly 50 ft more of average legibility than the older drivers.

Evaluation of Regulatory Sign Luminance Profiles. A split-plot model with Age and Reflective Level as main effects, Age*Reflective Level as a two-way interaction, and Driver nested within Age as a random effect is used as an initial model for internally illuminated regulatory signs with low headlight beams. Table 46 contains the reduced model results with Reflective Level and Age as main effects and Drivers as random blocks. Effect Details table for Reflective Level shows the least squares means for legibility distance for each level of Reflective Level and Age, suggesting that High reflective level leads to longer legibility distance and young drivers tend to see farther.

Table 46. JMP Output for the Reduced Model for Internally Illuminated Regulatory Signs.

Response Legibility Distance (ft) Reflectivity Type=II
Summary of Fit

RSquare	0.880819
RSquare Adj	0.875275
Root Mean Square Error	32.60583
Mean of Response	192.7907
Observations (or Sum Wgts)	46

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	1	1	22	15.3208	0.0007
Age	1	1	21	3.0809	0.0938

Effect Details

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	168.95142	14.011630
High	206.58598	14.011630

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	164.66768	20.536272
Young	210.86972	16.465649

The findings here show that the differences between the profiles result in significantly different legibility results. The high luminance profile of 27 cd/m^2 provided statistically longer legibility distances than the lower luminance profile of 10 cd/m^2.

Like the internally illuminated warning sign, the fixed effect variable age here was not statistically significant (p value = 0.0938). However, there is a substantial difference between the age-related legibility where younger drivers reported nearly 50 ft more of average legibility than the older drivers. This age-related finding is consistent with the differences identified in the warning sign analyses, too.

Evaluation Using High Beam Illumination. These regulatory signs were tested on the closed course with two levels of retroreflective sheeting. The signs were different from other regulatory signs tested in Phase III. These signs have 10-inch legends resembling speed limit signs. The retroreflective sheeting materials were ASTM Type III-beaded and ASTM Type IV (specifically, 3M's 3930 material). These signs were tested under high beam headlight illumination.

A split-plot model with Age and Reflective Level as main effects, and Age*Reflective Level as a two-way interaction, and Driver nested within Age as a random effect is used as an initial model for reflective sheeting regulatory signs with high headlight beams. It was assumed that sign ordering does not significantly affect the effect of Reflective Level on legibility distance. Table 47 contains the reduced model with Reflective Level and Age as main effects and Drivers (nested within Age) as random effects. It can be observed from the Fixed Effect Tests table that the effect of Reflective Level is significant at α=0.05, and the effect of Age is significant at α=0.1. The Effect Details table for Reflective Level shows the least squares means for legibility distance for each level of Reflective Level and Age, suggesting that Medium reflective level leads to longer legibility distance than Low reflective level and young drivers tend to see farther.

Table 47. JMP Output for the Reduced Model for Reflective Sheeting Regulatory Signs with High Headlight Beams.

Response Legibility Distance (ft)
Summary of Fit

RSquare	0.808555
RSquare Adj	0.806342
Root Mean Square Error	59.85432
Mean of Response	338.0146
Observations (or Sum Wgts)	176

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	1	1	152	11.1031	0.0011
Age	1	1	20.95	2.9756	0.0993

Effect Details

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low	316.89864	24.418711
Medium	346.98942	24.440412

Age
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old	290.52954	37.445603
Young	373.35852	30.058022

The luminance levels provided by these signs were measured at distances associated with the beginning and end of LOOK3 (i.e., at 20 and 40 LI or 200 ft and 400 ft). At 200 ft and under low beam illumination, the average luminance measured was 41 cd/m^2 for the medium retroreflective level and 7 cd/m^2 for the low retroreflective level. Under high beam illumination the average luminance measured was 814 cd/m^2 for the medium retroreflective level and 142 cd/m^2 for the low retroreflective level.

At 400 ft and under low beam illumination, the average luminance measured was 33 cd/m^2 for the medium retroreflective level and 14 cd/m^2 for the low retroreflective level. Under high beam illumination the average luminance measured was 1045 cd/m^2 for the medium retroreflective level and 310 cd/m^2 for the low retroreflective level.

Even under such bright sign luminance levels, remembering that the environment was rural, the legibility distance gained by the medium retroreflective level was statistically longer. Anecdotally, however, the participants of the study commented that these signs seemed too bright.

As with the internally illuminated signs test on the closed course, the fixed effect variable 'age' was not significant at α=0.05. However, the differences in legibility were substantial and worth noting. Overall, younger drivers had 80 ft more of legibility than their older counterparts.

Summary of Legibility Data Results

For the internally illuminated warning signs, the effect of luminance level was statistically significant (at α=0.05) despite the small difference in luminance level (6 versus 10 cd/m^2). This seems to be a critical range of luminance in terms of legibility.

For warning signs made with retroreflective materials, the effects of retroreflective level, course, and participant age were statistically significant (at α=0.05). Longer legibility distances are associated with higher retroreflective levels, closed course (rather than open course), and young drivers. The least squares means (predicted) legibility distances under each retroreflective level were 205 ft (for high), 207 ft (for medium), and 181 ft (for low), respectively. Fisher's Protected LSD multiple comparison tests suggest that there is not a significant difference between the high and medium retroreflective materials used in this study.

For internally illuminated regulatory signs, the effect of luminance level was statistically significant (at α=0.05) with luminance levels of 10 and 27 cd/m^2. This particular finding reinforces the results of Phase II. The least squares means (predicted) legibility distances under the high luminance level was 207 ft versus 169 ft for the legibility under the low luminance level.

For regulatory signs made with retroreflective materials and viewed with low beam headlamp illumination (these signs had 7-inch legends), the effects of retroreflective level and course were statistically significant (at α=0.05). The effect of participant age was marginally significant (p-value = 0.0520). Longer legibility distances were associated with higher retroreflective level, closed-course type, and young drivers. In particular, the high retroreflective level produced a statistically significant higher least squares means (predicted) legibility distance (192 ft) than either of the medium or low retroreflective levels (medium=157 ft and low =161 ft).

For regulatory signs made with retroreflective materials and viewed with low beam headlamp illumination (these signs had 10-inch legends), there was a statistically significant difference between the retroreflective levels and the legibility distances. The bright retroreflective level material had statistically higher least squares means (predicted) legibility distance than the less bright retroreflective level material (347 ft versus 317 ft, or LI=35 ft/in versus 32 ft/in). These are somewhat lower than the mean legibility distances reported in Phase I for similar regulatory signs with retroreflective materials viewed under low beam illumination. In Phase I, the legibility distances for low, medium, and high retroreflective levels were 409, 406, and 368 ft, respectively. Combined, the data from Phase I and Phase III indicate that for regulatory signs in rural conditions, there is a decrease in legibility distance as the overall brightness of the sign is increased from the low level in Phase I to the highest level in Phase III (obtained with the vehicle's headlamps in the high beam position). Figure 55 shows the Phase I and Phase III luminance and legibility results combined.

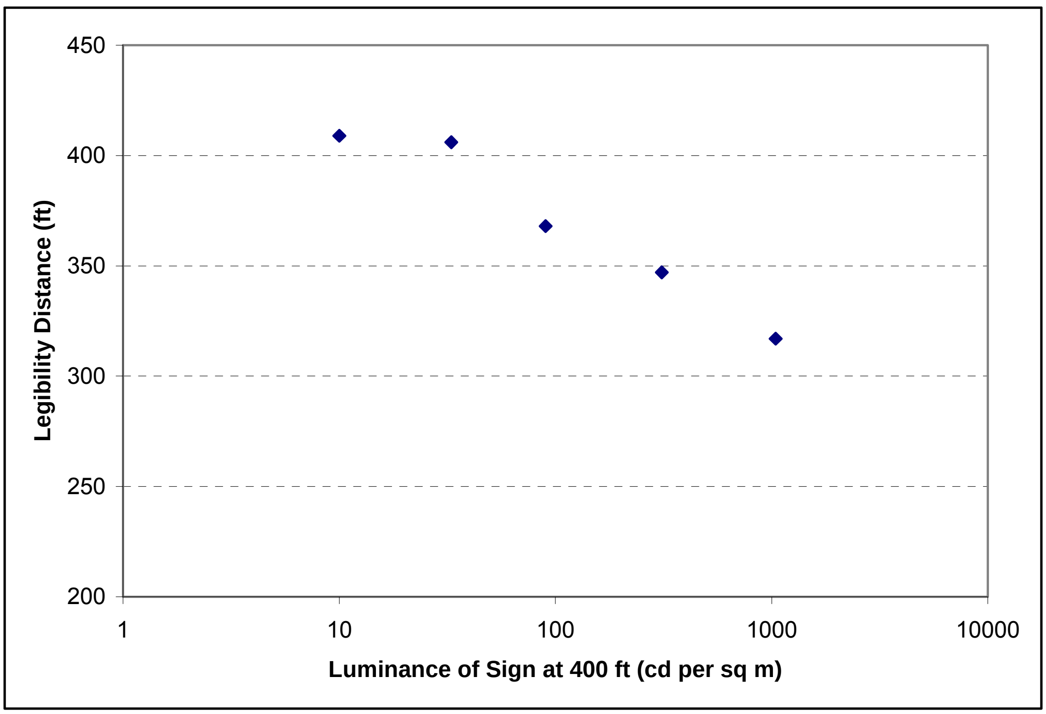


Figure 55. Combined Phase I and III Regulatory Sign Results (Legend = 10 Inch).

For guide signs, the effect of level of retroreflective material seems to be different depending on the course setting. For rural conditions, the medium and high retroreflective levels lead to longer legibility distances than the low retroreflective levels while there is no significant difference between medium and high. Also, the low retroreflective level seemed to work significantly better under the urban course setting (least square means legibility distance: 277 ft) than under the rural course setting (least square means legibility distance: 193 ft).

For street name signs, the effect of level of retroreflective material on legibility distances turned out to be insignificant. The effects of urban versus rural and participant age were significant. The legibility findings suggest that street name signs can be better read under urban setting than under rural setting and also young drivers can see better than old drivers (not a surprising finding). For the low, medium, and high retroreflective level street name signs, aggregated across all other variables, the least squares means (predicted) legibility distances were 123 ft, 133 ft, and 139 ft, respectively (equating to LIs of 20 to 23 ft/in).

Eye-Tracker Data

Descriptive statistics such as the average and standard deviation are shown in Table 48 and Figure 56 through Figure 59.

Table 48. Phase III Eye-Tracker Descriptive Statistics.

Scenario				Number of Glances		Legibility Duration		Total Duration		Average Glance Duration		Average Glance Duration w/o Leg.	
				Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.
Riverside	Internally Illuminated	Warning	Low	8	2	2.1	1.4	7.4	3.2	1	0.4	0.8	0.4
			High	8	3	2.4	2.1	7	3.3	1	0.5	0.7	0.4
		Regulatory	Low	9	1	2.4	1.5	8.7	3.8	1	0.5	0.8	0.4
			High	9	2	1.9	1.9	9	4.7	1	0.5	0.8	0.5
	Reflective	Warning	Low	8	2	1.7	1.3	8.5	5.1	1	0.5	0.9	0.5
			Medium	9	1	2.3	2	8.8	4.8	0.9	0.5	0.8	0.4
			High	9	2	2.3	1.8	8	3.2	0.9	0.4	0.7	0.3
		Regulatory	Low	9	2	2.4	1.9	8.5	4.1	1	0.5	0.8	0.4
			Medium	9	1	2.8	2.2	10.3	4.8	1.2	0.6	0.9	0.6
			High	9	2	3.6	2.3	10.1	4.3	1.3	0.7	0.9	0.5
Open Road	Rural	Warning	Low	7	3	2.9	3	10	7.5	1.5	1.2	1.1	0.8
			Medium	6	3	1.7	1.5	6.5	5.4	1.1	0.7	0.9	0.6
			High	6	4	3	3.3	6.8	3	2.4	3.3	0.6	0.4
		Regulatory	Low	7	3	3.1	2.1	7.5	2.2	1.4	0.9	0.9	0.5
			Medium	6	3	2.5	1.8	6.2	3.1	1.3	1.2	0.7	0.5
			High	6	3	2.9	2.1	7.9	3.4	1.5	0.8	0.9	0.5
		Guide	Low	5	3	2.2	1.7	6.4	4.4	1.8	1.6	0.7	0.6
			Medium	5	3	2.4	1.8	7.8	6.6	1.6	1.4	0.9	0.9
			High	5	2	3.4	1.6	6.4	2.7	1.6	0.7	0.8	0.6
		Street Name	Low	6	2	1.7	0.8	3.8	1.3	0.7	0.2	0.4	0.1
			Medium	6	3	1.9	0.9	5.1	1.1	1	0.4	0.7	0.3
			High	4	2	5	2.5	7.4	1.2	2.9	3.6	0.6	0.4
	Urban	Warning	Low	5	3	3.3	1.7	6.1	1.3	1.7	1.2	1.2	1.7
			Medium	6	2	2.7	1.8	6.4	1.7	1.1	0.2	0.7	0.3
			High	6	2	2	0.9	7.3	2.5	1.2	0.6	1.1	0.7
		Guide	Low	8	2	5.8	2.5	12	1.9	1.8	0.8	1.1	0.7
			Medium	5	3	5	3.2	8.6	3.3	2.4	1.7	0.8	1.3
			High	9	2	2.5	1.5	7.8	4.1	0.8	0.3	0.6	0.3
		Street Name	Low	4	2	2.3	2.4	3.8	2.2	1.3	0.8	0.6	0.5
			Medium	4	2	1.6	1	4	3.6	1.2	1	0.8	1.3
			High	4	2	1.3	0.7	2.7	1.1	0.8	0.4	0.5	0.3

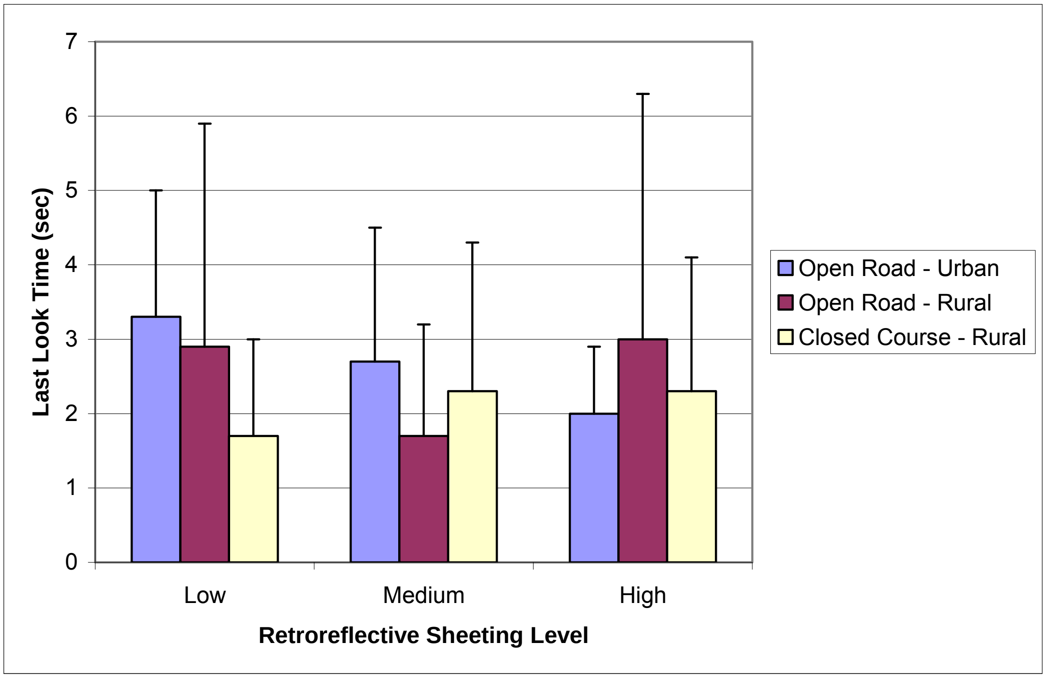


Figure 56. Warning Sign Last Look Duration.

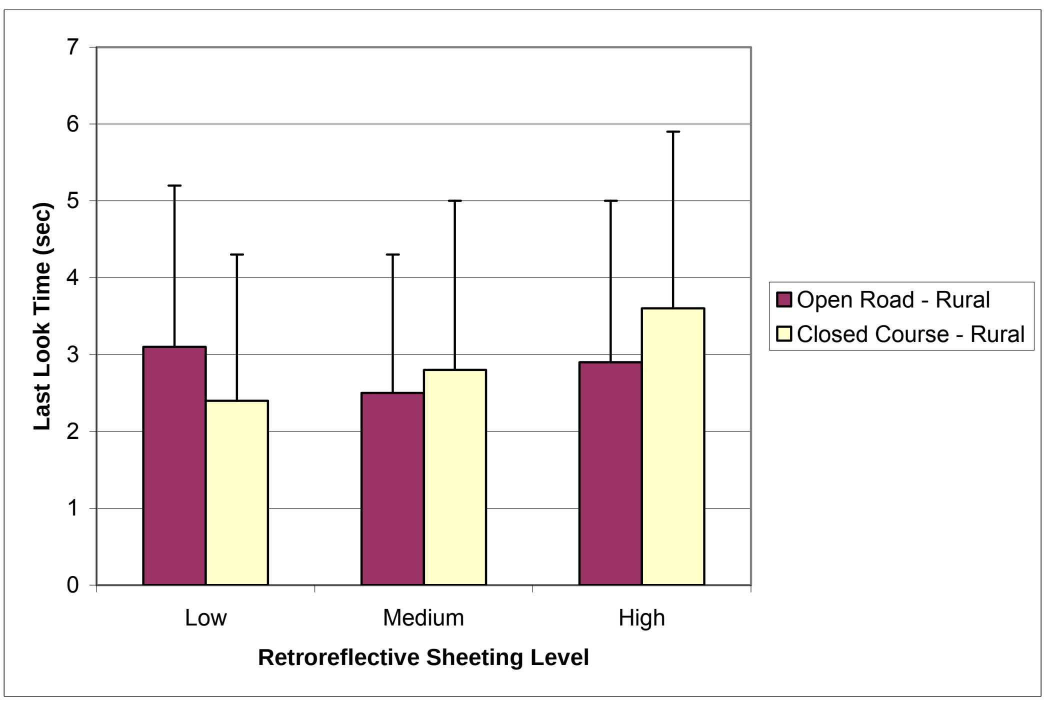


Figure 57. Regulatory Sign Last Look Duration.

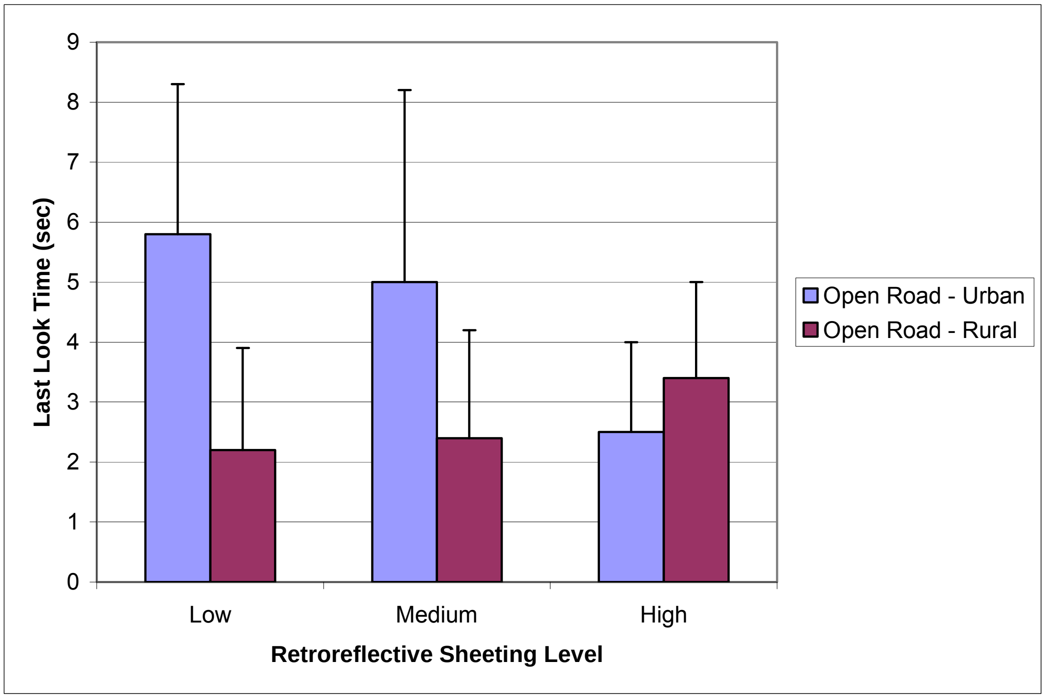


Figure 58. Guide Sign Last Look Duration.

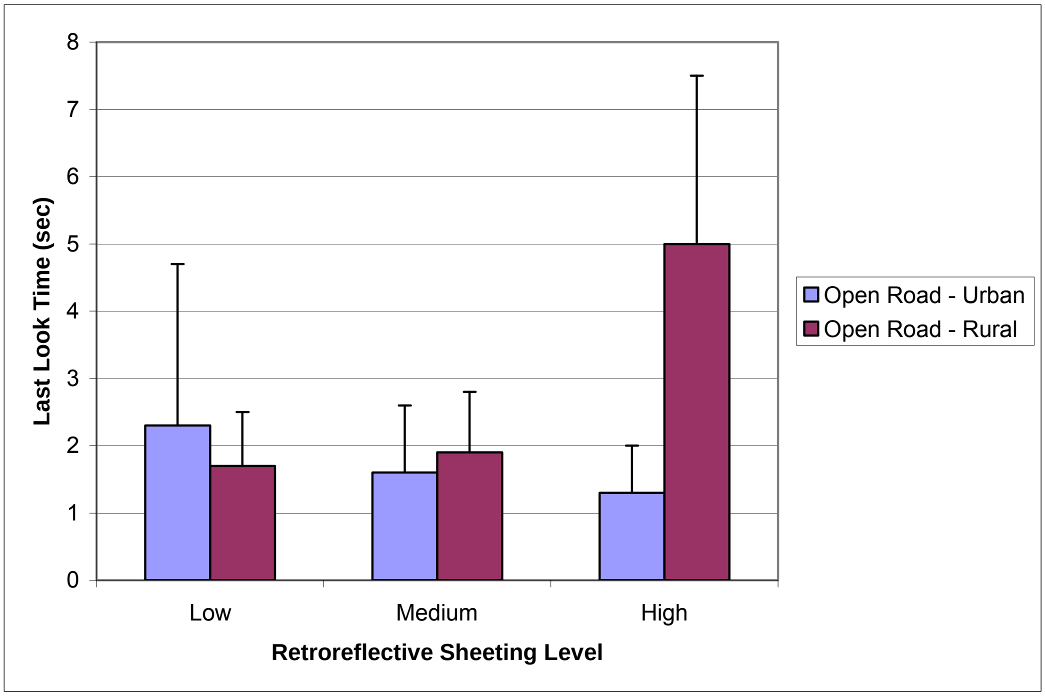


Figure 59. Street Name Sign Last Look Duration.

As noted in both Phase I and Phase II, the last look glance is typically the longest glance as a driver approaches a sign. The last look duration data shown in Figure 56 through Figure 59 indicate that there are no consistent trends associated with the last look glance time and level of brightness of retroreflective sheeting or environment (urban versus rural) or even closed versus open-road testing conditions. Based on these preliminary investigations, the distance associated with the end of the last look glance was compared to the reported legibility distance. Figure 60 shows these results.

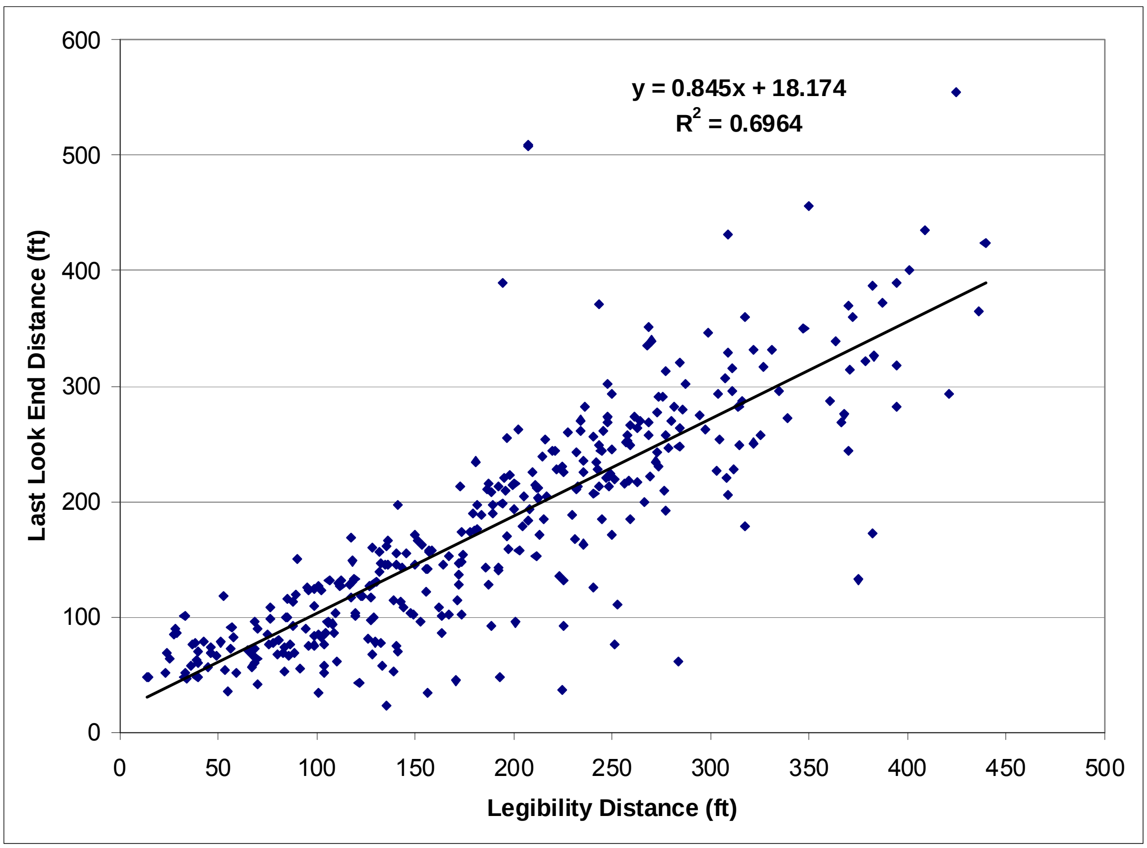


Figure 60. Comparison of Last Look End and Legibility Distances.

Figure 60 was generated to investigate the relationship between the end of the last look (also referred to as the legibility look) and the recorded legibility distance. While all of the conditions are aggregated here, the data show that drivers tended to report the legibility after they completed their legibility look.

As before with the legibility data, the statistical analyses were conducted separately by sign type. The objective of the eye-tracker analyses were to assess the effect of sign reflective levels on the number of glances (within 40 LI), legibility glance duration, total glance duration (within 40 LI), and legibility glance start distance (measured in feet). In addition, the researchers also explored average glance duration without the legibility glance (measured in sec). The details of the eye-tracker analyses are reported in Report 0-5235-1 Volume 2. A summary of the analyses is described below.

For each sign type, the data were analyzed utilizing the split-plot design with participant as a whole-plot and each treatment combination as a split-plot in the cases where there are repeated measures for each driver (to account for correlation among the measurements from the same driver). The variable Age was treated as a whole plot factor while some of the remaining variables mentioned above serve as split-plot factors. In the cases where there was mostly one measurement for each driver, the ordinary ANOVA was employed. For a discrete response variable Number of Glances, both the original Number of Glances and the transformed Number of Glances ($z=(y+3/8)^{1/2}$ where y is the number of glances) were analyzed in case that the underlying analysis assumptions such as normality and a constant variance assumption for errors are violated for the original variable. There were no noticeable differences between two analyses, and only the results based on the original variable are reported here.

The statistical analyses for the Phase III eye-tracker data that are included in the report are listed below.

1. Evaluation of number of glances. This includes the total number of glances up to a maximum of 10 per approach, and the number of glances within the LOOK3 region as defined from an LI of 40 ft/in to and LI of 20 ft/in, depending on the size of the legend on the sign. These analyses were conducted for the retroreflective warning signs, regulatory signs, guide signs, and street name signs tested on the closed course and open course (in rural and urban conditions).
2. Evaluation of last look (or legibility look) duration. These analyses were conducted for the retroreflective warning signs, regulatory signs, guide signs, and street name signs tested on the closed course and open course (in rural and urban conditions).

3. Evaluation of total glance time within LOOK3 as defined from a LI of 40 ft/in to a LI of 20 ft/in. Looks that overlapped these threshold criteria were included in the metric.
4. Evaluation of start of last look (or legibility look) duration.

Additional analyses were performed but not reported in the body of the report. For additional details, Report 0-5235-1 Volume 2 has information on the analyses conducted for total number of looks and the exploratory efforts using transformations of the discrete variables (i.e., number of glances).

Evaluation of Number of Glances for Retroreflective Signs. For the warning signs, there was no statistically significant difference in the total number of glances by retroreflective level (p value = 0.8712). However, there were significantly more glances at the warning signs on the closed course (average of 3.01) versus the open road (2.52 for rural conditions and 2.46 for urban conditions). For number of glances inside the LOOK3 region, there were no significant factors, including course type meaning that the number of glances within the LOOK3 on the closed course was not significantly different than the open course. The retroreflective level was not significant.

Again, for regulatory signs, there was no statistically significant difference in the total number of glances by retroreflective level (p value = 0.9149). As before, there were significantly more glances at the regulatory signs on the closed course (average of 8.87) versus the open road (average 6.07). For number of glances inside the LOOK3 region, course type was significant again. Inside LOOK3, there were statistically significant fewer glances at the regulatory signs on the open course versus the closed course (1.18 versus 1.53, respectively). Again, retroreflective level was not significant.

For the regulatory signs viewed under high beam illumination there were no statistically significant factors associated with number of total looks or total looks within the LOOK3 regions, including retroreflective level with a p value = 0.5978 for total number of looks and p value = 0.2501 for number of looks within LOOK3.

The guide signs were all on the open course but in different environment conditions. For the total number of glances, there was no statistically significant difference in the total number of glances by retroreflective level (p value = 0.6831). However, there were significantly more glances at the guide signs in urban areas (average of 7.17) versus the rural areas (4.93). The number of glances within LOOK3 was not significantly different between the guide signs in the urban versus rural setting. As shown in Table 49, the only term statistically significant was the interaction between age and retroreflective level (p value = 0.0336). The relationship offers little practical value, however, as the legibility look (or last look) for guide signs was rather long (compared to the other sign types) and therefore reduced the variability of glances within LOOK3. All in all though, there is a general trend of fewer looks as the brightness of the sheeting increases.

Table 49. Effect of Reflective Level on Number of Glances for Guide Signs.

Response Number of Glances (within LI=40)
Summary of Fit

RSquare	0.627375
RSquare Adj	0.534218
Root Mean Square Error	0.291528
Mean of Response	1.170732
Observations (or Sum Wgts)	41

PFixed Effect Tests

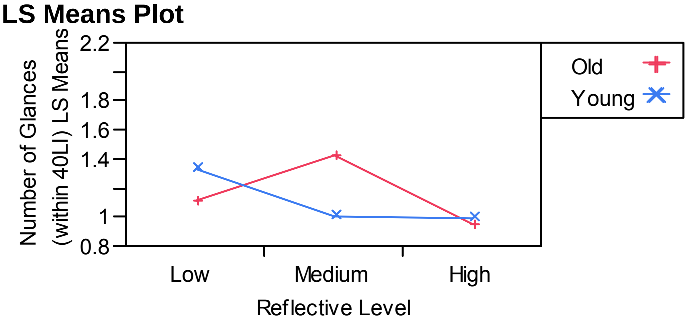
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Course Setting	1	1	20.53	2.6705	0.1175
Reflective Level	2	2	23.1	2.3182	0.1209
Age	1	1	15.18	0.2202	0.6455
Reflective Level*Course Setting	2	2	31.69	1.1836	0.3194
Age*Reflective Level	2	2	21.36	3.9937	0.0336

Effect Details

Age*Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Old, Low	1.1131172	0.14339848
Old, Medium	1.4292966	0.12977844
Old, High	0.9511530	0.13567627
Young, Low	1.3311664	0.13584036
Young, Medium	0.9992382	0.14442969
Young, High	0.9837918	0.14314976

LS Means Plot



LSMeans Differences Student's t
α=0.050

Level			Least Sq Mean
Old, Medium	A		1.4292966
Young, Low	A	B	1.3311664
Old, Low	A	B	1.1131172
Young, Medium		B	0.9992382
Young, High		B	0.9837918
Old, High		B	0.9511530

Levels not connected by same letter are significantly different.

The street name signs were all on the open course but in different environment conditions. For the total number of glances, there was no statistically significant difference by retroreflective level (p value = 0.5886). However, there were significantly more glances at the street name signs in rural areas (average of 5.50) versus the urban areas (3.87). This finding is the opposite of the guide sign finding but perhaps more related to site distance availability. For number of glances inside the LOOK3 region, there were no significant factors, including course type meaning that the number of glances within the LOOK3 in the rural conditions was not significantly different than the urban conditions. The retroreflective level was not significant.

Evaluation of Legibility Look (Last Look) Duration. For the warning signs, a split-plot model with Age, Reflective Level, and Course as main effects, Age*Reflective Level and Course*Reflective Level as two-way interactions, and Driver nested within Age as a random effect was employed. As with number of glances within the LOOK3 regions, none of the main effect or interaction variables were significant at $\alpha=0.05$. The retroreflective level had a p value of 0.8655.

For regulatory signs, a split-plot model with Age, Reflective Level, and Course Type as main effects, Age*Reflective Level and Course Type*Reflective Level as two-way interactions, and Driver nested within Age as a random effect was employed. None of the main effect variables or interactions were significant at $\alpha=0.05$. The retroreflective level had a p value of 0.9451. For regulatory signs viewed under high beam illumination, the retroreflective level was significant as shown in Table 50.

Table 50. Effect of Reflective Level on Leg Glance Duration for Reflective Sheeting Regulatory Signs Tested with High Headlight Beams.

Response Leg Glance Duration
Summary of Fit

RSquare	0.405669
RSquare Adj	0.374928
Root Mean Square Error	1.698265
Mean of Response	2.672581
Observations (or Sum Wgts)	62

Fixed Effect Tests

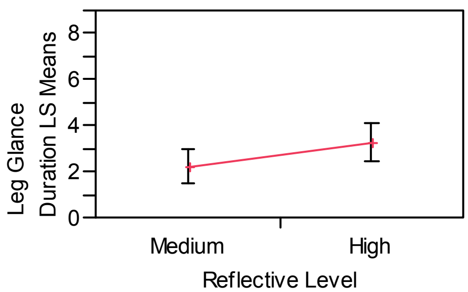
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	16.53	0.3353	0.5704
Reflective Level	1	1	42.37	6.0686	0.0179
Age*Reflective Level	1	1	42.37	0.0563	0.8136

Effect Details

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Medium	2.1897808	0.36324982
High	3.2759330	0.39848536

LS Means Plot



As mentioned before, the luminance levels provided by these signs were measured at distances associated with the beginning and end of LOOK3 (i.e., at 20 and 40 LI or 200 ft and 400 ft). At 200 ft and under low beam illumination, the average luminance measured was 41 cd/m^2 for the high retroreflective level and 7 cd/m^2 for the medium retroreflective level. Under high beam illumination the average luminance measured was 814 cd/m^2 for the high retroreflective level and 142 cd/m^2 for the medium retroreflective level.

At 400 ft and under low beam illumination, the average luminance measured was 33 cd/m^2 for the high retroreflective level and 14 cd/m^2 for the medium retroreflective level. Under high beam illumination the average luminance measured was 1045 cd/m^2 for the high retroreflective level and 310 cd/m^2 for the medium retroreflective level.

Even under such bright sign luminance levels, remembering that the environment was rural, the legibility distance gained by the high retroreflective level was statistically longer. Anecdotally, however, the participants of the study commented that these signs seemed too bright. Even so, the brighter the sign, the longer the legibility look.

For the guide sign, the course setting (urban versus rural) was the only significant variable associated with legibility look duration (see Table 51). For this case, the urban guide sign had significantly longer legibility look times (average of 4.42 seconds) compared to the rural guide sign (with an average of 2.80 seconds).

Table 51. Effect of Reflective Level on Leg Glance Duration for Guide Signs.

Response Leg Glance Duration
Summary of Fit

RSquare	0.818561
RSquare Adj	0.773201
Root Mean Square Error	1.196574
Mean of Response	3.273171
Observations (or Sum Wgts)	41

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Course Setting	1	1	18.4	17.5569	0.0005
Reflective Level	2	2	20.05	0.6274	0.5441
Age	1	1	16.29	1.0345	0.3240
Reflective Level*Course Setting	2	2	27.27	1.3581	0.2740
Age*Reflective Level	2	2	19.19	1.8924	0.1778

For the street name signs, Table 52 shows that there is a significant interaction effect between Reflective Level and Course Setting at α=0.05, which suggests that the effect of Reflective Level of street name signs on Leg Glance Duration is different for Rural and Urban course settings. The Reflective Level*Course Setting interaction plot is also contained in Table 52, which indicates that Leg Glance Duration for high reflective level leads to significantly longer Leg Glance Duration for rural course setting than for urban course setting while the other reflective levels do not make any significance difference in Leg Glance Duration between rural and urban course setting. Table 52 provides the multiple comparison test results.

Table 52. Effect of Reflective Level on Leg Glance Duration for Street Name Signs.

Response Leg Glance Duration
Summary of Fit

RSquare	0.507598
RSquare Adj	0.310637
Root Mean Square Error	0.973437
Mean of Response	1.834483
Observations (or Sum Wgts)	29

Fixed Effect Tests

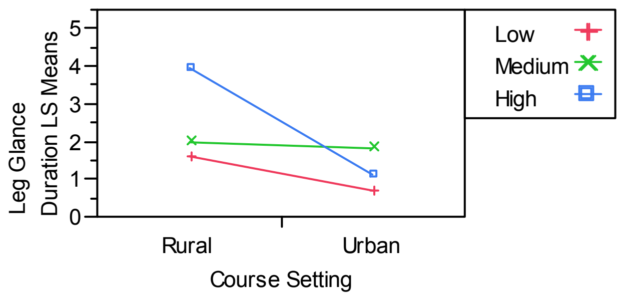
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	11.9	1.7357	0.2125
Reflective Level	2	2	16.97	4.8472	0.0216
Course Setting	1	1	12.5	10.1765	0.0074
Age*Reflective Level	2	2	17.59	0.0917	0.9128
Reflective Level*Course Setting	2	2	17.69	5.0249	0.0187

Effect Details

Reflective Level*Course Setting
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low, Rural	1.5767682	0.37685653
Low, Urban	0.7185678	0.55424118
Medium, Rural	1.9500000	0.46141874
Medium, Urban	1.8141145	0.50394763
High, Rural	3.9513152	0.46838397
High, Urban	1.1344301	0.37277184

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
High, Rural	A		3.9513152
Medium, Rural	A	B	1.9500000
Medium, Urban	A	B	1.8141145
Low, Rural		B	1.5767682
High, Urban		B	1.1344301
Low, Urban		B	0.7185678

Levels not connected by same letter are significantly different.

Evaluation of Total Look Duration within LOOK3. For the warning signs, none of the main effect or two-way interaction variables were significant. For regulatory signs, the two-way interaction between course setting (closed course versus open course) and retroreflectivity was significant, as shown in Table 53. Despite this finding, the results are difficult to interpret as they are not practical in terms of criteria that could be used for specifications.

Table 53. Effect of Reflective Level on Total Glance Duration for Reflective Sheeting Regulatory Signs Tested with Low Headlight Beams.

Response Total Glance Duration Reflectivity Type=RS
Summary of Fit

RSquare	0.474404
RSquare Adj	0.426073
Root Mean Square Error	1.591071
Mean of Response	3.2375
Observations (or Sum Wgts)	96

Fixed Effect Tests

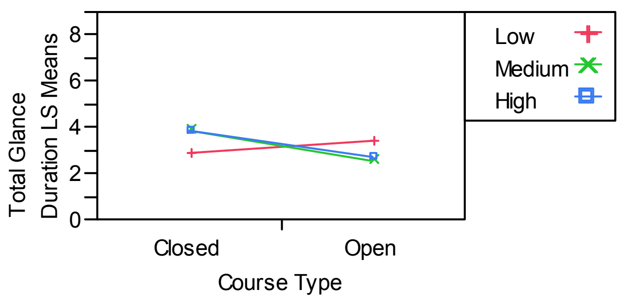
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Reflective Level	2	2	70.71	0.0565	0.9451
Course Type	1	1	73.92	3.2956	0.0735
Age	1	1	17.25	0.1819	0.6750
Reflective Level*Course Type	2	2	69.86	3.3144	0.0422
Age*Reflective Level	2	2	70.93	1.9189	0.1543

Effect Details

Reflective Level*Course Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low, Closed	2.8580795	0.45656828
Low, Open	3.4294726	0.49506649
Medium, Closed	3.8024141	0.47780597
Medium, Open	2.5765979	0.49491206
High, Closed	3.8815299	0.45550397
High, Open	2.6762524	0.50877489

LS Means Plot



LSMeans Differences Student's t

α=0.050

Level				Least Sq Mean
High, Closed	A			3.8815299
Medium, Closed	A	B		3.8024141
Low, Open	A	B	C	3.4294726
Low, Closed	A	B	C	2.8580795
High, Open		B	C	2.6762524
Medium, Open			C	2.5765979

Levels not connected by same letter are significantly different.

For the regulatory sign viewed under high beam illumination, Table 54 shows that there is a significant effect of Reflective Level on Total Glance Duration at α=0.05, which suggests that high Reflective Level leads to longer Total Glance Duration than medium Reflective Level does.

Table 54. Effect of Reflective Level on Total Glance Duration for Reflective Sheeting Regulatory Signs Tested with High Headlight Beams.

Response Total Glance Duration
Summary of Fit

RSquare	0.24682
RSquare Adj	0.207862
Root Mean Square Error	1.802858
Mean of Response	3.304839
Observations (or Sum Wgts)	62

Fixed Effect Tests

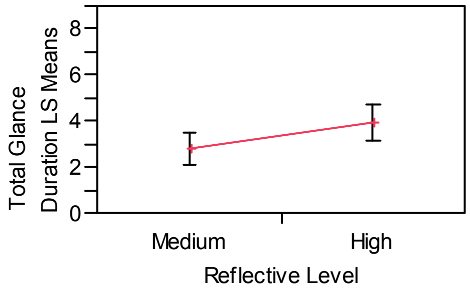
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	14.93	0.4104	0.5315
Reflective Level	1	1	41.76	5.6449	0.0222
Age*Reflective Level	1	1	41.76	0.0224	0.8818

Effect Details

Reflective Level
Least Squares Means Table

Level	Least Sq Mean	Std Error
Medium	2.8047599	0.33735435
High	3.9139110	0.37908950

LS Means Plot



For the guide signs, none of the main effect or two-way interaction variables were significant. For the street name signs, Table 55 shows that there is a significant interaction effect between Reflective Level and Course Setting at α=0.05, which suggests that the effect of Reflective Level of street name signs on Total Glance Duration is different for Rural and Urban course settings. The Reflective Level*Course Setting interaction plot is also contained in Table 55, which indicates that Total Glance Duration for high reflective level leads to significantly longer Total Glance Duration for a rural course setting than for an urban course setting while the other reflective levels do not make any significance difference in Leg Glance Duration between rural and urban course settings. Table 55 provides the multiple comparison test results.

Table 55. Effect of Reflective Level on Total Glance Duration for Street Name Signs.

Response Total Glance Duration
Summary of Fit

RSquare	0.476869
RSquare Adj	0.267617
Root Mean Square Error	0.973132
Mean of Response	2.127586
Observations (or Sum Wgts)	29

Fixed Effect Tests

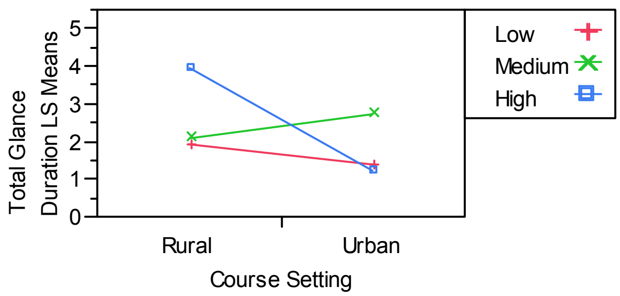
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	11.44	0.9323	0.3542
Reflective Level	2	2	16.83	2.3469	0.1262
Course Setting	1	1	11.89	4.6657	0.0519
Age*Reflective Level	2	2	17.04	0.2410	0.7884
Reflective Level*Course Setting	2	2	17.31	7.1860	0.0053

Effect Details

Reflective Level*Course Setting
Least Squares Means Table

Level	Least Sq Mean	Std Error
Low, Rural	1.9230615	0.38357818
Low, Urban	1.3920506	0.56571187
Medium, Rural	2.0750000	0.46927836
Medium, Urban	2.7258498	0.51447979
High, Rural	3.9658656	0.47762629
High, Urban	1.2522689	0.37931479

LS Means Plot



LSMeans Differences Tukey HSD
α=0.050

Level			Least Sq Mean
High, Rural	A		3.9658656
Medium, Urban	A	B	2.7258498
Medium, Rural	A	B	2.0750000
Low, Rural		B	1.9230615
Low, Urban		B	1.3920506
High, Urban		B	1.2522689

Levels not connected by same letter are significantly different.

Evaluation of Legibility Look Start Distance. For the warning signs, none of the main effect or two-way interaction variables were significant. Similarly, for regulatory signs none of the main effect or two-way interaction variables were significant. However, the start distance of the legibility look of the regulatory signs viewed under high beam illumination was statistically longer (p value = 0.0024) when the high retroreflective level was used (649 ft) compared to the medium retroreflective level (414 ft). For the guide signs, none of the main effect or two-way interaction variables were significant. For street name signs, both the age and course setting were significant, as shown in Table 56.

Table 56. Effect of Reflective Level on Legibility Glance Start Distance for Street Name Signs.

Response Legibility Glance Start Distance (ft)
Summary of Fit

RSquare	0.636918
RSquare Adj	0.491685
Root Mean Square Error	88.09391
Mean of Response	282.3946
Observations (or Sum Wgts)	29

Fixed Effect Tests

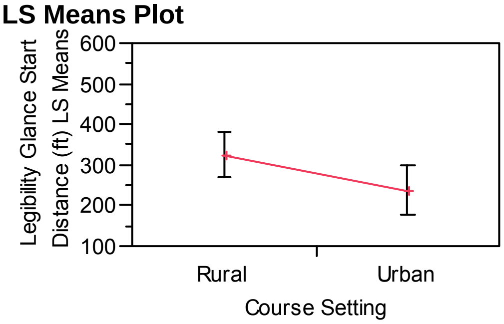
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Age	1	1	10.62	6.1665	0.0311
Reflective Level	2	2	17.51	1.0713	0.3640
Course Setting	1	1	9.922	5.3858	0.0429
Age*Reflective Level	2	2	13.76	0.1068	0.8994
Reflective Level*Course Setting	2	2	15.47	0.2833	0.7571

Effect Details

Course Setting
Least Squares Means Table

Level	Least Sq Mean	Std Error
Rural	324.20205	26.817846
Urban	237.47859	29.465197

LS Means Plot



Results for Low Beam Evaluations

Overall, the retroreflective level of the test signs had little impact on the number of glances. For total number of glances, there were no significant relationships identified as a function of the sign brightness for any of the signs. However, there were more glances on the closed-course environment compared to the open-course setting. This was not surprising as the level of workload is vastly different, and there are many other competing attention sources on the open course that the driver has to scan to be safe. Focusing in more on only the total number of glances within the LOOK3 region, which may be of more importance than all of the approach distance to a sign, the main effect variable of retroreflective level was not significant for any of the signs.

The evaluation of the duration of the last look, or the legibility look, provided slightly more information than the analyses of the number of glances or looks. In this case, the retroreflective level was deemed significant for the street name signs but not the other three sign types. For the street name signs, the main effect variable, course setting (urban versus rural) was also statistically significant as well as the two-way interaction variable between retroreflective level and course setting. The last look duration for the street name signs in the rural setting were longer than in the urban settings for each of the three sign retroreflective levels studied. Furthermore, the rural setting with high retroreflective level (3.95 sec) produced a much longer last look duration than any other retroreflective levels used in the rural setting (medium=1.95 and low=1.58 sec) or any retroreflective levels used in the urban setting (high=1.34, medium=1.81, and low=0.71 sec). The much longer last look duration time for the rural setting with high retroreflective level may be because of the combination of the available sight distance and the expectation of the participants of being able to read the sign earlier than their acuity permits (because of the brightness and their expectations regarding when signs are legibility based on brightness and not necessarily ability to make critical details in order to permit legibility or recognition). The total glance data help support this theory as well since there were statistically more glances in the rural condition than the urban condition (5.50 versus 3.87).

The eye-tracking metric that was based on the total look time within the LOOK3 region produced similar results as the duration of the last look. In other words, only the street name sign has statistical findings but even then they were weaker than the findings described for the duration of the last look.

The final eye-tracking metric that was investigated was the start of the last look or the legibility look. There were no statistically significant findings with respect to retroreflective level for any of the sign types studied.

Results for High Beam Evaluations

For the regulatory signs viewed under high beam illumination, there were no statistically significant relationships associated with the total number of glances or the number of glances within the LOOK3 region. However, the last looks duration had a statistically significant relationship with retroreflective level. In this case, the brighter signs had last look durations over a second longer than the less bright signs (3.27 versus 2.19 seconds). The researchers also noted that many of the subjects commented that these signs were too bright or produced too much glare. However, they were viewed in a rural environment on a closed-course facility. There was ample sight distance approaching these signs, and these conditions need to be considered as the results in an urban open-road setting may be different. The same phenomena described above for the street name sign results associated with the rural setting and high retroreflective level are possibly applicable in this case as well.

The eye-tracking metric for total look time within the LOOK3 region also produced statistically significant results for the retroreflective level. However, the majority of this metric is made up from the one long legibility look described in the previous paragraph. As such, there is substantial redundancy. The results are similar to that described in the immediate previous paragraph.

As expected from the results described so far, the start distance of the legibility look was statistically longer for the brighter retroreflective level (649 ft) compared to the less bright retroreflective level (414 ft). These signs had 10-inch legends meaning that participants started their last look for the brighter retroreflective level at an average distance of 649 ft or an LI of 65 ft/in. Even for the best eyes, this is much beyond a distance that would allow legibility based on the visual angle subtended by the critical detail of the legend on the sign. For the less bright retroreflective level, the last look started at an average of 414 ft or about an LI of 41 ft/in, which is a much more reasonable distance to begin a last look in terms of being able to quickly read the sign based on human visual acuity limits and the visual angle subtended by the critical details of the legend on the sign.

SUMMARY

The results of the legibility data provide additional details to refine the performance-based specification. The smaller ranges of luminance used in the internally illuminated signs proved to be significant in terms of legibility, demonstrating a critical range in luminance that can be used to separate performance in a luminance driven performance-based specification.

The results from of the legibility data, including evaluations conducted with both the low beam and high beam illumination settings, show that there is a point in luminance where performance with respect to legibility decreases. The eye-tracking data provide an explanation of this in that when the sign becomes so bright, drivers begin their last look much before their visual acuity threshold can discern the critical detail of the sign legend. The result is a longer last look duration for the extremely bright signs that begins before visual acuity thresholds and leads to shorter legibility distances. As noted, these results are applicable for rural settings with long sight distances.

The eye-tracker data also showed that the retroreflective levels of the signs used in this study had no statistically significant impact on the number of glances or the number of glances within the LOOK3 region. The only eye-tracking metric that showed any statistical significance to the retroreflective levels was the last look or legibility look duration. This metric was deemed statistically significant for bright signs viewed in rural conditions and with long sight distance—the street name signs with high retroreflective level material on the open rural road and the regulatory signs viewed on the closed-course facility under high beam illumination.

CHAPTER 6:
CONCLUSIONS AND BASIS FOR PROPOSED SPECIFICATION

The thorough analysis of the legibility and eye-tracking data described in the earlier chapters demonstrated a tie between retroreflective sheeting materials and nighttime legibility distance, and to a lesser extent, nighttime eye tracking. While luminance is a direct measure of the brightness of a nighttime sign, it changes throughout the approach to a retroreflective traffic sign. The internally illuminated signs provided the researchers a mechanism to test luminance without being restricted to the luminance profiles provided by specific retroreflective sheeting materials.

Using the results of the data described in the earlier chapters, with additional data published and referenced as noted below, the researchers developed an example of a performance-based specification for retroreflective sheeting materials. The specification is based on nighttime legibility and derived from empirical data applied to common signing situations. The specification is much different than current specifications used in the U.S. but provides a more systematic way for agencies to specify retroreflective sheeting performance that is based on the needs of the nighttime drivers.

Part of a conceptual sign seeing and looking model that has been developed, presented, discussed, and vetted through research and professional society meetings has been used, along with the findings from this study and other studies, as the foundation for the recommendations in this report. Figure 61 shows the overall concept. The eye-tracking data discussed in the earlier chapters of this report demonstrate the usefulness of the LOOK3 region in terms of quantifying nighttime sign performance. In the LOOK3 region, nighttime drivers tend to look and acquire information from traffic signs. The eye-tracking data from this study also demonstrate that LOOK1 and LOOK2 are not as well defined as LOOK3. Furthermore, there appears to be little if any correlation in the looks prior to LOOK3 and nighttime performance. Therefore, one of the fundamental concepts of the proposed specification is the emphasis on the LOOK3 region of sign seeing and looking.

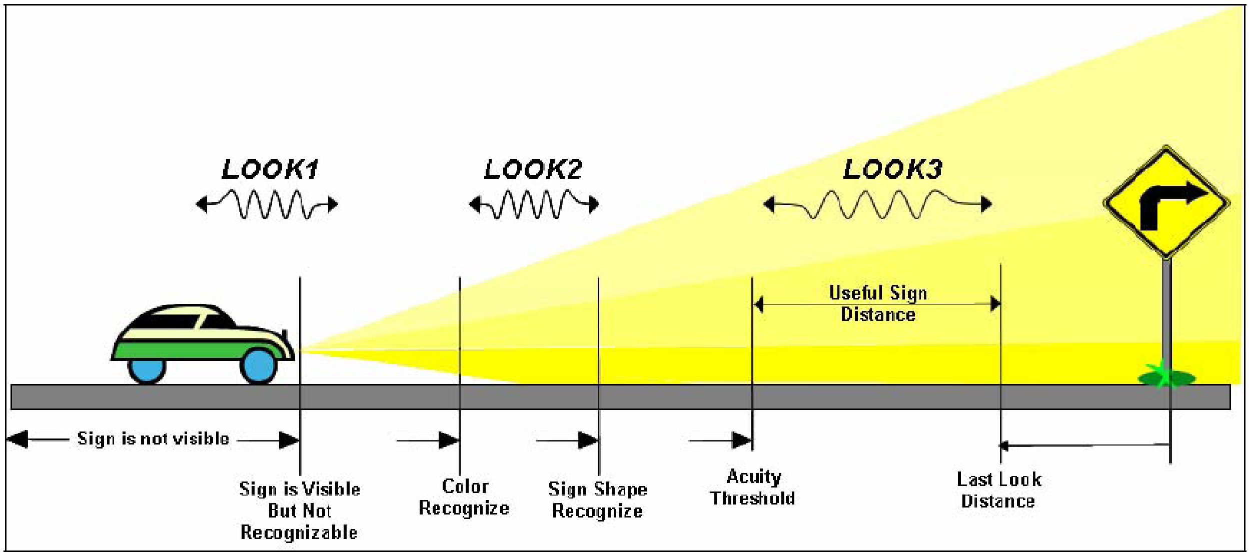


Figure 61. Three Sign Look Concept.

In the landmark research that led to the FHWA minimum retroreflectivity levels in the MUTCD, a set of luminance demand curves were empirically derived for older drivers in rural conditions. The data for the curves represent the luminance needed for legibility (see Table 57).

Table 57. Luminance Demand Levels for Legibility (*14*).

Cumulative percentage of correct responses	Overhead Signs *			Street Name Signs **		
	Legibility Index (ft/in)			Legibility Index (ft/in)		
	20	30	40	20	30	40
10	0.1	0.3	0.8	0.1	0.2	0.8
25	0.1	0.5	1.2	0.3	0.5	1.8
50	0.3	0.9	2.3	0.4	1.0	3.9
75	0.5	1.9	5.7	0.7	1.8	14.1
85	0.8	3.8	11.7	1.0	2.5	20.0
95	1.6	11.7	19.2	1.6	4.7	32.7
98	1.7	16.5	31.5	1.9	5.8	38.0

* For white Series E (Modified), 16/12-inch uppercase/lowercase (16" uppercase and 12" lowercase letters) words on a green background
** For white Series C, 6-inch uppercase words on a green background

In the CIE Technical Committee 4-40 work currently underway, the luminance levels shown in Table 57 were developed into a performance index used to evaluate retroreflective materials applied to traffic signs (*30*). Figure 62 shows how the data are applied and used to establish a performance metric for traffic signs based on luminance needs.

This work uses market-weighted vehicle dimensions, market-weighted headlamp flux patterns, typical roadway cross-sections, and sign legend design as a function of roadway speed to define reference scenarios. The reference scenarios are used in combination with various sign positions in order to calculate the supply luminance of different retroreflective sheeting materials.

The concept is based on dividing the LOOK3 region into five specific points at distances derived from the legend height and based on legibility indices of 40 to 20 ft/in at 5 ft/in intervals. At each testing point, the supply luminance is calculated. Then using the family of luminance demand curves, an interpolated performance metric is computed. This is repeated for the remaining four test locations in the LOOK3 region. Then the average of the five computations is made for a final performance metric. The CIE TC 4-40 has vetted this procedure and adopted it as acceptable and representative (however, it has not been formally approved by CIE).

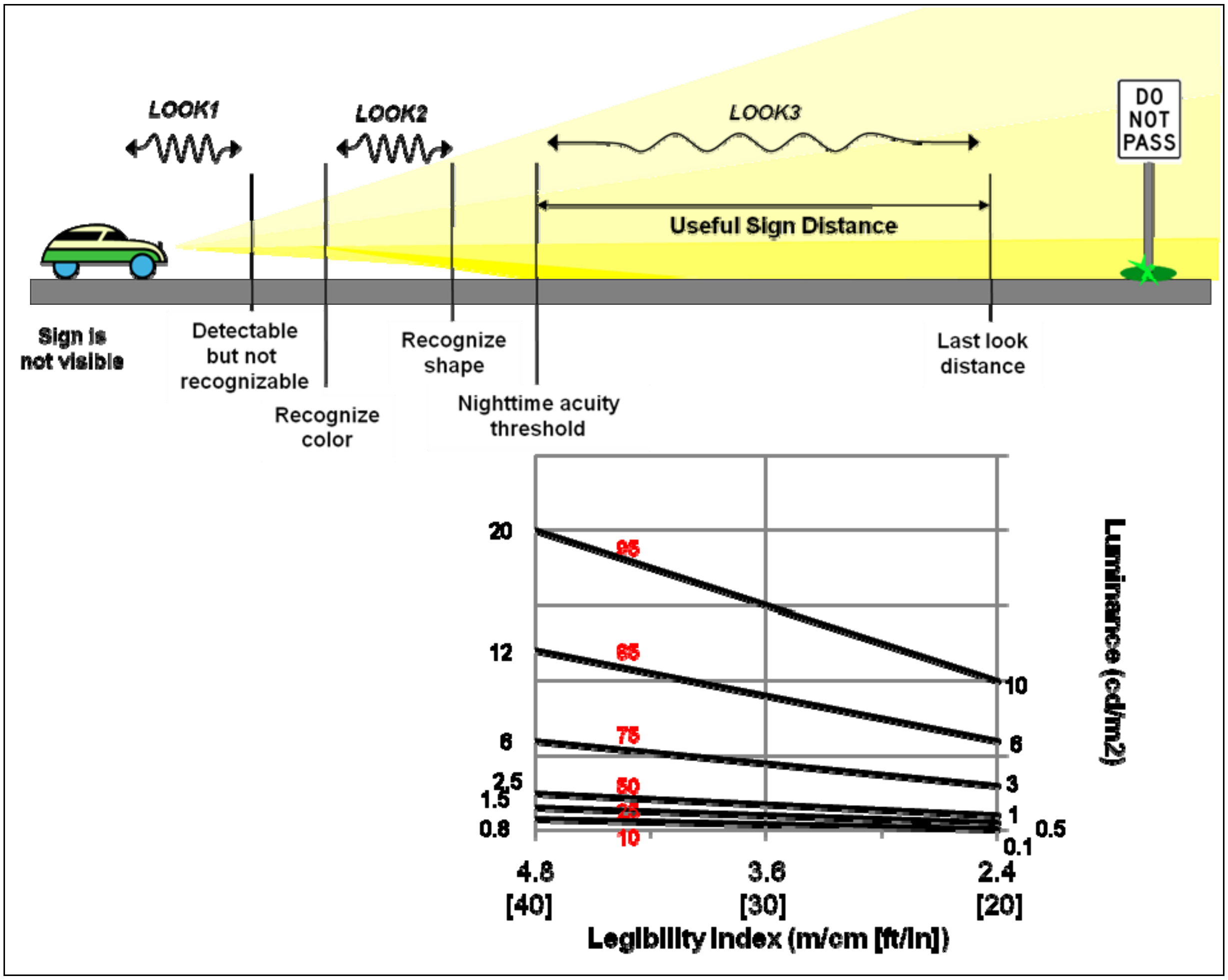


Figure 62. Luminance Required for Passenger Cars (*30*).

The CIE method is unique and a step in the direction of being a performance-based specification but fails to provide the specifier the information needed to make distinctions between performance to set performance levels. By design, the data obtained, analyzed, and reported in this study were aimed to provide information that could be used to make distinctions between sign performance to set nighttime driver based performance levels. Both nighttime legibility data and nighttime eye-tracking data were collected and analyzed to determine the breakpoints in performance. As reported, the eye-tracking data were not as robust and useful as the legibility data, although they did help support and explain some of the findings, thereby providing supplemental and useful data. Based on the legibility results from the internally illuminated signs, the following performance distinctions were found:

- Luminance profiles from Phase II of 30 cd/m^2 and 80 cd/m^2 were grouped as being statistically the same.
- Luminance profiles from Phase II of 1 cd/m^2 and 2.5 cd/m^2 were grouped as being statistically the same.
- Luminance profiles from Phase II of 30 cd/m^2 and 80 cd/m^2 were grouped as being statistically different from luminance profiles of 1 cd/m^2 and 2.5 cd/m^2.
- The luminance profile of peak-early from Phase II was grouped as being statistically different from the peak-late luminance profile.
- The luminance profile from Phase III of 6 cd/m^2 was statistically different than the luminance profile of 10 cd/m^2.
- The luminance profile from Phase III of 10 cd/m^2 was statistically different than the luminance profile of 27 cd/m^2.

With these results, the luminance demand curves in Figure 62 were modified as shown in Figure 63. Specifically, the modifications that make up Figure 63 include the following:

- Four luminance levels were set at a legibility index of 40 ft/in based on the results from the legibility data of the internally illuminated signs.
- Each of the four initial luminance levels are shown to decrease in brightness throughout the LOOK3 region using a square root function, which provides for above-minimum luminance needed throughout the LOOK3 region (based on the data shown in Table 57).
- Labels were added A through D, representing the four basic classes of performance, Class A being the best.

Using the proposed luminance curves in Figure 63, the researchers developed a specification using common roadway scenarios, common vehicles, and the most recently available market-weighted headlamp flux data. The proposed specification requires more data (i.e., measurements) than current sheeting specifications but the results are more representative of the driving geometries.

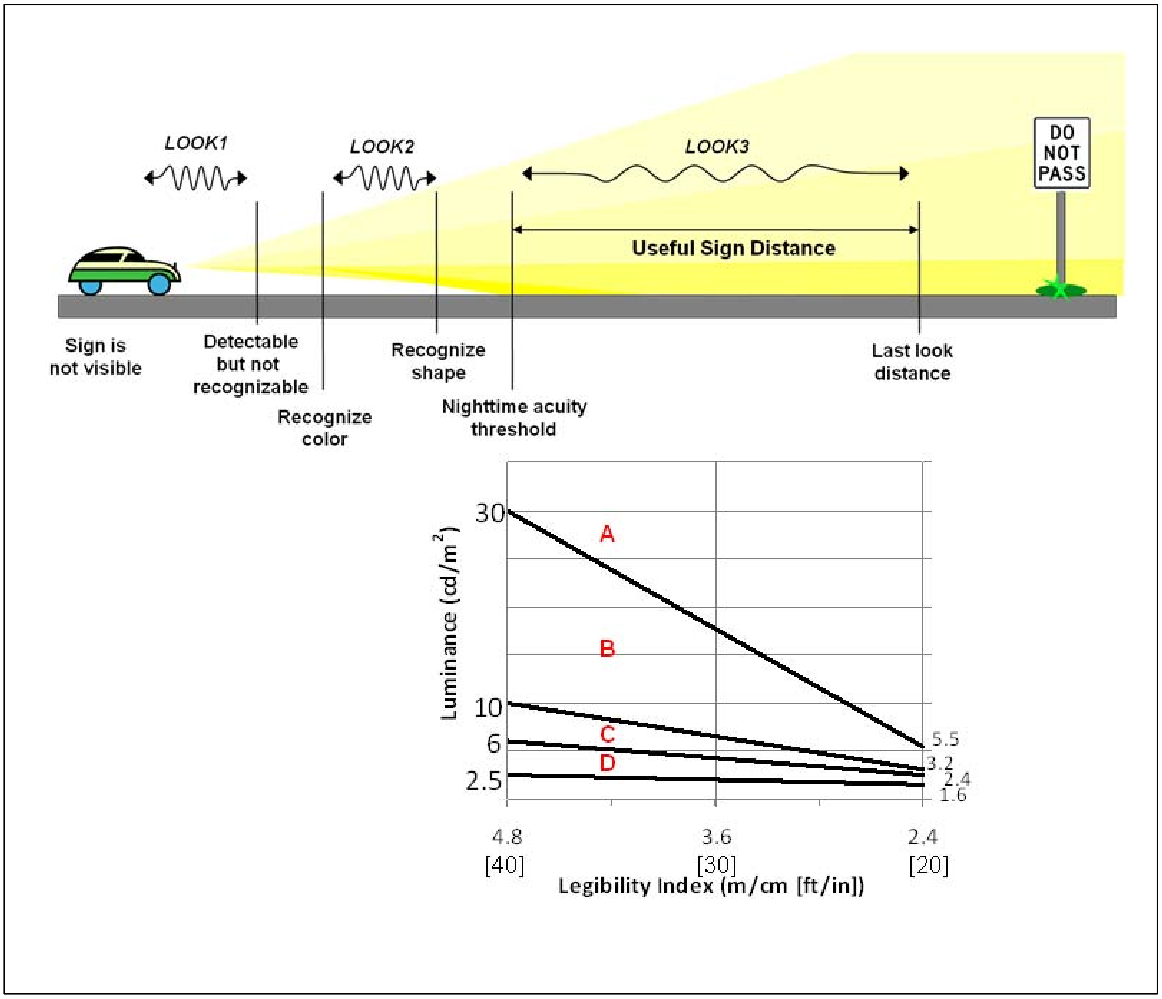


Figure 63. Proposed Luminance Demand Curves.

DEVELOPING THE SPECIFICATION

In order to develop the specification, some important data are needed. A list of the first set of data that are needed is shown below:

- vehicle dimensions,
- sign positions,
- typical roadway types, cross-sections, and speeds, and
- sign legend size as a function of speed.

With this information, it is possible to compute the angles of retroreflection needed for testing. Once the angles are known, and supplemented with market-weighted headlamp flux data, luminance value can be calculated. For the proposed specification, it is recommended that for each material under testing, three luminance values be calculated representing legibility indices of 40, 30, and 20 ft/in. The remainder of this section of the report will describe the recommendations for each set of data, including the supporting references.

Vehicle Dimensions

An important variable in determining the performance of road signs is the vehicle type. Passenger cars tend to provide drivers with smaller observation angles than do larger vehicles (trucks). Table 58 shows the two vehicle types included: a market-weighted U.S.-based large SUV style vehicle and a U.S.-based market-weighted large vehicle (from TxDOT research project 0-4269-1).

Table 58. Vehicle Dimensions.

Vehicle type	Vehicle dimensions (ft)				
	h_1	h_2	s_1	s_2	s_3
Passenger car	2.79	4.83	4.38	0.87	7.2
Large truck	3.58	7.67	6.17	1.33	4.1

h_1: height of headlamps above the road
h_2: height of driver's eyes above road
s_1: distance between headlamps
s_2: transverse distance of eyes from left headlamp
s_3: distance of eyes behind headlamps

Sign Position

Table 58 shows the sign positions used for the specification. These sign positions are meant to cover the majority of the signs but not all the signs. For instance, signs in curves are not directly covered by the conditions described in Table 59. Figure 64 shows the sign positions and Figure 65 shows the assumed sign twist and tilt.

Table 59. Common Sign Positions.

Sign Position		Common applications	Roadway Types	
			Interstate Highways and Divided Highways	Undivided Highways
Right Shoulder	RS	Most common signing position. Most regulatory and warning signs in this position.	X	X
Overhead	OV	Guide signs on freeways, expressways, and other major highways.	X	
Left Shoulder	LS	Supplemental signing on highways.	X	X
Far Right	FR	Guide signs on freeways, expressways, and other major highways.	X	

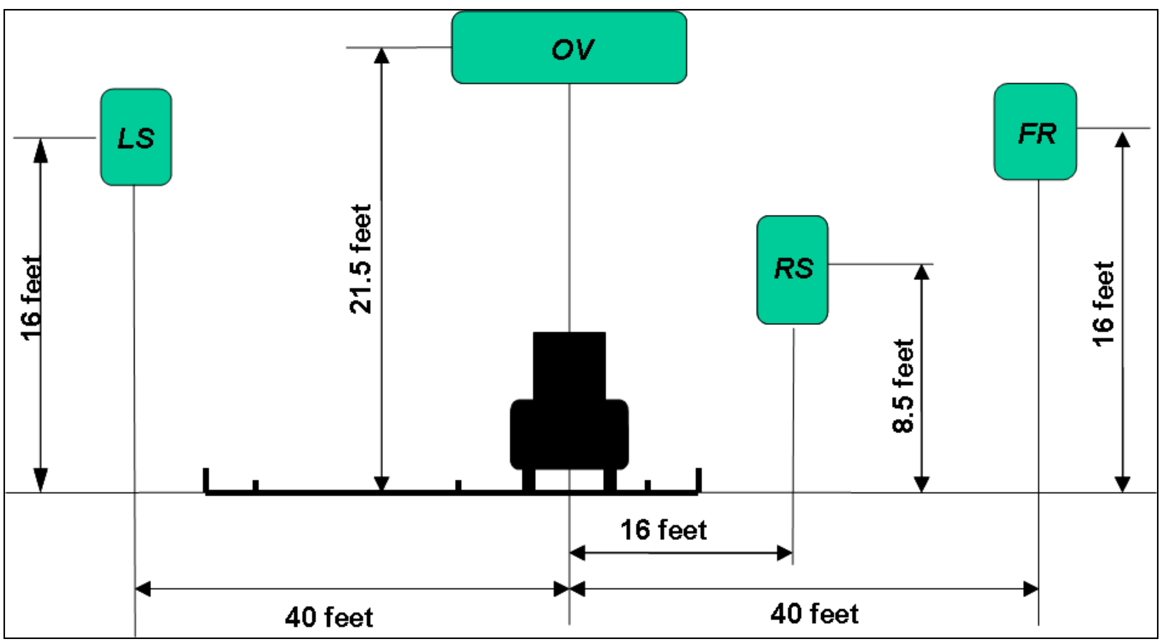


Figure 64. Most Common Sign Positions.

In addition to the sign positions shown above, the following sign twists and tilts were assumed. These are normally suggested to prevent specular glare (and keep the overhead signs clean).

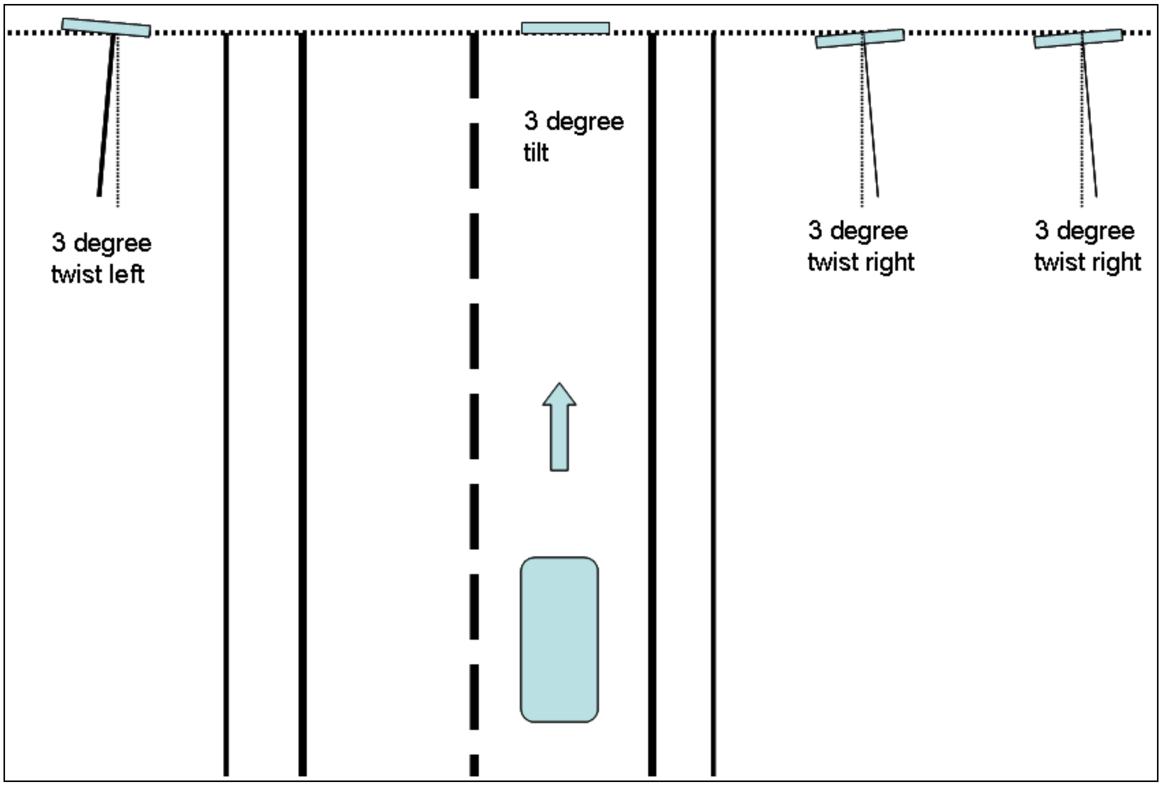


Figure 65. Twist and Tilt of Traffic Signs.

Sign Legend Size

In order to determine the range of interest for evaluation purposes, the technique described herein requires that the letter size (height) to be used on the sign is known. This is usually specified in an agency's traffic engineering documents, standard sheets, policies, or standard practices. It is the responsibility of agency with jurisdiction to select appropriate sign/legend size. For completeness, however, and because this assessment technique depends directly on the letter size, a recommended set of letter sizes were developed.

The letter size in this document is determined by the speed of the roadway and the intended maneuver required by the information portrayed on the sign. Of course, assumptions are typically made related to driver reaction times, deceleration rates, and either stopping or turning maneuvers. Appropriate letter sizes are assumed to be used, in accordance to the MUTCD, speed of the roadway, and action needed by the driver. Table 60 shows assumed conditions where commonalities can be expected.

Table 60. Example of Speeds by Sign Type and Vehicle Type.

Sign Position	Vehicle	Speed (mph)		
		≤ 35	40-55	≥ 60
LS	PC	x	x	x
	HV			x
OV	PC			x
	HV			x
RS	PC	x	x	x
	HV			x
FR	PC			x
	HV			x

There are a total of 14 scenarios that geometries were computed for to determine the testing needed for the specification. Using legends ranging from 8-inch to 16-inch, the geometries can be shown in eight tables (4 sign positions × 2 vehicle types). Table 61 through Table 68 show examples of the complete geometries.

Table 61. Retroreflective Geometries for Passenger Car – Right Side Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.07	42.5	9.7	78	1.07	7.9	5.6	43
200		0.83	40.9	8.4	79	0.83	6.6	5.1	41
240		0.67	39.7	7.5	79	0.67	5.7	4.8	40
280		0.57	38.9	6.8	80	0.57	5.1	4.5	39
320		0.49	38.2	6.3	81	0.49	4.7	4.3	38
360		0.43	37.6	6.0	81	0.43	4.3	4.1	38
400		0.38	37.2	5.7	82	0.38	4.0	4.0	37
440		0.35	36.8	5.4	82	0.35	3.8	3.9	37
480		0.31	36.4	5.2	82	0.31	3.6	3.8	37
520		0.29	36.2	5.0	83	0.29	3.5	3.7	36
560		0.27	35.9	4.9	83	0.27	3.3	3.6	36
600		0.25	35.7	4.8	83	0.25	3.2	3.5	36
640		0.23	35.5	4.7	84	0.23	3.1	3.5	36
720		0.21	35.2	4.5	84	0.21	2.9	3.4	35
800		0.18	35.0	4.3	85	0.18	2.8	3.3	35
880		0.17	34.8	4.2	85	0.17	2.7	3.2	35
960		0.15	34.6	4.1	85	0.15	2.6	3.2	35
1040		0.14	34.4	4.0	85	0.14	2.5	3.1	34
1120		0.13	34.3	3.9	86	0.13	2.5	3.1	34
1200		0.12	34.2	3.9	86	0.12	2.4	3.0	34
1280		0.11	34.1	3.8	86	0.11	2.4	3.0	34
160	Right Headlamp	1.15	-46.1	8.2	75	1.15	-4.3	7.0	-47
200		0.94	-48.3	7.1	77	0.94	-4.1	5.8	-49
240		0.80	-49.6	6.4	78	0.80	-3.9	5.1	-50
280		0.70	-50.6	5.9	79	0.70	-3.8	4.6	-51
320		0.62	-51.3	5.6	79	0.62	-3.6	4.2	-51
360		0.55	-51.8	5.3	80	0.55	-3.5	3.9	-52
400		0.50	-52.3	5.0	81	0.50	-3.4	3.7	-52
440		0.46	-52.6	4.9	81	0.46	-3.4	3.5	-53
480		0.42	-52.9	4.7	82	0.42	-3.3	3.3	-53
520		0.39	-53.1	4.6	82	0.39	-3.2	3.2	-53
560		0.36	-53.3	4.5	82	0.36	-3.2	3.1	-53
600		0.34	-53.5	4.4	83	0.34	-3.2	3.0	-54
640		0.32	-53.7	4.3	83	0.32	-3.1	2.9	-54
720		0.28	-53.9	4.1	84	0.28	-3.0	2.8	-54
800		0.26	-54.1	4.0	84	0.26	-3.0	2.7	-54
880		0.23	-54.3	3.9	85	0.23	-3.0	2.6	-54
960		0.22	-54.4	3.8	85	0.22	-2.9	2.5	-55
1040		0.20	-54.6	3.8	85	0.20	-2.9	2.4	-55
1120		0.19	-54.7	3.7	85	0.19	-2.9	2.4	-55
1200		0.17	-54.7	3.7	86	0.17	-2.8	2.3	-55
1280		0.16	-54.8	3.6	86	0.16	-2.8	2.3	-55

Table 62. Retroreflective Geometries for Heavy Vehicle – Right Side Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.79	35.5	10.2	80	1.79	7.3	7.2	36
200		1.42	34.8	8.8	81	1.42	6.1	6.3	35
240		1.18	34.3	7.8	81	1.18	5.3	5.7	34
280		1.01	33.9	7.1	82	1.01	4.8	5.3	34
320		0.88	33.6	6.6	82	0.88	4.4	5.0	34
360		0.78	33.4	6.2	83	0.78	4.0	4.7	34
400		0.70	33.2	5.9	83	0.70	3.8	4.5	33
440		0.64	33.1	5.6	83	0.64	3.6	4.3	33
480		0.58	32.9	5.4	84	0.58	3.4	4.2	33
520		0.54	32.8	5.2	84	0.54	3.3	4.1	33
560		0.50	32.8	5.1	84	0.50	3.1	4.0	33
600		0.46	32.7	4.9	85	0.46	3.0	3.9	33
640		0.43	32.6	4.8	85	0.43	2.9	3.8	33
720		0.39	32.5	4.6	85	0.39	2.8	3.7	33
800		0.35	32.4	4.4	85	0.35	2.7	3.5	32
880		0.32	32.3	4.3	86	0.32	2.6	3.5	32
960		0.29	32.3	4.2	86	0.29	2.5	3.4	32
1040		0.27	32.2	4.1	86	0.27	2.4	3.3	32
1120		0.25	32.2	4.0	86	0.25	2.4	3.3	32
1200		0.23	32.1	4.0	87	0.23	2.3	3.2	32
1280		0.22	32.1	3.9	87	0.22	2.3	3.2	32
160	Right Headlamp	2.23	-48.9	7.6	77	2.23	-4.4	6.1	-49
200		1.81	-49.5	6.6	78	1.81	-4.0	5.3	-50
240		1.52	-49.9	6.0	79	1.52	-3.8	4.7	-50
280		1.31	-50.1	5.6	80	1.31	-3.6	4.3	-50
320		1.15	-50.3	5.3	80	1.15	-3.4	4.0	-50
360		1.02	-50.5	5.0	81	1.02	-3.3	3.7	-51
400		0.92	-50.6	4.8	82	0.92	-3.2	3.6	-51
440		0.84	-50.7	4.6	82	0.84	-3.1	3.4	-51
480		0.77	-50.8	4.5	82	0.77	-3.1	3.3	-51
520		0.71	-50.9	4.4	83	0.71	-3.0	3.2	-51
560		0.66	-50.9	4.3	83	0.66	-3.0	3.1	-51
600		0.62	-51.0	4.2	84	0.62	-2.9	3.0	-51
640		0.58	-51.0	4.1	84	0.58	-2.9	2.9	-51
720		0.52	-51.1	4.0	84	0.52	-2.8	2.8	-51
800		0.47	-51.1	3.9	85	0.47	-2.8	2.7	-51
880		0.43	-51.2	3.8	85	0.43	-2.8	2.6	-51
960		0.39	-51.2	3.7	85	0.39	-2.7	2.6	-51
1040		0.36	-51.3	3.7	86	0.36	-2.7	2.5	-51
1120		0.33	-51.3	3.6	86	0.33	-2.7	2.5	-51
1200		0.31	-51.3	3.6	86	0.31	-2.6	2.4	-51
1280		0.29	-51.3	3.6	86	0.29	-2.6	2.4	-51

Table 63. Retroreflective Geometries for Passenger Car – Overhead Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.10	26.1	3.8	12	1.10	3.6	-0.9	26
200		0.85	27.1	2.4	15	0.85	2.4	-0.5	27
240		0.69	27.8	1.6	20	0.69	1.5	-0.2	28
280		0.58	28.4	0.9	28	0.58	0.9	0.0	28
320		0.50	28.8	0.5	48	0.50	0.5	0.2	29
360		0.44	29.2	0.3	93	0.44	0.2	0.3	29
400		0.39	29.5	0.4	135	0.39	-0.1	0.4	29
440		0.35	29.7	0.6	153	0.35	-0.3	0.5	30
480		0.32	29.9	0.8	161	0.32	-0.5	0.6	30
520		0.29	30.1	1.0	166	0.29	-0.7	0.7	30
560		0.27	30.3	1.1	168	0.27	-0.8	0.7	30
600		0.25	30.4	1.2	170	0.25	-0.9	0.8	30
640		0.23	30.5	1.3	172	0.23	-1.0	0.8	31
720		0.21	30.7	1.5	173	0.21	-1.2	0.9	31
800		0.19	30.9	1.7	175	0.19	-1.3	1.0	31
880		0.17	31.0	1.8	175	0.17	-1.5	1.0	31
960		0.15	31.2	1.9	176	0.15	-1.5	1.1	31
1040		0.14	31.3	2.0	176	0.14	-1.6	1.1	31
1120		0.13	31.3	2.0	177	0.13	-1.7	1.2	31
1200		0.12	31.4	2.1	177	0.12	-1.7	1.2	31
1280		0.11	31.5	2.2	177	0.11	-1.8	1.2	31
160	Right Headlamp	1.46	-47.5	3.8	-12	1.46	3.1	2.2	-47
200		1.15	-49.0	2.4	-15	1.15	2.0	1.4	-49
240		0.94	-50.0	1.6	-20	0.94	1.3	0.8	-50
280		0.80	-50.7	0.9	-28	0.80	0.9	0.4	-51
320		0.70	-51.3	0.5	-48	0.70	0.5	0.0	-51
360		0.62	-51.8	0.3	-93	0.62	0.3	-0.2	-52
400		0.55	-52.2	0.4	-135	0.55	0.1	-0.4	-52
440		0.50	-52.5	0.6	-153	0.50	-0.1	-0.6	-53
480		0.46	-52.8	0.8	-161	0.46	-0.3	-0.8	-53
520		0.42	-53.0	1.0	-166	0.42	-0.4	-0.9	-53
560		0.39	-53.2	1.1	-168	0.39	-0.5	-1.0	-53
600		0.36	-53.4	1.2	-170	0.36	-0.6	-1.1	-53
640		0.34	-53.5	1.3	-172	0.34	-0.6	-1.2	-54
720		0.30	-53.8	1.5	-173	0.30	-0.8	-1.3	-54
800		0.27	-54.0	1.7	-175	0.27	-0.8	-1.4	-54
880		0.25	-54.2	1.8	-175	0.25	-0.9	-1.5	-54
960		0.22	-54.3	1.9	-176	0.22	-1.0	-1.6	-54
1040		0.21	-54.4	2.0	-176	0.21	-1.0	-1.7	-54
1120		0.19	-54.5	2.0	-177	0.19	-1.1	-1.7	-55
1200		0.18	-54.6	2.1	-177	0.18	-1.1	-1.8	-55
1280		0.17	-54.7	2.2	-177	0.17	-1.2	-1.8	-55

Table 64. Retroreflective Geometries for Heavy Vehicle – Overhead Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.81	29.9	3.7	22	1.81	3.6	-0.5	30
200		1.44	30.2	2.4	27	1.44	2.4	-0.1	30
240		1.19	30.4	1.6	36	1.19	1.6	0.1	30
280		1.02	30.5	1.0	50	1.02	1.0	0.3	31
320		0.89	30.7	0.7	73	0.89	0.5	0.5	31
360		0.78	30.7	0.6	104	0.78	0.2	0.6	31
400		0.70	30.8	0.7	128	0.70	-0.1	0.7	31
440		0.64	30.9	0.8	143	0.64	-0.3	0.8	31
480		0.58	30.9	1.0	152	0.58	-0.5	0.8	31
520		0.54	31.0	1.1	158	0.54	-0.7	0.9	31
560		0.50	31.0	1.2	161	0.50	-0.8	0.9	31
600		0.47	31.0	1.3	164	0.47	-0.9	1.0	31
640		0.44	31.1	1.4	166	0.44	-1.0	1.0	31
720		0.39	31.1	1.6	169	0.39	-1.2	1.1	31
800		0.35	31.2	1.7	171	0.35	-1.3	1.1	31
880		0.32	31.2	1.9	172	0.32	-1.4	1.2	31
960		0.29	31.2	1.9	173	0.29	-1.5	1.2	31
1040		0.27	31.2	2.0	174	0.27	-1.6	1.2	31
1120		0.25	31.3	2.1	175	0.25	-1.7	1.2	31
1200		0.23	31.3	2.2	175	0.23	-1.7	1.3	31
1280		0.22	31.3	2.2	176	0.22	-1.8	1.3	31
160	Right Headlamp	2.41	-49.4	3.7	-22	2.41	3.2	1.7	-49
200		1.92	-49.8	2.4	-27	1.92	2.2	0.9	-50
240		1.60	-50.0	1.6	-36	1.60	1.5	0.4	-50
280		1.37	-50.3	1.0	-50	1.37	1.0	0.0	-50
320		1.20	-50.4	0.7	-73	1.20	0.7	-0.3	-50
360		1.06	-50.5	0.6	-104	1.06	0.4	-0.5	-51
400		0.95	-50.6	0.7	-128	0.95	0.1	-0.7	-51
440		0.87	-50.7	0.8	-143	0.87	0.0	-0.8	-51
480		0.79	-50.8	1.0	-152	0.79	-0.2	-1.0	-51
520		0.73	-50.9	1.1	-158	0.73	-0.3	-1.1	-51
560		0.68	-50.9	1.2	-161	0.68	-0.4	-1.2	-51
600		0.63	-51.0	1.3	-164	0.63	-0.5	-1.2	-51
640		0.59	-51.0	1.4	-166	0.59	-0.6	-1.3	-51
720		0.53	-51.1	1.6	-169	0.53	-0.8	-1.4	-51
800		0.47	-51.1	1.7	-171	0.47	-0.9	-1.5	-51
880		0.43	-51.2	1.9	-172	0.43	-1.0	-1.6	-51
960		0.40	-51.2	1.9	-173	0.40	-1.0	-1.6	-51
1040		0.36	-51.3	2.0	-174	0.36	-1.1	-1.7	-51
1120		0.34	-51.3	2.1	-175	0.34	-1.2	-1.7	-51
1200		0.32	-51.3	2.2	-175	0.32	-1.2	-1.8	-51
1280		0.30	-51.3	2.2	-176	0.30	-1.2	-1.8	-51

Table 65. Retroreflective Geometries for Passenger Car – Left Side Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	0.89	-8.0	16.9	-74	0.89	6.9	-15.5	-8
200		0.69	-0.9	14.2	-75	0.69	3.9	-13.6	-1
240		0.57	4.3	12.3	-75	0.57	2.2	-12.2	4
280		0.48	8.1	11.0	-76	0.48	1.1	-11.0	8
320		0.42	11.1	10.0	-76	0.42	0.4	-10.0	11
360		0.37	13.5	9.2	-77	0.37	-0.1	-9.2	14
400		0.34	15.4	8.6	-77	0.34	-0.4	-8.6	16
440		0.31	17.0	8.1	-78	0.31	-0.7	-8.1	17
480		0.28	18.3	7.7	-78	0.28	-0.9	-7.6	18
520		0.26	19.4	7.3	-78	0.26	-1.0	-7.2	20
560		0.24	20.4	7.0	-79	0.24	-1.1	-6.9	21
600		0.23	21.2	6.7	-79	0.23	-1.2	-6.6	21
640		0.21	21.9	6.5	-79	0.21	-1.3	-6.4	22
720		0.19	23.1	6.1	-80	0.19	-1.4	-5.9	23
800		0.17	24.1	5.8	-81	0.17	-1.5	-5.6	24
880		0.15	24.9	5.5	-81	0.15	-1.5	-5.3	25
960		0.14	25.5	5.3	-81	0.14	-1.6	-5.1	26
1040		0.13	26.1	5.1	-82	0.13	-1.6	-4.9	26
1120		0.12	26.5	5.0	-82	0.12	-1.6	-4.7	27
1200		0.11	26.9	4.8	-82	0.11	-1.6	-4.6	27
1280		0.11	27.3	4.7	-83	0.11	-1.6	-4.4	27
160	Right Headlamp	1.81	-61.9	18.3	-75	1.81	17.8	-4.4	-62
200		1.39	-61.0	15.4	-76	1.39	14.8	-4.0	-61
240		1.12	-60.4	13.3	-76	1.12	12.8	-3.7	-60
280		0.94	-59.9	11.9	-77	0.94	11.3	-3.5	-60
320		0.80	-59.5	10.8	-77	0.80	10.2	-3.3	-60
360		0.70	-59.1	9.9	-78	0.70	9.4	-3.2	-59
400		0.62	-58.9	9.2	-78	0.62	8.7	-3.1	-59
440		0.56	-58.6	8.6	-79	0.56	8.1	-2.9	-59
480		0.51	-58.4	8.2	-79	0.51	7.7	-2.9	-59
520		0.46	-58.3	7.8	-79	0.46	7.3	-2.8	-58
560		0.43	-58.1	7.4	-80	0.43	6.9	-2.7	-58
600		0.39	-58.0	7.1	-80	0.39	6.6	-2.7	-58
640		0.37	-57.9	6.9	-80	0.37	6.4	-2.6	-58
720		0.32	-57.7	6.4	-81	0.32	5.9	-2.5	-58
800		0.29	-57.5	6.1	-81	0.29	5.6	-2.4	-58
880		0.26	-57.4	5.8	-81	0.26	5.3	-2.4	-57
960		0.24	-57.3	5.6	-82	0.24	5.1	-2.3	-57
1040		0.22	-57.2	5.4	-82	0.22	4.9	-2.3	-57
1120		0.20	-57.1	5.2	-83	0.20	4.7	-2.2	-57
1200		0.19	-57.0	5.1	-83	0.19	4.6	-2.2	-57
1280		0.17	-57.0	4.9	-83	0.17	4.4	-2.2	-57

Table 66. Retroreflective Geometries for Heavy Vehicle – Left Side Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.59	19.3	16.3	-74	1.59	-1.2	-16.3	20
200		1.29	21.8	13.7	-75	1.29	-1.8	-13.6	22
240		1.09	23.5	11.9	-76	1.09	-2.0	-11.8	24
280		0.94	24.7	10.7	-76	0.94	-2.1	-10.5	25
320		0.83	25.5	9.7	-77	0.83	-2.1	-9.5	26
360		0.74	26.2	9.0	-77	0.74	-2.1	-8.7	27
400		0.67	26.8	8.4	-78	0.67	-2.1	-8.1	27
440		0.61	27.2	7.9	-78	0.61	-2.1	-7.6	27
480		0.56	27.6	7.5	-79	0.56	-2.1	-7.2	28
520		0.52	27.9	7.1	-79	0.52	-2.1	-6.8	28
560		0.48	28.2	6.8	-79	0.48	-2.1	-6.5	28
600		0.45	28.4	6.6	-80	0.45	-2.0	-6.2	29
640		0.42	28.6	6.3	-80	0.42	-2.0	-6.0	29
720		0.38	28.9	6.0	-80	0.38	-2.0	-5.6	29
800		0.34	29.2	5.7	-81	0.34	-2.0	-5.3	29
880		0.31	29.4	5.4	-81	0.31	-1.9	-5.1	30
960		0.28	29.6	5.2	-82	0.28	-1.9	-4.8	30
1040		0.26	29.8	5.0	-82	0.26	-1.9	-4.7	30
1120		0.24	29.9	4.9	-83	0.24	-1.9	-4.5	30
1200		0.23	30.0	4.8	-83	0.23	-1.9	-4.4	30
1280		0.21	30.1	4.7	-83	0.21	-1.8	-4.3	30
160	Right Headlamp	2.52	-54.9	18.8	-77	2.52	17.5	-7.1	-55
200		2.01	-54.3	15.7	-77	2.01	14.5	-6.2	-55
240		1.67	-53.9	13.7	-78	1.67	12.5	-5.5	-54
280		1.42	-53.6	12.2	-78	1.42	11.1	-5.0	-54
320		1.24	-53.4	11.0	-78	1.24	10.0	-4.7	-54
360		1.10	-53.2	10.1	-79	1.10	9.1	-4.4	-53
400		0.99	-53.1	9.4	-79	0.99	8.5	-4.1	-53
440		0.89	-53.0	8.8	-79	0.89	7.9	-3.9	-53
480		0.82	-52.9	8.3	-80	0.82	7.4	-3.8	-53
520		0.75	-52.8	7.9	-80	0.75	7.1	-3.6	-53
560		0.70	-52.7	7.6	-80	0.70	6.7	-3.5	-53
600		0.65	-52.6	7.3	-81	0.65	6.4	-3.4	-53
640		0.61	-52.6	7.0	-81	0.61	6.2	-3.3	-53
720		0.54	-52.5	6.6	-81	0.54	5.7	-3.2	-53
800		0.48	-52.4	6.2	-82	0.48	5.4	-3.0	-52
880		0.44	-52.3	5.9	-82	0.44	5.1	-2.9	-52
960		0.40	-52.3	5.7	-82	0.40	4.9	-2.8	-52
1040		0.37	-52.2	5.5	-83	0.37	4.7	-2.8	-52
1120		0.34	-52.2	5.3	-83	0.34	4.5	-2.7	-52
1200		0.32	-52.2	5.1	-83	0.32	4.4	-2.7	-52
1280		0.30	-52.1	5.0	-84	0.30	4.3	-2.6	-52

Table 67. Retroreflective Geometries for Passenger Car – Far Right Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.35	50.2	18.3	75	1.35	16.6	7.9	51
200		1.01	48.0	15.4	76	1.01	13.6	7.2	48
240		0.81	46.2	13.3	76	0.81	11.5	6.7	47
280		0.67	44.8	11.9	77	0.67	10.1	6.3	45
320		0.57	43.7	10.8	77	0.57	9.0	6.0	44
360		0.49	42.8	9.9	78	0.49	8.1	5.7	43
400		0.43	42.0	9.2	78	0.43	7.4	5.4	42
440		0.39	41.3	8.6	79	0.39	6.9	5.2	41
480		0.35	40.7	8.2	79	0.35	6.4	5.1	41
520		0.32	40.2	7.8	79	0.32	6.0	4.9	40
560		0.29	39.7	7.4	80	0.29	5.7	4.8	40
600		0.27	39.3	7.1	80	0.27	5.4	4.6	39
640		0.25	38.9	6.9	80	0.25	5.2	4.5	39
720		0.22	38.3	6.4	81	0.22	4.8	4.3	38
800		0.20	37.8	6.1	81	0.20	4.4	4.2	38
880		0.18	37.4	5.8	81	0.18	4.2	4.0	37
960		0.16	37.0	5.6	82	0.16	4.0	3.9	37
1040		0.15	36.7	5.4	82	0.15	3.8	3.8	37
1120		0.14	36.4	5.2	83	0.14	3.6	3.7	37
1200		0.13	36.2	5.1	83	0.13	3.5	3.7	36
1280		0.12	36.0	4.9	83	0.12	3.4	3.6	36
160	Right Headlamp	0.99	-26.2	16.9	74	0.99	-3.3	16.6	-27
200		0.83	-33.1	14.2	75	0.83	-4.5	13.5	-34
240		0.71	-37.5	12.3	75	0.71	-4.9	11.3	-38
280		0.63	-40.5	11.0	76	0.63	-5.0	9.8	-41
320		0.56	-42.7	10.0	76	0.56	-4.9	8.7	-43
360		0.51	-44.4	9.2	77	0.51	-4.8	7.9	-45
400		0.46	-45.7	8.6	77	0.46	-4.7	7.2	-46
440		0.43	-46.7	8.1	78	0.43	-4.6	6.7	-47
480		0.39	-47.6	7.7	78	0.39	-4.5	6.2	-48
520		0.37	-48.3	7.3	78	0.37	-4.4	5.8	-49
560		0.34	-48.9	7.0	79	0.34	-4.3	5.5	-49
600		0.32	-49.4	6.7	79	0.32	-4.2	5.3	-50
640		0.30	-49.8	6.5	79	0.30	-4.1	5.0	-50
720		0.27	-50.5	6.1	80	0.27	-4.0	4.6	-51
800		0.25	-51.1	5.8	81	0.25	-3.9	4.3	-51
880		0.23	-51.6	5.5	81	0.23	-3.8	4.1	-52
960		0.21	-52.0	5.3	81	0.21	-3.7	3.9	-52
1040		0.19	-52.3	5.1	82	0.19	-3.6	3.7	-52
1120		0.18	-52.6	5.0	82	0.18	-3.5	3.5	-53
1200		0.17	-52.8	4.8	82	0.17	-3.4	3.4	-53
1280		0.16	-53.0	4.7	83	0.16	-3.4	3.3	-53

Table 68. Retroreflective Geometries for Heavy Vehicle – Far Right Sign.

Distance (ft)	Headlamp	Application Geometry (deg)				Goniometer Geometry (deg)			
		Alpha	Rho	Beta	Omega-S	Alpha	Beta 1	Beta 2	Epsilon
160	Left Headlamp	1.88	39.0	18.8	77	1.88	15.0	11.5	40
200		1.49	37.8	15.7	77	1.49	12.2	10.0	38
240		1.23	36.9	13.7	78	1.23	10.4	8.9	37
280		1.05	36.3	12.2	78	1.05	9.1	8.1	37
320		0.91	35.7	11.0	78	0.91	8.1	7.5	36
360		0.81	35.3	10.1	79	0.81	7.4	7.0	36
400		0.72	35.0	9.4	79	0.72	6.8	6.6	35
440		0.66	34.7	8.8	79	0.66	6.3	6.2	35
480		0.60	34.4	8.3	80	0.60	5.9	5.9	35
520		0.55	34.2	7.9	80	0.55	5.5	5.7	34
560		0.51	34.1	7.6	80	0.51	5.2	5.5	34
600		0.48	33.9	7.3	81	0.48	5.0	5.3	34
640		0.44	33.8	7.0	81	0.44	4.8	5.1	34
720		0.39	33.5	6.6	81	0.39	4.4	4.9	34
800		0.35	33.3	6.2	82	0.35	4.1	4.6	33
880		0.32	33.2	5.9	82	0.32	3.9	4.5	33
960		0.29	33.1	5.7	82	0.29	3.7	4.3	33
1040		0.27	32.9	5.5	83	0.27	3.5	4.2	33
1120		0.25	32.8	5.3	83	0.25	3.4	4.1	33
1200		0.23	32.8	5.1	83	0.23	3.3	4.0	33
1280		0.22	32.7	5.0	84	0.22	3.2	3.9	33
160	Right Headlamp	2.06	-42.8	16.3	74	2.06	-7.8	14.4	-44
200		1.70	-44.8	13.7	75	1.70	-7.0	11.8	-46
240		1.45	-46.1	11.9	76	1.45	-6.4	10.1	-47
280		1.26	-47.0	10.7	76	1.26	-5.9	8.9	-48
320		1.11	-47.6	9.7	77	1.11	-5.5	8.0	-48
360		0.99	-48.1	9.0	77	0.99	-5.2	7.3	-49
400		0.90	-48.5	8.4	78	0.90	-5.0	6.7	-49
440		0.82	-48.8	7.9	78	0.82	-4.8	6.3	-49
480		0.76	-49.1	7.5	79	0.76	-4.6	5.9	-49
520		0.70	-49.3	7.1	79	0.70	-4.4	5.6	-50
560		0.65	-49.5	6.8	79	0.65	-4.3	5.3	-50
600		0.61	-49.6	6.6	80	0.61	-4.2	5.1	-50
640		0.57	-49.7	6.3	80	0.57	-4.1	4.9	-50
720		0.51	-50.0	6.0	80	0.51	-3.9	4.5	-50
800		0.46	-50.1	5.7	81	0.46	-3.7	4.3	-50
880		0.42	-50.3	5.4	81	0.42	-3.6	4.0	-50
960		0.39	-50.4	5.2	82	0.39	-3.5	3.9	-51
1040		0.36	-50.5	5.0	82	0.36	-3.4	3.7	-51
1120		0.33	-50.6	4.9	83	0.33	-3.3	3.6	-51
1200		0.31	-50.7	4.8	83	0.31	-3.3	3.5	-51
1280		0.29	-50.7	4.7	83	0.29	-3.2	3.4	-51

The data presented in Table 60 to Table 68 allow an agency to select specific retroreflective geometries to test to determine luminance as long as the associated illuminance available from the vehicle headlamps is also known. For this work, a U.S. market-weighted model year 2004 headlamp was used to generate illuminance data that could be used with the retroreflective geometries to evaluate luminance (*33*). Table 69 shows the calculated luminous intensity for each headlamp and each scenario. The illuminance is computed by dividing by the square of the distance. Table 70 shows the recommended testing geometries.

Table 69. Luminous Intensity Levels for Each Scenario (candela).

Distance (ft)	Headlamp	Passenger Car Right Side Sign	Heavy Vehicle Right Side Sign	Passenger Car Overhead Sign	Heavy Vehicle Overhead Sign	Passenger Car Left Side Sign	Heavy Vehicle Left Side Sign	Passenger Car Far Right Sign	Heavy Vehicle Far Right Sign
160	Left Headlamp	295	315	124	135	103	111	83	85
200		391	414	172	176	144	154	121	126
240		484	523	201	207	185	199	158	158
280		530	557	229	238	216	223	207	208
320		568	968	259	265	235	246	255	255
360		907	1372	276	292	257	268	290	297
400		1348	1773	306	322	281	297	317	328
440		1676	2150	331	349	307	321	365	370
480		1888	2372	355	371	327	344	409	417
520		2049	2490	375	390	352	371	471	475
560		2187	2578	393	408	375	392	485	509
600		2297	3140	410	423	395	413	489	514
640		2385	3667	425	437	415	435	524	535
720		3216	4514	451	472	456	483	570	636
800		4091	5217	499	516	517	558	756	978
880		4806	5829	539	552	582	615	1146	1343
960		5402	6339	572	584	630	665	1512	1697
1040		5905	6770	601	649	676	713	1743	1965
1120		6232	7139	745	881	726	768	1917	2120
1200		6494	7358	949	1081	778	819	2054	2242
1280		6709	7512	1126	1254	825	866	2174	2342
160	Right Headlamp	339	410	126	126	91	89	92	100
200		408	469	164	178	131	131	131	147
240		476	515	204	206	173	176	182	193
280		518	575	219	226	210	214	225	248
320		569	1074	249	253	230	232	274	285
360		940	1438	268	274	250	255	296	317
400		1288	1710	290	292	271	277	344	372
440		1558	1911	313	317	295	300	395	433
480		1764	2080	339	344	321	326	460	461
520		1924	2241	360	367	340	349	451	461
560		2080	2377	382	393	363	371	470	503
600		2220	2967	403	415	386	393	510	537
640		2341	3529	421	433	404	412	533	544
720		3217	4440	451	474	440	449	540	605
800		4084	5075	501	520	491	511	787	1057
880		4713	5553	542	559	558	574	1190	1407
960		5199	5924	576	591	617	633	1468	1652
1040		5584	6217	605	648	662	682	1681	1839
1120		5895	6454	734	837	705	724	1854	1998
1200		6149	6648	918	1005	745	764	1999	2125
1280		6361	6809	1081	1155	792	804	2116	2228

To choose specific geometries for specification purposes, the following guidelines were implemented in this report:

- Heavy vehicles were assumed to be operating on high speed roadways where LOOK3 started and stopped at 640 ft and 320 ft, respectively.
- Passenger vehicles were assumed to be operating on all speed roadways and therefore have the extreme distances of 640 ft and 160 ft.
- A “target value” was chosen for testing the conspicuity of signs to ensure they are conspicuous enough to be recognized as traffic signs for the driving task. This was based roughly on the scenarios described at a distance of 1280 ft. Compared to the LOOK3 geometries, there is less variance between scenarios so only one value was chosen for each headlamp.

Table 70. Testing Geometries.

Headlamp	Vehicle Type & Roadway Scenario	Distance (ft)	Goniometer Geometry (deg)			
			Alpha	Beta 1	Beta 2	Epsilon
Left Headlamp	Target Value		0.20	5.00	5.00	30.00
	PC-RS	160	1.07	7.93	5.61	42.73
	PC-RS	320	0.49	4.68	4.28	38.28
	PC-RS	640	0.23	3.11	3.47	35.61
	PC-OH	160	1.10	3.65	-0.92	26.04
	PC-OH	320	0.50	0.50	0.17	28.82
	PC-OH	640	0.23	-1.04	0.84	30.52
	PC-LS	160	0.89	6.87	-15.50	-8.25
	PC-LS	320	0.42	0.41	-10.01	11.30
	PC-LS	640	0.21	-1.29	-6.36	22.06
	PC-FR	160	1.35	16.61	7.87	50.65
	PC-FR	320	0.57	8.98	5.97	43.96
	PC-FR	640	0.25	5.18	4.52	39.08
	HV-RS	320	0.88	4.37	4.96	33.76
	HV-RS	640	0.43	2.95	3.78	32.68
	HV-OH	320	0.89	0.53	0.49	30.66
	HV-OH	640	0.44	-1.02	1.01	31.07
	HV-LS	320	0.83	-2.12	-9.47	25.91
	HV-LS	640	0.42	-2.02	-6.00	28.77
	HV-FR	320	0.91	8.12	7.47	36.06
	HV-FR	640	0.44	4.78	5.13	33.91
Right Headlamp	Target Value		0.20	-5.00	5.00	-55.00
	PC-RS	160	1.15	-4.33	6.96	-46.55
	PC-RS	320	0.62	-3.64	4.22	-51.48
	PC-RS	640	0.32	-3.11	2.92	-53.77
	PC-OH	160	1.46	3.06	2.19	-47.43
	PC-OH	320	0.70	0.53	0.00	-51.33
	PC-OH	640	0.34	-0.63	-1.18	-53.52
	PC-LS	160	1.81	17.82	-4.39	-61.91
	PC-LS	320	0.80	10.25	-3.32	-59.55
	PC-LS	640	0.37	6.37	-2.60	-57.96
	PC-FR	160	0.99	-3.29	16.60	-27.38
	PC-FR	320	0.56	-4.93	8.73	-43.29
	PC-FR	640	0.30	-4.13	5.01	-50.06
	HV-RS	320	1.15	-3.43	3.98	-50.49
	HV-RS	640	0.58	-2.90	2.91	-51.09
	HV-OH	320	1.20	0.66	-0.28	-50.42
	HV-OH	640	0.59	-0.61	-1.30	-51.01
	HV-LS	320	1.24	9.99	-4.67	-53.61
	HV-LS	640	0.61	6.17	-3.32	-52.69
	HV-FR	320	1.11	-5.54	7.97	-48.20
	HV-FR	640	0.57	-4.05	4.87	-49.98

Figure 66 shows that the difference between the amounts of illuminance reaching the sign for the test scenarios used in this research are within 10 percent. Given that the headlamp data used in the calculations represent a conglomerate of headlamps representing market-weighted model year 2004 vehicles, and therefore does not represent any particular headlamp or vehicle, there is obviously some liability. Furthermore, the modeled headlamp is ideal in that it is perfectly aimed and having a lens free of dirt and abrasions. Consequently, there is no measureable or significant sacrifice by using one illuminance value, the average of the left and right headlamp, for specification purposes. Using one illuminance level for both the right and left headlamps does allow significant gains in terms of building a luminance-based specification, however. The use of one illuminance level representing the right and left headlamps can be used with the luminance demand curves shown in Figure 63 to build a performance-based specification.

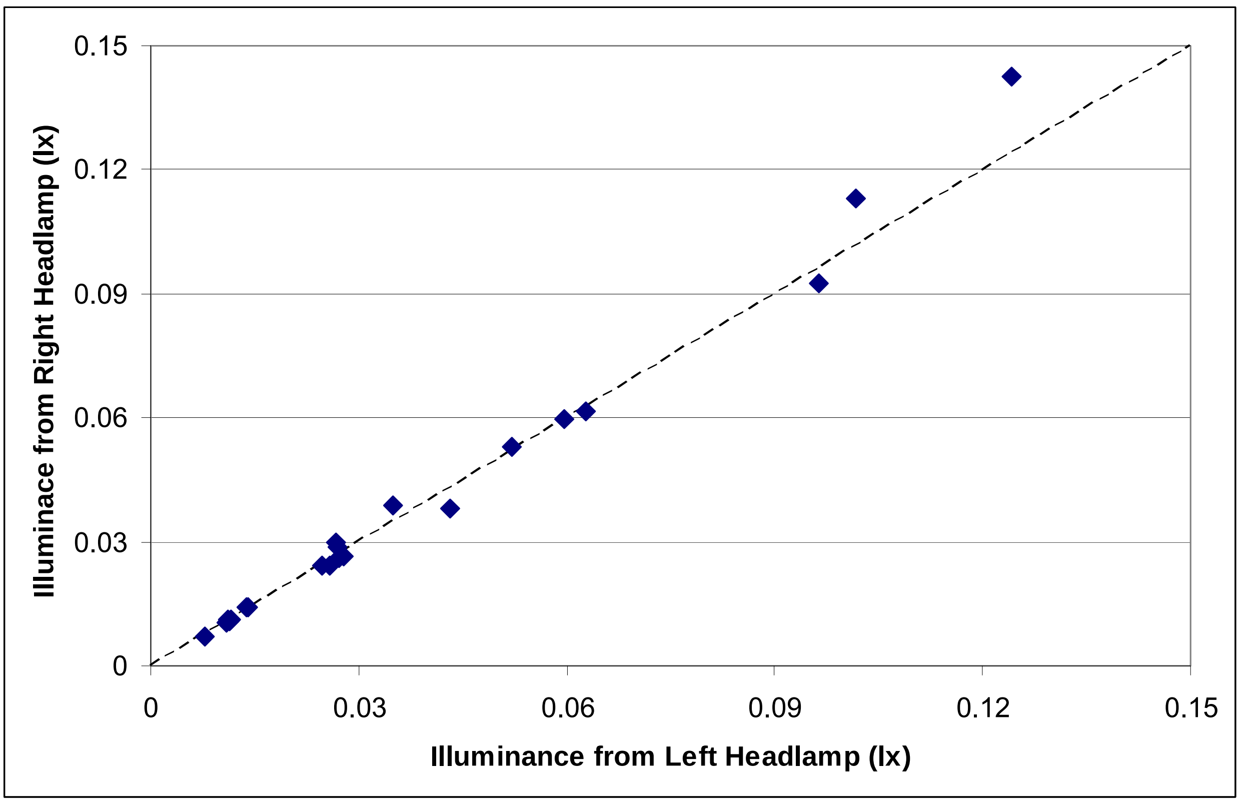


Figure 66. Comparison of Headlamp Illuminance Differences for Each Scenario.

Table 71 shows each combination of vehicle type and roadway scenario along with the goniometer geometries for the left and right headlamps. Measurements of retroreflectance can be made at each set of geometries. For the right and left headlamps, the measured retroreflectance can be summed and multiplied with the average illuminance to provide an estimate luminance. The estimated luminance can then be compared to the empirically derived luminance thresholds shown in Figure 63 to determine a material classification.

Table 71. Worksheet to Calculate Sign Luminance.

Vehicle Type & Roadway Scenario	Distance (ft)	Headlamp	Goniometer Geometry (deg)				Measured Retroreflectivity (cd/lx/m^2)	Summed Retroreflectivity (cd/lx/m^2)	Averaged Illuminance (lux)	Estimated Luminance (cd/m^2)
			Alpha	Beta 1	Beta 2	Epsilon				
PC-RS	160	L	1.07	7.93	5.61	42.73			0.133386	
		R	1.15	-4.33	6.96	-46.55				
PC-RS	320	L	0.49	4.68	4.28	38.28			0.059764	
		R	0.62	-3.64	4.22	-51.48				
PC-RS	640	L	0.23	3.11	3.47	35.61			0.062074	
		R	0.32	-3.11	2.92	-53.77				
HV-RS	320	L	0.88	4.37	4.96	33.76			0.107291	
		R	1.15	-3.43	3.98	-50.49				
HV-RS	640	L	0.43	2.95	3.78	32.68			0.094518	
		R	0.58	-2.90	2.91	-51.09				
PC-OH	160	L	1.10	3.65	-0.92	26.04			0.052661	
		R	1.46	3.06	2.19	-47.43				
PC-OH	320	L	0.50	0.50	0.17	28.82			0.026679	
		R	0.70	0.53	0.00	-51.33				
PC-OH	640	L	0.23	-1.04	0.84	30.52			0.011102	
		R	0.34	-0.63	-1.18	-53.52				
HV-OH	320	L	0.89	0.53	0.49	30.66			0.027242	
		R	1.20	0.66	-0.28	-50.42				
HV-OH	640	L	0.44	-1.02	1.01	31.07			0.011422	
		R	0.59	-0.61	-1.30	-51.01				
PC-LS	160	L	0.89	6.87	-15.50	-8.25			0.040646	
		R	1.81	17.82	-4.39	-61.91				
PC-LS	320	L	0.42	0.41	-10.01	11.30			0.024396	
		R	0.80	10.25	-3.32	-59.55				
PC-LS	640	L	0.21	-1.29	-6.36	22.06			0.010759	
		R	0.37	6.37	-2.60	-57.96				
HV-LS	320	L	0.83	-2.12	-9.47	25.91			0.025096	
		R	1.24	9.99	-4.67	-53.61				
HV-LS	640	L	0.42	-2.02	-6.00	28.77			0.011114	
		R	0.61	6.17	-3.32	-52.69				
PC-FR	160	L	1.35	16.61	7.87	50.65			0.036834	
		R	0.99	-3.29	16.60	-27.38				
PC-FR	320	L	0.57	8.98	5.97	43.96			0.027797	
		R	0.56	-4.93	8.73	-43.29				
PC-FR	640	L	0.25	5.18	4.52	39.08			0.013887	
		R	0.30	-4.13	5.01	-50.06				
HV-FR	320	L	0.91	8.12	7.47	36.06			0.028383	
		R	1.11	-5.54	7.97	-48.20				
HV-FR	640	L	0.44	4.78	5.13	33.91			0.014175	
		R	0.57	-4.05	4.87	-49.98				
Target Value		L	0.20	5.00	5.00	30.00			0.007552	
		R	0.20	-5.00	5.00	-55.00				

There are several items to note with this approach. While there are many more measurements here than currently used to specify retroreflective sheeting materials, TxDOT currently uses a computer-controlled goniometer. Therefore, the additional measurements can be programmed without a substantial impact on measurement time or complications. In addition, the full set of measurements might only be needed for qualifying new products. A subset of these geometries could be used for quality control measurements, after materials are adopted on a qualified products list. The reduced set of geometries for quality control measurements can be based on ASTM geometries for familiarity and cross referencing. It is evident that alphas of 0.2, 0.5, and 1.0 degrees in combination with a beta of 4 (or -4) degrees represent actual scenarios. Using these alpha/beta combinations with epsilons of 35 and -50 degrees would provide a minimum set of geometries for quality control purposes (see Table 72).

Table 72. Retroreflective Geometries for Quality Control Testing (Degrees).

Alpha	Beta1	Beta2	Epsilon
0.2	-4	0	35
0.2	-4	0	-50
0.5	-4	0	35
0.5	-4	0	-50
1.0	-4	0	35
1.0	-4	0	-50

Another item that is going to be realized if a specification such as this is implemented is that a particular material may be classified a Type D for some combinations of vehicle type and roadway scenarios but not a Type D on other combinations of vehicle type and roadway scenarios. It may be desirable to have materials classified as Type D on overhead sign structures but not on rural two-lane highways where they may appear too bright and possibly glaring and or distracting. The implication of this is that it might be appropriate to use different type of retroreflective sheeting materials on different types of roadways. Full testing of different retroreflective materials would be needed to determine if this is indeed an outcome. An ongoing research study, 0-6384, includes an effort to investigate if there is a point when high beam illumination is so bright it has a detrimental performance on nighttime legibility.

If testing for rotational sensitivity is of interest, then the specifier can test using the geometries shown here, in addition to added geometries of the same alphas and betas, but with varying ranges of epsilon. For instance, if sign sheeting on warning signs is applied so that it is oriented 45 degrees on the road, then additional testing can be added using 45 degree intervals of the epsilon values shown.

DISCUSSION

One item that is particularly noteworthy is that if an agency decides to have consistent performance levels across all roadway types and environment types (without considering vehicle types or headlamps for now), then it will become evident using the guidelines described in the report that different sign sheeting materials will be needed on different roadways and for different sign types. For example, on overhead guide signs, which are read farther away and have less headlamp illumination, very efficient materials are needed to obtain high levels of luminance. Those same materials, however, may be too bright for rural two-lane highway applications, particularly when the nighttime volumes are so low than the majority of drivers are using their high beam headlamps. Therefore, it is desirable that consideration be given to a policy that requires different performance levels for different types of roadways. For instance, perhaps Type C is deemed appropriate for rural two-lane highways while Type D is more appropriate for interstate highways.

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