Nighttime Driver Needs: An Analysis of Sign Usage based on Luminance

A Thesis Proposal

by

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INTRODUCTION

Nighttime driving presents roadway users with greater challenges than daytime driving due primarily to visibility constraints. The challenges are so great that some motorists choose to remain sequestered until dawn rather than drive at night. As a result, transportation engineers and researchers have gone to great lengths to improve safety and operations by making the driving task easier at night. One method to ease nighttime driving has been the development of retroreflective sign sheeting. Retroreflective material reflects light from a light back to its source; for driving, it returns the light from the headlamps back to the vehicle.

The use of retroreflective sign sheeting to return light to the driver increases the visibility of traffic signs and therefore their effectiveness. However, the evolution of sign sheeting has led to the American Society of Testing and Materials (ASTM) classification system essentially based on the order of production rather than how drivers use them or what drivers need. As a new sheeting product is developed with unique reflective characteristics, it is typically given its own designation. Currently, sheeting is classified as Type I, II, III, VII, VIII, IX, or X. This classification method has led to an ascending numerical ranking that is not based on the performance of the sheeting. For example, although Type IX sheeting would presumably be better than Type VII sheeting it is less bright at longer distances and intended for short sight distances.

An alternative strategy for improving the retroreflective sheeting classification process is to use driver needs to develop signs and materials for nighttime driving. This thesis is part of a Texas Transportation Institute research project to develop a performance-based retroreflective sheeting classification system based on nighttime driver needs. The thesis looks specifically at how sign brightness affects the driver’s viewing behavior using number of glances and total glance duration as measures of effectiveness. Using advanced eye-tracking technology, the author will be able to determine when a driver looks at a sign and for how long as a function of sign luminance.

Earlier research has been conducted which has used this technology to assign multi-look models to a driver’s sign viewing behavior. Most recently a three look model has been proposed to...
account for color recognition, shape recognition, and legibility according to Figure 1 as proposed by Paul Carlson in 2005. “Look 3” in the figure represents the legibility zone of the sign or the look used to actually read the sign. A deeper look into how drivers look at signs will improve how sign sheeting is developed.

![Figure 1. 3-Look Model](image)

This thesis will evaluate how drivers acquire information from signs in the as they approach them as a function of the sign brightness. The effect of sign brightness on its visibility is without question: as an object gets brighter it becomes more conspicuous and can be seen from farther away. This longer distance gives the driver more time to view the sign. Regardless of the recognition distance, however, the sign is not effective until the message is read. Unless the legend size increases with brightness, the sign legibility may not be improved. Despite the limitation of legend size on legibility, the increased viewing time may allow the driver to decipher parts of the sign as he approaches. This represents one of the potential effects of sign brightness addressed by this thesis.

**PROBLEM STATEMENT**

The effect of sign brightness on visibility and legibility has been studied and found to improve both. Its effect on the driver, however, has remained untested. This thesis will determine how sign brightness affects how a driver uses the sign to obtain information. Several possibilities are available to describe the effect of sign brightness on driver viewing characteristics. The brightness of signs could either decrease or increase the total viewing time of the sign. Another measure of the sign’s effect on driver usage is the number of looks to a sign as they approach it;
varying sign brightness may increase or decrease the total number of looks. This thesis will compare the performance as measured by these two criteria for signs of varying brightness in a nighttime setting.

**BACKGROUND**

The idea of basing traffic sign and sheeting design on driver’s needs is not a new one. There have been several attempts to address this topic that provide the platform for this thesis and the related project. In 1933, Mills (1) was one of the first to evaluate retroreflective materials by demonstrating an increase in the visibility of the sign from 200 feet to beyond 600. Since then, researchers have analyzed measures such as retroreflectivity, luminance, and contrast for their effect on legibility distance, visibility distance, and the conspicuity of traffic signs. However, assumptions made during these studies have limited their scope and the subsequent impact on assessing nighttime driver needs.

**Retroreflective Sheeting**

What the driver sees with respect to nighttime road signs is the result of four stages of light transformation: luminance intensity, illuminance, retroreflectivity, and luminance. *Luminous intensity* is the amount of light emitted from a source, such as a vehicle headlight. *Illuminance* is the light received by the viewing surface (sign). Light dissipates with distance and therefore illuminance is dependent on the distance between the vehicle and the sign. *Retroreflectivity* is the measure of how much light is reflected back to the light source and is dependent on both the sign sheeting being evaluated and the viewing angles between the light source (headlight), the viewing surface (sign), and the recipient (driver). The two most commonly referred to angles are the entrance angle ($\beta$, between the light source and the axis perpendicular to the viewing surface) and the observation angle ($\alpha$, between the light source and the recipient) as shown in Figure 2.

Historically, the method for measuring retroreflectivity has been limited to only a few entrance and observation angles not entirely representative of real-world characteristics which has led many to use luminance rather than retroreflectivity to evaluate traffic signs. *Luminance* is commonly referred to as the brightness of a sign; it is what the driver sees. Luminance “provides a means to match materials to roadway situations and driver needs (2)”
According to ASTM D4956 (4) retroreflectivity is the criteria used by ASTM to classify different types of retroreflective sheeting. However, the current trend for sheeting specification follows sheeting production rather than sheeting performance. Typically, as new and unique products are created by manufacturers new ASTM “Types” are assigned to classify them rather than classifying them in predetermined performance categories. The ASTM standards for most sheeting types are based upon just four combinations of two observation and two entrance angles:

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<th>Entrance Angle (β)</th>
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<td>0.2°</td>
<td>-4°</td>
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<tr>
<td>0.5°</td>
<td>30°</td>
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According to Bible and Johnson: “Material selection should be based on sign performance; material specifications should be based on measurable properties (5).” While this statement supports using a sheeting property such as retroreflectivity to classify the product it purports that this specific value isn’t relevant to all driving situations and therefore doesn’t adequately describe sign performance.
A key measure of sign performance is its legibility. Legibility denotes the ability of a sign to convey its intended message. It has been found that as luminance decreases, visual acuity decreases (6). In addition to the luminance of a sign, several factors are considered when assessing sign performance. The content, color, position, and size of a sign are all interrelated with luminance when it comes to sign legibility. As the content of a sign increases in volume or complexity, more luminance is required to accommodate drivers. Further, larger signs have been shown to require less retroreflectivity (7) and the size of a sign directly correlates to how far away it can be distinguished and therefore useful in the driving task (8).

Despite the variability of these sign characteristics for on-road installations, many visibility and legibility studies have taken place in laboratory settings. This is largely due to the drawbacks of on-road driver evaluation such as ensuring the safety of the subject, compensating for driver error, and the driver “over achieving” to match the stated study objective. Olson and Bernstein (10) found that the 90th percentile performance in a lab setting was equivalent to the 50th percentile in a field setting. Their finding points out the importance of dynamic field studies to evaluate sign performance. There are two methods typically used to evaluate the interaction between drivers and signs in real-world driving scenarios. The first is driver reporting. This technique is dependent on the driver knowing what is expected and providing required or requested information accordingly and is subject to driver error and bias to the study task. In order to eliminate driver’s bias, researchers have developed a second method using eye-scanning equipment to track where the driver is looking rather than depending on their responses.

Even studies employing the second method have their own limitations. These limitations included the use of existing retroreflective material or non-naturalistic detection methods. Non-naturalistic methods include those in a laboratory setting or on a controlled course with pre-stated objectives such as informing a subject they are evaluating certain types of signs, introducing bias. The majority of research reviewed has included one or both of the limitations listed. Forbes (9), Olsen and Bernstein (10), and Schnell, et al (11), used a projection system in a lab setting to evaluate the legibility or recognition of signs. Whereas this technique allows researchers to vary luminance values beyond the capabilities of existing sheeting, the driving task involves more dynamic workloads than these subjects experienced. Alternatively, Sivak and
Olson (12), Zwahlen (13, 14, 15, 16), Zwahlen et al. (17), and Schieber et al. (18) used on-road drivers to measure visibility and legibility distances. These studies used either self-reporting measures or experimental technology, which had their own set of limitations. The main drawback, however, was that each of these efforts analyzed the characteristics of existing signs and sheetings that were not designed specifically to meet driver’s needs. Finally, some studies such as that by Mercier et al. (7) used existing sheeting characteristics inside a laboratory setting further compounding the drawbacks.

Whereas earlier efforts to assess nighttime driver’s needs have evaluated existing retroreflective products, this research will not be hinged on the type of sheeting. Previous studies have focused on evaluating existing sign sheeting materials to enable traffic engineers to make decisions without having to evaluate each sheeting type based on their needs (10). While this thesis will utilize several types of existing retroreflective sheeting to provide varying luminance profiles, the results will be independent of the sheeting type. The results presented by this thesis could be used to develop new sheeting materials.

**Eye Tracking**

The restriction of earlier projects was due to the distance limitations of technology at the time. Eye tracking devices have been used since as early as 1968 (19) to evaluate how and if driver’s use particular signs. A compilation of data from several eye-tracking studies (13, 14, 17, 18) resulted in an average first-look distance of just over 500 feet. In their 2004 study, Schnell et al. (11) began analyzing the visibility of signs at the equivalent of 1100 feet. This leads to the assumption that drivers actually begin looking at signs much farther than 500 feet away. In fact, Zwahlen’s stated visibility distances are drastically longer than the driver’s first-look distances shown in Figure 4. The visibility distance is that at which the sign is visible by the driver. The “first-look” distance is the distance from the sign at which the driver’s first glance was detected. The difference between the visibility of a sign and the distance at which the first look was detected leaves a large gap between sign performance and perceived driver sign usage.

This could be attributed to the inaccuracy of eye-tracking systems beyond a certain distance. Schieber et al. (18) noted that their system was inaccurate beyond 980 feet. Based on a survey of
existing systems, those similar to the one used by Schieber et al. typically experience accuracy ranging from 2° to 6° which equates to the ability to detect a lateral glance of 30 to 100 feet from 980 feet away. New technology, including the system that will be used for this thesis, boasts accuracy from 0.25° to 1°: capable of detecting glances between 3 and 15 feet at the same distance.

Eye-tracking systems such as the one used for this research are able to map where a subject is looking by one of two methods. First, as infrared light is reflected on the cornea a glint appears on the eye which can be tracked and correlated to the position of gaze of the subject. Alternatively, infrared light illuminates the eye such that the pupil stands out as a dark circle against the lighter iris. Cameras are calibrated to the pupil’s location based on selected points of gaze and used to track the pupil’s location relative to the calibrated points. The direction of gaze can then be mapped to a scene captured by another camera based on the x-y coordinates provided by the eye cameras. This technology allows researchers to determine when drivers look at signs.

This thesis will evaluate how drivers use signs during nighttime conditions based on number of looks to the sign and total duration of the glances as a function of the sign’s luminance profiles. As a result, values will be obtained which will be established as a baseline for continuing luminance research to meet nighttime driver’s needs. The findings obtained will consist of
viewing distances and durations for various existing traffic signs with different luminance characteristics.

RESEARCH OBJECTIVES

This thesis will develop relationships between the number and lengths of looks that will be used to begin the development of a performance-based specification for traffic sign sheeting. The results of this thesis will be based on two primary objectives: how long and how often subjects look at signs and how those looks correlate with the brightness level of the sign and the distance from the sign. The findings will be reached in the following steps:

1. Determine the luminance profiles of the target signs
2. Record driver viewing behavior data approaching targets signs at night.
3. Determine the total duration of glances made as the driver approaches the sign as the sum of the duration of each glance made to a sign using both time and distance as a measure.
4. Count the total number of glances made to the sign within the legibility zone.
5. Using the known brightness levels of the signs, compare the look characteristics to sign luminance by answering questions such as the five below:
   - Do drivers look more often at bright signs?
   - Do drivers look more often at dim signs?
   - Do drivers look longer at bright signs?
   - Do drivers look longer at dim signs?
   - Does increasing the sign brightness affect the legibility distance of the sign?

In order to accomplish these objectives, three hypotheses will be tested. The first null hypothesis \( H_0 \) states that the mean number of glances \( G \) for the bright signs and the dim signs are the same; the alternative hypothesis \( H_A \) states that the mean number of glances for the bright signs is greater than that for the dim signs meaning the driver looks more often at brighter signs. \[
H_0: \mu_{G,B} - \mu_{G,D} = 0 \\
H_A: \mu_{G,B} - \mu_{G,D} > 0
\]

The second null hypothesis states that the mean glance duration within the legibility zone \( D \) for the bright signs and the dim signs are the same; the alternative hypothesis states that the mean
glance duration for the bright signs is greater than that for the dim signs meaning the driver spends more time fixated on the brighter signs.

\[ H_0: \mu_{D,B} - \mu_{D,D} = 0 \]
\[ H_A: \mu_{D,B} - \mu_{D,D} > 0 \]

The final null hypothesis states that the mean legibility distance (L) for the bright signs and the dim signs are the same whereas the alternative hypothesis states that the bright sign has a greater legibility distance.

\[ H_0: \mu_{L,B} - \mu_{L,D} = 0 \]
\[ H_A: \mu_{L,B} - \mu_{L,D} > 0 \]

**RESEARCH STUDY DESIGN**

*Literature Review*

In addition to the review of the literature presented here to establish the state-of-the-practice, further research will be done to determine the state-of-the-art. The visibility characteristics of traffic signs have been extensively studied since the 1930s with the introduction of retroreflective materials. Since then, the resultant luminance and its effect on sign performance measures such as legibility have led to proposed requirements for minimum retroreflectivity values by the Federal Highway Administration. These minimum values relate to the luminance required to convey the message on the sign. The conspicuity, visibility, and legibility of a sign are all directly affected by the retroreflectivity of its sheeting. The retroreflective products available for illuminating a sign dictate its capabilities. Each of these aspects of signing will be reviewed.

*Instrumentation*

The combination of two technologies provides a unique process to evaluate the performance of traffic signs. Eye tracking systems and digital measuring instruments will be used together to relate a driver’s viewing behavior with their location on the road. Individually, however, these two instruments will be adapted from their traditional use. Eye tracking systems have typically been used to evaluate the effectiveness of limited displays such as web-page layout while DMI is
widely used for measuring traveled distance and highway mapping. In order to effectively use these tools for this research, it is important to know of their limitations and capabilities.

Eye tracking systems follow the gaze of subjects by following the pupil as it focuses. By flooding the eye with infrared light the pupil appears as a black hole within a lightened view of the iris. This image is captured by infrared cameras for processing by the ViewPoint® software. ViewPoint® uses the contrast of the pupil against the iris to locate it and project its point of gaze. To effectively map the gaze, a calibration process is essential to orient the software with each subject. This research will push the limits of eye tracking by requiring long distance looks, allowing free movement of the subjects head, and presenting moving targets in the form of approaching signs. A preliminary analysis has been conducted to ensure the eye-tracking system will satisfy the needs of the project.

A distance measuring instrument uses electrical impulses generated by sensors in the vehicle to determine the distance traveled. Transmission sensors, for instance, provide six pulses for each revolution of the internal disk according to the NITESTAR® operation manual (20) from Nu-Metrics®. The DMI is calibrated by traveling a known distance and correlating that distance with the number of pulses recorded. The stated error of the NITESTAR® distance measuring instrument is 1 foot for every 1,000 feet traveled but previous use has witnessed 1 foot for every mile traveled.

These two systems will be run through a central computer from within the test vehicle through the use of video technology. The eye-tracking video is captured at a rate of 30 Hz. As the video is saved by the eye-tracking software, a video titling tool will implant the data from the DMI into the scene video every 0.1 seconds. This will allow the researcher to assess when the subject glances at a sign and the distance to the sign from one interface. The use of a single computing system is essential for post-processing efforts. Further equipment incorporated into the system will include power supplies and back up storage due to the large size of the video files. It is important to note that this system is highly portable and capable of a wide range of scenarios.
**Experimental Design**

The dynamic nature of this research will incorporate human subjects in on-road driving situations. In order to minimize the variability of driving situations there is a need to standardize what the subjects will see. As such, a 4-mile closed course will be established at the Riverside Campus of Texas A&M University, a former base for the Army Air Corps. The creation of a course will allow the researcher to control the signs presented based on their luminance and legend. This course will be situated on the runways of the Riverside Campus utilizing previously installed sign post locations as shown in Figure 5. Each of the signs on the closed course exhibit unique luminance profiles. In addition to the closed course, the subjects will navigate an open-road course near the Riverside Campus. The addition of an open-road portion of data collection is essential to compare data collected on the closed course with natural driving techniques.

![Figure 5. Riverside Test Course](image)

The real-world route will begin at the entrance to the Riverside Campus and progress to the south along State Highway (SH) 47, then loop back to Riverside. In addition to the existing signage, three test signs will be erected similar to those used by Schieber et al (18). These three signs will feature similar layouts resembling speed limit signs and use varied retroreflective sheeting to present three different luminance curves.
A variety of subjects will be selected based on their age, driving experience, visual acuity, visual correction, gender, and road network familiarity. Data collection will consist of at least 15 subjects who will be evaluated based on their eye-scanning behavior while being given additional tasks such as maintaining position in a narrow lane, counting off-colored pavement markers, searching for requested information on signs, or other road-based functions. Subjects will be selected such that they are familiar with the traffic laws and courtesies of American drivers.

**Data Collection**

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

Prior to running the first subject, luminance data will be collected for each of the signs presented. Luminance will be measured at distances based on legibility indices correlating the size of the lettering on the size. The closest measurement will be taken at a distance equivalent to 20 ft/in then incrementally increased by 50 feet or less to an index of 40 ft/in followed by two readings each 100 feet further. For example, a speed limit sign with 10 inch lettering will have measurements taken at 200, 250, 300, 350, 400, 500, and 600 feet. The signs will be measured three times to accurately assess the luminance characteristics of the signs. These measurements will be used to construct unique luminance curves for each sign based on its retroreflective material and approach geometry.

Data collection begins for the subject with a calibration process. A large grid has been installed on the side of a hangar at the Riverside campus to facilitate this step. Subjects will view each of 16 targets to calibrate the eye-tracker to their facial geometry. The calibration of the eye-tracker will be checked periodically throughout the three courses as well as at the end of the experiment to ensure the usability of the data. Next, the subject will begin the driving portion of the study on each of the closed and open courses. The signing along the closed course will be laid out to maximize the usable data. Eleven signs have been selected for the closed course. Within this
inventory there are signs of similar color and/or shape but varying legends and brightness. Only three of the signs on the closed course will be used for the data analysis. Next, the subjects will be instructed to begin the on-road portion of the study. Subjects will be given navigational instruction to complete this 6.6 mile loop and return to the Riverside Campus for the completion of the data collection. The on-road loop is intended to provide a comparison between real world driving and the closed course performance. The eye-tracking and distance measurement information for each subject will be collected and saved in electronic format for subsequent analysis.

**Data Reduction**

The eye tracking system assigns x-y coordinates to the point of gaze depending on the position of the pupil. These coordinates are assigned to the video captured by the forward facing scene camera. The calibration process uses the 16 points spaced across the forward scene to attune the individual eye to the *EyeFrame* geometry. The typical use of eye-tracking equipment is used to measure gaze against a constant or premeditated background whereas driving provides a completely dynamic scene. Even for long sections of straight roads the scene changes as objects approach the driver. As such, tools built in to the eye-tracker to indicate when a subject looks into a certain region of the scene cannot be utilized. Instead, the data analysis will require the researcher to review the video with gaze points overlaid to establish several aspects unique to each subject. An example of the video is provided in Figure 6.

![Figure 6. Typical Glance Behavior](image)

Several data points will be collected not only for each driver and each sign, but for each glance directed at that sign. Data reduction will consist of recorded information such as the time the
subject looks at a sign, the distance at which the subject looks at the sign, the time the subject looks away from the sign, and the distance at which the subject looks away from the sign. The author expects values of individual look durations to exceed Zwahlen’s reported 0.65-0.82 seconds (14) and the total durations to be close to Schieber’s findings of 6.2 seconds (18). Typical data is shown in Figure 7.

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Data Analysis

Once this data is compiled for each sign and subject, several graphical comparisons will be made. Such plots will include a graph for each driver including the looks for each sign and a graph for each sign including the looks from each subject.

Two measures of effectiveness will be recorded for each sign viewed by each subject: total look duration and number of looks. Statistical analysis of these measures will include a comparison of the look durations and total looks between bright, medium, and dim signs for each driver according to the test hypotheses stated in the objectives. A paired t-test will be used to account
for the individual viewing behavior of the subjects. Further analysis will consist of comparisons of last-look distances for each of the signs. Finally, the legibility distances for each of the signs will be compared to determine the impact of viewing time and the sign brightness on the legibility of the sign.

**Thesis Preparation**

The data collected, analyzed, and reduced will be used to evaluate how the brightness of signs affects the way drivers use them. Findings will be documented and presented as a Master’s Thesis in accordance with Texas A&M University Policies.

**POTENTIAL BENEFITS OF STUDY**

The MUTCD (21) requires that “signs shall be retroreflective or illuminated to show the same shape and similar color by both day and night”. This regulation has been interpreted to require minimum retroreflectivity levels at select angles dictated by the equipment used to measure them. A system based on driver needs would be based on when drivers actually look at signs. These parameters will then be used to develop luminance curves based on actual driver needs rather than existing sheeting performance. From here, a performance-based sign sheeting criteria can be established to accommodate nighttime road users rather than proprietary interests. This thesis will establish the distances and/or times at which drivers look at traffic signs to be used in the development of the performance based criteria.

**REFERENCES**


