Evaluation of Discomfort Glare and Pavement Marking Material Visibility for Eleven Headlamp Configurations

By

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Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
in
Industrial and Systems Engineering

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March 14, 2003
Blacksburg, Virginia

Keywords: discomfort glare, pavement marking materials, headlamps

ABSTRACT

Evaluation of Pavement Marking Material and Eleven Headlamp Configurations by Measuring Discomfort Glare and Pavement Marking Visibility

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Nighttime is considered to be the most dangerous time for driving. The number of fatalities greatly increases at night, especially when considering the significant reduction in the number of miles traveled. Many researchers attribute the higher fatality rate to the reduction of visibility due to the reduction of ambient lighting. Factors such as discomfort glare from oncoming drivers and inadequate road markings further reduce visibility.

This research effort focused on ascertaining the headlamp technology (of the eleven specified) that minimized the amount of discomfort glare and maximized the visibility of three types of pavement marking materials used in the study. Two baseline conditions, halogen low beam (HLB) and high-intensity discharge (HID) were measured both individually and in combination with three levels of UV-A. In addition, three other headlamp configurations were evaluated.

Discomfort glare was measured subjectively for each headlamp configuration. Pavement marking visibility was directly measured via pavement marking detection distances. Thirty participants representing three age groups participated in this study: young (18-25 years old), middle (40-50 years old), and older (60 years and older). The headlamp technology and the pavement marking material needed to be beneficial for all age groups as all would potentially use the new technology if it were implemented in vehicles and roadways in the future.

Participants evaluated discomfort glare at both a far and close distance using the nine-point DeBoer scale and evaluated pavement marking visibility by indicating when they could see the first and last pavement markings in each of the three sections.

Overall, it was found that the HID configurations (HID, Middle UV-A + HID, High UV-A + HID) with a sharp cut-off beam pattern provided the least amount of discomfort glare. In contrast, the halogen configurations (HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB) and high output halogen with a straight-ahead beam pattern provided the longest detection distances. Two of the pavement markings: a two part liquid system (developed by 3M) and a fluorescent paint provided longer detection distances than a thermoplastic marking.

ACKNOWLEDGEMENTS

I would like to thank my committee members, Dr. Tom Dingus, Dr. Maury Nussbaum, and Dr. Jon Hankey for their patience and guidance through this process. I would like to extend extra thanks to Dr. Hankey, who on more than one occasion went out of his way to help me reason through the many obstacles that developed over the course of this research project.

Thank you to the administration staff at the VTTI. They helped me in many ways, whether it was getting extra building keys or correcting errors in paperwork. They were always friendly and encouraging, and it did not go unnoticed. Also, many thanks to the hardware staff at the VTTI. They took on the challenge of equipping the vehicles with headlamps then helping with the maintenance when things (frequently) broke. A special thanks to Mark Young and Jared Bryson, who spent many hours with me trying to figure out how to best implement the hardware for the study.

Thank you to Julie Cook and Myra Blanco, who spent countless hours riding in a car on the Smart Road in the dark. They not only proved they could write very well in the dark but also could laugh (with me) at my silly jokes. A special thanks to Julie as she was invaluable during data collection- I could not have done this without her sanity during all the nights on the Smart Road.

A very special thanks to two very good friends, Julie and Charlie. They were always there, whether I needed a sounding board for protocols or a lunch with friends. Their help and friendship will not ever be forgotten.

I also need to thank my family, who supported my entire academic career.

Last but definitely not least, I need to thank my amazing husband, Justin. His patience, knowledge, and affection helped me through everything from headlamp alignment to sleep depravation. Words will never describe how much he has helped me and how much he means to me. Thank you.

DEDICATION

This is dedicated to my late father, Bill, who always supported my endeavors. Although he is not here to see this, I know how much this would have meant to him.

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CHAPTER 1. INTRODUCTION

Nighttime visibility has long been a safety concern of transportation professionals. As early as 1962 requests for additional nighttime driving studies were presented (Roper, 1962). Although a smaller percentage of miles traveled occur during the nighttime hours than daytime hours, a significantly larger percentage of fatalities occur between the hours of 6 P.M. and 6 A.M. (National Highway Transportation Safety Administration, 1997). For this and other reasons, increased night visibility is becoming a focus of much transportation research.

To accomplish enhanced night visibility, several technologies have been developed, including advanced headlamps technologies and various pavement marking materials. This research effort focused on each of those issues.

Eleven headlamp technologies and three pavement marking materials were evaluated in this research effort. The headlamp configurations were measured for both discomfort glare and pavement marking visibility. This research effort investigated the pavement marking visibility and effect of headlamp configurations across three age groups: young (ages 18 to 25), middle (ages 40 to 50), and old (ages 60 and over).

This research effort focused on two areas. The first was measuring the amount of discomfort glare participants experienced with the headlamp configurations. Participants subjectively rated both close and far discomfort glare with each headlamp configuration. The second focus was measuring the pavement marking visibility for each pavement marking material and headlamp configuration. To assess this, participants indicated when they saw the first and last pavement marking in each section of pavement marking materials.

One goal of this research effort was to determine, within the set of tested headlamp technologies, which technology provided the least amount of glare. Another goal was to determine which headlamp technology most increases the visibility of pavement markings. Finally, this research effort determined the most visible pavement marking material of the three tested.

CHAPTER 2. LITERATURE REVIEW

2.1 Nighttime Driving Issues and Hazards

Nighttime driving is considered to be more hazardous than daytime driving. Although a smaller percentage of miles traveled occur during the nighttime hours than daytime hours, a significantly larger percentage of fatalities occur between the hours of 6 P.M. and 6 A.M. (National Highway Transportation Safety Administration, 1997). Many factors have been determined to contribute to decreased nighttime driving performance, including a reduced ability to collect visual information, physiological impairments (e.g., night-blindness), and temporary impairments, namely alcohol and other drugs (Bartmann and Reiffenrath, 1991).

Nighttime vision functions differently than daytime vision. Human vision is equipped with two types of photoreceptors, cones and rods. Cones are specialized for lighted conditions and adjust quickly to changes in lighting conditions. Rods are specialized for dim conditions and respond slowly to changes in lighting conditions (Olson, 1993). To adjust for different lighting conditions, the human visual system changes the activity level of the rods and the cones in response to the level of light – this process is called adaptation (Sanders and McCormick, 1993). During night driving, the visual system will use adaptation when the driver moves from a dark to lighted environment by increasing the activity of the cones. Conversely, the eye will increase the activity of the rods when the driver moves from a lighted to dark environment. During these transitions, the person will have a difficult time detecting contrast between objects; therefore will have increased difficulty detecting objects (Tijerina, Browning, Mangold, Manigan, and Pierowocz, 1995).

Time for adaptation varies among individuals. In addition, adaptation time increases with age (Olson, 1993). While adaptation may require several seconds for a young driver, adaptation after exposure to high-beam headlamps could take as long as one minute for a person with reduced abilities (Olson, 1993). That is to say that for as long as one minute, the driver is not efficient at detecting objects in the road, therefore is at greater risk of accidents.

The decreased ability of the driver to detect objects in the roadway is a limitation that accompanies nighttime driving. To be able to detect an object, the object must have adequate luminance and contrast from the background (Kosmatha, 1995). Nighttime driving conditions are limited in luminance and contrast, thereby making detection difficult (Tijerina et al., 1995). The reduced detectability not only increases the likelihood of a collision with an object, but it also restricts navigational abilities. For example, roadway alignment objects and symbols, such as pavement markings, provide information that help the driver navigate safely on the road. When the ability to detect the pavement markings is reduced, such as at night, the number of cues for navigation the driver receives are also reduced (Schnell and Zwahlen, 2000).

Ninety- percent of information while driving is gathered through vision (Olson, 1993). The limited amount of visual information available at night can be considered a critical element in the increased risk of fatalities (Olson, 1993). Researchers have demonstrated that despite the reduced visibility, drivers do not compensate by changing their driving habits; specifically, drivers do not reduce their speed of travel (Tijerina et al., 1995). The combination of the continued high rate of speeds and the reduced visibility greatly increases the risk of accidents.

2.2 Discomfort Glare

Glare is another major concern of nighttime driving. Glare is caused by a bright light in the field of view (Sivak, Flannagan, Ensing, and Simmons, 1991). In the case of nighttime driving, glare most often comes from the headlamps of oncoming vehicles, and is of most concern among older drivers and in poorly lighted areas (Mortimer, 1988). Two types of glare are identified: discomfort glare and disability glare. Discomfort glare can be defined as the subjective discomfort level the person experiences through exposure to the glare source. Disability glare is characterized by a decline in visual performance and a physical sensation of discomfort and/or pain (Sanders and McCormick, 1993). The distinction between the two glare types is not well understood, and some overlap is possible (Sivak et al., 1991). That is to say, a stimulus may initially cause discomfort glare but, as the driver comes closer to the target, may develop into disability glare.

Poulton (1991) has attributed discomfort glare to the following physical characteristics:

- Intensity of the light source. As the intensity of the light source increases, the level of glare increases.
- Background luminance. The larger the contrast between the luminance of the light source and background, the greater the glare level.
- Glare source size and number of sources. The level of glare increases as the glare source size increases. In addition, the more sources there are the higher the level of discomfort glare.
- Position of the glare source, relative to the observer's eye position. As the glare source moves closer to the center of field of view, the more intense the glare. In fact, researchers agree that the discomfort glare level is inversely proportional to the square of the angle (Adrian and Bhanji, 1991). In addition, the glare is intensified as the driver approaches the oncoming vehicle (Olson and Sivak, 1981).

Boyce and Beckstead (1991) further defined factors affecting glare: physical, visual, procedural, and psychological. Physical factors include glare source location and size, similar to the factors named by Poulton (1991). Visual factors account for individual differences, such as how light scatters in the eye. One example is presbycusis, or aging effects of vision, which tends to increase the amount of scattering, therefore increasing the amount of glare the participant receives. Procedural factors involve how well the method is defined and explained to participants. For example, providing a clear explanation of discomfort glare to participants is one way to minimize procedural effects. Finally, psychological factors involve the affect of the participants, such as mood or prior experience. Participants that are in a negative mood may rate glare as more intense.

Discomfort glare has been found to be task dependent (Sivak et al., 1991). Researchers investigated the correlation between the participant's ability to determine the location of a gap (white space in the dark background) against the background when presented with a glare source. The gaps ranged in size, therefore varied the difficulty of the task. The glare level and source location were kept constant throughout the tasks. In addition to determining the location of the gap, the participants were asked to rate the glare on the DeBoer scale, a widely used battery consisting of nine numbers for rating discomfort glare (Sivak et al., 1991). The DeBoer scale ranges from 1 (unbearable) to 9 (just noticeable). Participants gave a lower discomfort glare rating (i.e., worse rating according to the scale) when the gaps were narrower (i.e., the task was more difficult). Sivak et al. concluded that the more difficult task resulted in an increased discomfort glare rating.

Interventions have been enacted to reduce the amount of discomfort glare from oncoming vehicles. Designing a more pronounced cutoff in the headlamp beam pattern reduce the amount of light the driver receives from oncoming vehicles (Sivak and Flannagan, 1993). Proper alignment of headlamps is strongly recommended as it ensures the intense spot of the light is not focused on oncoming drivers (Mortimer, 1988). Legislation preventing the use of halogen high beams in the proximity of oncoming traffic has been implemented in several countries, including the United States. Finally, different headlamp technologies, including UV-A, have been considered as means of reducing glare (Sivak and Flannagan, 1993).

2.3 Effects of Age on Driving Capabilities and Limitations

Age is an important factor when considering the risks of nighttime driving. Currently, the percentage of older drivers is increasing as the population grows older (Bishu, Foster, and McCoy, 1991). In 1999, there were 18.5 million older persons with licenses, which represented 10% of all drivers (National Highway Transportation Safety Administration, 2000a). Older drivers have been involved in an increasing number of traffic fatalities, especially at night. Specifically, from 1980 to 1989 the rate of fatalities overall fell 8.4%

for the entire driving population but increased 43% in drivers over 65 years old (Barr, 1991). Older drivers have needs different than younger drivers, including higher levels of illumination, more visible pavement markings, and minimal exposure to glare sources on the roadways (Mortimer, 1989; Zwahlen and Schnell, 1999; Bishu et al., 1991).

Vision impairments have a large impact on driving performance, and older drivers exhibit different nighttime driving performances due in part to age-related vision degradation (Bishu et al., 1991). Older persons are afflicted with a wide range of perceptual compromises, including:

- Reduced acuity, especially at low contrast targets. This will reduce the detection ability of the driver, thereby allowing less time to react to the stimulus (Olson, 1993).
- Reduced contrast sensitivity, especially at higher frequencies (Mortimer, 1988). Reduced contrast sensitivity will result in drivers not being able to detect objects that have little contrast differences, namely pavement markings at night.
- Reduced flexibility of the iris, thereby reducing the amount of light into the eye (Bishu et al., 1991). As a result, older persons require more illumination than younger drivers to detect objects (Mortimer, 1989). This inflexibility also inhibits adaptation, intensifying the effects of discomfort glare.
- Decreased color vision accuracy (Knoblauch, Saunders, Kusuda, Hynes, Podger, Higgings, and de Monasterio, 1987). Because many cues are provided by color, this limitation will inhibit the amount of cues the older driver is able to attain.

Through self-report, older drivers confirm that the above visual limitations result in driving difficulties (Bishu et al, 1991).

Researchers have objectively measured how the vision deficiencies affect driving performance. For example, Zwahlen and Schnell (1999b) compared the detection distances of pavement markings for young and old drivers. Young drivers were found to have a 55% increase in detection distances over the older drivers group. Such an increase in detection distances could put young drivers at a large advantage for navigating the roadways safely at night.

To meet other needs of older drivers, many researchers have investigated the best means for increasing safety. Mortimer (1989) presented vehicle improvements to create the greatest mobility for older drivers, some of which include automatic headlamp cleaning and appropriate headlamp beam adjustment. With these recommendations, however, the author stressed the best options are non-vehicle factors. That is to say that changes in infrastructure, such as more visible pavement markings, are the best options for supporting older drivers.

Even with all the deficits in older drivers' vision, younger drivers still have a higher fatality rate overall (Mortimer, 1989). Contributors to the higher fatality rate of young people include higher rates of travel and drug use (National Highway Transportation Safety Administration, 2000). So although young people have the benefit of increased detection distances, the benefits are countered with to the other high-risk behaviors. However, pavement markings that provide increased visibility would also benefit younger by providing even larger detection distances in which to react, therefore reducing the negative effects of the higher speeds (Schnell and Zwahlen, 1999b).

2.4 Pavement Markings

Pavement marking visibility is crucial in assisting the driver with guiding the vehicle safely on the road and navigating between locations. Pavement markings help guide drivers to proper roadway positions and provide other navigational assistance (Schnell and Zwahlen, 2000). Furthermore, pavement markings can be used to improve driver performance. For example, researchers implemented lane drop pavement markings (indicating when the lane is eliminated on a highway exit) on two freeway exit lanes (Fitzpatrick, Lance, and Lienau, 1995). Driver behavior was observed on both sites in addition to a control site. It was found that with the addition of such markings, drivers were more proactive and less erratic in their lane maneuvers than without such markings.

For pavement markings to be effective, it is suggested that they provide the driver with a 3.65 second preview (Schnell and Zwahlen, 1999b). To attain such conspicuity, the pavement markings must provide adequate contrast with the pavement and draw the attention of the driver (Theeuwes, 1991). Contrast is dependent on the luminance, or lightness, of both the marking (L_T) and the pavement (L_B), as demonstrated by the following equation (Sanders and McCormick, 1993):

$$C = \frac{L_T - L_B}{L_B}$$

Materials differ in the amount of contrast they provide. Researchers have investigated the differences between pavement marking materials, namely new paint, worn paint, new thermoplastic, and fluorescent thermoplastic (Turner, Nitzburg, and Knoblauch, 1998). It was found by Turner et al. that the most visible pavement marking material was the fluorescent thermoplastic when viewed with halogen and UV-A headlamps. In contrast, all other materials were shown to have lesser visibility than the fluorescent thermoplastic.

Pavement marking visibility depends in part on the retroreflectivity, i.e., the amount of light reflected back to the driver, of the material. For example, Schnell and Zwahlen (1999a) found that more reflective pavement markings altered driver fixation patterns by increasing the distance ahead the drivers looked. Reflective pavement markings also increased viewing distances and times. Longer viewing distances increase vehicular safety, as drivers are more apt to see obstructions in the roadway, deviations in the roadway alignment, or other potentially dangerous situations. The increased viewing distances also allow for more time to react, supporting a more appropriate reaction.

It should be noted that besides retroreflectivity, vehicular speed affects pavement marking detectability. One research effort found a 40% decline in pavement marking detectability from a stationary position to a dynamic viewing, with travel speeds of 24 km/h, or 14.9 m/hr (Jacobs, Hedblo, Bradshae, Hodson, and Austin, 1995). Considering a decline of visibility occurred at a relatively low speed, the researchers argued that higher speeds would create an even greater decline in visibility, further increasing the need for more visible pavement markings.

Researchers have indicated that different lighting configurations react with pavement markings differently, making the markings more or less visible. Recently, researchers have measured the visibility of roadway markings with different headlamps (Zwahlen and Schnell, 1999). The researchers involved in this effort have shown that highly reflective materials with low-beam headlamps compensate for medium-reflective materials with high-beam headlamps. Therefore, the authors concluded that the reflectivity of the pavement markings was considered to be more important in detectability than the headlamp configurations. It should be noted, however, that only the two headlamps were evaluated, and other headlamp configurations could be found to equally compensate for pavement marking reflectivity.

Another technology, raised pavement markings (RPMs), has been shown to be beneficial for nighttime drivers by providing more visibility. The raised component has two main benefits. One, they increase the visibility of pavement markings. When headlamps hit a standard pavement marking, much of the light is reflected away from the driver. With the raised marking, more light is reflected back to the driver. In fact, Zwahlen and Schnell (2000) found that properly maintained RPMs required less strict minimum retroreflectivity requirements. Another benefit of RPMs is that the raised markings allow more water to run off the markings, making them more visible in wet conditions (Schnell and Ohme, 2000).

As part of a larger research effort, Schnell and Ohme (2000) evaluated the detection distances of pavement markings with and without RPMs. Both young and old participants indicated when they saw the last pavement marking in each section. When comparing those sections with RPMs to those without, younger drivers experienced a 76.2% increase in detection distances and older drivers experienced an 89.4% increase in detection distances.

With the benefit of increased visibility, RPMs have one drawback. RPMs require more maintenance than typical pavement markings because they wear out quickly (Schnell and

Ohme, 2000). This may pose a large cost constraint for road maintenance organizations, and therefore would inhibit the widespread use of RPMs.

Visibility models are being created to predict pavement marking visibility. One model, CARVE (Computer Aided Road marking Visibility Evaluator), has integrated factors such as age, retroreflectivity of markings, and the road surface into the model, which is based on human threshold models (Zwahlen and Schnell, 1999b, 2000; Blackwell, 1946). Incorporating all of the above factors, the model can predict the visibility distance of the materials. The data for this model is collected using dynamic experimentation on both young and older drivers. Drivers are asked to drive on the test facility and indicate when they can detect the end of the pavement markings. The data is integrated with characteristics of the pavement markings, (e.g., level of contrast between the pavement marking and the pavement), vehicles (e.g., location of light source), and drivers (e.g., eye height) to form a complete model. This model has not yet integrated the impact of different headlamp configurations other than halogen low beam and halogen high beam.

2.5 Headlamp Technologies

Headlamps serve two purposes: lane-keeping and obstacle detection for the driver under low-ambient illumination conditions (Sivak and Flannagan, 1993). To assist with the detection and recognition of obstacles and pavement markings, many headlamp technologies have been developed over the past eighty years.

2.5.1 Halogen low beam.

Halogen low beam, also known as Tungsten halogen low beam, is currently the most common headlamp for vehicles in the United Stated and Europe. As a result of the common use, halogen low beams are often considered the baseline headlamp configuration in night visibility studies.

Halogen technology is a relatively inexpensive headlight configuration. Electricity is forced through a filament, which causes resistance. This resistance leads to a build up of heat and results in the emission of visible light. This method is inefficient as far as energy conservation as the majority of the energy is lost as heat. The benefit to this technology is the low cost – the incandescent bulb is relatively inexpensive and, when magnified with reflectors behind the bulb, can be used as vehicle headlamps.

2.5.2 Halogen high beam.

In addition to the halogen low beam, the halogen high beam was designed to provide a larger area of illumination. This is achieved by increasing the output of the bulb in addition to raising the angle of output. As a result, a driver can see further down the road. However, high beams have regulations for use and cannot be used with other traffic on the road as the headlamps cause a large amount of glare for oncoming vehicles. In addition, in fog and other forms of precipitation high beams create a backscatter, which is the headlamp light reflecting off particles in the air back to the driver, causing glare for the driver using the high beams.

2.5.3 High-intensity discharge (HID) Headlamps.

HID lamps are a capsule structure in which a high-voltage current flows between two electrodes. This design is unique in that vibration does not compromise the light output, making it ideal for vehicular applications. HID lights had a high level of luminous efficiency, again making it a good candidate for vehicular applications (Woerner and Neumann, 1993).

With HID lights, energy is emitted in high concentrations at narrow bands of light. Usually these narrow bands occur at lower frequencies, reducing the level of color perception for drivers. This is especially true for the color red (Sivak, Flannagan, Gellatly, and Luoma, 1992). In one study, participants provided subjective ratings for different hues of red under HID lights. Participants were found to have a strong preference for one color of red and were sensitive towards colors that shifted into the orange range. In addition, HID lights are found to have a warm-up period where colors may be distorted (Sivak and Flannagan, 1993).

HID lights are considered beneficial in that they provide less backscatter than other lighting systems. Backscatter is the effect of the emitted light reflecting on particles in the air, causing glare and reduced visibility for the driver. With less backscatter, HID headlamps perform better in precipitation, namely fog.

HID lights also provide more freedom with headlamp design in that they allow headlamp size to be smaller. The smaller light size is achieved through the capacity of the light to produce higher levels of illumination. This in turn will reduce the size of the headlamp unit. Alferdink (1996) investigated the trade-off between headlamp size and discomfort glare. He found an increase in the level of glare with a decrease in the size of the headlamp. However, it was also found that reducing the intensity of the headlamp could adequately offset the smaller lamp size.

This new technology, however, has not been well researched, especially concerning pavement markings and disability glare. Despite the limited amount of research, this headlamp configuration has already been implemented as standard components on some new automobiles. Therefore, it was important for this headlamp configuration to be included in current and future research efforts.

2.5.4 Ultraviolet-A headlamps.

Ultraviolet-A (UV-A) and ultraviolet-B (UV-B) light is outside of the visible light spectrum with wavelengths of 280 to 400 nanometers. Two types of UV radiation are present on the earth's surface (National Oceanic and Atmospheric Administration, 2002). UV-A is represented by wavelengths from UV-A radiation range between 320 and 400 nm. UV-A is the most prevalent form of UV radiation on the earth's surface. UV-A is considered the least harmful to humans, but can contribute to ailments such as photoaging (toughening of the skin) and, to a small extent, cataracts. UV-B radiation represents the range between 280 and 320 nm. UV-B is more hazardous to humans than UV-A, and has long-term effects of cancer, cataracts, and immune system suppression.

Research has been conducted to determine any potential health effects of UV-A lights. One such study showed that the filters used on UV headlamps eliminate the harmful components of the UV component (Sliney, Fast, and Ricksand, 1995). With the combination of filters and minimized stationary exposure, it was concluded that the UV-A headlamps do not pose a safety threat.

UV-A headlamps provide many improvements in nighttime driving. First, ultraviolet light is outside the visible light spectrum, reducing the amount glare from oncoming vehicles equipped with these headlamps (Sivak and Flannagan, 1993). A second advantage is that UV-A headlamps will fluoresce materials containing phosphors. This includes most fabrics washed in common laundry detergents, creating more visibility for most pedestrians and bicyclists. However, some materials, for example black wool, are completely unresponsive to UV-A lights regardless of laundering (Turner et al., 1998).

UV headlamps have received a lot of research attention in recent years. First implemented on Swedish snowplows, UV headlamps have shown great potential for increasing visibility. Mahach, Knoblauch, Simmons, Nitzburg, and Tignor (1997) implemented both dynamic and static testing to determine the enhanced visibility of fluorescent pavement markings. During the dynamic testing, participants were asked to give a subjective rating of pavement marking visibility. Participants gave a higher subjective rating for the fluorescent pavement markings when used in conjunction with UV-A headlamps. With the static testing, participants were asked to count the number of center lines they could see, determine the distance they could see the side line, and subjectively rate the visibility with the headlamp configuration. In all three cases, a significant improvement was found with the UV-A headlamp configurations (versus the non-UV-A headlamp configurations).

Fast (1994) evaluated the effectiveness of UV-A headlamps in both rural and urban settings. Of concern were the visibility of road markings, street islands, delineation posts, and pedestrians, all with fluorescent qualities. Participants were required to rate the visibility on a ten-point scale as well as estimate the visibility distance on two types of public roads: country (i.e., without ambient lighting) and city (i.e., with ambient lighting). The tasks were performed with halogen low-beam headlamps and halogen low-beam headlamps with UV-A headlamps. Participants rated the visibility of pavement markings with a two-point advantage on country roads when using the UV-A with halogen low beam versus the halogen low beam alone. On the city roads, the UV-A configuration attained an 0.8-point advantage. A similar advantage of UV-A lights was found when participants were asked to estimate detection distances, with an average detection distance of eighty meters (with an 11 meter confidence interval) for halogen low beam to 178 meters (with a 28 meter confidence interval) for UV-A and halogen low beam with fluorescent pavement markings. All results were found to be significant.

Fast (1994) also investigated the effect of UV-A headlamps on a test track. Participants drove on the test track under both wet and dry conditions. Under both conditions, they were required to rate the visibility of the pavement markings and estimate the visibility distance. The halogen low beam with UV-A configuration received higher ratings over the halogen low-beam only configuration for both the dry condition (3.3-point advantage) and wet condition (1.6-point advantage). When estimating distance, the UV-A configuration received much larger distances in both the dry and wet condition. All results were found to be significant.

Another set of researchers investigated the enhanced visibility of various types of pavement markings (Turner et al., 1998). For this research effort, a test track was established to represent three types of pavement markings: right curve, no passing, and crosswalk. The test track was treated with new thermoplastic (i.e., non-fluorescent) material for both the centerline and the sideline. The distance of the participants' detection and recognition were recorded for all types of pavement markings with both halogen low beams and halogen low beams with UV-A headlamps. For all conditions except the right curve detection, a significant improvement was found with the UV-A configuration. Of the significant differences, improvements of detection distances ranged from 43% to 55%. For recognition distances, the improvements ranged from 13.5% to 55.5%.

2.5.5 High output halogen.

High output halogen (HOH) is a newer technology to come onto the market. It is currently available to replace standard halogen headlamp bulbs with the newer, higher-intensity bulbs. HOH is a halogen bulb that produces greater output than the standard halogen bulb. The higher light output is expected to increase visibility. However, it may also cause more discomfort glare for other drivers and uses more energy than standard bulbs. To date, this technology has also not been researched.

2.6 Summary

Of concern in transportation research are the issues of discomfort glare and reduced visibility, including the visibility of pavement markings, as they are related to nighttime driving. Recommended measures to decrease discomfort glare include altering beam patterns and different headlamp technologies, including UV-A. Researchers have shown that UV-A headlamps can improve pavement marking visibility (e.g., Fast, 1994; Turner et al., 1998). Pavement marking material has been shown to effect pavement marking visibility, and highly retroreflective materials are not only more visible but positively affect driving behaviors. Taking into account all previous research, however, a need exists to investigate new headlamp technologies, namely high-intensity discharge, high-output halogen, halogen high beam, and different levels of UV-A. Research not only needs to look at the potential increased visibility but the amount of glare that the headlamps will produce. For pavement markings, research efforts need to focus on pavement markings that were not previously investigated (e.g., 3M Liquid System) and possible enhancements from different headlamp technologies.

CHAPTER 3. METHODOLOGY

This research effort was conducted with one study on the Smart Road test facility in Blacksburg, VA., an initiative of the Virginia Tech Transportation Institute. The study was composed as a mixed-factors design, with headlamp configuration and pavement marking material as within subject factors and age as a between subject factor.

3.1 Research Overview

This research effort focused on ascertaining the headlamp technology (of the eleven specified) that minimized the amount of discomfort glare and maximized the visibility of three types of pavement marking materials used in the study. Two baseline conditions, halogen low beam (HLB) and high-intensity discharge (HID) were measured both individually and in combination with three levels of UV-A. In addition, three other headlamp configurations were evaluated.

Discomfort glare was measured subjectively for each headlamp configuration. Pavement marking visibility was directly measured via pavement marking detection distances. Three age groups participated in this study: young (18-25 years old), middle (40-50 years old), and older (60 years and older). The headlamp technology and the pavement marking material needed to be beneficial for all age groups as all would potentially use the new technology if it were implemented in vehicles and roadways in the future.

To determine the headlamp that produced the least amount of discomfort glare, all participants evaluated the discomfort glare of the eleven headlamp configurations. The discomfort glare was evaluated twice for each headlamp configuration: once at a far distance (far glare rating) and once at a close distance (close glare rating).

This research effort examined which of the three pavement marking materials provided the greatest visibility of the eleven headlamps specified. To determine this, the participant indicated when they saw the first (beginning detection distance) and last (ending detection distance) pavement marking in each section.

The current research effort was designed to answer the following questions:

- Which headlamp technology provided the least amount of discomfort glare at both the close and far road segments?
- Which headlamp configuration provided the largest beginning and ending detection distance?
- Which pavement marking material was most visible with all the tested headlamp configurations?
- What age differences existed in regard to discomfort glare experienced and pavement marking visibility?
- Was there a difference in low- versus high-profile vehicles for discomfort glare and/or detection distances?
- Did the addition of UV-A headlamps affect either discomfort glare or pavement marking visibility?
- Do visual capabilities affect discomfort glare or pavement marking detection distances?
- Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

In addition, presentation order was evaluated to determine if it was a significant factor and, if so, whether or not it was systematic.

3.2 Participants

Thirty participants, ten in each age group, took part in this research effort. This number of participants exceeded the number of participants per age group according to the precedence set by similar research (e.g., Zwahlen and Schnell, 1999b). Ten participants were between the ages of 18 and 25 (young category of drivers), ten were between the ages of 40 and 50 (middle category of drivers), and ten were over 60 years old (old category of drivers). Young drivers (less than 25) represent the age group with the highest rate of fatalities; enhanced visibility could potentially reduce the number of deaths each year (Mortimer, 1988). The middle age group represents the population that has the largest number of drivers. Older drivers have difficulty detecting low-contrast objects and report discomfort glare as a major problem with nighttime driving (Sivak and Olson 1984a; Bishu et al, 1991).

Drivers were recruited by using a participant database of people that had previously expressed interest in driving studies. Participants in the database were contacted through the Virginia Tech Transportation Institute via a telephone call. Once contacted, the participants were screened using a questionnaire that addressed the following (see Appendix 1):

- Driving record: Participant was not have to caused any driving accidents that resulted in an injury for the past two years
- Frequency of driving: Participants were required to drive at least twice a week
- Possible health complications: Participants must not have had any serious health conditions, such as heart attack, diabetes that required insulin treatment, stroke, head injury, or similar conditions.
- Vision/hearing capabilities: Participants were required to have normal or correctable vision and hearing.
- Willingness to participate: All participants had to express interest in completing the study.

Once the participants were considered eligible, they were scheduled for the required two nights. All participants were scheduled for two consecutive nights to increase the consistency between sessions. Participants were required to read and complete an Informed Consent Form (see Appendix 2) before participating. Compensation for participants was $20 per hour.

3.3 Apparatus

3.3.1 Headlamp Configuration.

Eleven headlamp configurations were evaluated in this research effort. The headlamp configurations were selected to meet contract requirements and/or to evaluate technologies provided to the Virginia Tech Transportation Institute through vendors.

Two baseline conditions, halogen low beam (HLB) and high-intensity discharge (HID) were used in this research effort. The baseline conditions were evaluated independently and with three levels of ultraviolet-A (UV-A) headlamps.

Table 1 below represents the headlamp configurations used in this research effort. Also indicated are the headlamp specifications, beam patterns, and vehicle/headlamp profile (high versus low). There are several important distinctions to note when reading Table 1. The first is the difference between the baseline condition (HLB, HID) beam patterns. The HLB beam pattern has a straight-ahead pattern, which is designed to project light further down the road. This beam pattern is standard on American vehicles. The HID beam pattern contains a sharp cut-off, which is designed to reduce the amount of light for oncoming vehicles. This beam pattern is standard in European vehicles. Due to the wider beam pattern, this headlamp pattern provides more light to the sides of the road. High output halogen, halogen high beam, and halogen low beam- low profile also have the straight-ahead beam pattern.

The second distinction is between the halogen low beam and the halogen low beam- low profile. All headlamp configurations were mounted on high profile vehicles except the halogen low beam- low profile, which was mounted on a sedan. This arrangement will allow a relative comparison of HLB headlamp height. It should be noted, however, that different luminaries, or light housings, were used, so the comparison will be slightly limited.

The third distinction is that three headlamp configurations – high output halogen, halogen high beam, and halogen low beam- low profile – used the same housing but different bulbs. This is unique because all of the other headlamp configurations used different housings. This condition will facilitate some comparisons between bulb types.

Table 1. Headlamp configurations.

Headlamp Configuration	Description	Headlamp Specifications	Beam pattern (non-UV-A only)	Vehicle Profile
Halogen low beam (HLB)	Baseline condition.	Motorcraft halogen	Standard, straight on pattern	High profile (SUV)
Hybrid UV-A + HLB	Hybrid UV-A condition paired with the HLB baseline condition.	Hybrid UV-A: prototype lights from Visteon that contained a visible light component. HLB: Motorcraft halogen	HLB: Standard, straight-ahead pattern	High profile (SUV)
Middle UV-A + HLB	Middle UV-A condition paired with the HLB baseline condition.	Middle UV-A: Three ABM-1 spotlights. These UV-A lights had no visible light component. HLB: Motorcraft halogen	HLB: Standard, straight-ahead pattern	High profile (SUV)
High UV-A + HLB	High UV-A condition paired with the HLB baseline condition.	High UV-A: Five ABM-1 spotlights. These UV-A lights had no visible light component. HLB: Motorcraft halogen	HLB: Standard, straight-ahead pattern	High profile (SUV)
High Intensity Discharge (HID)	Baseline condition.	Bosch headlamps, made for Mercedes Benz.	Sharp cut-off, wider pattern	High profile (SUV)

Headlamp Configuration	**Description**	**Headlamp Specifications**	**Beam pattern (non-UV-A only)**	**Vehicle Profile**
Hybrid UV-A + HID	Hybrid UV-A condition paired with the HID baseline condition.	Hybrid UV-A: prototype lights from Visteon that contained a visible light component. HID: Bosch headlamps, made for Mercedes Benz.	HID: Sharp cut-off, wider pattern	High profile (SUV)
Middle UV-A + HID	Middle UV-A condition par paired with the HID baseline condition.	Middle UV-A: Three ABM-1 spotlights. These UV-A lights had no visible light component. HID: Bosch headlamps, made for Mercedes Benz.	HID: Sharp cut-off, wider pattern	High profile (SUV)
High UV-A + HID	High UV-A condition par paired with the HID baseline condition.	High UV-A: Five ABM-1 spotlights. These UV-A lights had no visible light component. HID: Bosch headlamps, made for Mercedes Benz.	HID: Sharp cut-off, wider pattern	High profile (SUV)

Headlamp Configuration	Description	Headlamp Specifications	Beam pattern (non-UV-A only)	Vehicle Profile
High Output Halogen	Non-baseline halogen, representative of a headlamp type available after-market.	AC Delco housing, made for Cadillac, with a GE high-output halogen bulb. (Note: This is the same luminaries as the halogen low beam- low profile condition but replaced the standard low beam bulb with the HOH bulb.)	Standard, straight-ahead pattern	High profile (pick up)
Halogen High Beam	Non-baseline halogen, representative of the high beam option on all vehicles.	AC Delco housing, made for Cadillac, with the standard high beam bulb. (Note: This is the same luminaries as the halogen low beam- low profile condition but using the high beam bulb.)	Standard, straight-ahead pattern	High profile (pick up)
Halogen low beam- low profile	The only low profile headlamp	AC Delco housing, made for Cadillac. This configuration was original equipment for this model vehicle.	Standard, straight-ahead pattern	Low profile (sedan)

3.3.2 Pavement Markings.

Three sections of pavement markings were placed on the Smart Road, consisting of fluorescent paint, fluorescent thermoplastic, and 3M Liquid System materials. Fluorescent paint contains phosphorous material, and is applied as a liquid. The fluorescent thermoplastic also contains phosphorus materials but is a tape instead of a liquid. The 3M Liquid system is applied as a liquid. The headlamp configurations were selected to meet contract requirements and/or to evaluate technologies provided to the Virginia Tech Transportation Institute through vendors.

Pavement markings were comprised of yellow centerline markings and white edge line markings of the same material; such a scheme is consistent with roadways in the United States. Each centerline pavement marking was ten feet long with a thirty-foot gap between each. The side pavement markings were continuous over each section.

For this research effort several center markings and the corresponding side markings at the beginning and ending of each section were concealed, thereby creating distinct sections (see Appendix 8). The created lengths for the fluorescent paint, fluorescent thermoplastic, and 3M Liquid System were 990 feet, 1333.8 feet, and 606.4 feet, respectively. The sections were different lengths for the following reasons. One, the sections were created in different lengths at 2240 feet for the fluorescent paint, 2400 feet for the fluorescent thermoplastic, and 2040 feet for the 3M Liquid System section. Two, the sections were set up so the roadway alignment did not obscure the beginning or ending of a section. The test facility is curvilinear over the testing section.

To minimize the effect of alignment, the beginning and last pavement markings were located in straight sections of road. If the section beginning or ending was located near a curve, there was a risk that the roadway alignment itself would obscure the pavement markings. This obstruction would occur if the pavement markings of interest were visible from a distance greater than the distance from the end of the curve to the marking. If that were the case, the participants would be able to see the pavement markings as soon as they drove out of the curve, creating data that would reflect not the visibility of the pavement marking but the distance from the curve to the marking. Therefore, the beginning and ending pavement markings were placed in straight segments of road, where the participants would be on the straight section before the pavement markings were visible.

3.3.3 Vehicles.

Six vehicles were used for the on-road study. Hardware professionals at the Virginia Tech Transportation Institute were responsible for installing the tested headlamps. Three of the vehicles were high-profile vehicles, two were sport utility vehicles and one was a pick-up truck. These vehicles were selected to ensure a similar headlamp height for all lighting conditions. Headlamp height influences the angle in which the headlamp light illuminates objects. By using vehicles of a similar height one confound, headlamp height was reduced. The height confound was not completely eliminated as the headlamps bulbs of the HLB and HID lights, the two baseline conditions, differed by 3.4 inches vertically and 10.77 inches laterally. This difference in height is due to the location of the bulb, or light source, within the headlamp casing and not the mountings, which were the same height. A similar confound, passenger height, was also minimized by using similar types of vehicles. The passenger height confound is discussed in detail later in this document.

The first vehicle, a Ford Explorer, was equipped with two Hybrid UV-A lights and the ability to interchange the baseline headlamps, HLB (not the low-profile) and the HID lamps. All lights were mounted on a metal plate on the front of the vehicle grill to maintain a minimal height and separation distance for the two baseline conditions. The HID and the HLB lights were on mounting plates that were exchanged each night, the UV-A lights were permanently mounted on a bar in front of the grill. By exchanging the HLB and the HID headlamps between data collection sessions, each baseline condition was paired with the Hybrid UV-A headlamps equipped on this vehicle.

The second vehicle, a Ford Explorer, was equipped with the Middle and High UV-A lights and the ability to interchange the baseline headlamps, HLB (not the low-profile) and the HID lamps. All lights were mounted on a metal plate on the front of the vehicle grill to maintain the same height and separation distance for the two baseline conditions. The HID and the halogen lights were on mounting plates that were exchanged each night. The UV-A Middle and High UV-A headlights were mounted on the metal bar in front of the vehicle grill. The Middle and High UV-A conditions were achieved by using three (Middle UV-A) or five (High UV-A) UV-A spotlights. By exchanging the HLB and the HID headlamps between data collection sessions, each baseline condition was paired with the Middle and High UV-A headlamps equipped on this vehicle.

The third vehicle, a Chevy 1500 full-size pick-up, was equipped with high-output halogen and halogen high-beam bulbs. Both bulb types were located in the same housing with the high-output halogen replacing the standard low-beam bulb that was standard in the lighting unit.

The fourth, a Cadillac DTS, was equipped with the halogen low beam- low profile headlamps. This headlamp configuration was original equipment for this model vehicle. Since this vehicle is a sedan and has a lower profile than the other vehicles used, the headlamps were also lower profiled.

The fifth and sixth vehicles were Chevrolet Cavaliers that participants drove during the glare portion of the experiment. These vehicles were not instrumented; the participants drove with the headlamp configuration (i.e., halogen low beam- low profile) that was equipped on the vehicles.

3.3.4 In-vehicle equipment configuration.

All vehicles were equipped with a NiteStar Distance Measuring Instrument (DMI), a laptop computer and a hand-held button. The NiteStar unit was directly wired to each vehicle to accurately measure distance, within one foot per mile (www.nu-metrics.com). During the pavement marking data collection, the laptops rested on the experimenter's lap. Participants pressed the hand-held buttons when they saw the first and last pavement marking in each section. The NiteStar unit and the hand-held button was directly connected to the laptop computer via serial ports, allowing for data input from both the in-vehicle experimenter and the participant.

All vehicles had a two-way radio for contact between experimenters. Communication was used to notify when the on-road experimenters were ready (i.e., when they were positioning vehicles for the glare portion of the experiment) and to communicate any problems that occurred during data collection.

The two UV-A equipped vehicles had master switches inside the vehicles to prevent inadvertent activation of the UV-A headlamps. The in-vehicle experimenter had the key for the switch, therefore was solely responsible for the activation of the lights. Researchers investigating the risk of UV-A have concluded that the exposure to damaging UV-A radiation is not greater than that of standard white lights (Sliney, Fast, and Ricksand, 1995). Despite the low risk, researchers have recommended limiting the exposure of UV-A while the vehicle is stopped (Nitzberg, Siefert, Knoblach, and Turner, 1998). By having the master switch where the experimenter can access it, they can be sure to shut off the lights while the vehicle is not in motion, thereby limiting exposure to UV-A.

3.3.5 Vision tests.

Three vision tests were implemented as described in Jennsen et al. (1996) and Sivak and Olson (1984b). The results for each participant were recorded according to the manufacturers instructions (see Appendix 3). Only the visual acuity test was used for screening; participants had to have at least 20/40 visual acuity (either corrected or uncorrected) to participate in the study.

The first vision test was a visual acuity test. Acuity, or the ability to detect detail, is important in detecting an object; reduced acuity can decrease detection distance, thereby allowing less time for accurate responses (Olson, 1993). The Snellen Eye Chart was implemented for this measurement. This test was implemented with the participant standing 20 feet from the eye chart. The Snellen consists of rows of letters, each row with letters of decreasing size. Participants were asked to read the letters in each row with both eyes open. The smallest row the person could accurately read represented their visual acuity. For this study, a minimum of 20/40 visual acuity, either corrected or uncorrected, was required. This requirement was consistent with the minimum requirements to attain a driver's license. The Snellen eye chart is the standard eye examination used for the majority of all driving experiments. The chart provided acuity to be measured in specific increments, including 20/10, 20/13, 20/15, 20/20, 20/25, and 20/40. The acuity score was recorded onto the participant's vision test form (see Appendix 3).

The second test measured the participant's contrast sensitivity, or the threshold of spatial frequency a person can detect between an object and the background (Sanders and McCormick, 1993). The Vistech Contrast Sensitivity chart was comprised of six rows each containing nine patches. Each row down the chart represented increasing spatial frequency and each column across the chart represented reduced contrast. The participant stood at a distance of ten feet and told the experimenter in which patch in each row they can determine the orientation of the lines: right, left, straight up, or was blank. The experimenter recorded each response in the graph on the participant's vision test form (see Appendix 3). This procedure was completed for both eyes, testing one eye at a time while the other eye was occluded. By filling in the graph provided by the manufacturer, one could quickly assess whether the participant had average contrast sensitivity (within the shaded area) or below average contrast sensitivity. Contrast deficiencies could impact the detectability of low-contrast items (i.e. pavement markings) throughout the study. The results of this test were not used for screening but were incorporated into analyses later.

The third test was the Ishihara Color Vision Test. This allowed the experimenters to determine any color deficiencies, which could in turn impact the detection distance in that the participant would not receive color cues to assist in pavement marking detection. No participants demonstrated color vision deficiencies; therefore this test was not used later in analyses.

3.4 Hardware

For this research effort, each equipped vehicle had a NiteStar Distance Measuring Instrument (DMI), a laptop computer and a hand-held button. The DMI was wired to the vehicle to provide an accurate measurement of distance, accurate within one foot per mile (www.nu-metrics.com). The laptop was connected to the hand-held button and to the DMI for the pavement marking task. For each pavement marking section three measurements were recorded: two button presses, which represented when the participant saw the first and last pavement marking in each section, and one space bar press, which represented when the vehicle passed the last pavement marking in each section and was completed by the in-vehicle experimenter. Every time the participant pressed the button or the in-vehicle experimenter pressed the spacebar on the laptop computer, the laptop attained the distance from the DMI and recorded that distance. Those three measurements provided a complete set of distance data.

The vehicles were equipped with a hand-held button for participants to press when they saw the first and last pavement marking in each section. The unit was slender with the button on the top (i.e., was pressed with the participant's thumb) so participants could fit the unit in their hand while holding the steering wheel.

3.5 Software

For this research effort, software was developed at the Virginia Tech Transportation Institute to allow data entry by the participant (i.e., button press) and by the experimenter (i.e., space bar press). In addition, the software allowed the experimenter to enter other information such as participant number, age and gender, headlamp configuration, and data collection night (first or second). The software converted the data input into distances as read from the NiteStar DMI and saved the three distances for each of the three pavement marking sections into a single file. All participant information (i.e., participant number, age, night of data collection, gender, time of data collection) was also integrated into the file.

3.6 Experimental Design

This research effort was an 11x3x3 mixed-factors design. The between subject factor was age. The within subject factors include headlamp configurations and pavement markings. Thirty participants provided glare ratings and pavement marking detection distances for all eleven headlamp configurations and three pavement marking materials.

3.7 Independent Variables

Three categories of independent variables were implemented in the research effort: headlamp configuration (11 levels), pavement markings (3 levels), and age (3 levels).

3.8 Dependent Variables

Dependent variables for this research effort were comprised of: (1) a far discomfort glare evaluation, (2) a close discomfort glare evaluation, (3) detection distances of the first pavement markings, and (4) detection distances of the last pavement markings.

3.9 Personnel

Two in-vehicle experimenters and three on-road experimenters were required for each data collection session. Responsibilities for in-vehicle experimenters included conducting vision tests, familiarizing participants to the Smart Road and the study, recording data, and answering questions the participants had throughout the study (see Appendix 4). In-vehicle experimenters were with the participants at all times. Responsibilities for on-road experimenters included preparing the road and vehicles, driving glare source vehicles, and orienting participants to vehicles (see Appendix 5).

3.10 Procedures

3.10.1 Headlamp Counterbalancing.

Due to hardware constraints, special considerations were taken while counterbalancing the headlamp configurations. The headlamp configurations that could be presented in the same night were grouped. The groups were based on the location of the baseline headlamps (HLB, HID) that night, either on the vehicle with the Hybrid UV-A headlamps or the vehicle with the Middle/High UV-A headlamps. That is, these headlamps had to be grouped together each night due to the placement of the baseline headlamps. The groups were as follows:

Group 1:	HLB
	Hybrid UV-A + HLB
	Middle UV-A + HID
	High UV-A + HID
Group 2:	HID
	Hybrid UV-A + HID
	Middle UV-A + HLB
	High UV-A + HLB

To evaluate the other lights, the HOH and halogen high beam was added to Group 1; the halogen low beam- low profile condition was added to Group 2. Therefore the groups were this:

Group 1:	HLB
	Hybrid UV-A + HLB
	Middle UV-A + HID
	High UV-A + HID
	Halogen high beam
	HOH
Group 2:	HID
	Hybrid UV-A + HID
	Middle UV-A + HLB
	High UV-A + HLB
	Halogen low beam - low profile

The headlamp groupings remained constant throughout the evaluation. However, the night in which they were presented (night one or two) alternated. This resulted in one-half of the participants presented with Group A on night 1 and the other half presented with Group B on night 1.

For each data collection session, two participants completed the evaluations at the same time. Within each group, 15 different presentation orders, one for each set of participants (i.e., each set of participants evaluated the headlamp configurations in a unique order) was selected from a list of randomized orders for the pavement marking evaluation. When selecting the presentation orders, one additional consideration was applied. For the glare evaluations, two vehicles would be on the road at the same time and presented immediately after one another, therefore the same vehicle could not be used twice in the same lap. Only orders that met this constraint were selected. Once the orders were selected, they were then paired so that two participants could be run at the same time without overlapping vehicles (see Appendix 9).

For the pavement marking evaluation, 30 different presentation orders, one for each participant (i.e., each participant was evaluated the headlamp configurations in a unique order) was selected from a list of randomized orders. The consideration for the pavement marking evaluation presentation orders was that participants could not be evaluating headlamps from the same vehicle in the same lap. Therefore, orders were selected and paired based on compatibility.

3.10.2 Vehicle Set-up.

Before each test session, the baseline headlamp configuration units were exchanged on vehicles and all headlamp configurations for that night were aligned. Headlamp alignment is crucial for both visibility and level of discomfort glare. Discomfort glare has been found to increase linearly as the glare angle increased exponentially (Alferdink, 1996).

One in-vehicle experimenter and one hardware personnel aligned the headlamps each night. The following headlamp alignment procedure was designed with consultation of an industry expert (J. Calderas, personal communications, August 22, 2000). To align the headlamps, the vehicles were positioned 35 feet from a white screen. Vehicles were pulled up to a piece of angle iron stationed on the floor parallel to the screen. The screen was a large piece of plastic with representations of the light source (i.e., bulb) location of each headlamp on the screen. For the non-UV-A lights the highest intensity spot was located in the fourth quadrant perpendicular to the horizontal and vertical representation on the screen. For the UV-A headlamp configurations the spot of highest intensity was concentrated on the horizontal and vertical representation on the screen. The lights were set using the angular adjustment screws. The highest intensity spot was measured by taking light measurements with an International Light IL 1400A photometer. The photometer had a visible light and a UV-A sensor attachment.

During the alignment, all UV lenses were inspected for any cracks or damage and were cleaned. Although UV-A radiation is considered safe for humans, any flaws in the protective lens of the light may increase the exposure to the UV, therefore increasing the risk of injury (Nitzburg, Seifert, Knoblauch, and Turner, 1998). No imperfections were found throughout the data collection process.

3.10.3 Test Facility.

This research effort took place on a portion of the Smart Road (see Appendix 6). The Smart Road provided an ideal testing facility for several reasons. One, it provided a closed-off road segment to maximize safety for the participants and experimenters. Two, the secluded roadway allowed customization of the road for the study. Three, the ambient lighting could be and was eliminated, therefore decreasing the variability of the data.

One confound in this research effort was the different pavements on the Smart Road. The fluorescent paint was on concrete, where the fluorescent thermoplastic and 3M Liquid System pavement markings were on asphalt. With the difference in contrast between the pavement types (concrete is much lighter, therefore had less contrast with the pavement marking), a confound was considered when interpreting the data and is discussed later in this document.

Some preparation to the Smart Road was completed before testing. The different pavement marking sections were defined by hiding pavement markings at the beginning and ending of each section, therefore making gaps where no pavement markings were visible. In addition, the locations indicating the segments of road used in the glare analysis were spray-painted on the side of the road. The road customizations were constant for this data collection process.

3.10.4 Test Conditions.

All participants drove in clear weather. Any precipitation on the roadway (e.g., rain, snow, or fog) resulted in rescheduling that night's sessions. Participants were rescheduled if there was a significant chance of precipitation.

The rationale behind the clear-weather only restriction was two-fold. First, any precipitation would alter the retroreflectivity of pavement markings, thereby altering the results if the study. Second, moisture in the air would affect the transmissivity of the atmosphere, thereby also altering visibility and glare (Schnell and Zwahlen, 2000).

3.10.5 Participant Screening and Familiarization.

Participants screening and familiarization took place as previously discussed. Once at the VTTI, participants completed the Informed Consent Form and the vision tests (see Appendix 2 and 3). Participants were then familiarized with the glare protocol, which included familiarization with the DeBoer scale and a diagram of the vehicle positions (see Appendix 7). The participants were taken to the vehicles the participants drove for the discomfort glare evaluation, two identical Chevrolet Cavaliers. The participants drove to the Smart Road test facility. On the Smart Road, the test vehicles were lined up at the first Smart Road turnaround location (see Appendix 6 for diagram).

3.10.6 Glare Protocol.

The discomfort glare protocol was adapted from Sivak and Olson (1988). Participants drove on the road at 25 miles-per-hour. The participants were asked to monitor their speed; if they exceed the speed limitation, the in-vehicle experimenter asked them to reduce their speed. On-road experimenters parked the glare source vehicles in the opposite lane from the traveling participant vehicle and turned on the appropriate headlamp configuration. Per Sivak and Olson's protocol (1988), the following represent the distances from the glare source for the glare evaluation: 1300 to 1000 feet and 450 to 150 feet. The beginning and end of the segments were indicated with cones on the shoulder of the road. Figure 1 below represents the positions of the vehicles during the glare evaluation. The white vehicle represents the vehicle the participants were driving; sections are represented on the right side of the diagram.

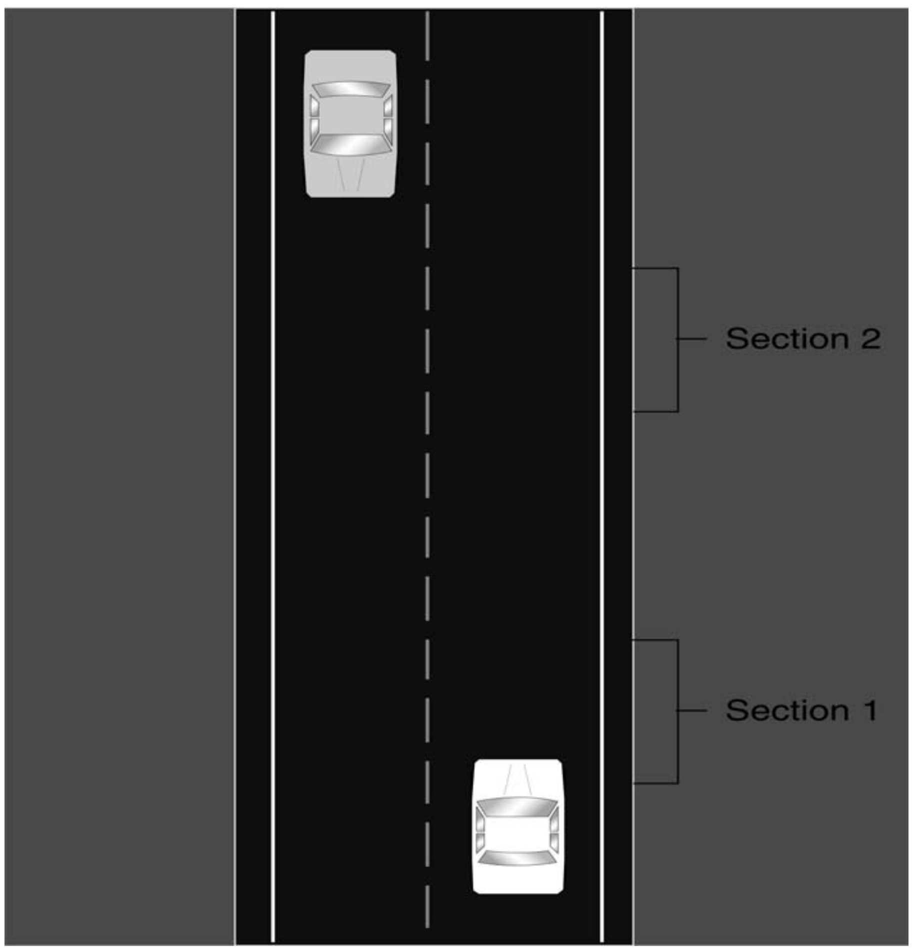


Figure 1. Vehicle positions during the glare evaluation.

At the beginning of each segment, the in-vehicle experimenter said, "Begin," and the participants were asked to begin thinking about the rating they feel most reflects their experience. At the end of the segment, the in-vehicle experimenter said, "Give me your rating." At that time, the participants gave the rating and the in-vehicle experimenter recorded the rating. Over the two segments of road, the participant was asked to evaluate the discomfort glare based on the DeBoer scale:

1	Unbearable
3	Disturbing
5	Just Acceptable
7	Satisfactory
9	Just Noticeable

Two discomfort glare stations were set up in each direction (both directions on the road), resulting in four stations on the road. Therefore, three laps were required to complete the evaluation of the five or six headlamp configurations each night. While conducting the discomfort glare portion, only the two vehicles required to serve as the glare source for that lap and the vehicles the participants were driving were on the road. On-road experimenters were responsible for moving the vehicles in and out of position for all three laps.

3.10.7 Pavement marking protocol.

The pavement marking task was only performed in one direction on the road; participants began the task at the second turn around at the bottom of the road. At the turn around, the in-vehicle experimenter gave the participants a hand-held button. Participants were asked to press the button when they detected the first and last pavement marking in each of three sections. The button press method had been used in other research efforts with success (e.g., Sivak and Olson, 1984b). By having the participant press a button, the participant's response was immediately recorded (versus having an experimenter respond to a vocalization of the participant), resulting in more accurate data. The participant completed this task for each of eleven headlamp configurations over all three pavement marking sections.

In order to provide a final distance to calculate the detection distances, the in-vehicle experimenters pressed a button when the participants were even with the last pavement marking. The distances was read from the NiteStar DMI and recorded by the laptop computer.

The method of detection used for this protocol is adapted from a methodology developed by Zwahlen and Schnell (1995). This research effort implemented indicated the beginning and ending pavement marking. Similar methodologies (without the detection of ending detection distance only) to the one selected have been shown to have positive results in numerous studies (i.e., Zwahlen and Schnell, 1997; Zwahlen and Schnell, 1996; etc.).

3.10.8 On-road data collection techniques.

Participants drove one-half of a lap for familiarization where no tasks were performed. The familiarization was to make persons unfamiliar with the Smart Road feel more comfortable with driving on the road at night in the absence of ambient lighting. Considering the familiarization was only to make the participants more comfortable with the road, it was thought that one-half a lap would be sufficient. In fact, no participant indicated more familiarization was needed. During this familiarization lap, the in-vehicle experimenter pointed out various points on the road, including the first and second turn around, and answered questions. Once at the second turn-around, the participants were shown a paper with the DeBoer scale and were reminded of the protocol. The participants then began the discomfort glare evaluation process. All experimenters had a presentation order sheet for each participant (see Appendix 10). After each lap, the participants were again shown the evaluation scale and the in-vehicle experimenter answered any questions.

At the conclusion of the last discomfort glare evaluation lap, the participants were instructed to park at the first turn-around. At this time, the participants were familiarized to the pavement marking protocol. The familiarization included verbal instructions as well as diagrams to illustrate the separation of the pavement markings sections (see Appendix 8). Participants were also told that they would be oriented to and driving different vehicles during the pavement marking section.

After the familiarization, the participants were oriented to their first vehicle by the on-road experimenters. All experimenters had a presentation order sheet for each participant (see Appendix 10). Once the participant was situated and the in-vehicle experimenter had prepared the laptop and initialized the appropriate headlamp configuration, the participant was instructed to drive down the road and wait at the second turn-around.

Once at the second turn-around, the pavement marking familiarization lap began. The participant was reminded of the protocol and given the button. Then, the participant performed the familiarization lap while driving twenty-five miles-per-hour up the road and performed the pavement marking detection task. After the familiarization lap, the participants completed the data collection laps.

If during the pavement marking task participants vocalized that they did not accurately indicate either the first or last pavement marking, the lap was either completed again or, in the case where the participant was showing signs of fatigue toward the end of the last planned lap, the data for the headlamp configuration was excluded and considered missing data. The latter occurred infrequently, less than 1% of the trails.

3.10.9 Second night protocol.

On the second night, participants returned to the VTTI. At that time, the in-vehicle experimenters answered questions about the protocol. Then, the in-vehicle experimenter took the participant to the Chevrolet Cavaliers and drove to the Smart Road. All protocols were repeated except no familiarization lap took place.

3.11 Pilot Participants

A total of six pilot participants were run in preparation of data collection. The participants completed both nights of the study. Pilot participants were used to refine protocols. During the pilots, improvements the data collection process (e.g., phrasing of familiarization) were noted and changed for the next session. Changes mainly consisted of procedural changes for conducting nighttime studies on the Smart Road at night, including moving vehicles between glare evaluations and vehicle positioning. No changes were made to the primary protocols, i.e., the glare protocol or the pavement marking protocol. The revisions required three sets of participants until the protocols were adequate for data collection. Each set of participants was run with the newest revision of the protocol. The pilot participant data was not used in later analyses.

3.12 Statistical Analyses

Statistical analyses were conducted using the SAS® Version 8 software package. All analyses of variance (ANOVAs) using the presentation order, discomfort glare and pavement marking data were conducted using the general linear model (GLM) procedure to adjust for missing data and utilized an alpha level of 0.05, meaning that there is a 5% chance that a significant result will not represent a real difference. In addition, Student Neuman Keuls (SNK) tests were conducted as post-hoc analyses of main-effect means. Means with the same letter (i.e., SNK grouping) are not significantly different.

Missing data only occurred when participants did not provide a complete set of data. For example, if during the pavement marking task participants vocalized that they did not accurately indicate either the first or last pavement marking, the lap was either completed again or, in the case where the participant was showing signs of fatigue toward the end of the last planned lap, the data for the headlamp configuration was excluded and considered missing data. The latter occurred infrequently, less than 1% of the trails. For this data, a placeholder was inserted into the dataset and was computed by SAS.

The first analysis was conducted to determine the presentation order affect. For this analysis, presentation order was evaluated as a lone factor (1) to determine if there is an effect and (2) if an effect does exist, determine whether or not the effect is systematic. A systematic cause would greatly influence the remaining results, therefore would be included in future analyses. In fact, the effect did not appear to be systematic; therefore the presentation order was excluded from further analyses (see Section 5.1 for a discussion).

The second set of analyses assessed the discomfort glare evaluation. For this set of two ANOVAs, one for close and one for far discomfort glare, the factors of interest included: headlamp configuration (designated as HL), and age (which is nested in subject, designated as Subject). The results of these analyses were used to answer the following research questions:

- Which headlamp technology provided the least amount of discomfort glare at both the close and far road segments?
- What age differences existed in regard to discomfort glare experienced and pavement marking visibility?
- Was there a difference in low- versus high-profile vehicles for discomfort glare and/or detection distances?
- Did the addition of UV-A headlamps affect either discomfort glare or pavement marking visibility?
- Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

The third set of analyses assessed the pavement marking evaluation. For this set of two analyses, one for beginning and one for far detection distances, the factors of interest included: headlamp configuration (designated as HL), pavement marking material (designated as Pvt.Mrkg), and age (which is nested in subject, designated as Subject). The results of these analyses were used to answer the following research questions:

- Which headlamp configuration provided the largest beginning and ending detection distance?

- Which pavement marking material was most visible with all the tested headlamp configurations?
- What age differences existed in regard to discomfort glare experienced and pavement marking visibility?
- Was there a difference in low- versus high-profile vehicles for discomfort glare and/or detection distances?
- Did the addition of UV-A headlamps affect either discomfort glare or pavement marking visibility?
- Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

A fourth set of analyses examined differences between the baseline configurations. The analyses looked at both close and far glare and beginning and ending detection distances for the two baseline conditions and the levels of UV-A paired with each. The factors of interest included level of UV-A (designated UV-A), baseline condition (designated Baseline), and age (designated Age). These evaluations were used to answer the following research question: Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

A fifth set of analyses will look for differences between the halogen low beam configurations (including high output halogen). The analyses looked at both close and far glare and beginning and ending detection distances for only the HLB conditions. The factors of interest included headlamp configuration (designated as HL), pavement marking material (designated as Pvt.Mrkg), and age (which is nested in subject, designated as Subject). These evaluations were used to answer the following research question: Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

The final analysis is a correlation analysis to determine whether or not there is a relationship between vision test results and pavement marking detection distances. This analysis was used to answer the following research question: Do visual capabilities affect discomfort glare or pavement marking detection distances?

CHAPTER 4. RESULTS

The results of the analyses are presented below in the following order: presentation order, discomfort glare, pavement marking, levels of UV-A, levels of HLB, and vision test results. For the presentation order analysis, the factor of interest was order (designated as Order), which represented the presentation order (1 to 11) across both nights. Immediately following the results of the presentation order analyses is a discussion as to whether or not the presentation order effect was systematic.

The second set of analyses assessed the discomfort glare evaluation. For this set of two ANOVAs, one for close and one for far discomfort glare, the factors of interest included: headlamp configuration (designated as HL), and age (designated as Age, which is nested in subject, designated as Subject). The results of these analyses were used to determine which headlamp technology provided the least amount of discomfort glare, what age differences existed in regard to discomfort glare experienced and pavement marking visibility, whether or not there was a difference in low- versus high-profile vehicles for discomfort glare, whether or not the addition of UV-A headlamps affected discomfort glare, and ultimately which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement.

The third set of analyses assessed the pavement marking evaluation. For this set of two analyses, one for beginning and one for far detection distances, the factors of interest included: headlamp configuration (designated as HL), pavement marking material (designated as Pvt.Mrkg), and age (designated as Age, which is nested in subject, designated as Subject). The results of these analyses were used to answer determine which headlamp configuration provided the largest beginning and ending detection distance, which pavement marking material was most visible with all the tested headlamp configurations, what age differences existed in regard to discomfort glare experienced and pavement marking visibility, whether or not there was a difference in low- versus high-profile vehicles for detection distances, whether or not the addition of UV-A headlamps affected pavement marking visibility, and ultimately which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement.

A fourth set of analyses examined differences between the baseline configurations. The analyses looked at both close and far glare and beginning and ending detection distances for the two baseline conditions and the three levels of UV-A paired with each. The factors of interest included level of UV-A (designated UV-A), baseline condition (designated Baseline), and age (designated as Age, which is nested in subject, designated as Subject). These evaluations were used to answer the following research question: Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

A fifth set of analyses will look for differences between the halogen low beam configurations and high output halogen configuration. The analyses looked at both close and far glare and beginning and ending detection distances for only the HLB conditions. The factors of interest included headlamp configuration (designated as HL), pavement marking material (designated as Pvt.Mrkg), and age (designated as Age, which is nested in subject, designated as Subject). These evaluations were used to answer the following research question: Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

The final analysis was a correlation analysis to determine whether or not there is a relationship between vision test results and pavement marking detection distances. This analysis was used to answer the following research question: Do visual capabilities affect discomfort glare or pavement marking detection distances?

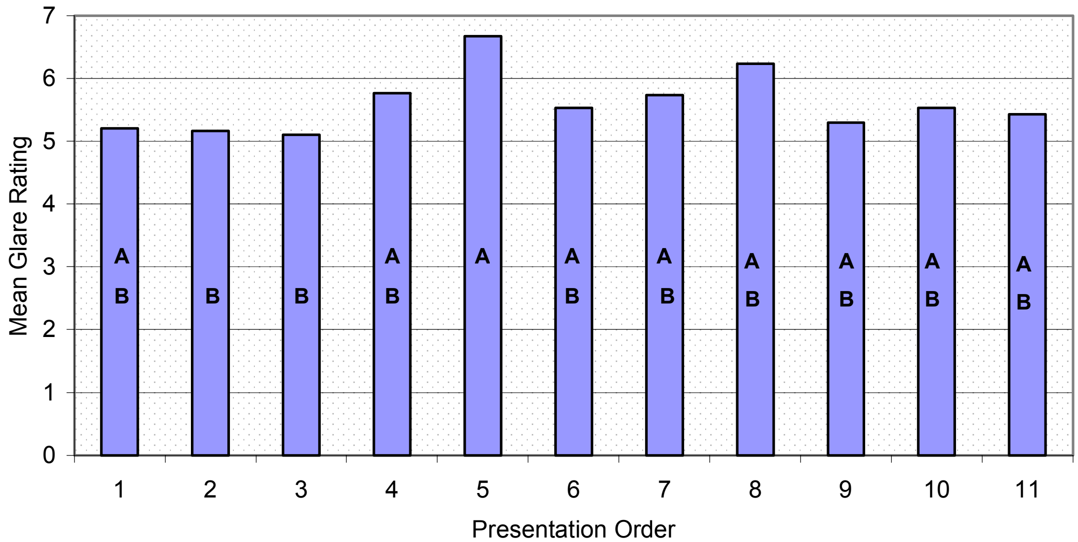
4.1 Presentation Order Effect

ANOVAs were completed to investigate presentation order effects for both discomfort glare evaluations and pavement marking visibility. The order of presentation was numbered one to eleven across nights for all headlamp configurations. Presentation orders were significant for the close and far glare evaluations. Table 2 and Figure 2 below represents the results of the ANOVA for presentation order for the far glare evaluation. The differences in presentation orders were found to be significant.

Table 2. ANOVA table for presentation order effect of the far glare evaluation for all participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Order	10	69.254545	6.925455	2.09	0.0253
Error	319	1059.533333	3.321421		
Corrected Total	329	1128.787879			

Figure 2 below represents the mean and SNK rankings for each presentation order. Of interest if whether or not the presentation order was systematic. A systematic effect would have a distinct pattern where the means would increase toward the end of the first night (Orders 5, 6) drop off, then increase again toward Order 11. As seen from Figure 1, that pattern was not present in this order effect. Order 5 was significantly different from Orders 2 and 3.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

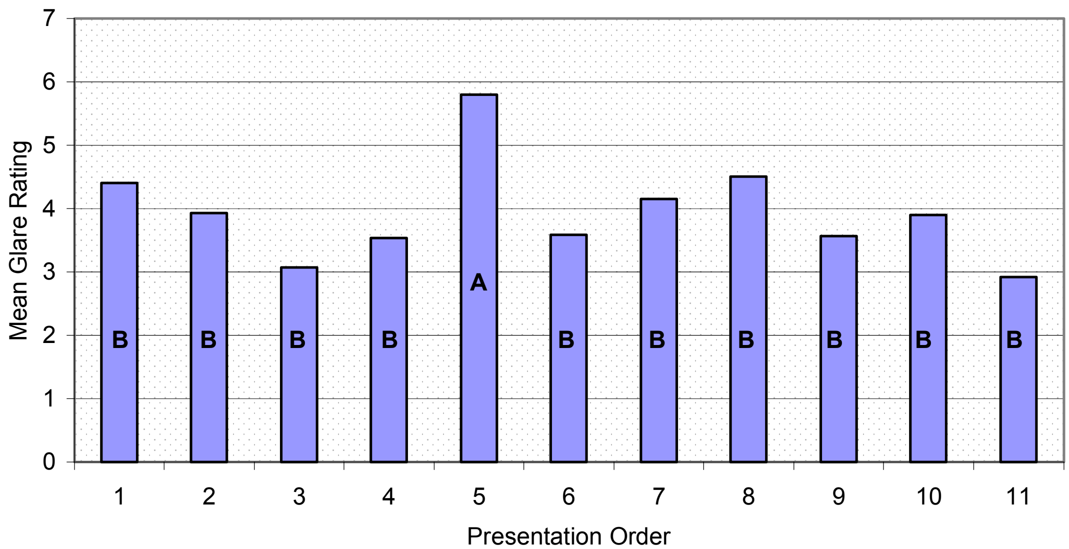
Figure 2. Mean glare evaluations for presentation order effect of the far glare evaluation, assessment for all participants.

An ANOVA was completed to investigate presentation order effects for both far and close discomfort glare evaluation. Table 3 below represents the results of the ANOVA for presentation order of the close glare evaluation. The differences in presentation order for close glare were found to be significant.

Table 3. ANOVA table for presentation order effect of the close glare evaluation, assessment for all participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Order	10	188.172727	18.817273	4.05	0.0001
Error	319	1480.425	4.640831		
Corrected Total	329	1668.597727			

Figure 3 below represents the mean and SNK rankings for each presentation order. Of interest if whether or not the presentation order was systematic. A systematic effect would have a distinct pattern where the means would increase toward the end of the first night (Orders 5, 6), drop off, and then increase again toward Order 11. As seen from Figure 1, that pattern was not present in this order effect. Only Order 5 was significantly different from all other orders.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

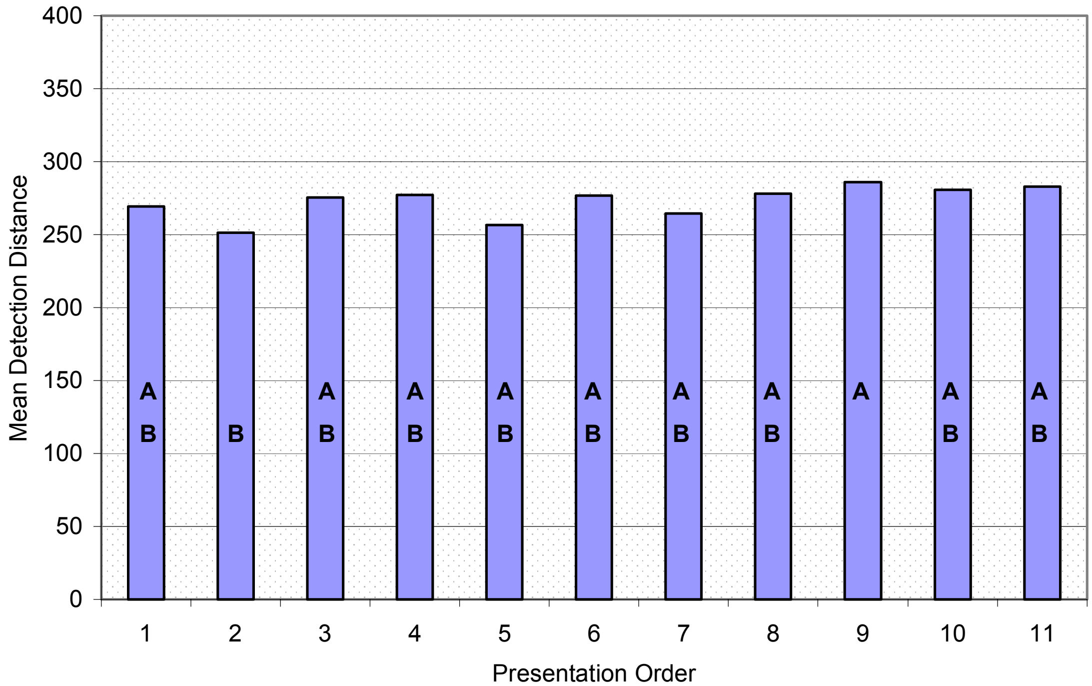
Figure 3. Mean glare evaluations for presentation order effect of the close glare evaluation, assessment for all participants.

ANOVAs were completed to investigate presentation order effects for beginning and ending detection distances order effects; only beginning detection distance was significant. Table 4 and Figure 4 below represents the results of the ANOVA for presentation order of the beginning detection distance. The differences in presentation order for beginning detection distances were found to be significant.

Table 4. ANOVA table for presentation order effect for beginning detection distance, assessment for all participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Order	10	108156.850	10815.685	2.13	0.0200
Error	973	4938157.314	5075.187		
Corrected Total	983	5046314.164			

Figure 4 below represents the mean and SNK rankings for each presentation order. Of interest if whether or not the presentation order was systematic. A systematic effect would have a distinct pattern where the means would increase toward the end of the first night (Orders 5, 6), drop off, and then increase again toward Order 11. As seen from Figure 4, that pattern was not present in this order effect. Orders 2 and 9 were significantly different from each other.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

Figure 4. Mean glare evaluations for presentation order effect of the beginning detection distance, assessment for all participants.

In summary, presentation order was significant for far and close glare evaluation and beginning detection distance. For close and far glare, Order 5 provided the highest mean Orders and 2 and 3 provided the lowest mean glare evaluations. For the beginning detection distance, Order 9 provided the largest beginning detection distance and Order 2 provided the shortest average detection distance.

The presentation order effect did not appear to be systematic for the following reasons. First, the pattern represented by the means did not indicate a systematic effect. Recall that a systematic effect would have a distinct pattern where the means would increase toward the end of the first night (Orders 5, 6), drop off, and then increase again toward Order 11. None of the results provided that pattern.

Another reason the presentation order does not appear to be systematic is the distribution of headlamp configurations presented in each order. The distribution of headlamp presentation for Order 5, which had the highest average for the glare evaluations, and Order 9, which provided the longest beginning detection distance is presented below in Table 5.

Table 5. Headlamp presentation frequency for presentation orders 5 for the glare evaluation and order 9 for the pavement marking evaluation.

Headlamp Configuration	Frequency of presentation for the discomfort glare evaluation- Order 5	Frequency of presentation for the pavement marking evaluation- Order 9
HLB	4	4
Hybrid UV-A + HLB	0	3
Middle UV-A + HLB	2	5
High UV-A + HLB	8	1
High intensity discharge	2	1
Hybrid UV-A + high intensity discharge	2	4
Middle UV-A + high intensity discharge	4	1
High UV-A + high intensity discharge	4	2
High output halogen	0	4
Halogen high beam	2	2
Halogen low beam- low profile	2	3

Order 5 of the discomfort glare evaluation, headlamps that attained higher glare ratings (i.e., the halogen configurations) were more represented than those with lower glare ratings. For Order 9 for the beginning detection distance, headlamps that attained higher pavement marking distances (i.e., the halogen configurations) were more represented than those with lower distances. From this, it is reasonable to conclude that the headlamp configurations represented in each of the orders elevated the order average, influencing an effect that is not otherwise present.

In addition, the presentation order was only significant for beginning detection distance. Since the orders were the same for both the beginning and the ending distances, a true presentation order effect should have equally affected both factors. Moreover, many of the orders in the significant analyses were not significantly different from one another, that is they had the same SNK rankings. This indicated that the orders were not statistically different from one another.

In summary, it can be concluded that the presentation order effect was not systematic. In fact, it was most influenced by the imbalanced distribution of headlamp configurations over the order. The imbalance of headlamps in each presentation order was due in part by procedural constraints. When determining the presentation orders, two considerations were applied. For the glare evaluations, two vehicles would be on the road at the same time, and would be presented immediately after one another. Therefore, the same vehicle could not be represented twice in the same lap. For the pavement marking evaluations, participants could not be driving the same vehicle in the same lap (recall that two participants completed the evaluations per each session). Only orders that met this constraint were selected. The orders that were selected resulted in the same headlamp configuration being presented more often in one position (i.e., Orders 2, 3, and 5) than others.

This procedural decision resulted from a practical trade-off: had the procedure only had one vehicle on the road at a time, the length of the glare portion would have been doubled, extending the length of the study over both nights. Similarly, for the pavement marking evaluation, if participants were required to share vehicles for some laps, the evaluation would have been significantly longer. Since the data was collected in the summer, the collection times were later at night, and participant fatigue was a major concern. Therefore, the decision was made to have two glare evaluations per lap, restricting the headlamp configurations that could be presented together.

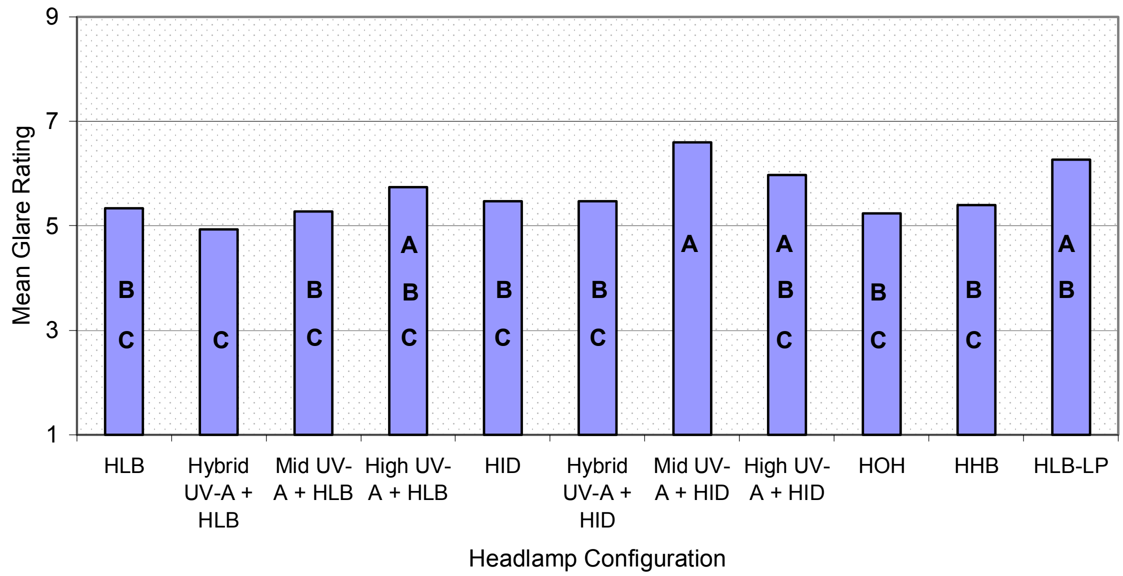
4.2 Glare Evaluations

An ANOVA was completed to investigate the main effects and interactions of age and headlamp configuration for both the close and far discomfort glare evaluation. The two measures of interest were the far glare evaluation, or the ratings given for the road section furthest from the glare source, and the close glare evaluation, or the ratings given for the road section closest to the glare source. Recall that according to the DeBoer scale, a higher glare evaluation represents less perceived glare. An ANOVA was conducted to examine the main effects and interactions of age and headlamp configuration for both far and close glare evaluations. Table 6 below represented the results of the ANOVA for the far glare evaluation. The differences in headlamp configurations were found to be significant.

Table 6. ANOVA table for far glare evaluation for all headlamp configurations, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	5.27878788	2.63939394	0.14	0.8716
HL	10	72.98787879	7.29878788	3.94	<.0001
Age*HL	20	34.92121212	1.74606061	0.94	0.5324
Subject (Age)	27	515.8727273	19.1063973		
Subject*HL(Age)	270	499.7272727	1.8508418		
Corrected Total	329	1128.787879	3.430966		

Figure 5 below represents the means and SNK rankings for the far glare evaluation for each of the headlamp configurations. Overall, many of the headlamp configurations not statistically different, with most ratings around 5, "Just Acceptable." No specific pattern emerged from the results as many of the configurations were not significantly different. The Middle UV-A + HID was significantly different from all configurations except the High UV-A + HLB, the High UV-A + HID, and the halogen low beam, low profile configurations.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

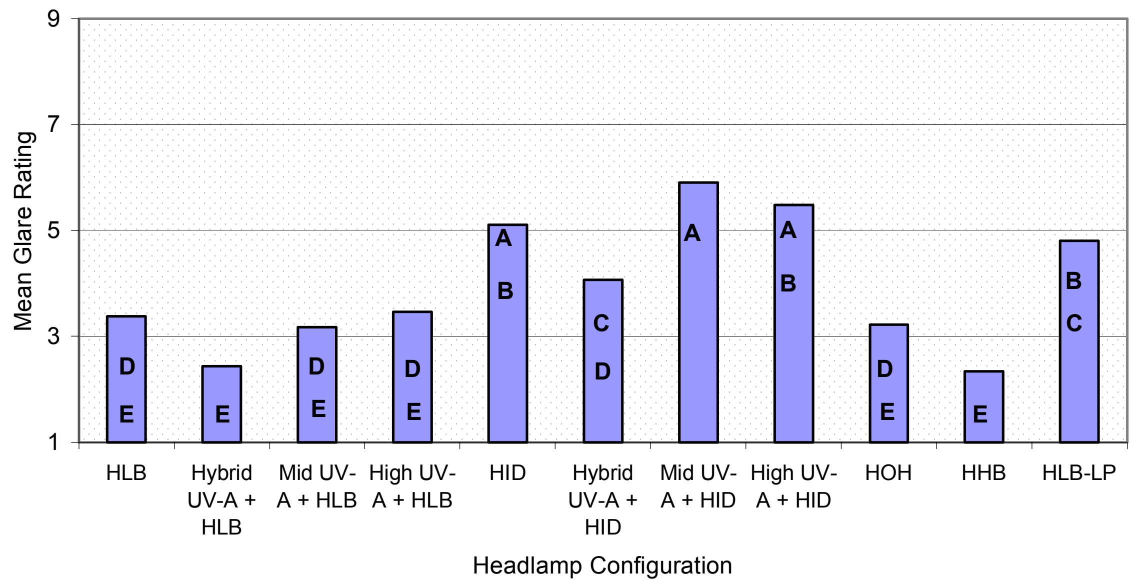
Figure 5. Mean far discomfort glare evaluations for all headlamp configurations, assessment for participants.

An ANOVA was completed to investigate the main effects and interactions of age and headlamp for both the close and far discomfort glare evaluation. The resulting ANOVA for close glare evaluation is represented in Table 7 below. The differences in headlamp configurations were found to be significant.

Table 7. ANOVA table for close glare evaluation for all headlamp configurations, assessment for participants

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	12.82272727	6.41136364	0.38	0.6875
HL	10	444.9393939	44.4939394	17.35	<.0001
Age*HL	20	62.7606061	3.1380303	1.22	0.2340
Subject(Age)	27	455.5931818	16.8738215		
Subject*HL(age)	270	692.4818182	2.5647475		
Corrected Total	329	1668.597727			

Figure 6 below shows the mean ratings and the SNK ratings for each configuration. For this evaluation, the HID baseline conditions (i.e., HID, Hybrid UV-A + HID, Middle UV-A + HID, High UV-A + HID) consistently provided the least amount of discomfort glare (i.e., higher rating), with ratings close to 5, "Just Noticeable." The HLB baseline conditions and high output halogen, halogen high beam provided lower glare ratings ranging between 1, "Unbearable," to just above 3, "Disturbing." Halogen low beam- low profile performed well, with a mean rating not significantly different than those of the HID configurations. The Hybrid UV-A + HID configuration was significantly different from the other HID configurations. In addition, the Middle UV-A + HID condition was significantly different from all configurations except the HID and High UV-A + HID configurations.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

Figure 6. Mean close discomfort glare evaluations for all headlamp configurations, assessment for participants.

4.3 Pavement Marking Evaluation

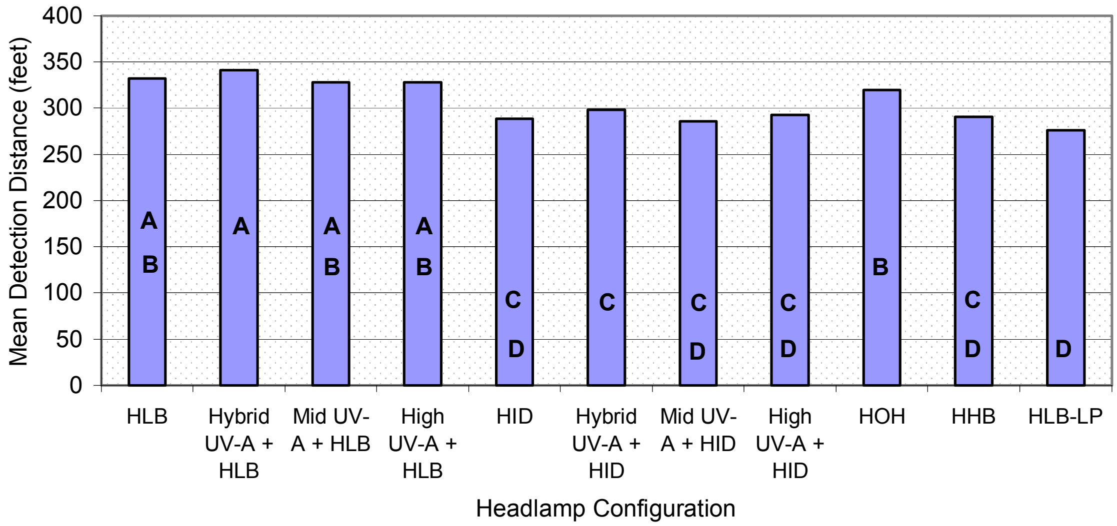
To measure the effectiveness of headlamp configuration on detecting pavement marking, two measures were collected for the beginning detection distance (when the participants indicated seeing the first pavement marking in each section) and ending detection distance (when the participants indicated seeing the last pavement marking in each section). ANOVAs were completed to look at the main effects and interactions of age, headlamp configurations, and pavement marking material for both the beginning distance and the end distance.

Table 8 below represents the results of the ANOVA for the beginning detection distance. The differences in headlamp configurations and pavement marking materials were significant. Also, the interaction between pavement marking and headlamp was found to be significant. Age was approaching significance for this evaluation.

Table 8. ANOVA table for beginning detection distance for all headlamp configurations and pavement marking materials, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	411512.9134	205756.4567	3.31	0.0518
HL	10	470638.243	47063.824	25.03	<.0001
Age*HL	20	41143.2800	2057.1640	1.09	0.3551
Pvt.Mrkg	2	442806.9349	221403.4674	28.73	<.0001
Age*Pvt.Mrkg.	4	3462.5007	865.6252	0.11	0.9777
HL*Pvt.Mrkg.	20	17849.5210	8912.4760	6.62	<.0001
Age* HL *Pvt.Mrkg.	40	55268.2384	1381.7060	1.03	0.4292
Subject(Age)	27	1678307.503	62159.537		
Subject* HL (Age)	270	507630.950	1880.115		
Subject*Pvt.Mrkg.(Age)	54	416131.996	7706.148		
Subject* HL *Pvt.Mrkg.(Age)	532	717617.491	1346.374		
Corrected Total	981	4915550.316	5005.652		

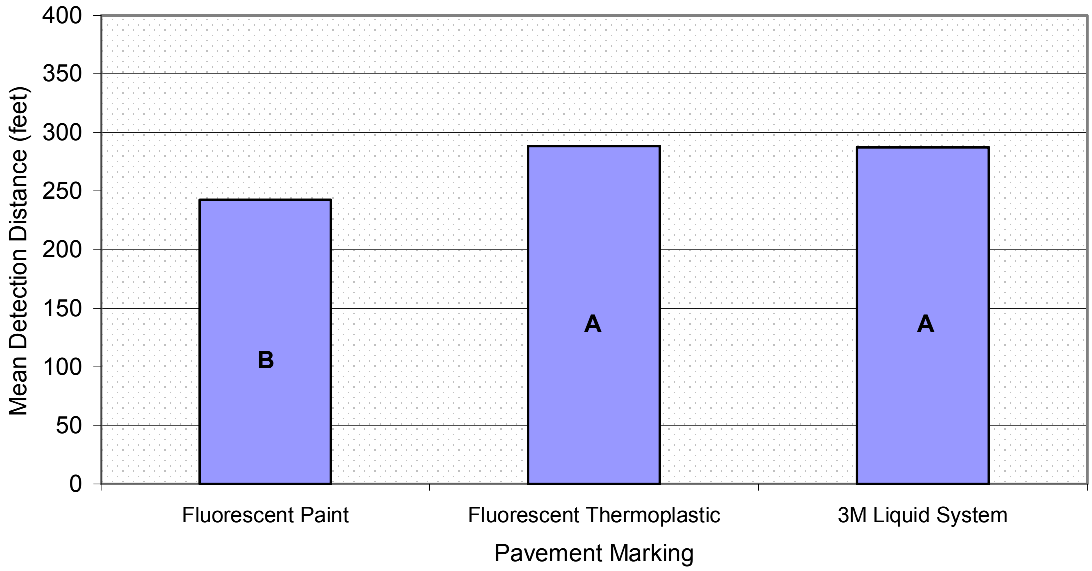
Figure 7 below shows the mean ratings and the SNK ratings for each configuration. For this evaluation, the HLB baseline conditions (i.e., HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB) and high output halogen configuration consistently provided the longest beginning detection distances and were significantly different from the HID configurations and the halogen high beam and halogen low beam, low profile configurations.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

Figure 7. Mean beginning detection distances (in feet) for all headlamp configurations, assessment for participants.

Figure 8 below shows the mean ratings and the SNK ratings for each pavement marking material. For this evaluation, the fluorescent paint and 3M Liquid System was most visible overall and was statistically different from the fluorescent thermoplastic condition.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

Figure 8. Mean beginning detection distances (in feet) for all pavement marking materials, assessment for all participants.

Figure 9 represents the interaction between pavement marking and headlamp configuration for beginning detection distances. Of interest is the decline in averages with the fluorescent paint and the HID configurations and the halogen high beam and halogen low beam- low profile.

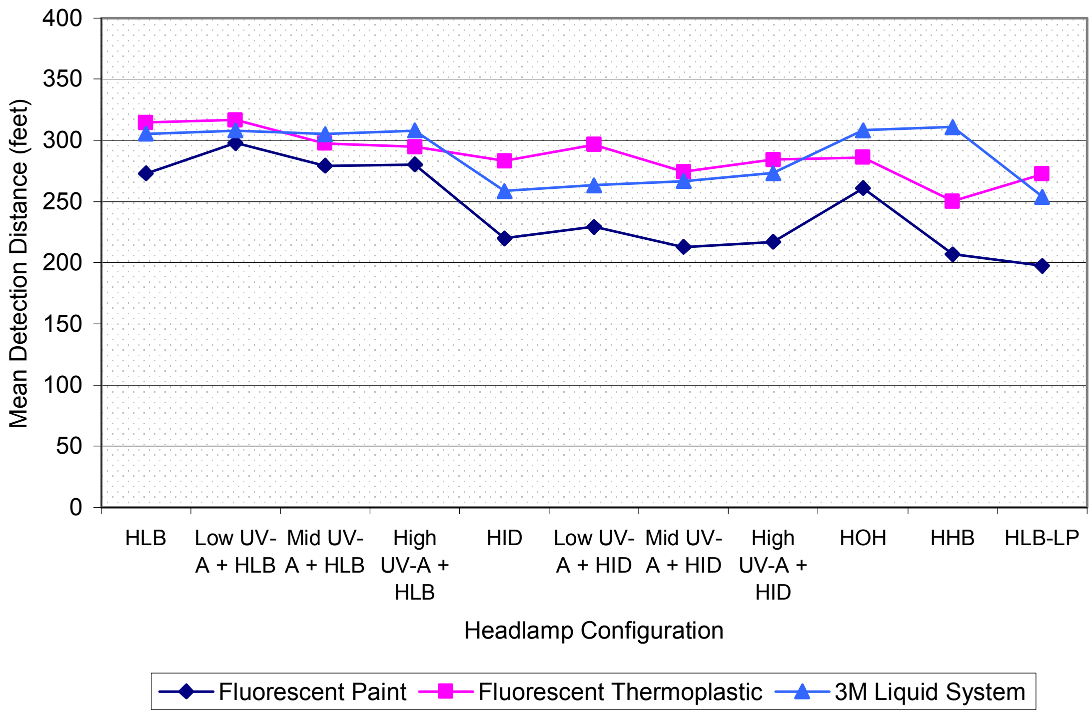
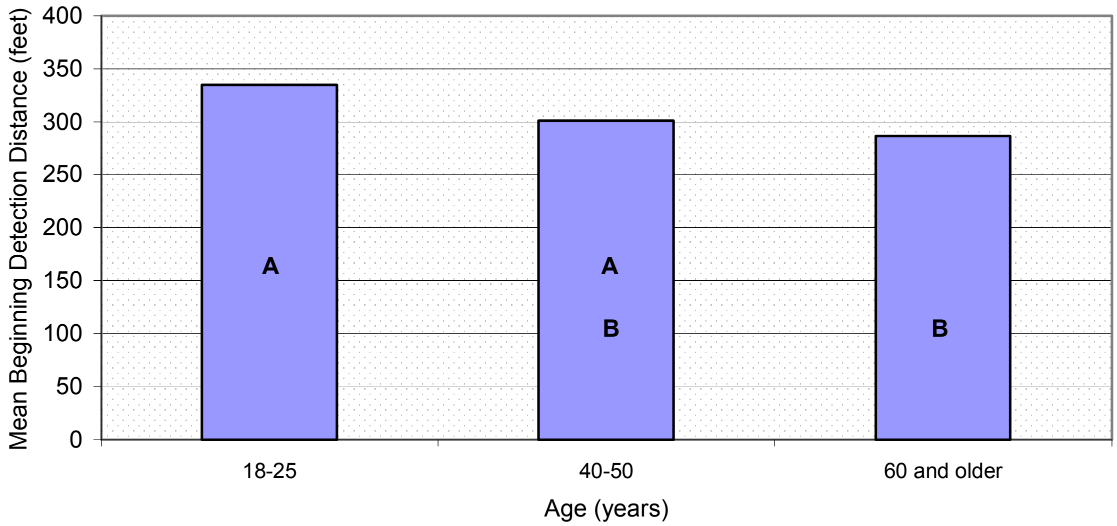


Figure 9. Mean beginning detection distance for headlamp configuration and pavement marking material, assessment for all participants.

Figure 10 below represents the means SNK rankings for age for beginning detection distances. The young age group attained the highest detection distances, but was not significantly different from the middle age group.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

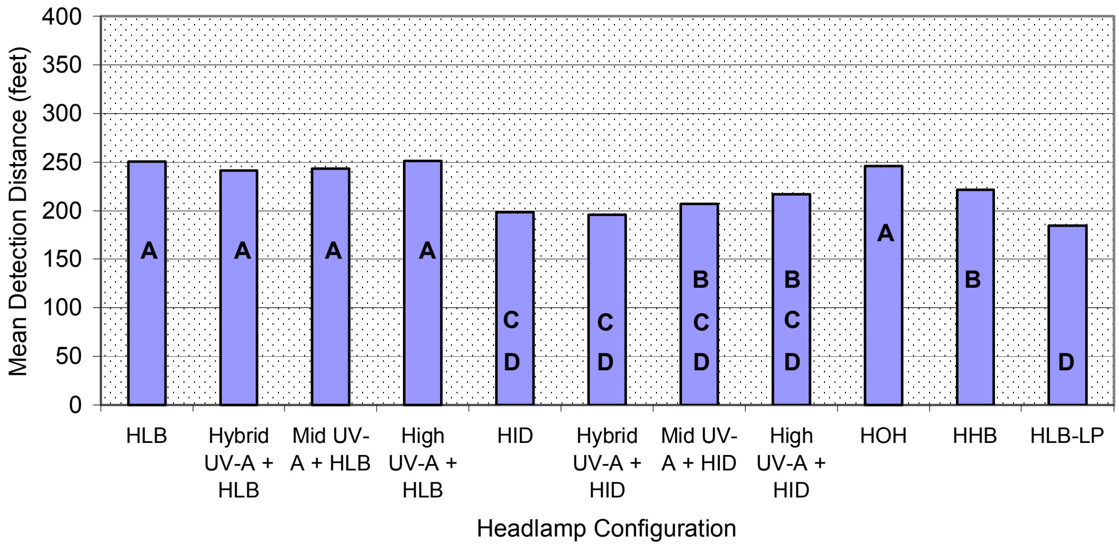
Figure 10. Mean beginning detection distances (in feet) for all age groups, assessment for all participants.

Table 9 below represents the results of the ANOVA for the ending detection distance. The differences in age, headlamp configurations, pavement marking materials were found to be significant. Also, the interaction between pavement marking and headlamp was found to be significant.

Table 9. ANOVA table for ending detection distance for all headlamp configurations and pavement marking materials, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	912645.9603	456322.9802	3.75	0.0367
HL	10	529420.3040	52942.0304	13.70	<.0001
Age* HL	20	133691.3142	6684.5657	3.13	0.6665
Pvt.Mrkg.	2	138943.0064	69471.5032	5.12	0.0092
Age*Pvt.Mrkg.	4	31107.0783	7776.7696	0.57	0.6831
HL*Pvt.Mrkg.	20	121992.684	6099.634	3.08	<.0001
Age*HL*Pvt.Mrkg	40	63765.6146	1594.1404	0.75	0.8735
Subject(Age)	27	3213675.677	119025.025		
Subject*HL(Age)	270	1052452.919	3897.974		
Subject*Pvt.Mrkg(Age)	54	732624.597	13567.122		
Subject*HL*Pvt.Mrkg(Age)	532	1140971.013	2136.650		
Corrected Total	981	8092123.142			

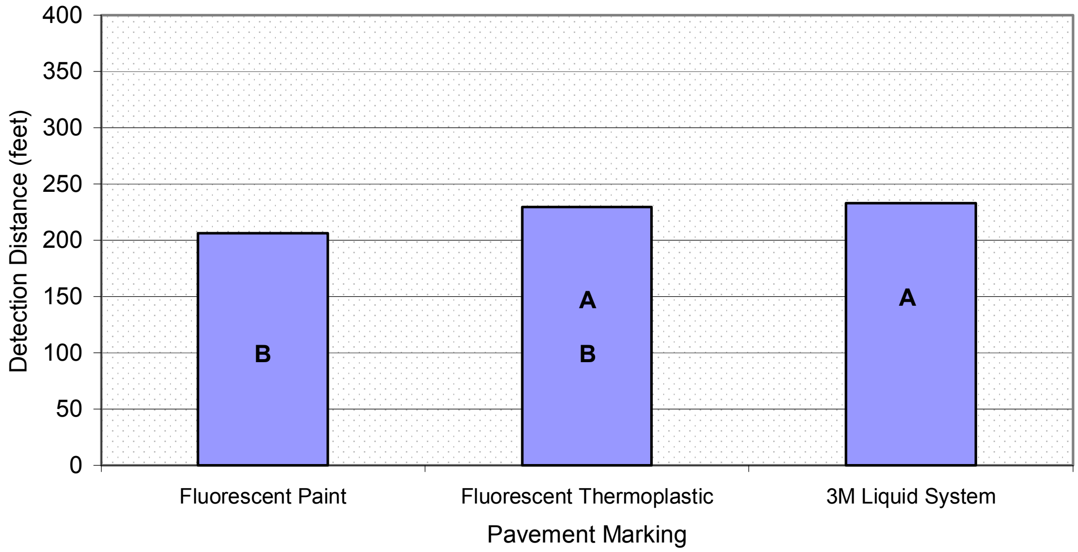
Figure 11 below shows the mean ratings and the SNK ratings for each configuration. For this evaluation, the HLB baseline conditions (i.e., HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB) and high output halogen consistently provided the longest beginning detection distances and were significantly different from the HID configurations and the halogen high beam and halogen low beam, low profile configurations.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

Figure 11. Mean ending detection distances (in feet) for all headlamp configurations, assessment for participants.

Figure 12 below shows the mean ratings and the SNK ratings for each pavement marking material. For this evaluation, the 3M Liquid System and fluorescent thermoplastic were most visible, but the fluorescent thermoplastic was not significantly different from the fluorescent paint.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

Figure 12. Mean ending detection distances (in feet) for all pavement marking materials, assessment for all participants.

Figure 13 below represents the interaction between pavement marking and headlamp configuration for ending detection distances. Of interest is the sharp decline in averages for the 3M Liquid System when interacting with the HID configurations and then again with the halogen low beam- low profile condition.

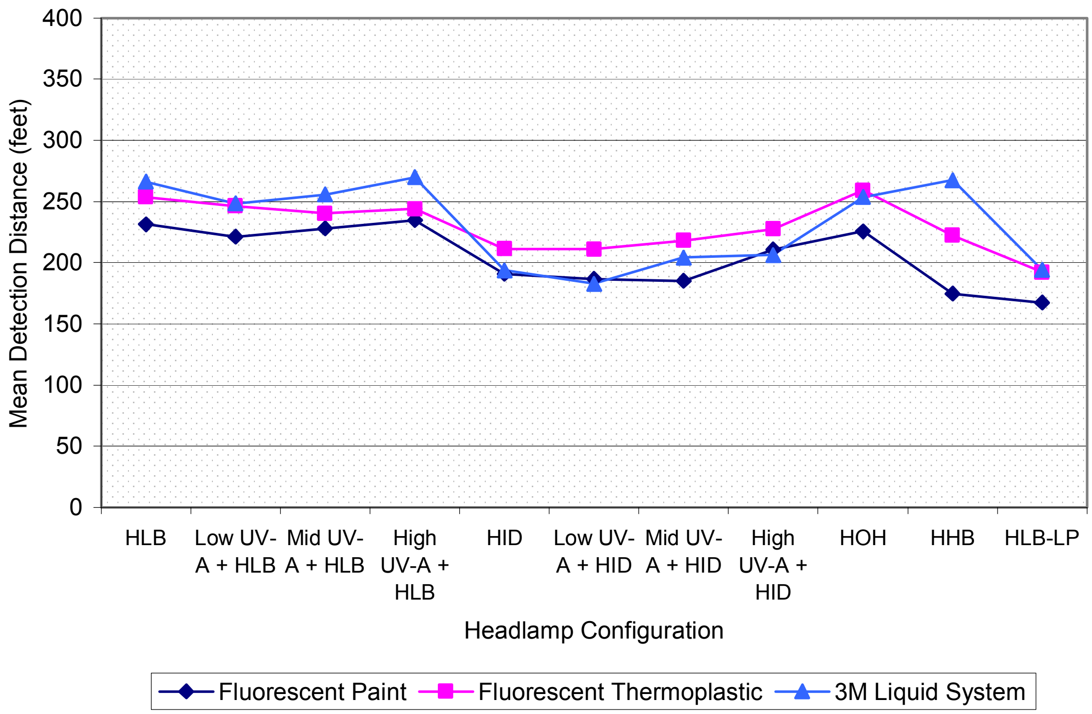
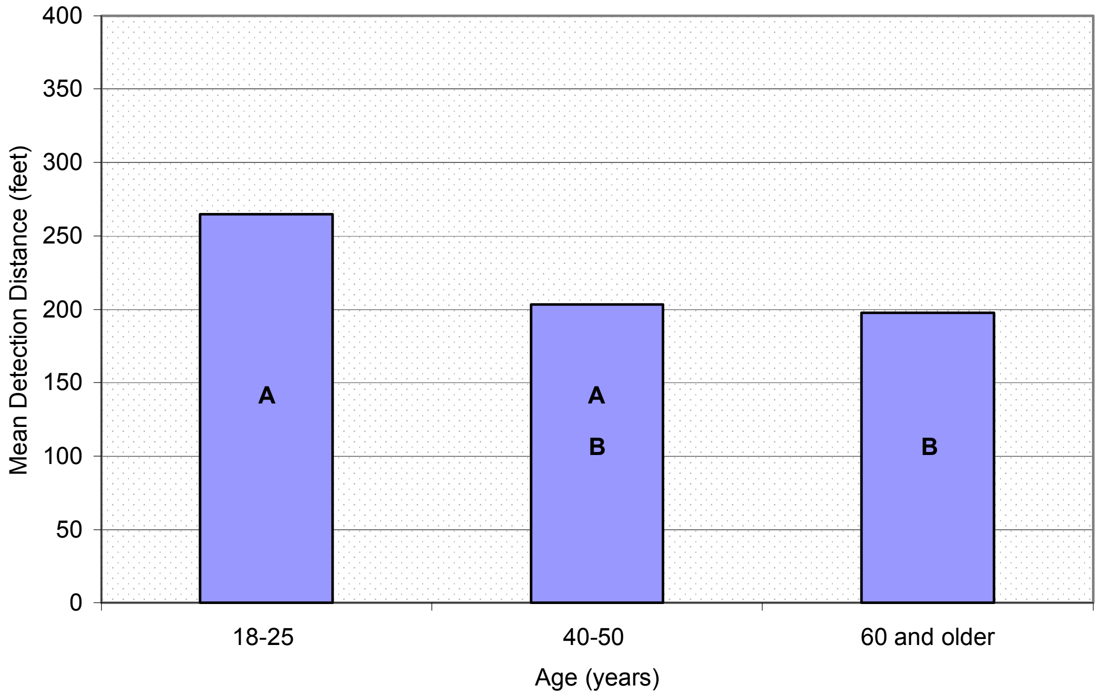


Figure 13. Mean ending distance for headlamp configuration and pavement marking material, assessment for all participants.

Figure 14 below represents the means and SNK rankings for age for ending detection distance. The young age group attained the highest detection distances, but was not significantly different from the middle age group.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

Figure 14. Mean ending detection distances (in feet) for all age groups, assessment for all participants.

4.4 Levels of UV-A

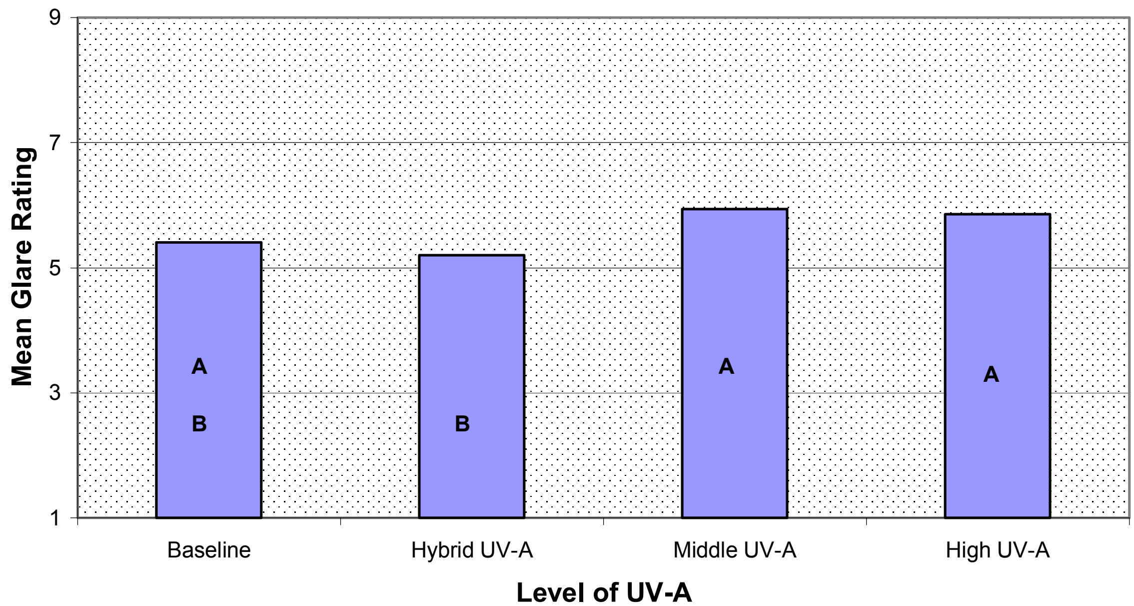
One primary goal of this research effort was to determine the headlamp configuration that provided the least amount of glare and most enhanced visibility of pavement markings. With the headlamp configurations two baseline conditions were established – HLB and HID. These configurations were tested individually and were paired and tested with each of the three levels of UV-A. To determine differences between the baseline conditions, analyses were completed to compare the baseline condition to each level of UV-A (No UV-A, Hybrid, Middle, and High). The No UV-A level represents the baseline condition. Student Neuman Keuls analyses was conducted to determine which levels of UV-A were significantly different.

Table 10 below represents the results of the ANOVA for the far glare evaluation. The differences in baseline condition and level of UV-A were found to be significant.

Table 10. ANOVA table for far glare evaluation for baseline conditions and levels of UV-A, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	2.708333333	1.35416667	0.10	0.9078
Baseline	1	18.70416667	18.70416667	11.71	0.0020
Baseline*Age	2	2.55833333	1.27916667	0.80	0.4592
UV-A	3	22.41250000	7.47083333	4.82	0.0039
UV-A*Age	6	19.12500000	3.18750000	2.06	0.0676
Baseline*UV-A	3	13.31250000	4.43750000	1.80	0.1532
Baseline*UV-A*Age	6	8.47500000	1.41250000	0.57	0.7500
Subject (Age)	27	2.7083333	1.3541667		
Subject*Baseline(Age)	27	43.1125000	1.5967593		
Subject*UV-A(Age)	81	125.5875000	1.5504630		
Baseline *UV-A*Subject(Age)	81	199.3375000	2.4609568		
Corrected Total	239	831.7958333			

Figure 15 below shows the mean ratings and the SNK ratings for each level of UV-A. Overall, ratings were between 5, "Just Acceptable" and 7, "Satisfactory." For this evaluation, no level of UV-A was significantly different from the baseline condition. However, the Middle UV-A and the High UV-A conditions were significantly different from the Hybrid UV-A condition; as expected based on previous results in this research effort, the Hybrid UV-A provided more glare.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

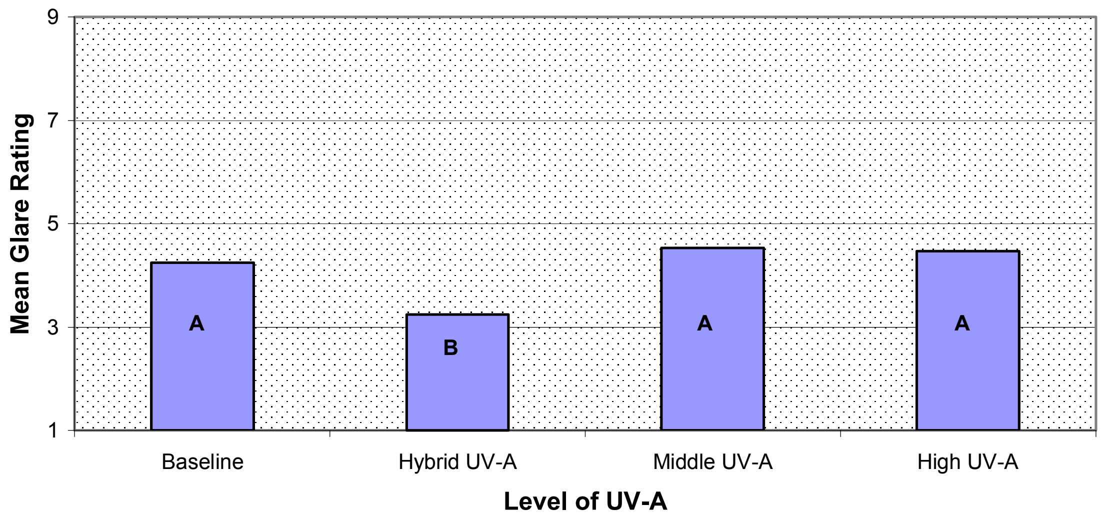
Figure 15. Mean far glare evaluation for level of UV-A, assessment for all participants.

Table 11 below represents the results of the ANOVA for the close glare evaluation. The differences in baseline condition and level of UV-A were found to be significant.

Table 11. ANOVA table for close glare evaluation for baseline conditions and levels of UV-A, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	21.2250000	10.61250000	0.81	0.4574
Baseline	1	246.0375000	246.0375000	88.63	<.0001
Baseline*Age	2	9.3250000	4.6625000	1.68	0.2053
UV-A	3	64.10833333	21.36944444	7.16	0.0003
UV-A*Age	6	31.74166667	5.29027778	1.77	0.1148
Baseline*UV-A	3	11.25416667	3.75138889	1.32	0.2726
Baseline *UV-A*Age	6	7.00833333	1.16805556	0.41	0.8691
Subject (Age)	27	21.2250000	10.6125000		
Subject*Baseline(Age)	27	74.9500000	2.7759259		
Subject*UV-A(Age)	81	241.5875000	2.9825617		
Baseline *UV-A*Subject(Age)					
	81	229.6750000	2.8354938		
Corrected Total	239	1292.750000			

Figure 16 below shows the mean ratings and the SNK ratings for each level of UV-A. Overall, ratings were between 3, “Disturbing,” and 5, “Just Acceptable.” For this evaluation, Hybrid UV-A was significantly different from the baseline (No UV-A) condition and the Middle and High UV-A conditions; as expected based on previous results in this research effort, the Hybrid UV-A provided more glare.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

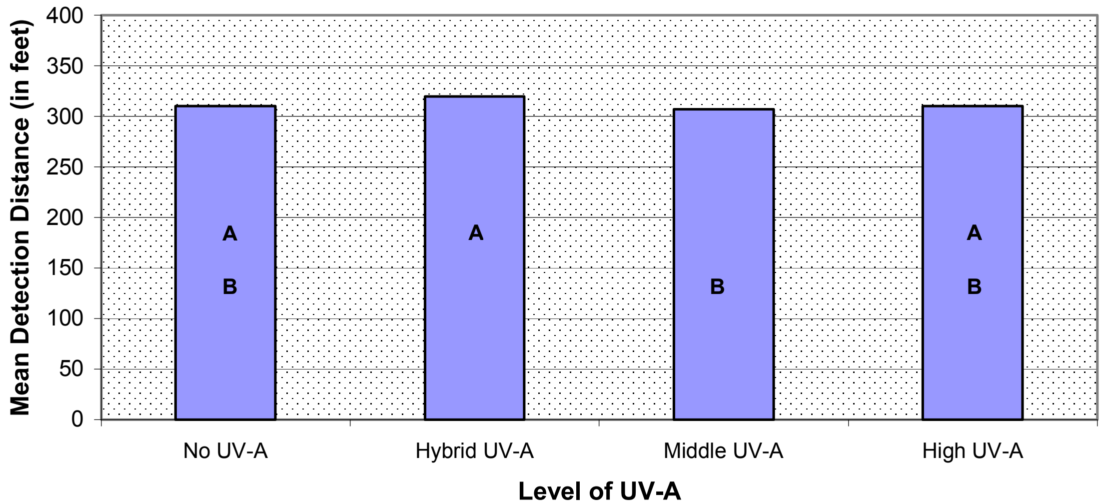
Figure 16. Mean far glare evaluation for level of UV-A, assessment for all participants.

Table 12 below represents the results of the ANOVA for the beginning pavement marking evaluation. The differences in baseline condition and levels of UV-A were found to be significant.

Table 12. ANOVA table for beginning pavement marking evaluation for baseline conditions and levels of UV-A, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	277472.3300	138736.1650	3.11	0.0607
Baseline	1	301643.5845	301643.5845	229.28	<.0001
Baseline*Age	2	1760.5572	880.2786	0.67	0.5205
UV-A	3	15293.39783	5097.79928	2.88	0. 0411
UV-A*Age	6	19385.63106	3230.93851	1.82	0.1046
Baseline*UV-A	3	2039.596215	679.865405	0.27	0.8445
Baseline *UV-A*Age	6	3732.664612	622.110769	0.25	0.9580
Subject (Age)	27	1199861.986	44439.333	13.27	
Subject*Baseline(Age)	27	35521.262	1315.602	0.39	
Subject*UV-A(Age)	81	143484.109	1771.409	0.53	
Baseline *UV-A*Subject(Age)	81	201542.405	2488.178	0.74	
Corrected Total	239	1292.750000			

Figure 17 below shows the mean ratings and the SNK ratings for each level of UV-A. For this evaluation, no level of UV-A was significantly different from the baseline (No UV-A) condition. The Hybrid UV-A and the Middle UV-A conditions were statistically different from each other.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

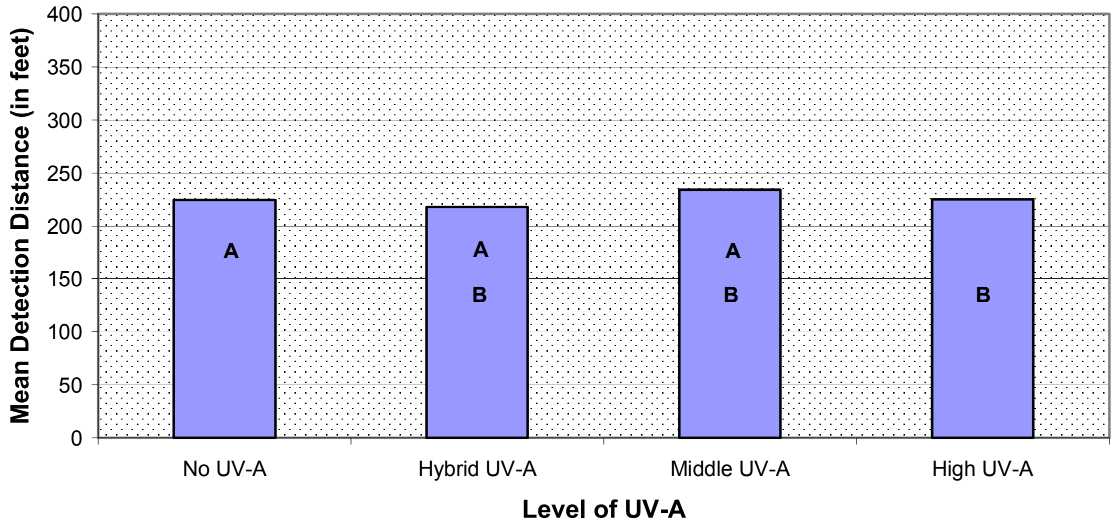
Figure 17. Mean beginning detection distance evaluation for level of UV-A, assessment for all participants.

Table 13 below represents the results of the ANOVA for the ending pavement marking evaluation. The differences in baseline condition (No UV-A) and levels of UV-A were found to be significant. Age was also significant, however the levels of age were not significantly different from each other.

Table 13. ANOVA table for ending pavement marking evaluation for baseline conditions and levels of UV-A, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	654956.5549	327478.2774	3.82	0.0346
Baseline	1	313413.3611	313413.3611	106.13	<.0001
Baseline*Age	2	8586.4634	4293.2317	1.45	0.2514
UV-A	3	20875.68356	6958.56119	3.05	0.0332
UV-A*Age	6	15020.53177	2503.42196	1.10	0.3709
Baseline*UV-A	3	8861.92882	2953.97627	0.53	0.6620
Baseline *UV-A*Age	6	37063.84320	6177.30720	1.11	0.3631
Subject (Age)	27	2313552.004	85687.111	26.82	
Subject*Baseline(Age)	27	79732.151	2953.043	0.92	
Subject*UV-A(Age)	81	184706.379	2280.326	0.71	
Baseline *UV-A*Subject(Age)	81	450259.953	5558.765	1.74	
Corrected Total	239	1292.750000			

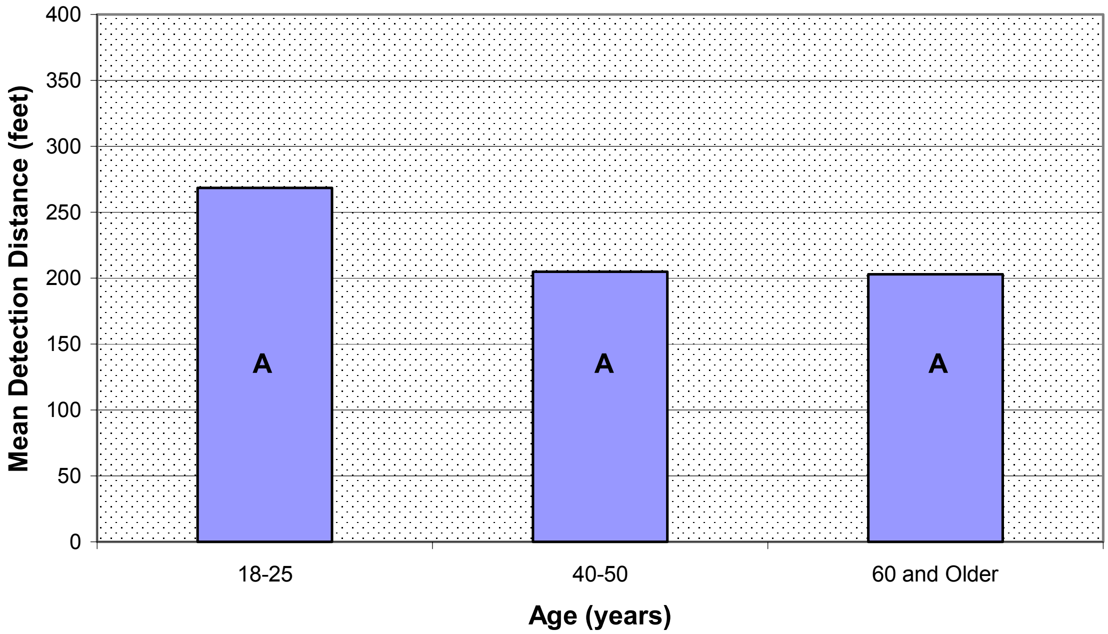
Figure 18 below shows the mean ratings and the SNK ratings for each level of UV-A. For this evaluation, the High UV-A was significantly different from the baseline (No UV-A) condition.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

Figure 18. Mean ending detection distance evaluation for level of UV-A, assessment for all participants.

Figure 19 below shows the mean ending detection distance and the SNK ratings for each age group. For this evaluation, no level of age was significantly different.



Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.

Figure 19. Mean ending detection distance evaluation for age groups, assessment for all participants.

4.5 Evaluations Within Halogen Low Beam Configurations

One primary goal of this research effort was to determine the headlamp configuration that provided the least amount of glare and most enhanced visibility of pavement markings. To determine which headlamp met those criteria, the means and SNK analyses were compiled for discomfort glare and pavement marking visibility. Table 14 below represents the means and the SNK groupings far glare, close glare, beginning detection distance and ending detection distance for each headlamp configuration. The SNK results were useful because they show a ranking of the results in addition to showing which results are significantly different. For the SNK grouping, an A ranking represents the highest glare evaluation, that is least amount of glare, and longest pavement marking detection distances. Headlamp configurations with the same ratings are not significantly different.

Table 14. Mean and Student Neumann Keuls groupings for all headlamp configurations by glare evaluation and pavement marking detection distance, assessment for all participants.

	SNK Rankings and means			
Headlamp Configuration	Far Glare Evaluation	Close Glare Evaluation	Beginning Pavement Distance	Ending Pavement Distance
HLB	Mean: 5.33 BC	Mean: 3.38 DE	Mean: 297.57 ft. AB	Mean: 250.47 ft. A
Hybrid UV-A + HLB	Mean: 4.93 C	Mean: 2.43 E	Mean: 307.53 ft. A	Mean: 241.12 ft. AB
Middle UV-A + HLB	Mean: 5.27 BC	Mean: 3.17 DE	Mean: 294.07 ft. AB	Mean: 243.05 ft. AB
High UV-A + HLB	Mean: 5.73 ABC	Mean: 3.47 DE	Mean: 294.44 ft. AB	Mean: 251.00 ft. A
High intensity discharge	Mean: 5.47 BC	Mean: 5.10 AB	Mean: 253.91 ft. CD	Mean: 198.62 ft. CDE
Hybrid UV-A + high intensity discharge	Mean: 5.47 BC	Mean: 4.07 CD	Mean: 263.00 ft. C	Mean: 195.65 ft. DE
Middle UV-A + high intensity discharge	Mean: 6.60 A	Mean: 5.90 A	Mean: 251.12 ft. CD	Mean: 206.80 ft. CDE
High UV-A + high intensity discharge	Mean: 5.97 ABC	Mean: 5.48 AB	Mean: 258.36 ft. CD	Mean: 217.05 ft. CD
High output halogen	Mean: 5.23 BC	Mean: 3.22 DE	Mean: 285.08 ft. B	Mean: 245.68 ft. A
Halogen high beam	Mean: 5.40 BC	Mean: 2.33 E	Mean: 255.97 ft. CD	Mean: 221.43 ft. BC
Halogen low beam- low profile	Mean: 6.27 AB	Mean: 4.80 BC	Mean: 241.21 ft. D	Mean: 184.52 ft. E

- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

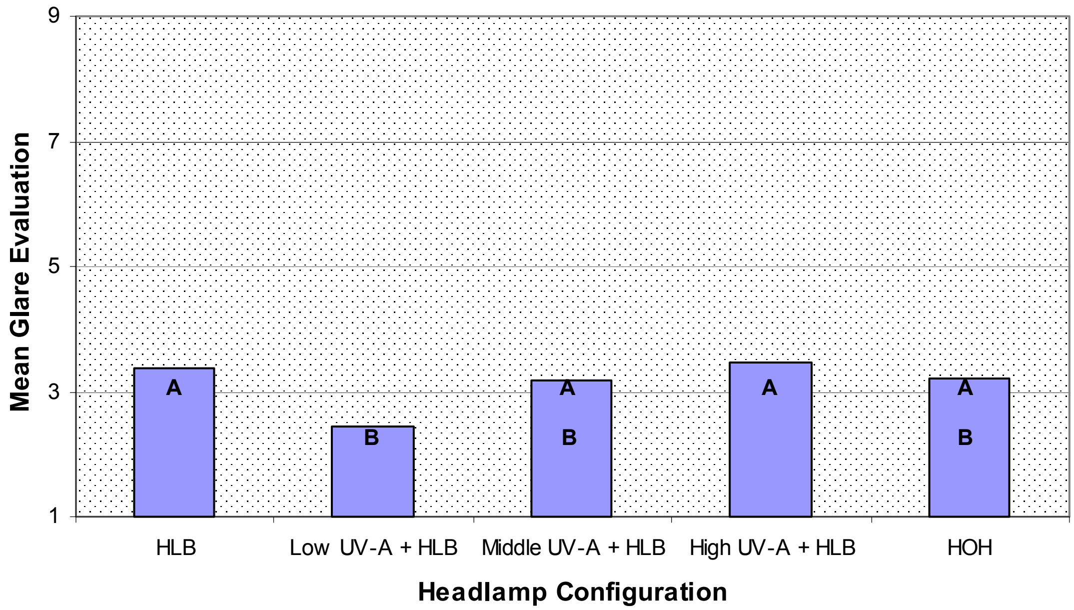
Upon examining Table 14, no headlamp configurations were consistently better for providing minimal glare and maximum pavement marking visibility. For the discomfort glare evaluations, configurations with HID provided lower glare ratings for the glare evaluations. For pavement marking visibility, HLB configurations - HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB - and HOH provided the best visibility, but did not necessarily provide low discomfort glare.

Because these five configurations consistently performed better for pavement marking visibility than the HID configurations, ANOVAs were conducted on only the HLB configurations and the HOH configuration to determine which of the five performed best. (The halogen low-beam, low profile was not included because it provided the lowest detection distances.) The ANOVAs were conducted using the statistical models represented in Tables 7 to 10. It was thought that significant results may arise when comparing the five headlamp configurations to each other. If one headlamp configuration performed better, a firm recommendation could be made about the best performing headlamp for the five evaluated. For the analyses, headlamp configuration was significant for close glare configuration and beginning detection distances- Tables 15 and 16 represent the results of the significant ANOVAs. Table 15 below represents the results of the ANOVA for the halogen low bean configurations for the close glare evaluation.

Table 15. ANOVA table for the close glare evaluation for halogen low beam headlamp configurations only, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	0.89333333	0.44666667	0.05	0.9513
HL	4	20.1500000	5.03750000	2.61	0.0398
Age*HL	8	27.6400000	3.45500000	1.79	0.0874
Subject(age)	27	241.340000	8.9385185		
Subject*HL(Age)	108	208.810000	1.9334459		
Corrected Total	149	498.3333333			

Figure 20 below shows the means and SNK results for this evaluation. All ratings were between 1, "Unbearable," and just above 3, "Disturbing." Overall, the Hybrid UV-A condition received a higher glare rating, i.e., was rated as providing more glare. This condition, however, was not significantly different from the Mid UV-A + HLB and the halogen high beam conditions. The HLB and the High UV-A + HLB conditions were significantly different from the Low UV-A + HLB condition.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

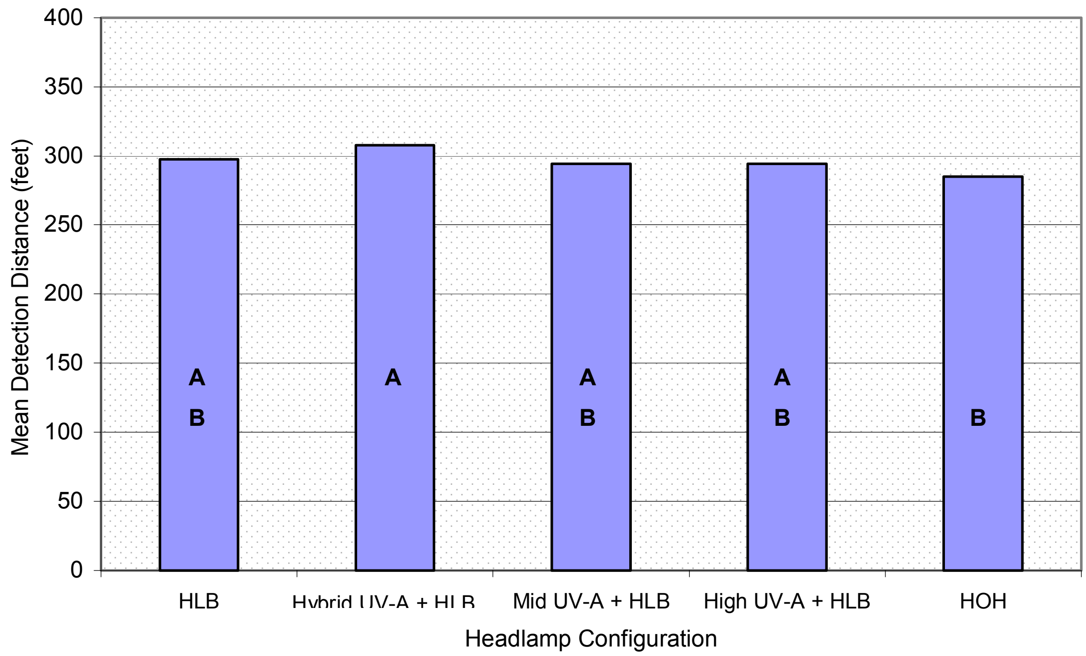
Figure 20. Mean close glare evaluation for only the five halogen headlamps, assessment for all participants.

An ANOVA was completed to look at the main effects and interactions of age, halogen headlamp configurations, and pavement marking material for both the beginning distance and the ending distance. Table 16 below represents the results of the ANOVA for the halogen headlamp configurations for the beginning detection distances. Headlamp configuration and pavement marking material was significant in this analysis.

Table 16. ANOVA table for beginning detection distance for all halogen headlamp configurations and pavement marking materials, assessment for participants.

Source	DF	SS	Mean Square	F Value	Pr > F
Age	2	193817.5751	96908.7875	3.03	0.0651
HL	4	23587.41587	5896.85397	2.73	0.0331
Age*HL	8	18718.05752	2339.75719	1.08	0.3817
Pvt.Mrkg	2	75754.40825	37877.20413	6.19	0.0038
Age*Pvt.Mrkg.	4	4871.09891	1217.77473	0.20	0.9378
HL*Pvt.Mrkg.	8	18290.10812	2286.26352	1.30	0.2451
Age*HL*Pvt.Mrkg.	16	16256.22485	1016.01405	0.58	0.8987
Subject(Age)	27	858970.1445	31813.7091		
Subject*HL(Age)	108	233530.1440	2162.3161		
Subject*Pvt.Mrkg.(Age)	54	330319.0771	6117.0199		
Subject*HL* Pvt.Mrkg.(Age)	213	374704.6547	1759.1768		
Corrected Total	446	2089478.004			

Figure 21 below shows the means and SNK results for this evaluation. Overall, the Hybrid UV-A condition was significantly different from the high output halogen condition.



- **Student-Newman-Keuls (SNK) multiple range test used to test main effects; means with the same SNK letter grouping are not significantly different.**

Figure 21. Mean beginning detection distance for only the five halogen headlamps, assessment for all participants.

4.6 Vision Test Results

One research question was to determine whether there was a relationship between the pavement marking detection and visual ability, measured by three vision tests: visual acuity, contrast sensitivity, and color vision. All participants passed the color vision test. With only one level of color vision ability throughout the sample, the color vision test was not included in future analyses. The results of the visual acuity tests were recorded for each participant resulting in six levels of acuity between participants (i.e., 20/40, 20/25, 20/20, 20/17, 20/15, 20/13). Based on the results of the contrast sensitivity test, the participants were divided into two categories, adequate or inadequate contrast sensitivity. The acuity scores (six levels), contrast sensitivity (two levels) were compared to the average beginning and ending detection distances for each participant to determine if a relationship existed between visual capabilities and pavement marking detection. A correlation analysis (i.e., product moment correlation coefficient) was conducted in Microsoft Excel®. The results of the correlation analyses are as follows, showing the factors compared and the resulting correlation coefficient, *r*:

- Average beginning detection distance with visual acuity score: r=0.0498
- Average ending detection distance with visual acuity score: r=0.5422
- Average beginning detection distance with contrast sensitivity: r=0.0705
- Average ending detection distance with contrast sensitivity score: r=0.1792.

Most of the correlations are low, however the ending detection distance with visual acuity was reasonably high. Figure 22 below represents the relationship between the average ending detection distance and visual acuity. As shown in the graph, one participant had a very long average detection distance and the highest visual acuity, thereby accounting for the stronger correlation.

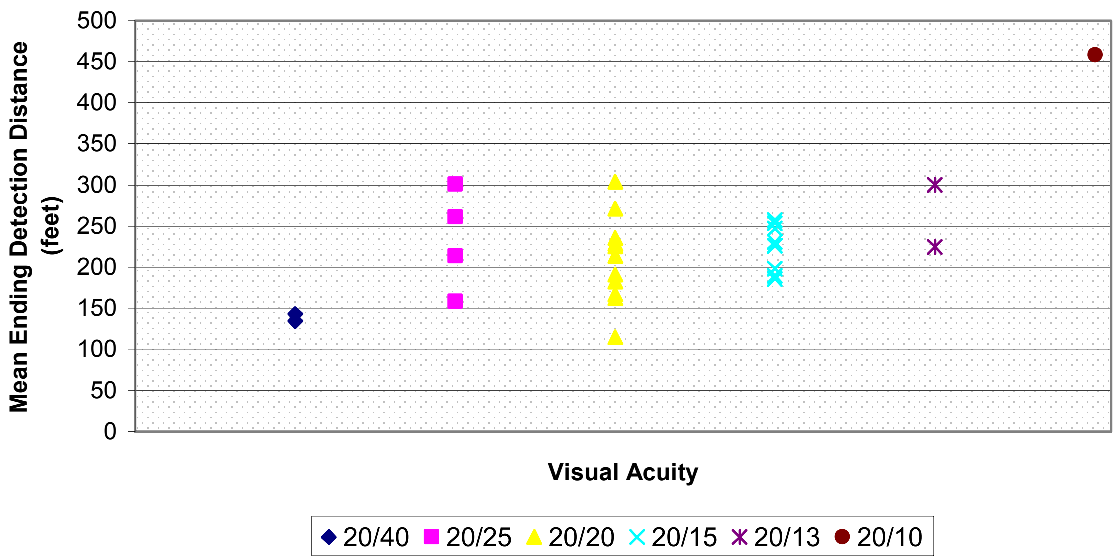


Figure 22. Visual acuity versus average ending detection distance.

CHAPTER 5. DISCUSSION

5.1 Overview

The discussion that follows is based on the following research questions:

- Which headlamp technology provided the least amount of discomfort glare at both the close and far road segments?
- Which headlamp configuration provided the largest beginning and ending detection distance?
- Which pavement marking material was most visible with all the tested headlamp configurations?
- What age differences existed in regard to discomfort glare experienced and pavement marking visibility?
- Was there a difference in low- versus high-profile vehicles for discomfort glare and/or detection distances?
- Did the addition of UV-A headlamps affect pavement marking visibility?
- Do visual capabilities affect pavement marking detection distances?
- Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

In addition, presentation order was evaluated.

This research effort investigated eleven headlamp configurations: halogen low beam (HLB), Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB, high intensity discharge (HID), Hybrid UV-A + HID, Middle UV-A + HID, High UV-A + HID, high output halogen (HOH), halogen high beam (HHB), and halogen low beam- low profile (HLB-LP). The HLB and HID were baseline conditions. In addition, three age groups were used: young (18-25 years), middle (40-50 years old), and older (60 years and older).

Significant results were found for the following main effects and interactions:

- Presentation orders for far and close discomfort glare evaluations and beginning detection distance.

- Headlamp configurations for the far and close discomfort glare.
- Headlamp configurations and pavement marking material for beginning and ending detection distances.
- Participant age for beginning detection distance and ending detection distance for the different levels of UV-A.
- Significant interaction for headlamp configuration and pavement marking material interaction for beginning and ending detection distances.

Presentation order was found to be significant for the far and close discomfort glare evaluation and the beginning detection distance. When examining the results, however, it was determined that this order effect was not systematic, therefore was not included in subsequent analyses.

When looking at the results from both the discomfort glare and pavement marking tasks, the results were most related to the baseline condition, either HID or HLB. In all but one case, the configurations for the different levels of UV-A were not statistically different than the baseline configuration. The baseline conditions provided the visible light, and are designed to be the primary source of visibility and consequently glare. The UV-A elements, in contrast, are designed to enhance visibility. Therefore, it is reasonable to expect the baseline condition to have the greatest influence throughout this evaluation.

When comparing the results of the discomfort glare evaluation, headlamp HID configuration(s) most consistently provided the least amount of discomfort glare. The specific HID headlamp tested contained a wide beam with a sharp cut-off which was specifically designed to reduce glare to oncoming drivers. Within the testing environment of this research effort, namely the low speed, the HID configurations provided adequate preview time (per Schnell and Zwahlen, 1999b) and reduced close discomfort glare. Therefore, for low speeds tested in this evaluation the HID configurations with the sharp cut-off beam pattern are optimal.

It is critical to remember, however, that pavement marking visibility is reduced at higher speeds, and the tested HID configurations may not provide adequate visibility at higher speeds. The results of this research effort reflected that the HLB configurations with the straight-ahead beam pattern, which is specifically designed to provide the longest detection distances even at the cost of increasing glare patterns. The HLB configuration tested consistently provided the longest detection distances, and this increased visibility may be critical at higher speeds. However, the results of this evaluation do not provide any prediction on how other HID headlamps, specifically with a straight-ahead beam patter, would perform. It is plausible that other HID configurations would provide better visibility as did the HLB configurations tested.

The results of this research provide justification for future research and development in headlamps that would increase visibility but reduce glare. This could be accomplished with the research and development of a hybrid beam pattern, i.e., one that is a compromise between the wide beam, sharp cut-off pattern tested with the HID headlamps and the straight-ahead beam pattern tested with the HLB configurations. An additional suggestion is to provide research and development into adaptive headlights that adjust the beam depending on the driving parameters.

The results of the pavement markings for all headlamp configurations showed that the 3M Liquid System consistently performed better than the other materials, but was not significantly different than the fluorescent thermoplastic material. One potentially influential factor was that of pavement material – the fluorescent paint was on concrete while the other materials were on asphalt. Although it is not known from the results of this research effort how much this factor influences the results, it should be considered when reviewing the results of this research effort. That said, it should also be noted that all three pavement marking materials provided adequate visibility (per Schnell and Zwahlen, 1999b) at low speeds.

Significant interactions were found between headlamp configuration and pavement marking material for beginning and ending detection distances. This may be due in part to properties of both the lights and the properties of the pavement marking material. For example, it was found that the detection distances of the 3M Liquid System dropped considerably when interacting with the HID configurations. Based on some physical property in the pavement marking material (e.g., bead pattern), there appears to be less compatibility with the bluer light emitted by the HID headlamps. The result implies the need to consider pavement material in addition to pavement marking material. That is, depending on the pavement marking material selected, the headlamp could enhance or detract from the marking visibility.

An age effect was found for the ending detection distance and approached significant for the beginning detection distance. As expected, the significant age effect showed younger drivers attaining the longest detection distances. This can be due in part to reaction times, which are faster in younger drivers (Mortimer and Fell, 1989). For the glare evaluations, other researchers have shown that glare affects all age groups equally (Olson and Sivak, 1982). Based on these results, it can be concluded that the technologies tested would benefit all age groups.

5.2 Responses to Research Questions

Below is a discussion of the research questions and the responses to each question based on the analyses of this research effort.

5.2.1 Which headlamp technology provided the least amount of discomfort glare at both the close and far road segments?

Overall, the close glare evaluations were worse than the far glare evaluations. Such a result was expected, as the level of glare increases as the driver is closer to the glare source (Olson and Sivak, 1981; Poulton, 1994).

For the far glare evaluation, many of the headlamp configurations were not significantly different. However, for the close glare evaluation, the HID, Middle UV-A + HID, High UV-A + HID, and halogen low beam- low profile configurations performed best. That is to say, for close glare the HID configurations provided less close glare than the HLB conditions. Based on the beam patterns tested in this research effort, the better performance of the HID configuration was expected. The HID headlamp tested had a beam pattern that contained a sharp cut-off, which is designed to reduce glare for oncoming drivers (Mace, Garvey, Porter, Schwab, and Adrian, 2001). This beam pattern could have affected the lower glare ratings as much as, if not more than, the HID component. In fact, HID lights generally emit three times more light than other headlamps (Sharke, 2001), therefore should cause more glare.

It must be noted, however, that one reason the HID (i.e., sharp cut-off) headlamps tested provided less discomfort glare is the precise alignment of the headlamps. With the sharp cut-offs, the highest intense spot of light is designed to be concentrated below the eye height of other drivers. However, if the headlamp is misaligned and the spot of concentration is too high, the amount of glare drivers receive is worse than that experienced with straight-on headlamps (Sharke, 2001).

The misalignment issue may be part of the recent surge in glare complaints about HIDs – the National Highway Transportation Safety Administration (NHTSA) reports a great increase in such complaints (www.nhtsa.gov). Therefore, even though this beam pattern does produce less glare, maintenance should be a top priority for all HID headlamps, especially for those headlamps with the cut-off beam patterns. The recommendation implies the implementation of technologies, such as auto-leveling mechanisms, in all HIDs with a sharp cut-off to reduce the risk of misalignment.

In summary, for this research effort the HID configurations provided the least amount of glare, especially for the close glare evaluation. This result is partly attributable to the beam pattern, which is comprised of a wide pattern with a sharp cut-off. This beam pattern was specifically designed to reduce the amount of glare to oncoming drivers; the results of this research effort seem to validate the design. However, within the confines of this research effort it is not known how well other HID headlamps would perform in this same evaluation – with a different beam pattern the HIDs could in fact provide more glare (e.g., a HID with a straight-ahead beam pattern). Therefore, it is suggested that more research be conducted on other HID headlamps to determine the level of glare induced for each headlamp.

5.2.2 Which headlamp configuration provided the largest beginning and ending detection distance?

For the beginning detection distance, the Hybrid UV-A + HLB provided the longest detection distance, but several other conditions, namely HLB, Middle UV-A + HLB, High UV-A + HLB and HOH also performed well. For the ending detection distance, the Middle UV-A + HLB condition provided the longest detection distance, immediately followed by HLB, Hybrid UV-A + HLB, and High + UV-A HLB.

The halogen low beam configurations tested in this evaluation are recommended for maximum visibility. In contrast with the HID beam pattern, the HLB baseline conditions and the high output halogen and halogen high beam conditions had a straight-ahead beam pattern that did not contain a sharp cutoff. The result of this shape of beam pattern is increased visibility (Mace et al., 2001). Based on the beam pattern, these results were expected.

In summary, the overall recommendation for pavement marking visibility is this specific light configuration, the HLB configuration with the straight-ahead beam pattern. However, within the confines of this research effort it is not known how well other HLB headlamps would perform in this same evaluation – with a different beam pattern the HLBs could in fact be less visible (e.g., a HLB headlamp with a wide, sharp cut-off beam pattern). Therefore, it is suggested that more research be conducted on other HLB headlamps to determine the visibility capabilities for each headlamp.

5.2.3 Which pavement marking material was most visible with all the tested headlamp configurations?

This research effort examined three pavement marking materials: fluorescent paint, fluorescent thermoplastic, and 3M Liquid System. The 3M Liquid System condition provided the longest detection distance for both the beginning and ending detection distances, closely followed (i.e., with the same SNK rating) by fluorescent thermoplastic. The performance of the fluorescent thermoplastic was expected based on Turner et al. (1998), where they found fluorescent thermoplastic to perform well compared to the other pavement marking materials (new paint, worn paint, new thermoplastic, and fluorescent thermoplastic).

The 3M Liquid System provided the longest average detection distances, but was not statistically different than the fluorescent thermoplastic material. Of the three pavement marking materials tested, both materials are recommended for visibility. It is important to note, however, that all three materials exceed the minimum visibility requirement suggested by Schnell and Zwahlen (1999b). Recall that the researchers suggested a 3.65 second visibility for pavement markings. At 25 miles-per-hour, which equates to a detection distance of approximately 134 feet – the means for all pavement marking materials for both the beginning and ending detection distances exceeded that distance. This is not to say that the pavement markings would provide adequate preview at higher speeds, but all pavement markings can be considered adequately visible at 25 miles-per-hour. That is, all pavement marking materials tested in this research effort could be effectively used on lower speed roadways knowing that they provide enough visibility for that road.

It should also be noted that the pavement marking materials were several months old when the data collection took place. It is possible that the fluorescent properties had decreased by then, therefore limiting the visibility of the markings, namely for those headlamp configurations that contained a UV-A element. This is an important consideration for real-world use of the materials. Any material that would exhibit a large degrade in performance in such a short time would either require additional maintenance or, more likely, would be left untouched on the roadways even with the reduced visibility. Assuming some physical properties of the materials decrease, therefore reducing visibility benefits, it would be advisable not to implement either of the fluorescent materials on a roadway unless proper maintenance could be guaranteed. The ideal would be a material that requires less maintenance. Of the three pavement marking materials tested, the 3M Liquid System appeared to be a good alternative in that it appeared to maintain an acceptable level of integrity over its time on the road.

5.2.4 What age differences existed in regard to discomfort glare experienced and pavement marking visibility?

This research effort focused on three age groups: 18-25 years, 40-50 years, and 60 years and older. The only significant age affect was ending detection distance; age effects approached significance ($p = 0.0528$) for beginning detection distance. For the ending detection distance with different levels of UV-A, age was also significant. However, the different age levels were not statistically different from one another.

For the beginning and ending pavement marking detection distances, younger drivers had longer detection distances than older drivers. Such results were as expected. Researchers have also shown that older drivers have longer reaction times than younger drivers, resulting in shorter detection distances (Mortimer and Fell, 1989).

No age effect was found for the far discomfort glare evaluation. Other researchers have found that glare can affect young and old drivers the same. In Olson and Sivak, (1982), for example, the experimenters provided a glare source to measure the effect on traffic sign legibility. Both young and old drivers showed the same performance degradation with the presence of glare. This result reinforces the notion that all age groups would benefit reduced glare, making enhanced nighttime visibility a salient issue for all drivers.

The results of this research effort did not yield any significant interactions with age. The fact that one technology did not benefit a particular age group differently than another is a positive indication that the technologies benefit all ages equally. If any of these technologies were implemented, it can be reasonably assumed that all drivers were benefit from any enhancements provided from the technology.

5.2.5 Was there a difference in low- versus high-profile vehicles for discomfort glare and/or detection distances?

This research effort investigated two halogen low beam headlamp configurations- high profile (referred to as halogen low beam) and low profile (referred to as halogen low beam, low profile). High profile is representative of the headlamp height of sport utility vehicles and pick-up trucks, whereas low profile is representative of the headlamp height of sedans. It was expected that the higher profile headlamps would provide greater pavement marking detection distances and worse discomfort glare. Raising the headlamp height shifts the beam pattern so that the point of greatest intensity is further down the road and causing more glare for other drivers. To reduce glare, researchers have recommended minimizing the headlamp height to 30 inches or less to reduce glare for drivers (Mortimer, 1988).

The results of the profile comparison were as expected. For the far glare evaluation, the HLB and the halogen low beam- low profile configurations were not significantly different (both ratings had an SNK grouping including B), but the halogen low beam- low profile provided significantly less close glare. The greater distance of the observer from the glare source during the far glare evaluation may have diffused the difference in headlamp height – the same effect would not occur with the close glare evaluation due to the close proximity to the glare source. For the beginning and ending detection distances, the HLB headlamp configurations performed significantly better than the halogen low beam- low profile.

Considering the effect headlamp height/vehicle height has on discomfort glare and pavement marking visibility, real world consequences exist for drivers. Both high and low profile vehicles drive on American roadways. According to the results of this research effort, the high profile vehicles would provide greater amounts of discomfort glare to oncoming vehicles. Although the low profile headlamps provide less discomfort glare, they do not provide as much pavement marking visibility. The reduced visibility may carry over to other objects as well, such as pedestrians and bicyclists.

For both increased glare and reduced visibility, reduced speed is the critical behavioral adjustment. With reduced visibility, drivers can compensate by reducing their speed to provide more time to detect and react to objects in the road. In the presence of discomfort glare, researchers have shown that drivers reduce their speed (Theeuwes, Alferdink, and Perel, 2002). Therefore, slightly more glare may not impose an unacceptable safety risk if enough visibility enhancement is provided.

For maximum safety, however, “engineering” the hazard out, that is reducing the amount of glare, is the most effective method. To limit the amount of glare, measures should be taken to reduce the amount of light the high-profile vehicles provide to oncoming drivers. Such measures can include intelligent headlamps, which either reduces beam intensity when they detect an oncoming vehicle or adjust the beam away from the driver when an oncoming vehicle is detected.

One caveat with this assessment is the difference in the physical characteristics of the headlamps. Although both were halogen low beam bulbs, different luminaries, or headlamp housings, were used for each condition. It is possible that some of the difference in performance can be attributed to differences in how the beam is projected down the road based on the luminaries. However, with the research that supports the benefits and drawbacks to each headlamp profile, it is reasonable to say that profile was a legitimate factor in this evaluation.

5.2.6 Did the addition of UV-A headlamps affect either discomfort glare or pavement marking visibility?

Based on the results of the analyses, headlamp configurations with UV-A elements were often not significantly different from the baseline configurations. For the pavement marking task, one possible explanation is that the UV-A did not enhance the visibility of the pavement markings due to the degradation of the fluorescent properties in the pavement marking materials. The pavement markings were several months old when this data collection took place. During this time, the fluorescent properties may have broken down, reducing the impact of the UV-A headlamps. This limitation of the fluorescent pavement marking materials is important from a maintenance aspect, and would increase the demand on maintenance resources required, therefore would restrict the implementation of the product on public roads.

Pertaining to discomfort glare, the UV-A headlamps again did not provide any benefits. Because UV-A is not visible light, it was expected that the UV-A elements would not negatively impact glare. However, one UV-A level, Hybrid UV-A, increased the amount of close discomfort glare but had no measurable effect on pavement marking visibility. The Hybrid U-A light did contain a visible light component and a wide beam pattern for the visible light component; however, the beam pattern did not contain a sharp cut-off. The beam pattern placed more visible light into the eyes of the participants but was not projected down the road as far, therefore did not increase pavement marking detectability. For this light to be optimal, it either should have the wide pattern but have a cut-off for the visible light or adopt more of the straight-ahead pattern. For the visible light component, the straight-ahead beam pattern would increase pavement marking visibility, therefore it is recommended to consider this beam pattern for future implementations of this headlamp. However, with that implementation the higher level of visible light from the UV-A lamp should be compensated with less intense light from the baseline headlamp.

In summary, this research effort did not provide adequate support for the implementation of UV-A headlamps as they did not enhance pavement marking visibility nor reduce discomfort glare. The Hybrid UV-A headlamps increased the level of close discomfort glare. In addition to the lack of increased performance, the UV-A component would provide additional costs to consumers. In order to convince consumers to pay the additional money for such a feature, the headlamps would need to enhance pavement marking visibility without increasing, if not decreasing, discomfort glare or provide other benefits not examined in this research effort. Based on the effect of discomfort glare and pavement marking visibility, this research effort did not provide evidence to support such an additional cost.

5.2.7 Do visual capabilities affect pavement marking detection distances?

Correlation analyses were conducted to determine if a relationship existed between vision test results, visual acuity and contrast sensitivity, and glare ratings and pavement marking detection distances. Only one correlation, ending detection distance with visual acuity, provided a strong correlation ($r = 0.5422$). This result can be attributed in part to one participant who had extremely good visual acuity and the longest ending detection distance. Excluding this example, many of the detection distances were similar regardless of the visual acuity.

With the other low correlations for this assessment, it is important to consider other measurements for visual abilities that can be indicative, if not predictive, of visual task performance. Previous researchers have shown a correlation between a dynamic visual acuity score and errors on driving tests ($r = .2346$, $p<0.040$), where a significant relationship did not occur with static visual acuity (National Highway Transportation Safety Administration, 1999). Similar results were found when comparing static and dynamic contrast sensitivity – dynamic contrast sensitivity and errors on driving tests were significant ($r = .2420$, $p<.034$) and were not significant for the static contrast sensitivity. Based on these results, future evaluations may want to consider dynamic testing in the future.

5.2.8 Overall, which headlamp(s) provided the greatest benefit for drivers in providing the least amount of glare and the greatest visibility enhancement?

Below is a summary of each headlamp configuration and their performance for both the discomfort glare and pavement marking task. Recall that discomfort glare was evaluated using the DeBoer scale, which is as follows:

1 Unbearable
3 Disturbing
5 Just Acceptable
7 Satisfactory

9 Just Noticeable

Halogen Low Beam. The HLB configuration was one of the two baseline conditions for this research effort, with a straight-ahead beam pattern. The HLB configuration provided a discomfort glare rating between "Slightly Acceptable" and "Satisfactory" for the far glare evaluation and near "Disturbing" for the close discomfort glare evaluation. With pavement marking visibility, the HLB provided middle to high results for the beginning detection distance and high for the ending detection distance. Overall, it was determined that the baseline configurations, HLB and HID, were the biggest influences in the outcome of this research effort as levels of UV-A were often not significantly different.

Hybrid UV-A + Halogen Low Beam. The Hybrid UV-A + HLB configuration was a combination of the HLB and the Hybrid UV-A, which contained a visible light component. This configuration provided a discomfort glare rating slightly below "Slightly Acceptable" for the far glare evaluation and between "Disturbing" and "Unbearable" for the close discomfort glare evaluation. Unlike the other UV-A configurations, this UV-A negatively influenced the results by increasing close glare. With pavement marking visibility, the Hybrid UV-A + HLB provided high results for the beginning detection distance and middle to high for the ending detection distance.

Middle UV-A + Halogen Low Beam. The Middle UV-A + HLB configuration was a combination of the HLB and the Middle UV-A. This configuration provided a discomfort glare rating between "Slightly Acceptable" and "Satisfactory" for the far glare evaluation and slightly above "Disturbing" for the close discomfort glare evaluation. With pavement marking visibility, the Middle UV-A + HLB provided middle to high results for the beginning detection distance and ending detection distance. This configuration was not significantly different from the HLB baseline condition.

High UV-A + Halogen Low Beam. The High UV-A + HLB configuration was a combination of the HLB and High UV-A. This configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far glare evaluation and between “Disturbing” and “Slightly Acceptable” for the close discomfort glare evaluation. With the pavement marking visibility distances, the middle UV-A + HLB condition provided middle to high visibility for the beginning and high distances for the ending markings. This configuration was not significantly different from the HLB baseline condition.

High Intensity Discharge. The HID configuration was one of the two baseline conditions for this research effort, which had a sharp cut-off beam pattern. The HID configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far glare evaluation and slightly above “Slightly Acceptable” for the close discomfort glare evaluation. With the pavement marking visibility, the HID condition provided middle to low visibility distances for the beginning and ending detection distances. Overall, it was determined that the baseline configurations, HLB and HID, were the biggest influences in the outcome of this research effort.

Hybrid UV-A + High Intensity Discharge. The Hybrid UV-A + HID configuration was a combination of the HID and the Hybrid UV-A, which contained a visible light component. This configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far glare evaluation and between “Disturbing” and “Slightly Acceptable” for the close discomfort glare evaluation. Unlike the other UV-A configurations, this UV-A negatively influenced the results by increasing close glare. The Hybrid UV-A + HID condition provided middle to low results for the pavement markings and detection distances.

Middle UV-A + High Intensity Discharge. The Middle UV-A + HID configuration was a combination of the HID and the Middle UV-A. This configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far and close discomfort glare evaluation. For the pavement markings, the headlamp configuration provided middle to low visibility distances for the beginning and ending pavement markings detection distances. This configuration was not significantly different from the HID baseline condition.

High UV-A + High Intensity Discharge. The High UV-A + HID configuration was a combination of the HID and High UV-A. This configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far and close discomfort glare evaluation. Concerning the pavement markings, the headlamp configuration provided low distance for the beginning and middle to low visibility distances for the ending pavement markings detection distances. This configuration was not significantly different from the HLB baseline condition.

High Output Halogen. The high output halogen configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far discomfort glare rating and slightly above “Disturbing” for the close discomfort glare evaluation. For pavement marking visibility, the high output halogen condition provided middle and high detection distances for the beginning and ending markings, respectively. This configuration had the same luminaries as the halogen high beam and halogen low beam-low profile conditions. Compared to the halogen high beam condition, high output halogen was not significantly different in the glare evaluations; however, performed better in the pavement marking task. Compared to the halogen low beam- low profile condition, the high output halogen condition had worse discomfort glare but better pavement marking detection distances.

Halogen High Beam. The halogen high beam configuration provided a discomfort glare rating between “Slightly Acceptable” and “Satisfactory” for the far discomfort glare rating and between “Disturbing” and “Unbearable” for the close discomfort glare evaluation. Concerning pavement marking visibility, the headlamp configuration provided low detection distances for the beginning pavement markings and middle to low detection distances and ending pavement markings. This configuration had the same luminaries as the high output halogen and halogen low beam- low profile conditions. Compared to the high output halogen condition, halogen high beam was not significantly different in the glare evaluations; however, performed worse in the pavement marking task. Compared to the halogen low beam- low profile condition, the high output halogen condition had worse discomfort glare but better pavement marking detection distances.

Halogen low beam- low profile. The halogen low beam- low profile condition provided middle to high ratings for the far and close glare evaluation. Concerning the pavement markings, the headlamp configuration provided low detection distances for the beginning and ending pavement markings. This configuration had the same luminaries as the high output halogen and halogen high beam conditions. Compared to the high output halogen condition and halogen high beam, halogen low beam- low profile had better glare ratings but worse pavement marking detection distances.

In summary, the baseline condition, either HLB or HID, was the key factor in overall performance. That is to say, UV-A did not provide an advantage for either glare or pavement marking ability, therefore is not considered a part of the optimal solution. The baseline conditions provided the visible light, and are designed to be the primary source of visibility and consequently glare. The UV-A elements, in contrast, are designed to enhance visibility. Therefore, it is reasonable to expect the baseline condition to have the greatest influence throughout this evaluation.

The HID headlamp configurations, with the cut-off beam pattern specifically designed to reduce glare, provided the least amount of glare, especially for the close glare evaluation. The HLB configurations, with the straight-ahead beam pattern designed to provide maximum visibility, provided the longest detection distances. Based on the results of this research effort, it cannot be concluded whether or not the baseline condition or the beam pattern were the bigger contributor. But it can be assured that beam pattern is critical in the effectiveness of headlamps, both for glare and pavement marking detectability.

The primary purpose of this research effort was to determine the headlamp configuration that provided the greatest pavement marking visibility with the least amount of discomfort glare. From the eleven configurations tested, the HLB provided the longest detection distances but provided increased close glare. The HID configurations provided the lowest discomfort glare but reduced pavement marking visibility. However, when comparing the detection distances for the HID configurations to the recommended pavement marking preview time of 3.65 seconds (at 25 miles-per-hour, about 134 feet), the HID configurations provided adequate visibility for the low speed tested. Therefore, for lower speed roads, the HID configurations are optimal because their beam pattern reduces the amount of glare to oncoming vehicles but allows for adequate preview time. Therefore, within the tested parameters of this research effort, the HID conditions are optimal.

This is not to say at higher speeds the HIDs tested would still be adequate – pavement marking visibility is reduced as speed is increased (Jacobs et al., 1995). For higher speeds, the HLB conditions may be required for adequate visibility. In fact, the straight-ahead beam pattern is widely implemented in American vehicles to provide optimal visibility, even at the cost of increased glare. In addition, the results of this evaluation do not provide any prediction on how other HID headlamps would perform at different speeds. It is plausible that other HID configurations would provide greater visibility as did the HLB configurations tested.

Similar to the high-profile effect, headlamp configuration/beam pattern has an affect on discomfort glare and pavement marking visibility, and real world consequences exist for drivers. Both beam patterns are represented on American roadways. According to the results of this research effort, the higher visibility headlamp/beam patterns would provide greater amounts of discomfort glare to oncoming vehicles. Although the low profile headlamps provide less discomfort glare, they do not provide as much pavement marking visibility. The reduced visibility may carry over to other objects as well, such as pedestrians and bicyclists.

For both increased glare and reduced visibility, reduced speed is the critical behavioral adjustment. With reduced visibility, drivers can compensate by reducing their speed to provide more time to detect and react to objects in the road. For discomfort glare, researchers have shown that when exposed to glare, drivers reduce their speed (Theeuwes et al., 2002).

For maximum safety, however, "engineering" the hazard out, that is reducing the amount of glare, is the most effective method. To limit the amount of glare, measures should be taken to reduce the amount of light the different beam patterns provide to oncoming drivers. Such measures can include researching and developing a hybrid beam pattern that would optimize the benefits provided by both patterns: the sharper, wider pattern that reduces glare and the straight-ahead pattern that provides the greatest visibility. An additional suggestion is to research and develop intelligent headlamps, which either reduces beam intensity when they detect an oncoming vehicle or adjust the beam away from the driver when an oncoming vehicle is detected.

5.3 Other Issues for Discussion

Presented below are other issues that resulted from the current research effort, including significant interactions between pavement markings and headlamp configurations and comparisons within the same headlamp luminaries.

5.3.1 Interaction of Pavement Marking and Headlamp Configuration.

Significant interactions were found between headlamp configuration and pavement marking material for both the beginning and ending detection distance (as represented in Tables 12 and 13). When looking at the mean detection distances for each headlamp, all pavement markings were even more visible with the HLB conditions (HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB) and the HOH condition. The fluorescent paint was noticeably less visible with the HID lights, which reduced the overall visibility of this material across all headlamp configurations.

The interaction between headlamp configuration and pavement marking material is important for real-world implementations of pavement markings and headlamps. When considering pavement marking materials, the decision should in part be based on which headlamps (HID versus HLB) will be used on that road. Currently, HLB is the most common headlamp configuration, therefore pavement marking materials should be optimized for that configuration. Based on the results of this research effort, any of the pavement marking materials tested provides appropriate visibility on lower speed roads. However, once other configurations become more widespread, pavement marking material should be optimized for all technologies.

One combination of headlamp/pavement marking material is not recommended based on the results of this research effort. The fluorescent paint with the HID configurations and halogen high beam and halogen low beam-low profile exhibited the lowest drop off of all the interactions for beginning detection distance. This may be due in part to properties of both the lights and the properties of the pavement marking material. For example, it was found that the detection distances of the 3M Liquid System dropped considerably when interacting with the HID configurations. Based on some physical property in the pavement marking material (e.g., bead pattern), appears to be less compatibility with the bluer light emitted by the HID headlamps. Although this trend was not as pronounced with ending detection distance, this combination of pavement marking materials should be implemented with caution.

5.3.2 Comparisons Within the Same Headlamp Luminaries.

For this research effort three headlamp configurations – high output halogen, halogen high beam, and halogen low beam- low profile – were housed in the same luminaries. Using the same luminaries, especially for vehicles with the same headlamp height, provides a consistency that affords direct comparison of headlamp configurations. Based on this factor, the results of the high output halogen and halogen high beam are discussed.

For the glare evaluations, the two configurations were not significantly different. However, for the pavement marking task the high output halogen consistently performed better that the halogen high beam. This result was unexpected – halogen high beam is often though of as the headlamp configuration that provides the greatest visibility. It is also considered as the headlamp configuration that provides unacceptable amounts of glare, therefore the use of this configuration is limited to situations in which there are no other vehicles on the road. Because these headlamps were not significantly different in the amount of glare they provided, which was more than the other halogen configurations for the close glare evaluations, it should be considered that the restrictions on use of the high output halogen should be similar to those of halogen high beam. However, before such restrictions are enacted, comparisons of the same headlamps in different luminaries than those used in this research effort should be conducted to ensure this effect is maintained across hardware.

5.4 Research Limitations

One confound that was present in the current research effort was that of pavement materials. The fluorescent paint was on concrete, where the fluorescent thermoplastic and 3M Liquid System pavement markings were painted on asphalt. The different materials provide different contrasts with the pavement markings, with concrete generally providing the least contrast. From the current data, it is difficult to determine how much the pavement material reduced the visibility of the fluorescent paint material, but the confound must be considered as a contributor to the lower averages. This is not to diminish the high visibility of the other pavement markings. However, it does indicate that if on the same pavement material, the fluorescent paint may have performed better. The result also implies the need to consider pavement material in addition to pavement marking material. That is, depending on the pavement, the pavement marking material selected could enhance or detract from the marking visibility.

Another limitation was the difference in participants' eye height between the vehicles. Table 17 below represents the vehicle, average participant eye height for that vehicle, and the configurations associated with each vehicle.

Table 17. Vehicle, average participant eye height, and headlamp configurations.

Vehicle	Average Participant Eye Height (in inches)	Headlamp Configurations
Explorer	58.12	HLB Hybrid UV-A + HLB HID Hybrid UV-A + HID
Explorer	58.69	Middle UV-A + HLB High UV-A + HLB Middle UV-A + HID High UV-A + HID
Pick-up	61.56	High output halogen Halogen high beam
Cadillac	47.87	Halogen low beam- low profile

There was slightly more than a three-inch difference between one Explorer and the pick-up. When looking at the differences in detection distances for these vehicles comparing similar headlamp configurations (i.e., halogen), the distances were not statistically different. This is especially important because the pick-up, that is the tallest of the vehicles, also had the highest-intensity headlamp configurations (high output halogen, halogen high beam). Based on these results, it is reasonable to conclude that the difference in seated height is minimal for this research effort.

The age of pavement marking was another limitation. The pavement markings were several months old when this evaluation took place. This could have limited the impact of UV-A. However, this was considered when discussing UV-A headlamps – if the pavement markings' optimal effectiveness was short-lived, that pavement marking material would be considered higher maintenance and therefore less desirable to municipalities and agencies.

Another confound were the three different luminaries used through this research effort. This constraint limits the comparison to the light type only and requires some consideration of the influence of the luminaries in the interpretation. It is a moderate limitation, minimized by defining the headlamp specifications previously in this document.

A limitation has been found with the DeBoer scale, the scale that was used for the discomfort glare evaluation. Researchers have determined that this scale is not a good indicator of driver performance (Theeuwes et al., 2002). This scale was selected because it is a widely used glare evaluation and is accepted in industry. By selecting such a widely used scale, the results of this evaluation can more easily be compared to previous research efforts.

The last limitation in this research effort was the partial factorial design concerning headlamp beam pattern. The sharp cut-off pattern was only represented in the HID conditions; the straight-forward beam pattern was found in all other configurations. The different beam patterns made direct comparisons more difficult. Therefore, all recommendations are made with acknowledgement to both baseline condition and beam pattern.

CHAPTER 6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The discussion that follows will include both an overview of the current research effort and suggestions for future research.

6.1 Overview of Current Research Effort

The intent of this research effort was as follows: (1) to determine the best, if any, headlamp configuration of the eleven tested in terms of highest visibility of pavement markings and minimal discomfort glare, and (2) to determine which of the three types of pavement marking material was most visible under all headlamp conditions. In addition, the topics of presentation order, age effects on discomfort glare and/or pavement marking visibility, low- versus high-profile headlamps, interactions of headlamp configurations and pavement markings, and benefits of UV-A headlamps are discussed. In this research effort, the participants evaluated the discomfort glare for all eleven headlamp configurations and indicated the detection distance of all pavement marking materials.

This research effort investigated eleven headlamp configurations: halogen low beam (HLB), Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB, high intensity discharge (HID), Hybrid UV-A + HID, Middle UV-A + HID, High UV-A + HID, high output halogen (HOH), halogen high beam, and halogen low beam- low profile. In addition, three age groups were used: young (18-25 years), middle (40-50 years old), and older (60 years and older).

Of the headlamp configuration of the eleven tested in terms of highest visibility of pavement markings and minimal discomfort glare, none consistently provided maximum visibility with less discomfort glare. The HID headlamp configurations with the wide, sharp cut-off beam pattern consistently provided the least amount of glare, especially close glare. However, any headlamp configuration with a halogen low beam component (HLB, Hybrid UV-A + HLB, Middle UV-A + HLB, High UV-A + HLB, HOH) provided the maximum visibility. Despite the reduced visibility, the HID conditions provided adequate visibility (per Schnell and Zwahlen, 1999b) for the test parameters specified. Therefore, at the lower speeds tested the HID headlamps were optimal in that they provided adequate preview time but reduced glare.

It is critical to remember, however, that pavement marking visibility is reduced at higher speeds, and the tested HID configurations may not provide adequate visibility at higher speeds. The results of this research effort reflected that the HLB configurations with the straight-ahead beam pattern, which is specifically designed to provide longer detection distances even at the cost of increasing glare patterns, might provide the needed increased visibility. However, the results of this evaluation do not provide any prediction on how other HID headlamps would perform at different speeds. It is plausible that other HID configurations would also provide better visibility.

Beam pattern was also considered to be a major contributor to the results of this research effort. The HLB conditions contained a sharp cut-off, designed to reduce glare to oncoming vehicles. The HID configuration had a straight-ahead beam pattern, designed for maximum visibility. Based on the designs, the headlamp configurations performed as expected. However, it is not possible to extract the effect of beam pattern versus headlamp type. Therefore, it is recommended that future research be applied to define the optimal headlamp beam pattern, such as a hybrid beam pattern, that would optimize the benefits of the wide, sharp cut-off beam pattern and the straight-ahead beam pattern.

Of the three types of pavement marking material tested under all headlamp conditions, the 3M Liquid System provided the longest average detection distances, but was not statistically different than the fluorescent thermoplastic material. Based on these results, both materials are recommended for optimal visibility. It is important to note, however, that all three materials exceed the minimum visibility requirement for lower speeds, and could be implemented on such roads with assurance that they are adequately visible (Schnell and Zwahlen, 1999b).

A significant age effect was found for the ending detection distance. As expected, young drivers attained longer detection distances than middle or older drivers. A significant age effect was also found for the ending detection distance with different levels of UV-A. However, the different age levels were not statistically different from one another.

It was concluded that there is a visibility advantage to high profile headlamps. However, it was also found that while these headlamps increased visibility, they also increased discomfort glare. Although drivers generally adapt their behavior in the presence of glare by reducing their speed (Theewes et al., 2002), research and development into technologies that would reduce glare to oncoming vehicles is recommended to as a potential remedy to this issue.

In this research effort, the benefit of UV-A was not supported. It is suggested that UV-A could provide other benefits to drivers besides increased pavement marking visibility or reduced discomfort glare, e.g., increased obstacle detection distances. It was concluded, however, that if UV-A headlamps with a visible light component were to be implemented, the baseline headlamp should compensate by emitting less light to reduce discomfort glare.

6.2 Suggestions for Future Research

Overall, beam pattern was assumed to be a major factor in this research effort. The HLB conditions contained a sharp cut-off, designed to reduce glare to oncoming vehicles. The HID configuration had a straight-ahead beam pattern, designed for maximum visibility. Based on the designs, the headlamp configurations performed as expected. However, it is not possible to extract the effect of beam pattern versus headlamp type. Therefore, it is recommended that future research include a complete set of all combinations of beam pattern and headlamp type to be able to recommend the optimal configuration. In addition, research can be applied to define the optimal headlamp technology for both minimizing discomfort glare maximum pavement marking visibility for halogen lamps, such as a hybrid beam pattern that would optimize the benefits of the wide, sharp cut-off beam pattern and the straight-ahead beam pattern.

As one of the first research efforts into using configurations comprised of combinations of HLB, HID, and various levels of UV-A, this research effort lays groundwork for important additional research. Subsequent research should collect more data using these configurations to determine the "optimal" headlamp configuration for not only pavement marking and discomfort glare, but also other safety aspects, such as visibility of other objects.

In this research effort, the 3M Liquid System and fluorescent thermoplastic provided the longest detection distances, however all materials exceeded the minimum visibility guidelines for pavement marking materials at the tested speed. Ideally, pavement marking materials should be tested at higher speeds to ensure complete visibility. Recall that higher speeds require more retroreflective pavement markings to maintain visibility (Jacobs, et al., 1995). Before a material is implemented on a public roadway, the material should be tested to ensure the retroreflectivity is adequate for the speed of travel on that roadway.

One important finding of this research effort was the findings related to the headlamp profile. It was determined that high-profile headlamps accommodated longer detection distances but also increased the amount of discomfort glare. Such results introduce an important trade-off – increased visibility or reduced glare. Although this document endorsed the greater visibility, a great opportunity exists to research alternatives for high-profile headlamps that would provide less discomfort glare without reducing visibility benefits.

Due to the premier nature of this study, data collection was conducted under clear weather conditions only. Future research concerning headlamp configurations and pavement markings should be conducted under inclimate weather. Schnell and Ohme (2000) commented on the degradation in pavement marking visibility under conditions of rain. Researcher have also discussed how precipitation effects the transmissivity of the atmosphere, which in turn could affect the amount of discomfort glare a driver experiences (Schnell and Zwahlen, 2000).

This research effort provided support for the notion that pavement material influences the pavement marking visibility due to the amount of contrast between the materials. In this study, one pavement marking was on concrete, which is a much lighter material than asphalt. The pavement marking material that was on concrete had the shortest detection distances, implying a potential relationship between the factors. Such a comparison between pavement marking materials and pavement material could be the basis for future research.

Once the best performing headlamp configuration is determined for all conditions, pavement marking materials and obstacles, a cost-benefit analysis should be conducted to determine the feasibility of implementing such technologies into the driving population. For example, if a headlamp configuration costs additional money to implement on a personal vehicle, consumers may not value the additional visibility as much as the option costs. A comprehensive cost-benefit analysis would then determine if the system could be implemented, or if additional research would be required to find a less-expensive system.

A similar analysis should be conducted for pavement marking materials. For example, although all pavement marking materials need maintenance, some need more frequent maintenance, such as repainting, to maintain visibility. Such markings would be expensive for agencies, and the increased visibility may not offset the cost of the maintenance. Such trade-offs are important in designing an optimal infrastructure that will best support drivers at night.

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FUNDING INFORMATION

This material is based upon work supported by the Federal Highway Administration under Contract No. DTFH61-98-C-00049.

Any opinions, findings, and conclusions or recommendations expressed in this publication shall be sent to the COTR, clearly referencing this contract number and any other appropriate handling information. Written notification shall also be provided to the Contracting Officer.

APPENDICES

Appendix 1- Participant Screening Questionnaire

Driver Screening and Demographic Questionnaire

Note to Researcher:

Initial contact between participants and researchers may take place over the phone. If this is the case, read the following Introductory Statement, followed by the questionnaire. Regardless of how contact is made, this questionnaire must be administered before a decision is made regarding suitability for this study.

Introductory Statement:

After prospective participant calls or you call them, use the following script as a guideline in the screening interview.

Good day. My name is _____ and I'm a researcher with the Virginia Tech Transportation Institute in Blacksburg, VA. The project involves participation in driving study to evaluate new vehicle headlamps.

This study will involve you driving a car for one night session on the Smart Road, which is a test facility equipped with advanced data recording systems here in Blacksburg, VA. The vehicle will be equipped with data collection equipment. Does this sound interesting to you?

Next, I would like to ask you several questions to see if you are eligible to participate.

Questions

1. Do you have a valid driver's license?

Yes _____ No _____

2. How often do you drive each week?

Every day ____ At least 2 times a week____ Less than 2 times a week_____

3. How old are you? _______

4. Have you previously participated in any experiments at the Virginia Tech Transportation Institute? If so, can you briefly describe the study?

Yes _____ ____

No _____

5. How long have you held your drivers' license?

____

6. What type of vehicle do you currently drive?

____

7. Are you able to drive an automatic transmission without assistive devices or special equipment?

Yes _____ No _____

7. Have you had any moving violations in the past 3 years? If so, please explain.

Yes _____

____

No _____

8. Have you been involved in any accidents within the past 3 years? If so, please explain.

Yes _____ ____

No _____

9. Do you have a history of any of the following? If yes, please explain.

Heart condition No____

Yes________________________________

Heart attack No____

Yes________________________________

Stroke No____

Yes________________________________

Brain tumor No____

Yes________________________________

Head injury No____

Yes________________________________

Epileptic seizures No____

Yes________________________________

Respiratory disorders No____

Yes________________________________

Motion sickness No____

Yes________________________________

Inner ear problems No____

Yes________________________________

Dizziness, vertigo, or other balance problems No____

Yes________________________________

Diabetes No____

Yes________________________________

Migraine, tension headaches No____

Yes________________________________

10. Have you ever had radial keratotomy, LASIK, or other eye surgeries? If so, please specify.

Yes _____ ____

No _____

11. (Females only, of course) Are you currently pregnant?

Yes _____ No _____

12. Are you currently taking any medications on a regular basis? If yes, please list them.

Yes _____ ____

No _____

13. Do you have normal or corrected to normal hearing and vision? If no, please explain.

Yes _____

No _____ ____

I would like to take your name, phone number or phone numbers where you can be reached and hours/days when it's best to reach you.

Name ____

Male/Female

Phone Numbers ____

Best Time to Call ____

Criteria For Participation:

1. ***Must hold a valid driver's license.***
2. ***Must be 18-25, 40-50, or 65+ years of age.***
3. ***Must drive at least 2 times a week.***
4. ***Must have normal (or corrected to normal) hearing and vision.***
5. ***Must be able to drive an automatic transmission without special equipment.***
6. ***Must not have more than two driving violations in the past three years.***

7. ***Must not have caused an injurious accident in the past two years.***
8. ***Cannot have a history of heart condition or prior heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures within 12 months, respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.***
9. ***Must not be pregnant.***
10. ***Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).***
11. ***No history of radial keratotomy, LASIK eye surgery, or any other ophthalmic surgeries.***

<u>Appendix 2- Informed Consent Form</u>

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants of Investigative Projects

Title of Project: Evaluation of the Degree of Enhanced Visibility of Pedestrians and Traffic Control Devices Under Various Vision Enhancement Systems

Investigators: Jon Hankey, Tom Dingus, Myra Blanco, and Stephanie Binder

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The Purpose of this Research/Project

The purpose of the project is to determine the degree of enhanced visibility of the roadway environment with various types of vision enhancement systems while driving at night.

<u>I. Procedures</u>

Show a current valid driver's license.
Read and sign this Informed Consent Form (if you agree to participate).
Participate in three vision tests.
Perform one or more of the following portions of the study (you will be performing the studies that are marked with a check mark):

Study 1: Drive a vehicle on the Smart Road at no more than 25-miles per hour and report when you see the first and the last pavement markings on a given portion of the road.

Study 2: Drive a vehicle on the Smart Road at no more than 25-miles per hour and evaluate the level of discomfort caused by glare from headlamps of vehicles coming in the opposite direction.

Study 3: Drive a vehicle along the Smart Road at no more than 25 miles per hour and respond when you see objects in and along the roadway.

Risks

The primary risks that you may come into contact with are the obstacles on the road for Study 3. It is for this reason that you are to maintain a speed of not more than 25- miles per hour (this will be maintained for all three studies) and to maintain a 200-foot area between the vehicle and the obstacles (only applies to Study 3). For your safety, the following precautions are taken:

The Smart Road is equipped with guardrails. Therefore, if you do lose control of the vehicle, the guardrails will prevent you from sliding off the road.

You are required to wear a seat belt at all times in the vehicle, and the vehicle is equipped with anti-lock brakes.

You do not have any medical condition that would put you at a greater risk, including but not restricted to heart conditions, head injuries, epilepsy, and balance disorders.

In addition, you have not had radial keratotomy, LASIK eye surgery, or any other ophthalmic surgeries.

The only other risk that your may be exposed to is fatigue after sitting in the driver's seat for a prolonged period of time. However, if you would like to take a break at any time, please inform the experimenter.

Benefits of this Project

While there are no direct benefits to you from this research (other than payment), you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Your participation will help to improve the body of knowledge regarding various vision enhancement systems.

Extent of Anonymity and Confidentiality

The data gathered in this experiment will be treated with confidentiality. Shortly after you have participated, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 3). After the experiment, the data will be kept in a locked safe.

Compensation

You will be paid $20 per hour for participating in this study. You will be paid in cash at the end of your voluntary participation in this study.

Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty.

Approval of Research

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Virginia Tech Transportation Institute. You should know that this approval has been obtained.

<u>Subject's Responsibilities</u>

If you voluntarily agree to participate in this study, you will have the following responsibilities:

To follow the experimental procedures as well as you can, and
To inform the experimenter if you incur difficulties of any type.
Wear your seat belt.
Abide by the 25 mile-per-hour speed limit.

II. **Subject's Permission**

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

____
Signature Date

Should I have any questions about this research or its conduct, I may contact:

Jon Hankey 231-1500

Tom Dingus	231-1500
David Moore, Chair, IRB Research Division	231-4991

Appendix 3- Participant Vision Test Form

Participant Number: __________

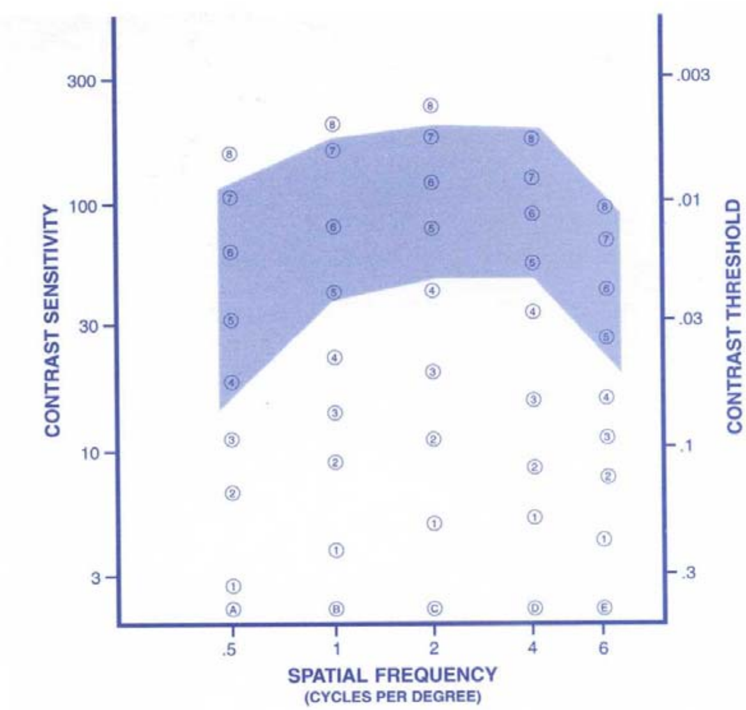
Vision Tests

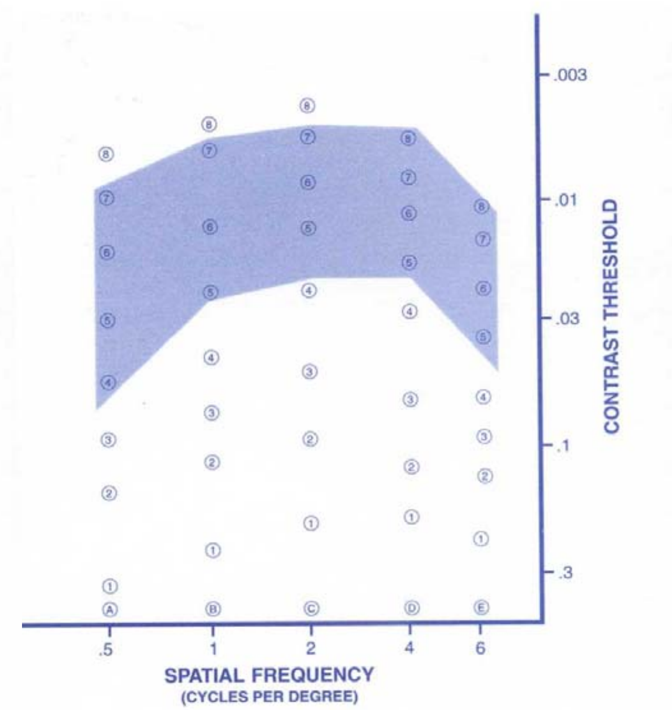
I – Acuity Test

Acuity Score:________

II – Contrast Sensitivity Test

Left   Right





III –Ishihara Test for Color Blindness

1._____ 4._____ 7.____

2._____ 5._____

3.______ 6.______

Appendix 4- In-Vehicle Experimenter Protocol

VIRGINIA TECH TRANSPORTATION INSTITUTE

Protocol for Enhanced Night Visibility Study- In-Vehicle Experimenters
Session One

Prior to the participants arrival, make sure that all the needed forms are available and label them with the subject number
Greet Participant
Record the time that the participant arrived on the debriefing form
Show driver's license.

Before we begin, it is required for me to verify that you have a driver's license. Would you please show me your license?

Must be a valid Class A driver's license to proceed with the study. Out of state is fine.

Experimenter:

This research is sponsored by the Federal Highway Administration. The purpose is to gather information that will be available to the public, including car manufacturers. The goal is to determine the best vision enhancement systems to help drivers see pavement markings at night. The lights need to also be safe and not cause any discomfort for other drivers on the road.

The study will take place on the Smart Road testing facility. The road will be closed off to all traffic except for experimental vehicles. There will be at most four experimental vehicles on the road at one time including the vehicle you will be in.

During the experiment, I will be in the vehicle with you at all times. I will be responsible for asking you questions during the drive, recording some data, and monitoring the equipment. In addition, I will be able to answer any questions you have during the drive.

You will be exposed to eleven different vision enhancement systems. You will make one lap on the Smart Road for each vision enhancement system. You will be exposed to different pavement markings with each VES. Your job will be to tell the experimenter when you detect the first and the last pavement marking in each section and to evaluate glare.

Do you have any questions at this time?
(Answer questions if needed).

Informed consent

Now I have some paperwork for you to fill out. This first form tells you about the study, what your job is, and any safety risks involved in the study. Please read through the document. If you have any questions, please feel free to ask. If not, please sign and date the paper on the last page.

Give the participant the form
Answer questions
Have participant sign and date both forms
Give the participant a copy of the informed consent

Tax Forms

Ask the participants if they are a university employee. If they are, just give them the W-9 form. If they are not, have them sign both the W-9 and the University Voucher.

To complete the W-9, the participant must fill out the following in the box:

Name

Address

Tax ID number (social security number)

Sign and date at the bottom

The second form is a University Voucher stating they are not being “permanently” employed by our project. Have them sign the back of the form.

Vision Tests

Follow me and I will go through the vision tests with you.

The results for all three parts must be recorded at the Vision Test Form

a) The first test is the Snellen eye chart test.

Take the participant over to the eye chart test area.

Line up their toes to the line on the floor (20 feet).

Participants can leave on their glasses if they wear them for driving.

Procedure: *Look at the wall and read aloud the smallest line you can comfortably read.*

If the participant gets every letter on the first line they try correct have them try the next smaller line. Continue until they miss a letter. At that time, record the below.

If they get the first line they attempt incorrect, have them read the previous line. Repeat as needed until they get one line completely correct. Record this acuity.

Particpant must have 20/40 or better vision using both eyes to participate in the study.

b) *The next vision test is the Contrast Sensitivity test.*

Take the participant over to the eye chart test area.

Line up their toes to the line on the floor (10 feet).

Participants can leave on their glasses if they wear them for driving.

Procedure*: We are going to test how well you see bars at different levels of contrast. Your ability to see these bars relate to how well you see everyday objects. It is VERY IMPORTANT you do not squint or lean forward while you are taking the test.*
Point out the sample patches at the bottom of the chart with the three possible responses (left, right, or straight).
Cover one eye with an occluder. (DO NOT let the participant use his/her hand to cover the eye since pressure on the eye may cause erroneous contrast sensitivity test results).
Instruct the participant to begin with Row A and look across from left to right. Ask the participant to identify the last patch in which lines can be seen and tell you which direction they tilt. If the response is incorrect, have the patient describe the preceding patch.
Use the table in the ENV binder to determine if subjects answers are correct.
Each vertical column of numbers on the second part of the Vision Test form corresponds to a horizontal row on the chart. Record the last patch the participant correctly identifies in each row by marking the corresponding dot on the form.
To form the participant's contrast sensitivity curve, connect the points marked.
Cover the other eye and repeat all the steps above.

c) *The last vision test is the Test for Color Blindness*.

Take the participant back to his/her desk.
Place the book containing the plates on the testing apparatus

Please hold the red end of this handle to your nose and read the number on the following plates.

Record the participants answers on the Vision Tests Form
Use the table in the ENV binder to determine if the subject is eligible to participate.
Subjects who are Red-Green Blind can not participate in the study.
Subjects who are Red-Green Weak are eligible to participate.

Nighttime Driving Questionnaire.

While the participant is waiting to complete their vision tests or after they have completed and are waiting until the other participant finishes, they can complete the Nighttime Driving Questionnaire located in the participant package. The participant needs to read each question and complete the questionnaire based on their driving practices. Ensure them that it is not going to be used against them but instead will be used to get a better idea of their current practices.

ENV Training

After the eye tests, have the participant sit at the table. Explain the following:

We will shortly go to the Smart Road. First I want to orient you to the study. For the first section, you will evaluate the glare for the different vision enhancement systems. Glare can be thought of as the amount of discomfort you experience from the oncoming lights of a vehicle. To do this, you will drive down the road and there will be a parked vehicle in the opposite lane from you with its lights on. Over two segments of road, I will ask you to evaluate the glare you experience during that segment of road. So, the road will look like this (show diagram). During that time, I want you to look straight ahead- never at the glare source- and rate the glare you experience with this scale (show scale). For this scale, you would give the glare a rating of 1 if you think it is unbearable. You would give a rating of 3 if you think the glare is disturbing. A rating of 5 would mean that you perceive the glare to be just acceptable. Seven would mean that you think the glare is satisfactory. And finally you would give a rating of nine if it is just noticeable. You can choose any number you want between 1 and9 to rate the glare. So, I will have you drive and, while looking straight ahead, I will tell you, "Begin" at the beginning of the road segment (point to on diagram). I want you to think about what rating you want to give the glare until I ask, "What is your rating?" At that time, I want you to tell me how you want to rate the glare according to the scale. For each parked vehicle we approach, we *will do that twice- once at a far distance and once at a closer distance.   Do you have any questions?*

Answer any questions.

For the second part of the study, we will be asking you to drive different vehicles. We will give you a training down on the road after we have completed this first portion.

We will now go to the road.

Take the participant to the rental vehicle. Orient them to the vehicle by showing them how to adjust their seat, lights and the steering wheel. Say,

You will notice that your side and rearview mirrors have been covered. This is to reduce the glare that you might get from other vehicles.

In addition, this is the windshield wiper. I am going to ask you not to use the wipers at all during the study. I am pointing them out to you so you can try to avoid accidentally starting them.

The participants will drive to the road. At the gate, have them stop in the correct lane. At that time, you can get out and punch in the code for the gate.

Radio the on-road experimenters that you are ready to begin.

Glare

First we will drive down the road to get you used to the road and the vehicle. Go ahead and drive down the road at a comfortable speed.

Allow the participant to drive down the road at their speed. The second vehicle can begin once the first vehicle is out of sight. If you feel the speed is excessive, you can ask them to slow down. You may also need to ask them to slow down if they are getting close to the vehicle in front of them.

First vehicle at the bottom of the hill

- pull all the way to the first parking space
- put the vehicle in park and have the participant take their foot off the brake
- close their eyes until the second vehicle is in place
- review glare training

Second vehicle at the bottom of the hill

- pull into the second parking space
- put the vehicle in park
- hold up poster board cut-out over passenger side window
- review glare training

Now we will complete the glare portion.

You will drive this vehicle up the road at 25 miles-per-hour. While you are driving, you need to look ahead and never directly at the oncoming lights. Along the way, parked vehicles will be facing you on the other side of the road. At two separate times, I will ask you to rate the glare for that vehicle. You will use a scale from 1 to 9. Again, the scale is as follows:

1: Unbearable

3: Disturbing

5: Just acceptable

7: Satisfactory

9: Just noticeable

Show them the sheet with the flashlight.

When I need you to begin evaluating the glare, I will say, "Begin." I then want you to think about the rating you want to give that headlight. I will then ask, "What is your rating?" At that time, I want you to tell me your rating for that entire stretch of road. We will repeat that for the light a second time over a different stretch of road for a total of two ratings per headlight. This will repeat until you see all of the headlights for this part of the study. And remember to always look straight ahead, never directly at the lights. Do you have any questions?

If they have no questions, wait at the bottom of the hill until the on-road experimenters indicate they are ready to begin. At that time, indicate to the on-road experimenters that you are beginning to drive up the road. Vehicle 2 must wait until Vehicle 1 is out of sight before driving up the road.

OK, let's begin.

Have the participants drive at 25 miles-per-hour until you have asked them to rate the oncoming headlights twice. You will know when to ask them to rate the glare when you pass the on-road cones. There are four cones on each side of the road. Using the ones on the right side of the road, have the participant start evaluating at the first cone (1300 feet from glare source) and give a rating at the second cone (1000 feet from glare source). Begin the second evaluation at the third cone (450 feet from glare source) and ask for a rating from the participant at the fourth cone (150 feet from glare source). Indicate the areas by saying "Begin" and "What is your rating?" Continue up the road to the second glare vehicle and repeat the procedure. Remind the participant before each rating to look straight-ahead and never directly at the light.

<u>First vehicle at the top of the hill</u>

Pull up to white line just before the top of hill

- Wait for headlight glow from 2^{nd} vehicle to appear
- Pull up to the first cone on the left side of road
- Put vehicle in park

- Remind participants of scale and to not look directly at the lights
- Go down the road once the on-road experimenters indicate they are ready

Second vehicle at the top of the hill

- Pull up to first cone on the right side of the road
- Put vehicle in park
- Remind participants of scale and to not look directly at the lights
- Go down the hill when the first vehicle is out of sight

Repeat the evaluating/rating procedures on the way down the hill.

First vehicle at the bottom of the hill

- Pull all the way to the first parking space
- Put the vehicle in park
- Close their eyes until the second vehicle is in place
- Go up the road once the on-road experimenters indicate they are ready

Second vehicle at the bottom of the hill

- Pull into the second parking space
- Put the vehicle in park
- Ask participants to close their eyes
- Hold up poster board over passenger side window
- Go up the road once the first vehicle is out of sight

Repeat the evaluating/rating procedures on the way up the hill.

When the participants return to the top of the hill after the final lap, they will park at the LAST cone they come to:

Vehicle 1-Left side of the road. Last cone they come to.

Vehicle 2-Right side of the road. Last cone they come to.

BEGIN PAVEMENT MARKING TRAINING WHILE WAITING FOR VALETS TO PICK UP CONES.

Hold up poster board over front windshield to block glare from experimental vehicles.

Pavement Markings

For the second part of the study we will ask you to drive 4 different vehicles. Once the vehicles arrive, you will meet the valet, who will escort you to your next vehicle. You will drive the vehicle down the road at a comfortable speed. Then you will drive up the road at 25 mph. You will need to indicate when you see the first and the last pavement markings in each section. By pavement markings I am referring to the lines down the middle of the road. We have three sections of pavement markings. Each section has a different type of paint, so some may or may not be more visible than other sections. You will press this button (show the button) when you see both the first and the last marking in each section. The sections are separated by segments of black tape. With the tape, the sections look like this.

Show the participant the drawing of the pavement markings. Point out the pavement tape.

Do you have any questions?

Once at the top of the hill, the valets will escort the participants to their first vehicle. In the mean time, you will get into the appropriate vehicle and set up the computer:

Turn computer on by pushing round button located on top left of keyboard.
Type in “Night”

Enter in **Participant Information**. (ID, Age, Gender)

Command	Function
Shift Z	Scrolls up numerically in Participant ID Field
Shift X	Scrolls down numerically in Participant ID Field
Shift A	Scrolls through age categories: Y = 18-25 M = 40-50 O = 60+
Shift G	Toggles through gender categories: M= Male F = Female

Enter **Current Setup** information

Command	Function
Shift H	Scrolls through options in "VES" field
Shift N	Scrolls through Number of Participants (should always be "1")
Shift B	Turns Beep "OFF" and "ON" (should always be "ON")
Shift D	Toggles between Day "1" and "2"

Wait while the valet performs the participant measurement. This will occur once the participant has adjusted the seats to their satisfaction

The measurements only occur when the participant is in that vehicle for the first time.

Once the valet is finished, make sure they check the vehicle lights for you. In addition, if you are in the Cadillac you will need to adjust the fan down as soon as the vehicle is started. For the practice lap, you will scroll to "Practice" VES in the VES field. When the valet is completed the measurements, instruct the person on the following:

We will now have a practice lap to help you get used to driving the vehicle on the Smart Road and using the push buttons. I would like you to drive down the road at a comfortable speed.

Point out the location of the pavement dip cones.

First vehicle at the bottom of the hill

- Pull all the way to the first parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 2nd vehicle is parked

Second vehicle at the bottom of the hill

- Pull into the second parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 1st vehicle is up the hill

Once stopped, explain the protocol again.

This is the pavement marking session. As I explained before, we have three sections of pavement markings. I need you to indicate when you see the first and the last middle line in each section. You will indicate when you see the markings by pressing this button (hand them the button). When you press the button you will hear a beep. So, you will hit the button a total of 6 times, two times in each section. The first pavement marking section begins as soon as you pull onto the road so you will need to start looking right away. You will need to maintain a speed of 25 miles-per-hour. We are going to drive up the road and practice. Do you have any questions?

Answer questions.

Start the computer as follows:

Command	Function
RUN/HOLD (DMI)	Starts the DMI counting
Shift S	Starts data collection

*Note that there is space at the bottom of the screen for error messages. Check to make sure that you are not receiving any error messages.

While going up the hill, you need to monitor the following on the computer:

Screen will read “Looking for object”
After they press button the first time, screen will say “Recognizing Object”
After they press button the second time, screen will say “Done”

…and perform the following tasks:

Press the computer space bar again when your body is in line with the last pavement marking. After space bar is pressed, screen will say “Set-up”

During the practice lap, you may need to assist the participant. For example, if they do not indicate the first pavement marking and the marking has passed, you need to say, “Did you see the first marking back there? As soon as you see that, you need to hit the button. You will also be pressing it soon when you see the last one in this section.”

In addition, you will need to point out the pavement dip cones and explain:

See the white cones there. Those cones represent indentations in the pavement. We put those cones there so you do not mistake those areas for the end of the pavement markings. So, when you see the white cones, you know the end of the pavement markings are not there.

Coax them through this practice lap as much as they need through similar interactions.

First vehicle at the top of the hill

Pull up to white line just before the top of hill

- Wait for headlight glow from 2nd vehicle to appear
- Continue back down the road at comfortable speed

Second vehicle at the top of the hill

- Pull up to first cone on the right side of the road
- Put vehicle in park
- Turn off lights
- Turn lights back on and go down the hill when the first vehicle is out of sight

First vehicle at the bottom of the hill

- Pull all the way to the first parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 2nd vehicle is parked
- Change VES field to appropriate condition (Shift + H)

Second vehicle at the bottom of the hill

- Pull into the second parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 1st vehicle is up the hill
- Change VES field to appropriate condition (Shift + H)

And tell the participant the following:

I would like you to do the same as before by indicating when you see the first and the last pavement marking in each section. You will push the button a total of six times. I need you to drive at 25 miles-per-hour again. Remember to begin looking as soon as you pull onto the road for the first section of markings. Any questions?

Repeat the protocol for monitoring and activating the computer functions:
Screen will read "Looking for object"
After they press button the first time, screen will say "Recognizing Object"
After they press button the second time, screen will say "Done"
Press the computer space bar again when your body is in line with the last pavement marking. After space bar is pressed, screen will say "Set-up"

This will repeat for all five or six vision enhancement systems. When the valets move the participants between vehicles, you will need to:

- Quit the computer program, using SHIFT Q
- Start the computer program in the new vehicle by typing "night"
- Enter the participant and current set-up information

Also be alert to the fact that some of the vehicles have automatic locking doors that do not unlock until the vehicle is shut off. In that situation you need to unlock the doors to let the valet inside.

Post-Experiment

After the pavement portion:

Shutdown all computers
Turn off DMI's
Collect the "ENV Clear Participant Measurement Form" of your participant back and check that all the measurements needed are there. The form should be sign and dated by the participants valet and his/her in-vehicle experimenter.
Ask the participant what was his/her "strategy" to detect the beginning and end of the pavement markings and document it on your participant's "ENV GLARE PARTICIPANT SHEET"
Take the participant up to the VTTI.
Have them complete the payment voucher and pay them, if it is the 2nd evening.

As part of the debriefing (1st and 2nd evening) tell the participant that we will like him/her to keep the details of the experiment confidential.

If it the first night, remind them of their next appointment. Tell them that if they have any questions, they can call Stephanie at 231-1521.

Thank him/her for the cooperation and have the participant sign the payment sheets.

At that time, the participant may leave.

Appendix 5- On-Road Experimenter Protocol

Enhanced Night Visibility Pavement Marking/ Glare Protocol-
On-Road Experimenters

General Policies

The primary goal of this research effort is safety. For that reason, you need to be safe at all times.
Drive in a safe manner at all times. This means observing the 25 mile-per-hour speed limit on the Road.
Use a spotter when moving vehicles in and out of the Simulator Bay.
Always step back from the road when participant vehicles begin to move.
Wear closed-toe shoes at all times.
Always wear your vest on the road.
Do not travel with the tailgate open.
Wear your safety glasses when checking ALL headlights.
Drive with your lights on until you reach the bridge coming up the road.

Over the course of the study, it is likely that apparatus will be broken. If you notice something is broken or you are the one who broke it, tell someone (namely Stephanie) immediately is it is crucial to the study or as soon as convenient if it is not crucial. At any rate, you must report such damage before you leave from your shift.

Each night, you will need to arrive to the VTTI on time. The nightly meeting will cover topics such as protocol changes, problems from the previous night, and schedule concerns. Make sure you document any problems from the previous night and make a note of them on the whiteboard.

Operation of the headlights are outlined with a diagram and description in each vehicle. Failure to follow the procedures will prevent the headlights from working, therefore leave gaps in the data. For this reason, you are to review the operations each night for your assigned vehicle.

While the study is being conducted, radio communications on Channel 3 need to be minimized (emergencies excluded). If, however, you have a question, first address it to another on-road experimenter. To minimize the traffic, get on the radio and say, "[Name] switch to Channel Two." Once you both switch channels you can speak freely. If none of the on-road experimenters can answer the question one of you will need to address it to the In-Vehicle Experimenters. Note that the in-vehicle experimenters cannot always respond to questions if they are interacting with the participant at that time. For this reason, you will need to give the in-vehicle experimenters extra time.

When you do receive a message, please acknowledge the message by saying, "[Your name] Copy." That way, the sender will know whether or not everyone received the message. If you do not hear a message, do not respond and it is not relayed to you, you can assume it was not directed towards you and can therefore disregard it. Do not get on the radio and ask them to repeat the message- if it is directed to you then someone will relay it to you. If there is a person in the Control Room, they will be responsible for relaying all messages. If there is not, the person who can hear both messages will be the relay.

Pre-Experiment.

After the nightly meeting, glare order sheets will be in Stephanie's cubicle each night. In addition, you will find which vehicles you are responsible for that night. You will be solely responsible for all aspects of that vehicle.

Radios will be located in the Control Room. Each Experimenter will need to sign out two (Explorer experimenters) or four (Cadillac/Pick-up experimenters) radios. The sign out sheet is located on the cabinet where the radios are located. Sign them out by writing in the numbers, then "Night Visibility, (Your Name)." Also, you need to get your vest from the Control Room. The vests are located to the right of the radio cabinet.

Each on-road experimenter will be responsible to prepare your vehicles each night. Each night, you will be required to perform the following tasks on the vehicles:
Review the headlamp operations procedure located between the seats of the vehicle.
Clean the windshield inside and outside. There is glass cleaner in the Simulator Bay and white rags in the blue storage container. Paper towels are also available.
Wipe off headlamps. You should not be using cleaning solutions but just a shop rag.
Clean the Cadillac IR sensor and HUD unit. HUD system is located on the driver's side of the instrument panel, next to the windshield and the camera is located behind the center of the front grille. Use only a clean, dry soft cloth. Be careful not to scratch the HUD or camera when cleaning. Do not use glass cleaner directly on HUD lens located inside your vehicle because the cleaner could leak inside the unit and cause damage.
Make sure all the headlights are working.
Make sure the radio is off.
Cover the side mirrors with the stuff sacks; cover the inside mirror with poster board. The poster board should be located inside the vehicle cab. If you cannot find it, make a new cover using the poster board located in the Simulator Bay.
Set dashboard lights to the minimum setting (not off).
Make sure the vehicle has the power inverter and the DMI cable.
Make sure the glare vehicles (i.e. Explorers, Cadillac, Pick-up) have a working flashlight. If it does not, check in the storage container for an extra flashlight.
Place all equipment not used for the Night Visibility study into the trunk/back of the vehicle.
Place one radio in each vehicle and turn it onto Channel 3 at a middle volume. Do not put the radios on the visor- instead put them either in the console (if deep enough), in the map holder or on the floor.
Place a flashlight in each vehicle- the best place is on the passenger-side floor.
Close sunroofs- glass and cover.

Check tire pressure. Tire pressure should be as prescribed on the inside of the driver door. If it is near the lower limit, you need to make a note on the white board in Stephanie's cubicle so someone can fill it the next day. If it is under the range, you will need to pump it up with our foot pump. The tire pressure should be indicated on the vehicle preparation checklist.
Load steps into one of the vehicles.

On-road experimenters will need to move all of the vehicles out of the garage area. The on-road experimenters will then take all the experimental vehicles to the road. This includes the Explorers and Cadillac/Pick-up (which vehicle goes first depends on whether it is Session 1 or Session 2). The in-vehicle experimenters will take the Cavaliers to the front entrance of the VTTI. Back the vehicles into the entrance area. Make sure the vehicles as staggered so the participant can easily get in and out.

To prepare the road:

The Cadillac/Pick-up will set up the parking space cones and set up the cone indicating the dip in the road. Cone location is indicated by spray paint marks on the side of the road. Place the cone in the middle of the road (i.e. on the yellow skip marks) perpendicular to the location. The dip cone are painted white.

The Explorers will set up the glare cones and cover the signs at the end of the road. The Explorers will also put out a cone in the middle of the second turn-around entrance. In addition, the Black Explorer driver will put the steps on the right-hand shoulder for the valets to use. The steps need to be far enough off the road so that the participants will not run the risk of running over them.

Once all the experimenters have returned, you will then set out the cones for the glare session. The locations should be indicated on the road with the word "cone" painted on the roadside. In addition, the locations of the black cones are indicated with a number (i.e. 1, 2, 3, 4) by the "Cone" marking.

Once the road is ready, move your vehicle to the nearest gravel area for the participant orientation. Orientation will take place down the hill only. After both vehicles are at the second turn-around, you can move into position for glare.

Glare

Positions three and four will be used first for glare. Note: You do not change the glare order itself but instead start the sequence at locations 3 and 4. To get into position for glare, move the first and second glare vehicle (according to the order sheet for that night) to the adjacent lane (i.e. the southbound lane) lined up with the headlamps even to the last (painted) cone on the right (east) side. The other vehicle will park in the gravel area nearest their first location. Gravel areas are across from the second turn around and next to Location 4. The driver of those vehicles will initiate the first VES. The vehicle will remain stationary with the lights on until the participant vehicles are out of sight for the experimental vehicle.

Once the participant vehicle is out of sight (i.e. around the next curve), Vehicle 3 will move to the nearest gravel area and Vehicle 2 will get into position in the opposite lane (i.e. northbound lane). Vehicle 2 will remain in the location until both vehicles are past them. At that time, vehicle 2 will move to the nearest gravel area and vehicle 3 will get into position.

It is important to note that for Location 3 the glare vehicle should not turn on their lights until the in-vehicle experimenter indicates that they are ready to go. At that time, turn on the lights.

Repeat steps 3 and 4 for the remaining four headlights. This will be a total of one-and-a-half laps. On the last lap, move to the shoulder of the road after the participant vehicle is past. Then be sure not to begin moving until the participant vehicles have gotten to the first turn-around. The in-vehicle experimenters will radio you when they are at the turn-around.

Return the vehicles to the first turn-around after participants have returned to the first turn-around. You should be driving with your lights on at all times. All cones will be left on the road. You will park in the first (furthest) space on the left and the first and second space on the right. At this time, the person that is not a valet will go up to the Control Room and monitor the radio. At this point, all radio communications between the on-road and in-vehicle experimenters will be done through the Control Room. Address all questions to the Control Room experimenter and they will get ahold of the in-vehicle experimenters if appropriate.

Valets

Two of the three on-road experimenters will serve as a valet. The other will take a Cavalier and serve as the Control Room Experimenter. As a valet, you will be responsible for one person for the entire night. That means one valet will be there only to assist the other valets. Once you have a person, you must stay with them the entire night. The experimenters whose vehicles are driven first will be the "personal" valets for that evening.

Each person is responsible for driving their experimental vehicles down to the turn around.
Each valet needs to get their valet box filled with measurement stuff. The boxes will be in the Simulator Bay.
Overall goal is to make subject feel as comfortable as possible in each car.
Be sure to be wearing a vest at all times.
Move the seat to the furthest position back before the participant gets in.
Put the stepstools on the side of the road so you can get them if the participant needs them.
Have a flashlight in hand.

Meet participants at the first vehicle (the Cavaliers) and show them to their first vehicle as per the experimenter sheet.

Introduce yourself to the participants before getting them out of the vehicle.

Assist subject when he or she is getting out of the vehicle if necessary. Use the stepstools if necessary. Lead/Guide participant from one vehicle to the next by shining the flashlight on the road in front of them.

Open the door for the participant and move the seat back before they get in.

Orient person to each vehicle and turn on the lights. Be sure to turn on the lights yourselves- do not let the participant do it. If they reach for the light switch, tell them, "That's OK, I'll take care of this for you."

Cadillac

This one you need to have them start the vehicle before orienting them because the seat and wheel move when you start it. Be sure to warn the participants of that before you start the car.

Button on left side of seat moves seat up and down, back and forth (show button).

Button for the steering wheel moves the wheel up and down, in and out.

There are many lights. The only ones they need to worry about are the speedometers, analog and digital (point each out). The subject is free to use whichever they feel most comfortable with.

Hand the participant the keys and have them start the car.

Turn on the headlights all the way (two clicks). Make sure they are on before you leave the vehicle.

Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

Black Explorer

Button on left side of seat moves seat up and down, back and forth (show button).

Button for the steering wheel moves the wheel up and down.

Hand the participant the keys and have them start the car.

Turn on the parking lights (one click only).

Show the participant how to adjust the interior lights. Note that with this vehicle the lights do not dim unless the door is closed.

White Explorer

Button on left side of seat moves seat up and down, back and forth (show button).
Button for the steering wheel moves the wheel up and down.
Hand the participant the keys and have them start the car.
Turn on the parking lights (one click only).
Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

Pick-up

Lever in front of seat moves seat up and down (show lever).
Button for the steering wheel moves the wheel back and forth.
Hand the participant the keys and have them start the car.
Turn on the parking lights (one click only).
Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is as bright as they would normally have it.
Remind the participant to keep their seatbelt on at all times.
Ask them if they have any questions.

Complete the measurements.

To do this, first explain to the participant that you are going to make a mark on the window as to where their eye level is located. Instruct them to adjust their seat to where they think they will be comfortable. Once they are situated, tell them to look ahead and relax. Close the door and take the measurements.
Measure the horizontal height by taking the level and moving it up the window until it "intersects" with the eye level. Make a line at that point with your marker.
Measure the vertical distance by taking the level and moving it across the window until it intersects with the eye level. Mark a vertical mark at the point.

Use this point to measure the distances.
Take vertical measurement with metal end of tape measure down where the glass intersects with the black plastic.
Take horizontal measurement with metal end of tape measure to the right where glass intersects with black plastic.
Before you return to a vehicle, walk in front of the experimental vehicle to ensure the headlights are on and working. The lights cannot be turned on until the vehicle is the furthest one forward so you may have to wait until the other vehicle leaves to check the lights. Be sure to step back from the vehicle as soon as you are done checking.

Cadillac: Regular headlamps only.

Black Explorer: If UV is required, make sure they are working. Otherwise, make sure the two standard ones are on.

White Explorer: The top three UV lights should be on at all times. In the high UV condition the bottom two should be on. Report if one is not working or extremely dull. The standard lights should be working at all times.

Pick-up: The two external headlamps on the front of the vehicle should be on.

The first parking space on each side is termed a "vehicle drop off" and needs to be available at the end of every lap. The valets will move any vehicle that is left in those locations.

Otherwise, you can wait in the other vehicle while the participants are taking their pavement laps. When you see the vehicles approaching the turn-around, move to the left shoulder of the road. NOTE: For the first headlamp there will be a training lap. The experimental vehicle will not stop at the turn-around. You must stay in the parked vehicle for safety.

When the participant gets back up to the turn-around, meet them at the car as soon as it comes to a complete stop. Once the participant sees you, you may open the door.

Turn off the parking lights (see above).

Ask the participant to turn off the vehicle and to hand you keys.

Help the participant out of the vehicle. Use the step if necessary. NOTE: Never move the participant so that they are in direct view of the oncoming lights. Have the participant wait until the other vehicle has turned off their lights before you take them out of the vehicle.

Put the keys to each car in the door lock when it is not being used.

Escort the participant to the next vehicle:
Repeat the orientation if they have not been in the vehicle before.
If they have been in the vehicle before, ask them if they remember the controls. Be sure to offer to answer questions.

Finally, never tell the participant how many more laps they have. This is because in the event of a computer failure, etc. they may repeat a lap at the end. If this is the case, the in-vehicle participant will tell you. We do not, however, want the participant to know that they are going to do an extra lap.

Before the last lap, the in-vehicle experimenters will call the Control Room Experimenters back to the road by saying, "[Name], return to the road." At that time they are to return to the road and wait at the first turn-around until the participants leave. Park the Cavaliers in one of the more forward spots.

Interim

The interim would occur is there are two groups of participants that night. If there are not two groups, then skip to 6. Post-Experiment. If there are two groups, you will set up for glare (Section 3) when the in-vehicle experimenters contact you. The entire procedure will repeat for the second group.

Night Two

Procedures for the second night will be the same except that the Cadillac/Pick-up will be exchanged. The VES on the Explorers will be switched during the day, therefore will be ready before 7:00. There will not be any practice laps the second night.

Post-Experiment

At the end of the last pavement markings, the participants and in-vehicle experimenters will return to the VTTI in the Cavaliers. In addition, the Explorers need to uncover the road-closed signs at the end of the road and fold the tarps. Explorers also need to pick up the glare cones. The Cadillac/pick-up driver need to collect the cones from the first turn-around as well as the cones for the pavement dip on the road.

Once the cones are collected, the vehicles return to the VTTI. The Explorers need to be parked in the Simulator Bay. The power inverters need to be unplugged and the DMIs need to be turned off. Do this by pressing the first button on the left.

Check the gas level in the vehicle. If it is below ¼ tank, put a note on the whiteboard in Stephanie's cubicle.

Return all keys to the lock box and make sure the box is locked. The Cadillac/Pick-up driver will make sure the doors are closed completely and locked. At this time, you can note any vehicle problems on the vehicle preparation sheets.

Return the radios and vests to the Control Room. Be sure to sign in the radios in the second column of the log book. Also, make sure the power is "off" when you put the radios into the charger.

Return the paperwork to Stephanie's cubicle. You will find a folder with the date on it- put them in there. Return the radios and vests to the Control Room. Note any vehicle problems on the white board. After you fill out your time sheet, you can leave for the night.

VALET Protocol for ENV- Glare

Each person is responsible for driving their experimental vehicles down to the turn around.

Each valet needs to get their valet box filled with measurement stuff. The boxes will be in the Simulator Bay.

Overall goal is to make subject feel as comfortable as possible in each car.

Be sure to be wearing a vest at all times.

Put the stepstools on the side of the road so you can get them if the participant needs them.

Have a flashlight in hand.

Meet participants at the first vehicle (the Cavaliers) and show them to their first vehicle as per the experimenter sheet.

Introduce yourself to the participants before getting them out of the vehicle.

Assist subject when he or she is getting out of the vehicle if necessary. Use the stepstools if necessary.

Lead/Guide participant from one vehicle to the next by shining the flashlight on the road in front of them.

Open the door for the participant and move the seat back before they get in.

Orient person to each vehicle and turn on the lights. Be sure to turn on the lights yourselves- do not let the participant do it. If they reach for the light switch, tell them, "That's OK, I'll take care of this for you."

Cadillac

This one you need to have them start the vehicle before orienting them because the seat and wheel move when you start it. Be sure to warn the participants of that before you start the car.

Button on left side of seat moves seat up and down, back and forth (show button).

Button for the steering wheel moves the wheel up and down, in and out.

There are many lights. The only ones they need to worry about are the speedometers, analog and digital (point each out). The subject is free to use whichever they feel most comfortable with.

Hand the participant the keys and have them start the car.

Turn on the headlights all the way (two clicks). Make sure they are on before you leave the vehicle.

Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

Black Explorer

Button on left side of seat moves seat up and down, back and forth (show button).

Button for the steering wheel moves the wheel up and down.

Hand the participant the keys and have them start the car.

Turn on the parking lights (one click only).

Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable

White Explorer

Button on left side of seat moves seat up and down, back and forth (show button).

Button for the steering wheel moves the wheel up and down.

Hand the participant the keys and have them start the car.

Turn on the parking lights (one click only).

Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

Pick-up

Lever in front of seat moves seat up and down, (show lever).

Button for the steering wheel moves the wheel up and down.

Hand the participant the keys and have them start the car.

Turn on the parking lights (one click only).

Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is as bright as they would normally have it.
Remind the participant to keep their seatbelt on at all times.

Ask them if they have any questions.

Complete the measurements. To do this, first explain to the participant that you are going to make a mark on the window as to where their eye level is located. Instruct them to adjust their seat to where they think they will be comfortable. Once they are situated, tell them to look ahead and relax. Close the door and take the measurements.

The participant will place the yardstick at their eye level on the bridge of nose (per the in-vehicle experimenter’s instructions).

Have the in-vehicle experimenter make sure the yardstick is level by using the level in the vehicle. They will give you a thumbs-up when they are ready.

The valet then marks the dot on vehicle glass where the corner of the ruler meets the window. It is important to ONLY use the red light.

Take vertical measurement with metal end of tape measure down where the glass intersects with the black plastic.

Take horizontal measurement with metal end of tape measure to the right where glass intersects with black plastic.

Before you return to a vehicle, walk in front of the experimental vehicle to ensure the headlights are on and working.

Cadillac: Regular headlamps only.

Black Explorer: If UV is required, make sure they are working. Otherwise, make sure the two standard ones are on.

White Explorer: The top three UV lights should be on at all times. In the high UV condition the bottom two should be on. Report if one is not working or extremely dull. The standard lights should be working at all times.

Pick-up: The two external headlamps on the front of the vehicle should be on.

The first parking space on each side is termed a "vehicle drop off" and needs to be available at the end of every lap. The valets will move any vehicle that is left in those locations.

Otherwise, you can wait in the other vehicle while the participants are taking their pavement laps. When you see the vehicles approaching the turn-around, move to the left shoulder of the road. NOTE: For the first headlamp there will be a training lap. The experimental vehicle will not stop at the turn-around. You must stay in the parked vehicle for safety.

When the participant gets back up to the turn-around, meet them at the car as soon as it comes to a complete stop. Once the participant sees you, you may open the door.

Turn off the parking lights (see above).

Ask the participant to turn off the vehicle and to hand you keys.

Help the participant out of the vehicle. Use the step if necessary.

Put the keys to each car in the door lock when it is not being used.

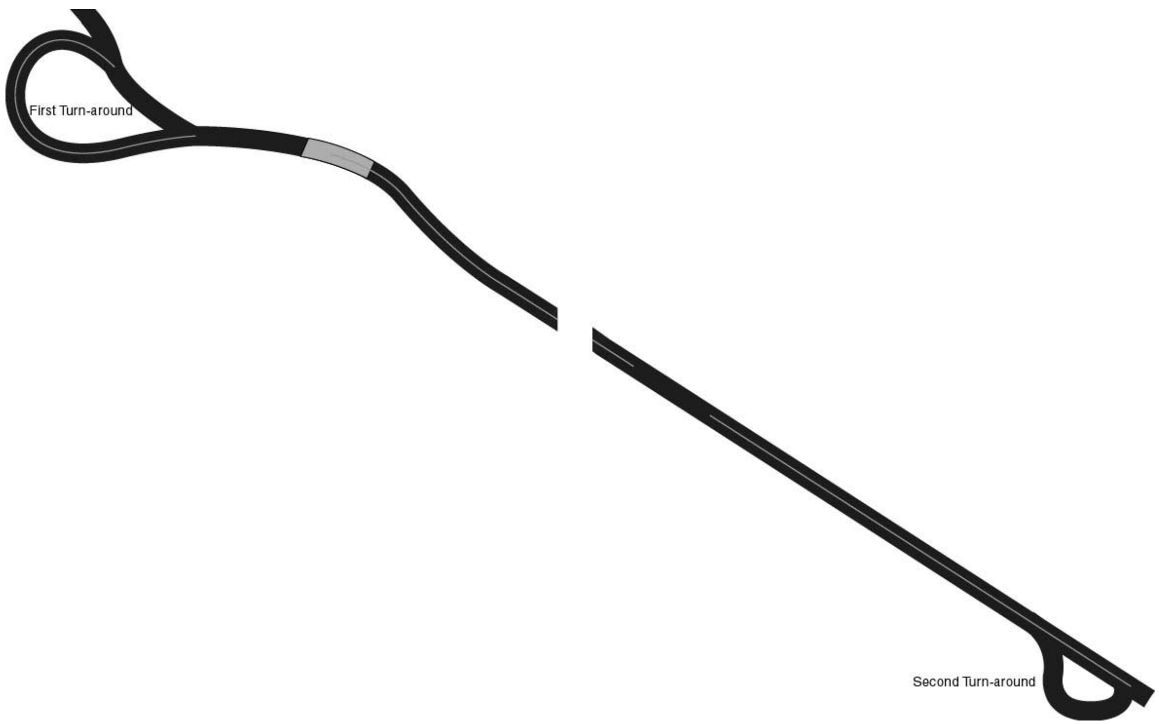
Escort the participant to the next vehicle:

Repeat the orientation if they have not been in the vehicle before.

If they have been in the vehicle before, ask them if they remember the controls. Be sure to offer to answer questions.

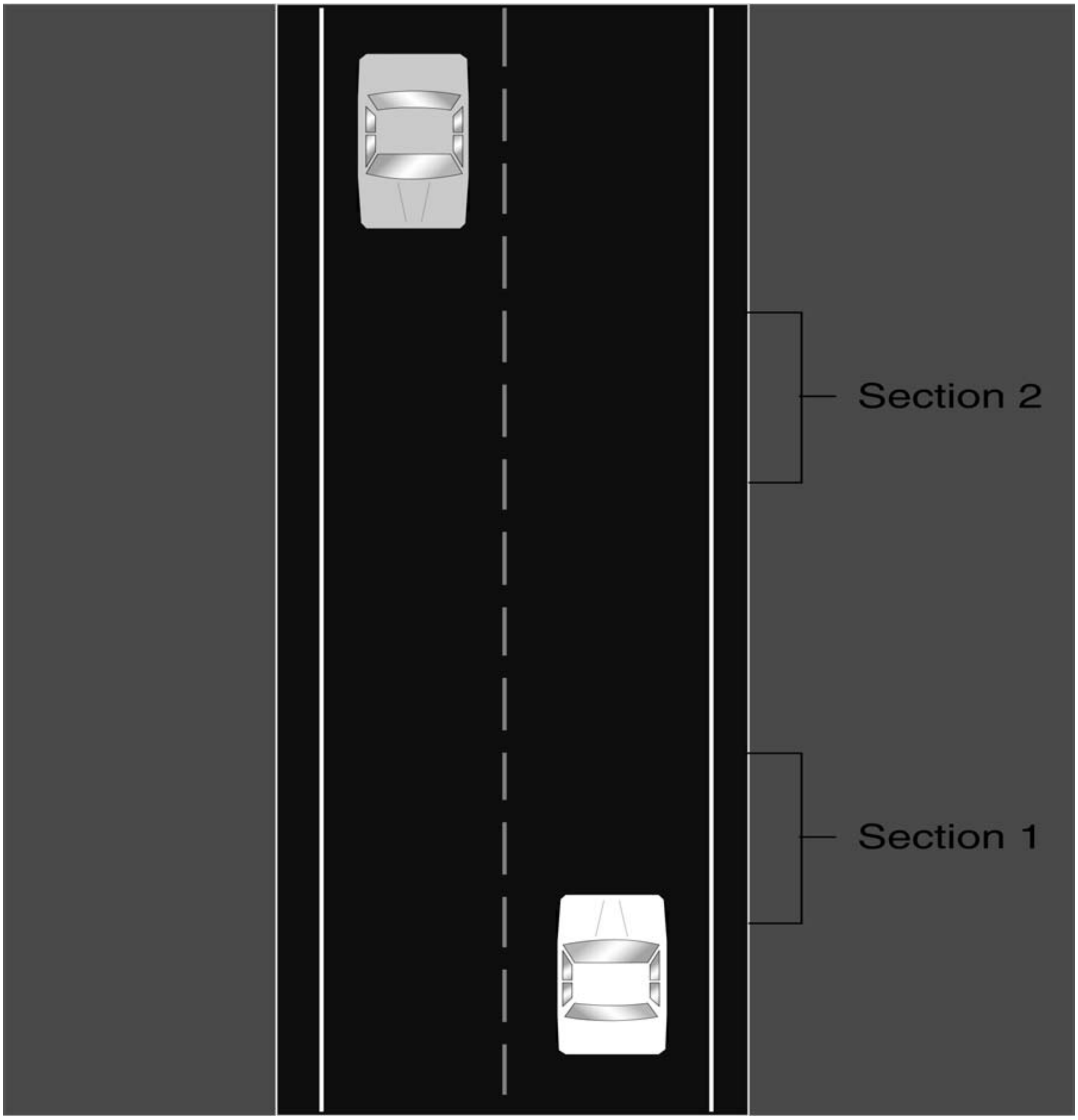
At the end of the night, return your Valet Boxes to the Simulator Bay.

Appendix 6- Smart Road Test Facility



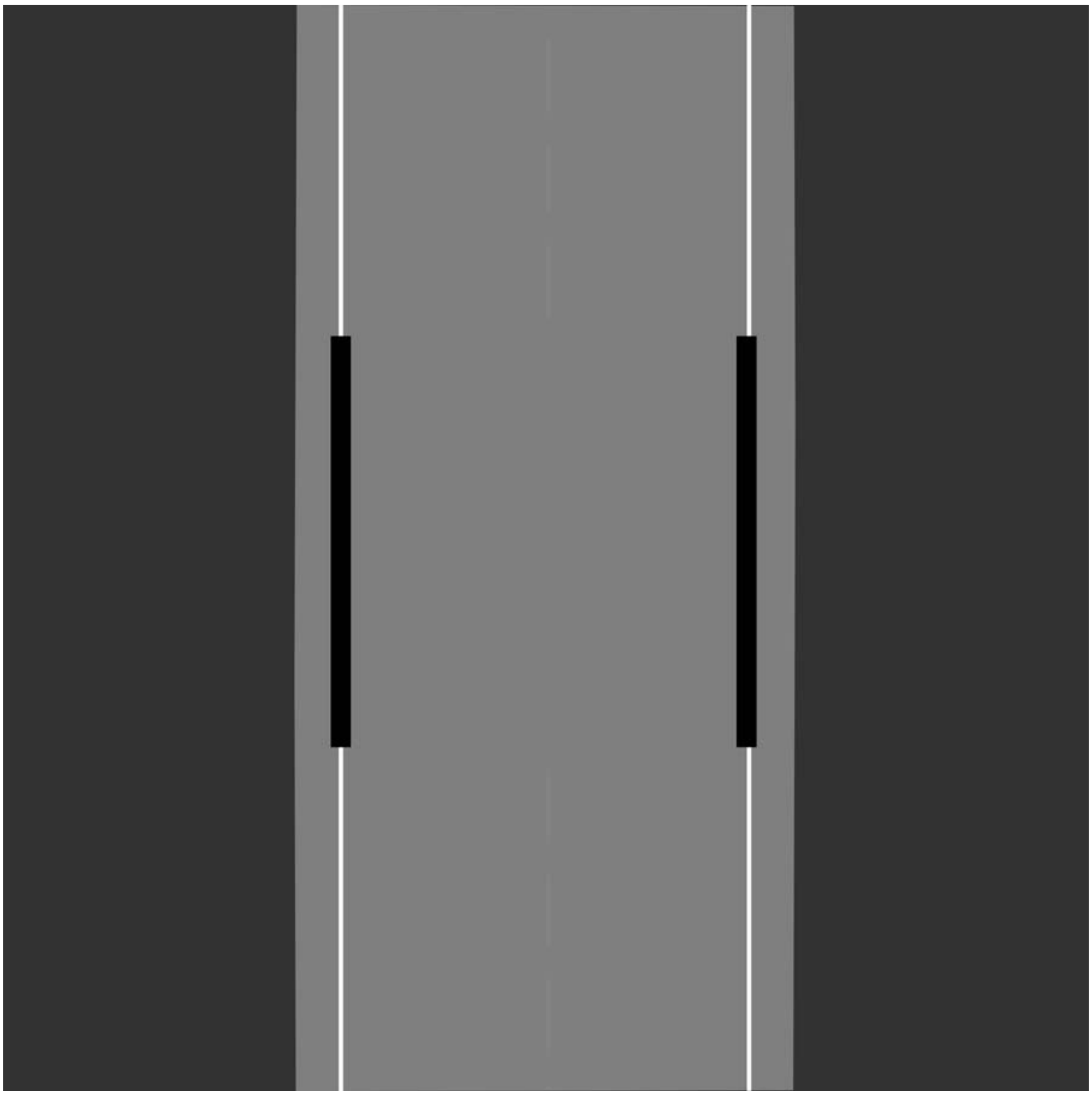
This diagram represents the Smart Road test facility. The first and second turn-around are marked on the diagram. This represents the 1.7 completed miles used when this data collection effort occurred.

Appendix 7- Familiarization material for glare protocol



This diagram was used during familiarization to the glare portion of the study. It was designed to represent the location of the vehicles during the glare portion and provide a visualization of the two separate sections of glare evaluation.

Appendix 8- Familiarization material for pavement marking protocol.



This diagram was used during familiarization to the glare portion of the study. It was designed to represent the separation of the pavement markings sections with black tape. The diagram was used to define pavement markings, show what would be considered the first pavement marking in each section, and the last pavement marking in each section.

Appendix 9- Counterbalance for Enhanced Night Visibility

1st	2nd	3rd	4th	5th
Hybrid UV-A + HID	HLB-LP	HID	High UV-A + HLB	Mid UV-A + HLB
High UV-A + HLB	HID	Hybrid UV-A + HID	HLB-LP	Mid UV-A + HLB
HLB-LP	Mid UV-A + HLB	Hybrid UV-A + HID	High UV-A + HLB	HID
Mid UV-A + HLB	HID	HLB-LP	High UV-A + HLB	Hybrid UV-A + HID
High UV-A + HLB	Hybrid UV-A + HID	Mid UV-A + HLB	HLB-LP	HID
HID	High UV-A + HLB	Mid UV-A + HLB	Hybrid UV-A + HID	HLB-LP
Hybrid UV-A + HID	Mid UV-A + HLB	HID	High UV-A + HLB	HLB-LP
High UV-A + HLB	HID	Mid UV-A + HLB	HLB-LP	Hybrid UV-A + HID
Mid UV-A + HLB	HID	Hybrid UV-A + HID	HLB-LP	High UV-A + HLB
HID	HLB-LP	Mid UV-A + HLB	High UV-A + HLB	Hybrid UV-A + HID
High UV-A + HLB	HLB-LP	Hybrid UV-A + HID	HID	Mid UV-A + HLB
HLB-LP	Hybrid UV-A + HID	High UV-A + HLB	Mid UV-A + HLB	HID
Hybrid UV-A + HID	High UV-A + HLB	HLB-LP	HID	Mid UV-A + HLB

Mid UV-A + HLB	Hybrid UV-A + HID	HID	High UV-A + HLB	HLB-LP
High UV-A + HLB	Hybrid UV-A + HID	HID	Mid UV-A + HLB	HLB-LP
Mid UV-A + HLB	HLB-LP	High UV-A + HLB	Hybrid UV-A + HID	HID
HID	HLB-LP	Hybrid UV-A + HID	Mid UV-A + HLB	High UV-A + HLB
HLB-LP	HID	Mid UV-A + HLB	High UV-A + HLB	Hybrid UV-A + HID
Mid UV-A + HLB	HLB-LP	High UV-A + HLB	HID	Hybrid UV-A + HID
HLB-LP	HID	Mid UV-A + HLB	Hybrid UV-A + HID	High UV-A + HLB
Hybrid UV-A + HID	HLB-LP	High UV-A + HLB	Mid UV-A + HLB	HID
HID	High UV-A + HLB	Hybrid UV-A + HID	Mid UV-A + HLB	HLB-LP
High UV-A + HLB	Hybrid UV-A + HID	HID	HLB-LP	Mid UV-A + HLB
Mid UV-A + HLB	HID	HLB-LP	Hybrid UV-A + HID	High UV-A + HLB
HID	Mid UV-A + HLB	High UV-A + HLB	HLB-LP	Hybrid UV-A + HID
Mid UV-A + HLB	HID	Hybrid UV-A + HID	HLB-LP	High UV-A + HLB
Hybrid UV-A + HID	HLB-LP	Mid UV-A + HLB	High UV-A + HLB	HID
High UV-A + HLB	HLB-LP	Hybrid UV-A + HID	HID	Mid UV-A + HLB

Hybrid UV-A + HID	High UV-A + HLB	Mid UV-A + HLB	HID	HLB-LP
Mid UV-A + HLB	HID	High UV-A + HLB	HLB-LP	Hybrid UV-A + HID
HLB-LP	HID	Hybrid UV-A + HID	High UV-A + HLB	Mid UV-A + HLB
Hybrid UV-A + HID	HLB-LP	HID	High UV-A + HLB	Mid UV-A + HLB
High UV-A + HLB	HLB-LP	Mid UV-A + HLB	Hybrid UV-A + HID	HID
HID	Hybrid UV-A + HID	Mid UV-A + HLB	HLB-LP	High UV-A + HLB
Mid UV-A + HLB	High UV-A + HLB	Hybrid UV-A + HID	HID	HLB-LP
Mid UV-A + HLB	High UV-A + HLB	HID	HLB-LP	Hybrid UV-A + HID

This represents the different orders, but are not in the order they were presented. In order to run two participants at the same time, the orders above were paired so that the participants would not be in the same vehicles at the same time.

In addition, this page was night 1 for half of the participants, the order represented on the next page was first for half of the participants.

1st	2nd	3rd	4th	5th	6th
Hybrid UV-A + HLB	HHB	HLB	High UV-A + HID	Mid UV-A + HID	HOH
High UV-A + HID	Hybrid UV-A + HLB	HHB	Mid UV-A + HID	HOH	HLB
Mid UV-A + HID	HOH	High UV-A + HID	HLB	Hybrid UV-A + HLB	HHB
HLB	Mid UV-A + HID	HOH	Hybrid UV-A + HLB	HHB	High UV-A + HID
HOH	High UV-A + HID	Hybrid UV-A + HLB	HHB	HLB	Mid UV-A + HID
HHB	HLB	Mid UV-A + HID	HOH	High UV-A + HID	Hybrid UV-A + HLB
Hybrid UV-A + HLB	HHB	Mid UV-A + HID	HLB	High UV-A + HID	HOH
HOH	HLB	High UV-A + HID	Mid UV-A + HID	Hybrid UV-A + HLB	HHB
HLB	HOH	HHB	High UV-A + HID	Mid UV-A + HID	Hybrid UV-A + HLB
Mid UV-A + HID	High UV-A + HID	HOH	Hybrid UV-A + HLB	HHB	HLB
High UV-A + HID	Hybrid UV-A + HLB	HLB	HHB	HOH	Mid UV-A + HID
HHB	Mid UV-A + HID	Hybrid UV-A + HLB	HOH	HLB	High UV-A + HID
HLB	HOH	Hybrid UV-A + HLB	HHB	High UV-A + HID	Mid UV-A + HID

Hybrid UV-A + HLB	HLB	Mid UV-A + HID	HOH	HHB	High UV-A + HID
HOH	High UV-A + HID	HHB	HLB	Hybrid UV-A + HLB	Mid UV-A + HID
High UV-A + HID	HHB	HOH	Mid UV-A + HID	Hybrid UV-A + HLB	HLB
Mid UV-A + HID	Hybrid UV-A + HLB	HLB	High UV-A + HID	HOH	HHB
HHB	Mid UV-A + HID	High UV-A + HID	Hybrid UV-A + HLB	HLB	HOH
Hybrid UV-A + HLB	Mid UV-A + HID	HLB	HHB	HOH	High UV-A + HID
Mid UV-A + HID	HLB	HOH	High UV-A + HID	HHB	Hybrid UV-A + HLB
HOH	HHB	Hybrid UV-A + HLB	Mid UV-A + HID	High UV-A + HID	HLB
High UV-A + HID	Hybrid UV-A + HLB	Mid UV-A + HID	HOH	HLB	HHB
HLB	High UV-A + HID	HHB	Hybrid UV-A + HLB	Mid UV-A + HID	HOH
HHB	HOH	High UV-A + HID	HLB	Hybrid UV-A + HLB	Mid UV-A + HID
HLB	HOH	Hybrid UV-A + HLB	High UV-A + HID	Mid UV-A + HID	HHB
HHB	High UV-A + HID	Mid UV-A + HID	HOH	Hybrid UV-A + HLB	HLB
HOH	Mid UV-A + HID	HLB	HHB	High UV-A + HID	Hybrid UV-A + HLB
Hybrid UV-A + HLB	HLB	High UV-A + HID	Mid UV-A + HID	HHB	HOH

High UV-A + HID	HHB	HOH	Hybrid UV-A + HLB	HLB	Mid UV-A + HID
Mid UV-A + HID	Hybrid UV-A + HLB	HHB	HLB	HOH	High UV-A + HID
HOH	HHB	High UV-A + HID	Mid UV-A + HID	Hybrid UV-A + HLB	HLB
Mid UV-A + HID	High UV-A + HID	Hybrid UV-A + HLB	HOH	HLB	HHB
Hybrid UV-A + HLB	HOH	Mid UV-A + HID	HLB	HHB	High UV-A + HID
High UV-A + HID	HLB	Hybrid UV-A + HLB	HHB	Mid UV-A + HID	HOH
HLB	Hybrid UV-A + HLB	HHB	HOH	High UV-A + HID	Mid UV-A + HID
Mid UV-A + HID	HHB	HLB	High UV-A + HID	Hybrid UV-A + HLB	HOH

This represents the different orders, but are not in the order they were presented. In order to run two participants at the same time, the orders above were paired so that the participants would not be in the same vehicles at the same time.

In addition, this page was night 1 for half of the participants, the order represented on the previous page was first for half of the participants.

Appendix 10- Sample participant order form

ENV GLARE PARTICIPANT SHEETS

Participant 1, Night 1

Glare

Location	VES	Vehicle	Rating 1	Rating 2
0	Practice			
3	Mid UV-A + HLB	Wht. Explorer		
4	HID	Blk. Explorer		
1	High UV-A + HLB	Wht. Explorer		
2	HLB-LP	Cadillac		
3	Hybrid UV-A + HID	Blk. Explorer		
4				

Pavement Markings

Order	VES	Vehicle
0	Practice	
1	Hybrid UV-A + HID	Blk. Explorer
2	HLB-LP	Cadillac
3	HID	Blk. Explorer
4	High UV-A + HLB	Wht. Explorer
5	Mid UV-A + HLB	Wht. Explorer

Pavement Marking Data Collection (In-Vehicle Experimenters)

VES System	Section No.	First Marking Detection Distance	Second Marking Detection Distance	Final Distance

Participant 1, Night 2

Glare

Location	VES	Vehicle	Rating 1	Rating 2
0	Practice			
3	Mid UV-A + HID	Wht. Explorer		
4	HHB	Pick-up		
1	HLB	Blk. Explorer		
2	High UV-A + HID	Wht. Explorer		
3	Hybrid UV-A + HLB	Blk. Explorer		
4	HOH	Pick-up		

Pavement Markings

Order	VES	Vehicle
1	Hybrid UV-A + HLB	Blk. Explorer
2	HHB	Pick-up
3	HLB	Blk. Explorer
4	High UV-A + HID	Wht. Explorer
5	Mid UV-A + HID	Wht. Explorer
6	HOH	Pick-up

VITA

Stephanie C. Binder

In 1998 Stephanie graduated with a B.A. (with honors) in psychology from the University of Iowa. She attended Virginia Tech in 1998 to pursue a M.S. degree in Industrial and Systems Engineering, with an emphasis in Human Factors Engineering and Safety. As a graduate student, Julie worked as a research assistant for the Virginia Tech Transportation Institute. She has also served as President of the Virginia Tech Student Chapter of the Human Factors and Ergonomics Society (1999) and as Secretary of the Virginia Tech Student Chapter of the American Society of Safety Engineers (2000).