Nighttime Driving Evaluation of the Effects of Disability and Discomfort Glare from Various Headlamps under Low and High Light Adaptation Levels

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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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November 17, 2004
Blacksburg, Virginia

Keywords: Adaptation, Disability Glare, Discomfort Glare, Glare, Nighttime Driving, Pedestrian, Reflectance.

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(ABSTRACT)

It has been found that traveling on the roadways at night is an inherently more dangerous task than driving during the daylight hours. Driving is primarily a visual task, and there are certain situations at night in which vision and safety may be compromised. The effects of glare produced by the headlamps of oncoming vehicles have become an interesting problem to many lighting researchers. Depending upon the opposing lighting design (beam distribution and intensity) and the lighting conditions inside the vehicle, oncoming headlamps can be both visually discomforting and disabling to drivers at night. In recent years, the newer High Intensity Discharge (HID) headlamps have raised some concern because of their increased light output and brighter appearance as opposed to traditional Halogen headlamps. The objective of this study was to evaluate the discomfort and disability glare produced by different oncoming headlamps under two driver light adaptation levels. This study took place on the Smart Road at the Virginia Tech Transportation Institute. During the Discomfort Glare portion, participants drove an experimental vehicle at 20mph past the oncoming headlamps and were asked to rate their overall discomfort with the subjective deBoer scale. The Disability Glare portion involved drivers detecting a static pedestrian in the roadway while approaching each different set of glare headlamps. It was hypothesized that there would be significant differences in detection distance and discomfort glare rating across the different glare headlamp and adaptation level combinations. It was also hypothesized that age would have a significant effect on detection distance, and the subjective ratings. The results of this study revealed many significant main effects and interactions for the discomfort and disability glare portions. The main effect of glare source was the only significant factor for discomfort glare. The main effects of age, glare source and pedestrian location were all significant for the disability portion. In addition, the interaction of pedestrian location and glare source was also significant. Overall, there was no clear relationship between subjective discomfort ratings and objective disability measures. The conclusions of this research will be valuable to the consumer as well as the manufacturers and designers of future headlamps in revealing how glare can affect drivers on the road at night. This information can help guide new designs to maximize forward visibility while minimizing glare.

ACKNOWLEDGMENTS

This study 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 document are those of the author and do not necessarily reflect the views of the Federal Highway Administration.

DEDICATION

I would like to thank all the individuals who made this project possible. The Virginia Tech Transportation Institute (VTTI) has been a great place to learn and develop as a young researcher over a period of five years. Jon Hankey has been an excellent mentor and gave me the great opportunities at VTTI for which I am truly grateful. Throughout my entire research project Ron Gibbons was an enormous help and a great teacher. Thank you Ron for all the work you did and long nights spent on the road to make this project possible. I am also grateful to have had someone like Myra Blanco to help guide me through the Human Factors and Ergonomics Program at Virginia Tech. Thank you Myra for all that I have learned from you about transportation research. I would also like to thank everyone in the APTE group that assisted me on this project. Julie Taverna, Clay Moulton, and Miguel Guerrero helped me get through this study. Also, Alyse Bixon, Caitie Hutter, Peter Jacobs, Jason Miller, Brad Westerman, and Anna Wallingford, I thank you all so much for the cold long nights you spent on the Smart Road. Without all of your efforts I could not have done this study.

I also want to let my friends and family know just how much I appreciate all the support. Mom, thank you from the bottom of my heart for everything you have done for Kevin, Bryan and I to allow us to all lead successful lives. We all love you. Dad, thank you for all the support over both my undergraduate and graduate years here at Virginia Tech. To the six pack, Bruce, Brett, Jeff, Mike and Rob, you guys are awesome and thanks for always being such good friends. Amy, Christina, Julie, and Mollie, thank you for all you have done over the years. You guys have been wonderful friends.

Finally, I would like to tell my girlfriend Amanda, how much she means to me and how much I appreciate all that she does. Through all the long nights of me on the Smart Road you were always there for me. You have helped me so much personally and with my career and I will always be grateful. I love you.

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INTRODUCTION

Rationale for the Study

Accidents involving motor vehicles accounted for nearly 95 percent of transportation-related deaths and an even greater percentage of injuries in the United States (Transportation Statistics Annual Report 2000). The U.S. Department of Transportation set specific goals in an effort to reduce these figures by at least 20 percent by the year 2008. Accomplishing this goal would save thousands of lives each year. In the year 2001 alone, 41,730 people lost their lives in automobile related accidents. Researchers have found that the highest fatality rates per one hundred million Vehicle Miles Traveled (VMT) occur in nighttime driving conditions (Blanco, Hankey and Dingus, 2001). These findings suggest that nighttime driving is an inherently more difficult task than normal daytime driving and perhaps even two to three times more dangerous, according to many experts (Rumar, 1990). In addition, age may have a significant impact on driver safety at night. It has been stated that the fatality rate at night is perhaps two times the daytime rate for drivers 65 and older. Therefore it is important to determine what the underlying cause of the difference is in performance between driving at night and in the day.

The task of driving a vehicle is one in which most of the information necessary for performance is acquired through the visual system. In fact, some estimate that up to 90 percent of the necessary information for operating a motor vehicle is visual (Alexander and Lunenfeld, 1990). Before the visual system can detect and recognize various objects in the field of view, there must first be sufficient lighting (Mace, Garvey, Porter, Schwab and Adrian, 2001). There are various methods of lighting the roadways for nighttime driving. Vehicle headlamps and overhead lighting are the two main sources of increasing the available light on the roadway. Although overhead lighting systems are used in many urban and highly populated roadways, the cost of installation and maintenance is too high for less populated roadways (Shinkai and Osumi, 1982). Headlamps alone are the most common lighting systems used for nighttime visibility of the roadway. Over the years, improvements in headlamp design such as beam pattern, aiming, light output, and intensity have helped increase visibility in night driving. However, when headlamps are designed there is a tradeoff in terms of the amount of light directed onto the roadway and subsequently how much light falls into the eyes of oncoming drivers as glare. Glare can be described as the blinding experience that results from bright light sources in the visual field of view (Theeuwes, Alferdinck, and Perel, 2002).

Public concern about the glare produced by an increasing number of new High Intensity Discharge (HID) headlamps continues to rise. In fact, just recently in 2001 the National Highway Traffic Safety Administration (NHTSA) called on drivers to submit their opinions on the issue of glare and its many sources. A good proportion of responses were in relation to headlamps being mounted too high on trucks and sport utility vehicles and subsequently producing indirect glare in the rearview mirror. Another common complaint was the use of fog lamps in normal weather conditions, producing unnecessary glare. Although these are important to consider, the single most complained about sources of glare were the HID headlamps. Many drivers state that these headlamps are too blinding and that they are dangerous. Others say that the blue color is distracting and uncomfortable. Still others that own the new headlamps cannot say enough about the increased visibility they provide. They comment on how safe they feel at night driving with these new lights and how well they light up their forward view (NHTSA, 2001). The proposed research is an effort to objectively identify the ability of new lighting designs to optimize night visibility by minimizing glare.

The effects of glare from oncoming headlamps on nighttime driver performance have been a concern of researchers for many years. Work has been done to investigate the cause of the discomfort drivers experience from the glare produced from oncoming vehicles. Researchers at the University of Michigan Transportation Research Institute have studied the discomfort glare produced by regular halogen beams as well as the newer technology of High Intensity Discharge lamps. They have found that there is a subjective preference for halogen beams over the newer HID (Flannagan and Sivak, 1992). Some researchers believe this subjective difference in the perception of brightness or visual discomfort may in part be due to the differences in spectral power distribution of the two headlamp designs. Halogen beams tend to have a warmer appearance due to their smooth spectral distribution being higher toward the longer wavelength values. In contrast, the new HID designs have distinct peaks of spectral power across a wider range of wavelengths with more output coming from the short end of the spectrum, leaving them with a slightly bluish appearance. This difference in distribution is illustrated in Figure 1.

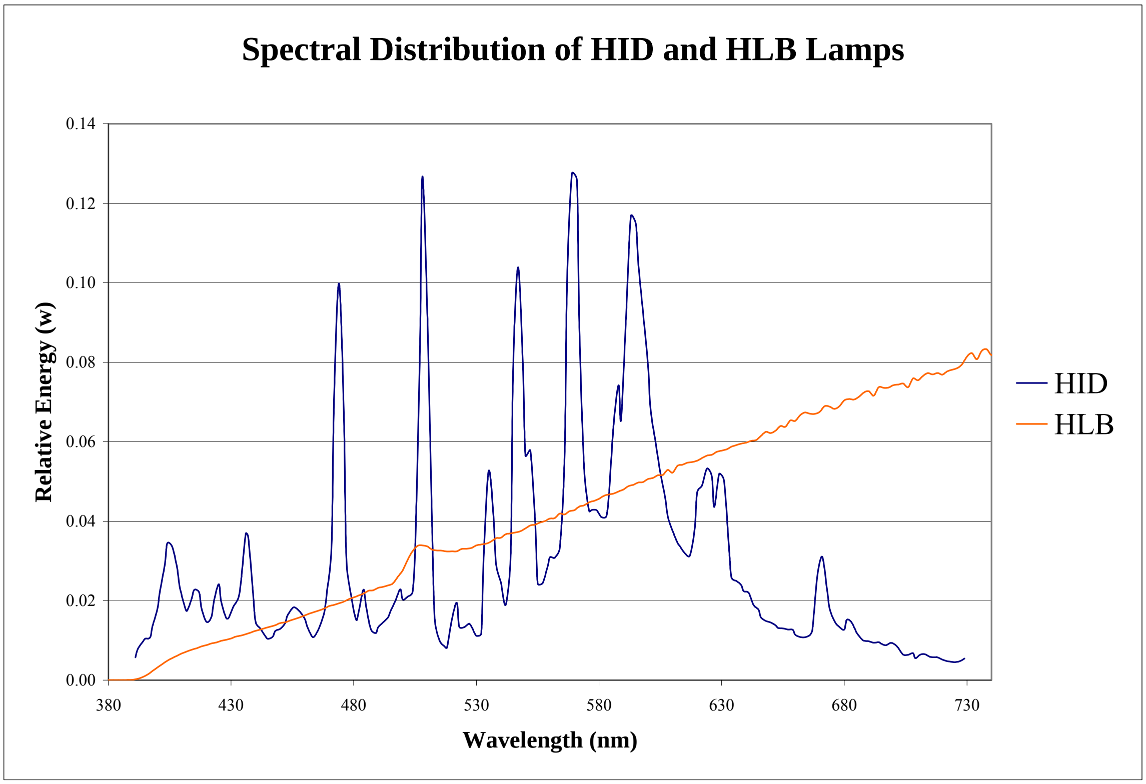


Figure 1. Line graph. Spectral Power Distribution of typical HID and Halogen headlamps.

This variation in appearance may be one of the reasons some perceive HID lamps to be more discomforting. In fact, a recent study of both discomfort and disability glare from halogen and HID light sources showed that two lamps of the same intensity (measured at the eye) had different discomfort ratings (Bullough, and Van Derlofske, 2002). The HID lamps were rated (using the deBoer scale) as being more discomforting than the halogen beams. Disability glare was not affected by the spectral power distribution.

Although many studies have been done to explain the perception of discomfort glare, there are still unanswered questions pertaining to the problem of disability glare from oncoming headlamps. Researchers in the past have investigated disability glare caused by conventional halogen headlamps. It has been found by many that glare from an oncoming vehicle can significantly reduce detection distances on the roadway at night. Theeuwes, Alferdinck, and Perel found that a glare source of 402.80fl (1,380 cd) could reduce a driver's detection capabilities from around 116 ft down to 90 ft (2002). It was also discovered that this glare situation resulted in many missed targets. Age was also found to have significant effects on detection performance. These kinds of results convey the importance of mitigating the disabling effects of glare. With newer headlamp designs emerging as technology improves, a need has arisen to evaluate the glare produced by various types of current HID headlamps. Manufacturers claim better visibility as one of the many advantages of these new headlamps. Drivers find it very comforting to be behind these lamps looking out into the night, but the effects of more light output to other traffic need to be understood. With more and more lights of varying intensities and beam patterns on U.S. roadways, the effect of different lighting systems meeting each other (e.g., halogen on HID) may be an interesting problem.

Experimental Goal

The main goal of this research was to evaluate the effects of the different headlamp beam characteristics—beam distribution and intensity of Halogen and HID headlamps—in terms of disability and discomfort glare across three age levels of participants. Different light adaptation levels and glare sources were also considered. The targets used in this study were pedestrians on the roadway. The focus of this research effort was on how the task of pedestrian detection was affected by different glare scenarios with different aged participants.

There is limited information on the effects of categorically different headlamps when certain factors such as age, adaptation level, and pedestrian location are considered in the detection task out on a real road environment. This effort moved towards a better understanding of these interaction effects by evaluating five different glare situations with two different driver light adaptation levels. In addition, several age categories were also considered as well as different pedestrian locations. A detailed discussion of the specific dependent and independent variables that were used in this study is located in the experimental methodology section of this report.

Research Questions

The goal of this research effort was to answer specific questions directly related to glare associated with nighttime driving due to various types of vehicle headlamp designs. These questions were:

- What effect measured by detection distance (ft) will different glare sources in terms of intensity/beam distribution (Low/Narrow, Low/Wide, Medium/Medium, High/Narrow, and High/Wide) have on the performance of the disability glare pedestrian detection task?

- What effect measured by detection distance (ft) will different light adaptation levels in terms of ambient lighting environment (Low of 0.15lx and High of 0.45lx) have on the performance of the disability glare pedestrian detection task?

- What effect measured by detection distance (ft) will different pedestrian locations in terms of location in the driving lane (Left and Right) have on the performance of the disability glare pedestrian detection task?

- What effect measured by detection distance (ft) will different age levels (Young 18 to 25 years, Middle 40 to 50 years, and Older 65 or more years) have on the performance of the disability glare pedestrian detection task?

- What effect measured by the deBoer rating scale will different glare sources in terms of intensity/beam distribution (Low/Narrow, Low/Wide, Medium/Medium, High/Narrow, and High/Wide) have on the perception of discomfort glare?

- What effect measured by the deBoer rating scale will different light adaptation levels in terms of ambient lighting environment (Low of 0.15lx and High of 0.45lx) have on the perception of discomfort glare?

- What effect measured by the deBoer rating scale will different age levels (Young 18 to 25 years, Middle 40 to 50 years and Older 65 or more years) have on the perception of discomfort glare?

LITERATURE REVIEW

Background

There is growing public concern related to various aspects of glare associated with nighttime driving in the research area of transportation safety and human factors. Glare has been a topic of debate ever since automobiles were fixed with their first headlamps a little less than a century ago. There are several factors that need to be considered when discussing glare and nighttime driving. The purpose of this section is to review the various topics that are closely related to transportation research involving glare in nighttime driving situations. Information related to personal differences in drivers, such as age, vision, types of glare, and glare sensitivity, as well as information on nighttime driving will be presented. In addition, previous work involving object detection as well as various types of automotive lighting systems will be reviewed.

Age and Driver Performance

There are many effects that age may have on nighttime driver performance. As motorists age, many critical driving-related functions decline. Individual abilities such as visual acuity, motor coordination, and cognition are negatively impacted by age (Marottoli, Ostfeld, Merrill, Perlman, Foley, and Cooney, 1993). For instance, aging has a substantial effect on the human visual system. The maximum area of the iris of the eyes of persons aged 60 years is approximately half that of those aged 20 years (Mortimer, 1989). This decrease in area results in less light reaching the photoreceptors in the eye. In other words, older individuals require substantially more light to have the same visual abilities. This fact has great significance for nighttime driver performance.

Declines in performance associated with age may give an explanation to why older drivers have the highest fatality rate per mile driven (McGwin, Chapman and Owsley, 2000). For every 100,000 miles driven, the crash rate for older individuals is twice that of younger drivers (Babizhayev, 2002). This rise in the fatality rate brings with it concerns because of the increase in proportion of elderly motorists in the population. Various changes in performance occur both physically and mentally as drivers grow older. The eye shows varied evidence of aging as does the rest of the body. Basic biochemical changes, including certain changes in the lens resulting in decreased plasticity and accommodation along with a reduction in flexibility in the iris occur naturally with age. Many older drivers cite glare produced from the headlamps of oncoming vehicles to be one of the main reasons they avoid driving at night. Understanding the effects of glare from various lighting technologies may help reduce harmful effects and keep the aging population driving safely.

Vision

To understand the primary tasks involved in driving, it is first necessary to define the major components of the human visual system. The human visual system is composed of the eye, its supporting neural mechanisms, and its inner projection elements. The eye is the receptor organ that responds to stimulation provided by photo energy. This energy can be described as the visible portion of the electromagnetic spectrum with radiation wavelengths ranging from around 350 to 760 nanometers.

There are three physical aspects of the eye that contribute to normal vision. The first is the proper functioning of the extrinsic muscles that surround the eyeball. These attached muscles allow the eye to move in multiple directions. The second part of a normal visual system is the internal structure of the eye. This serves as an optical system to help focus incident light rays as they enter the eye. The third component is the layer of receptor cells located in the innermost portion of the eye, which generates neural impulses when stimulated by light energy.

In a visual task such as driving an automobile, there are several mechanisms of the eye that have important implications with respect to visual performance (Olson, 1993). The first component of the eye that is important for vision is the crystalline lens. This structure is an optically active system and possesses the ability to focus light energy upon the retina, the innermost layer of the eye. The lens is held in place by ligaments that are attached to the ciliary body. The unique quality of the lens is its ability to change its shape by the contraction and relaxation of the different ciliary muscles. Contraction of these muscles will produce a bulging of the lens whereas relaxation of the muscles will have a flattening effect on the lens. Therefore the lens can alter its shape to optically focus objects viewed from various distances. This automatic response that keeps different objects in focus is referred to as accommodation. The range of accommodation for objects at different distances is dependent upon the contractile power of the surrounding ciliary muscle fibers as well as the elasticity of the crystalline lens itself.

Another critical feature of the visual system is the innermost layer of the eye, the retina, which covers over approximately two thirds of the interior surface (Corso, 1981). The optical components of the eye gather and focus external light entering the eye to produce an image on the retina. The most sensitive part of the retina is called the fovea. This is an area of bunched receptor cells in which the eye gets most of its detailed information. When an object is in focus, its image is focused on the fovea (Carlson, 1999). In the retina, there are two different types of photoreceptors called rods and cones. The eye contains approximately 125 million rods and 6 million cones. The primary functional difference between rods and cones stems from the fact that they have different responses to light energy because of two types of photosensitive substances. Rods, which line the retina far into the periphery, contain a substance called rhodopsin. This allows the eye to function in low-light situations, sacrificing detail for sensitivity when in dark viewing conditions. Cones, on the other hand, are for fine detail and color discrimination and are concentrated more towards the center of the retina. There are three types of cones which allow the retina to be trichromatic. The different cones have peaked spectral sensitivities at 450 nm, 525 nm, and 555 nm or blue, green and, red respectively.

Light and Dark Adaptation

The visual system is always changing to work efficiently in different lighting conditions. In fact, most individuals can adapt to varying levels of light over a span of up to eleven log units of illumination (Olson and Aoki, 1989). Most of these physiological changes occur in the retina of the eye. Light adaptation can be referred to as the process of the visual system becoming accustomed to an increase in the level of illumination at the eye (Schieber, 1994). After an individual is exposed to a light source (e.g., oncoming vehicle), their adaptation level (level of illumination at the eye) is increased proportionally to the intensity of the light. In the task of driving a vehicle, it is important to note that the human visual system takes time to adjust to the new level of illumination. The time it takes to adjust depends on which visual system is being stimulated. Foveal stimulation (cones) results in an immediate drop in sensitivity that begins to rise as the exposure continues. This system increases its sensitivity rapidly in the first three minutes of exposure. Depending upon the intensity of the light source, it may take ten minutes or longer to fully adapt the cones to the new level of light. Therefore oncoming headlamps could create a problem when exposures are short and sporadic and the foveal visual system is constantly trying to adapt to different conditions. Peripheral (rod) vision is similar in that sensitivity is lowest directly following an exposure to a new light source (Boff and Lincoln, 1988). However, it is different in its adaptation time. This system's sensitivity increases rapidly in the first 200 msec. Overall it may take approximately one minute to fully adapt the peripheral system, much quicker in comparison to the foveal system.

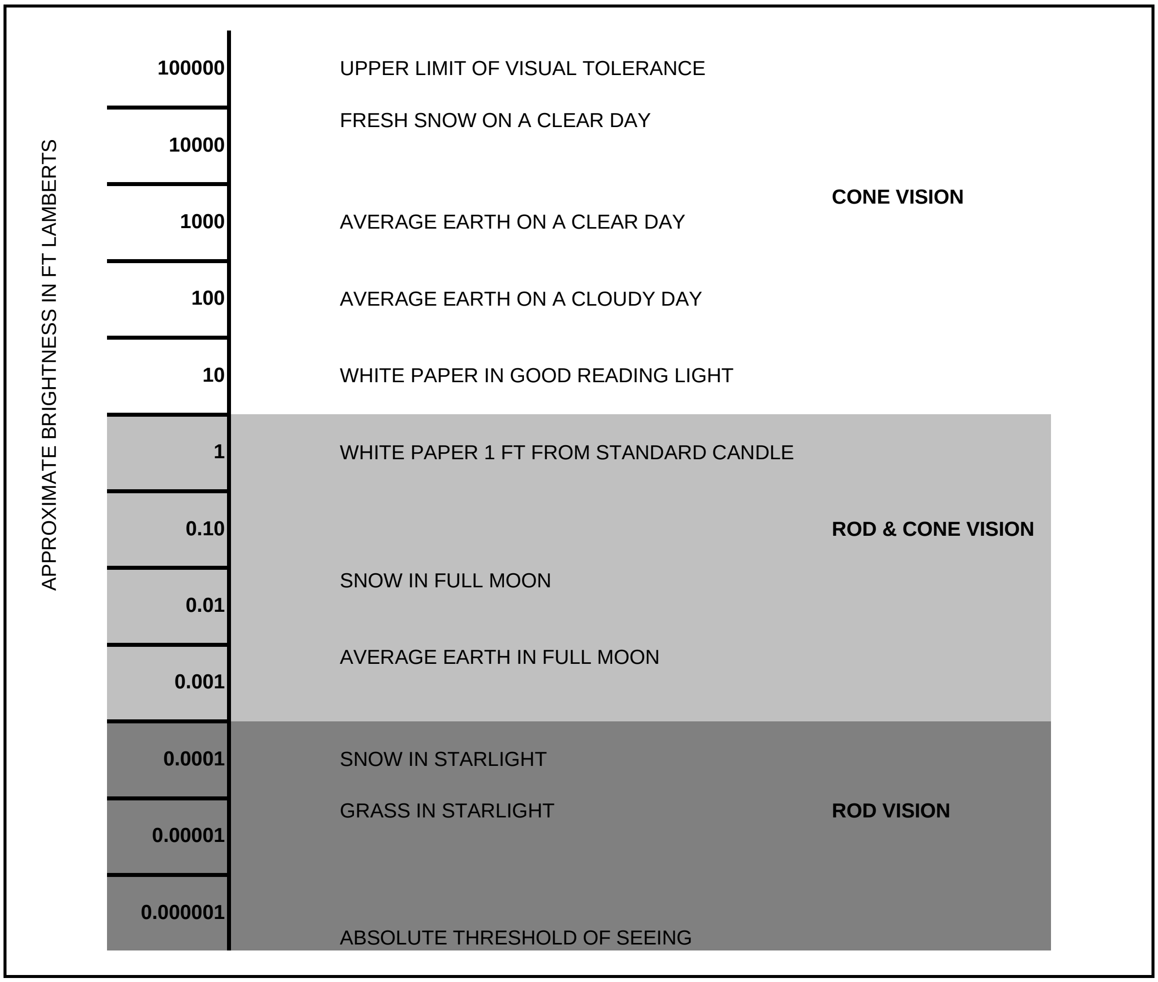
Dark adaptation is the process of the visual system becoming accustomed to a sharp drop in the level of illumination at the eye. This would occur directly after passing an oncoming vehicle on a roadway at night. When stimulated by a light source such as vehicle headlamps, the visual system begins to adapt, but when the light source is removed, sensitivity begins to recover. Overall it takes longer for dark adaptation to occur than light adaptation. The dark adaptation occurs in two stages: the initial rapid phase (approximately 5 to 7 minutes) due to cone adaptation and the slower phase (approximately 30 to 35 minutes) due to the rod adaptation. The rate of dark adaptation is slower after exposure to higher intensity light sources (Boff and Lincoln, 1988). Foveal vision seems to adapt more slowly when the light source is smaller but has consistent levels of illumination. This effect may have implications on the size of headlamps used in vehicles. Smaller headlamps with the same light output will cause a longer adaptation period.

Although it has been found that the human visual system may take as long as 5 to 7 minutes to completely readapt after light exposure, there are others who maintain that the process may be much quicker. A study done by Olson and Aoki (1989) found that after exposure to glare from oncoming halogen low beam headlamps, participants returned to their normal adaptation level (participants' own low beams with no glare) in an average time of a little under four seconds. The reason for this may be in part because the drivers are not fully dark adapted. Instead they are readapting to their original level of illumination, which includes their own headlamps and any other sources of light (e.g., overhead lighting, street signs, and other ambient lighting).

Nighttime Driving

An individual driving at night is operating in illumination levels well below daytime environments but above full darkness because of their vehicle headlamps. The eyes are in an in-between stage and are constantly adapting to the surroundings. For this reason, it is generally accepted that driving at night is two to three times more hazardous per mile driven than normal daytime driving. Night driving has been described as a situation for which humans have not evolved, leaving our visual system inadequate and inefficient for certain tasks (Rumar, 1990). In the context of driving a motor vehicle, the functional differences between the two types of visual photoreceptors are important to consider. Leibowitz and Owens (1977) came up with a framework for nighttime driving that could be used in the evaluation of different headlamp designs. They developed a distinction between ambient (rods) and focal (cones) modes in vision. Focal vision deals with the discrimination and identification of objects and the fine detail associated with them. Another commonly used term for this type of vision is the photopic system (cones). This focal vision is very sensitive to changes in available illumination and therefore may be compromised in nighttime driving. Ambient vision, otherwise known as scotopic vision (rods), determines spatial orientation and general peripheral cues. This type of vision is not as susceptible to changes in light and will have less of an effect on nighttime driving performance. The difference in performance of these two visual systems may be a plausible explanation for higher nighttime crash rates (Sivak and Flannagan, 1993). At middle levels of illumination, the visual system has the ability to take advantage of both photopic and scotopic vision. This combination of the rods and cones working in unison is referred to as the mesopic visual system. Table 1 demonstrates the visual system at different luminance levels.

Table 1 Range of illumination levels at which there is visual function.
(Adapted from Grether and Baker, 1972).



Object Detection

Many studies have been performed to measure the detection distances of various targets on the roadway at night. Detection refers to the moment at which an individual can see that an object is present. The detailed characteristics may not be known about the object but its presence can still be detected. There have been several studies performed involving an oncoming glare situation in nighttime driving. There are several factors that must be accounted for that can drastically change the detection distance. These factors include the age of the observing driver, the headlamp beam type, the illumination level at the eye, the type and location of the target, the reflectance of the target and finally the size of the target.

Vision Testing

The most common form of vision testing used by states to screen driver's license applicants is a static foveal visual acuity test under normal illumination (Sturgis and Osgood, 1982). The Snellen eye chart is a commonly used method for testing a driver's ability to resolve spatial detail. It must be noted that this type of vision testing is only slightly linked with predictions of accident involvement. However, static foveal visual acuity is easily measured and for the most part considered important for the task of driving (Shinar, 1977).

Another form of vision testing is the Contrast Sensitivity measure. This test may predict an individual's ability to discriminate fine details of objects in varying lighting conditions. Most tests for contrast sensitivity use a series of sine wave gratings with different contrast ratios. A contrast ratio or luminance ratio can be defined as the maximum available luminance compared to the minimum available luminance.
These measures are important because they provide the fundamental basis behind the original idea of glare and its effects (Holladay, 1927). One effect in particular is the veiling luminance experienced with glare. Contrast sensitivity measures were used to demonstrate that the veiling effects of glare become more pronounced with age (Chrysler, Danielson, and Kirby, 1996).

A different type of vision testing that applies to nighttime driving and glare is the specific measure of an individual's sensitivity to disability glare. There are many new methods for testing glare sensitivity. For this study, the Brightness Acuity Tester (BAT) was used to determine the participants' sensitivity to glare. The BAT is a handheld eye occluder with a domed aperture. This device is lit with three levels of luminance intensity representing low (12fl), medium (100fl) and high (400fl) levels of glare. It can also be used while turned off as a baseline measurement. The test involved the participant looking at the Snellen acuity chart through the BAT with one eye for all four induced glare light conditions (Off, Low, Medium, and High). Data for each eye was recorded, and the change from the baseline (Off) to the highest glare setting was noted. Participants that had a significant change as the glare increases were more sensitive to bright light. The typical Snellen acuity results of a participant with normal glare sensitivity can be seen in Table 2. As a participant became mildly sensitive, these results began to change (Table 3). A participant with severe light sensitivity had results typical to Table 4. This test was important because two individuals with the same visual acuity and contrast sensitivity may have had a different sensitivity to glare.

Table 2. Typical Results of Normal Glare Sensitivity with BAT.

BAT Setting	Off	Low	Medium	High
Right Eye	20/20	20/20	20/20	20/25
Left Eye	20/20	20/20	20/20	20/20

Table 3. Typical Results of Mild Glare Sensitivity with BAT.

BAT Setting	Off	Low	Medium	High
Right Eye	20/25	20/30	20/40	20/50
Left Eye	20/30	20/30	20/50	20/60

Table 4. Typical Results of Normal Glare Sensitivity with BAT.

BAT Setting	Off	Low	Medium	High
Right Eye	20/40	20/60	20/80	20/400
Left Eye	20/50	20/80	20/200	<20/400

Glare

Glare can defined as a bright, steady light or a shimmering reflection that occurs when the luminous intensity within the visual field is greater than the levels that the eyes are accustomed to (Mace Garvey, Porter, Schwab, and Adrian, 2001). Glare may be the cause of certain discomfort, annoyance, or degradation in visual performance and overall visibility. Therefore it is important to understand the various aspects of glare in relation to driver performance. The two types of glare are most commonly referred to as discomfort glare (psychological) and disability glare (physiological).

Discomfort Glare

Discomfort glare refers to a level of light which is bright enough to result in a measurable level of subjective discomfort or annoyance (Mace, Garvey, Porter, Schwab, and Adrian, 2001). It is known to be related to the degree of homogeneity between the glare source and its background (Schmidt-Clausen and Bindels, 1974). Characteristics of the light source affecting discomfort levels include the intensity, or luminance, as well as the size of the light source. Discomfort glare can vary among different individuals due to many factors, including personality, preference, and experience. This subjective rating is also affected by behavioral aspects. For instance, it was reported that the discomfort that a driver may feel when exposed to glare may depend partly on the difficulty of the visual task that the driver is engaged in (Sivak, Flannagan, Ensing and Simmons, 1991). The most common method for evaluating discomfort glare is the use of the deBoer scale rating system (deBoer, 1967). The deBoer scale has endpoints at 1 and 9 and has verbal anchors for each of the odd numbers as follows: (1) Unbearable, (3) Disturbing, (5) Just Acceptable, (7) Satisfactory, and (9) Just Noticeable. Although there are only descriptors for the odd numbers 1 through 9, the responses can be any number, odd or even.

Disability Glare

Disability glare occurs when the introduction of stray light into the eye reduces one's ability to resolve spatial detail (Scheiber, 1994). It is an objective impairment in visual performance (Vos, 1984). Many of the classic models of this type of glare attribute these deleterious effects to intraocular light scatter in the eye (Stiles, 1929). This scattering of light inside the eye produces a veiling luminance over the retina, which effectively reduces the contrast of stimulus images formed upon it. This disabling effect of the veiling luminance may have serious implications for nighttime visibility while driving.

Headlamps

Headlamps are used to provide forward illumination for the operation of a motor vehicle in situations in which the level of ambient lighting is insufficient. There are several main functions of automotive headlamps for the purpose of preserving the comfort and safety of drivers. One function of forward lighting systems is to allow for efficient lane-keeping in order for the driver to follow the intended path. Another purpose of headlamps is for the detection of potential obstacles, such as pedestrians and other vehicles in the roadway. In addition to potential obstacles, headlamps allow for the detection and legibility of various types of retroreflective traffic signs and other road markings in low-light conditions (Sivak and Flannagan, 1993). Finally, a different purpose of headlamps is to increase the conspicuity of a vehicle to oncoming traffic at night and in daytime. This is one of the only benefits of headlamps for oncoming drivers because in most cases it is generally accepted that headlamps impair the visual capabilities of other traffic.

Halogen Headlamps

Halogen headlamps use similar technology to most basic electrically powered light sources. Illumination is provided in this case onto the roadway by pulling electricity through a newer high-resistance tungsten filament in the bulb. The hot tungsten filament produces light in the visible spectrum that has been found to be more suited for the task of driving than previous designs. Today, with the use of complex reflectors and lenses, halogen lighting systems can provide an output of up to just over 1000 lumens running at 12.8 volts. The typical average luminance of halogen bulbs may be around 1400 candela per meter squared (Jost, 1995). One of the disadvantages to conventional filament designs is that roughly 80 percent of the output is lost as heat in the infrared spectrum (Zino, 1996). The filaments in halogen systems can be damaged from road vibrations and other impacts associated with long term use. As a result, halogens may not last as long as other components in the vehicle.

High Intensity Discharge Headlamps

The first production model of an automotive High Intensity Discharge (HID) lighting system was introduced by Bosch in the fall of 1991. The technology that has been used for years in street lights and other overhead lighting systems is now implemented into the automobile. These new systems were attractive to automotive manufacturers because of their longer life span, greater performance, and power efficiency as well as their new stylistic freedom.

One of the main reasons the HID headlamp is longer lasting and more durable is the fact that it does not contain the conventional tungsten filament that current halogen lighting systems use. The filaments used in halogen headlamps are relatively fragile and can be easily damaged or broken. Instead of filaments, the HID makes use of two metal electrodes. An arc is created between the two electrodes which excites a gas (commonly xenon) inside the lamp that vaporizes metallic salts. These metallic salts help sustain the arc while providing a consistent light source for the beam patterns (NHTSA, 2.2). As a result of this new design, these headlamps are estimated in normal conditions to be able to last the life of an automobile (10 years, 100,000 miles) (Jost, 1995). This is a significant improvement in overall durability compared to other conventional headlamps.

High Intensity Discharge headlamps have been found to have better performance and efficiency compared to conventional halogens. The luminous efficacy, which is the ratio of light output to electrical power consumption, is much greater in discharge lamps compared to halogen designs. Various lighting manufacturers claim that discharge lamps have at least twice the output in lumens as traditional halogens (Jost, 1995). The National Highway Traffic Safety Administration has stated that while HID lamps produce more light output, they only use two-thirds the power of traditional halogen lighting systems, making them more energy efficient (2.2).

Another characteristic of HID lighting systems that certain automobile designers find appealing is their flexibility in styling. Different shapes and sizes of headlamps may be advantageous for designers but may also have effects on glare. The size of headlamp fixtures has been linked to the subjective rating of discomfort glare (Alferdinck and Varkevisser, 1991). A smaller light source (e.g. projector type) with the same light output as a larger (e.g. reflector type) source headlamp may be rated differently on its perceived discomfort (Flannagan, 1999). It is therefore important to consider headlamp size when making direct comparisons of discomfort glare. Differences in headlamp size have yet to be associated with any changes in the objective experience of disability glare.

Headlamp Pattern Characterization

The different characterizations of headlamp beam patterns are based on the analysis of "isocandela" diagrams as well as "bird's eye" diagrams. An isocandela diagram gives a driver's-view analysis of the various levels of light (luminance readings) measured in the vertical and lateral dimensions against a flat vertical plane. The unit of measurement for these diagrams is degrees right ("R") and left ("L") as well as up ("U") and down ("D") as viewed by driver of the vehicle and relative to a point straight ahead in the center of the lamp. One degree in any direction is approximately 5.25ft at a distance of 25ft from the plane surface. Concentric rings give regions of different levels of light and their pattern as portrayed onto the forward view of road and horizon. Figure 2 below is an example of an isocandela diagram for an HID headlamp.

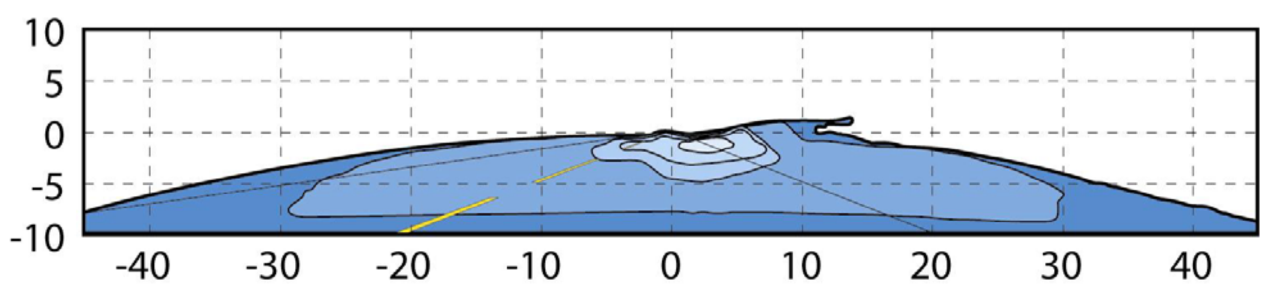


Figure 2. Example Isocandela Diagram for HID.

A "bird's eye" diagram is an overhead view of the different regions of luminance levels produced on the roadway surface by a particular headlamp. These diagrams allow researchers to compare distance down the road of certain intensities of light. A headlamp may be considered "longer" than another because it has greater intensities farther away from the vehicle in the forward direction. Usually the higher the luminance level is for a particular region above the horizon for a headlamp in an isocandela diagram, the longer it is in the bird's eye diagram. Below is an example of a bird's eye diagram for an HID headlamp (Figure 3).

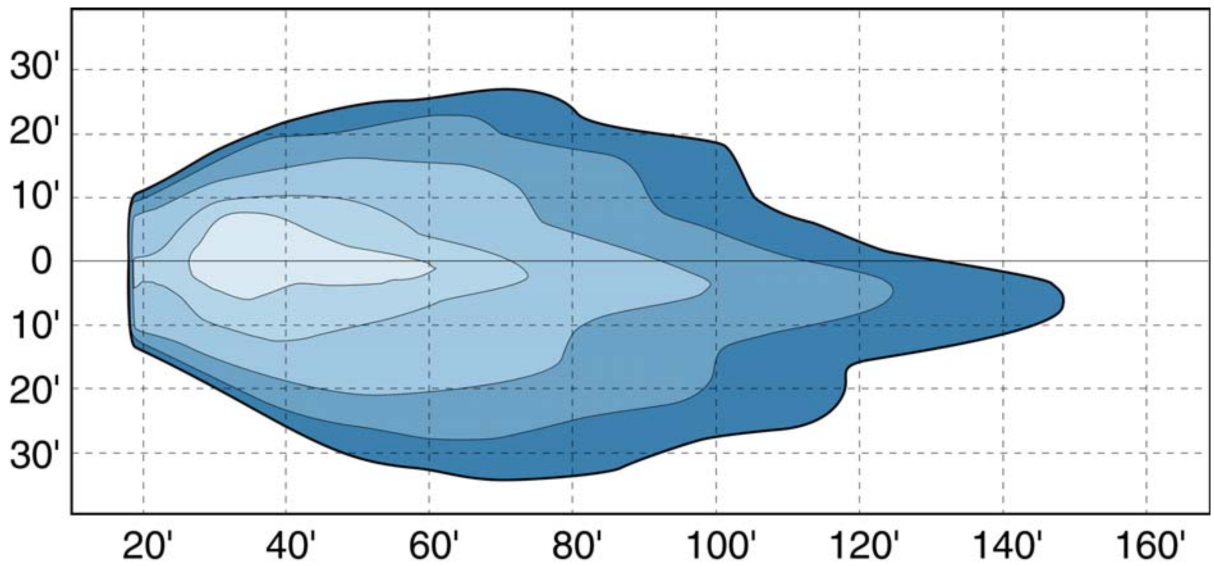


Figure 3. Example Birdseye Diagram for HID.

Overall, these two measurement techniques are valuable because they give information about not only how intense a particular beam may be but also where it directs its light.

EXPERIMENTAL METHODOLOGY

In an effort to answer the many research questions involving glare and to achieve the research objectives, an on-road empirical investigation was conducted during nighttime driving. The primary tasks involved driving under two levels of light adaptation while encountering five types of headlamps. The main focus of this study was to evaluate the effects of the different headlamp beam characteristics—beam distribution and intensity of Halogen and HID headlamps—in terms of disability and discomfort glare across three age levels of participants. The proposed method of characterizing different levels of disability glare was to measure how each combination affected the distance at which the driver could detect objects in the road. Discomfort Glare was evaluated with the use of the subjective deBoer rating scale.

This study took place at the Virginia Tech Transportation Institute and Smart Road testing facility. This testing area is a closed and gated facility and is only used for research and testing purposes. The road is inaccessible to all other public traffic except those involved with the study. The following sections give more information concerning the details of the experiment.

Participants

This research was conducted with the participation of 30 drivers divided into three different age groups. Each age group was equally divided into five males and five females. The first age group (young) consisted of ten drivers between the ages of 18 and 25 years with an overall average age of 22 years old (male average age was 23 years old, female average age was 21 years old). The second age group (middle) consisted of ten drivers between the ages of 40 and 50 years with an overall average age of 43 years old (male average age was 44 years old, female average age was 43 years old). Finally, the third age group (older) consisted of ten drivers at or above the age of 65 years with an overall age of 69 years old being the average (male average age was 70 years old, female average age was 68 years old).

The estimates of sample size requirements for this experiment were done using the "Best" of r Population Means method (Bechhofer, 1954). The formula used is written as $(\sigma \sqrt{n})/\lambda = 3.0552$, where σ = standard deviation and λ = minimum difference. The value of 3.0552 was the table value used for the probability of correct identification ($1-\alpha$) of .95. With five different glare headlamps being evaluated, 5 was used for "r." The results of previous studies involving detection distances of pedestrians in the presence of glare were referenced for this estimation. A standard deviation of detection distance at around 25 ft and a minimum difference of 25 ft were used in determining the sample size. (Theeuwees, Alferdinck and Perel, 2002). With these values inserted into the equation, the estimated sample population is 9.33. Therefore, using 10 participants in each age group (30 total) preserved the integrity of the counterbalancing scheme and reduced the potential for order effects.

Experimental Design

The data collection portion of the study included 10 different headlamp combinations. The following is a list of the different combinations of driver adaptation level and oncoming headlamps:

Driver Adaptation Level

- Low Adaptation (.15 Lux)
- High Adaptation (.45 Lux)

Glare Headlamp

- (High/Narrow) Higher Intensity with Narrow Beam Pattern (HID)
- (High/Wide) Higher Intensity with Wide Beam Pattern (HID)
- (Low/Wide) Lower Intensity with Wide Beam Pattern (HID)
- (Med/Med) Mid-Level Intensity with Medium Beam Pattern (HID)
- (Low/Narrow) Low Intensity with Narrow Beam Pattern (Halogen)

The setup of the study was a Mixed Factorial Design. The details of all the factors may be seen in Table 5. There were four independent variables for this experiment, which included: glare headlamp, age, driver light adaptation level, and pedestrian location. The between-subjects factor was age. The within-subjects factors were glare headlamp, driver light adaptation level, and pedestrian location.

Table 5 Factors for the experimental design.

Independent Variable	***Levels***
Glare Headlamp	Low/Narrow, Low/Wide, Medium/Medium, High/Narrow, High/Wide
Age	Young (18-25 years), Middle (40-50 years), Older (65 years and older)
Driver Light Adaptation	Low (.15 lux), High (.45 lux)
Pedestrian Location	Left (center of two lane road), Right (right shoulder)

The orders in which the Glare Headlamps were presented were counterbalanced to reduce order effects. The Pedestrian Location was also counterbalanced. The Driver Light Adaptation Level was also counterbalanced so that half of the participants began with low adaptation and the other half began with high adaptation levels.

Independent Variables

As mentioned earlier, glare headlamp, age, driver light adaptation level, and pedestrian location were the independent variables for this research. There were a total of five different sets of headlamps that were evaluated in this study. Each headlamp was specifically chosen for its beam distribution and output characteristics. Four of these systems were different designs of High Intensity Discharge lights that have recently become available for use on domestic roadways. The fifth system was a standard halogen headlamp that has been used in previous studies involving detection tasks. There were three different age groups, including young, middle, and older, that were used in this study. There were two different light adaptation levels: low and high. Finally, there were two different locations where pedestrians will be standing: left and right. The details of each independent variable are described in the following sections.

Determining the Independent Variables

The following sections are justifications for the specific parameters of the independent variables. The reasons for choosing each category as well as how the different levels were derived are also included below.

Glare Headlamp Selection

The possible headlamps for this study were categorized in terms of beam intensity and width based upon an analysis of available isocandela diagrams. A comparison across all designs was made by determining the width at the intensity level of 12,000cd (Table 6). This level was used because it was the closest region approximate to one half of the maximum intensity (i.e., beam angle) for the lowest available value (25,978cd) for a particular headlamp design. This level was also a good representation of light falling on the left and right lanes of the roadway in the forward view. The total list of available headlamps was divided in three equal parts by the particular observed widths.

Table 6 Available Headlamps categorized by width (Degrees) and intensity (Candela).

Selected Headlamps

Headlamp	Type	Max Intensity cd (UD/LR)	12000cd (Left)	12000cd (Right)	Width (12000cd)	Width
Mercedes-Benz E320	HID	34449 (.8D/2.6R)	-3	6	9	Narrow
Ford Explorer	**Halogen**	**30139.84(2D/0R)**	**-4**	**5.5**	**9.5**	
Mercedes-Benz E320B	**HID**	**40778 (1.0D/1.6R)**	**-3.5**	**6**	**9.5**	
BMW Mini Cooper	HID	26984 (.8D/1.8R)	-5.5	6.5	12	
Audi A8	HID	30666 (1.4D/1.8R)	-7	7	14	
Lincoln Towncar	HID	32882 (1.6D/1.8R)	-5.5	9.5	15	
Audi A4	HID	27145 (.6D/2R)	-7	9	16	
Acura 3.2	HID	38795 (1.8D/2.0 R)	-9	8	17	
Lexus GS 400	HID	30753 (1.2D/1.8R)	-7.5	10.5	18	Medium
Audi TT	HID	39953 (.8D/2.0R)	-8	11.5	19.5	
Lexus LS 430	HID	41431 (1.4D/2.8R)	-8.5	11	19.5	
BMW 328	HID	41830 (1.D/2.2R)	-5	14.5	19.5	
Lincoln Aviator	HID	28120 (.8D/3.6R)	-8	12	20	
Nissan Altima	**HID**	**35771 (.8D/2.2R)**	**-9**	**11**	**20**	
Mercedes- Benz C230	HID	28864 (1D/1.8R)	-9	11.5	20.5	
Audi A6	HID	35916 (1.8D/2.2R)	-9.5	11	20.5	
Acura	HID	43430 (.8D/2.40R)	-11	12.5	23.5	
BMW 740	HID	45034 (1.0D/2.4R)	-9.5	14	23.5	Wide
Mercedes-Benz SL500	HID	27127 (1.4D/2.0R)	-13	11	24	
Nissan Maxima	HID	36847 (1.2/3.0R)	-11	13	24	
Lexus	HID	41562 (1.2D/2.0R)	-11	13	24	
Lexus ES 300	HID	36061 (1.6D/2.2R)	-11	13.5	24.5	
Cadillac Catera	HID	40472 (.8D/.2R)	-12	12.5	24.5	
Mercedes-Benz S500	**HID**	**28772 (.2D/2.0R)**	**-10.5**	**14.5**	**25**	
BMW	HID	25978 (.8D/3.2R)	-12.5	13.5	26	
Lincoln Navigator	**HID**	**43181 (2.2D/.4R)**	**-13**	**13.5**	**26.5**	

The group of headlamps that was selected for this study represented the extremes and midpoints for beam width and light intensity. These combinations of width and intensity can be seen in the matrix below (Table 7). The only halogen headlamp represented the low intensity and narrow beam width parameters. The rest of the headlamps in the other combinations of beam characteristics were HID designs. Detailed information on each headlamp that was chosen can be referenced in Appendix 4.

Table 7 Headlamp Characteristic Matrix.

Beam Intensity	Narrow		Wide
High	Mercedes-Benz E320 (HID)		Lincoln Navigator (HID)
		Nissan Altima (HID)	
Low	Ford Explorer (Halogen)		Mercedes-Benz S500 (HID)
	Beam Width		

Age Groups

For this experiment, the age factor had three distinct levels. These were determined by assessing the different changes that occur in visual capabilities at certain ages. The age groups were young (18 to 25 years old), middle (40 to 50 years old), and older (65 years and above). Ten participants from each age group were involved in the study.

Driver Light Adaptation Level

The light adaptation level of the driver was varied by using a dimmable light source to create a low and a high level of adaptation. The light adaptation was kept at two significantly different levels, both in the mesopic range. These two levels were set at a low value of 0.15 lx and a high value of 0.45 lx. An in-vehicle evaluation of illuminance readings at the driver's eye level in different road and traffic conditions was performed to establish a range of possible Lux values. The results of this test are illustrated in Figure 4. The results from the on-road measurements were considered along with previous methods in similar studies involving glare and object detection (Flannagan, Sivak, Traube and Kojima) to establish these values. These levels were checked with an illuminance meter in the vehicle at the height of the driver's eye mounted on the rear view mirror. This dimming range was therefore controlled to avoid chromatic shifts in the light source. The driver had sufficient time to become adapted to each level, and measures were taken to prevent any unwanted variations as the study proceeded.

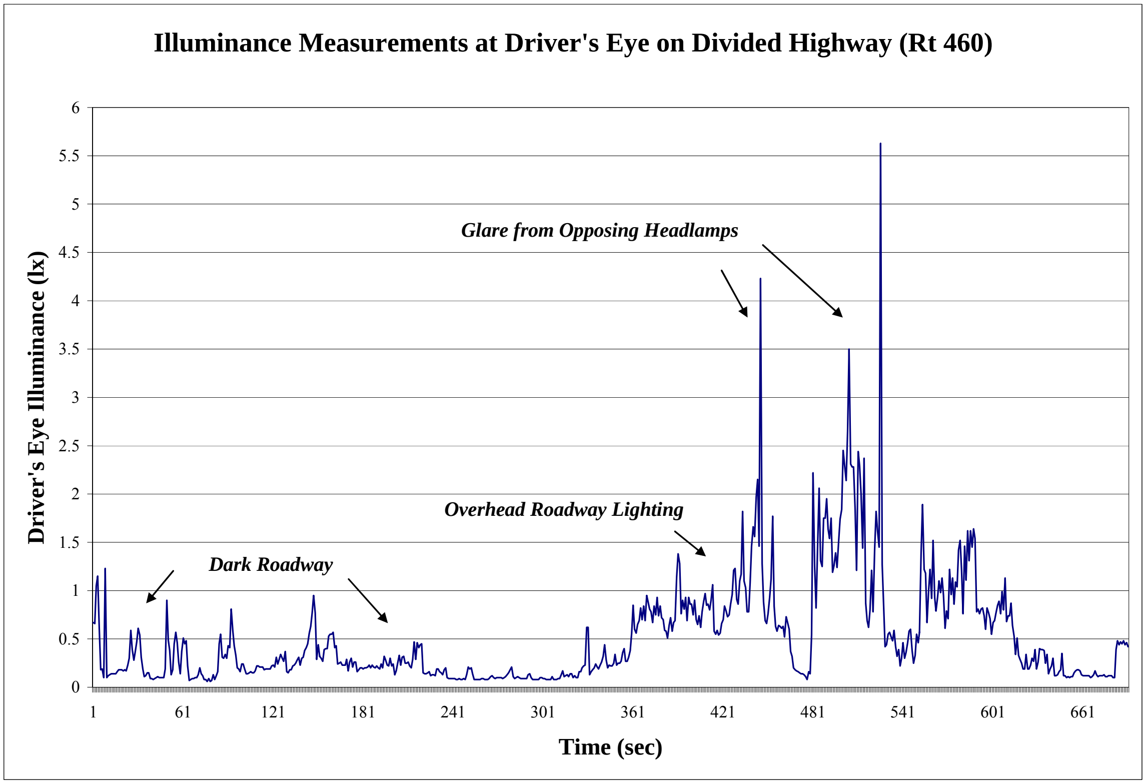


Figure 4. Illuminance Readings Taken on Route 460 at Night with and without Overhead Lighting and Glare.

Pedestrians

Vehicle accidents involving pedestrians are a major concern for the field of transportation safety (NHTSA, 2002). The physical characteristics of a human being are difficult to replicate. Therefore, it was preferable to use humans with research of this type involving detection of on-road pedestrians. Different research has been done involving glare using varying types of pedestrian clothing. In the past, different clothing colors such as black, gray, white, denim, and khaki have all been used as the target reflectance (Zwahlen and Schnell, 1999). The reflectance and the color characteristics of the clothing were important factors to consider when dealing with different types of headlamps. Due to the short detection distances and difficulty with glare, the pedestrians were dressed in white clothing for this study.

Pedestrian Location

The location at which a pedestrian was walking in the roadway significantly affected their visibility in the presence of glare relative to the driver. A pedestrian located on the center yellow line of the road is in a location where the glare is substantially greater for the driver (Mortimer, 1989). On the other hand, a pedestrian located on the right white line of the roadway is farther away from the glare source in the lateral direction. There were two pedestrian locations for this study to further understand these differences, as seen in Table 8. There was either a pedestrian on the yellow centerline or the right white line. Both locations were 50ft behind the glare headlamps. This distance was determined to be a safe stopping distance at the driving speed of 20mph. All pedestrians stood facing the oncoming vehicle. It was important that pedestrians did not cross lines or cover lines on the road because this may have affected detection distances due to a sharp change in contrast.

Participants were instructed to detect pedestrians as they drove down the roadway. They first needed to say when they just detected that something was in the road. They then needed to accurately identify what the object was (e.g., "pedestrian walking") and where the pedestrian was located (e.g., "center" or "right").

Table 8. Description of the on-road pedestrians.

Pedestrian	***Location***	***Instructions***
(Left)	Center Line on Roadway	Stand dressed in white clothing facing Driver (parallel to line) 1 ft inside center line. Important that feet do not cross or cover any portion of the line.
(Right)	Right Line on Roadway	Stand dressed in white clothing facing Driver (parallel to line) 1 ft inside right line. Important that feet do not cross or cover any portion of the line.

Dependent Variables

The dependent variables that were gathered to evaluate the effects of different glare produced by headlamp designs were the objective measurement of detection distance (ft) and the subjective measurement of deBoer discomfort ratings. Detection distance is defined as the distance measured in feet from the driver of the experimental vehicle to the pedestrian at the moment at which they can first detect the pedestrian. The deBoer scale rating is defined by the overall discomfort the participant feels due to the oncoming glare sources from the start point all the way (1000 ft) to the glare source. The discomfort rating is from 1-9 on the deBoer scale. More details concerning the selection of the dependent variables and how they were measured are described below in the experimental procedures section.

Apparatus and Materials

The driving portion of the study took place in a 2001 Cadillac DTS, the only vehicle to be used in this study. Participants did not need to move or adjust their seats once the study had begun. As mentioned earlier, the Cadillac sedan was instrumented with sensors that determined speed, eye level illuminance measurements, and distance traveled. These sensors fed into a laptop computer that was located in the back seat with the in-vehicle experimenter. This computer was equipped with a special version of MODCAR, which was a software program developed specifically for this particular type of data collection. This software allowed the experimenter to collect distances, collect illuminance readings, and keep track of orders as well as any other information pertaining to the participant.

Glare Headlamps

The different glare headlamps were positioned on the road using special headlamp mounting rigs. The lighting rig and experimental vehicle can be seen in Figure 6. This headlamp assembly, as seen in Figure 5, was designed to simulate the height and width of a real vehicle. For this particular study the headlamps were set at a height of 33 in., which is comparable to a standard SUV (center point of luminaire to road surface). The advantages to using the lighting rigs as opposed to real vehicles were: (1) they were lightweight and easier to maneuver; (2) they could be more accurately and reliably aligned in a fixed position along the roadway; and (3) for safety reasons, an entire vehicle was not in the oncoming lane of traffic. The power supply to these lighting rigs was a regular AC outlet. The lights were kept at 12.8 volts with the use of an electrical inverter for consistent performance. The headlamps were aligned according to the manufacturer's specifications and checked before each experimental session. The alignment methods and protocol can be seen in Appendix 13.

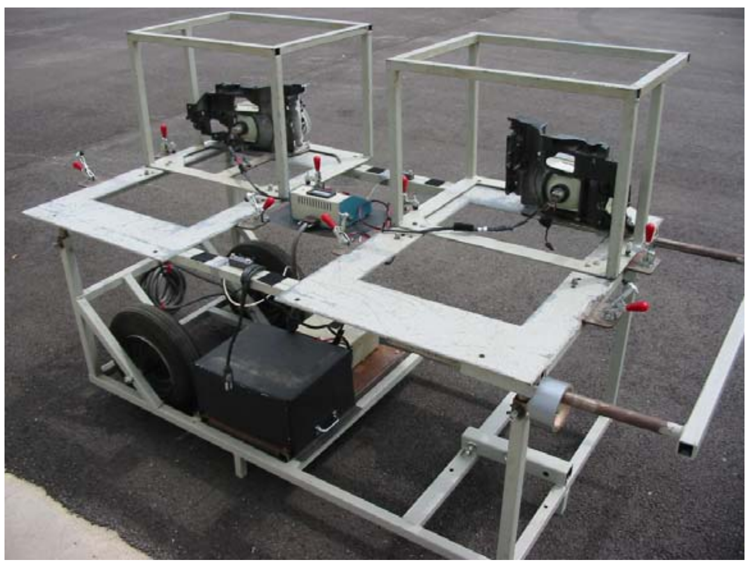


Figure 5. Back view of glare cart with Explorer halogen headlamps (Low/Narrow) mounted.

Figure 6. Glare Headlamps and Experimental Vehicle on the Smart Road.

Figure 7. Glare Headlamps at Night with Left Pedestrian.

Smart Road Testing Facility

The driving portion of the study took place on the Smart Road, pictured in Figure 8, at the Virginia Tech Transportation Institute. There was one specific station at which glare headlamps and pedestrians were presented on the roadway. This particular location was on the concrete (as opposed to the asphalt) section of the Smart Road. This was to ensure that the contrast of the pedestrian in relation to the roadway was kept consistent for all experimental trials. The Smart Road is a facility that is closed off to the general public, so there were no other vehicles on the roadway besides the experimental vehicle. The facility was monitored by the Smart Road Control Tower 24 hours a day. The dispatcher in the Control Tower was able to assist the experimenter if needed. Before entering the road, an experimenter had to establish radio contact with the dispatcher. Radios were used to communicate with other on-road experimenters as well as the Control Tower. A headset was worn when in the vehicle so as to not disturb the participant and the data collection process.

Figure 8 Overhead view of the upper section of the Smart Road test route.

Experimental Procedure

Prior to participating in this study, all drivers had to complete a Participant Screening Questionnaire over the telephone (Appendix 1). If the individual fit the criteria necessary for this study, they were then scheduled to participate as a driver. Only one individual at a time participated in this study. Each participant went over a description of the study, all the necessary forms and documents, and any important questions before entering the vehicles. The experiment consisted of a training lap that allows participants to become familiar with the experimental vehicles as well as the detection tasks. An overview of the protocol for this experiment is listed with the participant's different tasks in Table 9.

Table 9. Description of the on-road pedestrians.

Experimental Protocol Overview	
1	*Pre-Drive Information and Vision Tests*
2	*Training Procedures*
3	*Vehicle Familiarization*
4	*Driving Instructions*
5	*Practice Run*
6	*Data Collection*
7	*Subjective Ratings (Discomfort Glare Portion)*
8	*Detection Distance (Disability Glare Portion)*

Pre-Drive Information and Vision Tests

The participants met the lead experimenter at the Virginia Tech Transportation Institute (VTTI) located in Blacksburg, Virginia. Directions to VTTI were provided if needed by the participant. After meeting the experimenter, the participant was given a brief overview of the study and a description of the night's activities. The experimenter then verified that the participant had a valid driver's license for the driving portion of the study. The participant was then given an informed consent form (Appendix 2) to read over and sign before continuing. After completing this form and answering any questions, the experimenter gave a series of informal visual acuity tests. These tests included the Snellen Eye chart, Contrast Sensitivity Test, Brightness Acuity Test, and a Color Vision Test (Appendix 3). These informal tests were done to ensure that the participant had corrected 20/40 visual acuity and did not have any other conditions that could have in some way influenced the results. After these tests were completed and if there were no apparent problems, the participants were given a pre-drive questionnaire (Appendix 6) to gather more information about them. Some examples of information gathered in this questionnaire included the type of vehicle the person drove most often, how often they drove at night, and what was the biggest concern while driving at night. After the preliminary information was gathered, the participants were trained on the tasks that they would be performing on the road for the experimental portion of the study.

Each driver received a payment of $20 per hour for their participation. All participants were screened prior to driving to ensure that they met all the specific requirements listed in the Driver Screening Questionnaire (Appendix 1). Participants who did not present a valid driver's license, successfully pass the visual acuity test with a score of corrected 20/40 or better (as required by Virginia Law), or who revealed health conditions that would have made operating the research vehicles a risk were not be allowed to drive in the study. In addition, the participant were required to sign an Informed Consent Form (Appendix 2) and complete a series of informal vision tests (Appendix 3). The mean Snellen acuity was found to be 20/20 for male participants and 20/23 for females. Information on glare sensitivity was valuable in understanding certain variations in performance related to the detection tasks of this experiment. The BAT® (Brightness Acuity Tester) was used to evaluate participants' susceptibility to glare. This piece of equipment is a handheld eye occluder with a single aperture and its own interior source of illumination, as pictured in Figure 9. This glare at the eye can be set to three different levels to track changes in visual acuity as the brightness increases. The standard Snellen chart may be used to test acuity in one eye while looking through the BAT® at the chart. This information was ultimately used to help understand outlying results in both the disability and discomfort portions.

Figure 9 BAT® (Brightness Acuity Tester).

After the vision test was administered, the participants were given a Pre-Drive Questionnaire to complete (Appendix 6). The questionnaires included eight questions that gathered different demographic information from each participant. For instance, the results revealed that five participants wore contact lenses while driving at night, four participants wore bifocal glasses, four participants wore single lens glasses and two participants wore trifocals. The rest of the participants did not use any corrective lenses while driving at night.

The nighttime driving behavior of each participant was also gathered in this questionnaire. The majority of participants drove at night three times per week. Eleven participants drove every night and only five participants drove one time per week. When asked if they experienced difficulty with nighttime driving, the majority of the participants said they encountered little difficulty. Twenty-seven percent of the participants said they encountered no difficulty, and 10 percent responded to moderate difficulty, leaving 3 percent of the participants experiencing extreme difficulty while driving at night. According to the questionnaire, the addition of oncoming headlights and streetlights while driving at night did not seem to affect the majority of participants' driving difficulty at night. The majority of participants again agreed to experiencing little difficulty driving. Twenty-seven percent said they experienced moderate difficulty, 10 percent replied "no difficulty," and again only 3 percent experienced extreme difficulty. Sixty-one percent of participants indicated that they were "very comfortable" driving at night in good weather, and 30 percent said they were "somewhat comfortable." The responses "neither comfortable nor uncomfortable," "somewhat uncomfortable," and "very uncomfortable" were chosen by nine percent of the drivers. In addition, driving at night in typical bad weather left 39 percent feeling "somewhat uncomfortable," 27 percent feeling "somewhat comfortable," and 17 percent feeling "very comfortable"; 17 percent were "neither comfortable nor uncomfortable."

Training Procedures

The driver was instructed on how the tasks of detection could be performed successfully as well as how the subjective discomfort ratings could be made. A breakdown of the procedures relating to these tasks was reviewed. The specific definition of detection was given along with directions on how to use the push button for these tasks. The deBoer scale (Appendix 5) was also reviewed with the participant, and there was a chance for the experimenter to answer any questions or concerns. The purpose of this pre-drive summary was for the participants to understand the basic procedures of the experiment in addition to what was expected of them during the study. If there were no more questions or concerns, the participant was ready to be introduced to the experimental vehicle. All participants were informed that they were free to withdraw from the study at any time for any reason without penalty. All data and personal information collected during the different phases of the study were treated with anonymity.

Vehicle Familiarization

The participant was shown to the experimental vehicle by the in-vehicle experimenter. The experimenter demonstrated to the driver how to correctly adjust the seat and seatback, the steering wheel position, and the side and rearview mirrors. They also gave instructions on the operation of the headlamps, windshield wipers, and climate control system if needed. It was important to ensure that all the adjustments were made so that the driver was in a normal, comfortable position. Once everything was adjusted, the experimenter took eye height measurements of the participant (Appendix 4). If there were no questions or concerns, the participant was ready to begin the driving portion of the study.

Driving Instructions

Participants were informed that the speed limit for the Smart Road was 25mph and that they should use the right-hand lane. The participants were told to stop and park the car at specific areas during the study. They were also informed that while in the test section of roadway, which was indicated by the in-vehicle experimenter, the speed limit was 20mph for the safety of the on-road experimenters. To make the task of staying at 20mph less difficult, the participants were instructed to use second gear in the vehicle's automatic transmission. Drivers were permitted to lower their speed if they desired to do so in any situation during testing.

Practice Run

The drivers had the opportunity to become accustomed to the Smart Road and the experimental vehicle during a practice lap. They also had a chance to practice the tasks of performing the subjective discomfort ratings as well as detecting the different pedestrians on the second half of the practice run.

Data Collection

The discomfort ratings were gathered during the evaluation of each combination of driving and glare headlamps. The primary task of the participant was to safely drive the vehicle at or below the set speed of 20mph. The experimenter had a handheld push button to use when the participant called out pedestrians on the road. The deBoer scale ratings were given verbally by the driver when prompted. The in-vehicle experimenter was seated behind the participant in the back right seat of the vehicle. The role of the in-vehicle experimenter was to guide the participant through the test procedure and to ensure that the data collection equipment was functioning properly and that all the data points were collected. A detailed explanation of the in-vehicle experimenter's role can be seen in the In-Vehicle Protocol (Appendix 5). In addition to the in-vehicle experimenter, there were four on-road experimenters. The on-road experimenters were responsible for setting up the road and changing the headlamps as specified by each order. The full responsibilities of the on-road staff may be seen in more detail in the On-Road protocol (Appendix 11).

In-Vehicle Test Sequence

The in-vehicle testing procedures were followed with each participant to collect data points for all of the possible lighting combinations. These specific procedures are illustrated in figures 10 and 11.

Subjective Ratings (Discomfort Glare Portion)

As participants approached the glare headlamps, they were asked to rate the discomfort they experienced from the lights. For this particular task, the discomfort rating was an overall perception of the glare from the beginning to the end of the approach from 0 to 1000ft. The rating occurred only after the participant passed the glare source. The in-vehicle experimenter asked the participant to stop the vehicle and rate the overall discomfort experienced from the glare by using the deBoer scale. The single subjective rating was an overall impression of the headlamps as the glare sources were approached. As mentioned earlier, this scale has endpoints at 1 and 9 and has verbal anchors for each of the odd numbers as follows: (1) Unbearable, (3) Disturbing, (5) Just Acceptable, (7) Satisfactory and (9) Just Noticeable (deBoer, 1967). The scale and its anchors were reviewed with the participant before each trial to ensure accurate rating.

(1) While approaching the glare source, the participants were preparing to give a rating of their overall perceived discomfort.

(2) If an error occurred during testing, the trial was allowed to be repeated at the end of the night.

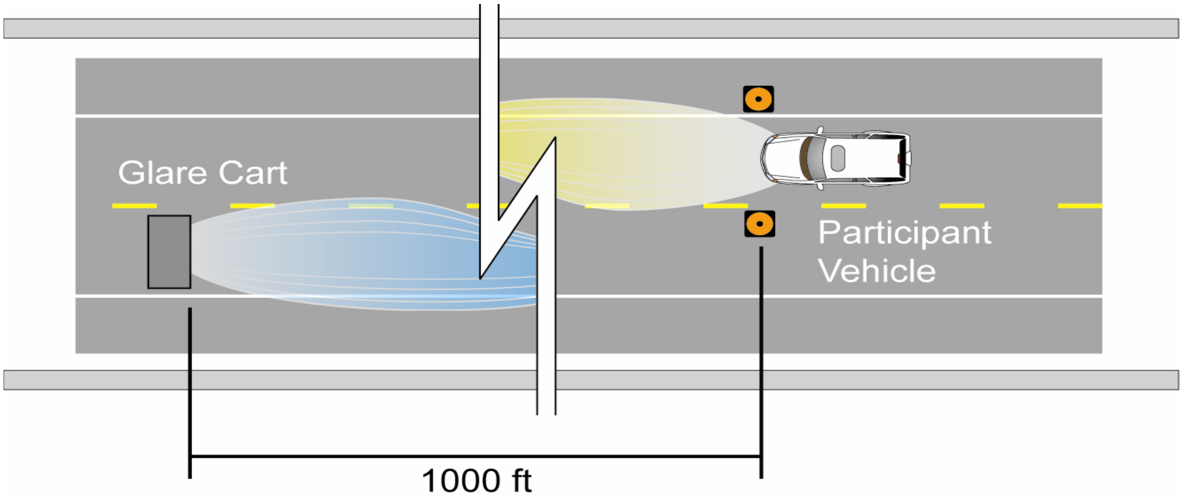


Figure 10. Plan view of the experimental vehicle at the start point in the Discomfort Glare portion.

Detection Distance (Disability Glare Portion)

Detection distances are important when determining nighttime visibility (Nilsson and Alm, 1996). Detection distance were collected by the use of an instrumentation package set up in the experimental vehicle. This instrumentation included sensors in the vehicle as well as an integrated software program. This specially developed computer program (MODCAR) was able to track several variables at one time while traveling down the road (e.g., distance in feet). A push button was connected to the computer so the participant could accurately communicate when they detected pedestrians. This was a very efficient method of collecting data points for this type of study. Participants were given specific instructions on how to accurately complete their detection tasks. Each participant was informed that detection was when they could first tell that an object was in the roadway and they could identify what side of the road it was on. Finally, as the vehicle passed the pedestrian's location along the road, the in-vehicle experimenter pressed a separate button to mark the actual location of the pedestrian. This was later used as a method of checking to make sure the pedestrians were located in the correct position for each trial. All experimental trials were videotaped with an audio feed. This was important because any missed button presses could be retrieved manually through video analysis.

(1) A pedestrian paired with a set of glare headlamps was present at the glare station for each configuration. There were also trials with no pedestrian or a blank.

(3) While approaching a station, the participant indicated vocally when he or she could detect and recognize the pedestrian. The in-vehicle experimenter pressed a button to record responses.

(4) When the experimental vehicle passed the pedestrian, the in-vehicle experimenter pressed a separate button to indicate the pedestrian's location.

(5) If an error occurred during testing, the trial was allowed to be repeated at the end of the night.

(6) Once all headlamp combinations and pedestrian locations had been evaluated under both levels of light adaptation, the participant was instructed to return to the VTTI building.

(7) Participants were paid for the total number of hours they contributed.

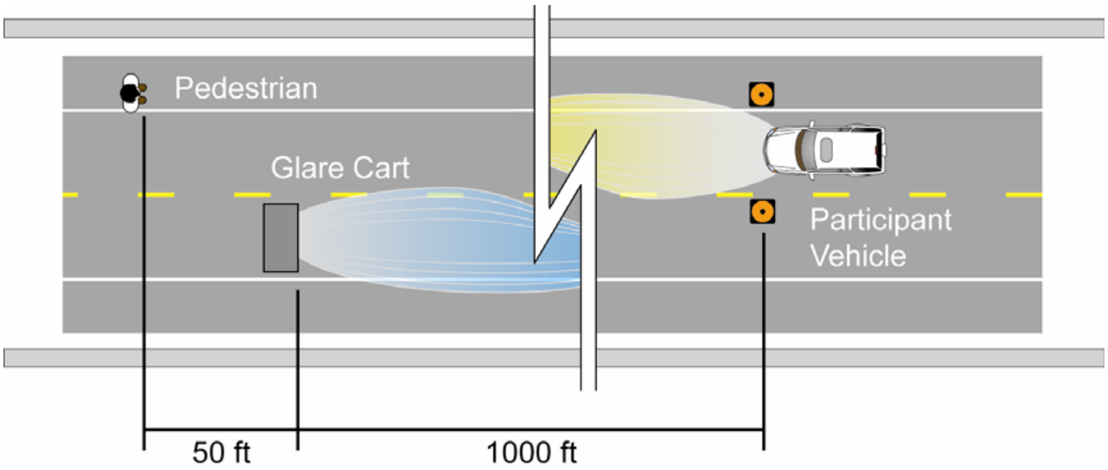


Figure 11. Plan view of the experimental vehicle at the start point for the Disability Glare portion.

In-Vehicle and On-Road Safety

This research involved participants driving vehicles on a closed roadway with real pedestrians as objects in induced glare situations. Therefore, many measures were taken to ensure the safety of all those involved in the project. These measures included: (1) all data collection equipment, both electrical and mechanical, were installed in a manner such that it would not, to the fullest extent possible, create a hazardous situation in any instance; (2) participants and in-vehicle experimenters were required at all times to wear the vehicle seatbelts; (3) any individual that had had corrective laser or LASIK eye surgery could not participate in this study due to the increased risk of injury from the deployment of the driver supplemental restraint system (airbag) in the participant vehicle; (4) the data collection equipment could not have interfered with the normal field of view of the participant; (5) a trained in-vehicle experimenter had to be in the vehicle at all times to guide the participant and to answer any questions; (6) on-road experimenters (pedestrians and other workers) knew when to clear the road when a vehicle approached even if the radio communication failed; and (7) a list of emergency procedures were developed and reviewed before testing.

Data Analysis

The raw data for all participants, collected from the in-vehicle computer program, were first sorted and merged into one data file. Each participant run had a separate data file for every headlamp combination and light adaptation level. All the data from each of the 30 participants were consolidated into one main database. These data were then ready to be analyzed to determine the participants' performance under each of the experimental conditions. An analysis of variance (ANOVA) was performed to determine the different effects of the treatment conditions. The procedure "PROC GLM" was used in SAS® (SAS Institute, Cary, NC) to compute the ANOVA for the detection distances. This procedure revealed whether or not there were significant differences among the headlamp combinations relating to the objective and subjective dependent variables.

Discomfort Glare Analysis

The main effects in this study included: (1) glare headlamp (GLARE); (2) age (AGE); and (3) driver light adaptation level (ADAPT). Table 10 shows the full model of the experimental design for the analysis of this study.

Table 10 Mixed Factorial Design.

Source
<u>Between</u>
AGE
PARTNUM (AGE)
<u>Within</u>
GLARE
GLARE by AGE
GLARE by PARTNUM (AGE)
ADAPT
ADAPT by AGE
ADAPT by PARTNUM (AGE)
GLARE by ADAPT
GLARE by ADAPT by AGE
GLARE by ADAPT by PARTNUM (AGE)

A univariate test for normality revealed that the subjective data (discomfort ratings; deBoer scale) were distributed normally. Therefore, because the distribution was normal the data were run through an analysis of variance (ANOVA). Once the ANOVA had been completed, it was noted that a significant main effect or interaction effect did not mean that all levels within it were significant. For this reason a post-hoc analysis was performed to separate out which levels were statistically significant ($p < 0.05$). The analyses that were considered were the Student-Newman-Keuls (SNK) and the Bonferroni t (BON) tests. The Bonferroni t test can be used in a situation in which there is an incomplete data set (Winer, 1991). Both of these procedures are valuable because they can pinpoint which level is the cause of the differences. The SNK analysis was performed to determine which levels were significant within each group.

Disability Glare Analysis

The main effects in this study included: (1) glare headlamp (GLARE); (2) age (AGE); (3) driver light adaptation level (ADAPT); and (4) pedestrian location (PEDESTRIAN). Table 11 shows the full model of the experimental design for the analysis of this study.

Table 11 Mixed Factorial Design.

Source
Between
AGE
PARTNUM (AGE)
Within
GLARE
GLARE by AGE
GLARE by PARTNUM (AGE)
ADAPT
ADAPT by AGE
ADAPT by PARTNUM (AGE)
PEDESTRIAN
PEDESTRIAN by AGE
PEDESTRIAN by PARTNUM (AGE)
GLARE by ADAPT
GLARE by ADAPT by AGE
GLARE by ADAPT by PARTNUM (AGE)
GLARE by PEDESTRIAN
GLARE by PEDESTRIAN by AGE
GLARE by PEDESTRIAN by PARTNUM (AGE)
ADAPT by PEDESTRIAN
ADAPT by PEDESTRIAN by AGE
ADAPT by PEDESTRIAN by PARTNUM (AGE)
GLARE by ADAPT by PEDESTRIAN
GLARE by ADAPT by PEDESTRIAN by AGE
GLARE by ADAPT by PEDESTRIAN by PARTNUM (AGE)

A univariate test for normality revealed that the objective data (detection distance) were distributed normally. Therefore, because the distribution was normal the data were run through an analysis of variance (ANOVA).Once the ANOVA had been performed, it was be noted that a significant main effect or interaction effect did not mean that all levels within it were significant. For this reason, a post-hoc analysis was performed to separate out which levels were statistically significant ($p < 0.05$). The analyses that could have been performed were the Student-Newman-Keuls (SNK) and the Bonferroni t (BON) tests. The Bonferroni t test can be used in a situation in which there is an incomplete data set (Winer, 1991). Both of these procedures are valuable because they can pinpoint which level is the cause of the differences.

RESULTS

The results of this study showed significant main effects and interaction effects for both the discomfort glare and disability glare sections (Table 11). The effect of pedestrian location (PEDESTRIAN) and its subsequent interactions was specific to the objective detection task of the Disability Glare portion of this study.

Table 12 Significant Main Effects and Interactions

Source	**Disability Glare** *Detection Distances*	**Discomfort Glare** *deBoer Scale Ratings*
Between		
Age	x	
Participant(Age)		
Within		
Glare	x	x
Glare by Age		
Glare by Participant(Age)		
Adaptation		
Adaptation by Age		
Adaptation by Participant(Age)		
Pedestrian	x	
Pedestrian by Age		
Pedestrian by Participant(Age)		
Glare by Adaptation		
Glare by Adaptation by Age		
Glare by Adaptation by Partipant(Age)		
Pedestrian by Glare	x	
Pedestrian by Glare by Age		
Pede by Glare by Partipant(Age)		
Pedestrian by Adaptation		
Pedestrian by Adaptation by Age		
Pede by Adaptation by Partipant(Age)		
Pedestrian by Glare by Adaptation		
Pedestrian by Glare by Adaptation by Age		
Pedestrian by Glare by Adaptation by Participant(Age)		

x = $p < 0.05$ (significant)

Subjective Measurements

deBoer Scale Ratings

An ANOVA was performed on the subjective measurements (deBoer Scale) recorded during the driving portion of this study. The model for the subjective (Discomfort Glare) portion of this experiment was a 2 (ADAPT) x 5 (GLARE) x 3 (AGE) factorial design. ANOVA summary tables were developed for the dependent measure of the subjective deBoer scale rating (1-9).

The main effect of glare headlamp (GLARE) is significant for the subjective measure of discomfort with ($F_{(4, \infty)} = 14.36$; $p < .05$). The main effect of GLARE included five different sets of headlamps. The glare produced by the "Low/Narrow" halogen headlamp was rated the most discomforting with the lowest mean deBoer scale rating of 5.15. On the other hand the glare produced by the "Medium/Medium" High Intensity Discharge (HID) headlamp was rated the least discomforting with a mean deBoer scale rating of 7.2. All five glare sources and their results may be seen below in Figure 12. The complete ANOVA table for the discomfort glare portion may be seen in Appendix 8.

Figure 12. deBoer Discomfort Ratings for the Main Effect of Glare Source (Scale of 1-9).

Table 13 Student-Newman-Keuls Groupings for Discomfort Glare ratings..

SNK Grouping	*(deBoer)*		*Glare*
C	5.15	60	Low/Narrow
AB	6.77	60	Low/Wide
A	7.20	60	Med/Med
B	6.15	60	High/Narrow
B	6.15	60	High/Wide

A *post-hoc* analysis was performed to determine the specific relationships of each particular headlamp inside the main group (GLARE). The Student Newman Keuls (SNK) procedure revealed three significantly different groupings of detection distance among the five glare sources. The first group A includes two headlamps (Low/Wide and Medium/Medium). The second group B includes three headlamps (High/Narrow, High/Wide and Low/Wide). The third grouping consists of only one headlamp

(Low/Narrow). The mean detection distances and SNK groupings can be seen in Table 12. The bars marked with the same letter are not significantly different.

Objective Measurements

Detection Distance.

An ANOVA was performed on the objective measurement of detection distance taken during the driving portion of this study. The model for the objective (disability glare) portion of this experiment was a 2 (ADAPT) x 2 (PEDESTRIAN) x 5 (GLARE) x 3 (AGE) factorial design. ANOVA summary tables were developed for the dependent measurement of detection distance (Appendix 9). It should be noted that a shorter detection distance suggests more oncoming glare and a longer detection distance may be due to little or no glare.

A total of 599 observations of the objective measurement were gathered during the driving portion of the study with only one missing data point. The results yielded several significant main effects and interactions.

The main effects of glare headlamp (GLARE), pedestrian location (PEDESTRIAN), and age (AGE) were significant ($p < .05$) for the performance measurement of detection distance. The main effect of GLARE had ($F_{(4, \infty)} = 26.89$; $p < .05$) and included five different sets of headlamps. The glare produced by the "Low/Narrow" halogen headlamp afforded the drivers a mean detection distance of 219ft. On the other hand the glare produced by the "Low/Wide" High Intensity Discharge (HID) headlamp allowed a significantly longer detection distance of 362ft. All five glare sources and their results may be seen in Figure 13.

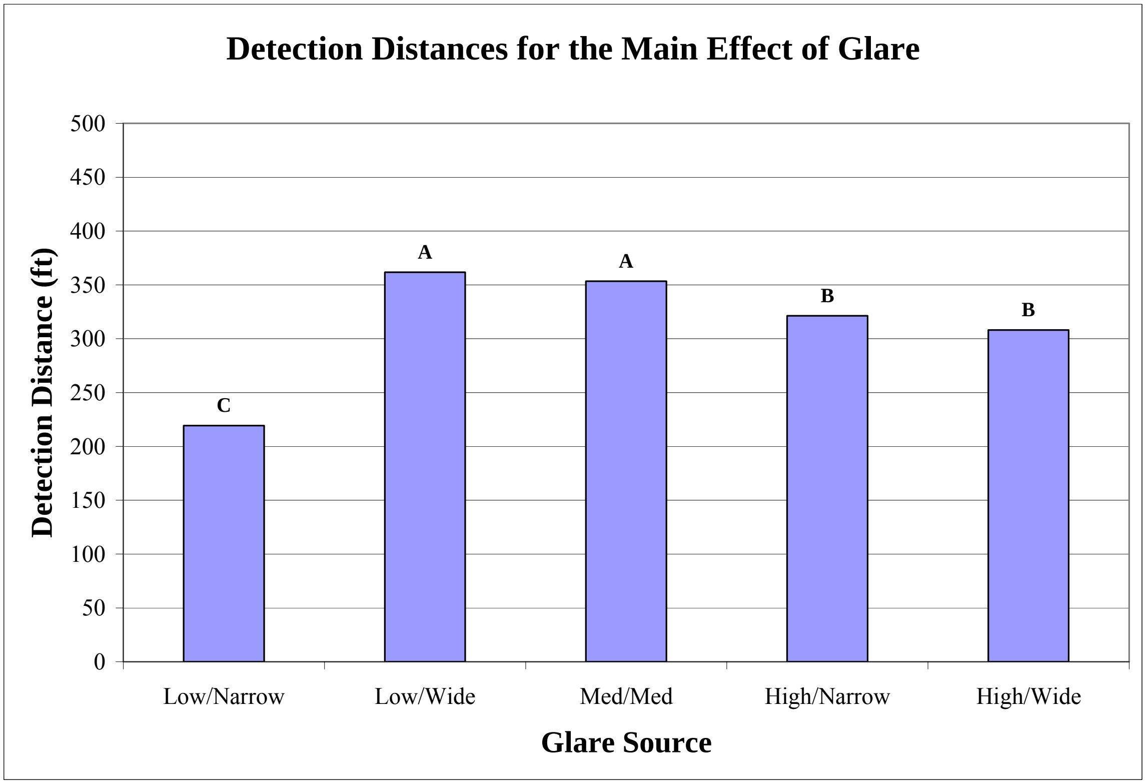


Figure 13 *Mean Detection Distances for the Main Effect of Glare Source with SNK Groupings.*

Table 14 Student-Newman-Keuls Groupings for Glare Source.

SNK Grouping	***Mean (ft)***	***N***	***Glare***
C	219.38	120	Low/Narrow
A	361.66	120	Low/Wide
A	353.51	120	Med/Med
B	321.32	119	High/Narrow
B	308.14	120	High/Wide

A *post-hoc* analysis was performed to determine the specific relationships of each particular headlamp inside the main group (GLARE). The Student Newman Keuls (SNK) procedure revealed three significantly different groupings of detection distance among the five glare sources (Table 13). The first group A includes two headlamps (Low/Wide and Medium/Medium). The second group B includes two headlamps (High/Narrow and High/Wide). The third grouping consists of only one headlamp (Low/Narrow). The mean detection distances and SNK groupings can be seen in Figure

13. The bars marked with the same letter are not significantly different in the figure above.

The main effect of (PEDESTRIAN) has an ($F_{(1, \infty)}$ =86.11; $p < .05$)and included the left and right pedestrian locations. The left pedestrian location yielded a mean detection distance of 222ft. The mean detection distance for the right pedestrian was much further at 403ft. This difference may be seen in Figure 14 below.

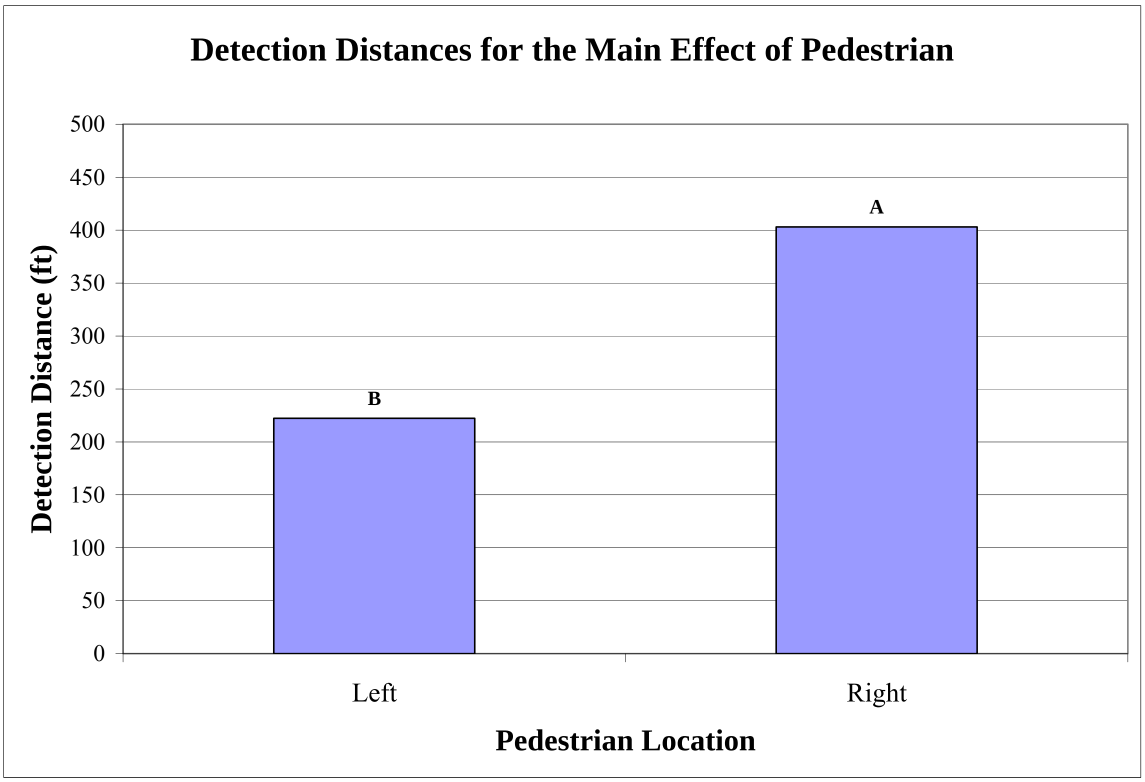


Figure 14. Mean Detection Distances for the Main Effect of Pedestrian Location with SNK Groupings.

Table 15 Student-Newman-Keuls Groupings for Pedestrian Location.

SNK Grouping	***Mean (ft)***	***N***	***Pedestrian***
B	222.31	299	Left
A	402.96	300	Right

A *post-hoc* analysis was performed to determine the specific relationship of both pedestrian locations inside the main group (PEDESTRIAN). The SNK procedure revealed two significantly different groupings of detection distance among the two different pedestrian locations, as seen in Table 14. The first group A includes the detection distances for the right pedestrian. The second group B includes the detection distances for the left pedestrian. The mean detection distances and SNK groupings can be seen in Figure 12 above.

The main effect of AGE results in ($F_{(2, \infty)} = 15.92$; $p < .05$) and has three levels. Young drivers detected the pedestrians with a mean distance of 376ft. The mean distance for middle aged drivers was 313ft and for older drivers the distance fell down to 252ft. As age increased detection distance was significantly decreased. This trend is illustrated in Figure 15.

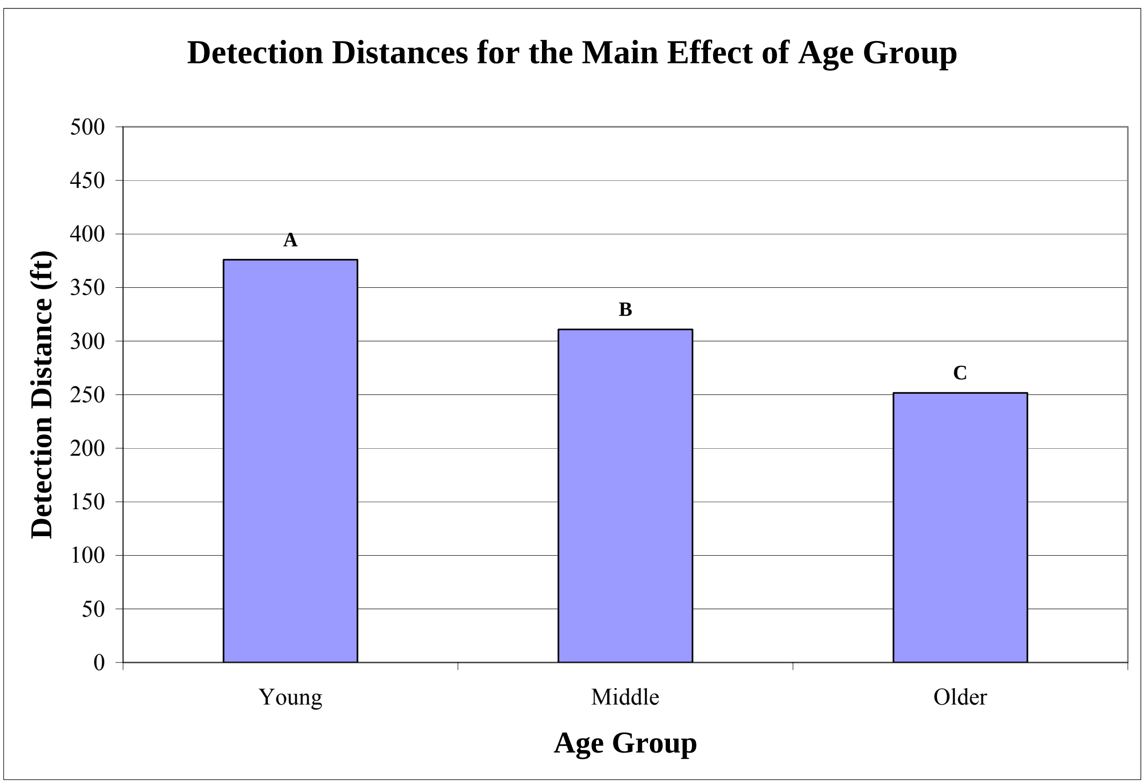


Figure 15. Mean Detection Distances for the Main Effect of Age Group with SNK Groupings.

Table 16 Student-Newman-Keuls Groupings for Age Group.

SNK Grouping	***Mean (ft)***	***N***	***Age***
A	376.01	199	Young
B	310.91	200	Middle
C	251.76	200	Older

Another *post-hoc* analysis was performed to determine the specific relationship of all three participant ages inside the main group (AGE). The SNK procedure revealed three significantly different groupings of detection distance among the three different age levels as seen in Table 15. The first group A includes the detection distances for the young participants. The second group B includes the detection distances for the middle aged participants. The third group C includes detection distances for the older participants. The mean detection distances and SNK groupings can be seen above in Figure 15.

The main effect of driver light adaptation level (ADAPT) was not significant with an ($F_{(1, \infty)}$ =.66; $p < .05$). There were two levels of light adaptation and both were found to have no significant effect on detection distance. The low and high adaptation levels both allowed similar mean detection distances of 309ft and 317ft.

The interaction of pedestrian location and glare headlamp (PEDESTRIAN*GLARE) was significant ($F_{(4, \infty)}$ =10.18; $p < .05$). The left pedestrian was detected in glare produced by the Low/Narrow headlamps at a mean distance of 164ft. This was the shortest distance for this interaction effect. The left pedestrian was detected in glare produced by the Low/Wide headlamps at a mean distance of 265ft. This mean detection distance was over 100ft further than the distance the Low/Narrow halogen headlamps allowed. In addition, the right pedestrian was detected in glare produced by the Low/Narrow headlamps at a mean distance of 275ft whereas the Low/Wide headlamps yielded a mean detection distance of 458ft. Although the distances of detection are different due to the left or right pedestrian location, the differences between glare sources remains the same. These relationships are further illustrated below in Figure 16.

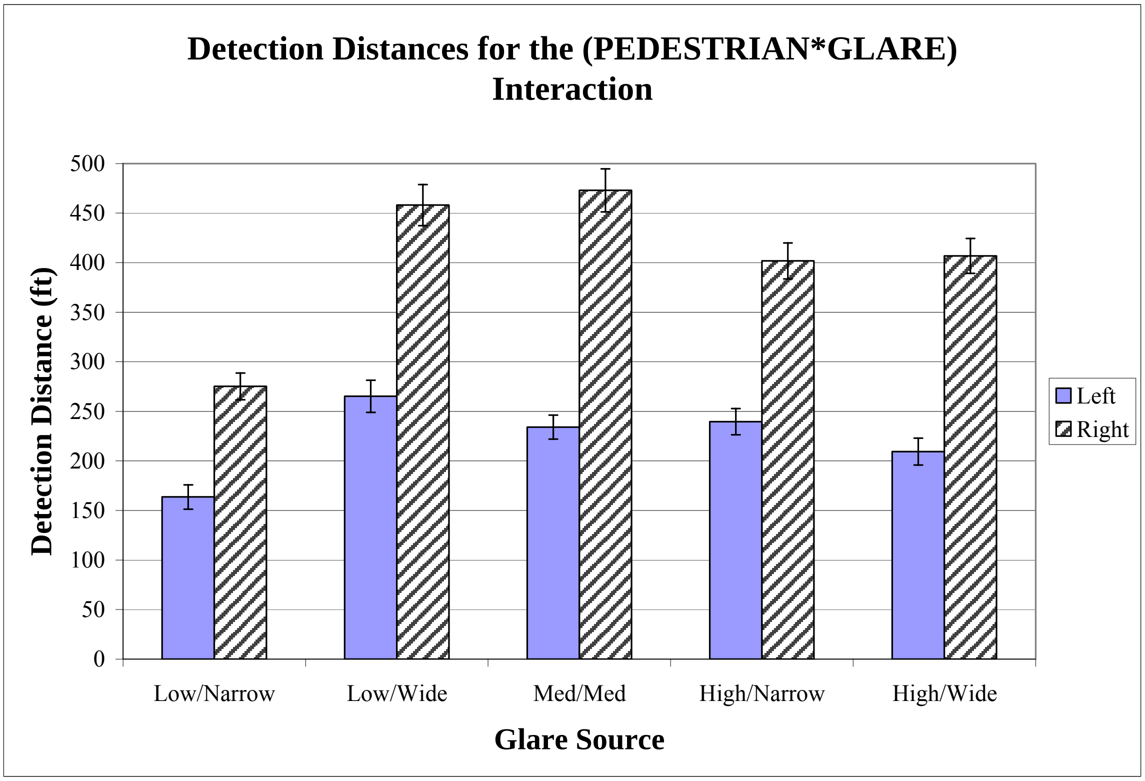


Figure 16. Mean Detection Distances for the Interaction of Pedestrian and Glare.

DISCUSSION

The glare produced by oncoming traffic and the subsequent visibility decrement for drivers at night is a primary concern of transportation research. Different headlamp designs can improve forward visibility but may be reducing the visibility of oncoming drivers. The introduction of High Intensity Discharge (HID) headlamps has increased light output to levels much greater than conventional Halogen headlamps yet the implications of this to glare are still unclear. With so many vehicles using different types of headlamps, whether they are Halogens or HIDs, the goal of this study was to compare a set of categorically different headlamp designs in relation to glare. Glare can be described both subjectively and objectively. This study was therefore separated into the Discomfort Glare portion (subjective) and the Disability Glare portion (objective). A comprehensive evaluation of different headlamp designs with respect to certain driver characteristics such as age and light adaptation would be valuable to designers in mitigating the effects of glare while maximizing driver visibility.

This chapter ties the Disability and Discomfort Glare portions of the study together by looking at each headlamp design with an overall perspective on performance. Furthermore, this section will discuss the research questions which have laid the foundations for this study and how they relate to the focus of this research. These questions include specific factors directly related to oncoming glare associated with nighttime driving due to various types of vehicle headlamp designs.

Answers to the Research Questions

> ***Research Question 1:*** *What effect will different glare sources in terms of intensity/beam distribution (Low/Narrow, Low/Wide, Medium, Medium, High/Narrow, and High/Wide) have on the performance of the disability glare pedestrian detection task?*

Before the specific relationships of each of the five glare headlamps are discussed it is important to determine the overall impact glare had on visibility and therefore the task of detection. In addition, it is not only necessary to look at the differences in detection distance among headlamps under glare conditions but to also compare these detection distances to a baseline or no-glare condition. This comparison would then reflect a difference in performance solely due to glare. The experiment necessary to demonstrate this difference in driver performance would have a similar detection task but with no oncoming glare to disable visibility. In fact, another night visibility study was done at the Virginia Tech Transportation Institute that utilized a similar pedestrian detection task yet with no oncoming glare (Blanco, 2001). The experimental conditions for both studies were very similar. Factors such as driver age groups, participant demographics, experimental roadway, and experimental protocol were all comparable. In addition, both studies used the same experimental vehicle and low profile halogen headlamps (HLB-LP). The previous research used a "Static Pedestrian-High Contrast Clothing" (Blanco, 2002). The static pedestrian in Blanco's study had a mean detection distance using the HLB-LP headlamps of 805.4ft. The static pedestrian could be compared to the right pedestrian in this glare study. The right pedestrian location in this study had a mean detection distance of 402.96ft. It may be concluded that the addition of an oncoming glare source lead to a fifty percent reduction in visibility of the right pedestrian and that disability glare should be an issue of concern. Now that is evident that glare causes a detrimental effect on driver performance, it is vital to determine which lamps are the best and the worst in terms of causing glare. The relationship between glare source and detection distance can be seen in Figure 18. The perspective view in this diagram is also separated in terms of pedestrian location.

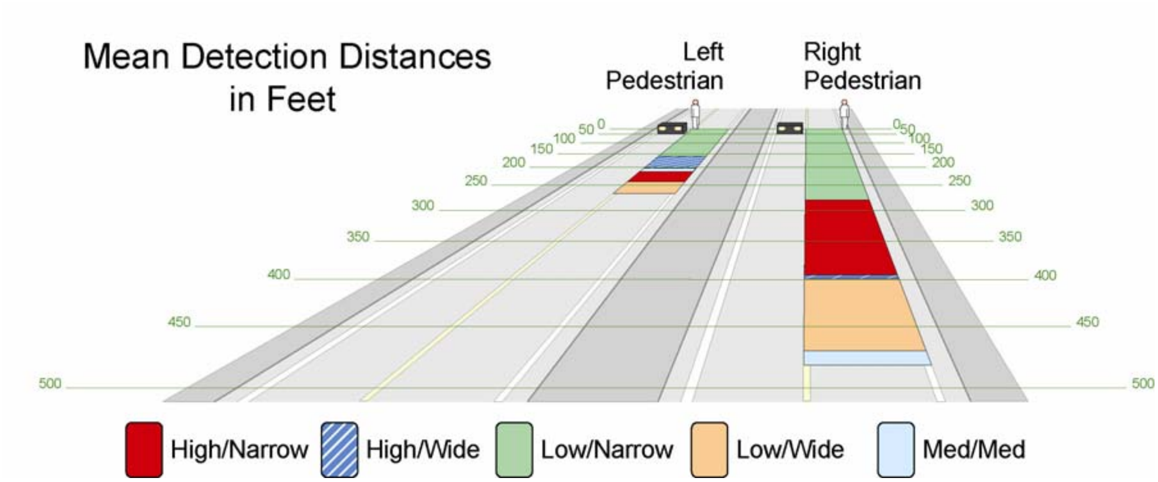


Figure 17. Perspective View of the Mean Detection Distances by Left and Right Pedestrian for All Glare Sources.

There were significant differences among the five different glare sources used in this study in relation to the pedestrian detection task. The Halogen (Low/Narrow) glare source allowed oncoming drivers the shortest mean detection distance among all the lighting designs. In other words, drivers have less time to react and less time to stop when encountering an obstacle while approaching these lamps. In fact, the Halogen headlamp allowed for detections of over 88ft closer to the pedestrian than any other headlamp. The Low/Wide (HID) headlamp allowed a mean detection distance of over 142ft further than the halogen. One explanation for the Low/Narrow halogen lamp yielding shorter detection distances is that it does not have a distinguished pattern and cutoff like the HID headlamps. The halogen beam is emitting light in a less controlled pattern; therefore driving towards this type of beam may be more glaring because of the higher illumination at the driver's eye. On the other hand, a set of HIDs may have a brighter, more distinct hot spot with a precise beam pattern emitting more light onto the roadway surface but not into the oncoming driver's eyes. Studies have shown that although HID headlamps may produce two to three times the brightness of halogen lamps, if properly aimed, these HID's will not produce an increase in glare (Mace, Garvey, Porter Shwab and Adrian, 2001). In fact, it has been found that on straight roads like the test segment used in this study, halogen headlamps may be more glaring. Research performed at the University of Michigan Transportation Research Institute

(UMTRI) suggests that at all inter-vehicle distances on a straight road, illuminance at the driver's eye was significantly lower from HID headlamps than Tungsten-Halogen lamps (Sivak, Flannagan, Scoettle, and Nakata, 2002). Whe comparing the four sets of HID headlamps, the higher output HIDs, both narrow and wide beam pattern, were found to be significantly more glaring than the Low/Wide and Medium/Medium HIDs. This relationship seems to be affected mostly by the intensity or output of the headlamps. Both of the Higher intensity beams had an output of over 40.000cd where as the other lower intensity HID's were no more than 31,000cd.

> ***Research Question 2*** *What effect will different light adaptation levels in terms of ambient lighting environment (Low of 0.15lx and High of 0.45lx) have on the performance of the disability glare pedestrian detection task?*

The two different adaptation levels were set inside the vehicle to determine whether pre-exposure to different light levels would make a driver more or less susceptible to glare. The two levels of driver illumination were 0.15 (Low) and 0.45lx (High). These levels are comparable to the extreme levels of illumination a driver may encounter at night due to different driving lights, interior lights and other changes in ambient lighting. The results of this study showed no significant difference in detection distance for adaptation level. The results revealed mean detection distances of 316.78ft (High) and 308.81ft (Low). Drivers seemed to experience or perceive glare the same whether they were adapted to the low or the high level of illumination. One explanation may be that the difference in illumination at the eye is so great going from a no glare situation into glare that the change in the original level of adaptation is simply too little to make any difference. It has been found in the past that increasing the adaptation level of the driver is one method of mitigating the effects of disability glare (Keck, 1983). The observations made by Keck were in relation to the different adaptation levels produced by driving with and without overhead lighting. The levels of adaptation in this study were not to simulate overhead lighting but were to account for different light levels at the driver's eye due to other factors. These factors include the driver's own headlamp type, overall intensity of the lamps, low and high beams, interior lighting levels, and any other variations in ambient lighting. The differences in adaptation for these variations were a lot smaller than the differences Keck found. It may be that no matter what the original adaptation level was for the driver, the adaptation level achieved by the moment of detection was so great that the difference from Low to High (0.30lx) was insignificant.

> ***Research Question 3:*** *What effect will different pedestrian locations in terms of location in the driving lane (Left and Right) have on the performance of the disability glare pedestrian detection task?*

The two different pedestrian locations were used to evaluate the difference between the right and left sides of the driving lane. As expected, the right pedestrian location yielded a detection distance of almost twice the left pedestrian location. One reason for this large disparity is the different angle of incidence as the driver approaches the glare source. The left pedestrian is slightly to the right of the glare source. In fact, from the starting distance of 1000ft, the left pedestrian is in the same line of sight as the approaching glare source's left headlamp. The right pedestrian is 12ft to the right on the other side of the driving lane and out of the direct line of sight of the glare source. The differences in detection distance by headlamp and pedestrian location can be seen in Figure 19 below.

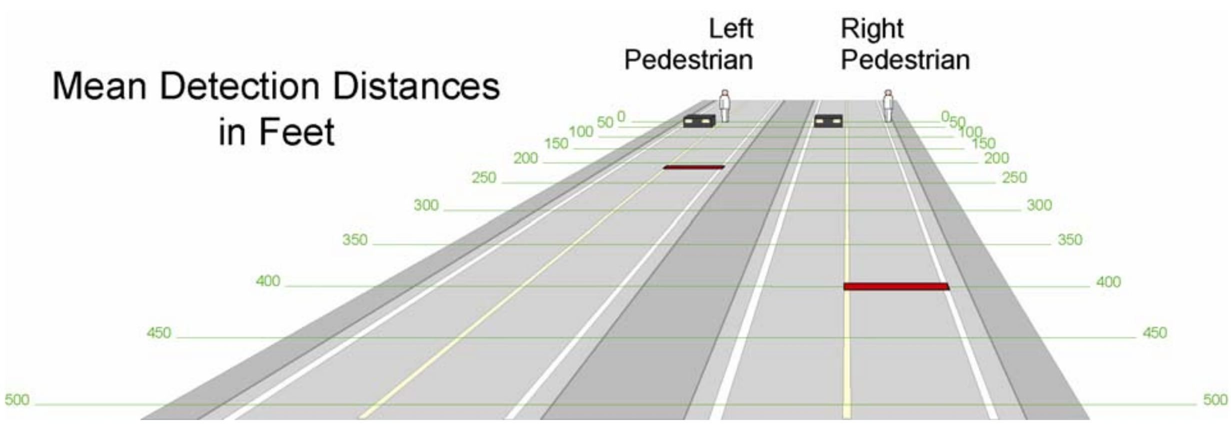


Figure 18. Perspective View of the Mean Detection Distances by Left and Right Pedestrian Locations.

Research Question 4: *What effect will different age levels (Young 18-25 years, Middle 40-50 years and Older 65+ years) have on the performance of the disability glare pedestrian detection task?*

Multiple age groups of participants were used to understand the effect age has on a driver's visibility and performance in relation to oncoming glare. There were significant differences in the mean pedestrian detection distance for the three age groups. As the participant age became greater the mean detection distance became shorter and shorter.

The pedestrian detection task has many physiological mechanisms working that are important in driver performance. As mentioned earlier, driving a vehicle is primarily a visual task (Alexander and Lunenfeld, 1990). The perception and reaction to necessary visual information is even more important when driving on dark roadways at night with glare from oncoming vehicles. One crucial aspect of visibility in this difficult situation is the ability to not only track the course of the road but also to detect unforeseen obstacles in the vehicle's path. It has been found that age can not only deteriorate visual acuity but can increase sensitivity to glare (Scheiber, 1994). This may be one of the main reasons for the incrementally decreasing detection distances as age increases from Young, to Middle aged and then to Older individuals. Many older drivers scored well on the visual acuity tests but then were found to be more sensitive to glare than younger drivers.

Research Question 5: *What effect will different glare sources in terms of intensity/beam distribution (Low/Narrow, Low/Wide, Medium, Medium, High/Narrow, and High/Wide) have on the perception of discomfort glare?*

The five sets of glare headlamps not only significantly affected driver performance but were also perceived differently in terms of discomfort to the driver's eye. The subjective deBoer scale was used to determine how driver comfort levels were influenced by the five glare sources. As mentioned in the first chapter, past research has demonstrated a subjective preference for viewing halogen headlamps over HID's (Flannagan, 1999).

The increased brightness and bluish white tint to the HID glare sources was perceived to be more discomforting than conventional halogen lamps. Yet, in this study, participants found the glare from the halogen (Low/Narrow) beam to be the most discomforting. These results match the objective detection distance results because the halogen beam also had the shortest detection distance. The ratings of discomfort are an overall rating as the glare sources are approached. The dynamic aspect (i.e. moving vehicle on real roadway) of this particular study may have been one of the reasons for these different findings. The headlamps were evaluated while the angle of incidence continued to change. If the halogens with a less confined beam pattern continued to appear bright throughout the approach, then might have been viewed as more glaring overall. The second level of discomfort was represented by the two higher intensity HID's. The fact that intensity level mostly determined discomfort level for all four HID's demonstrated the drivers' ability to identify the incremental differences between each lamp. This relationship between maximum output of the glare source and perceived discomfort is further illustrated in figure 20.

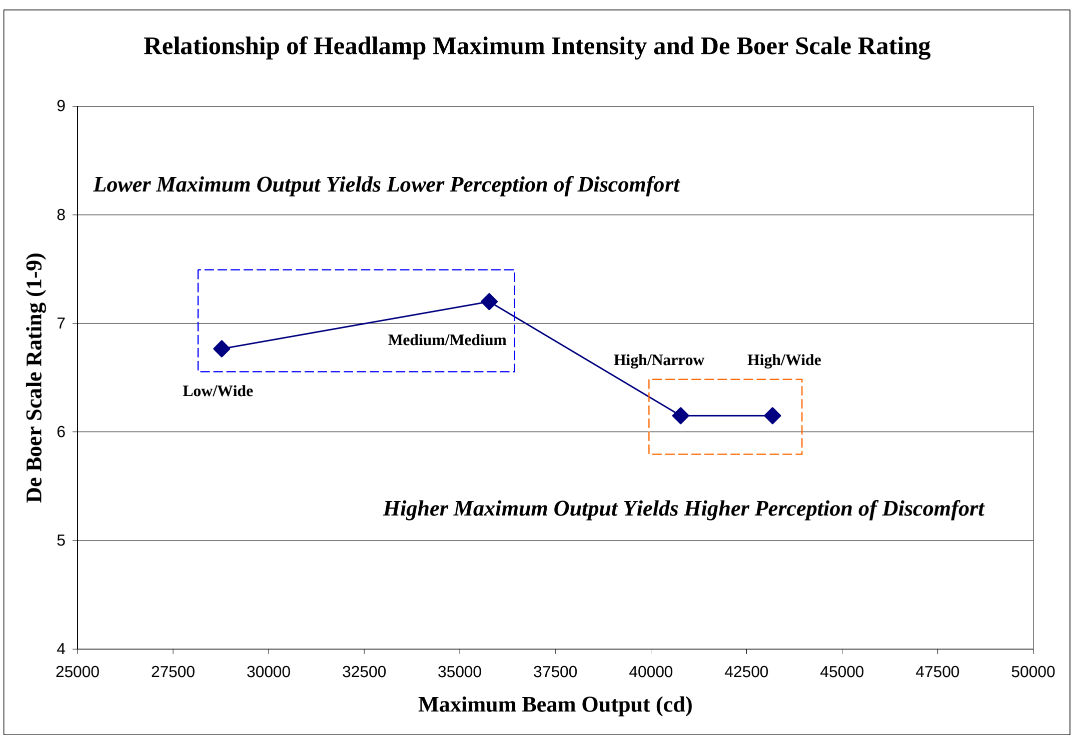


Figure 19. The relationship between headlamp intensity and perceived glare.

Research Question 6: *What effect will different light adaptation levels in terms of ambient lighting environment (Low of 0.15lx and High of 0.45lx) have on the perception of discomfort glare?*

Each discomfort glare rating was performed under both the low and high adaptation levels. There was no significant difference of perceived glare due to adaptation level. One reason for there being no difference may have been because participants were essentially evaluating the addition of a glare source to their current adaptive state. Therefore, whether the adaptation level was low or high to begin with they still perceived the same difference in glare due to the headlamps. Another reason for there not being an effect due to adaptation is the fact that the glare from the headlamps may outweigh the difference in illumination from the adaptation source. As the driver approaches the glare, illumination levels rise to anywhere from 1.5 to 2.5 lux. These levels are much higher and may be perceived as much brighter than the adaptation sources.

Research Question 7: *What effect will different age levels (Young 18-25 years, Middle 40-50 years and Older 65+ years) have on the perception of discomfort glare?*

The three age groups of drivers in this study had no significant differences in discomfort due to the glare sources. In general, no matter what the age of the driver their perception of the glare sources remained basically the same. These findings suggest that age may influence certain performance factors (e.g. object detection) due to changes in physiology but does not have an effect on subjective discomfort ratings. One important physiological measure in this study was visual acuity. Multiple vision tests were administered before each experiment to document the participants' visual characteristics. As mentioned in chapter two, visual acuity is gradually degraded with age (Marottoli, Ostfeld, Merrill, Perlman, Foley, and Cooney, 1993). An acute sense of vision may allow for greater detection distances but may not affect subjective ratings of discomfort. Another measure of visual acuity used in this study was an individual's sensitivity to glare. Older drivers are not only more limited with visual acuity but may be more sensitive to glare. An individual may have perfect visual acuity but then the exposure to glare may reduce their ability to see. The BAT glare sensitivity tester (Brightness Acuity Tester) used in this study measures the decrement in acuity caused by increasingly brighter glare sources. An increase in sensitivity would be represented by a decrease in visual acuity (Snellan eye chart). For this particular test it is unknown whether an increase in sensitivity would be represented by an increase in discomfort. It may be gathered that a raised sensitivity to glare can lower detection distances but it is unknown whether it alters the subjective feeling of discomfort. If declining visual acuity and glare sensitivity only affects object detection then there would be no expected age effect for discomfort glare ratings.

Limitations of the Study

There are several limitations to this study that need to be considered:

Glare Headlamps

There are many types of halogen and HID headlamps used on today's roadways. Various headlamp designs have different and unique characteristics including intensity level, gradient or cutoff, and spectral power distribution. The glare sources used in this particular study are just a sample of all the available headlamps on the market. Therefore, certain generalizations about the performance of these particular halogen and HID designs compared to others may not be accurate.

Participant Training

The drivers used in this study were put through multiple training sessions before completing the experimental tasks. In the Disability Glare portion of the study the participants were familiar with the pedestrian types and roadway before beginning. Participants were also expecting pedestrians in the road and were therefore looking more attentively. Some of the results may have differed if unexpected or surprise objects and pedestrians could have been introduced. In general, results from this portion of the study may not fully represent a real world nighttime driving situation in which obstacles in the road need to be detected. Drivers were also trained before the Discomfort Glare portion of the study. The glare may have been rated differently if participants were not solely concentrating on the task of rating the glare.

Differences in Vision

Participants within the same age group had different visual acuity characteristics. The groups were not balanced in terms of Snellan acuity and Contrast Sensitivity. Controlling for these visual characteristics in future studies may further our understanding of night visibility. This may be especially true in learning more about aging effects related to glare.

Illuminance Measurements

The illuminance measurements recorded during the discomfort and disability glare tasks were taken in an effort to replicate the illuminance at the driver’s eye. The illuminance meter was mounted facing straight forward in the direction of the vehicle’s travel. The illuminance meter is therefore not accounting for driver head and eye movements. As drivers approach the oncoming glare they may divert their gaze to avoid looking directly into the light source. After analyzing the in-vehicle videos for eye and head movements, it is apparent that some drivers look away from the glare more than others. It was found that approximately one in three participants moved their eyes and adjusted their head position as they approached the glare. The eye movements were mostly glances down or to the right side and increased as the glare became closer. Some drivers adjusted their head position either down or to the right in attempt to mitigate the effects of the glare as they approached. The remaining drivers had a fixed eye and head position throughout the detection task and were looking straight ahead. One of the reasons drivers may have been staring straight ahead more than they normally would is because they were in a searching mode. The participants, during the disability glare portion, were primed of the pedestrians and were diligently fixating on the road ahead in order to detect the object. Overall, after video analysis, it appears that the illuminance measurements taken during the detection tasks may not fully represent the light reaching the eye, and that driver behavior affects their level of glare.

Glare Sensitivity

Many participants with similar visual acuity scores had differing sensitivities to glare. Although glare sensitivity was not controlled the vision test results revealed that no participant had a severe (Table 4) change in acuity due to light exposure. Controlling for glare sensitivity may in future studies help researchers better understand the objective and subjective effects of glare and the different mechanisms involved.

Experimental Protocol

The glare headlamps were stationary in this experiment to increase the safety and the accuracy of data collection. A dynamic glare source would change the angle of approach and also the contrast of the pedestrian. These factors would cause the driver to have different detection distances than if the glare source was static. In addition, for the same reasons, the experimental vehicle was only traveling at a speed of 20mph. The results may have been different if both vehicles were dynamic and at higher speeds.

CONCLUSIONS

The primary focus of this research effort was to evaluate the discomfort and disability glare associated with different sets of oncoming headlamps and their associated beam distributions and intensities including conventional halogen beams as well as newer HID designs. The visual performance portion of the study evaluated each headlamp in its ability to allow oncoming drivers to detect different pedestrians in the roadway. This portion is simply determining what physical effect these lights have on visibility measured by detection distances. The subjective portion of the study included drivers making discomfort ratings (deBoer, 1967) while approaching each of the five sets of headlamps. This portion of the study was to better understand how drivers subjectively perceive the newer HID headlamps compared to a more conventional beam. The data from the two portions of this research effort were compared to se whether or not a relationship existed between detection distance and the perception of glare. Although initial findings revealed that overall, the most discomforting (i.e. Low/Narrow) headlamp also yielded the shortest detection distances, there was no significant relationship to be able to correlate the detection distance and discomfort ratings. Overall, this study was an empirical breakdown of four categorically different HID headlamp designs and one halogen beam on their ability to mitigate oncoming glare.

Many issues have been raised with the introduction of HID headlamps onto the roadways with their higher intensity bulbs and their unique and/or discomforting appearance. Drivers state that passing these HID lights on the roads at night is not only irritating and discomforting but also unsafe. Although it is important to understand the implications of discomfort glare on roadways at night, disability glare is the bigger issue related to safety. Again, disability glare is the visibility decrement or reduction in contrast of objects on the road due to a veiling luminance in the ocular media of the eye. The disabling effects from such glare can not only hinder but can also eliminate the ability of drivers to detect obstacles (i.e. pedestrians) in the vehicle's path.

One of the main safety concerns when dealing with disability glare and its effects on driver performance is the significant reduction in detection distances caused by the lower visibility. Although detection distance is a good way to compare different sets of headlamps in terms of their associated oncoming glare, this measure does not give an on-road performance scenario. Therefore, to apply these findings to natural nighttime driving settings, the measure of detection distance can be directly applied to stopping distances. Stopping distances are calculated by considering brake force or acceleration, roadway surface and its coefficient of friction and reaction time of the driver. It has been found that on normal roadway conditions a driver can come to a complete stop from a speed of 35mph when there is an unexpected obstacle in 174.8 ft (Blanco, 2002). It was found in this study that when approaching glare form the Low/Narrow headlamp the mean detection distance for a left pedestrian was 164ft. Therefore, a driver traveling at 35mph approaching the Low/Narrow headlamps would not have enough time to react and stop for a pedestrian in the center of the road. The driver would have even less time to react and stop if the pedestrian or obstacle was not a high reflectance (40%) object. In addition, at highway speeds of 65 mph the stopping distance for drivers on normal roads increases to 398.7ft (Blanco, 2002). At this distance, not one of the glare sources tested would afford drivers enough time to detect, react and stop for an object in the center of the road. In fact, the Low/Narrow glare source would also disable drivers to the point at which they could not stop for the right pedestrian with a mean detection of 275ft. These examples of the decrement in detection distance and stopping distance caused by oncoming glare demonstrate how dangerous nighttime driving can truly be. Glare can not only cause drivers discomfort on roadways at night but can also disable them to the point in which in many cases a collision is inevitable and unfortunately unavoidable.

Few studies have been performed that evaluate the disability glare from various HID headlamps in a dynamic nighttime driving situation. There are still many questions to be answered concerning glare related to HID headlamps as well as other new types of vehicle lighting. This study can be used as a guideline to help further the research effort in an attempt to maximize forward visibility while minimizing glare on the roads at night. The findings in this study reflect the fact that certain halogen headlamp designs as well as newer HID models produce enough glare to have serious highway safety implications. In fact, glare from oncoming vehicles can significantly reduce visibility even when pedestrian are dressed in light (high reflectance) clothing. These findings contradict previous work that states that "higher reflectance targets (40%) are not significantly affected by headlamp glare even up to 5 lx at the eye (Van Derlofske, Bullough, Dee, Chen and Akashi, 2004). In contrast, this study found significant differences in detection distance with pedestrians in the right and left pedestrian locations as well as at driver's eye illuminance readings less than 5lx. Therefore, new headlamp designs must be evaluated in terms of disability glare in relation to other oncoming vehicles before they are implemented into new automobiles.

In addition, the relationship between age and glare sensitivity needs to be investigated further to determine the potential deleterious effects on older drivers over the age of 65. The mental and physiological aspects of driving a vehicle may be exaggerated at night especially with the addition of oncoming glare. The mechanisms involved need to be understood before a solution to the problem can be presented.

One of the most interesting findings was performance of the Low/Narrow halogen beam in both portions of the study. This particular halogen beam was used in previous night visibility studies in comparison with an HID headlamp and was found to outperform it in the object detection and recognition tasks (Blanco, 2002). It was therefore known that this particular headlamp was higher in output for a halogen design but when comparing maximum intensities to other HID's for this study it was categorized as a low intensity light. The halogen headlamp performed the worst behind all four HID's in the disability glare study allowing significantly shorter detection distances to oncoming drivers. In addition, the halogen beam was rated the most discomforting out of all five headlamps. The fact that the headlamp with lowest rated intensity level produced the highest level of glare raises certain interesting questions. One main issue is that beam pattern may be just as important in determining the perception of "brightness" of an oncoming headlamp as luminous output. Having a more powerful, higher intensity light with a precisely controlled pattern may be less glaring than a lower powered headlamp with little or no pattern distinction.

Design Guidelines

The following guidelines were created due to the results of this study and are recommended for future consideration:

Designing an HID headlamp with no more than low to medium output (25,000-30,000cd) may mitigate the reduction in visibility due to glare.

Designing an HID with a higher intensity (40,000-50,000cd) may increase oncoming drivers' perception of discomfort and also reduce visibility.

Practical Implications

Several relevant implications surface from this research effort. For one, technical societies along with various lighting commissions must be aware of emerging technology and stay one step ahead. Certain regulations on new lighting designs may help reduce the problems associated with the glare from new products. Secondly, testing a new lighting product in terms of its forward visibility as well as its subsequent potential for glare before it is put in to production vehicles is very important. Realizing a problem with glare in preliminary testing may be easier than receiving complaints from other drivers on the road after the new technology has been implemented. Another implication is that new headlamps, such as HID's, should be standardized in an effort to maximize driver visibility while reducing glare. Currently there are so many variations of HID's that no two designs seem to appear the same. The intensities and beam patterns of these lights are all different and each has its particular distribution. In addition, with age having such an effect in this study on the perception of glare and night visibility in general, a more proactive visual acuity testing program may be needed. Aging drivers should be required to undergo periodic visual acuity and glare sensitivity testing to ensure they are safe on the roads at night. Current testing may not reveal vision problems that could exaggerate the effects of glare.

Future Research

Several avenues for future research concerning glare and night visibility exist. As technology continues to improve in the area of automotive lighting, human factors research must keep up with the changing designs and ensure the newest headlamps are not only more efficient and stylish but also provide better visibility and less glare. Certain technologies such as High Output Halogens (HOH's) and Light Emitting Diodes (LED's) are making there way into the market in other lighting applications and may soon be introduced as a headlamp alternative into production automobiles. A more comprehensive evaluation of multiple types of automotive lighting technology and various nighttime driving scenarios may be necessary to understand the overall effects of glare. The lighting situation inside the vehicle, especially at the driver's eye needs further research to determine the relationship between illuminance levels at the eye and performance of detection tasks. It would also be interesting to evaluate the relationship between the amount of light reaching the driver's eye and the associated subjective deBoer scale rating. In addition, different roadway materials and roadway infrastructure characteristics may increase or decrease the perception of glare. For instance, high barriers on busy interstates reduce the effects of glare so there may be certain design implications for lighting and roadway engineers. In addition, overhead lighting may affect the perception of glare from different headlamps in various ways. A study that could test the interaction of both overhead lighting and new automotive lighting designs may be beneficial in further understanding the mechanisms behind glare.

Summary

This study demonstrates the importance of understanding the implications of glare when designing automotive headlamps. In order to keep drivers satisfied headlamps must not appear too bright and discomforting to approaching vehicles. Lights with very high intensities can not only be aggravating but also a distraction to other vehicles. Certain headlamps, whether they are HID's or halogens have the ability to severely reduce forward visibility of an oncoming driver. The halogen headlamp (Low/Narrow) and the two higher intensity HID's (High/Wide and High/Narrow) used in this study have several detection distances so low that pedestrian safety becomes a real concern. These headlamps were also rated the lowest on the deBoer scale for being the most discomforting. Age is also another factor that significantly reduced detection distances. In fact, older participants were on average almost 125ft closer to the pedestrians at detection than younger drivers. Although age affected visibility it seemed to have no influence on the perception of glare. As expected, pedestrian location also drastically affected detection distances. Pedestrians on the right shoulder of the road were detected almost double the distance away from the vehicle as pedestrians on the left side of the lane.

In general, certain attributes of automotive headlamps including luminous output and beam pattern can significantly affect an oncoming driver's comfort level and visibility. Nighttime visibility is particularly important in the safety of vehicle drivers and passengers as well as non-motorists on poorly lit roadways. Understanding the effects of glare on overall driver performance and therefore designing vehicles to accommodate certain visual capabilities and restrictions is imperative in order to increase safety.

APPENDIX 1

Screening Questionnaire

Name ____ Male / Female
Phone Numbers (Home) __________________________ (Work)
____
Best Time to Call ____
Best Days to Participate_____________________

DRIVER SCREENING AND DEMOGRAPHIC QUESTIONNAIRE: ENV-DISABILITY GLARE

Note to Screening Personnel:

Initial contact with the potential participants will take place over the phone. Read the following Introductory Statement, followed by the questionnaire (if they agree to participate). Regardless of how contact is made, this questionnaire must be administered before a decision is made regarding suitability for this study.

Introductory Statement (Use the following script as a guideline in the screening interview):

My name is _____ and I work at the Virginia Tech Transportation Institute in Blacksburg, VA. I'm recruiting drivers for a study to evaluate new night vision enhancement systems for vehicles.

This study will involve you driving different vehicles instrumented with data collection equipment on <u>the Smart Road at</u> night and filling out questionnaires. Participants will come in for <u>one driving session that will last approximately 3 hours</u>. We will pay you <u>$20 per hour</u>. Would you like to participate in this study?

If they agree:

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

If they do not agree:

Thanks for your time. Would you like me to remove you from the database?

****

Questions

Do you have a valid driver's license?

Yes _____ No _____

How often do you drive each week?

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

How old are you? ______

What is your date of birth? __________

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

Yes ____Description:____

No _____

How long have you held your drivers' license? ________________________________

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

Yes _____ No _____

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

Yes _____ ____

No _____

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

Yes _____ ____

No _____

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__________________________________

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

Yes _____ ____

No _____

(Females only) Are you currently pregnant?

Yes _____ No _____

(If "yes" then read the following statement to the subject: "*It is not recommended that pregnant women participate in this study. However, female subjects who are pregnant and wish to participate must first consult with their personal physician for advice and guidance regarding participation in a study where risks, although minimal, include the possibility of collision and airbag deployment.*"

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

Yes _____

____

No _____

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

Yes _____

No _____

****

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 the last 12 months, lingering effects from respiratory disorders, motion***

sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.

9. ***Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).***
10. ***No history of radial keratotomy, LASIK eye surgery, or any other ophthalmic surgeries.***

****

Accepted: ________

Rejected: ________   Reason: ____

Screening Personnel (print name):______________________   (Date):________

APPENDIX 2

Informed Consent Form

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

Title of the Project:

Nighttime Driving Evaluation of the Effects of Disability and Discomfort Glare from Various Headlamp Designs under Low and High Light Adaptation Levels

Investigators: **Jonathan M. Hankey, Ronald B. Gibbons and Jason Clark**

The Purpose of the Research
The purpose of this study is to objectively identify the levels of discomfort and disability glare produced by various oncoming headlamps under two levels of light adaptation.

Procedures
During the course of this experiment you will be asked to perform the following tasks:

Read and sign an Informed Consent Form.
Show a current driver's license.
Complete four vision tests.
Drive a vehicle on the Smart Road at 20 miles per hour, and notify the experimenter when you can detect and identify different objects along the roadway.
Complete questionnaires
Listen to the instructions regarding any tasks you may perform.

It is important for you to understand that we are evaluating the technology, not you. Any tasks you perform, mistakes you make, or opinions you have will only help us do a better job of designing these systems. Therefore, we ask that you perform to the best of your abilities. The information and feedback that you provide is very important to this project.

Risks

There are risks or discomforts to which you are exposed in volunteering for this research. They include the following:

The risk of an accident normally associated with driving an unfamiliar automobile at 20 miles per hour or less, on straight and slightly curved roadways in clear conditions.
Possible fatigue due to the length of the experiment. However, you will be given the option to take breaks when you choose.
Possible discomfort associated with driving at night in the presence of normal glare similar to that of an approaching vehicle.
The following precautions will be taken to ensure minimal risk to you.

The in-vehicle experimenter will monitor your driving and will ask you to stop if he/she feels the risks are too great to continue. However, as long as you are driving the research vehicle, it remains your responsibility to drive in a safe, legal manner.
You will be required to wear the lap and shoulder belt restraint system while in the car. The vehicle is also equipped with a driver's side and passenger's side airbag supplemental restraint system.
The Smart Road test track is equipped with guardrails to prevent vehicles from slipping off the road.
The vehicle is equipped with a fire extinguisher and first-aid kit, which may be used in an emergency.
If an accident does occur, the experimenters will arrange medical transportation to a nearby hospital emergency room. You will be required to undergo examination by medical personnel in the emergency room.
All data collection equipment is mounted such that, to the greatest extent possible, it does not pose a hazard to you in any foreseeable situation.
None of the data collection equipment or the display technology interferes with any part of your normal field of view in the automobile.
The in-vehicle experimenters are aware of the location of other work vehicles on the road, and maintain radio contact with each other.
If you are pregnant, you have reviewed this consent form with your obstetrician and discussed the risks of participating in this study with him/her. You are willing to accept all possible risks of participation.
You do not have any medical condition that would put you at a greater risk, including but not restricted to epilepsy, balance disorders, and lingering effects of head injuries or stroke.

In the event of an accident or injury in an automobile, the automobile liability coverage for property damage and personal injury is provided. The total policy amount per occurrence is $2,000,000. This coverage (unless the other party was at fault, which would mean all expense would go to the insurer of the other party's vehicle) would apply in case of an accident for all volunteers and would cover medical expenses up to the policy limit.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation; under Commonwealth of Virginia law, worker's compensation does not apply to volunteers; therefore, if not in an automobile, the participants are responsible for their own medical insurance for bodily injury. Appropriate health insurance is strongly recommended to cover these types of expenses.

IV. Benefits of this Project

There are no direct benefits to you from this research other than payment for participation. No promise or guarantee of benefits will be made to encourage you to participate. Subject participation may have a significant impact on future night vision systems.

V. Extent of Anonymity and Confidentiality

The data gathered in this experiment will be treated with confidentiality. Shortly after participation, 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. 1). You will be allowed to see your data and withdraw the data from the study if you so desire, but you must inform the experimenters immediately of this decision so that the data may be promptly removed. At no time will the researchers release the results of this study to anyone other than the client and individuals working on the project without your written consent. The client has requested that the video, including your eye movement data and image, be given to them when the study is completed. They would only use the video for research purposes. VTTI will not turn over the video of your image to the client without your permission.

VI. Compensation

You will receive $20.00 per hour for your participation in this study. This payment will be made to you at the end of your voluntary participation in this study. If you choose to withdraw before completing all scheduled experimental conditions, you will be compensated for the portion of time of the study for which you participated.

VII. Freedom to Withdraw

As a participant in this research, you are free to withdraw at any time for any reason. 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 questions or respond to any research situations without penalty.

VIII. Approval of Research

This research has been 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.

X. Participant's Responsibilities

If you voluntarily agree to participate in the study, you will have the following responsibilities: To be physically free from any substances (alcohol, drugs, etc.) that might impair your ability to drive for 24 hours prior to the experiment, and to conform to the laws and regulations of driving.

Participant's Permission
Check one of the following:

VTTI **has my permission** to give the videotape including my image to the client who has sponsored this research. I understand that the client will only use the videotape for research purposes.

VTTI **does not have my permission** to give the videotape including my image to the client who has sponsored this research. I understand that VTTI will maintain possession of the videotape, and that it will only be used for research purposes.

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 understand that I may withdraw at any time without penalty. I agree to abide by the rules of this project.

____ ________________________

Participant's Signature Date

Should I have any questions about this research or its conduct, I may contact:
Jon Hankey (540) 231-1500
Jason Clark (540) 231-1500
David Moore, Chair, IRB (540) 231-4991

______________________________________ ________________________
Experimenter's Signature Date

APPENDIX 3

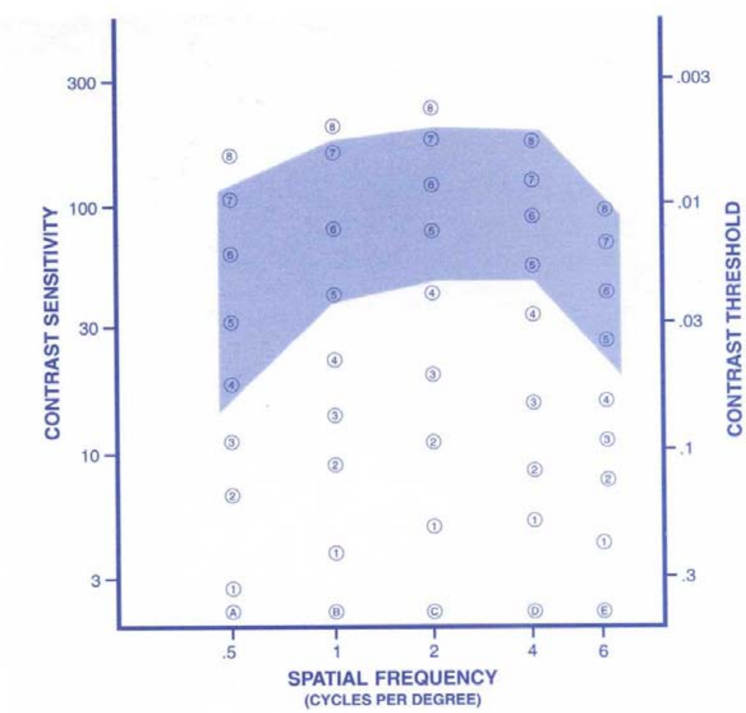
Vision Test Form
ENV-Disability Glare

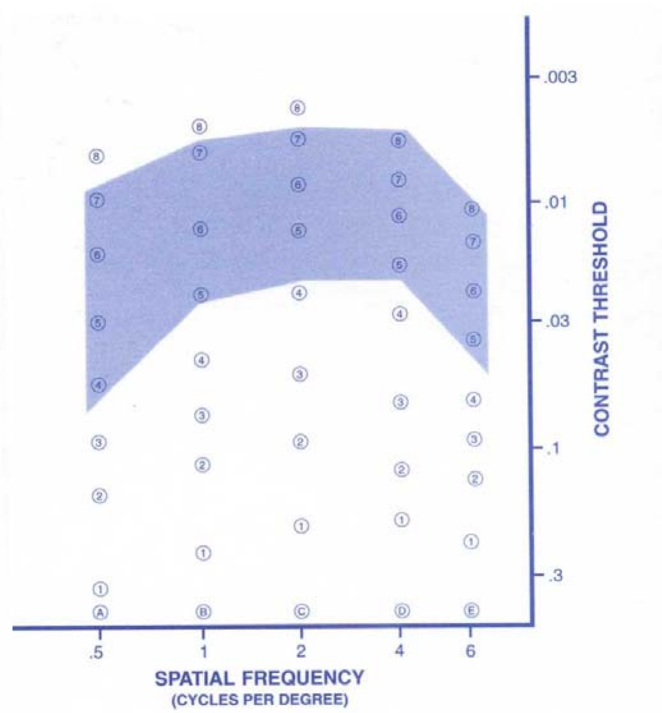
I – Acuity Test

- **Acuity Score:________**

II – Contrast Sensitivity Test

Left **Right**





III – Color Blind Test

1_____ **4_______** **7_______**
2_____ **5_______**
3_____ **6_______**

IV Brightness Acuity Tester (BAT)

- **Acuity Score:**

  Left Off ______ Low ____Med ____High _____

  Right Off ______ Low ____Med _____High ____

V Standing Height ________+ 20 inches

____

APPENDIX 4

<u>Glare Headlamps</u>

HID 1 2001 Mercedes-Benz E320

This system makes use of a complex multi-reflector lens to focus the beam pattern created by the HID light source. The intensity of this beam is relatively low when compared to other recent headlamp designs. This means that when compared to other lamps using isocandela diagrams this design put out lower levels of light at specific points on the road. In addition to a bright light source, the beam pattern on this particular headlamp is quite narrow, meaning that much of the available light is directed more towards the center of the roadway and not as much to the periphery or the side of the roadway.

Figure 20. Front view of E320 HID (High/Narrow).

HID 2 2003 Lincoln Navigator

This system also makes use of a complex multi-reflector lens to focus the beam pattern created by the HID light source. The intensity of this beam is again relatively high when compared to other recent headlamp designs. The beam pattern on this particular headlamp would be considered to be fairly wide. A wide beam pattern not only directs light in the center of the roadway but also a considerable amount to the periphery or the side of the roadway.

Figure 21. Front view of Navigator HID (High/Wide).

HID 3 2001 Mercedes-Benz S500

This system again makes use of a complex multi-reflector lens to focus the beam pattern created by the HID light source. The intensity of this beam is relatively high when compared to other headlamps according to the different isocandela diagrams. The pattern of the beam of this lamp is wider than most others.

Figure 22. Front view of S500 HID (Low/Wide).

HID 4 2003 Nissan Altima

Like all the others this system focuses its light output with a multi-reflector lens. The intensity of this headlamp when compared to the others was in the middle-range. The beam width was also average when compared to the other designs.

Figure 23. Front view of Altima HID (Medium/Medium).

Halogen 1999 Ford Explorer

This beam is a conventional beam that that has intensity characteristics to be relatively low than the average halogen beams. The width of this beam can be seen as fairly narrow and similar to other halogens.

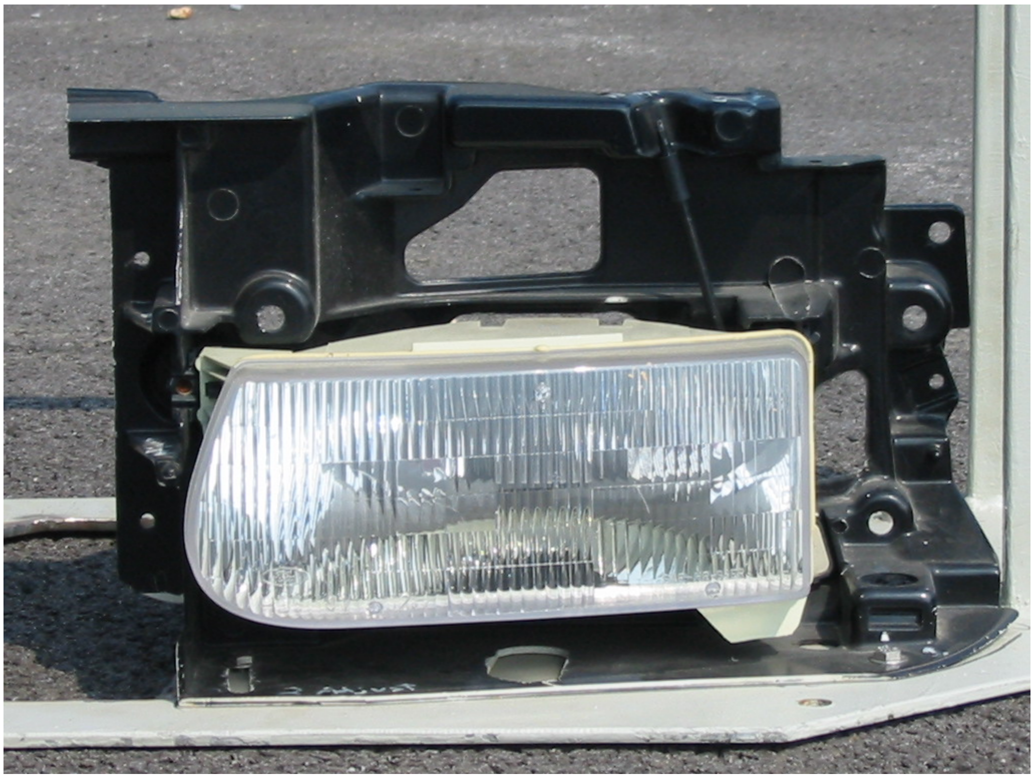
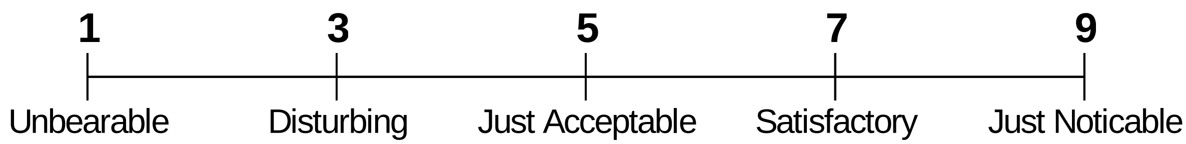


Figure 24. Front view of Explorer Halogen headlamp (Low/Narrow).

APPENDIX 5

Discomfort Glare Rating

Please rate the glare you experienced from the oncoming headlights using the following scale:



APPENDIX 6

Pre Drive Questionnaire

ENV-Disability Glare Pre-Drive Questionnaire

---

1. **Please indicate approximately how often you drive at night *(Please check only one)***
   - O Every night
   - O Three times per week
   - O Once per week
   - O Less often that one time per week

2. **When driving at night, do you mostly wear … *(Please check only one)***
   - O Single vision eyeglasses
   - O Bifocal eyeglasses
   - O Trifocal eyeglasses
   - O Contact lenses
   - O Do not wear corrective lenses when driving

3. **Would you say you drive at night with: *(Please circle only one)***

no difficulty	***little difficulty***	***moderate difficulty***	***extreme difficulty***

4. **While driving at night, oncoming headlights and streetlights cause you … *(Please circle only one)***

no difficulty	***little difficulty***	***moderate difficulty***	***extreme difficulty***

5. **In general, how do you feel about driving at <u>night</u> in <u>good weather</u>? *(Please circle only one)***

very comfortable	***somewhat comfortable***	***neither comfortable nor***	***somewhat uncomfortable***	***very uncomfortable***

uncomfortable

6. In general, how do you feel about driving at night in typical bad weather conditions (light rain, snow, and fog)? ***(Please circle only one)***

very comfortable	***somewhat comfortable***	***neither comfortable nor uncomfortable***	***somewhat uncomfortable***	***very uncomfortable***

7. What Vehicle do you most often drive at night?

Make _______________

Model _______________

Year _____________

8. What are you most concerned about when driving at night?

APPENDIX 7

Question 1 Results

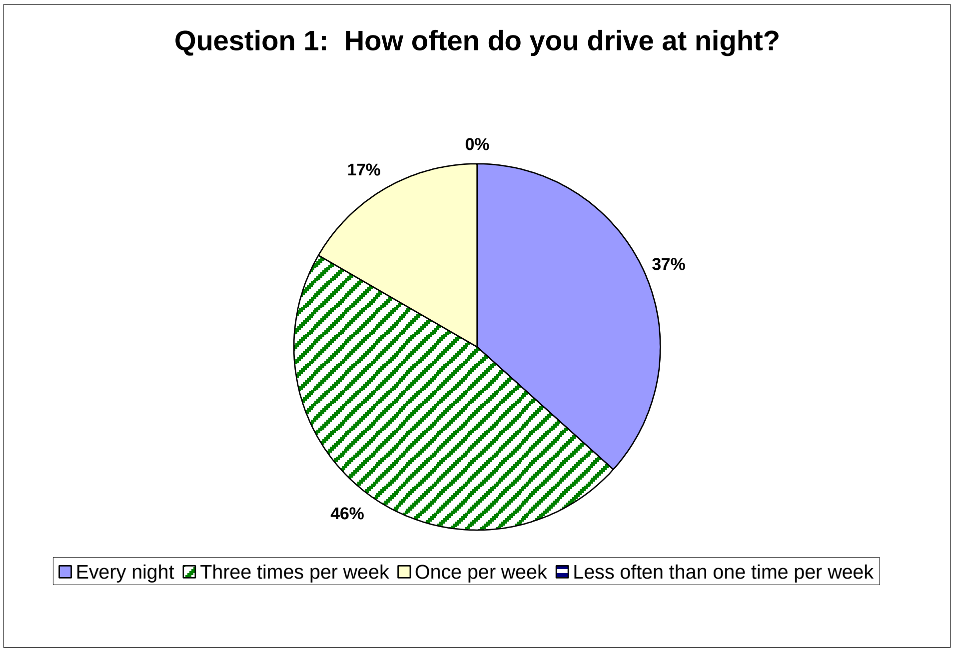


Figure 25. Question 1in Pre-Drive Questionnaire.

Question 2 Results

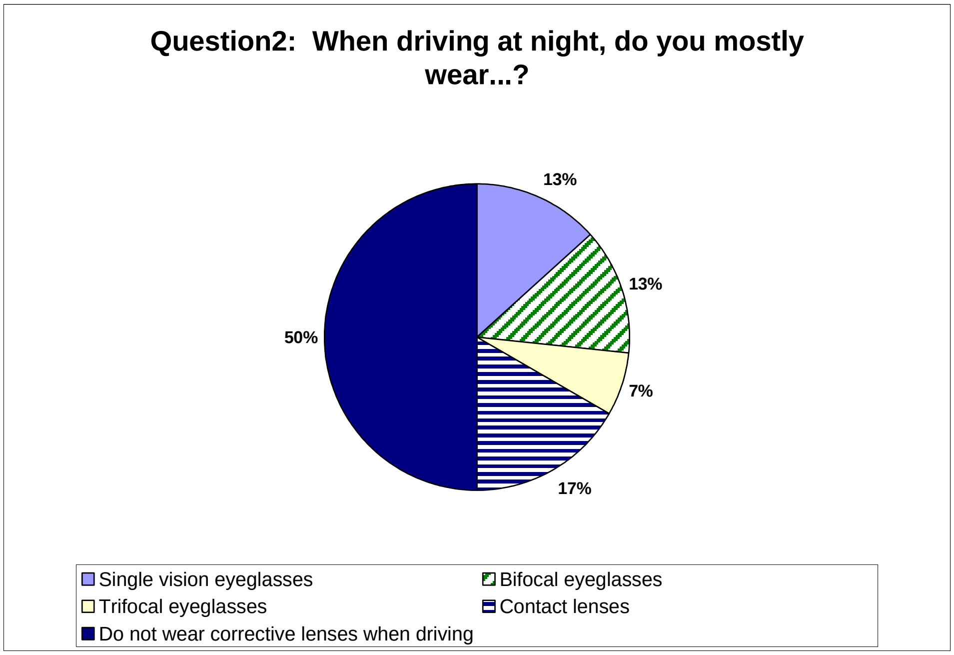


Figure 26. Question 2in Pre-Drive Questionnaire.

Question 3 Results

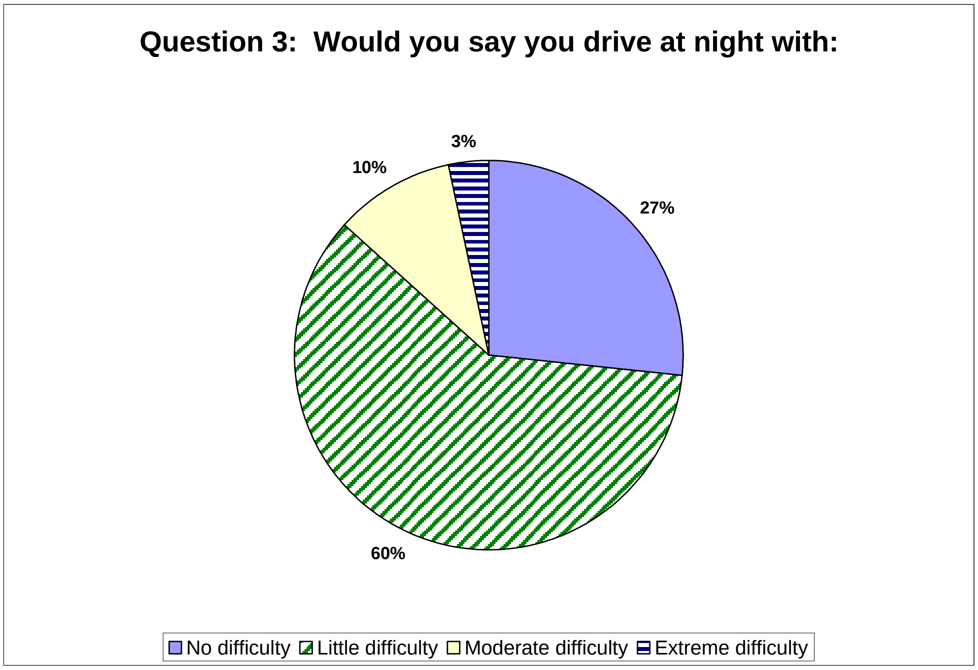


Figure 27. Question 3in Pre-Drive Questionnaire.

Question 4 Results

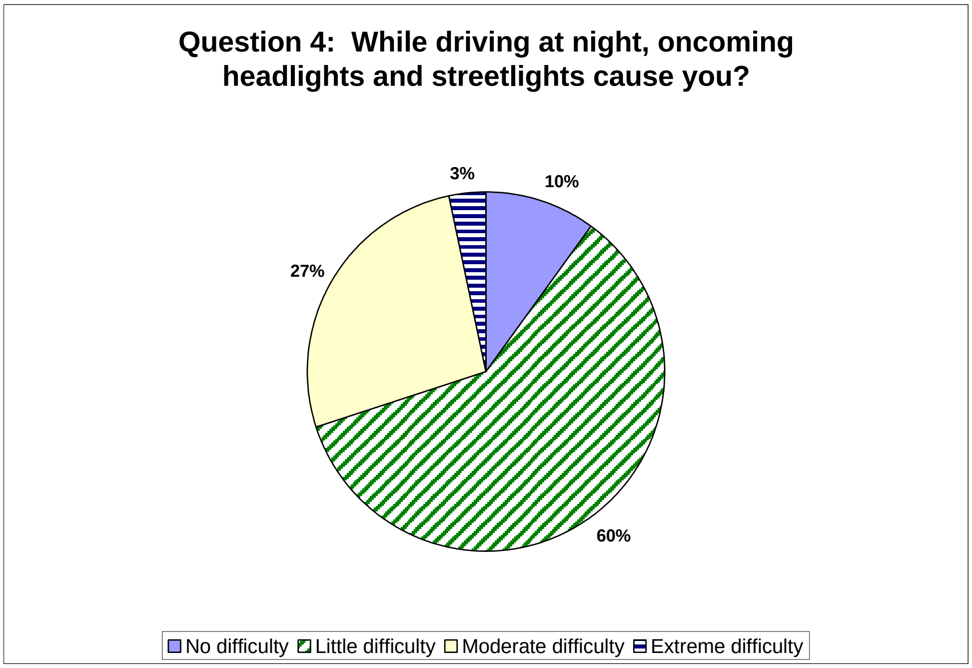


Figure 28. Question 4 in Pre-Drive Questionnaire.

Question 5 Results

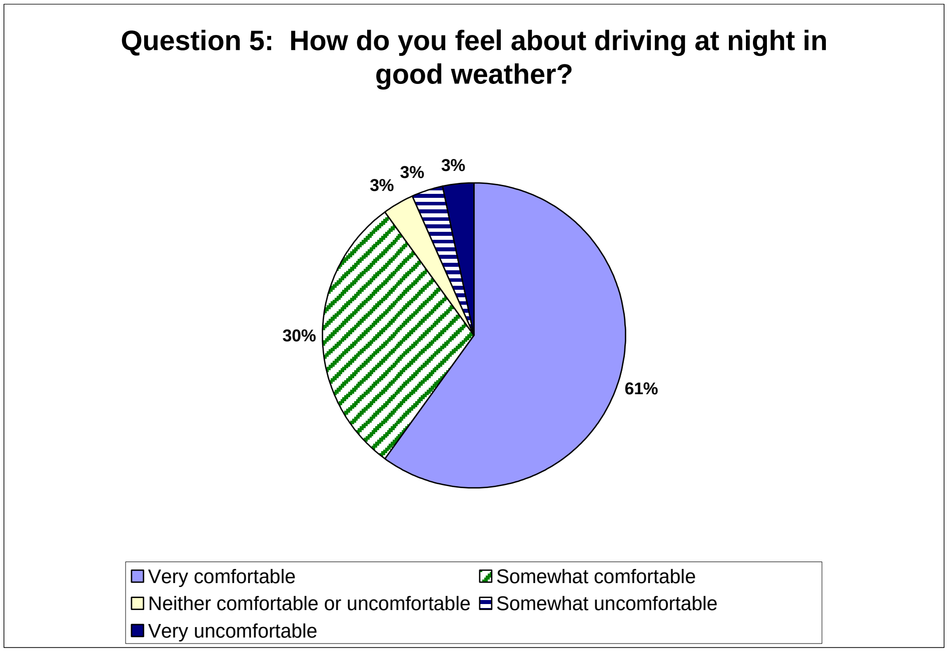


Figure 29. Question 5in Pre-Drive Questionnaire

Question 6 Results

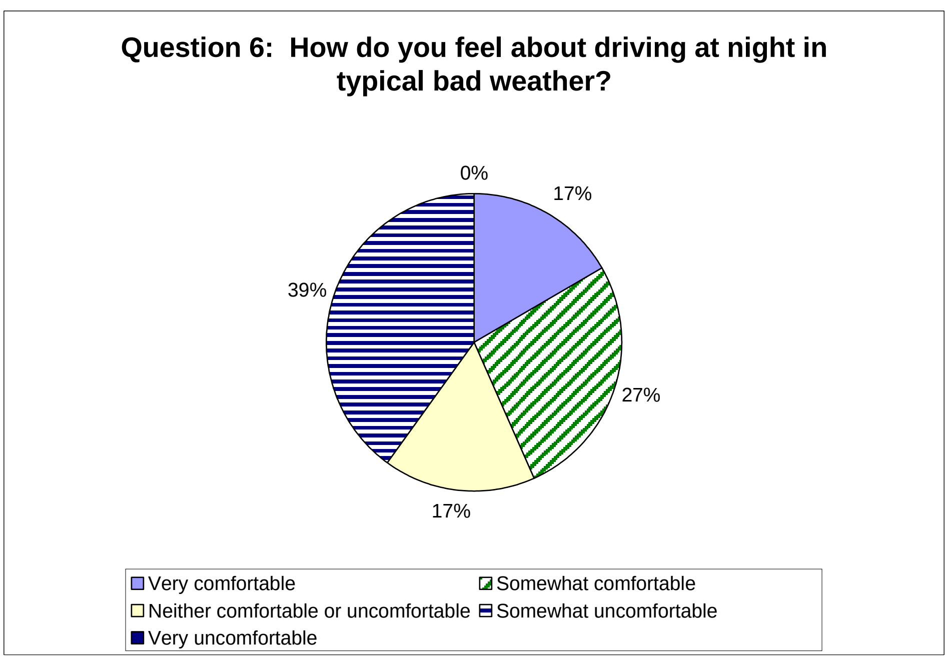


Figure 30. Question 6 in Pre-Drive Questionnaire.

Question 7 Results

Table 17. Participants' personal vehicles by make.

Question 7			
Vehicle Make	**Counts**	**Vehicle Year**	
VW	1	Average	1996
Buick	3	Median	1997
Chevorlet	3	Range	16
Dodge	1		
Ford	4		
GMS	1		
Honda	2		
Jeep	3		
Kia	1		
Mazda	2		
Mercury	2		
Mitsubishi	1		
Oldsmobile	2		
Pontiac	1		
Subaru	1		
Toyota	3		

Question 8 Results

Table 18. Participants' nighttime driving concerns.

Question 8	
Concern	**Frequency**
Animals	2
Deer	7
Bad Weather	5
Lights Oncoming	4
Cops	1
Road Markings	1
Drunk People	1
Falling Asleep	1
Other Drivers	4
Glare with Rain/Snow	3
Not Being Able to See	3
No Concerns	1
People in Road	1
Unseen Objects in Road	1

APPENDIX 8

Table 19. ANOVA Table for Discomfort Glare Results.

Source	DF	SS	MS	F Value	P Value
Between					
Age	2	42.5	21.2	0.92	0.4112
Participant(Age)	27	624.3	23.1		
Within					
Glare	4	143.6	35.9	14.36	<.0001 *
Glare*Age	8	32.9	4.1	1.65	0.1199
*Glare*Participa(Age)*	108	270.0	2.5		
Adaptation	1	0.6	0.6	0.22	0.6466
Adaptation*Age	2	3.2	1.6	0.61	0.5496
*Adaptation*Participa(Age)*	27	70.7	2.6		
Glare*Adaptation	4	0.8	0.2	0.19	0.9424
Glare*Adaptation*Age	8	8.0	1.0	1.02	0.4254
*Glar*Adaptation*Parti(Age)*	108	106.2	1.0		
ADJUSTED TOTALS	299	1302.9			

** p < .05 (significant)*

APPENDIX 9

Table 20. ANOVA table for the objective measurement of disability glare with detection distance.

Source	DF	SS	MS	F Value	P Value
Between					
Age	2	1768349.8	884174.9	15.92	<.0001 *
Participant(Age)	27	1499180.6	55525.2		
Within					
Glare	4	1541883.0	385470.7	26.89	<.0001 *
Glare*Age	8	175486.4	21935.8	1.53	0.155
*Glare*Participant(Age)*	108	1547940.8	14332.8		
Adaptation	1	8474.2	8474.2	0.66	0.4235
Adaptation*Age	2	48880.7	24440.3	1.91	0.1683
*Adaptation*Participant(Age)*	27	346393.3	12829.4		
Pedestrian	1	4864076.3	4864076.3	86.11	<.0001 *
Pedestrian*Age	2	47114.7	23557.4	0.42	0.6632
*Pedestrian*Participant(Age)*	27	1525224.5	56489.8		
Glare*Adaptation	4	4099.3	1024.8	0.17	0.9524
Glare*Adaptation*Age	8	39558.4	4944.8	0.83	0.5794
*Glar*Adaptation*Partipant(Age)*	108	644631.6	5968.8		
Pedestrian*Glare	4	268031.5	67007.9	10.18	<.0001 *
Pedestrian*Glare*Age	8	24537.8	3067.2	0.47	0.8776
*Pedestrian*Glare*Partipant(Age)*	108	710820.4	6581.7		
Pedestrian*Adaptation	1	16062.1	16062.1	2.66	0.1143
Pedestrian*Adaptation*Age	2	18858.3	9429.1	1.56	0.2278
*Pedestrian*Adaptation*Partipant(Age)*	27	162826.8	6030.6		
Pedestrian*Glare*Adaptation	4	13723.3	3430.8	0.55	0.7011
Pedestrian*Glare*Adaptation*Age	8	16110.7	2013.8	0.32	0.9563
*Pedestrian*Glare*Adaptation*Participant(Age)*	107	670372.6	6265.2		
ADJUSTED TOTALS	598	16036520.3			

** p < .05 (significant)*

APPENDIX 10

Disability Glare Protocol for On-Road Experimenters

The Disability Glare Study consists of a Detection task and a subjective rating of the oncoming headlamps.

1. **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. (When towing light rack NO MORE than the 2 Explorer lights and 15 mph.)*
- *Use a spotter when moving vehicles in and out of the Simulator Bay.*
- *Wear closed-toe shoes at all times.*
- *Wear dark clothes and dark shoes with non-reflective materials.*
- *Always wear your vest on the road while doing prep and shut down.*
- *Do not travel with the tailgate open.*
- *Wear your safety glasses whenever you are exposed to headlights.*
- *Always drive with your lights on.*

- ❑ **If it's broken, tell someone**.
- ❑ Attend the nightly meeting.
- ❑ Minimize communications on Channel 1.
- ❑ **Acknowledge all messages you receive.**

-
- *Over the course of the study, it is likely that apparatus will break. If you notice something is broken or you are the one who broke it, tell someone (namely Ron, Jason or Julie) immediately as it is crucial to the study, or as soon as it's 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.*

While the study is being conducted, radio communications on Channel 1 need to be minimized (emergencies excluded). 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, 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.*

2. Pre-Experiment

- ❑ Nightly meeting.
- ❑ Car prep sheets need to be picked up in the Prep Room.
- ❑ Each Experimenter is responsible for signing out radios from the Subject Prep Room. Each on-road experimenter is to have one radio and one extra battery.
  - *Each on-road experimenter is responsible for making sure that they have everything in the blue boxes that they need for the lighting station. They are also expected to load the light boxes and any other equipment into the white pick-up.*
- ❑ Put on vests.
- ❑ Load boxes and cones into truck and hook up lighting trailer.
- ❑ **Close the doors of the Simulator Bay.**
- ❑ The 3 on road experimenters should travel to the road in the pick-up truck. The lead experimenter will drive the truck pulling the trailer.
- ❑ The on-road experimenters will be responsible for:
  - ❑ Setting up parking spaces in Turnaround number 2 by putting out the cones at the appropriate locations. (See Diagram)
  - ❑ Setting up cones at turn-around number 3. (See Diagram)
  - ❑ Setting Up cones (2 each) at both start points. (See Diagram)
  - ❑ Making sure all cones and/or objects on the road that are not part of the IR study are removed from the road.
  - ❑ **Trailer Hitch Arm MUST be removed before lighting rack is put in roadway.**
  - ❑ Unloading boxes at the station.

- Each night you will be assigned one of the following responsibilities:
  - Light Rack Operator, Lead Experimenter
  - Light Rack Operator
  - White Pedestrian
- Each Experimenter must ensure that they are dressed appropriately for the participant training and experimental sessions.

Each experimenter is responsible for making sure that they have a complete set of equipment, including the following:

- Storage container with black and white scrubs (pedestrian only), flashlight, safety glasses, order sheets, BUG SPRAY etc. (located in prep room).
- 2 Extension cords
- 1 Radio and one extra battery with one handset.

- Once you have the equipment at your station DOUBLE CHECK to make sure you have all of the necessary items. Radios are to be worn at all times. (Two lighting operators can use one radio to eliminate interference.)

- As soon as the participants are on the road, the following radio rules will begin:
  1. **Radios are only to be used for communicating information pertaining to the experiment.** There is to be no communication about procedure on channel 8 unless there is a deviation from the usual protocol. All on-road experimenters are expected to know the protocol without confirmation from others. As soon as you receive a message (providing it pertains to you), you must acknowledge that message immediately by saying, "Name and copy." If there is an emergency you are to get on the radio IMMEDIATELY and contact the in-experimenter and the dispatcher.
  - As the trials progress, you will need to make sure the light racks are out and aligned correctly before the experimental vehicle gets to the start point. Pedestrians should be cleared before the passes. You also need to make sure all equipment (including yourselves) is hidden. To ensure least visibility, you need to wear dark clothing on the side of the road as much as possible.
  - If a given run needs to be repeated, confirm the order with the lead experimenter.

3. Travel to the Smart Road

- When the experimental Session begins, the on-road experimenters will be taken to the Smart Road in the White Pick-Up truck. This will be driven by the Lead experimenter.
- Truck and trailer must **NOT** exceed **15** mph.

4. Training Protocol

- The on-road experimenters must be positioned for the participant training. The training will consist of one lap before both experimental sessions (Disability and Discomfort).
- Three on-road experimenters will be required for the training. One white pedestrian (Disability Only) and two light rack operators.
- When the lights are in place and the pedestrian is ready, the lead experimenter will radio on Channel 8 that the in-vehicle may proceed for the training.
- After the completion of the training the road must be prepared for the first experimental lap. (Order Sheet)

5. Objects Protocol

- After completion of the training the road must be ready for the first discomfort glare experimental lap for the session. The entire experimental portion consists of a participant driving 15 laps on the Smart Road testing the various lighting systems. There are four different sessions of testing that occur each night. There are discomfort glare ratings as well as disability glare performance measurements at two levels of adaptation.
- The drivers will be oriented to the road by driving down the hill. During this time on-road experimenters and the light boxes need to remain hidden.
  - *Then lead experimenter is responsible for telling the in-car experimenters when they can proceed onto the road on channel 8.*

After completion of the training lap, the on-road experimenters are to begin putting out objects as indicated on object order sheets. The in-vehicle experimenters will indicate when the object trials begin.

Set up so that the first set of lights needed is readily accessible.

- Hide all light boxes and extension cords from view of the participants when not being used.
- If you are wearing white shoes and/or shoes with reflective fabric, cover your shoes with the provided shoe covers.
- **SAFETY NOTE:** Experimental vehicles are not to come within 50 feet of a pedestrian on the roadway. It is primarily your responsibility to make sure you move off the road at that distance, as in-vehicle experimenters will be primarily concerned with the participants. Also, the in-vehicle experimenters will ask you to clear once they have detected you. In that case, you can clear as soon as you hear "X clear." However, you cannot rely on that and you **MUST** clear at a safe distance.
-
- *After you step off the road, maintain your position on the shoulder. This will allow the in-vehicle experimenters to record the distances of detection on the distance measuring devices.*
- *As soon as the experimental vehicle passes the lighting station the light stand should be switched for the next trial.*
- This methodology will be repeated for all four VES configurations. If there will be two sessions that night, the work truck will drive around and collect the on-road experimenters to provide a break. You will return to the road after your break and set up for the second session that will begin shortly. If there is only one session that night, the work truck will drive around and collect all experimenters and objects after the final configuration.
- If you notice any problems or mistakes occurring during the night record them on the vehicle preparation sheets.

6. Lead Experimenter

- The lead experimenter will be responsible for maintaining the object presentations at location AE.
- The lead experimenter will also be responsible for maintaining the order status to avoid confusion for the on-road experimenters.
- The lead experimenter must also notify the in-vehicle when the road is ready.

7. Valet

- The valet will be responsible for maintaining the object presentations at location F, as well as performing eye height measurements and valet duties at Turnaround 2.
- Perform the Glare Station functions for the Glare activity.
- The valet has to get the valet box that contains measurement materials if measurements need to be taken. The boxes will be in the Prep Room.
- Take care of object orders, and materials. This includes changing out the radio batteries during the break on evenings when we run doubles.
- Be sure to be wearing a vest at all time.
- After Completion of the Participant Training, the Turnaround 2 cones must be moved from the starting position to the experimental position.

10. Ending Protocol

Gather all experimental equipment and return to VTTI. The Work truck driver will be responsible for picking up all equipment. Work truck will also be responsible for picking up boxes, cones. The Lead Experimenter will drive the sedan back to the building. At the end of each night there will be a checklist of items for you to complete (see below). After the items are checked, you will be free to leave.

- Collect cones from the second and third turn-around (Work truck).
- Collect the start cones from the top and bottom of the road. (Work truck).
- Return the vehicles to the VTTI.
- Return glare cart, headlamps and equipment to the Simulator Bay.
- Make sure all the doors are locked and the garage door is closed.
- Return the keys to the lock box.
- Return the radios (personal and in-vehicle) to the Subject Prep Room.

- ❑ Put away scrubs.
- ❑ Sign radios back in. Make sure all radios that have been checked out are returned at the end of the night!
- ❑ Make sure the power is off when you put the radios into the charger.
- ❑ Submit paperwork to the in-vehicle experimenter.

Vehicle Preparation/Shutdown Checklist
Disability Glare

Sedan

- ❑ At least ½ tank of gas.
- ❑ Clean the windshield inside and outside.
- ❑ Wipe off the headlamps.
- ❑ Check that all headlights work.
- ❑ Make sure the car radio is off.
- ❑ Set dashboard lights to the lowest setting.
- ❑ Make sure the vehicle has a working regular flashlight and red flashlight.
- ❑ Place all equipment, etc. not for the Disability Glare study into the trunk/back of the vehicle.
- ❑ Close the sunroof.
- ❑ Make sure pens are in the passenger side door, fire extinguishers and flashlights are in the vehicles.
- ❑ Make sure there is a valet box in the back seat (level, pen, dry erase, tape measurer).
- ❑ Check and Adjust tire pressure.
- ❑ Cover all mirrors with black stuff sacks.

Light Rack/Trailer

- ❑ Check and Adjust tire pressure on trailer.

- ❑ Check light boxes for loose connections or misalignment.
- ❑ Clean all 10 light boxes.
- ❑ Check trailer hitch arm connection.
- ❑ Check light rack power supply to make sure it is functioning.
- ❑ Cover front license plate of truck with felt.

Experimenter_______________ Date__________

APPENDIX 11

Disability Glare Protocol for In-Vehicle Experimenters

1. **Prior to the participant's arrival, make sure that all the needed forms are available.**

2. **The in-vehicle experimenter must have a cell phone with them during the experiment.**

3. **Set up the conference room.**
   - Close all the shades
   - Turn on all overhead lights
   - Turn off halogen lamps
   - Position work light for vision contrast by placing it within the tape on the floor. Place chairs or tables around the work light to prevent anyone from being burned.
   - Get BAT, color vision test, eye occluder, alcohol and cotton balls from prep room.

4. **Greet Participant.**

5. **Record the time that the participant arrived on the debriefing form.**

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

7. **Informed consent.**
   - Give the participant the form-encourage them to read it.
   - Answer questions
   - Have participant sign and date both forms
   - Give the participant a copy of the informed consent

8. **Tax Forms.**
   - 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.

If the participants make more than $500.00 doing studies from Jan 1 to Dec 31, this will be reported to the IRS as income.

Back side of tax form- Print the participants name at the top. If they question what this is for…. This says we are not hiring them full time. There won't be any health benefits or paid vacation etc. We can not fire them because we are not really hiring them. They can quit at any time without being held liable for services by the University. They are a one-time contractor. If they already work for Tech, this is completely separate from their job, and their performance will not have any effect on their employment with Tech.

9. **Vision Tests.**

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

a) 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 one that they were able to read in full (line above).
- 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.
- Participant must have 20/40 or better vision using both eyes to participate in the study.

b) Contrast Sensitivity Test

- 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: *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 subject's 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) Test for Color Blindness.

Procedure:

- 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 participant's answers on the Vision Tests Form.

d) Brightness Acuity Tester

Procedure:

- Go to the 20 ft line for the Snellen Test.
- Give the participant the BAT to hold up to one eye.
- Instruct the participant to cover their other eye.
- Repeat Snellen Test in each eye for all levels of the BAT (off/ low/ medium/ high)

10. **Measure height of participant**

11. **Administer Pre- Drive Questionnaire**.

12. **Orient driver to the study**

Tonight you will drive one vehicle for approximately 2.5 to 3 hours. We will drive under two different levels of interior lighting in the vehicle. You will be driving past several different sets of oncoming headlamps and looking for pedestrians along the roadway.

I will be in the vehicle with you at all times. I will provide directions where to go, record data, and I can answer any questions you have. As you drive, there will be pedestrians I would like you to identify.

At the moment when you can first detect the object as a person and you can tell which side of the road they are on, say ***"Person Left" or "Person Right".***

If there are no pedestrians you do not need to say anything.

(Show picture of pedestrian)

There will also be other cars on and around the road. You never need to call out a vehicle as an object.

We'll first do a practice lap before we begin where I'll tell you what to look for and you can get used to the vehicle , then we'll do the experimental portion.

The maximum speed limit during the drive will be ***20mph****. To assist you with keeping the vehicle at the low speed of 20 mph we will use second gear. The vehicle should also be on low beams at all times.*

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

13. **Review the Discomfort Rating Scale**

During a portion of tonight's study, after you are finished driving past a set of oncoming headlamps, I will ask you to rate the discomfort you experienced from the lights.
(Review Scale)

Once you give an answer, you will not be able to change it.

14. Before leaving the building ask if they want to use the restroom.

APPENDIX 12

Disability Glare Protocol for In-Vehicle Experimenters

1. **Go to the experimental vehicle**
   - Ask the participant if they are ready to go out to the car.
   - Take participant to the experimental vehicle parked outside the front door.

2. **Turn on headlamps (low beams and no fog lamps)**

3. **Orient the participant to the vehicle.**

.

Sedan

Occupant position

The seat controls are on the side of the seat near the door. You can adjust up down, forward backward and the seat back recline.

Steering wheel
There is a control also to adjust the steering wheel on the left side of the steering column.

Check
Okay, are you comfortable?

Dashboard Lights

The interior lights are set on a specific brightness level. For this study we will not be able to adjust the interior lights.

4. Eye Height Measurements

Now that you are situated I'm going to close the door. I'd like you to relax and look straight ahead and sit as still as possible while I take some eye measurements.

5. Get in vehicle

Check driver eyes visible in two views with room for head movement

Check for radio connection.

Check Luminance Meter

Check radio on and connected to VCR

Make sure red record symbol visible and counter is moving – if visible, don't press record. This will set it up for a time limited recording.

Put on seatbelt

Have order sheet ready

6. Eye glance calibration

- Have the participant look at each of the following locations, while they say each one aloud.
    1. *Speedometer*
    2. *Straight Ahead*
    3. *Covered Rear View mirror*
    4. *Covered Left mirror*
    5. *Covered Right mirror*

Set Order

Set Adaptation Level (Should be done down on road before first practice)

I am now going to measure the amount of light in the vehicle. I will hold this light meter **(show them)** near your head to get an accurate measurement. Please just look straight ahead.

Adjust dimmer switch to get desired brightness level.

Low Adaptation: **0.15 Lux**

High Adaptation: **0.45 Lux**

Shift-S to begin / Shift Q to quit/Save

7. Orientation/Practice lap

Have button ready in hand

Radio on road that participant vehicle is ready and to turn lights on.

The following should be read before the <u>Discomfort Rating</u> practice lap at the downhill starting point.

We will now drive down the Smart Road to get you used to the road and the vehicle. While driving down the road try not to stare at the oncoming lights, and drive as you normally would. After we have passed the oncoming headlamps we will stop and I will ask you to rate the discomfort you experienced from the lights. To rate the discomfort from the oncoming headlamps we will use the scale located on the dashboard.

Remember the scale goes from 1 to 9, 1 being Unbearable and 9 being Just Acceptable

Remember the speed limit is 20 mph.

Any questions?

- Drive down the road at 20 mph for the downhill practice run.

- Guide participant where to pull into T3 - at the end of the loop put the car in park near the cone at the exit of T3.

- Repeat the discomfort practice going uphill.

The following should be read before the Discomfort Rating practice lap at the downhill starting point.

We are going to another practice trial to get you used to rating the discomfort you experience from the oncoming headlamps.

The following should be read before the Disability Glare Practice.

Remember to say "Person Left" or Person Right" when you can just detect the position of the pedestrian on the road.

If there are no pedestrians you do not need to say anything.

If you realize you made a mistake, just say "No" and give the correct location when you realize it.

We will now drive back up the road to get you used to detecting the pedestrians. While proceeding up the road please drive as you normally would and try not to stare at the oncoming headlamps.

Remember the speed limit is 20 mph.

Any questions?

-Repeat going downhill.

8. Experimental Run (Discomfort Glare)

Computer set to correct order and adaptation level?

Adaptation level set?

Okay, we will now begin the first portion of the study**. Please look straight ahead until I say begin.** When you have driven past the oncoming headlamps you will be rating the discomfort you experienced from the oncoming headlamps. Please use the scale provided for you on the dashboard. Remember to look for pedestrians on the way up the hill.

Tell the participant to pause after passing the lights.

Shine flashlight on the deBoer scale and review with participant.

Please rate the discomfort you experienced from the oncoming headlamps.

Record response in Discomfort Rating data sheet and then continue to next turnaround.

9. Experimental Run (Performance/Disability)

Computer set to correct order and adaptation level?

Adaptation level set?

Luminance meter working?

VCR (L-1 & EP)?

Okay, we will now begin the next portion of the study, when you are able to detect what side of the road the person is on, say Person RIGHT or person LEFT, if you make a mistake, say something like NO, LEFT. I will not be telling you what to look for anymore. ***Please look straight ahead until I say begin***

Any questions?

***Remember to hit spacebar at first cone in T2 for the Reflective Pedestrian location.**

**** When the truck is behind you wait for it before turning in to T2 to avoid crossing headlamps.**

- *It is VERY important that you do not talk to the drivers when you are collecting data. EMERGENCIES EXCLUDED!!!!*
- *Monitor the computer while going up the hill (see computer instructions)*
- *Radio the on-road experimenter to notify them when they should clear the road.*
- *On-Road should be asked to clear the road once the driver has identified them. This may be delayed for longer detection distances to reduce the confirmation of a correct identification. False clears without transmitting should also be inserted periodically for the same reason.*
- *Press the computer space bar when your body is in line with the object. After space bar is pressed, the arrow will scroll down to the next object.*

Document any unexpected events that occurred during the run using the In-Vehicle Notesheet.

Examples include but are not limited to the following:

- Note if an object was not set up according to protocol (incorrect object, order, etc)

Repeat any incorrect headlamps or incorrect pedestrian locations.

10. Switch to next Adaptation level and repeat experimental runs.

11. Pay the participant

- *Document Time on Participant's Debriefing Sheet and give them the sheet.*
- *Pay the participant $20.00 per hour, rounding up to the next half hour if necessary.*
- Make sure the participant signs the payment log.

APPENDIX 13

<u>Disability Glare Headlamps Alignment Protocol</u>

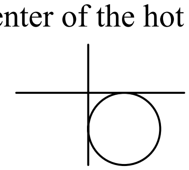
- Pull the vehicle/headlamp cart up to the alignment plate mounted onto the ground. This should be located 35 feet from the alignment wall. Make sure the wheels are straight against the plate.
- Use the laser to make sure the target board is centered to the vehicle/headlamp cart. Each headlamp has a different line on the target board. The lines are labeled directly on the target board.
- Locate the appropriate markings on the target board for each headlamp.
- Turn on the appropriate headlamps, making sure no auxiliary lights (parking lights, fog lights, and daytime running lights) are on.
- Cover up or unplug one headlamp so that you are only taking readings for one light at a time.

<u>Finding the Hotspot:</u>
Align the VES so that the "hot spot" is located in the first (or lower right) quadrant, tangent to both the horizontal and vertical lines. The sensor, when measuring the hotspot in that quadrant, will touch both axes of the crosshairs. The headlamps have both gross and fine adjustments. Typically, only fine adjustments will be required if the headlights are not switched; gross will be required if the headlights are switched.

Note: Why do we align these lights off-center point?

When these types of lights are aligned straight ahead, the lights are placed in a "High Beam" configuration. *We <u>do not</u> want to use the "High Beam" configuration* in this study. Our alignment procedure allows each light to be directed slightly to the right and below the exact centerline for that light

Hot Spot Location: The circle represents the target hot spot location with respect to the target crosshairs. The center of the circle is the center of the hot spot.



- *Using the Photometer:*
- *To determine if the hotspot is in the correct location, you will need to use the International Light, Inc., IL1400A Radiometer/Photometer to measure the area of greatest intensity. There are two sensors for the photometer; the sensor for the visible*

light is marked with a "REG" label, and the sensor for the UV light is marked with a "UV-A" label. Use the sensor marked "REG."

-
- *Zero the Photometer:*
- *Remember to "ZERO" the photometer prior to checking each measurement. To do this, make sure that all headlamps are turned off. Remove the cap from the photometric sensor. Place the sensor at the alignment location for the headlamp to be aligned. Press the "ZERO" button; this will allow the photometer to measure any undesired background light and remove its effects from the actual light source value. The photometer is ready when the "ZEROING" message has changed back to the "SIGNAL" message. Turn the headlamp on and begin alignment.*
-
- *Isolating the Hotspot:*
- *Once you find the area you believe has the highest intensity, readings need to be taken in all directions around that location to ensure that is the hot spot. If the hotspot is in the correct location, the light is aligned and you can align the other light(s).*
-
- *Note that for non-UV lights, the HLBs in particular; the hotspots actually span a large horizontal swath, 2-4 inches wide. It is relatively easy to determine the hotspot vertically, but determining the hotspot horizontally requires more effort and patience given that the horizontal hotspot can be 2-4 inches wide.*
-
- *Special Instructions for HID alignment:*
- *Remember that the HIDs require alignment with the photometer for rightmost (no. 2) headlamp and visual alignment based of the left (no. 1) headlamp based on the aligned right headlamp. This is noted on the alignment form. Below is an example diagram of how to visually aim the HID lights in Figure 38. Each headlamp has its own diagram located on the server in the Disability Glare/Headlamps folder.*

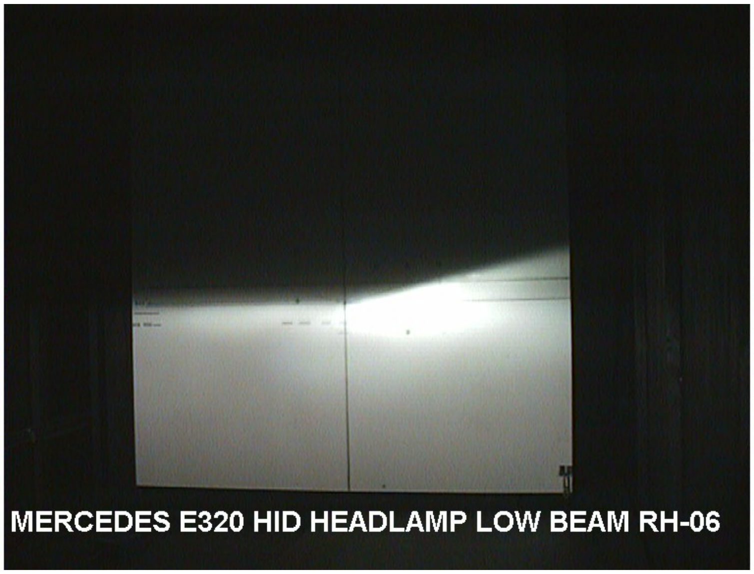


Figure 31. Example of correctly aligned HID headlamp.

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