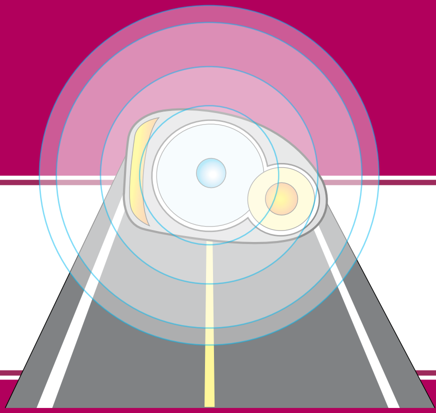

ENV

# Volume XV

# Enhanced Night Visibility Series: Phase III–Study 3: Influence of Beam Characteristics on Discomfort and Disability Glare

PUBLICATION NO. FHWA-HRT-04-146

DECEMBER 2005

U.S. Department of Transportation
**Federal Highway Administration**

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

# FOREWORD

The overall goal of the Federal Highway Administration's (FHWA) Visibility Research Program is to enhance the safety of road users through near-term improvements of the visibility on and along the roadway. The program also promotes the advancement of new practices and technologies to improve visibility on a cost-effective basis.

The following document summarizes the results of a study evaluating the influence of headlamp beam characteristics on discomfort and disability glare from various headlamp systems. The study was conducted under Phase III of the Enhanced Night Visibility (ENV) project, a comprehensive evaluation of evolving and proposed headlamp technologies in various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume XV. It is anticipated that the reader will select those volumes that provide information of specific interest.

This report will be of interest to headlamp designers, automobile manufacturers and consumers, third-party headlamp manufacturers, human factors engineers, and people involved in headlamp and roadway specifications.

Michael F. Trentacoste
Director, Office of Safety
Research and Development

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16. Abstract

The objective of this study was to evaluate the discomfort and disability glare produced by oncoming headlamps with varying beam intensity and distribution. Oncoming headlamps can be visually discomforting and disabling to drivers at night. In recent years, high intensity discharge (HID) headlamps have raised some concern because of their increased light output and brighter appearance than traditional halogen headlamps.

During the discomfort glare portion of this study, participants drove an experimental vehicle at 32 km/h (20 mi/h) past stationary glare headlamps. They were asked to rate their overall discomfort using the subjective deBoer scale. The disability glare portion involved drivers detecting a static pedestrian either near the road centerline or near the road edgeline while approaching different sets of glare headlamps. It was hypothesized that there would be significant differences in detection distance, illuminance at the driver's eye, and discomfort glare rating across the different glare headlamp, pedestrian position, adaptation level, and participant age combinations.

The main effect of glare headlamp was the only significant factor in the analysis for discomfort glare. The main effects of age, glare headlamp, and pedestrian location were all significant in the analysis for the disability glare portion. In addition, the interaction of pedestrian location and glare headlamp was significant. Overall, headlamps that had higher subjective discomfort ratings were the same lamps that had worse 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.

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| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

## ENHANCED NIGHT VISIBILITY PROJECT REPORT SERIES

This volume is the 15th of 18 volumes in this research report series. Each volume is a different study or summary, and any reference to a report volume in this series will be referenced in the text as "ENV Volume I," "ENV Volume II," and so forth. A list of the report volumes follows:

| Volume | Title | Report Number |
|---|---|---|
| I | Enhanced Night Visibility Series: Executive Summary | FHWA-HRT-04-132 |
| II | Enhanced Night Visibility Series: Overview of Phase I and Development of Phase II Experimental Plan | FHWA-HRT-04-133 |
| III | Enhanced Night Visibility Series: Phase II—Study 1: Visual Performance During Nighttime Driving in Clear Weather | FHWA-HRT-04-134 |
| IV | Enhanced Night Visibility Series: Phase II—Study 2: Visual Performance During Nighttime Driving in Rain | FHWA-HRT-04-135 |
| V | Enhanced Night Visibility Series: Phase II—Study 3: Visual Performance During Nighttime Driving in Snow | FHWA-HRT-04-136 |
| VI | Enhanced Night Visibility Series: Phase II—Study 4: Visual Performance During Nighttime Driving in Fog | FHWA-HRT-04-137 |
| VII | Enhanced Night Visibility Series: Phase II—Study 5: Evaluation of Discomfort Glare During Nighttime Driving in Clear Weather | FHWA-HRT-04-138 |
| VIII | Enhanced Night Visibility Series: Phase II—Study 6: Detection of Pavement Markings During Nighttime Driving in Clear Weather | FHWA-HRT-04-139 |
| IX | Enhanced Night Visibility Series: Phase II—Characterization of Experimental Objects | FHWA-HRT-04-140 |
| X | Enhanced Night Visibility Series: Phase II—Visual Performance Simulation Software for Objects and Traffic Control Devices | FHWA-HRT-04-141 |
| XI | Enhanced Night Visibility Series: Phase II—Cost-Benefit Analysis | FHWA-HRT-04-142 |
| XII | Enhanced Night Visibility Series: Overview of Phase II and Development of Phase III Experimental Plan | FHWA-HRT-04-143 |
| XIII | Enhanced Night Visibility Series: Phase III—Study 1: Comparison of Near Infrared, Far Infrared, High Intensity Discharge, and Halogen Headlamps on Object Detection in Nighttime Clear Weather | FHWA-HRT-04-144 |
| XIV | Enhanced Night Visibility Series: Phase III—Study 2: Comparison of Near Infrared, Far Infrared, and Halogen Headlamps on Object Detection in Nighttime Rain | FHWA-HRT-04-145 |
| XV | Enhanced Night Visibility Series: Phase III—Study 3: Influence of Beam Characteristics on Discomfort and Disability Glare | FHWA-HRT-04-146 |
| XVI | Enhanced Night Visibility Series: Phase III—Characterization of Experimental Objects | FHWA-HRT-04-147 |
| XVII | Enhanced Night Visibility Series: Phases II and III—Characterization of Experimental Vision Enhancement Systems | FHWA-HRT-04-148 |
| XVIII | Enhanced Night Visibility Series: Overview of Phase III | FHWA-HRT-04-149 |

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# LIST OF ACRONYMS AND ABBREVIATIONS

## General Terms

BAT™ ............................... Brightness Acuity Tester
ENV ................................ Enhanced Night Visibility
LED ................................. light emitting diode
NHTSA ............................ National Highway Traffic Safety Administration
SUV ................................. sport utility vehicle
UV–A ............................... ultraviolet A (wavelength 315 to 400 nanometers)
VES ................................. vision enhancement system
VMT ................................ vehicle miles traveled

## Vision Enhancement Systems

HLB ................................. halogen (i.e., tungsten-halogen) low beam
HLB–LP ........................... halogen low beam at a lower profile
HID ................................. high intensity discharge

## Statistical Terms

ANOVA ........................... analysis of variance
DF ................................... degrees of freedom
F value ............................. F-ratio
MS ................................... mean square
N ...................................... sample size
P value ............................. statistical significance
SNK ................................. Student-Newman-Keuls test
SS .................................... sum of squares

## Measurements

Δ lux ................................ calculated change in illuminance at the driver's eye
cd ..................................... candela
cd/m$^2$ ............................... candela per square meter
cm .................................... centimeters
D ...................................... degrees down
fL ..................................... footlamberts
ft ...................................... feet
km/h ................................ kilometers per hour
L ...................................... degrees left
lm .................................... lumens
lx ...................................... lux
m ..................................... meters
mi .................................... miles
mi/h ................................. miles per hour
min .................................. minutes

ms....................................milliseconds
nm ...................................nanometers
R......................................degrees right
s .......................................seconds
U......................................degrees up
V......................................volts
W.....................................Watts

# CHAPTER 1—INTRODUCTION

Most of the information necessary for the task of driving a vehicle is acquired through the driver's visual system. Some estimate that up to 90 percent of the necessary information for operating a motor vehicle is visual.[1] Before the visual system can detect and recognize various objects in the field of view, there must first be sufficient lighting.[2] Headlamps are the most common lighting systems used for nighttime visibility of the roadway. Over the years, improvements in headlamp design, including parameters such as beam pattern, aiming, luminous output, and intensity have helped increase visibility in night driving; however, headlamp design requires a tradeoff in illumination directed onto the roadway and the illumination directed farther down the road. Some portion of this illumination is directed into the eyes of oncoming drivers, resulting in glare. Glare can be described as the blinding experience that results from bright light sources in the visual field of view.[3] More specifically, glare can be further described in terms of disability glare and discomfort glare. Disability glare is the glare that results in reduced visual performance, while discomfort glare is glare that results in physical discomfort, but which does not necessarily result in reduced visual performance.

## DISABILITY GLARE

Disability glare occurs when the introduction of stray light into the eye reduces the ability to resolve spatial detail.[4] It is an objective impairment in visual performance.[5] Many of the classic models of this type of glare attribute these deleterious effects to intraocular light scatter in the eye.[6] This scattering produces a veiling luminance over the retina, which effectively reduces the contrast of stimulus images formed on the retina. The disabling effect of the veiling luminance may have serious implications for nighttime driving visibility. Researchers investigating disability glare caused by conventional halogen headlamps have found 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 1,380 candela (cd) reduced detection distances for a given scenario from around 35.4 m (116 ft) down to 27.4 m (90 ft) and also resulted in many missed targets.[3] Age was also found to have significant effects on detection performance under a glare situation.

## DISCOMFORT GLARE

Discomfort glare has been defined as the level of illumination bright enough to result in a measurable level of subjective discomfort or annoyance.[2] It is known to be related to the degree of homogeneity between the glare source and its background.[7] Light source characteristics affecting discomfort levels include the intensity, or luminance, as well as the size of the light source. Discomfort glare can vary among different individuals because of many factors including personality, preference, and experience. It has also been shown that the degree of discomfort that a driver feels when exposed to glare may depend partly on the difficulty of the driver's visual task;[8] as the difficulty of the driver's visual task increases, the subjective rating of discomfort may increase. The most common method for evaluating discomfort glare is the use of the deBoer scale rating system.[9] The deBoer scale has endpoints at 1 and 9 and verbal anchors for each of the odd numbers as follows: (1) "Unbearable," (3) "Disturbing," (5) "Just acceptable," (7) "Satisfactory," and (9) "Just noticeable." Although only odd numbers 1 through 9 have descriptors, the responses can be any number, odd or even. The Enhanced Night Visibility (ENV) discomfort glare study discussed previously used this scale to measure the discomfort glare of the 11 vision enhancement systems (VESs) (ENV Volume VII).

## HEADLAMPS

At present, the two most common types of headlamp systems are those based on tungsten-halogen incandescent lamps (halogen headlamps) and those based on metal-halide high intensity discharge lamps (HID headlamps).

### Halogen Headlamps

Halogen headlamps use technology similar to most basic electrically powered light sources in which passing an electric current through a high-resistance tungsten filament generates light. The use of a halogen gas in the bulb allows the lamp to operate at a higher temperature, and it produces light in the visible spectrum that is better suited for driving than light from standard incandescent filament lamps. With the use of complex reflectors and lenses, halogen lighting systems can provide an output of just over 1,000 lumens (lm) while operating at 12.8 volts (V). The average luminance of halogen bulbs can be around 1,400 candela per square meter (cd/m$^2$)

(408 footlamberts (fL)).[10] One of the disadvantages of halogen lamps (indeed, of all incandescent lamps) is that roughly 80 percent of the output is lost as heat in the infrared spectrum.[11] In addition, the filaments in halogen systems can be damaged from road vibrations and other effects associated with long-term use. As a result, halogen headlamps may not last as long as other components in the vehicle.

### High Intensity Discharge Headlamps

High intensity discharge (HID) lamps have been in use for many years in roadway luminaires and other outdoor lighting systems. Bosch developed the first automobile HID headlamp in the fall of 1991. HID headlamp systems are attractive to automotive manufacturers because of their longer lifespan, better durability, greater performance and power efficiency, and new stylistic freedom.

One of the main reasons that HID headlamps are more durable is the lack of a current-carrying filament, such as is found in halogen lighting systems. Instead of a filament, an arc is created between two electrodes, which excites a gas (commonly xenon) inside the lamp that vaporizes metallic salts. These metallic salts help sustain the arc and provide a consistent light source.[12] HID headlamps are estimated to be able to last the life of an automobile (10 years, 160,394.4 km (100,000 mi)) under normal operating conditions.[10] This is a significant improvement in overall durability compared to halogen headlamps.

HID headlamps also provide better performance and efficiency compared to conventional halogen headlamps. The luminous efficacy, which is the ratio of luminous 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 lumen output as halogen lamps with comparable wattage.[10]

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 they also may have effects on glare. The size of headlamp fixtures has been linked to the subjective rating of discomfort glare.[13] A smaller light source (e.g., projector type) with the same light output as a larger source headlamp (e.g., reflector type) may be rated differently on its perceived discomfort;[14] therefore, it is important to consider headlamp size when making direct comparisons of discomfort glare.

## COMPARISON OF HID AND HALOGEN GLARE

Public concern continues about the glare produced by an increasing number of new HID headlamps. In 2001, the National Highway Traffic Safety Administration (NHTSA) asked drivers to submit their opinions on the issue of glare and its many sources. Although drivers complained about the use of fog lamps in normal weather conditions and indirect glare in the rearview mirror from sport utility vehicles (SUVs) and trucks, the single most complained-about source of glare was the HID headlamp. Many drivers stated that these headlamps are too blinding and dangerous. Other drivers said the blue color is distracting and uncomfortable. On the other hand, drivers who own the new headlamps praise the increased visibility they provide. The owners commented on how safe they feel at night driving with these new headlamps and how well the headlamps light their forward view.[12] However, Phase II of the ENV project showed that drivers' preference for HID lamps was not associated with increased visibility. Although drivers rated the HID lamps as helping them better detect and recognize objects, the objective data indicated that the HID lamps chosen for this study often performed worse than other VESs (ENV Volume XII). Other research has found a subjective preference (i.e., less discomfort glare) for halogen headlamps over the HIDs.[15] Some researchers believe this subjective difference in the perception of brightness or visual discomfort may result in part from the differences in spectral power distribution of the two headlamp designs. Halogen headlamps tend to have a warmer appearance because their spectral distribution is predominantly comprised of longer wavelengths. In contrast, HID designs have distinct peaks of spectral power throughout the visible spectrum, with more output in the short wavelength portion of the spectrum. This results in HID lamps having a slightly bluish appearance. Spectral power distributions for typical HID and halogen headlamps are illustrated in figure 1.

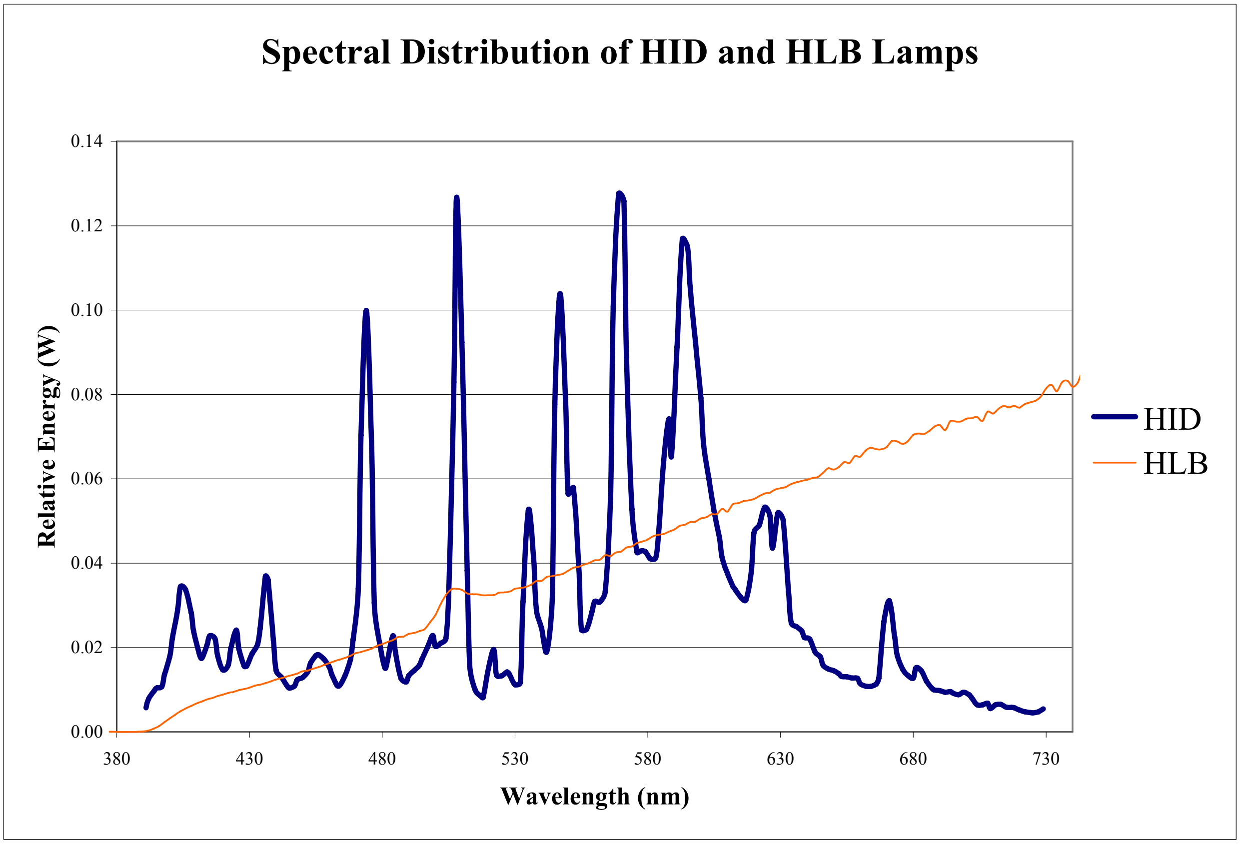



**Figure 1. Line graph. Spectral power distribution of typical HID and halogen headlamps.**

This variation in appearance may be one reason some drivers perceive HID lamps to be more discomforting. A recent study of both discomfort and disability glare from halogen and HID light sources showed that two headlamps of the same intensity (measured at the eye) had different discomfort ratings.(16) Drivers rated the HID headlamps (using the deBoer scale) as being more discomforting than the halogen beams. Disability glare, however, was not affected by the spectral power distribution.

On the other hand, another part of the ENV project indicated that the HID headlamp used in this research was rated as acceptable using the deBoer scale and as causing less glare than the halogen headlamp tested (ENV Volume VII). However, these were only two specific headlamps and should not be considered representative of the headlamp types.

## STUDY OBJECTIVES

The main goal of this study was to evaluate the disability and discomfort glare of headlamps with varying beam distributions and intensities. A total of five different sets of VESs were evaluated in this study. Each VES was specifically chosen for its beam distribution and output characteristics. Four of these systems were different designs of HID headlamps that recently have become available for use on public roadways. The fifth system was a standard halogen headlamp that has been used in previous ENV studies involving detection tasks and discomfort glare evaluation. In addition, the effect of three different driver ages, two driver light adaptation levels, and two pedestrian locations were also assessed. Disability glare was measured as detection of pedestrians against oncoming glare. Discomfort glare was measured using the deBoer scale ratings. All the experimental variables are discussed in more detail in chapter 2. The following are specific questions this study was designed to answer:

1. What effect will different glare sources, in terms of intensity and beam distribution (low/narrow, low/wide, medium/medium, high/narrow, and high/wide), have on the performance of drivers in the pedestrian detection task?
2. What effect will different light adaptation levels, in terms of ambient lighting environment (low of 0.15 lux (lx) and high of 0.45 lx), have on the performance of drivers in the pedestrian detection task?
3. What effect will different pedestrian locations in the driving lane (left and right) have on the performance of drivers in the pedestrian detection task?
4. What effect will different age levels (young (18 to 25 years old), middle (40 to 50 years old), and older (65 years and older)) have on the performance of drivers in the pedestrian detection task?
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?
6. What effect will different light adaptation levels, in terms of ambient lighting environment (low of 0.15 lx and high of 0.45 lx), have on the perception of discomfort glare?

7. What effect will different age levels (young (18 to 25 years old), middle (40 to 50 years old), and older (65 years and older)) have on the perception of discomfort glare?
8. 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 illuminance value at the driver's eye at the moment of detection?
9. What effect will different light adaptation levels, in terms of ambient lighting environment (low of 0.15 lx and high of 0.45 lx), have on the illuminance value at the driver's eye at the moment of detection?
10. What effect will different pedestrian locations in the driving lane (left and right) have on the illuminance value at the driver's eye at the moment of detection?
11. What effect will different age levels (young (18 to 25 years old), middle (40 to 50 years old), and older (65 years and older)) have on the illuminance value at the driver's eye at the moment of detection?

# CHAPTER 2—METHODS

## PARTICIPANTS

Thirty drivers participated in this study. Participants were divided into three different age groups. The first age group (young) comprised 10 drivers between 18 and 25 years old with an average age of 22. The second group (middle aged) comprised 10 drivers between 40 and 50 years old with an average age of 43. Finally, the third group (older) comprised 10 drivers 65 years or older with an average age of 69. Each age group was equally divided into five males and five females. Candidates were screened before being accepted as participants to ensure that they met all the specific requirements listed in the screening questionnaire (appendix A). Candidates who revealed health conditions that would have made operating the research vehicles a risk were not eligible to participate. All participants were required to sign an Informed Consent Form (appendix B).

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 study were treated with anonymity. Participants received payment of $20 per hour for his or her participation.

## EXPERIMENTAL DESIGN

A 5 (VES) by 3 (Age) by 2 (Driver Light Adaptation Level) by 2 (Pedestrian Location) mixed-factor design was used. The five VESs varied in intensity and beam distribution. The three age groups were young, middle, and older. The two different driver light adaptation levels were defined as "low" and "high." There were two different pedestrian locations: one pedestrian stood just inside the right edgeline of the driving lane, and the other stood on the left side of the driving lane near the centerline. These four variables are discussed in the Independent Variables section. The details of all the factors appear in table 1 and table 2. The between-subjects factor was age. The within-subjects factors were VES, driver light adaptation level, and pedestrian location.

The data collection portion of the study included 10 different combinations of driver adaptation levels and VESs. Following is a list of the oncoming VESs and driver adaptation levels:

- VES:
  - (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).
  - (Medium/medium) Mid-level intensity with medium beam pattern (HID).
  - (Low/narrow) Low intensity with narrow beam pattern (halogen).

- Adaptation level:
  - Low adaptation level (0.15 lx).
  - High adaptation level (0.45 lx).

**Table 1. Factors for the experimental design: 5 (VESs) by 3 (age) mixed factor design.**

| VES | Young Age Group | Middle Age Group | Older Age Group |
|---|---|---|---|
| High/Narrow (HID) | | | |
| High/Wide (HID) | | | |
| Medium/Medium (HID) | | | |
| Low/Narrow (halogen) | | | |
| Low/Wide (HID) | | | |

**Table 2. Two pedestrian locations and two adaptation levels corresponding to each cell in table 1.**

| Left Pedestrian | Right Pedestrian |
|---|---|
| High Adaptation Level | High Adaptation Level |
| Low Adaptation Level | Low Adaptation Level |

The presentation order of the VESs and pedestrian locations were counterbalanced to mitigate order effects. The driver light adaptation level was counterbalanced so that half of the participants began with low adaptation levels, and the other half began with high adaptation levels.

## INDEPENDENT VARIABLES

### VES

The VESs considered for use in this study were categorized in terms of beam intensity and width based on an analysis of available isocandela diagrams. A comparison across designs was made by measuring the beam width. This width was determined by finding the angle to the left and to the right of the headlamp center where the beam intensity fell to 12,000 cd. The sum of these angles represents the angular beam width, which is shown in table 3. The 12,000-cd intensity was selected because it was approximately equal to half the maximum intensity value of the headlamp with the lowest peak intensity (25,978 cd), and it was felt that this value was also a good representation of the luminous intensity directed to the left and right edgelines of the roadway in the forward view. The available VESs were divided into three subcategories (narrow, medium, and wide) by the measured beam widths.

**Table 3. Available VESs categorized by width (degrees) and intensity (candela).**

| Headlamp Type | Max Intensity cd (UD/LR) | 12,000 cd (Left) | 12,000 cd (Right) | Width (12,000 cd) | Width |
|---|---|---|---|---|---|
| HID | 34449 (.8D/2.6R) | −3 | 6 | 9 | Narrow |
| **Halogen*** | **30139.84(2D/0R)** | **−4** | **5.5** | **9.5** | **Narrow** |
| **HID*** | **40778 (1.0D/1.6R)** | **−3.5** | **6** | **9.5** | **Narrow** |
| HID | 26984 (.8D/1.8R) | −5.5 | 6.5 | 12 | Narrow |
| HID | 30666 (1.4D/1.8R) | −7 | 7 | 14 | Narrow |
| HID | 32882 (1.6D/1.8R) | −5.5 | 9.5 | 15 | Narrow |
| HID | 27145 (.6D/2R) | −7 | 9 | 16 | Narrow |
| HID | 38795 (1.8D/2.0R) | −9 | 8 | 17 | Narrow |
| HID | 30753 (1.2D/1.8R) | −7.5 | 10.5 | 18 | Medium |
| HID | 39953 (.8D/2.0R) | −8 | 11.5 | 19.5 | Medium |
| HID | 41431 (1.4D/2.8R) | −8.5 | 11 | 19.5 | Medium |
| HID | 41830 (1D/2.2R) | −5 | 14.5 | 19.5 | Medium |
| HID | 28120 (.8D/3.6R) | −8 | 12 | 20 | Medium |
| **HID*** | **35771 (.8D/2.2R)** | **−9** | **11** | **20** | **Medium** |
| HID | 28864 (1D/1.8R) | −9 | 11.5 | 20.5 | Medium |
| HID | 35916 (1.8D/2.2R) | −9.5 | 11 | 20.5 | Medium |
| HID | 43430 (.8D/2.40R) | −11 | 12.5 | 23.5 | Medium |
| HID | 45034 (1.0D/2.4R) | −9.5 | 14 | 23.5 | Wide |
| HID | 27127 (1.4D/2.0R) | −13 | 11 | 24 | Wide |
| HID | 36847 (1.2/3.0R) | −11 | 13 | 24 | Wide |
| HID | 41562 (1.2D/2.0R) | −11 | 13 | 24 | Wide |
| HID | 36061 (1.6D/2.2R) | −11 | 13.5 | 24.5 | Wide |
| HID | 40472 (.8D/.2R) | −12 | 12.5 | 24.5 | Wide |
| **HID*** | **28772 (.2D/2.0R)** | **−10.5** | **14.5** | **25** | **Wide** |
| HID | 25978 (.8D/3.2R) | −12.5 | 13.5 | 26 | Wide |
| **HID*** | **43181 (2.2D/.4R)** | **−13** | **13.5** | **26.5** | **Wide** |

* VESs evaluated in this study
U = degrees up
D = degrees down
L = degrees left
R = degrees right

The group of VESs that was selected for this study represented the extremes and midpoints for beam width and luminous intensity. These combinations of width and intensity are listed in table 4. The one halogen VES represented the low intensity and narrow beam width parameters. The rest of the VESs in the other combinations of beam characteristics were HID designs. Detailed information on each selected VES can be found in appendix G and ENV Volume XVII.

**Table 4. VES characteristic matrix.**

| | Narrow Beam Width | Medium Beam Width | Wide Beam Width |
|---|---|---|---|
| **High Beam Intensity** | HID 1 | | HID 2 |
| **Medium Beam Intensity** | | HID 3 | |
| **Low Beam Intensity** | Halogen | | HID 4 |

### Age Groups

For this experiment, the age factor had three levels, which were created based on literature-review findings (ENV Volume II) that suggest changes in vision during certain ages. (See references 17, 18, 19, 20, and 21.) 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, five males and five females, were involved in this study. This is the same representation of age and gender used in the majority of studies in the ENV project.

### Pedestrian Location

Vehicle crashes involving pedestrians are a major concern for the field of transportation safety. The physical characteristics of a human being are difficult to replicate; therefore, it was preferable to use real pedestrians in research involving detection of onroad pedestrians. Research has been done involving glare using varying types of pedestrian clothing including black, gray, white, denim, and khaki.[22] The reflectance and color characteristics of the clothing are important factors to consider when dealing with different VESs. Because of the short detection distances and difficulty with glare, the pedestrians were dressed in white clothing for this study. White clothing is higher in reflectance and, in this particular onroad environment, was easier to detect than other colors. This result was shown in previous ENV research conducted in the same onroad environment (e.g., ENV Volume III).

The locations of pedestrians in the roadway significantly affect their visibility in the presence of glare relative to the driver. A pedestrian located on the centerline of the road is in a location where the glare from oncoming headlamps is substantially greater for the driver.[17] On the other hand, a pedestrian located on the right edgeline of the roadway is farther away from the glare source in the lateral direction. These two locations were used in this study to further investigate these differences (table 5). Both locations were 15.2 m (50 ft) behind the glare headlamps. This distance was determined to be a safe stopping distance at the driving speed of 32 km/h (20 mi/h). All pedestrians stood facing the oncoming vehicle. It was important that pedestrians did not cover the road markings because this may have affected detection distances due to the sharp change in contrast.

Each participant was instructed to drive on the roadway and verbally inform the experimenter immediately when he or she detected a pedestrian.

**Table 5. Object descriptions.**

| Object | Location | Instructions |
|---|---|---|
| Left pedestrian | Centerline on roadway | Stand dressed in white clothing facing driver (parallel to line) 1 ft inside centerline. Important that feet do not cross or cover any portion of the line. |
| Right pedestrian | Right edgeline on roadway | Stand dressed in white clothing facing driver (parallel to line) 1 ft inside right edgeline. Important that feet do not cross or cover any portion of the line. |

1 ft = 0.305 m

**Driver Light Adaptation Level**

To establish a range of possible illuminance values for the independent variable of driver light adaptation level, an in-vehicle evaluation of illuminance readings at the driver's eye level in different road and traffic conditions was performed. These measurements were made by mounting an illuminance meter in a vehicle at the driver's eye height. The values were measured while driving on an unlit highway and a highway with overhead lighting. The results are illustrated in figure 2. The low ambient light conditions in the left half of the graph are from the unlit highway, and the conditions in the right half are from the highway with overhead lighting. Some of the spikes represent oncoming glare from approaching vehicles. These onroad measurements were considered along with previous methods in similar studies involving glare and object detection to establish the two experimental values of driver light adaptation.(23) These two levels, kept in the mesopic range, were set at a low value of 0.15 lx and a high value of 0.45 lx. The driver light adaptation level was switched between the two by using a dimmable, narrow band of diffuse lighting located across the top of the vehicle's instrumentation panel (figure 3). These levels were checked with an illuminance meter in the vehicle at the driver's eye. The dimming range was 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.

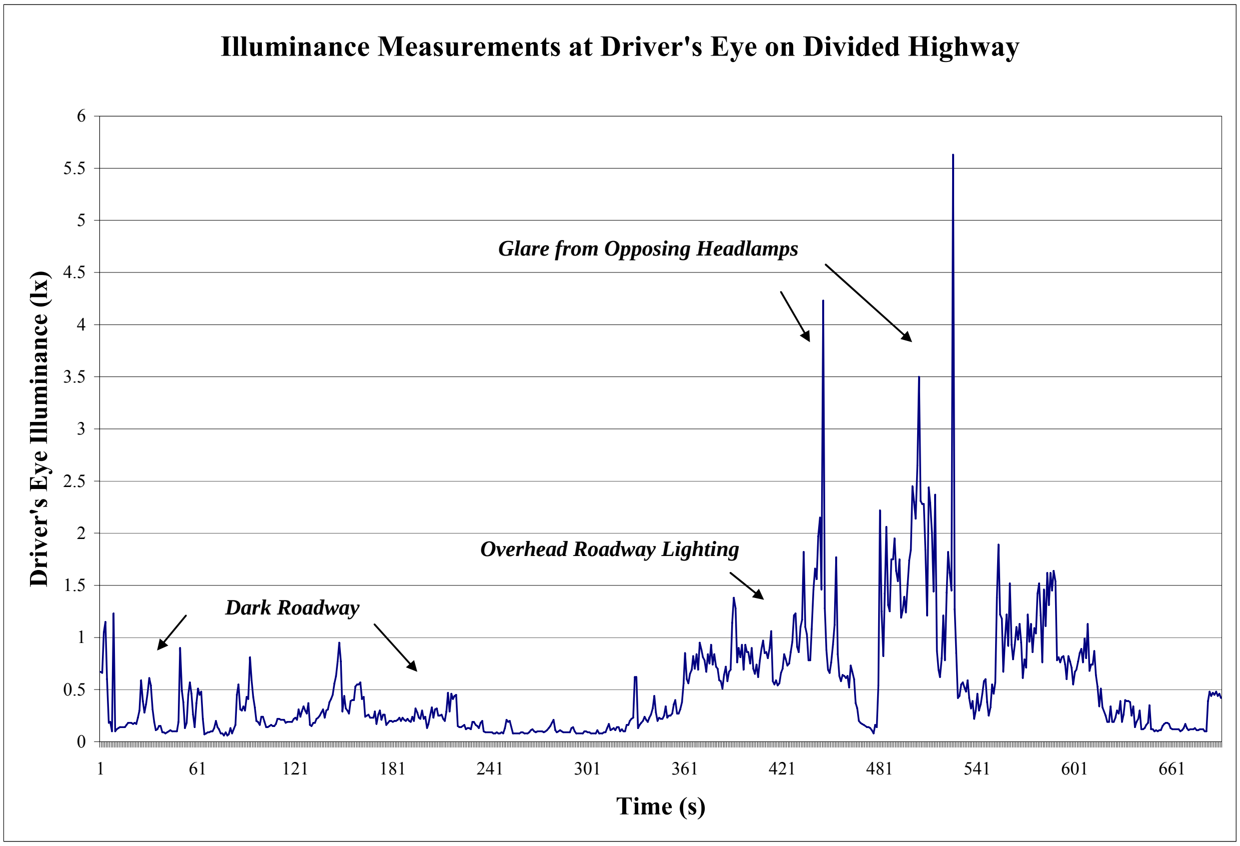



**Figure 2. Line graph. Illuminance readings taken on a divided highway at night with and without overhead lighting and glare.**

**Figure 3. Photo. Light source used to control driver light adaptation level.**

## DEPENDENT VARIABLES

The dependent variables gathered were detection distance (m (ft)), driver illumination level (lx), and the deBoer scale rating of discomfort glare. Distance and driver illuminance data were collected at 10 hertz by the in-vehicle instrumentation package.

### Detection Distance

Detection distances are important when determining nighttime visibility.[24] Detection distances were collected during the disability glare portion of the study. The participant was instructed to verbally inform the experimenter immediately when he or she could detect a pedestrian. The in-vehicle experimenter flagged the data each time the participant detected a pedestrian. As the vehicle passed the pedestrian's location on the road, the in-vehicle experimenter pressed a separate button to flag the actual location of the pedestrian. These flagged points were used to calculate the detection distance. All experimental trials were videotaped with an audio track, providing a means of data verification by way of post hoc video analysis.

### Illuminance Measurements

In addition to tracking detection distances, the computer program also collected a series of illuminance measurements. An illuminance meter was placed in the vehicle in a position that represented the height of the participants' eye. Illuminance readings (in lux) were then gathered every tenth of a second so that the approximate illuminance reaching the eye at the moments of detection as well as during the discomfort ratings could be determined. This allowed the analysis to account for certain variables such as lane positions (i.e., angle of glare) and ambient lighting conditions. This method also gave a baseline ambient illuminance reading so that changes in adaptation levels could be tracked.

### Discomfort Glare Ratings

Subjective ratings were collected during the discomfort glare portion of the study. As the participant approached the VESs, he or she was asked to evaluate the discomfort experienced from the headlamps. After passing the VES, 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 scale and its anchors were reviewed with the participant before each trial to ensure accurate rating (appendix I). The participant's discomfort glare rating was an overall rating from the starting point at 305 m (1,000 ft) away and continuing up to the VES.

## IN-VEHICLE AND ONROAD SAFETY

This research involved participants driving vehicles on a closed roadway with real pedestrians in induced glare situations; therefore, many measures were taken to ensure the safety of all those involved, including: (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) the data collection equipment did not interfere with the normal field of view of the participant; (4) a trained in-vehicle experimenter had to be in the vehicle at all times to guide the participant and answer questions; (5) onroad experimenters (pedestrians and other workers) knew when to clear the road when a vehicle approached even if the radio communication failed; and (6) a list of emergency procedures was developed and reviewed before testing.

## APPARATUS AND MATERIALS

### Brightness Acuity Tester

The Brightness Acuity Tester™ (BAT) was used to evaluate participants' susceptibility to glare. The BAT is a handheld eye occluder with a domed aperture, pictured in figure 4. This device provides three levels of ambient luminance: 41.2 cd/m$^2$ (12 fL), 343 cd/m$^2$ (100 fL), and 1,372 cd/m$^2$ (400 fL), producing low, medium, and high levels of glare, respectively. It can also be used while turned off to permit a baseline measurement of visual acuity. The test involved the participant looking at the Snellen acuity chart with one eye through the BAT set sequentially for all four veiling luminance (glare) lighting conditions (off, low, medium, and high). Data for each eye was recorded, and the change from the baseline (off) to the different glare settings was noted. Participants who had a significant change as the luminance level was increased were more sensitive to glare. The typical Snellen acuity results of a participant with normal glare sensitivity can be seen in table 6. The results changed for mildly sensitive participants (table 7). A participant with severe light sensitivity had results typical to table 8. This test is important because two individuals with the same visual acuity and contrast sensitivity may have different sensitivities to glare.

**Table 6. Typical results of normal glare sensitivity with BAT.**

| | 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 7. Typical results of mild glare sensitivity with BAT.**

| | 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 8. Typical results of severe glare sensitivity with BAT.**

| | Off | Low | Medium | High |
|---|---|---|---|---|
| **Right Eye** | 20/40 | 20/60 | 20/80 | 20/400 |
| **Left Eye** | 20/50 | 20/80 | 20/200 | <20/400 |

**Figure 4. Photo. Brightness Acuity Tester.**

## Test Vehicle

The driving portion of the study took place in a full-sized sedan with factory-installed halogen headlamps. The sedan was equipped with sensors that determined speed, eye-level illuminance, and distance traveled. These sensors fed into a laptop computer located in the back seat with the in-vehicle experimenter. This computer was equipped with a software program developed specifically for this data collection. The software allowed the experimenter to collect distances, illuminance readings, and keep track of orders as well as other information pertaining to the participant. A narrow band of diffuse lighting was installed on the dashboard across the top of the instrumentation panel. Experimenters used a dimmer switch to change the driver light adaptation level between the low and high settings.

## VESs

The different VESs were positioned on the road using special headlamp mounting carts. This cart, as seen in figure 5, was designed to position the headlamps at the same height and width of a real vehicle. The daylight photo in figure 6 shows the headlamp cart and experimental vehicle. The nighttime photo in figure 7 shows the cart as seen from the experimental vehicle. The headlamps were positioned at a height of 83.8 cm (33 inches) from the center point of the headlamp to the road surface, which is comparable to the mounting height on a standard SUV. The headlamps were laterally separated by 109.2 cm (43 inches). The advantages of using the carts rather than real vehicles were that they were lightweight and easier to maneuver, they could be more accurately and reliably aimed in a fixed position along the roadway, and they did not represent as much of a safety hazard as an entire vehicle in the oncoming lane of traffic would. The headlamps were powered at 12.8 V with the use of an electrical inverter for consistent performance. The headlamps were aimed according to the manufacturer's specifications and checked before each experimental session. The aiming methods and protocol can be seen in appendix F.

To avoid exposing participants to the tested VESs during the practice portion of the study, a pickup truck equipped with standard halogen headlamps was used instead of the glare cart.

**Figure 5. Photo. Back view of glare cart with halogen VESs (low/narrow) mounted.**

**Figure 6. Photo. Glare cart and experimental vehicle on the Smart Road.**

**Figure 7. Photo. Glare cart with VESs at night with left pedestrian.**

### Smart Road Testing Facility

The driving portion of the study took place on the Virginia Smart Road. The study used only one specific station on a concrete section rather than on asphalt to present VESs and pedestrians. This was done to ensure that the contrast of the objects in relation to the roadway was kept consistent for all experimental trials. The Smart Road is a test-only facility that is closed to the general public; no vehicles other than the experimental vehicle were on the roadway. No overhead lighting was in use. The facility was monitored by the Smart Road control tower, and the dispatcher in the control tower could assist the experimenters if needed. Before the experimental vehicle entered the road, an experimenter had to establish radio contact with the dispatcher. Radios were used to communicate with other onroad experimenters and the control tower. To avoid disturbing the participant or the data collection process, the in-vehicle experimenter wore a headset inside the vehicle.

## EXPERIMENTAL PROCEDURE

Candidates for the experiment were screened by telephone using a participant screening questionnaire (appendix A). Candidates who met the eligibility criteria were then scheduled to participate in the study. A single driver was scheduled for each data collection session.

An experimenter met each participant when he or she arrived at the testing facility. The participant was given a brief overview of the study and a description of the night's activities. The experimenter verified that the participant had a valid driver's license and then provided the participant with an informed consent form (appendix B) to read and sign before continuing. After all questions were answered and the form was signed, the experimenter administered a series of informal vision tests. These tests included the Snellen eye chart, contrast sensitivity test, brightness acuity test, and a color vision test (appendix C). Results from the vision tests were recorded, but participants were not excluded based on the results. The participant was then given a predrive questionnaire (appendix H) to gather information about nighttime driving habits. After the preliminary information was gathered, the participant was instructed on the experimental tasks.

**Training Procedures**

The experimenter explained the detection task and explained that the participant should verbally alert the experimenter at the moment he or she detected the pedestrian on the road. The deBoer scale (appendix I) was also reviewed with the participant, and the participant had a chance to ask the experimenter questions or express concerns. The purpose of this predrive overview was for the participant to understand the basic procedures of the experiment and what was expected of him or her during the study. When there were no more questions or concerns, the participant was familiarized with the experimental vehicle.

**Vehicle Familiarization**

The participant was shown to the experimental vehicle by the in-vehicle experimenter. The experimenter demonstrated how to correctly adjust the seat and seatback, the steering wheel position, and the side and rearview mirrors. The experimenter also gave instructions on the operation of the headlamps and climate control system if needed. It was important to ensure that all adjustments were made so that the driver was in a normal, comfortable position. Then the experimenter took eye height measurements of the participant as described in the in-vehicle experimental protocol (appendix D). After all questions and concerns were addressed, the participant began the driving portion of the study.

## Driving Instructions

The participant was informed that while on the test section of roadway, which was indicated by the in-vehicle experimenter, the speed limit was 32 km/h (20 mi/h) for the safety of the onroad experimenters. To make the task of staying at 32 km/h (20 mi/h) less difficult, the participant was instructed to use second gear in the vehicle's automatic transmission. The driver was permitted to lower the speed if he or she desired to do so in any situation during testing. The participant was also told to drive in the right-hand lane during the study.

## In-Vehicle Test Sequence

Each participant completed a practice lap before beginning data collection for the discomfort glare portion of the study. Then the participant was exposed to each VES under a predetermined driver light adaptation level. After each run, the participant stopped the vehicle, and the in-vehicle experimenter collected the subjective discomfort glare data. After the participant evaluated the discomfort glare of all VESs, and while remaining under the same driver light adaptation level, the experimenter guided the participant through another practice lap before beginning the data collection for the disability glare evaluation. The participant was then exposed to all the VESs and object combinations to examine disability glare under the given driver light adaptation level. When this was complete, the driver light adaptation level was changed, and the participant was guided through another session of the discomfort glare protocol followed by the disability glare protocol under this second level of driver light adaptation.

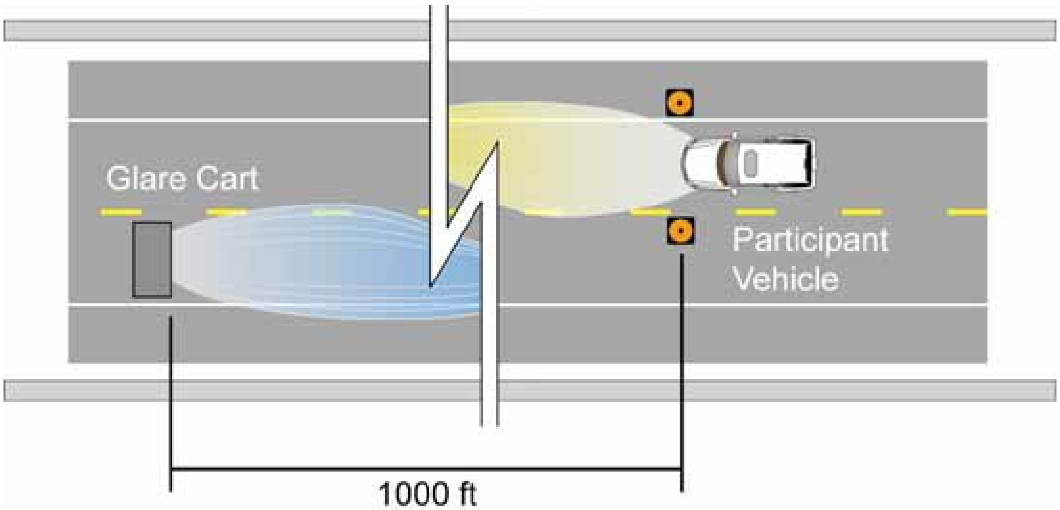
## Discomfort Glare Practice Lap

The first lap on the Smart Road was considered a practice lap. Participants were given these two runs, one up the road and one down the road, to become familiar with the road, the test vehicle, and the experimental procedures for the discomfort glare portion of the study. During the practice session, a pickup truck equipped with standard halogen headlamps was used rather than the glare cart. The participant was asked to evaluate the glare from the truck's high and low beams. During these practice runs, the in-vehicle experimenter guided the participant through the driving procedures and subjective ratings.

### Discomfort Glare Data Collection

The discomfort glare subjective ratings were gathered for each combination of driver adaptation level and VES. The primary task of the participant was to safely drive the vehicle at or below the set speed of 32 km/h (20 mi/h). The in-vehicle experimenter was in the back right seat of the vehicle. Appendix D contains a detailed explanation of the in-vehicle experimenter's role. In addition to the in-vehicle experimenter, the testing process included four onroad experimenters. Appendix E explains the responsibilities of the onroad experimenters.

During data collection for the discomfort glare study, onroad experimenters set up the glare cart in the opposite lane, facing the direction of approach of the participant's vehicle. The VES was positioned on the glare cart according to the predetermined order. The onroad experimenters placed black felt in front of the VES and then notified the in-vehicle experimenter when the headlamps were stabilized. The in-vehicle experimenter instructed the participant to drive the vehicle to a set of cones placed 305 m (1,000 ft) from the front of the glare cart (see figure 8). When the participant vehicle was in position, the onroad experimenters removed the felt, and the participant was instructed to drive in the right lane toward the glare cart at 32 km/h (20 mi/h). The participant was told to consider his or her rating of overall perceived discomfort while approaching the glare cart. The in-vehicle experimenter instructed the participant to stop the vehicle at the designated location 30.5 m (100 ft) past the glare cart. While the vehicle was parked, the experimenter asked the participant to verbally rate the discomfort glare using the deBoer scale. The scale and its anchors were reviewed with the participant before each trial to ensure accurate rating. If an error occurred during testing, the trial was repeated at the end of the night.



1 ft = 0.305 m

**Figure 8. Diagram. Plan view of the participant vehicle at the start point in the discomfort glare portion.**

### Disability Glare Practice Lap

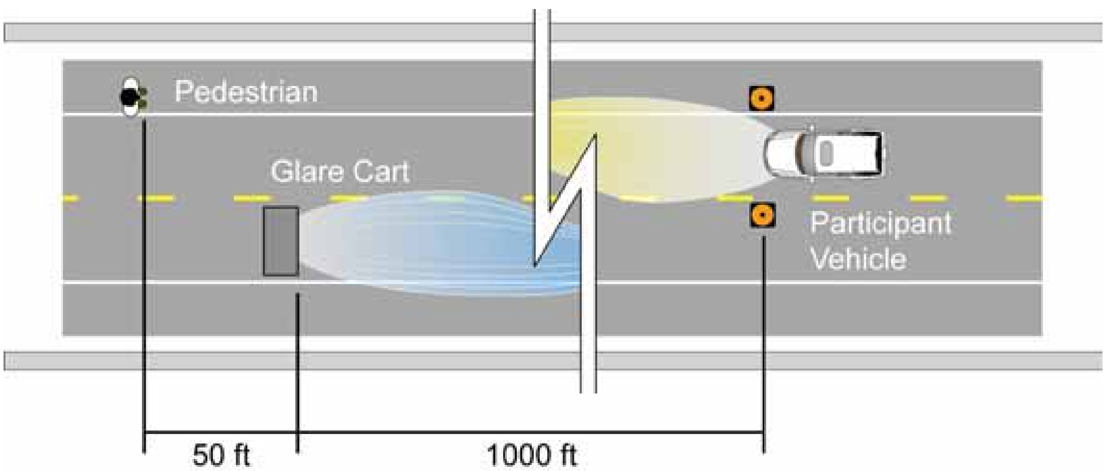
Before data collection for the first disability glare session, the participant completed a practice lap. These two runs, one up the road and one down the road, ensured that the participant was familiar with the object detection task before data collection began. A pickup truck equipped with standard halogen headlamps was used in place of the glare cart during the practice lap, during which participants were presented with the pedestrian in the glare of the truck's high beams and its low beams.

### Disability Glare Portion

During the disability glare portion of the experiment, data were collected for each VES, driver light adaptation level, and pedestrian location combination. The primary task of the participant was to drive the vehicle safely at or below the set speed of 32 km/h (20 mi/h). The in-vehicle experimenter was in the back right seat of the vehicle, monitoring the data collection equipment and guiding the participant through the tasks. The initial steps were similar to the setup in the discomfort glare study. The onroad experimenters set up the glare cart, positioned a VES on the cart, and covered it with felt. The in-vehicle experimenter instructed the participant to drive the vehicle to a set of cones placed 305 m (1,000 ft) from the front of the glare cart (see figure 9).

When the participant's vehicle was in position, the onroad experimenters removed the felt, and the participant was instructed to drive in the right lane toward the glare cart at 32 km/h (20 mi/h).

The participant was instructed to verbally alert the in-vehicle experimenter immediately when he or she could detect a pedestrian. The experimenter flagged the data and recorded the participant's responses. As the vehicle passed the pedestrian, who had cleared the road for safety reasons, the in-vehicle experimenter pressed a separate button to flag the data again, indicating the pedestrian's location. If an error occurred during testing, the trial was repeated at the end of the data collection. After the participant had been exposed to all the combinations of variables, he or she returned to the testing facility and received payment at the rate of $20 per hour.




1 ft = 0.305 m

**Figure 9. Diagram. Plan view of the participant vehicle at the start point for the disability glare portion with right pedestrian.**

## DATA ANALYSIS

All participants' raw data collected from the in-vehicle computer program were first sorted and merged into one data file. Each participant had a separate data file for every headlamp combination and light adaptation level. 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 discomfort glare ratings, the detection distance data, and the illuminance values. The independent variables in this study and their naming conventions are as follows: VES glare (VES), age (age), driver light adaptation level (adapt), and pedestrian location (pedestrian).

Age was the only between-factor variable. Two different models were used in this study. For the discomfort glare rating, a mixed-factor model including VES, age, and adaptation level was used (table 9). The model shown in table 10, which includes VES, age, adaptation level, and pedestrian position, was used in the analysis of the detection distances and illuminance values under disability glare. For significant main effects ($p < 0.05$), a post hoc Student-Newman-Keuls (SNK) test was performed to determine which levels were significantly different. Statistically different means are designated by different letters in the figures and tables.

**Table 9. Mixed-factor design for discomfort glare.**

| SOURCE |
|---|
| ***BETWEEN*** |
| **Age** |
| ***Participant (Age)*** |
| ***WITHIN*** |
| **VES** |
| **VES by Age** |
| ***VES by Participant (Age)*** |
| **Adapt** |
| **Adapt by Age** |
| ***Adapt by Participant (Age)*** |
| **VES by Adapt** |
| **VES by Adapt by Age** |
| ***VES by Adapt by Participant (Age)*** |

**Table 10. Mixed-factor design for detection distance and illuminance.**

| **SOURCE** |
| --- |
| ***BETWEEN*** |
| **Age** |
| ***Participant (Age)*** |
| ***WITHIN*** |
| **VES** |
| **VES by Age** |
| ***VES by Participant (Age)*** |
| **Adapt** |
| **Adapt by Age** |
| ***Adapt by Participant (Age)*** |
| **Pedestrian** |
| **Pedestrian by Age** |
| ***Pedestrian by Participant (Age)*** |
| **VES by Adapt** |
| **VES by Adapt by Age** |
| ***VES by Adapt by Participant (Age)*** |
| **VES by Pedestrian** |
| **VES by Pedestrian by Age** |
| ***VES by Pedestrian by Participant (Age)*** |
| **Adapt by Pedestrian** |
| **Adapt by Pedestrian by Age** |
| ***Adapt by Pedestrian by Participant (Age)*** |
| **VES by Adapt by Pedestrian** |
| **VES by Adapt by Pedestrian by Age** |
| ***VES by Adapt by Pedestrian by Participant (Age)*** |

# CHAPTER 3—RESULTS

## PREDRIVE QUESTIONNAIRE

During the preparation for the experimental session, the participants completed a predrive questionnaire, which included a question on the concerns of the drivers when driving at night. This question was used to establish if a driver perceived that he or she was sensitive to glare. None of the younger drivers expressed a concern about glare, but 5 of the 10 older participants named glare or other headlights as an area of concern.

## ANOVA RESULTS

The significant main effects and interactions for each dependent variable are marked with an "x" in table 11. The effect of pedestrian location and its interactions were specific to the disability glare portion of this study.

**Table 11. Significant main effects and interactions.**

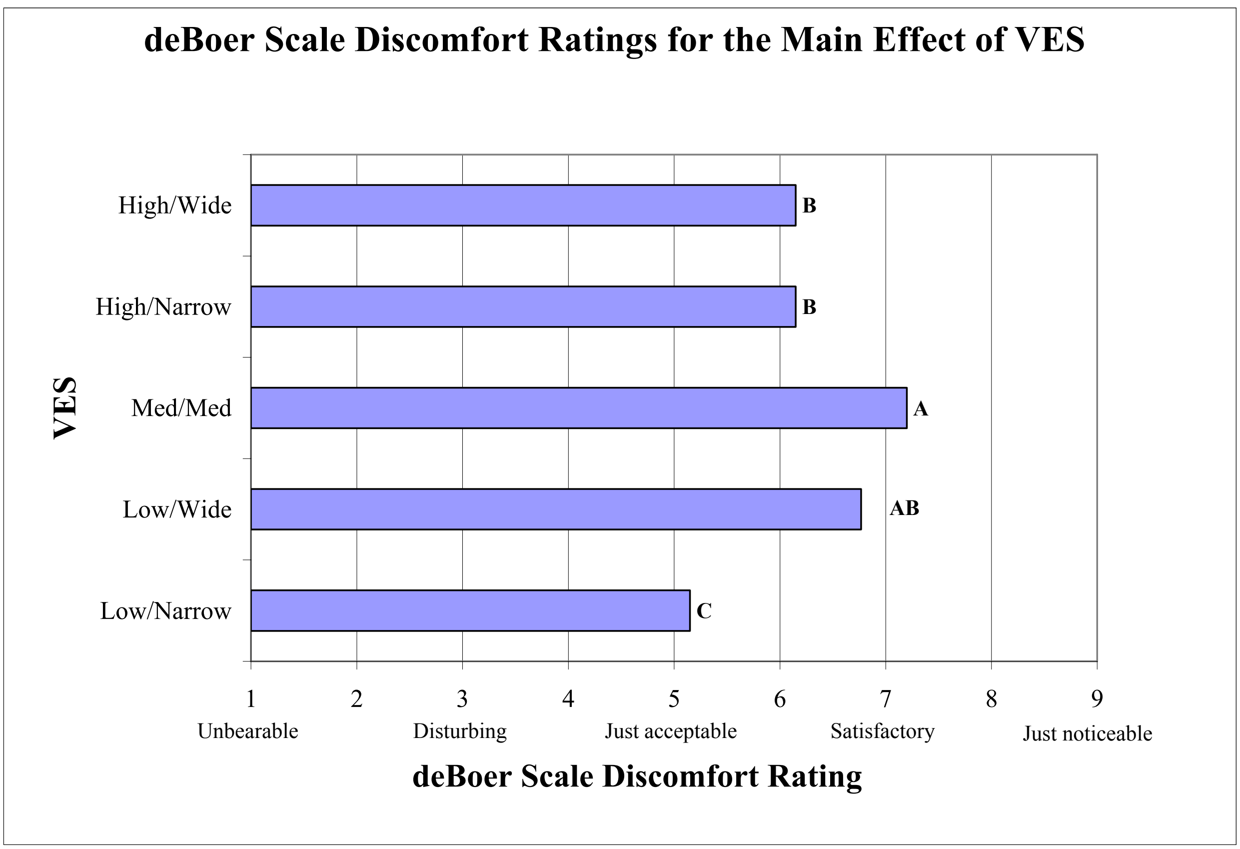
| Source | Disability Glare Detection Distances | Disability Glare Driver's Eye Illuminance | Discomfort Glare deBoer Scale Ratings |
|---|---|---|---|
| ***Between*** | | | |
| Age | x | x | |
| *Participant (Age)* | | | |
| | | | |
| ***Within*** | | | |
| VES | x | x | x |
| VES by Age | | x | |
| *VES by Participant (Age)* | | | |
| | | | |
| Adaptation | | | |
| Adaptation by Age | | | |
| *Adaptation by Participant (Age)* | | | |
| | | | |
| VES by Adaptation | | | |
| VES by Adaptation by Age | | | |
| *VES by Adaptation by Participant (Age)* | | | |
| | | | |
| Pedestrian | x | x | |
| Pedestrian by Age | | x | |
| *Pedestrian by Participant (Age)* | | | |
| | | | |
| Pedestrian by VES | x | x | |
| Pedestrian by VES by Age | | x | |
| *Pedestrian by VES by Participant (Age)* | | | |
| | | | |
| Pedestrian by Adaptation | | | |
| Pedestrian by Adaptation by Age | | | |
| *Pedestrian by Adaptation by Participant (Age)* | | | |
| | | | |
| Pedestrian by VES by Adaptation | | | |
| Pedestrian by VES by Adaptation by Age | | | |
| *Pedestrian by VES by Adaptation by Participant (Age)* | | | |

x = $p < 0.05$ (significant)

## DEBOER SCALE RATINGS

An ANOVA was performed on the deBoer scale ratings recorded during the driving portion of this study. The model for this portion of the study was a 2 (Adaptation) by 5 (VES) by 3 (Age) mixed-factor design. ANOVA summary tables were developed for the dependent measure of the subjective deBoer scale rating. The complete ANOVA table for the discomfort glare portion appears in appendix J.

Only the main effect of VES glare (VES) was significant for the subjective measure of discomfort ($p < 0.05$), with an F value of 14.36. The post hoc analysis indicated three significantly different groupings of discomfort glare among the five VESs (figure 10, table 12). The glare produced by the low/narrow halogen VES was rated the most discomforting, with the lowest mean deBoer scale rating of 5.15. This rating of "Just acceptable" was statistically different than the other VESs. On the other hand, the glare produced by the medium/medium HID was rated the least discomforting, with a mean deBoer scale rating of 7.2 ("Satisfactory"). This VES was statistically different from the other VESs, with the exception of the low/wide VES. The high/narrow and high/wide have the same average deBoer rating (6.15).




Means marked with the same letter are not significantly different.

**Figure 10. Bar graph. deBoer discomfort ratings for the main effect of VES (scale of 1 to 9).**

**Table 12. Discomfort glare SNK groupings for the VES main effect.**

| VES | N | Mean deBoer Rating | SNK Grouping |
|---|---|---|---|
| Low/Narrow | 60 | 5.15 | C |
| Low/Wide | 60 | 6.77 | AB |
| Medium/Medium | 60 | 7.20 | A |
| High/Narrow | 60 | 6.15 | B |
| High/Wide | 60 | 6.15 | B |

N = sample size

## DETECTION DISTANCE

An ANOVA was performed on the detection distances taken during the disability glare portion of this study. The model for this variable was a 2 (Driver Light Adaptation Level) by 2 (Pedestrian) by 5 (VES) by 3 (Age) factorial design. ANOVA summary tables were developed for the dependent measurement of detection distance (appendix J). It should be noted that a shorter detection distance suggests more oncoming glare and a longer detection distance suggests less glare. In the graphs for this section, standard error bars are included on top of the means.

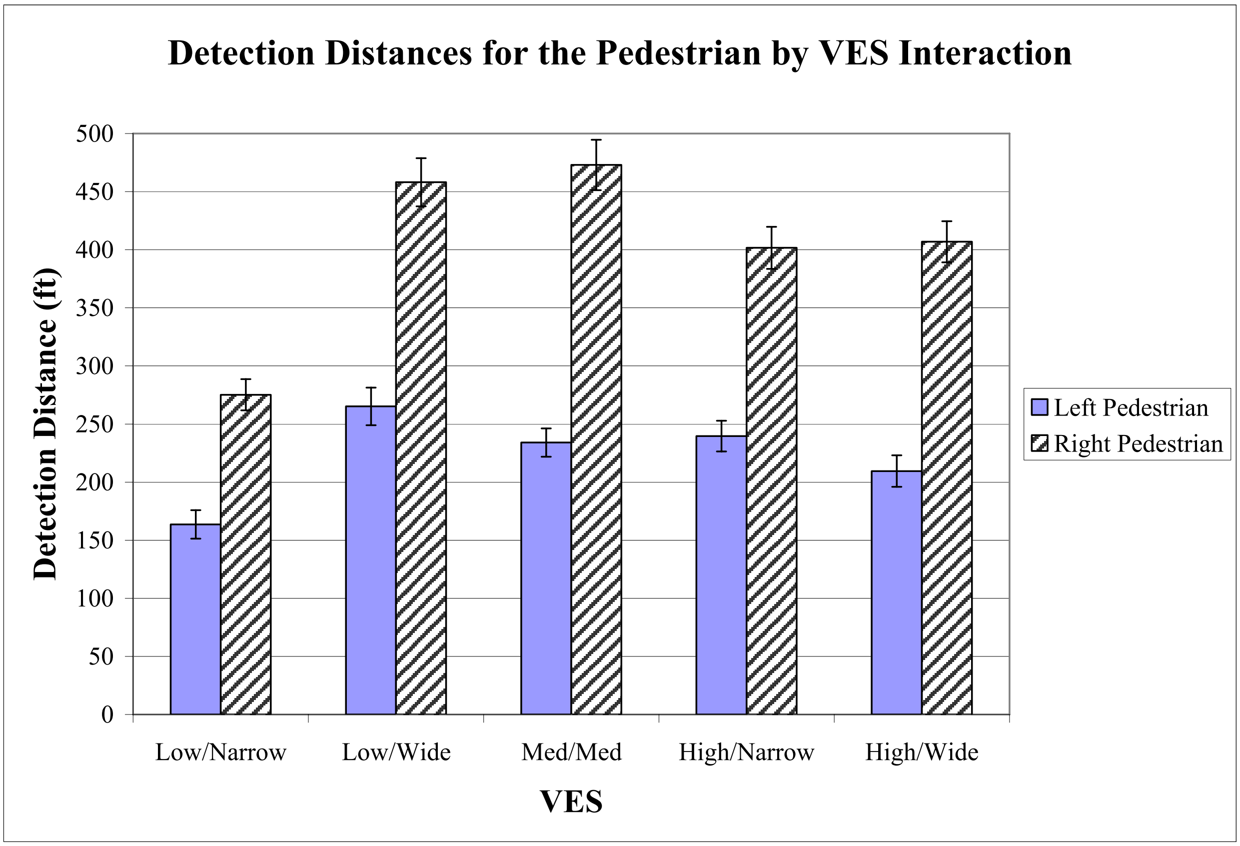
A total of 599 observations of the detection distance measurement were gathered during the driving portion of the study, with only one missing datapoint. The results yielded a significant two-way interaction—Pedestrian by VES—and three main effects—VES, pedestrian location, and age.

The main effect of driver light adaptation level was not significant, with an F value of 0.66. The low and high adaptation levels both allowed similar mean detection distances of 94.2 m (309 ft) and 96.6 m (317 ft).

### Pedestrian by VES Interaction

The interaction of pedestrian location and VES was significant ($p < 0.05$), with an F value of 10.18. As illustrated in figure 11, the low/narrow VES had the lowest detection distance for both the pedestrian on the left and the right. The other VESs had similar distances to each other for the pedestrian on the left; however, the pedestrian on the right appeared to have longer detection for VESs rated as less glaring by the deBoer scale. Low/wide and medium/medium, the two

VESs rated the least glaring, allowed detection of the pedestrian on the right at more than 137 m (450 ft). High/narrow and high/wide, the VESs rated as the next least glaring, allowed detection of the pedestrian on the right at approximately 122 m (400 ft). These results indicate that detection of pedestrians on the right may be more susceptible to changes in glare than detection of pedestrians on the left; however, all the pedestrians on the left were detected much later than pedestrians on the right regardless of VES.

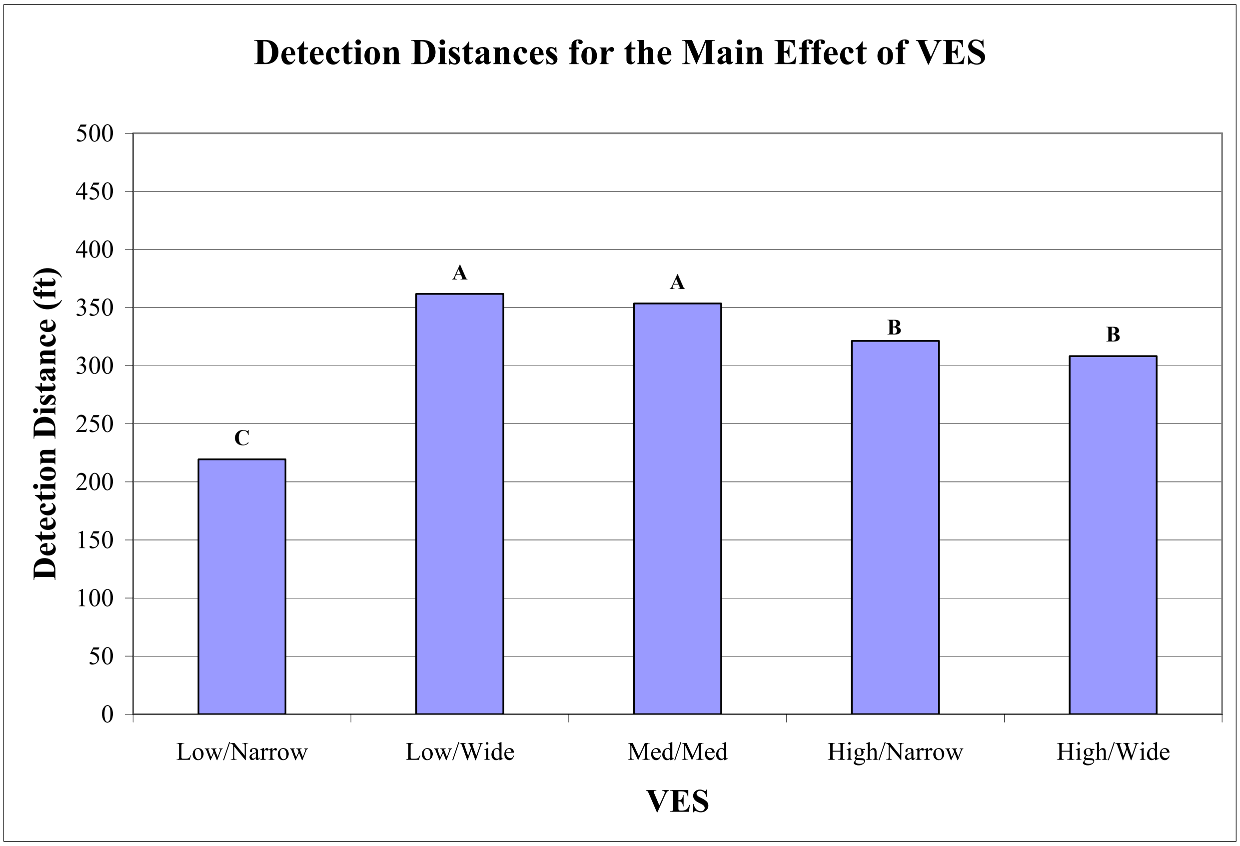



1 ft = 0.305 m

**Figure 11. Bar graph. Mean detection distances for the interaction of pedestrian and VES.**

**VES Main Effect**

The main effect of VES was significant ($p < 0.05$), with an F value of 26.89. The glare produced by the low/narrow halogen headlamps led to the lowest mean detection distance of 66.8 m (219 ft). The post hoc test (figure 12, table 13) showed the same grouping described in the Pedestrian by VES interaction (figure 11). As discussed previously, the grouping of VESs is more likely caused by differences in detection of the right-side pedestrian, with the exception of the poorest-performing VES (low/narrow).




1 ft = 0.305 m
Means marked with the same letter are not significantly different.

**Figure 12. Bar graph. Mean detection distances for the main effect of VES with SNK groupings.**

**Table 13. Detection distance SNK groupings for the VES main effect.**

| VES | N | Mean Detection Distance (ft) | SNK Grouping |
|---|---|---|---|
| Low/Narrow | 120 | 219 | C |
| Low/Wide | 120 | 362 | A |
| Medium/Medium | 120 | 354 | A |
| High/Narrow | 119 | 321 | B |
| High/Wide | 120 | 308 | B |

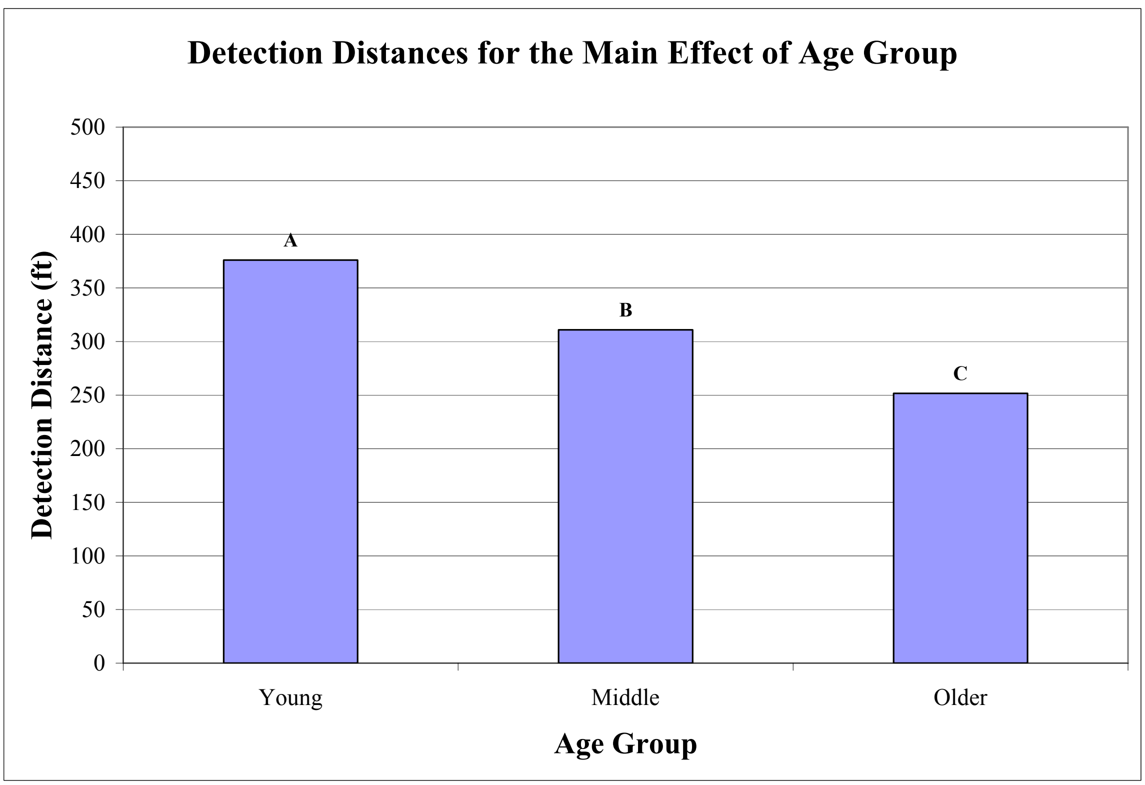
1 ft = 0.305 m
N = sample size

### Pedestrian Main Effect

The main effect of pedestrian position was significant ($p < 0.05$), with an F value of 86.11. The left-pedestrian location yielded a mean detection distance of 67.7 m (222 ft). The mean detection distance for the right pedestrian was much farther at 122.8 m (403 ft).

### Age Main Effect

The main effect of age was significant ($p < 0.05$), with an F value of 15.92 and had three levels. The post hoc SNK indicated that as age increased, detection distance significantly decreased. Young drivers detected the pedestrians with a mean distance of 114.6 m (376 ft). The mean distance for middle-aged drivers was 95.4 m (313 ft), and for older drivers the distance fell to 76.8 m (252 ft). This trend is illustrated in figure 13.




1 ft = 0.305 m
Means marked with the same letter are not significantly different.

**Figure 13. Bar graph. Mean detection distances for the main effect of age group with SNK groupings.**

## DRIVER'S EYE ILLUMINANCE MEASUREMENTS

An ANOVA was performed on the calculated change in illuminance at the driver's eye (Δ lux) because of the oncoming glare measured during the disability portion of this study. The specific illuminance levels at the moments of detection were the datapoints of interest; therefore, there was one illuminance reading that coincided with each detection distance. The model for the disability glare portion of this experiment was a 2 (Adapt) by 2 (Pedestrian) by 5 (VES) by 3 (Age) factorial design. ANOVA summary tables for the dependent measurement of driver's eye illuminance (Δ lux) can be seen in appendix J.

A total of 599 observations of driver's eye illuminance were gathered during the disability glare portion of the study, with only one missing datapoint. The results yielded a significant three-way interaction: Pedestrian by VES by Age. The two-way interactions of Pedestrian by VES, Pedestrian by Age, and VES by Age were also significant, as well as the main effects of VES, pedestrian, and age. Adaptation level did not result in significant interactions nor a significant main effect. The illumination levels at detection were 1.12 lx and 1.15 lx under the low and high adaptation levels, respectively.

### Pedestrian by VES by Age Interaction

The interaction of pedestrian and VES and driver age was significant ($p < 0.05$), with an F value of 7.75. The primary cause of the interaction was the mean illuminance of 5.69 lx at the moment of detection for older drivers viewing low/wide headlamps with the left pedestrian, whereas the same scenario produced an illuminance level of 0.90 lx at the moment of detection for younger drivers (figure 14). A further analysis of this data indicated that exceptionally high illuminance values were recorded for 7 of the 10 older participants at the time of detection. In an effort to isolate the cause of these high illuminance values, the data were reviewed in more detail. It appeared that the high values all occurred during the end of the data collection effort. In addition to these seven older participants, two middle-aged participants and one younger participant also participated during this time period. These three participants also had high illuminance values, indicating that something may have occurred to the headlamp during this time period that was not detected by the experimental team. Even with this possible confound, the low/wide VES was the second least glaring and allowed the longest detection distance of the pedestrians; however, if the last 10 participants had experienced the same glare level as the first 20 participants for this VES, this VES may have been rated as less glaring and allowed greater detection distance. More detail can be found in chapter 4, Discussion.

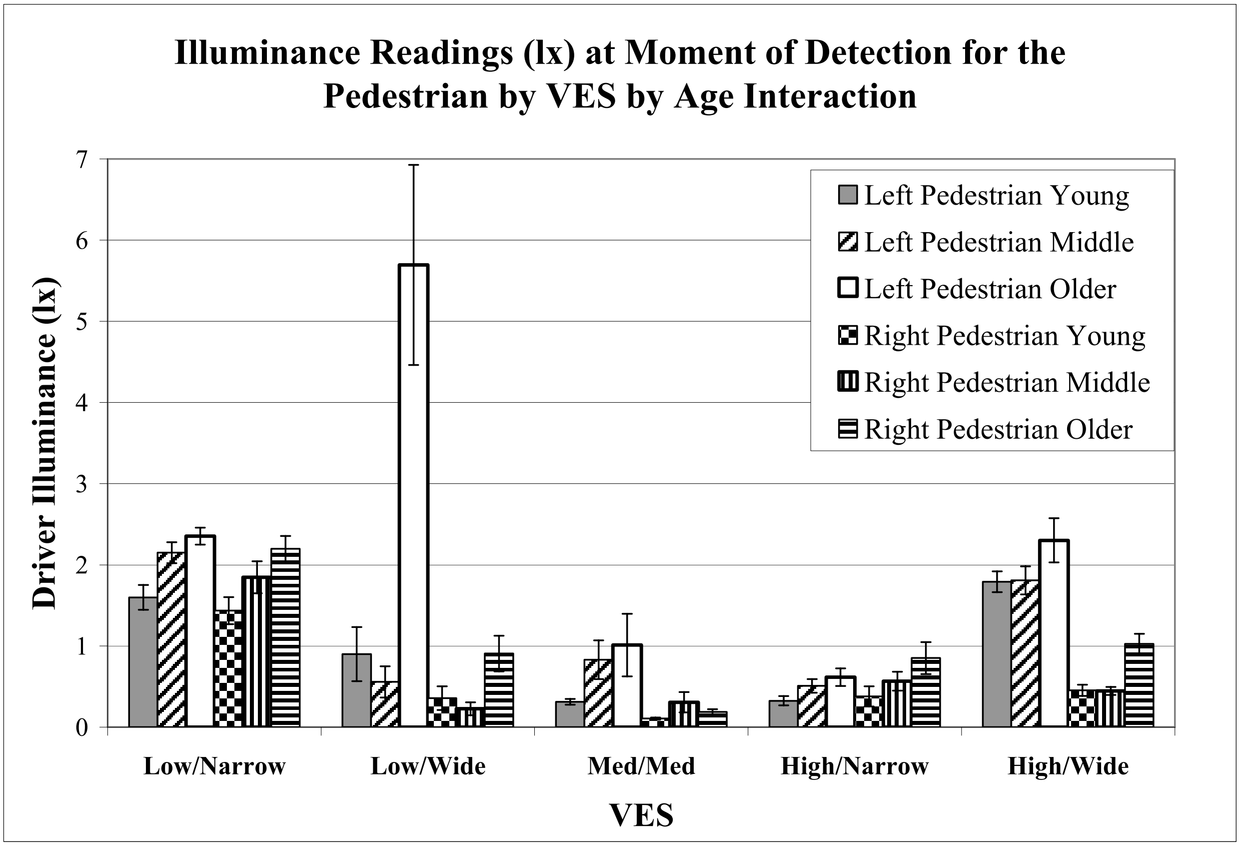



**Figure 14. Bar graph. Mean illuminance readings (lx) at moment of detection for the Pedestrian by VES by Age interaction.**

**VES by Age Interaction**

The interaction of VES by Age was significant ($p < 0.05$), with an F value of 5.7. The primary reason this interaction was significant is because of the older participants with the low/wide VES as discussed above. Other than this effect, it appears that the high/narrow VES and the low/narrow VES follow the expected trend of younger participants experiencing the least illuminance, older participants experiencing the most illuminance, and middle-aged participants being in between the extremes (figure 15). On the other hand, the medium/medium VES had similar illuminance for both the middle and older age groups, and the high/wide VES had similar illuminance for both the younger and middle age groups.

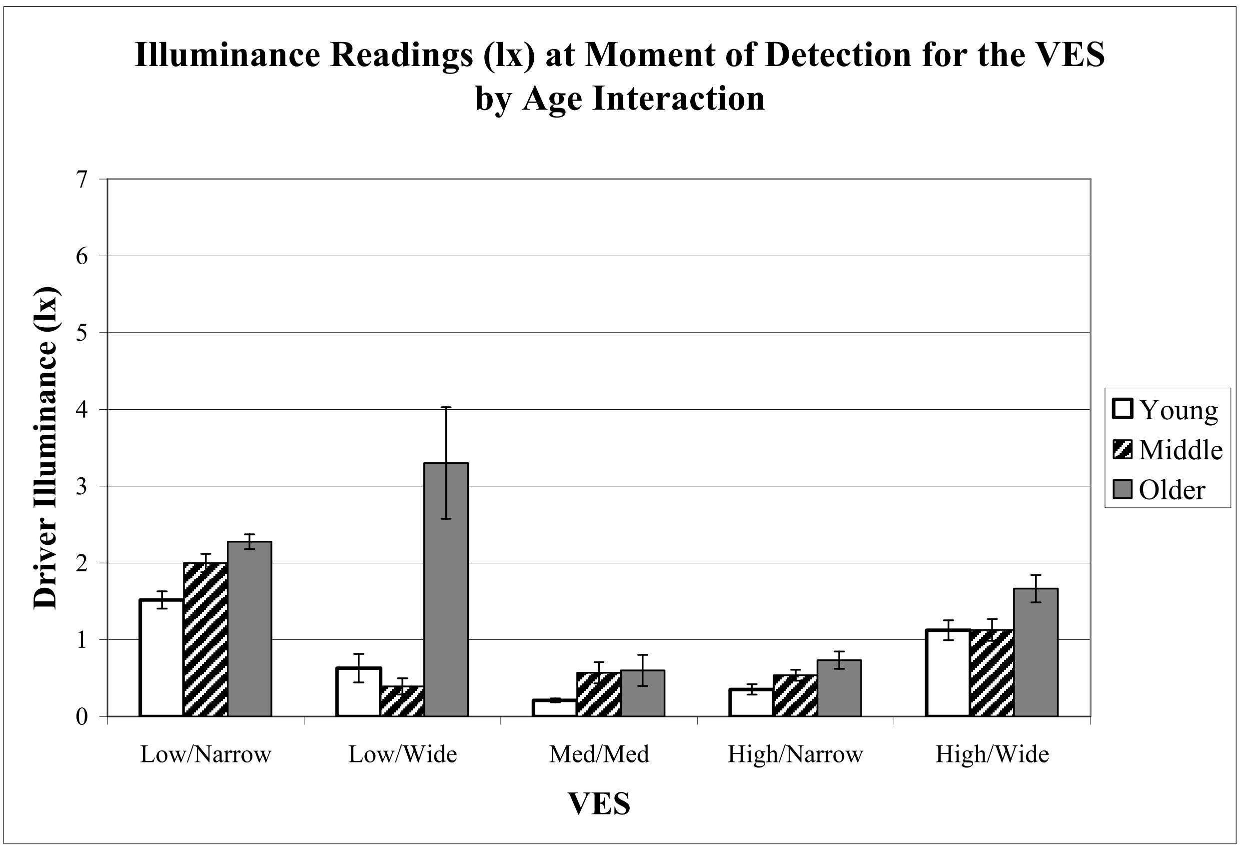



**Figure 15. Bar graph. Mean illuminance readings (lx) at moment of detection for the VES by Age interaction.**

**Pedestrian by Age Interaction**

The interaction of Pedestrian by Age was significant ($p < 0.05$), with an F value of 6.0. The primary reason this interaction was significant is also because of the older participants with the low/wide VES as discussed in the VES by Age by Pedestrian interaction paragraph. The left pedestrian was the pedestrian associated with the high illuminance for the low/wide headlamp, causing the interaction shown in figure 16.

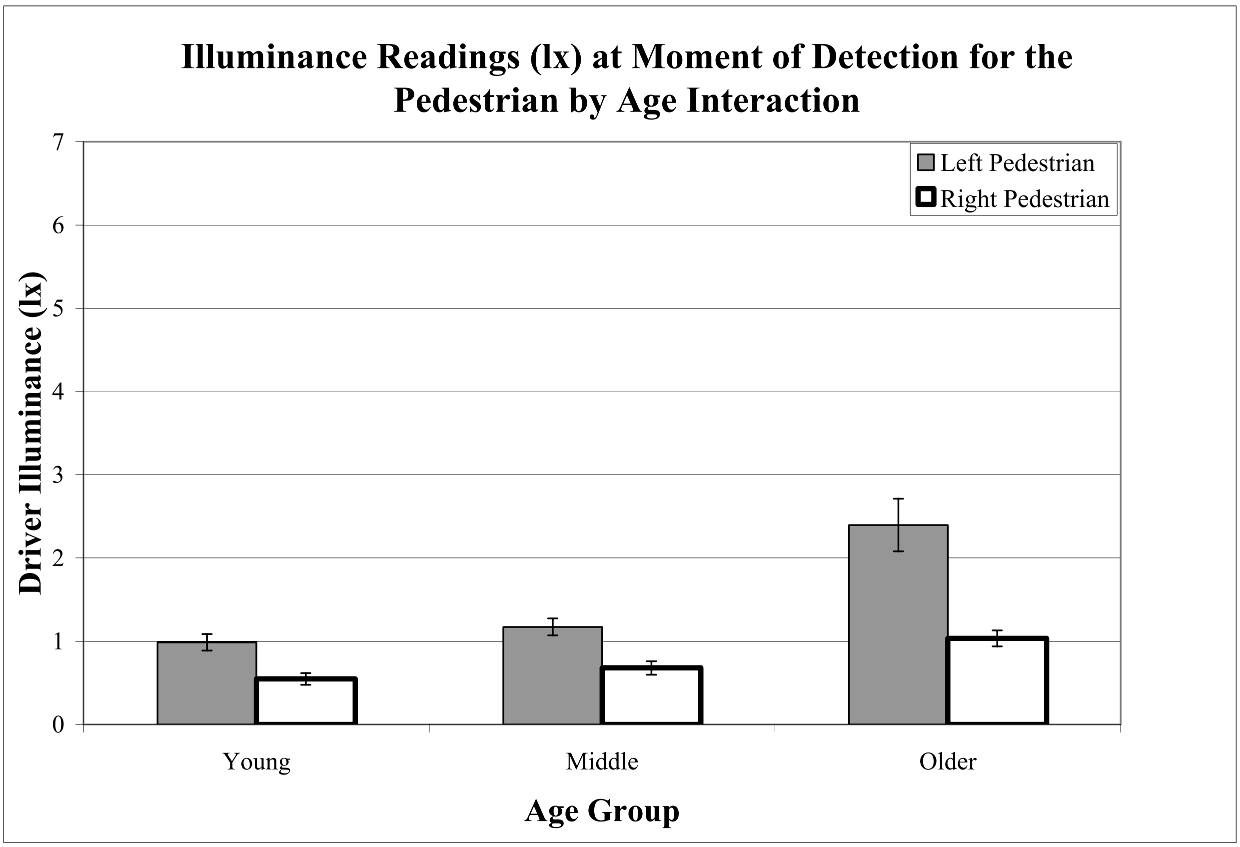



**Figure 16. Bar graph. Mean illuminance readings (lx) at moment of detection for the Pedestrian by Age interaction.**

**Pedestrian by VES Interaction**

The interaction of Pedestrian by VES was significant ($p < 0.05$), with an F value of 12.4. Although this interaction is also influenced by the Pedestrian by Age by VES interaction, there are some other interesting aspects of this interaction. As shown in figure 17, both of the wide-beam VESs had the largest illuminance at detection of the left pedestrian, which was also more than three times that of their illuminance at detection of the right pedestrian. The medium/medium VES also seemed to follow this trend; however, both the narrow-beam VESs had similar illuminances at the point of detection for both the left and right pedestrians.

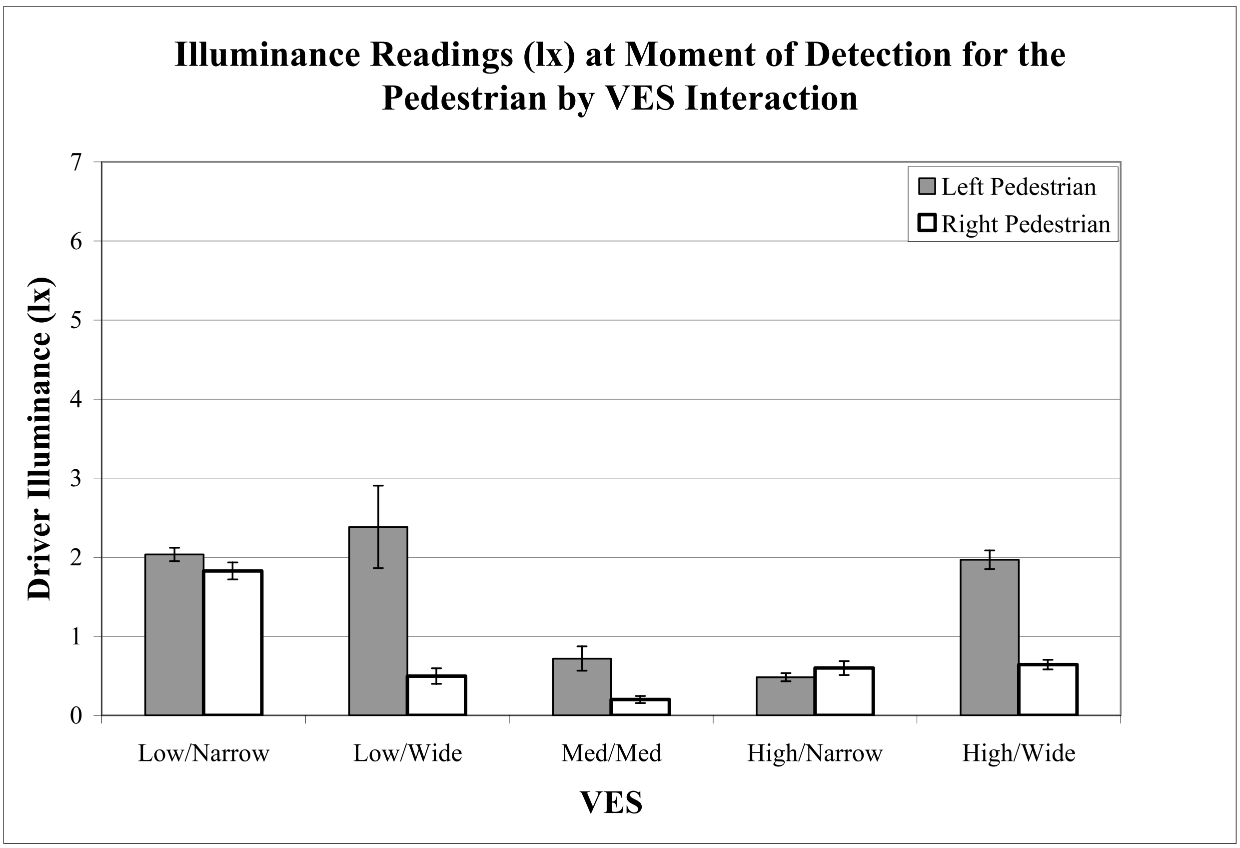
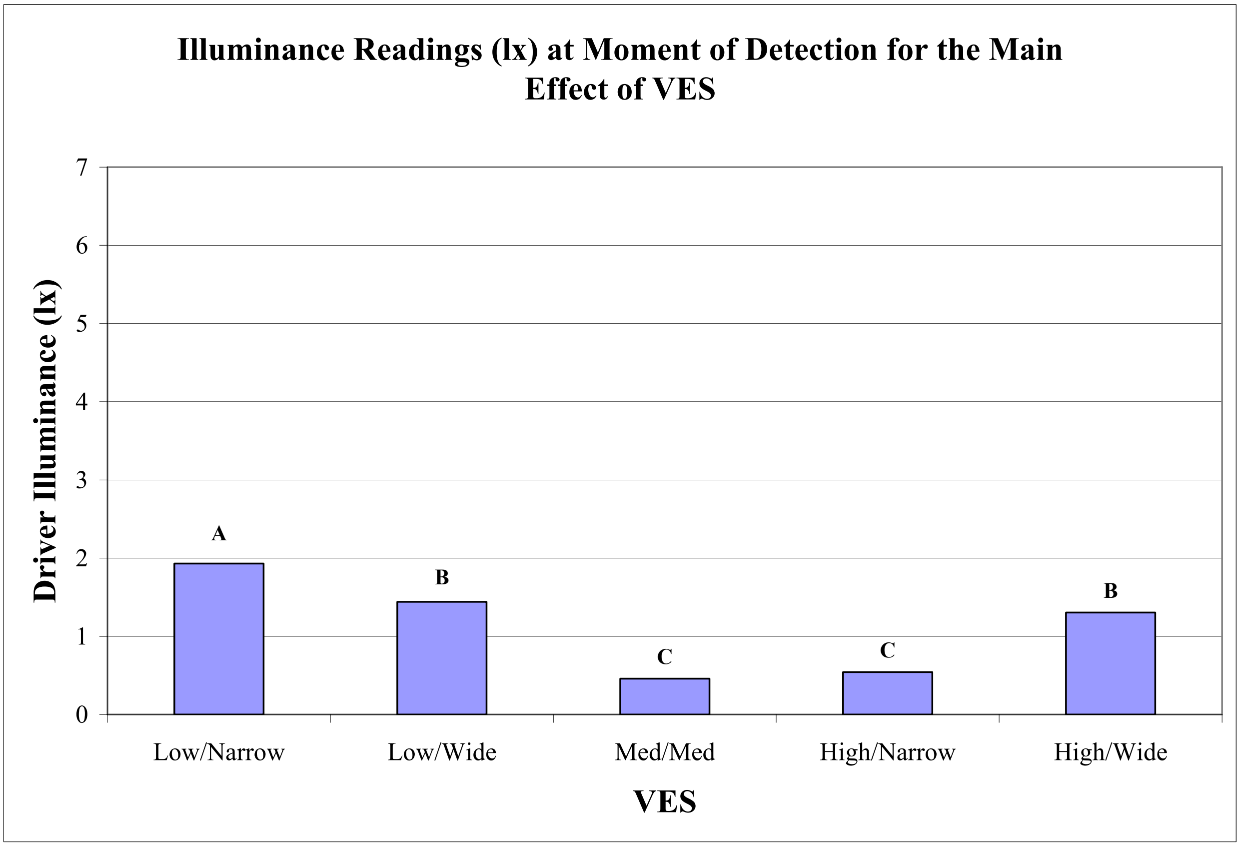



**Figure 17. Bar graph. Mean illuminance readings (lx) at moment of detection for the Pedestrian by VES interaction.**

**VES Main Effect**

The main effect of VES included five different sets of VESs. The SNK revealed three significantly different groupings of driver's eye illuminance (Δ lux) among the five VESs (figure 18, table 14). The low/narrow VES produced the highest mean driver's eye illuminance level at detection, 1.93 lx. Both the wide-beam VESs were in the second group with similar illuminances at the point of the detection. The medium/medium VES and high/narrow VES were grouped together with the lowest illuminance at detection (0.46 lx and 0.54 lx, respectively).




Means marked with the same letter are not significantly different.

**Figure 18. Bar graph. Mean illuminance readings (lx) at moment of detection for the main effect of VES with SNK groupings.**

**Table 14. Illuminance SNK groupings for the VES main effect.**

| VES | N | Mean Illuminance (lx) | SNK Grouping |
|---|---|---|---|
| Low/Narrow | 120 | 1.93 | A |
| Low/Wide | 120 | 1.44 | B |
| Medium/Medium | 120 | 0.46 | C |
| High/Narrow | 120 | 0.54 | C |
| High/Wide | 120 | 1.31 | B |

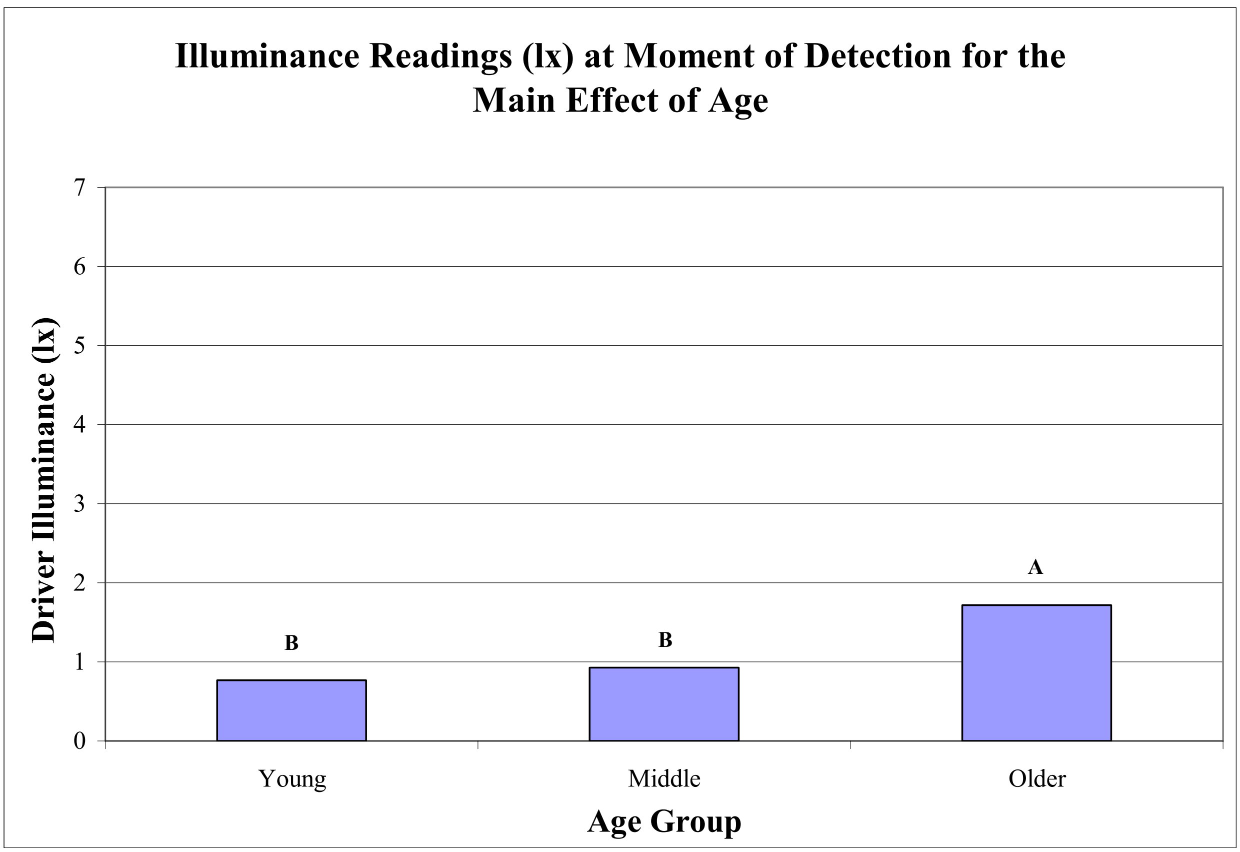
N = sample size

### Pedestrian Main Effect

The main effect of pedestrian included the left- and right-pedestrian locations. The left-pedestrian location had a mean illumination level at detection of 1.52 lx. The mean illumination level for the right pedestrian was approximately half as high, 0.75 lx.

### Age Main Effect

The main effect of age indicated that as age increased, illumination at detection increased (figure 19). Young drivers had a mean illumination level at detection of 0.77 lx. The mean illumination level for middle-aged drivers was 0.93 lx, and for older drivers the level rose to 1.72 lx. The younger and middle-aged participants were not statistically different from each other, but both age groups had significantly less illuminance at detection than the older age group.




Means marked with the same letter are not significantly different.

**Figure 19. Bar graph. Mean illuminance readings (lx) at moment of detection for the main effect of age group with SNK grouping.**

# CHAPTER 4—DISCUSSION

The glare produced by oncoming traffic and the subsequent visibility decrement for drivers at night is a primary concern of transportation research. Different VES designs improve forward visibility, but they may reduce visibility for oncoming drivers. HID headlamps have increased light output to levels much greater than conventional halogen headlamps, yet the implications of this increase for glare are still unclear. With so many vehicles using different headlamp types, 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; therefore, this study was separated into the subjective discomfort glare portion and the objective disability glare portion. A comprehensive evaluation of different headlamp designs with respect to certain characteristics such as driver 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. This section also discusses the research questions that laid the foundation for this study, including specific factors directly related to oncoming glare associated with nighttime driving resulting from various types of vehicle headlamp designs.

As discussed in the Results section, something may have happened to the low/wide VES two-thirds of the way through the study that caused this VES to have substantially larger illumination at the driver's eye point when detecting pedestrians on the left. To determine the potential influence of this VES on some of the following research questions, a secondary ANOVA was conducted with this VES eliminated from the models. This analysis resulted in no changes in the statistical differences for the dependent variables of detection distance and deBoer glare rating. Not surprisingly, this analysis did eliminate all the significant interactions for the illumination at the driver's eye point with the exception of the Pedestrian by VES interaction. The results for this analysis are shown in appendix J. Where applicable, the impact of this VES's potential change is discussed in the following answers to research questions.

## RESEARCH QUESTIONS AND ANSWERS

### Research Question 1

*What effect will different glare sources in terms of intensity and 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 VESs are discussed, it is important to determine the overall effect glare had on visibility, and therefore, the task of detection. That is, in addition to looking at the differences in detection distance under various glare conditions, it would be useful to compare these detection distances to a baseline or no-glare condition. This comparison would allow an estimate in pedestrian detection difference caused by glare. The ENV clear weather study (ENV Volume III) had a task similar to the detection of the pedestrian on the right but with no oncoming glare to degrade visibility. Factors such as participant demographics, experimental conditions, and roadway were comparable between the two studies. In addition, both studies used the same experimental vehicle with the same headlamps, halogen headlamps at a low profile (HLB–LP), so the data from the ENV clear weather study will be used as the baseline for this comparison. The static pedestrian on the right side of the road in the ENV clear weather study had a mean detection distance of 242.6 m (796 ft) using the HLB–LP headlamps. This static pedestrian can be compared to the right pedestrian in this glare study, which yielded a mean detection distance of 122.8 m (403 ft); therefore, the addition of an oncoming glare source led to approximately a 50-percent decrement in the visibility of the right-side pedestrian. This decrement confirms that glare can have a detrimental effect on driver performance.

The relationship between the individual glare VES source and detection distance shows that the halogen (low/narrow) VES allowed oncoming drivers the shortest mean detection distance among all the lighting designs. In other words, drivers would have the least time to react and stop when encountering an obstacle in the glare of these headlamps. In fact, the halogen headlamp detection distances were more than 26.8 m (88 ft) shorter than any other headlamp. These lamps also had the highest illuminance at the driver's eye at the point of detection. The low/wide (HID) headlamps allowed a mean detection distance of more than 43.3 m (142 ft) farther than the halogen. A likely reason the low/narrow halogen headlamps were more glaring is the aiming procedure used in this study, which aimed headlamps higher and more to the left than typical; however, as shown in the ENV discomfort glare study (ENV Volume VII), the different aiming strategies did not elicit a difference in perceived glare. Another possible explanation for the low/narrow headlamp being more glaring is the lack of a distinct pattern and cutoff such as the HIDs. The halogen headlamp emits light in a less controlled pattern; therefore driving toward this type of beam may be more glaring because the perceived intensity of the light remains high throughout the approach. On the other hand, a set of HIDs may have a brighter, more distinct hotspot, but the precise beam pattern of the headlamp may reduce intensity toward the approaching driver, which would result in a lower perceived glare.

The higher-output HIDs, with both narrow- and wide-beam patterns, were perceived by the participants to be significantly more glaring than the low/wide and medium/medium HIDs. The participant's detection performance reflected this finding, with both higher-output VESs underperforming the low/wide and medium/medium lamps. Therefore, both discomfort and disability glare seem to be affected mostly by the intensity or output of the headlamps. Both of the higher-intensity beams had an output of more than 40,000 cd, whereas the other, lower-intensity HIDs were no more than 31,000 cd. This would tend to indicate that headlamps with higher peak output also have higher intensity values throughout the beam pattern, resulting in greater intensity directed toward oncoming drivers. The horizontal and vertical angles from the glare sources to the oncoming driver ranged from approximately 0.58 deg (horizontal) and 0.063 deg (vertical) for the left glare source at 300 m (984 ft) to 2.39 deg (horizontal) and 0.189 deg (vertical) for the right glare source at 100 m (328 ft). A second factor that might affect disability glare could be the reflected light from the pavement. Higher-output headlamps will result in higher levels of illuminance due to this reflected light.

### Research Question 2

*What effect will different light adaptation levels in terms of ambient lighting environment (low of 0.15 lx and high of 0.45 lx) have on the performance of the disability glare pedestrian detection task?*

Two different light adaptation levels were set inside the vehicle to determine if 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 lx (low) and 0.45 lx (high). These levels are comparable to the levels of illumination a driver may encounter at night caused by different vehicle headlamps, vehicle interior lighting, and other changes in ambient illuminance. The results indicated no significant difference between the mean detection distance for high adaptation, 96.6 m (317 ft), and low adaptation, 94.1 m (309 ft). This lack of significant difference might be a result of the range of the high and low adaptation levels. When the participant vehicle approached the glare source, the eye was adapted to a lighting level based on the reflected light from the road surface, the interior lighting (in this case the adaptation light source) and the veiling luminance from the glare source. Both the interior illuminance and the road reflection remained constant, but the veiling luminance changed with the angle between the line of sight and the glare source. The average illuminance at the driver's eye at the point of detection was 0.75 lx for the pedestrian on the right and 1.52 lx for the pedestrian on the left. This indicates that the glare source is the dominant source of illuminance at the participant's eye at the point of detection, especially for the pedestrian on the left. It is possible that had a wider range of illuminance been tested, such as 0.75 lx, the adaptation level may have been significantly different; however, the values tested represent illuminance on real roadways in both lit and unlit conditions as measured during this investigation.

### Research Question 3

*What effect will different pedestrian locations in the driving lane (left or right) have on the performance of the disability glare pedestrian detection task?*

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 almost twice that of the left pedestrian location. One reason for this large disparity is the different angle of incidence as the driver approached the glare source. The left pedestrian was slightly to the right of the glare source. In fact, from the starting distance of 305 m (1,000 ft), the left pedestrian was in the same line of sight as the approaching glare source's left headlamp. The right pedestrian was 3.66 m (12 ft) to the right, on the other side of the driving lane and, at the same starting distance, out of the direct line of sight of the glare source. Not surprisingly, the illumination at the eye of the driver was 50 percent less at the detection point for the right pedestrian as compared to the illumination at the point of detection for the left pedestrian.

**Research Question 4**

*What effect will different age levels (young (18 to 25 years old), middle (40 to 50 years old), and older (65 or more years)) have on the performance of the disability glare pedestrian detection task?*

The pedestrian detection task involves many physiological mechanisms that are important in driver performance. As mentioned in the Introduction, driving a vehicle is primarily a visual task. The perception of 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 not only to track the course of the road but also to detect obstacles in the vehicle's path. The same three age groups used in previous ENV studies were used to examine the effect age has on a driver's ability to detect pedestrians in oncoming glare. The mean detection distances of each of the three age groups were statistically different. Not surprisingly, as the participant age increased, the mean detection distances decreased. Because each condition was conducted with oncoming glare, it is not known how much of this decrease was the result of disability glare being more troublesome for older drivers or how much was caused by older drivers' deteriorated visual acuity. Previous research has shown not only a decrease in visual acuity with age, but also an increased sensitivity to glare.(4) Recall that the brightness acuity test was performed during the training to determine participants' sensitivity to glare. The results of this test are shown in figure 20. In this figure, it is apparent that the older age group results were shifted toward a higher glare sensitivity than the younger group, indicating that disability glare likely played a role in this age-related decrement.

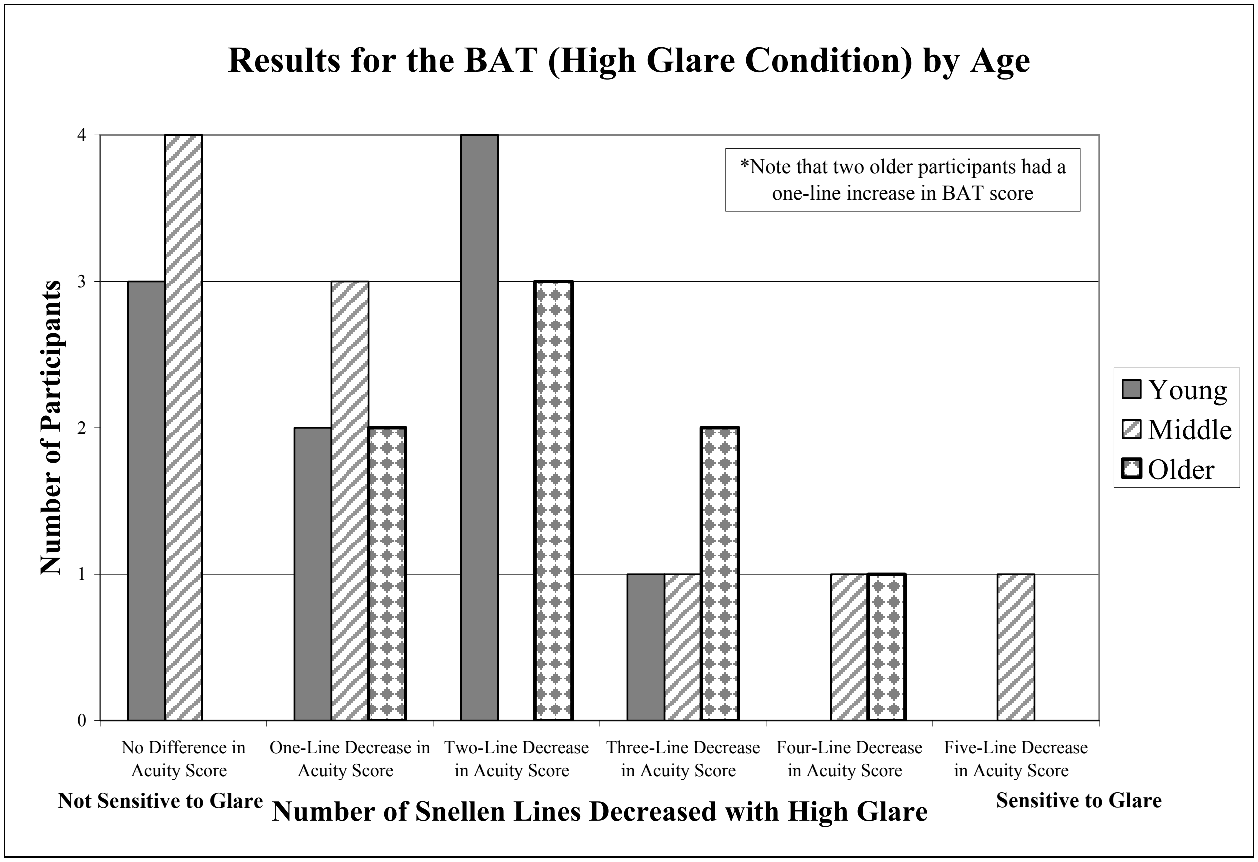



**Figure 20. Bar graph. BAT results by age group.**

A comparison of these results to those of the ENV clear weather study (ENV Volume III) also indicates that disability glare had a larger effect on the older age group than on the other age groups. Recall that the clear weather study used the same VES and vehicle in a detection task similar to the disability glare study's detection of the pedestrian on the right but without oncoming glare to degrade visibility. The three age groups detected the clear weather study's static pedestrian on the right side of the road at the following mean detection distances: young, 257.6 m (845 ft); middle-aged, 222.7 m (731 ft); and older, 247.5 m (812 ft). When drivers were exposed to glare in the disability glare study, the mean detection distances of the three age groups were as follows: young, 143.2 m (470 ft); middle-aged, 121.8 m (400 ft); and older, 94.9 m (311 ft). This comparison shows a detection distance decrement due to glare for the young and middle-aged groups of approximately 45 percent and a detection distance decrement due to glare for the older group of approximately 62 percent.

**Research Question 5**

*What effect will different glare sources have in terms of intensity/beam distribution (low/narrow, low/wide, medium/medium, high/narrow, and high/wide) have on the perception of discomfort?*

The five sets of glare headlamps not only significantly affected driver performance but also produced different perceptions of discomfort. The subjective deBoer scale was used to determine how driver comfort levels were influenced by the five glare sources. Perhaps the most interesting aspect of this study is how closely discomfort glare and disability glare were associated. For the most part, the more discomforting the VES, the worse the performance on pedestrian detection. As mentioned in the Introduction, research has demonstrated a subjective preference for viewing halogen headlamps over HIDs.(14) The increased brightness and bluish-white tint to the HID glare sources was perceived as 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. A likely reason the low/narrow halogens were more glaring is the aiming procedure used in this study; however, as shown in the ENV discomfort glare study (ENV Volume VII), the different aiming strategies did not elicit a difference in perceived glare. Another reason for this finding may be the dynamic aspect of this study; the headlamps were evaluated while the angle of incidence was changing. If the halogen headlamps, with a less confined beam pattern, continued to appear bright throughout the approach, then they might have been viewed as more glaring overall.

For the four HIDs, the beam intensity appeared to be more important than the beam pattern in causing discomfort glare. The two higher-intensity HIDs caused more discomfort glare than the less intense HID-based VESs. The fact that intensity level mostly determined discomfort level for all four HIDs demonstrates the drivers’ ability to identify the incremental differences between each headlamp. This relationship between maximum output of the glare source and perceived discomfort is further illustrated in figure 21; the blue dashed box represents the low- and medium-intensity VESs, and the orange dashed box represents the high-intensity VESs. The graph shows that the low/wide VES does not follow this same relationship of lower maximum output being associated with less glare; however, recall that there was an apparent increase in illuminance at the driver's eye at the point of detection later in the study for this VES. A subsequent analysis was performed to look at the difference between the discomfort glare for this VES before and after this apparent increase. Before the apparent increase, drivers rated this VES as less glaring, with an average of 7.4 as compared to an average of 5.6 after the apparent increase. The 7.4 rating of the earlier participants is more in line with the expected discomfort rating caused by maximum intensity. Through this analysis, it is apparent that at some point during the performance of the study, the luminous intensity directed towards the driver from the low/wide headlamp changed. This most likely was caused by either an aiming or headlamp output issue as a result of damage to the headlamps that was not caught during the experimental process.

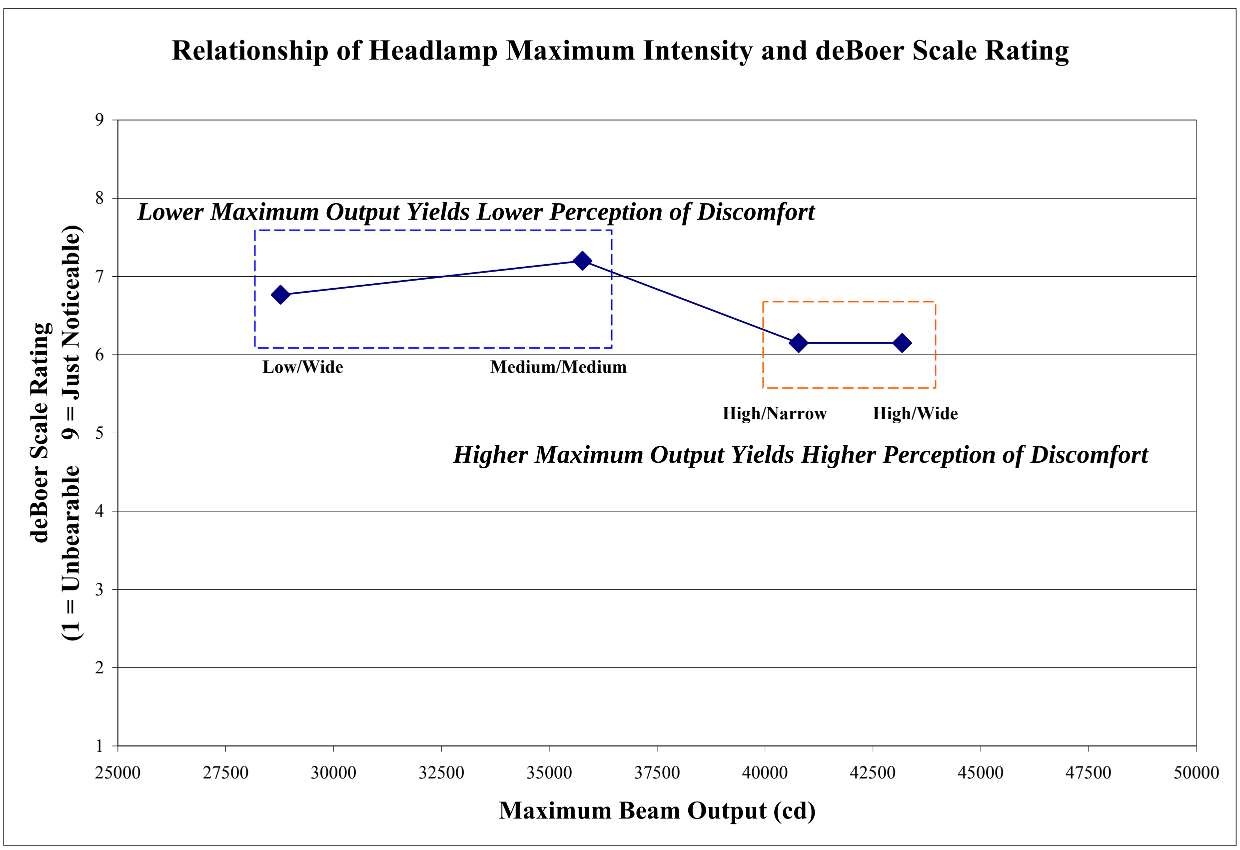



**Figure 21. Line graph. The relationship between headlamp intensity and perceived glare.**

### Research Question 6

*What effect will different light adaptation levels in terms of ambient lighting environment (low of 0.15 lx and high of 0.45 lx) have on the perception of discomfort glare?*

Each discomfort glare rating was performed under both the low and high light adaptation levels. Adaptation level caused no significant difference in perceived glare. One reason there was no difference is likely because participants essentially were 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 from the headlamps. As discussed previously, as the participant vehicle approached the glare source, the adaptation level remained constant and the veiling luminance from the opposing headlamps changed. As the driver approached the glare, illumination levels rose to anywhere from 1.5 lx to over 5 lx. These levels are much higher than the adaptation sources tested, and the participant likely evaluated the dominant source that changed across VESs, not the unchanging adaptation level.

### Research Question 7

*What effect 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?*

The three age groups of drivers in this study had no significant differences in discomfort from the glare sources. In general, no matter what the age of the driver was, perception of the glare sources remained basically the same. These findings suggest that age may influence certain performance factors (e.g., object detection) because of changes in physiology, but it does not have an effect on subjective discomfort ratings. Multiple vision tests were administered to document the participants' visual characteristics. One important physiological measure in this study was visual acuity, which gradually degrades with age.[25] A higher visual acuity may allow for greater detection distances, but it may not affect subjective ratings of discomfort. Another measure of visual acuity used in this study was an individual's sensitivity to glare. According to Scheiber, older drivers are not only more limited with visual acuity but also may be more sensitive to glare.[4] An individual may have perfect visual acuity, but then the exposure to glare may reduce the ability to see. As discussed earlier, the BAT glare sensitivity 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 under glare (measured with a Snellen 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, then, that a raised sensitivity to glare can lower detection distances, but it is unknown if it alters the feeling of discomfort. If declining visual acuity and glare sensitivity affect only pedestrian detection, then there would be no expected age effect for discomfort glare ratings.

**Research Question 8**

*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 illuminance value at the driver's eye at the moment of detection?*

The concept of an illuminance reading at the moment of detection is interesting because it is related to detection distance. If a glare source has a low mean detection distance, then it would be predicted that that same glare source would have a higher illuminance value; the reading should be higher because in theory it is taken closer to the light source. The illuminance measurements taken at the moment of detection during the low/narrow trials (1.93 lx) followed this prediction, allowing a mean detection of only 66.8 m (219 ft); therefore, the lowest detection distance had the highest illuminance. The other four glare sources did not follow the same pattern. In fact, instead of falling into groups based on intensity, as detection distances did, the HID headlamps were separated more by beam distribution (narrow, medium, and wide). The low/wide and high/wide glare sources had similar mean illuminance readings of 1.44 lx and 1.31 lx. The other two HID sources (high/narrow and medium/medium) had mean illuminance values of 0.54 lx and 0.46 lx. This is somewhat expected. When drivers first approached a glare source, they perceived its maximum beam from a long distance with a very small angle between the driver and the source. As the approach continued, this angle increased, and the light reaching the driver actually came from the side of the beam rather than the end of the beam. If the beam was wider, more light went to the side, and a higher illuminance resulted; therefore, it is likely that the width of the beam has a greater influence on illuminance levels at the detection point than the maximum intensity of the glare source.

### Research Question 9

*What effect will different light adaptation levels in terms of ambient lighting environment (low of 0.15 lx and high of 0.45 lx) have on the illuminance value at the driver's eye at the moment of detection?*

The results of this study showed no significant difference in driver's eye illuminance levels at the moment of detection for light adaptation level. The results revealed similar mean illuminance measurements of 1.12 lx (low adaptation) and 1.15 lx (high adaptation) for the two adaptation levels.

### Research Question 10

*What effect will different pedestrian locations in the driving lane (left and right) have on the illuminance value at the driver's eye at the moment of detection?*

As expected, the two pedestrian locations yielded two significantly different levels of illuminance at the moment of detection. The right pedestrians were detected nearly twice as far away as the left pedestrians. The mean illuminance value at the moment of detection for the left pedestrian was 1.52 lx. The right pedestrian was detected with a mean illuminance of half the left pedestrian's, 0.75 lx. The main reason for this difference in illuminance is that the participants were much closer to the glare source when they detected the left pedestrian, and therefore, had a higher illuminance at the eye. These findings are consistent with a similar study reporting that the target closest to the glare source was very difficult to detect.(26)

### Research Question 11

*What effect will different age levels (young (18 to 25 years old), middle (40 to 50 years old), and older (65 or more years)) have on the illuminance value at the driver's eye at the moment of detection?*

There were three age groups in this study and three significantly different levels for detection distance, yet there were only two significant levels of illumination at the eye. The older age group had a mean illuminance value at detection of 1.72 lx. The middle-aged and younger drivers had mean illuminance levels of 0.93 lx and 0.77 lx, respectively, which were not significantly different. The main reason for the difference in SNK groupings may involve visual acuity. The older drivers detected the pedestrians much closer to the glare source, and therefore, at higher illuminance levels. The middle-aged participants needed to be significantly closer than the younger drivers to detect the pedestrian. Still, both the middle and younger age groups were far enough away from the glare source that their illuminance values were not significantly different.

## DESIGN GUIDELINES

Few studies have evaluated disability glare caused by various HID headlamps in dynamic nighttime driving situations, and many questions concerning glare related to HID headlamps and other new types of vehicle lighting remain. This study can help guide future research to maximize forward visibility while minimizing glare. The findings in this study indicate that glare from oncoming vehicles can significantly reduce visibility even when pedestrians are dressed in light-colored clothing with a high reflectance of 40 percent. These findings differ from previous research that found that "higher reflectance targets [40 percent] are not significantly affected by headlamp glare even up to 5 lux at the eye."(26) The current study found significant differences in detection distance with pedestrians in the right and left locations with driver's eye illuminance readings less than 5 lx; therefore, new headlamp designs must be evaluated in terms of disability glare from oncoming vehicles before they are implemented into new automobiles.

The findings in this study led to the following guidelines for future consideration:

- An HID headlamp designed with a higher intensity (40,000 to 50,000 cd) may increase oncoming drivers' perception of discomfort and reduce their ability to detect pedestrians and other objects in the roadway.
- An HID headlamp designed with no more than low to medium output (25,000 to 30,000 cd) may mitigate reduced visibility resulting from glare.

## LIMITATIONS OF THIS STUDY

### Glare Headlamps

Many types of halogen and HID headlamps are in use on today's roadways. Various headlamp designs have different characteristics that include intensity level, gradient or cutoff, and spectral power distribution. The collection of glare sources used in this particular study is only a sample of all the available headlamps on the market; therefore, certain generalizations about the performance of these particular halogen and HID designs may not be accurate when compared to other designs.

### Participant Training

The drivers used in this study were given multiple training sessions before they completed the experimental tasks. In the disability glare portion of the study, the participants were familiar with the pedestrian types and roadway before beginning the data collection portion of the experiment. Participants were also expecting pedestrians to appear in the roadway, and therefore they were looking more attentively. Some of the results may have differed if unexpected objects and pedestrians had 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 without warning. Drivers also received training before the discomfort glare portion of the study. The glare may have been rated differently if participants were not concentrating solely on the task of rating the glare. For example, if drivers drove as they normally would without being trained for the discomfort rating task, they may have not paid as much attention to the glare sources. This inattention may have led to smaller differences in discomfort ratings.

### Illuminance Measurements

The illuminance measurements recorded during the discomfort and disability glare tasks were taken to measure the illuminance at the driver's eye. The illuminance meter was mounted facing straight forward in the direction of the vehicle's travel, and therefore, the meter did not account for driver head and eye movements. As drivers approached oncoming glare, they may have diverted their gaze to avoid looking directly into the light source. After analyzing the in-vehicle videos for eye and head movements, it was found that eyes and head positions moved for approximately one in three participants as the glare source was approached. The eye movements were mostly glances down or to the right side and increased in frequency as the glare became closer. Some drivers adjusted their head position either down or to the right in an attempt to mitigate the effects of the glare as they approached. The remaining drivers often had a fixed eye and head position throughout the detection task and looked straight ahead. One of the reasons drivers may have stared straight ahead more than they normally would is because they were in a searching mode. During the disability glare portion, the participants were primed for pedestrian detection, and the drivers were diligently fixating on the road ahead to detect pedestrians. The illuminance measurements may not fully represent the light reaching the eye of the participants who moved their head or eyes. It is also important to understand that the driver's avoidance of a glare source is probably a normal response in a driving environment.

### Glare Sensitivity

Many participants with similar visual acuity scores had differing sensitivities to glare. Although glare sensitivity was not a controlled factor, the vision test results revealed that no participant had a severe change in acuity resulting from the glare exposure (figure 20). In future studies, controlling for glare sensitivity may 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 accuracy of data collection. For the same reasons, the experimental vehicle traveled at a speed of only 32 km/hr (20 mi/h). The results may have been different if both vehicles were dynamic and traveling at higher speeds.

## FUTURE RESEARCH

Several avenues exist for future research concerning glare and night visibility. As technology continues to evolve in the area of automotive lighting, human factors research must keep up with the changing designs and ensure that the newest headlamps not only are more efficient and stylish but also provide better visibility and less glare. Certain technologies such as light emitting diodes (LEDs) are making their way into the market in other lighting applications and soon may be introduced as headlamp alternatives in 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.

In addition, different roadway materials and roadway infrastructure characteristics may increase or decrease the perception of glare. For example, high barriers on busy interstates reduce the effects of glare by blocking some of the light, resulting in 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.

# CHAPTER 5—SUMMARY

The primary focus of this research was to evaluate the discomfort and disability glare associated with different sets of oncoming headlamps, including conventional halogen headlamps as well as newer high intensity discharge designs and their associated beam distributions and intensities. The visual performance portion (i.e., disability glare) of the study evaluated the ability of each headlamp to allow oncoming drivers to detect pedestrians on the right or left side of the roadway. This portion of the study looked specifically at how oncoming glare affects detection distances. Drivers also rated the discomfort glare using the deBoer scale while approaching each of the five sets of headlamps.[9] This portion of the study was performed to better understand how drivers subjectively perceive these headlamps. Overall, this study empirically broke down the oncoming glare of four categorically different HID headlamp designs and one halogen beam design. This effect was measured by pedestrian detection distance, discomfort glare rating, and illuminance level at the driver's eye.

With the introduction of HID headlamps on the roadways, many issues have arisen because of the higher luminous output and unique—and sometimes discomforting—appearance these headlamps have. Drivers state that passing these HID headlamps on the road 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. When comparing data from this study with data previously collected in the ENV clear study (ENV Volume III), it appears that disability glare led to a 50-percent reduction in pedestrian detection distance. This study produced the following conclusions:

- Results showed similar findings for both discomfort glare and disability glare for the VESs. The VESs that were rated as more discomforting were the same VESs that allowed shorter detection distances.

- Although participant age did not cause a difference in discomfort glare ratings, the pedestrian detection distance significantly decreased as participant age increased.

- The right pedestrian location yielded a detection distance almost twice that of the left pedestrian location. Not surprisingly, the left pedestrian location had almost twice the illuminance at the driver's eye at the point of detection when compared to the right.
- Beam intensity, or the maximum output of the headlamp, had more of an effect on disability and discomfort glare than beam pattern. VESs with higher maximum output were rated as more discomforting, and they were associated with shorter pedestrian detection distances than VESs with lower maximum output.
- Beam width was a better indicator of illuminance levels at the detection point than the maximum intensity of the glare source.
- Adaptation level from 0.15 lx to 0.45 lx had little effect on the glare rating, detection distances, and the illuminance at the driver's eye at the detection point.

## APPENDIX A—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 [contractor]. I'm recruiting drivers for a study to evaluate new night vision enhancement systems for vehicles.*

*This study will involve you driving at vehicle instrumented with data collection equipment <u>on 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

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

   Yes _____ No _____

2. How often do you drive each week?

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

3. How old are you? _______

4. What is your date of birth?___________

5. Have you previously participated in any experiments at the [contractor facility]? If so, can you briefly describe the study?

   Yes ____Description:____________________________________________________________
   No _____

6. How long have you held your drivers' license?___________________________________

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

   Yes _____ No _____

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

   Yes _____ ____________________________________________________
   No _____

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

   Yes _____ ___________________________________________________________
   No _____

10. 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_________________________________

11. Have you ever had radial keratotomy, [corrective] eye surgery, or other eye surgeries? If so, please specify.
    Yes _____ _______________________________________________________
    No _____

12. (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.*"

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

    Yes _____ _______________________________________________________
    No _____

14. 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, [corrective] eye surgery, or any other ophthalmic surgeries.***
*******************************************************************

***Accepted: ________***

***Rejected: ________***  ***Reason:___________________________________________***

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

## APPENDIX B—INFORMED CONSENT FORM

[NAME OF UNIVERSITY]
Informed Consent for Participants of Investigative Projects

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

Investigators: (List names of investigators here)

### 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:

1) Read and sign an Informed Consent Form.
2) Show a current driver's license.
3) Complete four vision tests.
4) 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.
5) Complete questionnaires
6) 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:

1) 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.

2) Possible fatigue due to the length of the experiment. However, you will be given the option to take breaks when you choose.
3) 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.

1) 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.
2) 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.
3) The Smart Road test track is equipped with guardrails to prevent vehicles from slipping off the road.
4) The vehicle is equipped with a fire extinguisher and first-aid kit, which may be used in an emergency.
5) 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.
6) 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.
7) None of the data collection equipment or the display technology interferes with any part of your normal field of view in the automobile.
8) The in-vehicle experimenters are aware of the location of other work vehicles on the road, and maintain radio contact with each other.
9) 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.
10) 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.

**Benefits**

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.

**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. Researchers will not turn over the video of your image to the client without your permission.

**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.

**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.

**Approval of Research**

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at (Name of University) and by the (Name of Research Institute).

**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:

- ☐ (Name of Research Institute) **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.
- ☐ (Name of Research Institute) **does not have my permission** to give the videotape including my image to the client who has sponsored this research. I understand that (name of research institute) 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: (List name and contact information of PI, IRB Chair, and Experimenter)

## APPENDIX C—VISION TEST FORM

PARTICIPANT NUMBER: __________

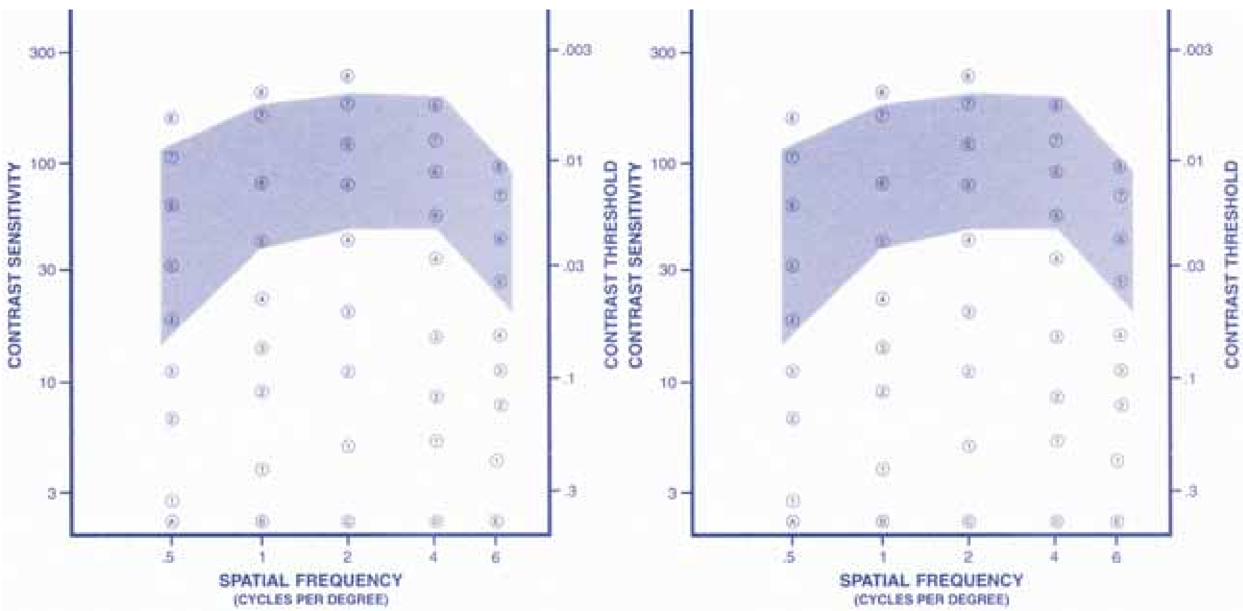
VISION TESTS

I – Acuity Test

- Acuity Score:________

II – Contrast Sensitivity Test

Left Right




III – Ishihara Test for Color Blindness

| | | |
|---|---|---|
| 1._____ | 4._____ | 7.____ |
| 2._____ | 5._____ | |
| 3._____ | 6._____ | |

IV – Brightness Acuity Tester (BAT)

- Acuity Score:

  Left Off ______ Low____ ____Med _______High _____

  Right Off ______ Low____ ____Med _____High ______

V – Standing Height ________+ 20 inches ______________________

## APPENDIX D—IN-VEHICLE EXPERIMENTAL PROTOCOL

1. Prior to the participants' arrival, make sure that all the needed forms are available.
2. 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. Get color vision test, BAT, eye occluder, alcohol, and cotton balls from prep room.
3. Greet participant.
4. Record the time that the participant arrived on the debriefing form.
5. Show driver's license.

*Before we begin, it is required for me to verify that you have a driver's license. Would you please show me your license?*
Must be a valid Class A driver's license to proceed with the study. Out of state is fine.

**Experimenter reads all text in italics aloud to each participant:**

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

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

**6.** 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

The other side of the form is a University Voucher stating they are not being "permanently" employed by our project. Have them print their name on the top of the form.

**7.** Vision tests.

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

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

The first test is the Snellen eye chart test.

- Take the participant over to the eye chart test area.
- Line up their toes to the line on the floor (20 feet).
- Participants can leave on their glasses if they wear them for driving.

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

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

The next vision test is the Contrast Sensitivity test. Take the participant over to the eye chart test area.

- Line up their toes to the line on the floor (10 feet).
- Participants can leave on their glasses if they wear them for driving.

Procedure: *We are going to test how well you see bars at different levels of contrast. Your ability to see these bars relates to how well you see everyday objects. It is VERY IMPORTANT you do not squint or lean forward while you are taking the test.*

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

The next vision test is the 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 participants answers on the Vision Tests Form

The last test is the Brightness Acuity Test

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).

**8.** Measure participant height
**9.** Administer PreDrive Questionnaire
**10.** 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.*

*When you can detect the pedestrian 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).

**11.** 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 headlamps.*
(Review Scale)

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

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

## APPENDIX E—ONROAD EXPERIMENTAL PROTOCOL

### 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 headlamps and 15 mph.)
- Use a spotter when moving vehicles in and out of the garage.
- 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 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.

While the study is being conducted, radio communications on Channel 1 need to be minimized (emergencies excluded). If none of the onroad experimenters can answer the question, one of you will need to address it to the in-vehicle experimenter. Note that the in-vehicle experimenter cannot always respond to questions if he/she is interacting with the participant at that time. For this reason, you will need to give the in-vehicle experimenter extra time.

**1.** Pre Experiment
   - Nightly meeting.
   - Prep vehicles.
   - Each experimenter is responsible for signing out radio and should have one radio and one extra battery.
   - Each onroad experimenter is responsible for making sure that they have everything that they need for the lighting station. They are also expected to load the light boxes and any other equipment into the white pickup.
   - Put on vests.
   - Load boxes and cones into truck and hook up lighting trailer.
   - The 3 on road experimenters should travel to the road in the pickup truck. The lead experimenter will drive the truck pulling the trailer.

- Setup parking spaces in Turnaround 2 by putting out the cones at the appropriate locations. (See Diagram)
- Setup cones at Turnaround 3. (See Diagram)
- Setup cones (2 each) at both start points. (See Diagram)
- Make sure all cones and/or objects on the road that are not part of the study are removed from the road.
- Trailer hitch arm must be removed before lighting rack is put in roadway.
- Unload 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 white scrubs (pedestrian only), flashlight, safety glasses, order sheets, bug spray etc.
  - 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.)

**2.** Discomfort Glare Practice Lap (1 Lap)
- The truck will be used instead of the glare cart for this lap.
- Make sure all light boxes, extension cords, etc. are hidden from participant view.
- Position the truck and radio to the in-vehicle experimenter when ready.
- When in-vehicle experimenter confirms participant is ready, turn on the appropriate headlights (low or high beam) as per the order sheet.
- After the participant vehicle has passed and cleared the test section of road, repeat for the second half of the participant lap.

**3.** First Half of Discomfort Glare Data Collection (2 ½ laps-one pass for each of the 5 VESs)
- Make sure all light boxes, extension cords, etc. are hidden from participant view when they are not being used.
- Position the glare cart on the road using the marks on the pavement as a guide which ensures that the glare is properly aimed..
- Setup the appropriate VES on the cart, referring to the order sheet.
- Place felt in front of the VES and turn them on.
- Wait 30 seconds for the VES to stabilize, then radio the in-vehicle experimenter to let him/her know you are ready.
- Remove the felt when the in-vehicle experimenter radios that the participant vehicle is ready for approach.

- Hide off of the road while participant vehicle is approaching.
- Repeat for all VES on the order sheet.

**4.** Disability Glare Practice Lap (1 Lap)
- The truck will be used instead of the glare cart for this lap.
- Make sure all light boxes, extension cords, etc. are hidden from participant view .
- Light operators -position the truck.
- Pedestrian-stand in appropriate location as described in table below. Refer to order sheet. Radio in-vehicle experimenter when ready.

| Object | Location | Instructions |
|---|---|---|
| Left Pedestrian | Centerline on roadway | Stand dressed in white clothing facing driver (parallel to line) 1 ft inside centerline. Important that feet do not cross or cover any portion of the line. |
| Right Pedestrian | Right edgeline on roadway | Stand dressed in white clothing facing driver (parallel to line) 1 ft inside right edgeline. Important that feet do not cross or cover any portion of the line. |

- Light operators-when in-vehicle experimenter radios that participant is ready, turn on the appropriate headlights (low or high beam) as per the order sheet.
- Pedestrian- clear off the roadway when the in-vehicle experimenter radios “clear” or when the vehicle reaches the 50 feet mark.-whichever comes first.
- Pedestrian- after you step off the roadway, maintain your position on the shoulder to allow the in-vehicle experimenter to flag the data with the object location.
- Pedestrian-as the participant vehicle passes you, say the run number over the radio to ensure that everyone keeps track of the order.
- After the participant vehicle has passed and cleared the test section of road, repeat for the second half of the practice lap.

**5.** Light Operators -First Half of Disability Glare Data Collection- (5 ½ laps-one pass for each VES and object combination and one pass for a blank condition).
- Make sure all light boxes, extension cords, etc. are hidden from participant view when they are not being used.
- Position the glare cart on the road using the tape marks on the pavement as a guide. This ensures that the glare cart is properly aimed.
- Setup the appropriate VES on the cart, referring to the order sheet.
- Place felt in front of the VES and turn them on.
- Wait 30 seconds for the VES to stabilize, then radio the in-vehicle experimenter to let him/her know you are ready.

- Remove the felt when the in-vehicle experimenter radios that the participant vehicle is ready for approach.
- Hide off of the road while participant vehicle is approaching.
- Repeat for all VES as per the order sheet.
- Note that there will be a "blank" on the order sheet.  For this condition, you will use the truck instead of the glare cart, following the steps from the practice lap.
- If you notice any problem or mistakes, document them on the vehicle prep sheet.

**6.** Pedestrian-First Half of Disability Glare Data Collection- (5 ½ laps-one pass for each VES and object combination and one pass for a blank condition).
- Follow the protocol as described in the practice lap.
- There will be a "blank" on the order sheet.  For this condition, you will hide off of the road.
- Note that the participant vehicle is 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.
- If you notice any problems or mistakes, document them on the vehicle prep sheet.

**7.** Second half of Discomfort Glare Data Collection- (2 ½ laps- one pass for each VES)
- Refer to protocol above.

**8.** Second half of Disability Glare Data Collection (- (5 ½ laps-one pass for each VES and object combination and one pass for a blank condition).
- Refer to protocol above.

**9.** Shut Down Protocol
- Collect cones
- Return glare cart, headlamps and equipment to the garage.
- 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)-make sure they are turned off when you put them in the charger.
- Put away scrubs.
- Submit paperwork to the in-vehicle experimenter.

Vehicle Preparation
<u>Sedan</u>

- 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 unrelated to 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.

## APPENDIX F—AIMING PROTOCOL

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, daytime running lights) are on.

Cover up or unplug one headlamp so that you are only taking readings for one light at a time.

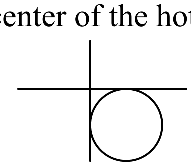
*Finding the Hotspot:*

Align the VES so that the "hotspot" 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 do not 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 center line for that light.

*Hotspot Location*: The circle represents the target hotspot location with respect to the target crosshairs. The center of the circle is the center of the hotspot.



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 hotspot. If the hotspot is in the correct location, the headlamp is aligned and you can align the other headlamp(s).

Note that for non-UV headlamps, 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. Each headlamp has its own diagram located on the server in the Disability Glare/Headlamps folder.

# APPENDIX G—VES CHARACTERISTICS

## HID 1—HIGH/NARROW (HIGHER INTENSITY WITH NARROW BEAM PATTERN)

This system uses a complex multireflector lens to focus the beam pattern created by the HID light source. The intensity of this beam is relatively low compared to other recent headlamp designs. This means that when compared to other headlamps using isocandela diagrams, this HID design puts 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 toward the center of the roadway and not as much to the periphery or the side of the roadway.

**Figure 22. Photo. Front view of HID 1 headlamp (high/narrow).**

## HID 2—HIGH/WIDE (HIGHER INTENSITY WITH WIDE BEAM PATTERN)

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

**Figure 23. Photo. Front view of HID 2 headlamp (high/wide).**

## HID 3—MEDIUM/MEDIUM (MEDIUM BEAM INTENSITY WITH MEDIUM BEAM PATTERN)

As with all the other VESs, this system focuses its light output with a multireflector lens. The intensity of this headlamp compared to the others is in the middle range. The beam width is also average compared to the other designs.

**Figure 24. Photo. Front view of HID 3 headlamp (medium/medium).**

## HID 4—LOW/WIDE (LOW BEAM INTENSITY WITH WIDE BEAM PATTERN)

This system again makes use of a complex multireflector 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 headlamp is wider than most of the others.

**Figure 25. Photo. Front view of HID 4 headlamp (low/wide).**

## HALOGEN—LOW/NARROW (LOW BEAM INTENSITY WITH NARROW BEAM PATTERN)

This conventional headlamp has lower intensity characteristics relative to average halogen beams. The width of this beam is fairly narrow, similar to other halogens.

**Figure 26. Photo. Front view of halogen headlamp (low/narrow).**

## APPENDIX H—PREDRIVE QUESTIONNAIRE

### ENV-Disability Glare Predrive 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 night in good weather? *(Please circle only one)***

| | | | | |
|---|---|---|---|---|
| ***very comfortable*** | ***somewhat comfortable*** | ***neither comfortable nor uncomfortable*** | ***somewhat uncomfortable*** | ***very uncomfortable*** |

**6. In general, how do you feel about driving at night in typical bad weather conditions (light rain, snow, 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 I—RESULTS ANOVA TABLES

**Table 15. 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*** | | | | | | |
| VES | 4 | 143.6 | 35.9 | 14.36 | <.0001 | * |
| VES by Age | 8 | 32.9 | 4.1 | 1.65 | 0.1199 | |
| *VES by Participant (Age)* | 108 | 270.0 | 2.5 | | | |
| | | | | | | |
| Adaptation | 1 | 0.6 | 0.6 | 0.22 | 0.6466 | |
| Adaptation by Age | 2 | 3.2 | 1.6 | 0.61 | 0.5496 | |
| *Adaptation by Participant (Age)* | 27 | 70.7 | 2.6 | | | |
| | | | | | | |
| VES by Adaptation | 4 | 0.8 | 0.2 | 0.19 | 0.9424 | |
| VES by Adaptation by Age | 8 | 8.0 | 1.0 | 1.02 | 0.4254 | |
| *VES by Adaptation by Participant (Age)* | 108 | 106.2 | 1.0 | | | |
| **ADJUSTED TOTALS** | 299 | 1302.9 | | | | |

* $p < 0.05$ (significant)

**Table 16. ANOVA table for the objective measurement of disability glare with detection distances.**

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

* $p < 0.05$ (significant)

**Table 17. ANOVA table for the objective measurement of driver's eye illuminance.**

| Source | DF | SS | MS | F Value | P Value | |
|---|---|---|---|---|---|---|
| ***Between*** | | | | | | |
| Age | 2 | 103.27 | 51.64 | 11.83 | 0.0002 | * |
| *Participant (Age)* | 27 | 117.85 | 4.36 | | | |
| | | | | | | |
| ***Within*** | | | | | | |
| VES | 4 | 187.68 | 46.92 | 16.26 | <.0001 | * |
| VES by Age | 8 | 131.67 | 16.46 | 5.7 | <.0001 | * |
| *VES by Participant (Age)* | 108 | 311.64 | 2.89 | | | |
| | | | | | | |
| Pedestrian | 1 | 87.62 | 87.62 | 39.24 | <.0001 | * |
| Pedestrian by Age | 2 | 26.79 | 13.40 | 6 | 0.007 | * |
| *Pedestrian by Participant (Age)* | 27 | 60.29 | 2.23 | | | |
| | | | | | | |
| Pedestrian by VES | 4 | 81.59 | 20.40 | 12.4 | <.0001 | * |
| Pedestrian by VES by Age | 8 | 101.92 | 12.74 | 7.75 | <.0001 | * |
| *Pedestrian by VES by Participant (Age)* | 108 | 177.58 | 1.64 | | | |
| | | | | | | |
| Adaptation | 1 | 0.20 | 0.20 | 0.39 | 0.5355 | |
| Adaptation by Age | 2 | 0.15 | 0.08 | 0.15 | 0.8647 | |
| *Adaptation by Participant (Age)* | 27 | 14.00 | 0.52 | | | |
| | | | | | | |
| VES by Adaptation | 4 | 1.34 | 0.34 | 0.34 | 0.848 | |
| VES by Adaptation by Age | 8 | 2.07 | 0.26 | 0.26 | 0.976 | |
| *VES by Adaptation by Participant (Age)* | 108 | 105.66 | 0.98 | | | |
| | | | | | | |
| Pedestrian by Adaptation | 1 | 0.06 | 0.06 | 0.13 | 0.7231 | |
| Pedestrian by Adaptation by Age | 2 | 0.30 | 0.15 | 0.3 | 0.7428 | |
| *Pedestrian by Adaptation by Participant (Age)* | 27 | 13.54 | 0.50 | | | |
| | | | | | | |
| Pedestrian by VES by Adaptation | 4 | 2.82 | 0.71 | 0.98 | 0.4196 | |
| Pedestrian by VES by Adaptation by Age | 8 | 5.27 | 0.66 | 0.92 | 0.5038 | |
| *Pedestrian by VES by Adaptation by Participant (Age)* | 108 | 77.40 | 0.72 | | | |
| **ADJUSTED TOTALS** | 599 | 1610.72 | | | | |

* $p < 0.05$ (significant)

## APPENDIX J—RESULTS FOR ANOVA WITHOUT THE LOW/WIDE VES

In order to assess the influence of the low/wide VES on the original results, a secondary analysis was performed. This analysis used the same models, excluding the low/wide VES, as the original analysis of the detection distance, illuminance at the driver's eye, and deBoer glare rating as discussed in the Results section.

The significant main effects and interactions for each dependent variable are marked with an "x" in table 18. The effect of pedestrian location and its interactions were not applicable to the deBoer glare ratings. The secondary ANOVA indicated no changes in significant difference for the detection distance or the deBoer glare ratings. Not surprisingly, with the exception of the Pedestrian by VES interaction, all the significant interactions in the original analysis (indicated by a dash in table 18) were not significant in this analysis.

**Table 18. Secondary analysis ANOVA significant main effects and interactions.**

| Source | Disability Glare Detection Distances | Disability Glare Driver's Eye Illuminance | Discomfort Glare deBoer Scale Ratings |
|---|---|---|---|
| ***Between*** | | | |
| Age | x | x | |
| *Participant (Age)* | | | |
| | | | |
| ***Within*** | | | |
| VES | x | x | x |
| VES by Age | | — | |
| *VES by Participant (Age)* | | | |
| | | | |
| Adaptation | | | |
| Adaptation by Age | | | |
| *Adaptation by Participant (Age)* | | | |
| | | | |
| VES by Adaptation | | | |
| VES by Adaptation by Age | | | |
| *VES by Adaptation by Participant (Age)* | | | |
| | | | |
| Pedestrian | x | x | |
| Pedestrian by Age | | — | |
| *Pedestrian by Participant (Age)* | | | |
| | | | |
| Pedestrian by VES | x | x | |
| Pedestrian by VES by Age | | — | |
| *Pedestrian by VES by Participant (Age)* | | | |
| | | | |
| Pedestrian by Adaptation | | | |
| Pedestrian by Adaptation by Age | | | |
| *Pedestrian by Adaptation by Participant (Age)* | | | |
| | | | |
| Pedestrian by VES by Adaptation | | | |
| Pedestrian by VES by Adaptation by Age | | | |
| *Pedestrian by VES by Adaptation by Participant (Age)* | | | |

x = $p < 0.05$ (significant)
— indicates significance in original analysis

## DEBOER SCALE RATINGS

Table 19 shows the secondary ANOVA results for the deBoer glare ratings. Only the main effect of VES glare (VES) was significant for the subjective measure of discomfort ($p < 0.05$). Results of a post hoc analysis of this main effect, shown in table 20, show no differences between the results of the original analysis and the secondary analysis.

**Table 19. Secondary analysis ANOVA table for discomfort glare rating.**

| Source | DF | SS | MS | F Value | P Value | |
|---|---|---|---|---|---|---|
| ***Between*** | | | | | | |
| Age | 2 | 89.6 | 44.8 | 1.24 | 0.3054 | |
| *Participant (Age)* | 27 | 975.0 | 36.1 | | | |
| ***Within*** | | | | | | |
| VES | 3 | 252.2 | 84.1 | 17.00 | <.0001 | * |
| VES by Age | 6 | 45.1 | 7.5 | 1.52 | 0.1825 | |
| *VES by Participant (Age)* | 81 | 400.5 | 4.9 | | | |
| Adaptation | 1 | 1.0 | 1.0 | 0.23 | 0.6390 | |
| Adaptation by Age | 2 | 6.3 | 3.2 | 0.71 | 0.5029 | |
| *Adaptation by Participant (Age)* | 27 | 120.9 | 4.5 | | | |
| VES by Adaptation | 3 | 1.5 | 0.5 | 0.30 | 0.8252 | |
| VES by Adaptation by Age | 6 | 3.1 | 0.5 | 0.31 | 0.9299 | |
| *VES by Adaptation by Participant (Age)* | 81 | 134.2 | 1.66 | | | |
| **ADJUSTED TOTALS** | 239 | 2029.4 | | | | |

* $p < 0.05$ (significant)

**Table 20. Discomfort glare SNK groupings comparison for the VES main effect.**

| VES | N | Mean deBoer Rating | Original SNK Grouping | Secondary SNK Grouping |
|---|---|---|---|---|
| Low/Narrow | 60 | 5.15 | C | C |
| Low/Wide | 60 | 6.77 | AB | n/a |
| Medium/Medium | 60 | 7.20 | A | A |
| High/Narrow | 60 | 6.15 | B | B |
| High/Wide | 60 | 6.15 | B | B |

N = sample size
n/a = not applicable

## DETECTION DISTANCE

Table 21 shows results of the secondary ANOVA for detection distance. The significant results of the original analysis and the secondary analysis were the same: a significant two-way interaction—Pedestrian by VES—and three main effects—age, VES, and pedestrian location.

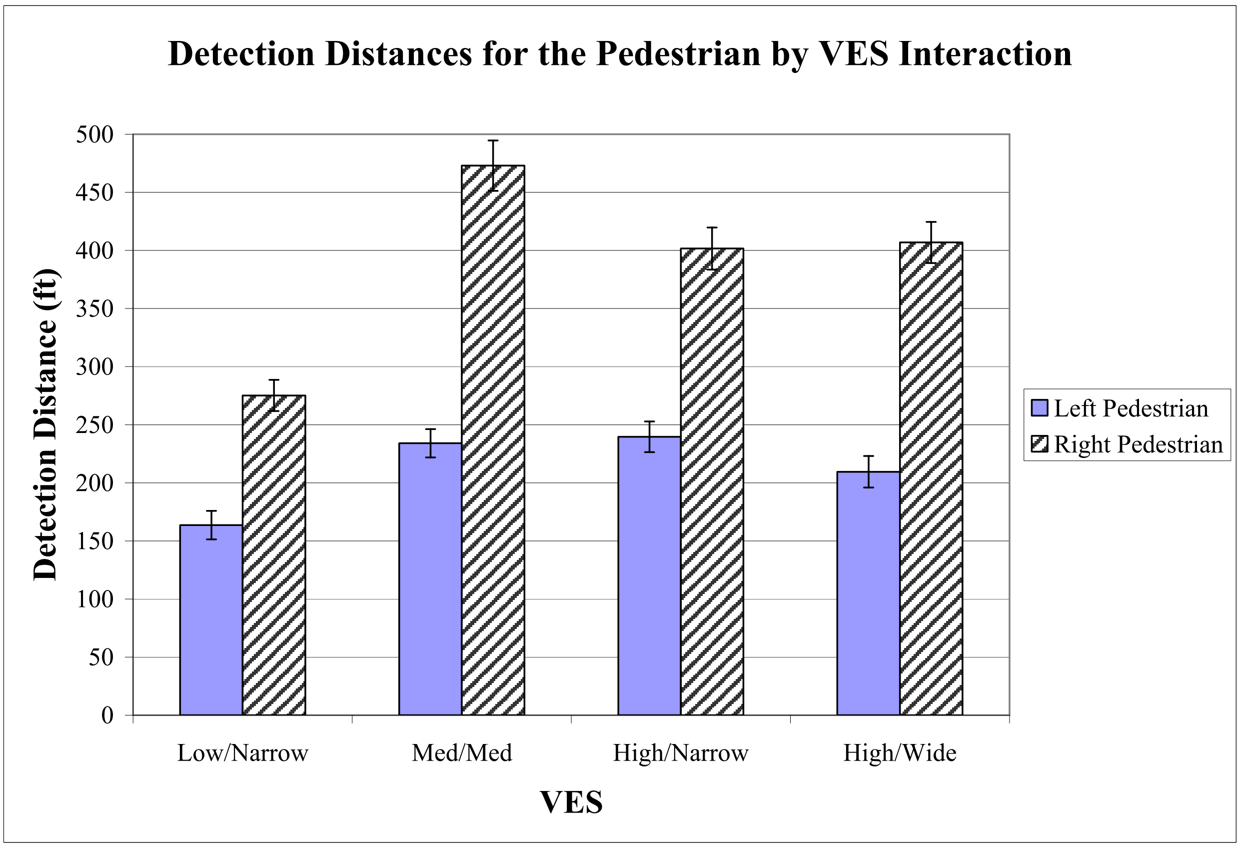
**Table 21. Secondary analysis ANOVA table for detection distances.**

| Source | DF | SS | MS | F Value | P Value | |
|---|---|---|---|---|---|---|
| ***Between*** | | | | | | |
| Age | 2 | 1148008.3 | 574004.2 | 13.97 | <.0001 | * |
| *Participant (Age)* | 27 | 1109334.1 | 41086.4 | | | |
| | | | | | | |
| ***Within*** | | | | | | |
| VES | 3 | 1053434.8 | 351144.9 | 30.43 | <.0001 | * |
| VES by Age | 6 | 56419.2 | 9403.2 | 0.81 | 0.5615 | |
| *VES by Participant (Age)* | 81 | 934660.3 | 11539.0 | | | |
| | | | | | | |
| Adaptation | 1 | 125.2 | 125.2 | 0.02 | 0.8975 | |
| Adaptation by Age | 2 | 18931.1 | 9465.5 | 1.28 | 0.2946 | |
| *Adaptation by Participant (Age)* | 27 | 199776.1 | 7399.1 | | | |
| | | | | | | |
| Pedestrian | 1 | 3555805.6 | 3555805.6 | 91.93 | <.0001 | * |
| Pedestrian by Age | 2 | 91456.5 | 45728.2 | 1.18 | 0.3220 | |
| *Pedestrian by Participant (Age)* | 27 | 1044345.4 | 38679.5 | | | |
| | | | | | | |
| VES by Adaptation | 3 | 3302.3 | 1100.8 | 0.19 | 0.9041 | |
| VES by Adaptation by Age | 6 | 23820.4 | 3970.1 | 0.68 | 0.6668 | |
| *VES by Adaptation by Participant (Age)* | 81 | 473474.6 | 5845.4 | | | |
| | | | | | | |
| Pedestrian by VES | 3 | 210072.9 | 70024.3 | 9.62 | <.0001 | * |
| Pedestrian by VES by Age | 6 | 11041.0 | 1840.2 | 0.25 | 0.9568 | |
| *Pedestrian by VES by Participant (Age)* | 81 | 589729.2 | 7280.6 | | | |
| | | | | | | |
| Pedestrian by Adaptation | 1 | 13875.4 | 13875.4 | 3.82 | 0.0612 | |
| Pedestrian by Adaptation by Age | 2 | 6012.8 | 3006.4 | 0.83 | 0.4481 | |
| *Pedestrian by Adaptation by Participant (Age)* | 27 | 98138.4 | 3634.8 | | | |
| | | | | | | |
| Pedestrian by VES by Adaptation | 3 | 2462.9 | 821.0 | 0.15 | 0.9297 | |
| Pedestrian by VES by Adaptation by Age | 6 | 8975.1 | 1495.8 | 0.27 | 0.9483 | |
| *Pedestrian by VES by Adaptation by Participant (Age)* | 80 | 439203.2 | 5490.0 | | | |
| **ADJUSTED TOTALS** | 478 | 11092405 | | | | |

* $p < 0.05$ (significant)

**Pedestrian by VES Interaction**

The significant interaction of pedestrian location and VES is illustrated in figure 27. The results are the same between the original analysis and the secondary analysis. The low/narrow VES had the lowest detection distance for both the pedestrian on the left and the pedestrian on the right. The other VESs had similar distances to each other for the pedestrian on the left; however, the pedestrian on the right appeared to have longer detection with the medium/medium VES, which was rated as less glaring on the deBoer scale.




1 ft = 0.305 m

**Figure 27. Bar graph. Secondary analysis mean detection distances for the interaction of pedestrian and VES.**

### VES Main Effect

The secondary analysis found the main effect of VES to be significant ($p < 0.05$). Post hoc analyses for the original and secondary analyses indicated the same results (table 22).

**Table 22. Detection distance SNK groupings comparison for the VES main effect.**

| VES | N | Mean Detection Distance (ft) | Original SNK Grouping | Secondary SNK Grouping |
|---|---|---|---|---|
| Low/Narrow | 120 | 219 | C | C |
| Low/Wide | 120 | 362 | A | n/a |
| Medium/Medium | 120 | 354 | A | A |
| High/Narrow | 119 | 321 | B | B |
| High/Wide | 120 | 308 | B | B |

1 ft = 0.305 m
N = sample size
n/a = not applicable

### Pedestrian Main Effect

The main effect of pedestrian position was significant ($p < 0.05$) in the secondary analysis. In the original analysis, the left pedestrian yielded a mean detection distance of 67.7 m (222 ft) and the right pedestrian a much farther detection distance of 122.8 m (403 ft). The secondary analysis indicated a similar result: left pedestrian at 64.4 m (211 ft) and right pedestrian at 117.1 m (384 ft).

### Age Main Effect

The secondary analysis also found the main effect of age to be significant ($p < 0.05$). In both the original and secondary analyses, the post hoc SNK indicated that as age increased, detection distance significantly decreased. These results and both analyses' means are shown in table 23.

**Table 23. Detection distance SNK groupings comparison for the age main effect.**

| Age | N | Original Mean Detection Distance (ft) | Secondary Mean Detection Distance (ft) | Original SNK Grouping | Secondary SNK Grouping |
|---|---|---|---|---|---|
| Young | 160 | 376 | 358 | A | A |
| Middle-Aged | 160 | 313 | 298 | B | B |
| Older | 160 | 252 | 237 | C | C |

1 ft = 0.305 m
N = sample size for secondary analysis

## DRIVER'S EYE ILLUMINANCE MEASUREMENTS

Table 24 shows secondary analysis ANOVA results of the illuminance at the driver's eye. The significant results were the same as those for the original analysis for the main effects and the Pedestrian by VES interaction; however, the original analysis' significant results that could be tied directly to the possible change in the low/wide VES were not significant in the secondary analysis. Specifically, the three-way interaction Pedestrian by VES by Age and the two-way interactions Pedestrian by Age and VES by Age were not significant in this analysis.

**Table 24. Secondary analysis ANOVA table for the objective measurement of driver's eye illuminance.**

| Source | DF | SS | MS | F Value | P Value | |
|---|---|---|---|---|---|---|
| ***Between*** | | | | | | |
| Age | 2 | 21.5 | 10.7 | 10.64 | 0.0004 | * |
| *Participant (Age)* | 27 | 27.2 | 1.0 | | | |
| ***Within*** | | | | | | |
| VES | 3 | 173.7 | 57.9 | 86.76 | <.0001 | * |
| VES by Age | 6 | 4.8 | 0.8 | 1.19 | 0.3205 | |
| *VES by Participant (Age)* | 81 | 54.1 | 0.7 | | | |
| Adaptation | 1 | 0.0 | 0.0 | 0.01 | 0.9295 | |
| Adaptation by Age | 2 | 0.7 | 0.3 | 1.61 | 0.2186 | |
| *Adaptation by Participant (Age)* | 27 | 5.8 | 0.2 | | | |
| Pedestrian | 1 | 28.1 | 28.1 | 65.19 | <.0001 | * |
| Pedestrian by Age | 2 | 0.3 | 0.2 | 0.36 | 0.6989 | |
| *Pedestrian by Participant (Age)* | 27 | 11.6 | 0.4 | | | |
| VES by Adaptation | 3 | 0.7 | 0.2 | 0.37 | 0.7772 | |
| VES by Adaptation by Age | 6 | 0.8 | 0.1 | 0.23 | 0.9672 | |
| *VES by Adaptation by Participant (Age)* | 81 | 50.5 | 0.6 | | | |
| Pedestrian by VES | 3 | 34.3 | 11.4 | 32.78 | <.0001 | * |
| Pedestrian by VES by Age | 6 | 2.0 | 0.3 | 0.95 | 0.4642 | |
| *Pedestrian by VES by Participant (Age)* | 81 | 28.3 | 0.3 | | | |
| Pedestrian by Adaptation | 1 | 0.2 | 0.2 | 0.39 | 0.5351 | |
| Pedestrian by Adaptation by Age | 2 | 1.9 | 0.9 | 1.98 | 0.1582 | |
| *Pedestrian by Adaptation by Participant (Age)* | 27 | 12.9 | 0.5 | | | |
| Pedestrian by VES by Adaptation | 3 | 0.6 | 0.2 | 0.55 | 0.6525 | |
| Pedestrian by VES by Adaptation by Age | 6 | 1.3 | 0.2 | 0.54 | 0.7730 | |
| *Pedestrian by VES by Adaptation by Participant (Age)* | 81 | 31.2 | 0.4 | | | |
| **ADJUSTED TOTALS** | 479 | 492.5 | | | | |

* $p < 0.05$ (significant)

**Pedestrian by VES Interaction**

The significant interaction of Pedestrian by VES is shown in figure 28. As in the original analysis, the wide-beam VES had the largest illuminance at detection of the left pedestrian, which was also more than three times that of the VES's illuminance at detection of the right pedestrian. The medium/medium VES also seemed to follow this trend; however, both the narrow-beam VESs had similar illuminances at the point of detection for both the left and right pedestrians.

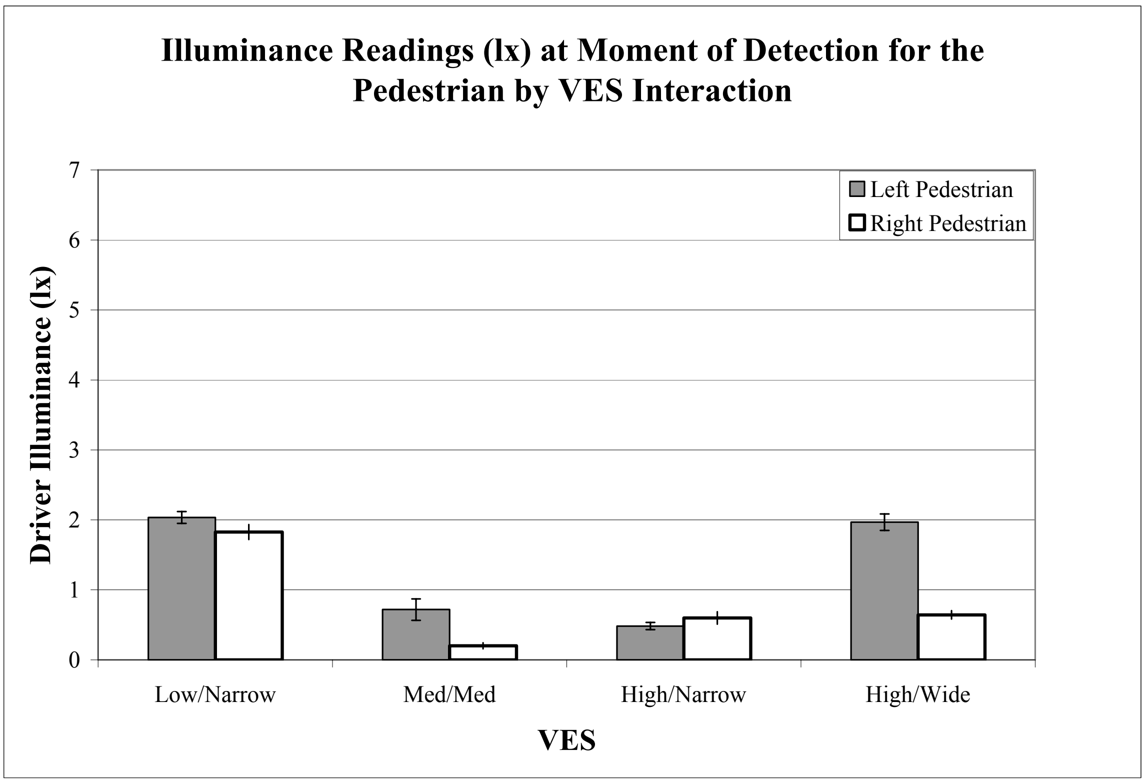



**Figure 28. Bar graph. Mean illuminance readings (lx) at moment of detection for the Pedestrian by VES interaction without the low/wide VES.**

**VES Main Effect**

The secondary SNK post hoc test of VES indicated the same three significantly different groupings of driver's eye illuminance (Δ lux) among the VESs (table 25). The low/narrow VES produced the highest mean driver's eye illuminance level at detection, 1.93 lx. The wide-beam VES was in the second group with the second highest illuminance at detection. The medium/medium VES and high/narrow VES were grouped together with the lowest illuminance at detection (0.46 lx and 0.54 lx, respectively).

**Table 25. Illuminance SNK groupings comparison for the VES main effect.**

| VES | N | Mean Illuminance (lx) | Original SNK Grouping | Secondary SNK Grouping |
|---|---|---|---|---|
| Low/Narrow | 120 | 1.93 | A | A |
| Low/Wide | 120 | 1.44 | B | n/a |
| Medium/Medium | 120 | 0.46 | C | C |
| High/Narrow | 120 | 0.54 | C | C |
| High/Wide | 120 | 1.31 | B | B |

N = sample size
n/a = not applicable

### Pedestrian Main Effect

The main effect of pedestrian location was also similar between the original analysis and the secondary analysis. Originally, the left-pedestrian location had a mean illumination level at detection of 1.52 lx. The mean illumination level for the right pedestrian was approximately half as great, 0.75 lx. In the secondary analysis, the illumination for the left was 1.30 lx, and for the right it was 0.82 lx.

### Age Main Effect

The significant main effect of age is shown in table 26. In both the original and secondary analyses, as age increased, illumination at detection increased. However, the original post hoc analysis did not indicate a significant difference between younger and middle-aged drivers whereas the secondary analysis indicated that each age group was statistically different.

**Table 26. Illuminance SNK groupings comparison for the age main effect.**

| Age | N | Original Mean Illuminance (lx) | Secondary Mean Illuminance (lx) | Original SNK Grouping | Secondary SNK Grouping |
|---|---|---|---|---|---|
| Young | 160 | 0.77 | 0.80 | B | C |
| Middle-Aged | 160 | 0.93 | 1.06 | B | B |
| Older | 160 | 1.72 | 1.32 | A | A |

N = sample size for secondary analysis

## REFERENCES


1. Lunenfeld, H., & Alexander, G.J. (1990). *A Users' Guide to Positive Guidance* (FHWA-SA-90-017) (3rd ed.). Final report. Washington, DC: Federal Highway Administration, Office of Traffic Operations and Positive Guidance Applications, Inc.
2. Mace, D., Garvey, P., Porter, R.J., Schwab, R., & Adrian, W. (2001). *Countermeasures for Reducing the Effects of Headlight Glare*. Washington, DC: AAA Foundation for Traffic Safety.
3. Theeuwes, J., Alferdinck, J., & Perel, M. (2002). "Relation Between Glare and Driving Performance." In *Proceedings of the Human Factors Society 44th Annual Meeting, 1*, 95–107.
4. Scheiber, F. (1997). "Age and Glare Recovery Time for Low-Contrast Stimuli." In W.A. Rogers (Ed.), *Designing for an Aging Population* (pp. 11–14). Santa Monica, CA: Human Factors and Ergonomics Society.
5. Vos, J.J. (1984). "Disability Glare—A State of the Art Report." *Commission Internationale de l'Eclairge Journal*, *3*(2), 39–53.
6. Stiles, W.S. (1929). "The Scattering Theory of the Effects of Glare on the Brightness Difference Threshold." *Proceedings of the Royal Society: London, 105B,* 131–139.
7. Schmidt-Clausen, H., & Bindels, J. (1974). "Assessment of Discomfort Glare in Motor Vehicle Lighting." *Lighting Research and Technology, 6*(2) 79–88.
8. Sivak, M., Flannagan, M., Ensing, M., & Simmons, C.J. (1989). *Discomfort Glare Is Task Dependent* (Report No. UMTRI-89-27). Ann Arbor, MI: University of Michigan Transportation Research Institute.
9. deBoer, J.B., & Schreuder, D.A. (1967). "Glare as a Criterion for Quality in Street Lighting." *Transactions of the Illuminating Engineering Society*, *32*, 117–135.
10. Jost, K. (1995). "High-Intensity Discharge Headlamps." *Automotive Engineering, 11*, 38–42.
11. Zino, K. (1995, August). "Technology Update: On the Beam." *Road and Track*, 134–138.
12. National Highway Traffic Safety Administration (NHTSA). (2001). *Glare from Headlamps and Other Front Mounted Lamps* (Docket No. 01-8885). Washington, DC: U.S. Department of Transportation.
13. Alferdinck, J., & Varkevisser, J. (1991). *Discomfort Glare from D1 Headlamps of Different Size* (Report No. IZF 1991 C-21). Soesterberg, The Netherlands: TNO Institute for Perception.

14. Flannagan, M. (1999). *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution* (Report No. UMTRI 99-36). Ann Arbor, MI: University of Michigan Transportation Institute.

15. Flannagan, M.J., Sivak, M., Gellatly, A.W., & Luoma, J. (1992). *A Field Study of Discomfort Glare from High-Intensity Discharge Headlamps* (Report No. UMTRI-92-16). Ann Arbor, MI: University of Michigan Transportation Research Institute.

16. Bullough, J.D., Fu, Z., & Van Derlofske, J. (2002). "Discomfort and Disability Glare from Halogen and HID Headlamp Systems (Report No. SAE 2002-01-0010)." *Society of Automotive Engineers World Congress & Exhibition 2002* (SP-1668, pp. 1–5). Warrendale, PA: Society of Automotive Engineers.

17. Mortimer, R.G. (1989). "Older Drivers' Visibility and Comfort in Night Driving: Vehicle Design Factors." In *Proceedings of the Human Factors Society 33rd Annual Meeting,* 154–158.

18. Richards, O.W. (1966). "Vision at Levels of Night Road Illumination: XII Changes of Acuity and Contrast Sensitivity with Age." *American Journal of Optometry/Archives of the American Academy of Optometry*, 43.

19. Richards, O.W. (1972). "Some Seeing Problems: Spectacles, Color Driving and Decline from Age and Poor Lighting." *American Journal of Optometry/Archives of the American Academy of Optometry,* 49.

20. Weale, R. (1961). "Retinal Illumination and Age." *Transactions of the Illuminating Engineering Society,* 26, 95.

21. Weymouth, F.W. (1960). "Effects of Age on Visual Acuity." In: M.I. Hirsch, and R.E. Wick, (Eds.), *Vision of the Aging Patient.* Chilton: Philadelphia, PA (pp. 37–62).

22. Zwahlen, H., & Schnell, T. (1999). "Visual Target Detection Models for Civil Twilight and Night Driving Conditions (Report No. 99-1545)." *Transportation Research Record 1692*, 49–65.

23. Flannagan, M.J., Sivak, M., Traube, E.C., & Kojima, S. (2000). "Effects of Overall Low-Beam Intensity on Seeing Distance in the Presence of Glare." *Transportation Human Factors, 2*(4), 313–330.

24. Nilsson, L., & Alm, H. (1996). "Effects of a Vision Enhancement System on Drivers' Ability to Drive Safely in Fog." In A.G. Gale, I.D. Brown, C.M. Haslegrave, & S.P. Taylor (Eds.), *Vision in Vehicles V* (pp. 263–272). Amsterdam: Elsevier Science B.V., North-Holland.

25. Marottoli, A., Ostfeld, A.M., Merrill, S., Perlman, G., Foley, D., & Cooney, L. (1993). "Driving Cessation and Changes in Mileage Driven Among Elderly Individuals." *Journal of Gerontology, 48*(5), S255–260.

26. Van Derlofske, J., Bullough, J., Dee, P., Chen, J., & Akashi, Y. (2004). "Headlamp Parameters and Glare (Report No. SAE 2004-01-1280)." *Society of Automotive Engineers World Congress & Exhibition 2004* (SP-1875, pp. 195–203). Warrendale, PA: Society of Automotive Engineers.

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