Volume VII

Enhanced Night Visibility Series: Phase II–Study 5: Evaluation of Discomfort Glare During Nighttime Driving in Clear Weather

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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 discomfort glare from various headlamp systems during nighttime driving in clear weather. The study was conducted under Phase II of the Enhanced Night Visibility (ENV) project, a comprehensive evaluation of evolving and proposed headlamp technologies under 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 VII. 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

Phase II—Study 5 helped expand the knowledge of how current vision enhancement systems (VESs) affect the discomfort glare experienced by nighttime drivers. The empirical testing for this study was performed on the Smart Road. Sixty participants were involved in the study, which consisted of two data collection efforts. An 11 (VES) by 3 (Age) experimental design was used to investigate the effects of different types of VESs and driver's age on discomfort glare. In addition, an evaluation of the Schmidt-Clausen and Bindels equation was performed to determine its predictive value in driving scenarios with oncoming glare.

The results of the empirical testing suggest that halogen headlamps selected for this testing produce more discomfort glare than the high intensity discharge headlamps tested. There was also some indication that ultraviolet (UV)–A may add slightly to discomfort glare. In addition, modifications of the Schmidt-Clausen and Bindels equation may provide headlamp designers with insight into how drivers will rate discomfort glare of proposed headlamps.

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Age, Discomfort Glare, Halogen, Headlamp, High Intensity Discharge (HID), Nighttime, Vision Enhancement System

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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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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 seventh 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
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LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

ANSI	American National Standards Institute
BCD	borderline between comfort and discomfort
D	average discomfort reported by participants
ENV	Enhanced Night Visibility
FHWA	Federal Highway Administration
IESNA	Illuminating Engineering Society of North America
ITS	Intelligent Transportation Systems
RP–8	Recommended Practice for Roadway Lighting
SUV	sport utility vehicle
UV–A	ultraviolet A (wavelength 315 to 400 nanometers)
VDOT	Virginia Department of Transportation
VES	vision enhancement system

Vision Enhancement Systems

HLB	halogen (i.e., tungsten-halogen) low beam
hybrid UV–A + HLB	hybrid UV–A/visible output together with halogen low beam
three UV–A + HLB	three UV–A headlamps together with halogen low beam
five UV–A + HLB	five UV–A headlamps together with halogen low beam
HLB–LP	halogen low beam at a lower profile
HHB	halogen high beam
HOH	high output halogen
HID	high intensity discharge
hybrid UV–A + HID	hybrid UV–A/visible output together with high intensity discharge
three UV–A + HID	three UV–A headlamps together with high intensity discharge
five UV–A + HID	five UV–A headlamps together with high intensity discharge

Statistical Terms

ANOVA	analysis of variance
DF	degrees of freedom
F value	F-ratio
MS	mean square
p value	statistical significance
SNK	Student-Newman-Keuls
SS	sums of squares

Measurements

cd/m^2	candela per square meter
cm	centimeters
fL	footlamberts
fc	footcandles
ft	feet
km	kilometers
km/h	kilometers per hour
lx	lux
m	meters
mi	miles
mi/h	miles per hour
min	minutes
mm	millimeters
nm	nanometers
W/cm^2	watts per square centimeter
µW/cm^2	microwatts per square centimeter

Schmidt-Clausen and Bindels Equation

θ_i	glare angle between observer's line of sight and the ith source (minutes of arc)
θ_{last}	glare angle between observer's line of sight and the headlamps at last location (minutes of arc)
θ_{max}	glare angle between observer's line of sight and the headlamps at location where maximum illumination occurs (minutes of arc)
E_i	illumination directed toward the observer's eye from the ith source (lux)
E_{last}	last level of illumination directed toward the observer's eye from the headlamps (lux)
E_{max}	maximum level of illumination directed toward the observer's eye from the headlamps (lux)
L_a	adaptation luminance (cd/m^2)
R	sample correlation coefficient
W	mean value on deBoer's scale
wavg	predicted discomfort based on average illumination over the 91.5-m (300-ft) segment
wlast	predicted discomfort based on the last illumination experienced
wmax	predicted discomfort based on maximum illumination over the 91.5-m (300-ft) segment

CHAPTER 1—INTRODUCTION

BACKGROUND

Although the number of vehicle miles driven at night represents only about 25 percent of the total vehicle miles driven in the United States, 46 percent of driving fatalities occur at night.(1) This translates into a nighttime traffic fatality rate of 2.84 deaths per 100 million vehicle miles, more than 2.5 times higher than the daytime traffic fatality rate.(1)

Nighttime driving, of course, entails several visual difficulties. Glare from oncoming headlamps is known to have deleterious effects on the visual system, but it is rarely reported as a causal factor in police accident reports.(2) This may be partly because many accident reporting systems do not specifically reference glare, and when they do, it often is categorized poorly.(3) In addition, it is unlikely that drivers who are involved in accidents are even aware of the effects of glare on their visual system; however, because driving is a visual task and glare has known deleterious effects on vision, it can be inferred that glare has an unsafe effect on driving performance, perhaps resulting in accidents.(3)

Research on glare caused by roadway and vehicle lighting dates back to the mid-1920s. This early work recognized that glare resulted in a loss of visibility, but it also showed that visibility loss was not the only effect—glare also can evoke feelings of discomfort. As a result, glare research has commonly been divided into studies of disability glare (glare that results in a loss of visibility) and discomfort glare (glare that causes some level of pain or annoyance).

Disability glare is the result of light scattering in the ocular media. Light from a glare source, such as the headlamps of an opposing vehicle, enters the eye and is scattered, creating a uniform, or veiling, luminance over the small angular subtense of the fovea. Regardless of whether an object is brighter or darker than its background, veiling luminance decreases the contrast of the object. Because contrast is required for an object to be perceived, this reduction makes it more difficult to detect obstacles in the path of the driver.

Discomfort glare is a result of light that is bright or nonuniform in the field of view. Although discomfort glare may accompany disability glare, it is a distinctly different and less understood phenomenon.(4) Fry and King were able to attribute the discomfort glare sensation to neuronal interactions indicated by pupillary activity.(5) However, a better understanding of the relationship between discomfort glare and other physiological functions is needed before such knowledge is applied to engineering practice.

Much of the existing research on discomfort glare relates to the size and luminance of the glare source, the number of glare sources, the location of the glare source relative to the line of sight (i.e., glare angle), and the background or adaptation luminance. To attempt to quantify discomfort glare, many experiments have used a measure of the luminance necessary to cause discomfort, commonly referred to as the borderline between comfort and discomfort (BCD); however, the scale that most often is used to measure automotive discomfort glare was developed by deBoer and Schreuder.(6) It is a nine-point subjective scale with qualifiers at the odd points:

1. Unbearable
2.
3. Disturbing
4.
5. Just acceptable
6.
7. Satisfactory
8.
9. Just noticeable

The development of deBoer’s scale was followed by the work of Schmidt-Clausen and Bindels.(7) Through a series of laboratory experiments, they developed an equation to predict the mean deBoer rating of a light source from the adaptation luminance, the illumination directed toward the observer’s eye, and the glare angle. A form of the Schmidt-Clausen and Bindels equation is shown in figure 1.(7)

$$W = 5.0 - 2.0LOG\frac{Ei}{0.003*\left(1+\sqrt{\frac{La}{0.04}}\right)*\theta_i^{0.46}}$$

Figure 1. Equation. Schmidt-Clausen and Bindels equation.

In the equation in figure 1, W = mean value on deBoer's scale, E_i = illumination directed toward the observer's eye from the ith source (in lux or lx), θ_i = glare angle between observer's line of sight and the ith source (minutes of arc), and L_a = adaptation luminance (in candela per square meter or cd/m^2).

Other parameters not included in the Schmidt-Clausen and Bindels equation may also affect the discomfort experienced by an observer. For example, Lulla and Bennett showed that judgments of glare in a laboratory setting may be affected by the range of glare experienced, a phenomenon known as "range effect."(8) In their study, participants who were exposed to a greater range of glare (3.4 cd/m^2 to 1,000,000 cd/m^2 (0.99 footlamberts (fL) to 291,900 fL)) set the BCD much higher than participants who were exposed to a smaller range (3.4 cd/m^2 to 100,000 cd/m^2 (0.99 fL to 29,190 fL)).

Olson and Sivak demonstrated that the range effect, which was discovered previously in a laboratory setting, also can occur in a realistic driving environment.(9) They demonstrated that in real driving scenarios, the average discomfort reported for varying glare conditions was from one to two scale intervals more comfortable than that predicted by the Schmidt-Clausen and Bindels equation, except for situations with high deBoer glare ratings (i.e., lower discomfort).

In summary, the causes and effects of discomfort glare potentially are important but not well understood, at least from an applications perspective. With continuous technological advancements being made in roadway and vehicle lighting, further studies in both discomfort and disability glare would be valuable. Because of its direct deleterious effects on vision, research on disability glare may have a greater effect on safety than research on discomfort glare; however, driver comfort is very important and ultimately may decide whether a new technology is adopted universally.

RESEARCH OBJECTIVES

Headlamp design should provide the maximum visibility for drivers while minimizing the disability and discomfort effects of glare from oncoming traffic. Advances in headlamp technology, such as tungsten-halogen lamps, as well as the introduction of newer technology including high intensity discharge (HID) lamps, high output halogen (HOH) lamps, and supplemental ultraviolet A (UV–A) lamps have been made in an attempt to optimize these design goals.

The purpose of this study was to evaluate, for three different age groups, the discomfort glare effects of these new technologies designed to enhance night vision and evaluate the applicability of the Schmidt-Clausen and Bindels equation. Data were collected for 11 different vision enhancement systems (VES) that combined HID, UV–A, and halogen lamps. Some of these technologies already have been implemented by car manufacturers, while others are being tested for future applications. This report will be augmented with current and future research projects, with an end result of identifying the benefits and possible drawbacks of different VESs. These other projects will investigate important issues, including the following points:

- The distances at which drivers detect and recognize nonmotorists, objects, and pavement markings under different weather conditions.
- The disability glare effects of new VESs.
- The visibility of objects in the peripheral view (i.e., farther away from the road).

CHAPTER 2—METHODS

PARTICIPANTS

Sixty individuals participated in the data collection studies. Participants were divided into three different age categories: 20 participants were between the ages of 18 and 25 years (younger category of drivers), 20 were between the ages of 40 and 50 (middle-aged category of drivers), and 20 were age 60 or over (older category of drivers). An equal number of males and females were in each age category. Participation was allowed after a screening questionnaire was completed, and only if the selection conditions were fulfilled (appendix A). Participants were required to sign an informed consent form (appendix B), present a valid driver's license, pass the visual acuity test (appendix C) with a score of 20/40 or better corrected vision (as required by Virginia State law), and have no health conditions that would make operating the research vehicles a risk. The participants' visual acuities ranged from 20/10 to 20/40 using a Snellen eye chart. Based on findings of earlier research, no distinction was made between participants with and without visual correction with regard to study participation.(10)

Participants were instructed about their right to withdraw freely from the study at any time without penalty. They were told that no one would try to make them participate if they did not want to continue. If they chose at any time not to participate further, they were instructed that they would be paid for the amount of time of actual participation. Participants received $20 per hour for their participation. All data gathered as part of this experiment were treated with complete anonymity.

INDEPENDENT VARIABLES

VES

Following are the definitions for the 11 VES configurations used in the study:

- Halogen (i.e., tungsten-halogen) low beam (HLB).
- Hybrid UV–A/visible output together with halogen low beam (hybrid UV–A + HLB).
- Three UV–A headlamps together with halogen low beam (three UV–A + HLB).
- Five UV–A headlamps together with halogen low beam (five UV–A + HLB).

- Halogen low beam at a lower profile (HLB–LP).
- Halogen high beam (HHB).
- High output halogen (HOH).
- High intensity discharge (HID).
- Hybrid UV–A/visible output together with high intensity discharge (hybrid UV–A + HID).
- Three UV–A headlamps together with high intensity discharge (three UV–A + HID).
- Five UV–A headlamps together with high intensity discharge (five UV–A + HID).

For a more indepth look at the technical specifications of each headlamp, refer to ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

These 11 VES configurations were selected based on several considerations. The HLB and the HID headlamps currently are available on the market and are what most drivers have traditionally used in their vehicles; therefore, they were added as baseline conditions to allow comparing new VES alternatives to what is readily available.

HID lamps have a high level of luminous efficiency, providing much more luminous flux than conventional halogen lamps. These traits have made HID lamps good candidates for vehicular applications, and they already have been implemented as standard components in some new automobiles. Since these headlamps were introduced, however, public concern and media coverage about the glare associated with them have become increasingly prevalent. The HID lamps appear much brighter to oncoming drivers, and they have a blue-white color, which appears different from the yellow light produced by halogen lamps.

These characteristics have led to a perceived increase in discomfort glare when nighttime drivers approach a vehicle equipped with HID lights. In turn, this perception has led to a growing number of complaints made to the U.S. Department of Transportation, which has called for additional research to determine if the increase in discomfort is an acceptable tradeoff for the possible increase in visibility. Similar research is also needed for HOH lamps. The HOH lamp provides approximately 20 percent more visible light in a low-beam configuration than a standard halogen lamp; however, its effects on visibility and glare are unknown.

Supplemental UV–A headlamps have the promise of improving the visibility distance of objects while minimizing glare. UV–A headlamps emit radiation with a wavelength ranging from 320 to 400 nm. This radiation causes materials that contain phosphors and selected other materials to fluoresce. Studies conducted in Sweden and the United States have found that nighttime driving visibility increases as much as 30 to 200 percent when these devices are used.(11) Furthermore, because UV–A radiation falls outside of the visible spectrum, it is possible that the disability and discomfort glare caused by UV–A headlamps would be minimal—perhaps even nonexistent. The hybrid UV–A headlamps used in this study include visible light, but it is not known whether this increased light will, in conjunction with standard HLB or HID headlamps, increase discomfort glare.

Age

As mentioned, there were three age variables: younger participants (18 to 25 years), middle-aged participants (40 to 50 years) and older participants (60 years or older). These age groups were created based on literature review findings (ENV Volume II) that suggest changes in vision during certain ages. (See references 12, 13, 14, 15, and 16.) Gender was used as a control but not as a factor of interest. An equal number of males and females was assigned to each age group.

DEPENDENT VARIABLES

The dependent variables were two subjective discomfort glare ratings—a far rating and a near rating—using the deBoer scale. The far rating was the discomfort that a participant experienced while driving a segment of road that stretched from 396.2 to 304.8 m (1,300 to 1,000 ft) away from the opposing headlamps. The near rating reflected the discomfort that a participant experienced while driving a segment of road that stretched from 137.2 to 45.7 m (450 to 150 ft) away from the opposing headlamps.

For both discomfort ratings, participants used the scale developed by deBoer and Schreuder. As discussed earlier, the deBoer scale is the most common method to measure subjective glare discomfort, and its use was recommended by Sivak and Olson in their attempt to develop a universally acceptable methodology for evaluating discomfort glare from vehicle headlamps.(17) It is a nine-point scale with qualifiers only for the odd points:

1. Unbearable
2.
3. Disturbing
4.
5. Just acceptable
6.
7. Satisfactory
8.
9. Just noticeable

EXPERIMENTAL DESIGN

An 11 (VES) by 3 (Age) experimental design was used to assess discomfort glare. Because of voltage fluctuations, some discomfort glare resulting from VESs was reassessed in an additional data collection effort. As a result, two separate data collection efforts were used to complete this study. The data collection details for each effort are discussed below.

The initial data collection effort was an 11 (VES) by 3 (Age) mixed factor design. Three age groups were used with 10 participants in each age group for a total of 30 participants. The 11 VESs were treated as a within-subjects variable with each participant rating the discomfort glare for each VES. Because of the hardware constraints of combining the different headlamps (detailed in the Apparatus and Materials section), special considerations were taken while counterbalancing the VES configurations for the initial data collection effort. Data were collected on two nights. The VES configurations that could be presented in the same night were grouped into experimental sessions. Because the UV headlamp setups were mounted permanently on different vehicles, the base headlamps (HLB and HID) had to be moved between vehicles to achieve the desired configurations. This movement of base headlamps was time-consuming, so it was done only once per night before the participants arrived. This constraint forced the grouping of the UV–A configurations into sessions A and B. To evaluate the other VESs, the HOH and HHB were added to session A; the HLB–LP condition was added to session B. Session A had six VESs, and session B had five VESs (table 1).

Table 1. VES configurations used in the experimental sessions.

Session A	Session B
HLB	HID
Hybrid UV–A + HLB	Hybrid UV–A + HID
Three UV–A + HID	Three UV–A + HLB
Five UV–A + HID	Five UV–A + HLB
HHB	HLB–LP
HOH	

The VES sessions remained consistent throughout the evaluation. The initial data collection effort required that the two experimental sessions occur on two separate nights; however, to avoid any order effects, the participant pool was split in half, and each half was assigned a different presentation order. This resulted in half of the participants being presented with session A on night 1 and the other half being presented with session B on night 1; the presentations reversed on night 2. In addition, the presentation of the VESs within a session was counterbalanced for each participant. Two participants performed the experiment simultaneously.

After reviewing the results from the initial data collection effort, there was some indication that some of the lights may have had variations in their output caused by fluctuations in the glare vehicle voltage. The following lights could have been affected by these fluctuations:

- HLB.
- Hybrid UV–A + HLB.
- Three UV–A + HLB.
- Five UV–A + HLB.
- HHB.
- HOH.

To compensate for this potential problem, the data for these VESs were excluded from analysis, and a second data collection effort was designed that included only these six VESs. An additional 30 participants were selected from the same three age groups used in the initial data collection effort (i.e., 10 from each group). The six VESs included in the second data collection effort also were treated as a within-subjects variable, with each participant rating the discomfort glare on each of these VESs. This data collection effort was completed on a single night. The VESs were counterbalanced to reduce order effects. The same protocol was followed in both data collection efforts.

These two data collection efforts resulted in an experiment that used an incomplete block design. The initial data collection effort was one block, and the second data collection effort was the second block. In a complete block design, each block receives a replication of the entire experiment, as was the initial intent of the first data collection effort. The design of this experiment was an incomplete block because each block was exposed to only certain VESs. The VESs included in each block are shown in table 2.

Table 2. Experimental blocks.

Block A VESs from the Initial Data Collection Effort	Block B VESs from the Second Data Collection Effort
HID	HLB
Hybrid UV–A + HID	Hybrid UV–A + HLB
Three UV–A + HID	Three UV–A + HLB
Five UV–A + HID	Five UV–A +HLB
HLB–LP	HHB
	HOH

SAFETY PROCEDURES

Safety procedures were implemented as part of the instrumented vehicle system. These procedures were used to minimize possible risks to participants during the experiment. There were five required safety measures:

- All data collection equipment be mounted so that, to the greatest extent possible, it did not pose a hazard to the driver in any foreseeable instance.
- Participants wear the seatbelt restraint system anytime the car was on the road.
- The data collection equipment did not interfere with any part of the driver's normal field of view.
- A trained in-vehicle experimenter be in the vehicle at all times.
- An emergency protocol was established before testing.

APPARATUS AND MATERIALS

Vehicles

The VESs were configured on four glare vehicles, including two sport utility vehicles (SUV), a pickup truck, and a sedan. One SUV (black) was equipped to provide the HLB, HID, hybrid UV–A + HLB, and hybrid UV–A + HID configurations. The HLB and HID headlamps were mounted on plates that could be exchanged, depending on the desired combination, and the hybrid UV–A lamps were mounted permanently on a bar in front of the grill (figure 2). The second SUV (white) was equipped to provide the HLB, HID, three UV–A + HLB, five UV–A + HLB, three UV–A + HID, and five UV–A + HID configurations (figure 3). As with the black SUV, the HLB and HID lamps were mounted on plates that could be exchanged each night, and the UV–A lamps were permanently mounted in front of the grill.

Figure 2. Photo. Headlamp setup on black SUV with hybrid UV–A and HID.

Figure 3. Photo. Headlamp setup on white SUV with five UV–A and HLB.

The pickup truck provided the HHB and HOH VES configurations. Both bulb types were located in the same housing unit, with the HOH lamps replacing the standard HLB lamps that were installed originally. The sedan was equipped with the HLB–LP system by the manufacturer. Table 3 summarizes the headlamps mounted on each glare vehicle.

Table 3. Headlamps mounted on each glare vehicle.

Vehicle	Headlamp Type 1	Headlamp Type 2	Headlamp Type 3	Headlamp Type 4
Black SUV	HLB	HID	Hybrid UV–A	
White SUV	HLB	HID	Three UV–A	Five UV–A
Pickup	HHB	HOH		
Sedan	HLB–LP			

During the experiment, participants drove in one of two identical compact vehicles using the conventional HLB configuration equipped by the manufacturer.

Smart Road

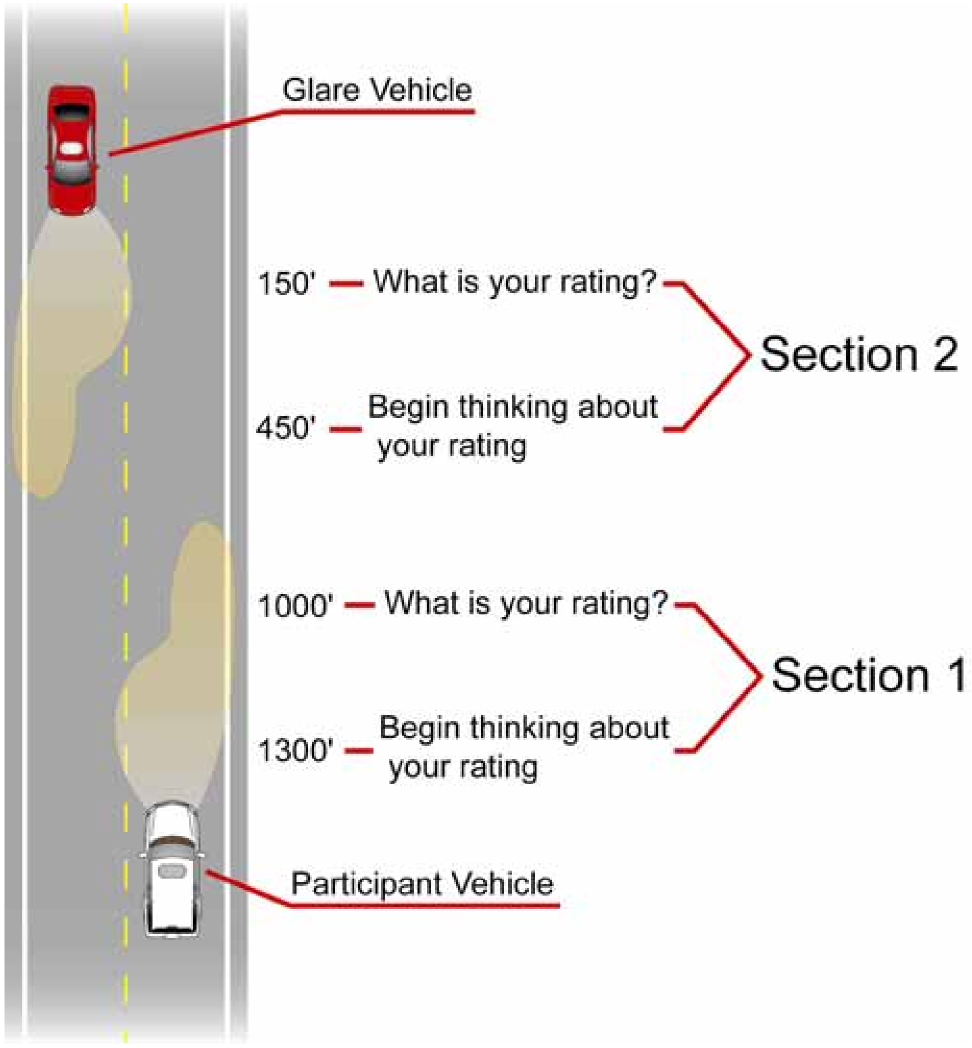
The Virginia Smart Road (all overhead lighting turned off) was used for the onroad study (figure 4 and appendix F). The Smart Road is a cooperative research effort between the Virginia Department of Transportation (VDOT), the Federal Highway Administration (FHWA), and the research contractor. The road is a two-lane highway that is approximately 3.2 km (2 mi) long with turnaround sections at both ends. The road has a vertical grade, which is fairly constant, and some horizontal curvature, as well as one section composed of asphalt pavement and one section of concrete pavement.

The area surrounding the Smart Road consists mostly of open fields and mountains with few extraneous light sources; therefore, the ambient lighting was controlled fairly easily, decreasing the variability of the data. The secluded area and closed-off road also helped maximize the safety of the participants and provided convenience to the experimenters, who were able to position the test vehicles easily without disrupting traffic or surrounding neighborhoods.

Figure 4. Photo. Smart Road.

The locations of the parked glare vehicles were marked on the pavement before beginning data collection. Two locations were chosen in each of two travel lanes (in one experimental run, the participant would pass two glare vehicles in the opposing lane) in areas with minimal horizontal curvature. The locations were 798 m (2,592 ft) apart.

For each glare vehicle, four orange cones were located on the right shoulder of the Smart Road to denote the separation distance between the driver and the glare vehicle. The first and second cones were located at 396.2 and 304.8 m (1,300 and 1,000 ft), respectively, from the glare vehicle (denoting the road segment corresponding to the far rating). The third and fourth cones were located at 137.2 and 45.7 m (450 and 150 ft) from the glare vehicle (denoting the road segment corresponding to the near rating). The two selected glare source positions were based on Sivak and Olson's discomfort glare protocol.(17) The setup is illustrated in figure 5.



1 ft = 0.305 m

Figure 5. Diagram. Experimental onroad setup.

Headlamp Aiming

The headlamps used for the HLB, HID, HOH, HHB, and UV–A configurations were located on external light bars. To change from one configuration to another, the HLB and HID headlamps were moved onto, off of, and between vehicles. Each light assembly movement required a re-aiming process, which took place before starting the experimental session each night. At the beginning of the Phase II studies, a headlamp aimer was not available to the contractor, so an aiming protocol was developed with the help of experts in the field. (See references 18, 19, 20, and 21.) The details of the aiming protocol used for this specific study are described in appendix G. During the photometric characterization of the headlamps, it was discovered that the position of the maximum intensity location of the HLB, HOH, and HHB configurations was aimed higher and more toward the left than is typical, which likely resulted in these lights being rated as having increased discomfort glare; however, a secondary study comparing the discomfort glares associated with a standard optical aimer method and the method used for this study showed a minimal difference for the halogen baseline lights. More information on this secondary study can be found in the Discussion section of this report. Details about the aiming procedure and the maximum intensity location are discussed in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

EXPERIMENTAL PROCEDURE

The driving performance portion of the study took place at the Smart Road testing facility. The road was closed to all traffic except for experimental vehicles. The experimental procedures were adapted from Sivak and Olson's field tests, which involved a proposed discomfort glare evaluation methodology at intermediate speeds.(17) To increase the efficiency of the data collection effort, data for two participants, each driving in a separate vehicle with one following the other, were collected simultaneously. During pilot testing, protocol adjustments were made so that the drivers in each vehicle would not be distracted by each other or by the onroad experimenters who changed the glare vehicles after each run. Participants drove only in clear weather conditions. The test session was cancelled if there was any precipitation on the roadway (e.g., rain, snow, fog).

Participant Screening

Before beginning the glare experiment, each participant completed vision tests and a study familiarization process (appendix D). This included signing the informed consent form shown in appendix B and participating in three vision tests to determine visual acuity, contrast sensitivity, and any color vision deficiencies. The only vision requirement to participate in the discomfort glare study was normal or corrected vision with an acuity of 20/40 or better. Results of the contrast sensitivity and color blindness tests were documented but were not used for screening. A detailed experimenter protocol for vision testing is presented as part of appendix D.

Training

Each participant was given an orientation of the glare study (appendix E). He or she was told the purpose of the experiment and, using a map of the Smart Road, was shown where he or she would be driving, where the glare vehicles would be parked, and when he or she would be asked to evaluate the glare. Each participant was also instructed to drive as he or she normally would drive, in the right lane at a speed of 25 mi/h (40 km/h), always looking straight ahead and never directly into the lights of the opposing vehicle. Finally, each participant was familiarized with deBoer's scale until he or she felt comfortable with the nine-point rating system.

General Onroad Procedure

Following the completion of the vision tests and instructions, the participant drove to one end of the Smart Road with an in-vehicle experimenter in the front passenger seat.

Run 1 was a practice run to familiarize the participants with the road and vehicle. During this run, there were no glare vehicles in the opposite lane. When the participant reached the end of the Smart Road, he or she parked in the turnaround area, where he or she was prepared for run 2. While the participant was parked in the turnaround area, onroad experimenters positioned two glare vehicles in the opposing lane and turned on the headlamps. Run 2 was the first experimental run. Before beginning the run, the in-vehicle experimenter read the following instructions to the driver (see figure 5):

> "You will drive this vehicle up and down the road at 25 miles per hour. While you are driving, always look directly ahead and never directly at the oncoming headlights. Along the way, there will be vehicles parked in the opposite lane with the headlights facing you. For each vehicle, I will ask you to rate the discomfort you experience from the glare two different times. You will use the nine-point scale that we reviewed during the screening (while showing the scale, the experimenter read the scales qualifiers).
>
> "When I need you to begin evaluating the glare, I will say, 'Begin.' You will then begin thinking about the discomfort rating you want to give the headlights. I will then ask, 'What is your rating?' At that time, I want you to tell me your rating for the discomfort you experienced on the stretch of road from where I said 'begin' to where I asked for the rating. We will then repeat that procedure for the same headlights on a different stretch of road. Do you have any questions?"

If there were no questions, the participant began driving up the road at 40 km/h (25 mi/h). As explained previously, for each glare vehicle, there were four orange cones located on the right shoulder. Cones 1 and 2 marked the near road segment where the discomfort was rated, and cones 3 and 4 marked the far road segment. Therefore, at cones 1 and 3, the in-vehicle experimenter would say, "Begin," and at cones 2 and 4 the experimenter would say, "Give me your rating." At the end of run 2, the participant pulled into another turnaround area while the onroad experimenters positioned the glare vehicles for the next run.

Runs 3 and 4 both repeated the procedure followed in run 2. The in-vehicle experimenter protocol used in the study is in appendix E.

Photometric Measurements

After completion of the participant data collection, a series of photometric measurements were taken to determine two important parameters of each VES: the vertical illumination directed toward the driver's eye for each VES configuration and the driver's adaptation luminance. These measurements will be used in the analysis to help interpret the results.

Vertical Illumination

A Konica Minolta™ T-10 illuminance meter was used to measure the vertical illumination directed toward the participant's eye. The meter was placed inside a compact vehicle identical to the one driven by the participant during testing; the meter was then positioned to replicate the driver's eye position. An average driver eye height of 119.4 cm (47 inches) was assumed. The onroad experimental setup for each VES configuration was replicated so that the measurement vehicle was in the right lane with the glare vehicle facing it in the opposing lane.

The vertical illumination measurements were taken at 15.2-m (50-ft) intervals in the far rating segment of road (i.e., 396.2 m, 381.0 m…304.8 m (1,300 ft, 1,250 ft …1,000 ft)) and near rating segment (i.e., 137.2 m, 121.9 m…45.7 m (450 ft, 400 ft …150 ft)). The complete set of vertical illumination measurements are shown in appendix H.

Adaptation Luminance

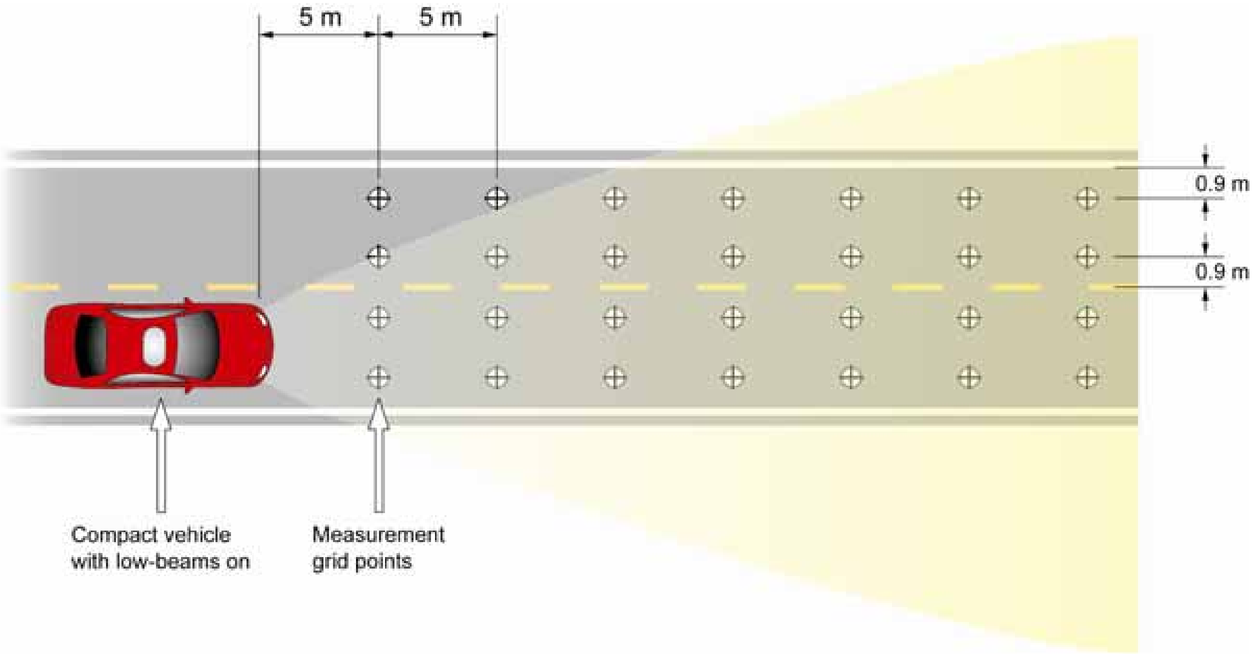
During testing, the participant drove a compact vehicle with the HLBs turned on. Because a driver's adaptation level may affect the level of discomfort glare experienced, an attempt was made to quantify this parameter.(7) It was assumed that the driver's adaptation level would be the average pavement luminance provided by the HLB headlamps.

A Pritchard® PR-1980A photometer with a 6-min aperture was used to make the luminance measurements. To evaluate an average adaptation luminance, the measurements were taken in a grid similar to that used in the Illuminating Engineering Society of North America (IESNA) American National Standards Institute (ANSI) Recommended Practice for Roadway Lighting (RP–8–00) to evaluate the luminance of pavement surfaces.(23) As illustrated in figure 6, grid points were spaced longitudinally every 5 m (16 ft) and laterally 0.9 m (3 ft) inside the edges of each lane (one quarter of the lane width).

The measurement vehicle was parked in the right lane with the photometer positioned inside the vehicle to represent the driver's eye position (119.4 cm (47 inches)). Luminance measurements were then taken at each grid point, starting with the first lateral row, located 5 m (16 ft) from the front of the vehicle, and ending at the final row, located 80 m (263 ft) from the front of the vehicle; the distance from the front of the vehicle to the observer was approximately 2 m (6 ft).

This method assumed a stationary observer, meaning that the observer perceived the entire roadway at once; therefore, the measurement angle varied for each measurement, which is different than the moving observer method used in IESNA RP–8–00. The RP–8–00 model also assumes an observer line-of-sight of 1° below horizontal, spanning a distance of 83 m (272 ft) before intersecting the ground.(23) A similar model was used here.

It was assumed that the observer would have an adaptation luminance equal to the average pavement luminance over this span. The adaptation level provided by the low beam on the vehicle driven by the participant was 0.14 cd/m^2 (0.04 fL). The luminance measurements for each grid point are in appendix I.



1 m = 3.28 ft

Figure 6. Diagram. Location of luminance measurement points to determine adaptation level.

CHAPTER 3—RESULTS

ANALYSIS OF VARIANCE

An analysis of variance (ANOVA) was conducted on the 11 (VES) by 3 (Age) model for both near and far ratings of the discomfort glare. Recall that two glare ratings (i.e., near and far) were given for each VES by each participant using the deBoer scale. The deBoer scale ranges from 1, "Unbearable," to 9, "Just noticeable." Therefore, if a participant experiences more glare, this will result in a lower rating. The results of the ANOVA discomfort ratings for the VES by Age model are described in the following paragraphs. The results of the ANOVA are summarized in table 4 and table 5.

Table 4. Summary of far rating ANOVA.

Source	DF	SS	MS	F Value	*p* Value
VES	10	117.6	11.8	6.93	<.0001
Age	2	14.3	7.2	0.79	0.4604
Age by VES	20	43.4	2.2	1.28	0.1951
Error	240	407.6	1.7		
Total	272				

Table 5. Summary of near rating ANOVA.

Source	DF	SS	MS	F Value	*p* Value
VES	10	415.1	41.5	37.5	<.0001
Age	2	22.7	11.4	0.82	0.4454
Age by VES	20	53.4	2.7	2.41	0.0009
Error	240	265.7	1.1		
Total	272				

For the far discomfort rating (table 4), the effect of VES was statistically significant ($p < 0.0001$). The effect of age was not statistically significant ($p = 0.46$), with younger participants reporting a mean discomfort of 5.5, middle-aged participants reporting a mean discomfort of 5.7, and older participants reporting a mean discomfort of 5.2. There was also no significant interaction between VES configuration and age ($p = 0.2$).

The effect of VES was also statistically significant ($p < 0.0001$) for the near discomfort rating (table 5). The effect of age was not statistically significant ($p = 0.45$), with younger participants reporting a mean discomfort of 3.7, middle-aged participants reporting a mean discomfort of 4.3, and older participants reporting a mean discomfort of 3.8; however, there was a significant interaction between VES configuration and age (*p* = 0.0009) for the near discomfort rating.

VES MAIN EFFECT

Because VES had a statistically significant main effect for both the near and far discomfort ratings, a post hoc analysis was conducted for this variable using Student-Newman-Keuls (SNK) tests. These tests provide a way to compare means and determine significant differences between each configuration. The SNK tests were used because they do not produce overly conservative results when many levels of a single independent variable are compared. The results of the SNK tests are shown in table 6 and table 7, which list the VESs and their mean discomfort ratings in descending order. In other words, the VESs are ordered from the least amount of discomfort (therefore receiving the highest rating) to the most discomfort (therefore receiving the lowest rating). Table 6 and table 7 also show the SNK result grouping. In SNK tests, means that are assigned the same letter are not significantly different from each other.

For the far rating, the range of mean discomfort ratings was small, varying from 6.6 for the three UV–A + HID to 4.7 for the three UV–A + HLB (table 6). Accordingly, the SNK groupings were rather large, indicating that when the distance between the participant and the opposing vehicle was 396.2 to 304.8 m (1,300 to 1,000 ft), there were not many significant differences between the different VESs tested. The three VESs rated most discomforting were the three UV–A + HLB, five UV–A + HLB, and HOH; they all scored below a 5 (“Just acceptable”) on deBoer’s scale. The significant difference shown between the three UV–A + HID and the HID alone is surprising because adding the UV–A systems to the base lamps should not add enough visible light to affect driver discomfort and should certainly not reduce it.

Table 6. Mean far discomfort ratings in descending order.

VES	Mean	SNK Grouping
Three UV–A + HID	6.6	A
HLB–LP	6.3	A, B
Five UV–A + HID	6.0	A, B, C
HHB	5.8	A, B, C, D
HLB	5.5	B, C, D, E
HID	5.5	B, C, D, E
Hybrid UV–A + HID	5.5	B, C, D, E
Hybrid UV–A + HLB	5.0	C, D, E
Five UV–A + HLB	4.9	D, E
HOH	4.8	E
Three UV–A + HLB	4.7	E

For the near rating, the mean discomfort ratings ranged from 5.9 for the three UV–A + HID to 2.6 for the HHB (table 7). The three UV–A + HID, five UV–A + HID, and HID provided the least amount of discomfort when there was 137.2 to 45.7 m (450 to 150 ft) of separation between the driver and the opposing car. All three of these lighting configurations were classified above the "Just acceptable" boundary of deBoer's scale. The ratings for HLB–LP indicated significantly more glare discomfort than the three UV–A + HID and five UV–A + HID.

The HHB headlamps caused a "Disturbing" amount of discomfort to the drivers at the near separation distance from the glare source, with a significantly lower mean deBoer rating (higher discomfort) than the HLB; however, the HHB did not result in significantly more discomfort than the HOH or any of the HLB and UV–A combinations. The HLB did not cause significantly less discomfort than the HOH or any of the HLB and UV–A combinations.

Table 7. Mean near discomfort ratings in descending order.

VES	Mean	SNK Grouping
Three UV–A + HID	5.9	A
Five UV–A + HID	5.5	A, B
HID	5.1	B, C
HLB–LP	4.8	C
Hybrid UV–A + HID	4.1	D
HLB	3.5	E
Three UV–A + HLB	3.1	E, F
Five UV–A + HLB	3.0	E, F
HOH	3.0	E, F
Hybrid UV–A + HLB	2.9	E, F
HHB	2.6	F

Table 8 shows a comparison of far rating and near rating for each VES. As expected, a higher level of discomfort was always reported for the near rating. The largest differences are observed for the halogen configurations, with the HHB causing a reported level of discomfort three deBoer scale levels lower at the near distance than at the far distance. HID alone and with nonhybrid UV–A configurations showed the smallest differences of less than one deBoer scale level.

Table 8. Differences between near and far discomfort ratings.

VES	Near Rating − Far Rating
HHB	3.2
Hybrid UV–A + HLB	2.1
HLB	2.0
Five UV–A + HLB	1.9
HOH	1.8
Three UV–A + HLB	1.6
HLB–LP	1.5
Hybrid UV–A + HID	1.4
Three UV–A + HID	0.7
Five UV–A + HID	0.5
HID	0.4

VES CONFIGURATION BY AGE INTERACTION

Results of the ANOVA showed a significant interaction between VES and age for the near discomfort ratings ($p = 0.0009$). Figure 7 shows a plot of near discomfort rating versus VES for each age group. This figure illustrates three differences in VES condition means: (1) for the three UV–A + HID, the older and middle-aged participants reported less discomfort than the younger participants; (2) for the HID headlamps, the middle-aged participants experienced less discomfort than the younger participants; and (3) for the hybrid UV–A + HLB, the middle-aged participants reported less discomfort than the younger participants.

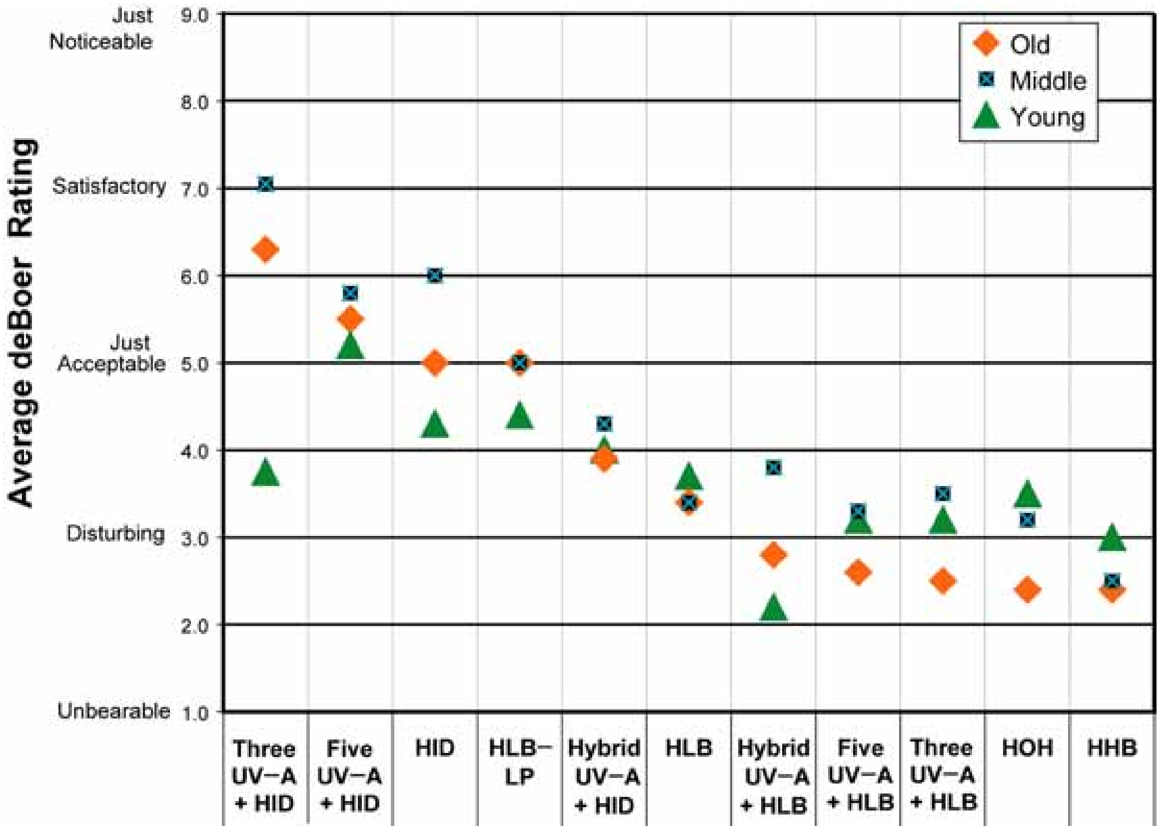


Figure 7. Graph. Near discomfort rating versus VES for each age group.

CHAPTER 4—DISCUSSION AND CONCLUSIONS

As mentioned in the Methods section (chapter 2), the aiming protocol used for this study resulted in a deviation in the maximum intensity location from where it typically is for some headlamp types. Details about this deviation are discussed in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*. The protocol used in this study would be expected to result in higher discomfort glare for the HLB, HOH, and HHB than would be found if these headlamps were aligned more typically.

To determine the difference in glare ratings between the two aiming methods, an additional study was conducted comparing discomfort glares associated with an optical aimer method and with the aiming method used in this study (i.e., ENV method). The additional study used the HLB headlamps because they were included in each of the Phase II and Phase III studies. The additional study was conducted using the same experimental methods as the original discomfort glare study. Two SUVs of the same make, model, and year were used. One SUV had its HLB headlamps aimed using the ENV aiming protocol. The headlamps on the second SUV were aimed using an optical aiming device that aimed the headlamps lower and more to the right. This is considered a more typical alignment than the ENV aiming protocol provided. Participants included 12 younger and 12 older gender-matched participants who were selected using the same participant selection criteria as the original discomfort glare study. Exposure to the different aiming methods was counterbalanced to eliminate order effects. Participants evaluated the glare by providing deBoer ratings as was done previously.

A paired, two-sample t-test indicated no statistical difference between the two aiming methods for either the far discomfort rating ($p = 0.46$) or the near discomfort rating ($p = 0.35$). The average far rating was 5.0 (“Just acceptable”) for both aiming methods with a standard deviation of 2.1 for the optical aimer method and 1.9 for the ENV method. A frequency count indicated that 11 participants rated the ENV method as having more discomfort glare, nine participants rated the optical aimer method as having more discomfort glare, and four participants rated both methods the same. The average near rating was also similar between the two aiming methods with a mean of 3.6 for the optical aimer method and 3.4 for the ENV method (both just above “Disturbing”). The standard deviation was 2.1 for both aiming methods. A frequency count indicated that 10 participants rated the ENV method as having more discomfort glare, 12 participants rated the optical aimer method as having more discomfort glare, and 2 participants rated both methods the same.

This additional study shows no indication that the ENV aiming method made any difference in the results for the HLB headlamps despite the likelihood that the ENV method directed more illumination toward the oncoming participant's eyes than the optical aimer method. Even so, it is important to consider the results presented in this discomfort glare study in the context and conditions tested; if different halogen headlamps or aiming methods had been used, different results might have been obtained.

Finally, although not tested in the additional study, with respect to glare, the headlamp system that was most likely to be affected by the ENV aiming method is the halogen high beam (HHB). Recall that this headlamp was in the same housing as the HOH; therefore, when the HOH was adjusted higher and more toward the center of the road, the HHB was directed higher still and into the oncoming driver's lane. This aiming method likely led to an overestimate of discomfort glare in the near rating and possibly an underestimate of discomfort glare in the far rating. The amount of vertical illumination measured at the driver's eye supports this premise. Table 12 in appendix H indicates that the illumination for the HHB was higher than expected during the near rating. The illumination was similar to the other headlamps in the far rating, where the HHB would be expected to have a higher illumination. It is important to take these expectations into account when reviewing the following results.

VES CONFIGURATION

The results of the discomfort glare evaluation are consistent with existing knowledge and previous research on the subject. The amount of light directed toward the observer's eye by the opposing headlamps seems to be the overriding factor contributing to the reported discomfort sensation. The effects of both age and the spectral content of the visible lights are much smaller and less consistent.

In general, the addition of the UV–A headlamps, which were used along with a base headlamp (HLB or HID) for the three UV–A and five UV–A configurations, do not add substantially to the discomfort caused by the base headlamp alone; however, the hybrid UV–A headlamp, which was used along with the HID and HLB headlamps for the hybrid configurations, does add to the discomfort caused by the base headlamp alone. Both of these results are expected because the UV–A headlamps have very little visible light, whereas the hybrid UV–A headlamp has a noticeable amount of light.

The far discomfort ratings indicate that there are not many significant differences between the different VESs when the separation distances are between 396.2 and 304.8 m (1,300 and 1,000 ft); however, there are significant differences at the near separation distances between 137.16 and 45.72 m (450 and 150 ft). The HID used in this study alone and in combination with the UV–A configurations cause significantly less discomfort than any of the halogen configurations, excluding the HLB–LP.

It is surprising that the three UV–A + HID configuration was perceived as causing less discomfort than the HID alone. Not surprisingly, the vertical illumination at the participant's eye level was nearly identical between the two conditions (table 12). The five UV–A + HID was also rated as causing less discomfort than the HID alone, although the difference was not significant. On the other hand, the three UV–A + HLB and five UV–A + HLB both were rated as causing more discomfort than the HLB alone, although the difference was not significant. The reason behind these differences in perceived discomfort is unknown.

In laboratory settings, the spectral power distribution of HID headlamps, which results in a blue-white color, has been shown to cause more discomfort than the yellow light of traditional tungsten-halogen headlamps.(24) Although the goal of this study was not to retest that hypothesis, it can be inferred from the results that it may also be applicable in a realistic driving environment. Over the near segment of road, which stretched from 137.2 to 45.7 m (450 to 150 ft) from the opposing headlamps, the HLB–LP provided an average vertical illumination at the participant's eye of 2.26 lx (0.21 foot-candles (fc)) with a maximum of 2.9 lx (0.27 fc). The HID provided an average vertical illumination of only 0.33 lx (0.03 fc) with a maximum of 0.75 lx (0.07 fc); however, the discomfort ratings for these two VESs are not significantly different. Although this result may be attributed partly to the difference in spectral power distribution, with the discomfort from the blue-white color of the HID replacing the discomfort lost by its low illumination, it must be noted that the low profile of the HLB–LP slightly increased the glare angle; therefore, no firm conclusion about the effect of spectral power distribution alone in a realistic driving environment should be drawn from this study.

The illuminance measurements show that the HID used for this study has a beam pattern that directs a minimal amount of light onto the opposing lane. If this type of pattern can offset the discomforting effects caused by the perceived brightness of the blue-white color while still providing an acceptable visibility distance, then HID lamps in vehicular applications may become more widely accepted by the public. It should be noted that, in previous research using these VESs under similar weather conditions, drivers could see objects farther away with the baseline halogen lights than with the baseline HID lights (ENV Volume III).

An observable trend (figure 7) shows that younger participants reported more discomfort than the older participants at lower reported glare levels, with the pattern reversing at higher reported glare levels. Specifically, the younger drivers reported significantly more discomfort for the HID, three UV–A + HID, and hybrid UV–A + HLB configurations. This result may indicate that the younger participants, because of the increased amount of light that strikes their retinas relative to the middle and older age groups, are somehow more sensitive to these conditions. All three of these configurations have a larger blue spectral component than most of the other configurations.

COMPARISON OF RESULTS TO SCHMIDT-CLAUSEN AND BINDELS EQUATION

Schmidt-Clausen and Bindels developed an equation to predict the mean deBoer discomfort rating from the adaptation luminance, the illumination directed toward the observer's eye, and the glare angle.(7) Olson and Sivak found that in real driving scenarios, the average discomfort reported was one to two scale intervals more comfortable than predicted by the equation.(9) Therefore, it was logical to determine how well the Schmidt-Clausen and Bindels equation predicted the mean discomfort ratings obtained for each VES tested in this study.

The first step was to calculate two predicted deBoer ratings for each VES: a predicted far discomfort rating and a predicted near discomfort rating. To do this, a single value for the vertical illumination and glare angle was needed for each rating; however, because the participants rated the discomfort glare while traveling over a 91.44-m (300-ft) section of road, these two parameters were changing constantly. To reach a single predicted value, three different calculations attempted to model how participants estimated discomfort glare. Each calculation assumed that participants based their rating on one of the following: (1) the average level of vertical illumination to which he or she was exposed over the 91.4-m (300-ft) segment; (2) the maximum level of vertical illumination to which he or she was exposed over the 91.4-m (300-ft) segment; or (3) the very last level of vertical illumination to which he or she was exposed (i.e., he or she would base the rating on whatever he or she felt at the moment when the experimenter asked for the rating). For situation 1, researchers used the average glare angle over each 91.4-m (300-ft) segment for the calculation (wavg). For situation 2, the glare angle at the distance where the maximum illumination occurred (as recorded in the vertical illumination measurements) was used (wmax). For the near discomfort rating, the maximum illumination always corresponded to the last point on the 91.4-m (300-ft) segment (table 9). For the far discomfort rating, the maximum illumination often occurred before the last point was reached (table 10). For situation 3, researchers used the glare angle at the distance where the experimenter asked for the rating for the calculation (wlast).

The second step was to compare the predicted deBoer ratings to the ratings obtained during the study (*D*). Table 9 and table 10 show predicted and obtained deBoer ratings for the near ratings and far ratings, respectively.

Table 9. Predicted and actual deBoer near discomfort ratings.

VES	wavg	wmax	wlast	*D*
Three UV–A + HID	3.1	2.8	4.0	5.9
HLB–LP	2.8	2.1	2.1	4.8
Five UV–A + HID	3.1	2.8	4.0	5.5
HHB	3.0	0.8	0.8	2.6
HID	3.1	2.9	4.1	5.1
HLB	2.8	1.7	1.9	3.5
Hybrid UV–A + HID	3.0	2.8	3.3	4.1
Hybrid UV–A + HLB	2.9	1.6	1.8	2.9
Five UV–A + HLB	2.8	1.7	1.9	3.0
HOH	2.6	1.5	1.9	3.0
Three UV–A + HLB	2.8	1.7	1.9	3.1

wavg = Predicted discomfort based on average illumination over the 91.4-m (300-ft) segment
wmax = Predicted discomfort based on maximum illumination over the 91.4-m (300-ft) segment
wlast = Predicted discomfort based on the last illumination experienced
D = Average discomfort reported by participants

Table 10. Predicted and actual deBoer far discomfort ratings.

VES	wavg	wmax	wlast	*D*
Three UV–A + HID	4.0	3.8	3.8	6.6
HLB–LP	4.1	3.9	3.9	6.3
Five UV–A + HID	4.0	3.8	3.8	6.0
HHB	4.6	4.2	4.2	5.8
HID	4.1	3.9	3.9	5.5
HLB	4.0	3.8	3.8	5.5
Hybrid UV–A + HID	4.0	3.8	3.8	5.5
Hybrid UV–A + HLB	4.0	3.7	3.7	5.0
Five UV–A + HLB	4.0	3.8	3.8	4.9
HOH	4.2	3.8	3.8	4.8
Three UV–A + HLB	4.0	3.8	3.8	4.7

wavg = Predicted discomfort based on average illumination over the 91.4-m (300-ft) segment
wmax = Predicted discomfort based on maximum illumination over the 91.4-m (300-ft) segment
wlast = Predicted discomfort based on the last illumination experienced
D = Average discomfort reported by participants

It appears that the observation made by Olson and Sivak, in which the average discomfort reported in a realistic driving environment was one to two scale intervals more comfortable than predicted by the Schmidt-Clausen and Bindels equation, also applied to these experimental conditions.(9)

A regression analysis was then performed to determine if a correlation existed between the predicted and actual values. If a strong correlation did exist, it would suggest that the average value on the deBoer scale could be predicted reasonably in a realistic driving environment from the Schmidt-Clausen and Bindels equation by using vertical illumination, adaptation luminance, and glare angle as parameters; however, the regression coefficients in this equation would need to be reevaluated to account for the lower discomfort ratings observed in this experiment.

Linear regression was done using the average discomfort rating (*D*) as the dependent variable and either wavg, wmax, or wlast as the independent variable. Results are summarized in table 11.

Table 11. Linear regression results for predicted discomfort ratings.

D	R (sample correlation coefficient)
1.38×wavg−0.06	0.51
1.00×wmax+1.79	0.74
1.04×wlast+1.41	0.78

Based on the correlation coefficients in table 11, it appears likely that a participant based his or her ratings either on the maximum amount of illumination or on the very last level of illumination experienced before giving the rating. It can be concluded that the average deBoer rating in a realistic driving environment can be reasonably predicted using one of the variations of the Schmidt-Clausen and Bindels equation calculated by the linear regressions to the data. The variations are shown in figure 8 and figure 9.

$$W = 6.79 - 2.0LOG_{10}\frac{E\max}{0.003 * \left(1 + \sqrt{\frac{La}{0.04}}\right) * \theta_{\max}{}^{0.46}}$$

Figure 8. Equation. Variation of Schmidt-Clausen and Bindels equation based on maximum illumination experienced.

In the equation in figure 8, W = mean value on deBoer's scale, $E_{\max}$ = maximum level of illumination directed toward the observer's eye from the headlamps (lx), $\theta_{\max}$ = glare angle between observer's line of sight and the headlamps at location where maximum illumination occurs (minutes of arc), and L_a = adaptation luminance (cd/m^2).

$$W = 6.61 - 2.08 LOG_{10} \frac{Elast}{0.003 * \left(1 + \sqrt{\frac{La}{0.04}}\right) * \theta_{last}{}^{0.46}}$$

Figure 9. Equation. Variation of Schmidt-Clausen and Bindels equation based on last illumination experienced.

In the equation in figure 9, W = mean value on deBoer's scale, E_{last} = last level of illumination directed toward the observer's eye from the headlamps (lx), θ_{last} = glare angle between observer's line of sight and the headlamps at last location (minutes of arc), and L_a = adaptation luminance (cd/m^2).

These equations can be used to provide insight into the ratings that could be given by participants in a real driving experiment. During the design stage of beam development, headlamps could be evaluated to help assess the effect of the beam pattern on the perception of opposing drivers.

APPENDIX A—SCREENING QUESTIONNAIRE

Driver Screening and Demographic Questionnaire: ENV–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 in italics as a guideline in the screening interview):

Good morning/afternoon! My name is _____ and I work at the (testing facility) in Blacksburg, VA. I'm recruiting drivers for a study to evaluate new night vision enhancement systems for vehicles.

This study will involve you driving a vehicle for two 3-hour night sessions on the Smart Road. The Smart Road is a test facility equipped with advanced data recording systems here in Blacksburg, VA. We will pay you $20 per hour. 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.

****

Questions

1. Do you have a valid driver's license?
Yes _____ No _____

2. How often do you drive each week?
Every day ____ At least 2 times a week____ Less than 2 times a week_____

3. How old are you? ______

4. Have you previously participated in any experiments at the [contractor facility]? If so, can you briefly describe the study?
Yes _____ Description:____
No _____

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

6. What type of vehicle do you currently drive? ____

7. Are you able to drive an automatic transmission without assistive devices or special equipment?
Yes _____ No _____

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, (laser eye surgery), or other eye surgeries? If so, please specify.
Yes _____ ____
No _____

12. (Females only, of course) Are you currently pregnant?
Yes _____ No _____

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 _____ ____

I would like to confirm your full name, phone number(s) (home/work) where you can be reached, hours/days when it's best to reach you, and preferred days to participate.

Name ____ Male / Female

Phone Numbers (Home)________________________(Work)________________________

Best Time to Call ____

Best Days to Participate___________________

****

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 two 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 3 years.
7. Must not have caused an injurious accident in the past 2 years.
8. Cannot have a history of heart condition or prior heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures within 12 months, respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.
9. Must not be pregnant.
10. Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).
11. No history of radial keratotomy, (laser) eye surgery, or any other ophthalmic surgeries.

****

APPENDIX B—INFORMED CONSENT FORM

[Contractor Facility]
Informed Consent for Participants of Investigative Projects

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

Investigators: ________________________________

THE PURPOSE OF THIS RESEARCH/PROJECT

THE PURPOSE OF THE PROJECT IS TO DETERMINE THE DEGREE OF ENHANCED VISIBILITY OF THE ROADWAY ENVIRONMENT WITH VARIOUS TYPES OF VISION ENHANCEMENT SYSTEMS WHILE DRIVING AT NIGHT.

I. PROCEDURES

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

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

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

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

II. RISKS

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

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

- You are required to wear a seatbelt at all times in the vehicle, and the vehicle is equipped with antilock brakes.

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

- In addition, you have not had radial keratotomy, (laser) eye surgery, or any other ophthalmic surgeries.

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

III. BENEFITS OF THIS PROJECT

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

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

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

V. COMPENSATION

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

VI. FREEDOM TO WITHDRAW

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

VII. APPROVAL OF RESEARCH

Before data can be collected, the research must be approved, as required, by the (name of review board). You should know that this approval has been obtained.

VIII. SUBJECT'S RESPONSIBILITIES

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

1. To follow the experimental procedures as well as you can.

2. To inform the experimenter if you incur difficulties of any type.

3. Wear your seatbelt.

4. Abide by the 25 miles per hour speed limit.

IX. SUBJECT'S PERMISSION

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

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

Signature   Date

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

(Names of researchers and review board)   (Phone number)

APPENDIX C—VISION TEST FORM

PARTICIPANT NUMBER: __________

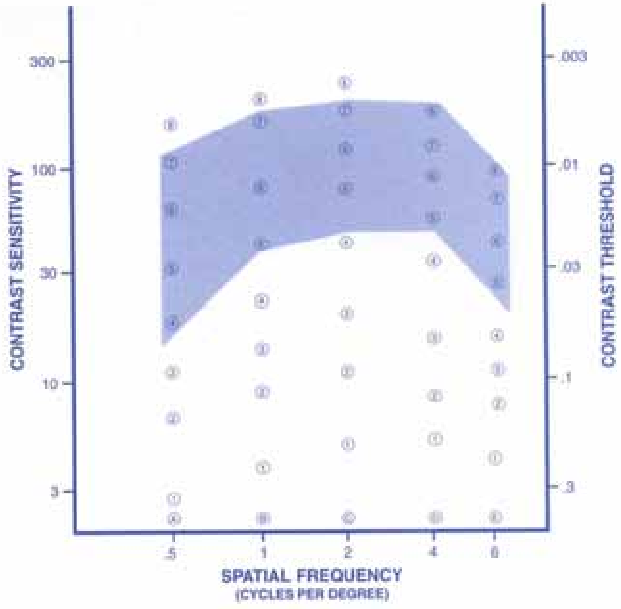
VISION TESTS

Acuity Test

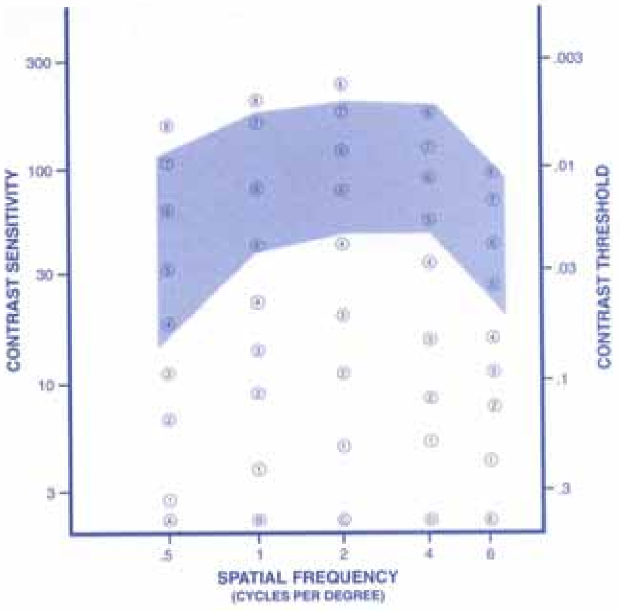
- Acuity Score:_________

Contrast Sensitivity Test

Left



Right



Ishihara Test for Color Blindness

1._____

2._____

3._____

4._____

5._____

6._____

7.____

APPENDIX D—TRAINING PROTOCOL

SESSION ONE

(Experimenter reads all text in italics aloud to participant.)

1. Prior to the participants' arrival, make sure that all the needed forms are available and label them with the subject number.

2. Greet participant.

3. Record the time that the participant arrived on the debriefing form.

4. Show driver's license. It must be a valid Class A driver's license to proceed with the study. Out of State is fine.

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

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

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

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

You will be exposed to 11 different vision enhancement systems. You will make one lap on the Smart Road for each vision enhancement system. Your job will be to evaluate glare. Do you have any questions at this time?

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.

5. Ask the participants if they are a university employee. If they are, just give them the W–9 form. If they are not, have them sign both the W–9 and the University Voucher.
To complete the W–9, the participant must fill out the following in the box:

- Name
- Address
- Tax ID number (social security number)
- Sign and date at the bottom

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

6. 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.
  - Participant must have 20/40 or better vision using both eyes to participate in the study.

The next vision test is the contrast sensitivity test. Take the participant over to the eye chart test area.

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

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

  - Point out the sample patches at the bottom of the chart with the three possible responses (left, right, or straight).
  - Cover one eye with an occluder. (DO NOT let the participant use his/her hand to cover the eye since pressure on the eye may cause erroneous contrast sensitivity test results).

- Instruct the participant to begin with Row A and look across from left to right. Ask the participant to identify the last patch in which lines can be seen and tell you which direction they tilt. If the response is incorrect, have the 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 last 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 participant's answers on the vision test form.

APPENDIX E—IN-VEHICLE EXPERIMENTAL PROTOCOL

1. After the eye tests, have the participant sit at the table. Read the following (all text in italics is read aloud to participant):

We will go to the Smart Road shortly. First I want to orient you to the study. For the first section, you will evaluate the glare for the different vision enhancement systems. Glare can be thought of as the amount of discomfort you experience from the oncoming lights of a vehicle. To do this, you will drive down the road and there will be a parked vehicle in the opposite lane from you with its lights on. Over two segments of road, I will ask you to evaluate the glare you experience during that segment of road. So, the road will look like this (show diagram)*. During that time, I want you to look straight ahead—never at the glare source—and rate the glare you experience with this scale* (show scale). *For this scale, you would give the glare a rating of 1 if you think it is unbearable. You would give a rating of 3 if you think the glare is disturbing. A rating of 5 would mean that you perceive the glare to be just acceptable. Seven would mean that you think the glare is satisfactory. And finally you would give a rating of nine if it is just noticeable. You can choose any number you want between 1 and 9 to rate the glare. So, I will have you drive and, while looking straight ahead, I will tell you "Begin" at the beginning of the road segment* (point to on diagram). *I want you to think about what rating you want to give the glare until I ask, "What is your rating?" At that time, I want you to tell me how you want to rate the glare according to the scale. For each parked vehicle we approach, we will do that twice—once at a far distance and once at a closer distance. Do you have any questions?*

2. Answer any questions.

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

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

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

3. The participants will drive to the road.

4. Radio the onroad experimenters that you are ready to begin.

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

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

First vehicle at the bottom of the hill:

- Pull all the way to the first parking space.
- Put the vehicle in park and have the participant take their foot off the brake.
- Ask participant to close their eyes until the second vehicle is in place.
- Review glare training.

Second vehicle at the bottom of the hill:

- Pull into the second parking space.
- Put the vehicle in park.
- Hold up poster board cut-out over passenger side window.
- Review glare training.

Now we will complete the glare portion.

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

1: Unbearable
3: Disturbing
5: Just acceptable
7: Satisfactory
9: Just noticeable

6. Show them the sheet with the red flashlight.

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

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

8. Have the participants drive at 25 miles per hour until you have asked them to rate the oncoming headlamps twice. You will know when to ask them to rate the glare when you pass the onroad cones. There are four cones on each side of the road. Using the ones on the right side of the road, have the participant start evaluating at the first cone (1300 feet from glare source) and give a rating at the second cone (1000 feet from glare source). Begin the second evaluation at the third cone (450 feet from glare source) and ask for a rating from the participant at the fourth cone (150 feet from glare source). Indicate the areas by saying

"Begin" and "What is your rating?" Continue up the road to the second glare vehicle and repeat the procedure. Remind the participant before each rating to look straight ahead and never directly at the light.

First vehicle at the top of the hill:

- Pull up to white line just before the top of hill.
- Wait for headlamp glow from 2nd vehicle to appear.
- Pull up to the first cone on the left side of road.
- Put vehicle in park.
- Remind participants of scale and to not look directly at the lights.
- Go down the road once the onroad experimenters indicate they are ready.

Second vehicle at the top of the hill:

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

9. Repeat the evaluating/rating procedures for remaining VES.

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

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

APPENDIX F—SMART ROAD

Figure 10. Photo. Aerial view of the Smart Road.

The Virginia Smart Road (figure 10) is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of Intelligent Transportation Systems (ITS) concepts, technologies, and products. It is the first facility of its kind to be built from the ground up with its research infrastructure incorporated into a section of public roadway. Originating in Blacksburg, VA, the Smart Road presently consists of 3.2 km (2 mi) of two lanes of roadway, which are closed to public traffic and are designated a controlled test facility. When completed, the Smart Road will be a 9.6-km (6-mi) long, four-lane section of the U.S. Interstate system, connecting Blacksburg, VA with U.S. Interstate (I) 81. This connection will serve an important role in the I–81 and I–73 transportation corridor. After completion, provisions will be made to route traffic around controlled test zones on the Smart Road to allow for ongoing testing.

Construction of the Smart Road project was made possible through a cooperative effort of several Federal and State organizations, including Virginia's Center for Innovative Technology, VDOT, the Virginia Transportation Research Council, FHWA, and Virginia Tech.

The research-supported infrastructure of the Smart Road makes it an ideal location for safety and human factors evaluation. Following is a list of some of the unique research capabilities of the facilities:

- All-weather testing facility.
- Variable lighting test bed.

- Ultraviolet (UV) pavement markings.
- Magnetic tape installed on roadway.
- Onsite data acquisition capabilities.
- In-house differential Global Positioning Systems (GPS).
- Surveillance camera systems.

APPENDIX G—AIMING PROTOCOL

[Note that the HOH lamp and the HHB lamp were paired within the same housing and in fixed positions relative to each other. Therefore, when the HOH was aimed, the HHB was automatically aimed in the high-beam position, making individual aiming for HHB unnecessary.]

PROTOCOL SUMMARY

The protocol presented below represents the consensus of experts in the field on the appropriate procedure that should be followed for headlamp alignment:

- An alignment plate should be mounted onto the ground 35 ft from and parallel to the alignment wall.
- The alignment wall should be as flat as possible.
- The wheels should be straight against the plate and perpendicular to the alignment wall.
- The perpendicular position can be reached by creating a 90-degree angle configuration on the floor that will guide the vehicle to the right position. A simple “L”-shaped mark on the floor should suffice.
- A laser that marks the center of the vehicle should be used to make sure the screen is centered to the vehicle. Each vehicle should have its own line on the screen. The lines are labeled directly on the screen to avoid confusion.
- Markings of the photometric center of the headlamp beam should be performed for each headlamp with respect to the floor.
- The appropriate headlamps should be turned on, while making sure no auxiliary lights (parking lights, fog lights, daytime running lights) are on.
- One headlamp should be covered up or unplugged so that readings are taken for only one light at a time.
- For the HID, HLB, and HOH configurations, align the headlamps so that the “hotspot” is located in the lower right quadrant. This can be performed by positioning the photometer sensor tangent to both the horizontal and vertical lines. When measuring the hotspot in that quadrant, the outside top and left borders of the sensor’s circumference (the sensor is one inch in diameter) need to touch both axes of the crosshairs. This will position the hotspot one half inch down and to the right from the center of the crosshair.
- The photometer should be zeroed prior to checking each measurement. To do this, make sure that all headlamps are turned off. Remove the cap from the 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 the background and remove its effects from the actual source value. After zeroing, turn the headlamp on and begin alignment.
- Adjustment of the headlamp aim should be performed as needed.

The only difference between the alignment of the UV–A headlamps and this previous headlamp alignment procedure (HID, HLB, and HOH) is that the “hotspot” must be at the center of the crosshairs.

DETAILED PROTOCOL

Vehicle/Headlamp Combinations Acronym List

BLK HID1	BLK HID 2	Black SUV High Intensity Discharge 1 and 2
BLK HLB 1	BLK HLB 2	Black SUV Halogen Low Beam 1 and 2
BLK LO UV–A 1	BLK LO UV–A 2	Black SUV Low Output UV–A 1 and 2
WH HID 1	WH HID 2	White SUV High Intensity Discharge 1 and 2
WH HLB 1	WH HLB 2	White SUV Halogen Low Beam 1 and 2
WH MID/HI UV–A 1 through WH MID/HI UV–A 5		White SUV Mid/High Output UV–A 1 through 5
P/U HOH (HHB) 1	P/U HOH (HHB) 2	Pickup Truck, High Output Halogen (Halogen High Beam)

SPECIAL NOTES FOR SIM BAY ROOM PREP:

- It is very important to make sure that you have enough time to align all of the headlamps prior to the team meeting, and especially prior to the road preparations. Minimum alignment time is 1 hour when no headlamps need to be switched between vehicles, but you should plan on 1 ¼ - 1 ½ hours as a general rule. Alignment times will be greater on days when headlamps must be moved.
- Turn on the ventilation fans in the garage prior to beginning the alignment process.
- Since we are leaving half of the lights, it is important to remember to use the ZERO function on the photometer prior to aligning each light. This is particularly important when recording the photometer values on the Headlamp Alignment form.

1. Setting up the Non-UV–A headlamps

Applies to the following Vehicle/Headlamp combinations:

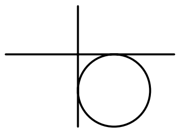
- WH HID (1&2), BLK HID (1&2)
- WH HLB (1&2), BLK HLB (1&2)
- P/U HOH(HHB) (1&2)

- Pull the vehicle 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 screen is centered to the vehicle. Each vehicle has a different line on the screen. The lines are labeled directly on the screen.
- Locate the appropriate markings on the wall for each VES.

- 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.
- 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 headlamps are not switched; gross will be required if the headlamps are switched.

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

When these types of lights are aligned straight ahead, the lights are placed in a high beam configuration. We <u>do not</u> want to use the high beam for these configurations. 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.

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.”

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.

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 light is aligned and you can align the other light(s).

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.

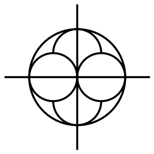
2. Setting up the UV–A headlamps

Applies to the following Vehicle/Headlamp combinations*:*

  - WH MID/HI UV–A (1-5)
  - BLK LO UV–A (1&2)

- Pull the vehicle up to the alignment plate on the ground. This should be located 35 feet from the alignment wall. Make sure the wheels are straight against the plate. In addition, the vehicle needs to be centered along the white line painted from the wall.
- Turn on the appropriate headlamps, making sure no auxiliary lights (parking lights, fog lights, daytime running lights) are on.
- Locate the appropriate markings on the wall for that headlamp.
- Cover up one headlamp so that you are only taking readings for one light at a time.
- Align the headlamps so that the “hotspot” is located on the crosshairs. The UV–A low headlamps have fine adjustments. The UV–A high headlamps require shimming for the vertical location and wrench adjustments for the horizontal adjustment.

Note that it is sufficient to line up the sensor on the crosshairs such that at least the edge of the sensor touches the center of the crosshairs. This means that there is a circular space around the center of the crosshairs, with a radius the size of the sensor in all directions (about 2 inches in diameter), in which the hotspot may be found. This is a larger margin of alignment error than allowed for the non-UV lights and is due to the nature of the mounting of the lights.



Hotspot Location: The large outer circle represents the overall target area. The center of the large circle is the target hotspot location.

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. For UV–A light, use the photometer sensor marked “UV–A.”

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.

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 light(s).

REFERENCE VALUES FOR THE VARIOUS HEADLAMPS:

Note: You look at this table as you look at the wall for calibration; it’s backwards when looking directly at the vehicles.

P/U HOH(HHB) [Pickup truck]	
1 (Left)	*2 (Right)*
42.2 W/cm^2	45.2 W/cm^2

WH HID; BLK HID [either SUV]	
1 (Left)	*2 (Right)*
visual alignment based on other light	41.6 W/cm^2

WH HLB; BLK HLB [either SUV]	
1 (Left)	*2 (Right)*
44.7 W/cm^2	50.1 W/cm^2

BLK LO UV–A [Black SUV]	
1 (Left)	*2 (Right)*
100 µW/cm^2	92.0 µW/cm^2

<table>
<tr><th colspan="6">WH MID/HI UV–A [White SUV]</th></tr>
<tr><td colspan="6"><i>Top Row lights</i></td></tr>
<tr><td colspan="2"><i>1 (Top Left)</i></td><td colspan="2"><i>2 (Top Center)</i></td><td colspan="2"><i>3 (Top Right)</i></td></tr>
<tr><td colspan="2">590 µW/cm^2</td><td colspan="2">472 µW/cm^2</td><td colspan="2">484 µW/cm^2</td></tr>
<tr><td colspan="6"><i>Bottom Row lights</i></td></tr>
<tr><td colspan="3"><i>4 (Bottom Left)</i></td><td colspan="3"><i>5 (Bottom Right)</i></td></tr>
<tr><td colspan="3">486 µW/cm^2</td><td colspan="3">565 µW/cm^2</td></tr>
</table>

HEADLAMP ALIGNMENT FORM

Date:_______________
Initials:_______________
Reference values for the various headlamps are included on the top line. Actual/current values are written inside each box as appropriate. Alignment data should be recorded once a week to provide a continuous record of the health of the headlamps. Note: You look at this table as you look at the wall for calibration; it's backwards when looking directly at the vehicles.

P/U HOH(HHB) [Pickup truck]	
1 (Left)	*2 (Right)*
42.2 W/cm^2 Actual:	45.2 W/cm^2 Actual:

WH HID; BLK HID [either SUV]	
1 (Left)	*2 (Right)*
visual alignment based on other light Actual:	41.6 W/cm^2 Actual:

WH HLB; BLK HLB [either SUV]	
1 (Left)	*2 (Right)*
44.7 W/cm^2 Actual:	50.1 W/cm^2 Actual:

BLK LO UV–A [Black SUV]	
1 (Left)	*2 (Right)*
100 µW/cm^2 Actual:	92.0 µW/cm^2 Actual:

WH MID/HI UV–A [White SUV]		
Top Row lights		
1 (Top Left)	*2 (Top Center)*	*3 (Top Right)*
590 µW/cm^2 Actual:	472 µW/cm^2 Actual:	484 µW/cm^2 Actual:
Bottom Row lights		
4 (Bottom Left)	*5 (Bottom Right)*	
486 µW/cm^2 Actual:	565 µW/cm^2 Actual:	

APPENDIX H—VERTICAL ILLUMINANCE MEASUREMENTS

Table 12. Vertical illuminance (lx): VES by distance from opposing headlamps (ft).

	HLB	HID	HOH	HHB	Hybrid UV–A + HLB	Three UV–A + HLB	Five UV–A + HLB	HLB–LP	Hybrid UV–A + HID	Three UV–A + HID	Five UV–A + HID
1,300	0.13	0.12	0.11	0.07	0.14	0.14	0.14	0.12	0.13	0.13	0.13
1,250	0.17	0.13	0.13	0.09	0.18	0.18	0.18	0.12	0.14	0.14	0.14
1,200	0.13	0.11	0.14	0.08	0.14	0.14	0.14	0.13	0.12	0.12	0.12
1,150	0.13	0.12	0.15	0.09	0.14	0.14	0.14	0.13	0.13	0.13	0.13
1,100	0.14	0.13	0.16	0.09	0.15	0.15	0.15	0.13	0.14	0.14	0.14
1,050	0.15	0.15	0.17	0.10	0.16	0.16	0.16	0.15	0.16	0.16	0.16
1,000	0.17	0.16	0.18	0.11	0.19	0.18	0.18	0.16	0.18	0.17	0.17
450	1.07	0.75	1.35	0.83	1.13	1.09	1.09	1.08	0.81	0.77	0.77
400	1.40	0.40	1.89	1.18	1.48	1.42	1.42	1.56	0.48	0.42	0.42
350	1.96	0.19	2.59	1.80	2.08	1.98	1.98	2.05	0.31	0.21	0.21
300	2.77	0.20	3.34	3.01	2.95	2.79	2.79	2.52	0.38	0.22	0.22
250	3.73	0.20	4.41	4.69	4.01	3.77	3.75	2.66	0.48	0.24	0.22
200	4.06	0.24	5.18	7.60	4.47	4.09	4.10	2.99	0.65	0.27	0.28
150	3.62	0.31	3.67	14.19	4.07	3.65	3.65	2.99	0.76	0.34	0.34

1 ft = 0.305 m
1 lx = 0.0929 fc

APPENDIX I—LUMINANCE MEASUREMENTS FOR EACH GRID POINT

Table 13. Luminance measurements for calculation of adaptation luminance; lateral positions are 1 through 4, left to right.

Distance from Vehicle (m)	Luminance at Lateral Position 1 (cd/m^2)	Luminance at Lateral Position 2 (cd/m^2)	Luminance at Lateral Position 3 (cd/m^2)	Luminance at Lateral Position 4 (cd/m^2)
80	0.02	0.03	0.04	0.06
75	0.02	0.03	0.04	0.06
70	0.02	0.03	0.05	0.08
65	0.02	0.03	0.05	0.07
60	0.03	0.03	0.05	0.08
55	0.03	0.04	0.05	0.08
50	0.04	0.03	0.05	0.11
45	0.04	0.04	0.05	0.08
40	0.05	0.04	0.09	0.16
35	0.07	0.10	0.13	0.18
30	0.09	0.12	0.16	0.19
25	0.13	0.13	0.21	0.25
20	0.20	0.17	0.27	0.33
15	0.24	0.41	0.46	0.36
10	0.11	0.52	0.58	0.45
5	0.03	0.20	0.36	0.43

1 m = 3.28 ft
1 cd/m^2 = 0.2919 fL

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