Volume XIV

Enhanced Night Visibility Series: Phase III–Study 2: Comparison of Near Infrared, Far Infrared, and Halogen Headlamps on Object Detection in Nighttime Rain

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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 on the performance of drivers during nighttime driving in rain using visual headlamp technologies and visual headlamp technologies augmented with in-vehicle displays for near- and far-infrared sensors. The study was conducted under Phase III of the Enhanced Night Visibility (ENV) project, a comprehensive evaluation of evolving and proposed headlamp technologies in various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume XIV. 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.

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Director, Office of Safety
Research and Development

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16. Abstract
Enhanced Night Visibility Series Phase III, Study 2 (rainy weather) was performed following the same procedures used for Phase III, Study 1 (clear weather). Study 2 served to expand the knowledge of how current vision enhancement systems can affect detection and recognition of different types of objects while driving during adverse weather, specifically during rainy conditions. The empirical testing for this study was performed on the Virginia Smart Road; the rain was controlled by weather-making equipment. Fifteen participants were involved in the study. A 4 by 8 by 3 mixed factorial design was used to investigate the effects of different types of vision enhancement systems, different types of objects on the roadway, and driver's age on detection and recognition distances; subjective evaluations also were obtained for the different vision enhancement systems.

The results of the empirical testing suggest that well-designed infrared (IR) systems are consistently associated with often significantly longer detection distances for most types of pedestrian objects during rainy conditions. In particular, the use of the near IR (NIR) systems resulted in earlier detection of nearly all tested pedestrian types than did the use of either far IR (FIR) or baseline halogen (HLB) systems. The exception to this finding is the case in which the pedestrian is on the right side of a right (1,250-m (4,101-ft) radius) curve. In this case, the NIR system was associated with similar or shorter (though not significantly so) detection distances than the FIR and HLB systems. Drivers in this study detected the nonpedestrian object (tire tread) at similar distances regardless of the headlamp system in use (NIR, FIR, or HLB). This indicates that there is no significant loss in detection distance for small, low-contrast objects (such as tire treads) among the types of headlamps tested in this study. All of these findings appear to be applicable regardless of driver age. Subjective comments by the drivers in this study tend to be consistent with the objective results discussed above.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

ENHANCED NIGHT VISIBILITY PROJECT REPORT SERIES

This volume is the 14th of 18 volumes in this research report series. Each volume is a different study or summary, and any reference to a report volume in this series will be referenced in the text as “ENV Volume I,” “ENV Volume II,” and so forth. A list of the report volumes follows:

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

ENV ....Enhanced Night Visibility
FOV....................................field of view
HHD....................................high head down
IR..infrared
SAE....................................Society of Automotive Engineers
SUV....................................sport utility vehicle
VES....................................vision enhancement system

Vision Enhancement Systems

FIR ....far infrared vision system
HLB....................................halogen (i.e., tungsten-halogen) low beam
NIR....................................near infrared vision system

Objects

BlueLF ....pedestrian, denim clothing, left
BlueRT...............................pedestrian, denim clothing, right
LFtrnLF.............................pedestrian in left turn, left side (denim clothing)
LFtrnRT ....pedestrian in left turn, right side (denim clothing)
PedDyno.............................dynamic pedestrian
RTtrnLF ....pedestrian in right turn, left side (denim clothing)
RTtrnRT.............................pedestrian in right turn, right side (denim clothing)

Statistical Terms

ANOVA ....analysis of variance
DF ....degrees of freedom
F value................................F-ratio
MS......................................mean square
P value................................statistical significance
SE.......................................standard error
SNK....................................Student-Newman-Keuls
SS ....sums of squares

Measurements

cm/h....................................centimeters per hour
ft ....feet
ft/s^2 ....feet per second squared
inches/hr.............................inches per hour
km ....kilometers
km/h ....kilometers per hour

m ....meters
m/s^2 ....meters per second squared
mi/h ....miles per hour
s ....seconds

Stopping Distance

BRT....................................braking reaction time
d_{BD} ....braking distance
f ....coefficient of friction
g..acceleration
G...gradient
V ....velocity

CHAPTER 1—INTRODUCTION

During previous phases of the Enhanced Night Visibility (ENV) project, far infrared (FIR) systems and near infrared (NIR) systems showed promise for pedestrian detection capabilities (ENV Volumes III and XIII). FIR technology, which presents images based on the temperature differential between an object and its background, is available on production vehicles. The images presented by FIR do not contain many details; for example, FIR images do not show headlamp light, pavement markings, signs, or raised retroreflective pavement markers (RRPMs). Despite this lack of detail, FIR allows for the early detection of pedestrians, cyclists, or animals (i.e., objects generating heat) on the roadway (see ENV Volumes III and XIII). NIR systems, which present features of the forward road scene in a more picture-like quality, are a more recent addition to automotive vision enhancement systems (VESs). These systems use IR emitters to act as IR headlamps when viewed through the IR camera and its associated display.

This study in the ENV project extends the investigation of NIR and FIR vision enhancement systems to determine how well they assist drivers in pedestrian and object detection in a heavy rain condition. In this study, the VESs tested include two NIR systems, one FIR system, and one halogen (i.e., tungsten-halogen) system (HLB). Each system was tested on a sport utility vehicle (SUV). The HLB served as a baseline condition, allowing a comparison between readily available technologies and new VES alternatives.

The IR systems tested in this phase of the research were provided by automotive manufacturers and IR vision system suppliers. The manufacturers and suppliers provided the contractor with preinstalled prototype systems as well as descriptive information about the specific implementations tested such as IR emitter types or field of view (FOV). Details beyond those provided were not recorded to protect proprietary system characteristics. The headlamp systems tested were production headlamps purchased by the contractor.

CHAPTER 2—METHODS

PARTICIPANTS

Fifteen individuals participated in this study. The participants were divided into three different age categories: five participants were between the ages of 18 and 25 years (younger category of drivers), five were between the ages of 40 and 50 (middle category of drivers), and five were over the age of 65 (older category of drivers). Each age category had two males and three females. All these individuals participated in the previous IR study conducted in clear weather conditions (ENV Volume XIII). Candidates were allowed to participate in the study after they completed a screening questionnaire and if they fulfilled the selection conditions listed in appendix A. Participants had 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 as required by Virginia State law, and have no health conditions that made operating the research vehicles a risk.

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

During the experiment, each participant drove with four different VESs during one night of driving. The session included training in which the study was described and the forms and questionnaires were completed (appendixes A and B). The participant completed a practice lap in the first experimental vehicle to become familiar with the Virginia Smart Road and the detection and recognition methods.

The presentation orders for each VES were counterbalanced (table 1). A detailed explanation of each VES configuration appears in the Independent Variables section of this report. The VES configurations for this study were defined as follows:

- Halogen low beam (HLB).
- Prototype far infrared vision system (FIR).
- Prototype near infrared vision system (NIR 1).
- Prototype near infrared vision system (NIR 2).

Table 1. VES orders for participants. Each participant was assigned an order (1, 2, 3, or 4) that indicates the VES used for each lap.

	Order 1	Order2	Order 3	Order 4
Practice	NIR 1	HLB	FIR	NIR 2
Lap 1	NIR 1	HLB	FIR	NIR 2
Lap 2	NIR 1	HLB	FIR	NIR 2
Lap 3	HLB	FIR	NIR 2	NIR 1
Lap 4	HLB	FIR	NIR 2	NIR 1
Lap 5	NIR 2	NIR 1	HLB	FIR
Lap 6	NIR 2	NIR 1	HLB	FIR
Lap 7	FIR	NIR 2	NIR 1	HLB
Lap 8	FIR	NIR 2	NIR 1	HLB

EXPERIMENTAL DESIGN

The study was a four (VES configuration) by eight (Object) by three (Age) mixed factor design. The between-subjects factor of the experiment was age, which had the same three levels used in the other ENV studies (i.e., younger, middle-aged, and older). VES type was a within-subjects factor that included the four VESs in table 1. As shown in table 2, there were eight different objects, including seven pedestrian scenarios and a tire tread. Participants were exposed to the left, right, and dynamic (i.e., crossing the road) pedestrian scenarios in the straight segment of the test road (table 2). Each participant was exposed to only two of the four turn scenario pedestrians; therefore, the participant was exposed to either a left- or right-positioned pedestrian in a left turn and either a left- or right-positioned pedestrian in a right turn. A detailed explanation of the independent variables follows.

Table 2. The eight objects used in this study.

Analysis	Object	Abbreviation
Within Subjects	Pedestrian, Denim Clothing, Left	BlueLF
Within Subjects	Pedestrian, Denim Clothing, Right	BlueRT
Within Subjects	Dynamic Pedestrian	PedDyno
Within Subjects	Tire Tread	Tire Tread
Between Subjects	Pedestrian in Left Turn, Left Side (Denim Clothing)	LFtrnLF
Between Subjects	Pedestrian in Left Turn, Right Side (Denim Clothing)	LFtrnRT
Between Subjects	Pedestrian in Right Turn, Left Side (Denim Clothing)	RTtrnLF
Between Subjects	Pedestrian in Right Turn, Right Side (Denim Clothing)	RTtrnRT

INDEPENDENT VARIABLES

This experiment incorporated the independent variables of VES configuration, age, and object. The age factor had three levels: younger participants (18 to 25 years), middle-aged participants (40 to 50 years) and older participants (65 years or older). These age groups were created based on literature review findings that suggest changes in vision during certain ages. (See references 1, 2, 3, 4, and 5.) Each age group was made up of two males and three females that had participated in the previous IR clear study (ENV Volume XIII).

The four VESs were also tested in a previous study that evaluated detection and recognition of 17 objects in clear weather (ENV Volume XIII). Note that the configurations include an SUV 1 with an FIR system and an SUV 1 with a NIR 2 system. These SUVs were not the same vehicle, but they were the same make, model, and year of vehicle; therefore, the same naming convention was used for both vehicles. Following are detailed descriptions of the four VESs and the vehicle platform used to mount them.

SUV 1 with Prototype Far Infrared Vision System

A prototype FIR system was tested on an SUV. This system is referred to as “FIR” throughout this document. The system display used a direct-reflect virtual image with an 11.7° horizontal by 4° vertical FOV. The reflective mirror was located in a high head down (HHD) position on the instrument panel surface above the instrument cluster and on center with the driver. The reported magnification at the eye was approximately 1:1. The production halogen headlamps used were for this vehicle.

SUV 2 with Prototype Near Infrared Vision System

A prototype NIR system that used a laser IR emitter was tested on a second SUV. This system is referred to as “NIR 1” throughout this document. The system used a curved mirror display with an 18° horizontal by ~6° vertical FOV. The mirror was located in a HHD position on the instrument panel surface above the instrument cluster and on center with the driver. The reported minification was ~2:3 at the eye. The production halogen headlamps were used for this vehicle.

SUV 1 with Prototype Near Infrared Vision System

A prototype NIR system that used halogen IR emitters was tested on the same type of SUV as the FIR system. This system is referred to as "NIR 2" in this document. The system display used a direct-reflect virtual image with an 11.7° horizontal by 4° vertical FOV. The reflective mirror was located in a HHD position on the instrument panel surface above the instrument cluster and on center with the driver. The reported magnification at the eye was approximately 1:1. The production halogen headlamps were used for this vehicle.

SUV 3 with Halogen Low Beam

The halogen low beam (HLB) headlamps were tested on SUV 3 using a light rack as shown in figure 1. These headlamps were tested to provide a halogen benchmark for the other VESs tested and a comparison point to previous studies. These headlamps are referred to as "HLB" throughout this document.

Figure 1. Photo. Headlamp testing rack.

Table 3 lists the different VESs, the vehicles on which the VESs were tested, the headlamps on the vehicle, and, where applicable, the display method, FOV, and image minification or magnification. Specification of display, display FOV, and minification/magnification were provided by the system engineers responsible for designing the systems.

Table 3. VES configurations.

Tested Technology	Test Vehicle	Headlamps	Display	Display FOV	Image Size
Halogen headlamps	SUV 3	HLB	None	n/a	n/a
Far IR	SUV 1	FIR	Direct reflect virtual image	11.7° by 4°	~1:1
Near IR with laser emitter	SUV 2	NIR 1	Curved mirror virtual image	18° by ~6°	Minification ~2:3 actual
Near IR with halogen emitters	SUV 1	NIR 2	Direct reflect virtual image	11.7° by 4°	~1:1

Headlamp technical specifications appear in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

Objects

Using the four VESs, detection and recognition distances were measured for seven pedestrian scenarios and a tire tread. The main reason pedestrians were included in this study was because of their high crash-fatality rates.(6,7) Although pedestrian mockups have been used in previous research of this type,(8) human pedestrians were used here to permit performance measurement of the FIR VES, which functions based on temperature characteristics of the object of interest.

To investigate the interaction of beam patterns and FOV as well as road geometry when viewed from the driver's perspective, pedestrians were presented in various positions along the roadway. The pedestrians, wearing denim clothing, either were static on the side of the road and facing oncoming traffic or walking across the lane, perpendicular to the approaching vehicle, with their faces looking toward the approaching vehicle. The static pedestrians were positioned on the left or right shoulder in straight sections of the roadway and in left and right curves of 1,250-m (4,101-ft) radius.

The tire tread represented low-contrast objects common in public roadways. The tire tread was selected because of its potential for very low detection distances, which often lead to last moment object-avoidance maneuvers. The tire tread also provided a point of comparison to previous ENV studies.

Table 4 and figure 2 through figure 9 describe the objects used and their locations. (For visual clarity, the figures do not represent the environmental conditions in this study).

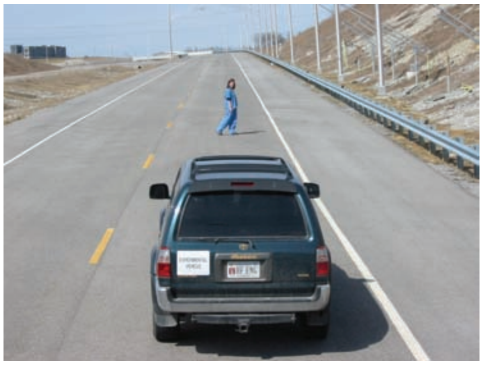
Table 4. Object descriptions and illustrations.

Object Description	Picture
Pedestrian wearing blue denim scrubs stood on the left side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) outside the far lane boundary on a straight segment of roadway. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 2. Photo. Object: pedestrian, blue denim clothing, left (BlueLF).**
Pedestrian wearing blue denim scrubs stood on the right side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) to the right of the participant's right lane boundary on a straight segment of roadway. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 3. Photo. Object: pedestrian, blue denim clothing, right (BlueRT).**
In a 1,250-m (4,101-ft) radius left-hand curve, a pedestrian wearing blue denim scrubs stood on the left side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) outside the far lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 4. Photo. Object: pedestrian in left turn, left side (LFtrnLF).**

Table 4. Object descriptions. (continued)

Object Description	Picture
In a 1,250-m (4,101-ft) radius left-hand curve, a pedestrian wearing blue denim scrubs stood on the right side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) to the right of the participant's right lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 5. Photo. Object: pedestrian in left turn, right side (LFtrnRT).**
In a 1,250-m (4,101-ft) radius right-hand curve, a pedestrian wearing blue denim scrubs stood on the left side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) outside the far lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 6. Photo. Object: pedestrian in right turn, left side (RTtrnLF).**
In a 1,250-m (4,101-ft) radius right-hand curve, a pedestrian wearing blue denim scrubs stood on the right side of the road as viewed from the participant vehicle. Pedestrian stood 30.5 cm (12 inches) to the right of the participant's right lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 7. Photo. Object: pedestrian in right turn, right side (RTtrnRT).**

Table 4. Object descriptions. (continued)

Object Description	Picture
Pedestrian walked forward and backward on the roadway from the centerline to the right lane boundary and back, always presenting a right profile of the body. Pedestrian turned his or her head to face the approaching driver.	 **Figure 8. Photo. Object: dynamic pedestrian (PedDyno).**
Tire tread was centered on participant's right lane boundary.	 **Figure 9. Photo. Object: tire tread.**

OBJECTIVE DEPENDENT VARIABLES

Two objective performance measures were collected : (1) the distance at which a participant could first detect something in the road ahead and (2) the distance at which the participant could correctly recognize (i.e., identify) the object ahead. The participant was provided with a definition of detection: "Detection is when you can just tell that something is ahead of you. You cannot tell what the object is, but you know something is there." Each participant was also given the definition of recognition during data collection and analysis: "Recognition is when you not only know something is there, but you also know what it is." The method for translating into distance measurements is described in the Apparatus and Materials section.

SUBJECTIVE RATINGS

Using a seven-point Likert-type scale, the participant was asked to indicated agreement or disagreement with a series of seven statements for each VES. The two anchor points of the scale were “1” (indicating “Strongly Agree”) and “7” (indicating “Strongly Disagree”). The scale shown in figure 10 was located on the instrument panel for the participant to refer to while responding to the statements.

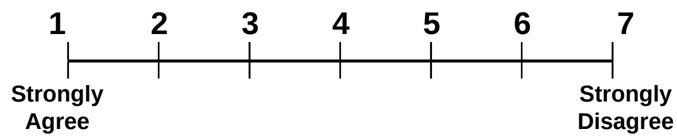


Figure 10. Diagram. Likert-type subjective rating scale.

The statements were intended to address the participant’s perception of improved vision, safety, and comfort after using a particular VES. The participant was asked to compare each VES to his or her “regular headlights” (i.e., the headlights on his or her own vehicle); the assumption was made that the participant’s personal vehicle represented what he or she knew best, and therefore, was most comfortable using. The statements used for the scaled response questionnaire included the following (note that while the word “headlamp” is used throughout the ENV series, the subjective questions posed to the participants used the synonymous word “headlight,” as reflected below):

- This VES allowed me to *detect* objects sooner than my regular headlights.
- This VES allowed me to *identify* objects sooner than my regular headlights.
- This VES helped me to stay on the road (not go over the lines) better than my regular headlights.
- This VES allowed me to see which direction the road was heading (i.e.; left; right; straight) beyond my regular headlights.
- This VES did not cause me any more visual discomfort than my regular headlights.
- This VES makes me feel safer when driving on the roadways at night than my regular headlights.
- This is a better VES than my regular headlights.

The following open-ended questions also were presented to each participant:

- If you could provide any advice to the manufacturer of this vision system, what would it be?
- Anything else?

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. The safety measures required that all data-collection equipment be mounted, to the greatest extent possible, so that it did not pose a hazard to the driver in any foreseeable instance; participants had to wear the seatbelt restraint system any time the car was on the road; none of the data-collection equipment could interfere with any part of the driver's normal field of view; a trained in-vehicle experimenter had to be in the vehicle at all times; and an emergency protocol was established before the testing began. The participant was required to maintain a speed of 16 km/h (10 mi/h) while driving under the rain towers and 40 km/h (25 mi/h) otherwise. Two-way communications were maintained between the onroad crew and the in-vehicle experimenter to ensure the onroad scenarios were ready and the vehicle was following the expected path. Onroad pedestrians also visually monitored the approach of the participant's vehicle and moved away from the lane boundary about 1.5 s before its approach.

APPARATUS AND MATERIALS

Onroad driving was conducted using four vehicles. The experimental vehicles included four SUVs, two of which were the same model. All vehicles were instrumented to collect distance information on a laptop computer using software specifically developed for this study. The software logged information such as the participant's age, gender, and assigned identification number, prompted the experimenter with the appropriate object order for each participant and VES trial, and collected detection and recognition distances. Figure 11 shows the screen used by the experimenters to provide turn guidance, monitor object presentation orders, and collect data.

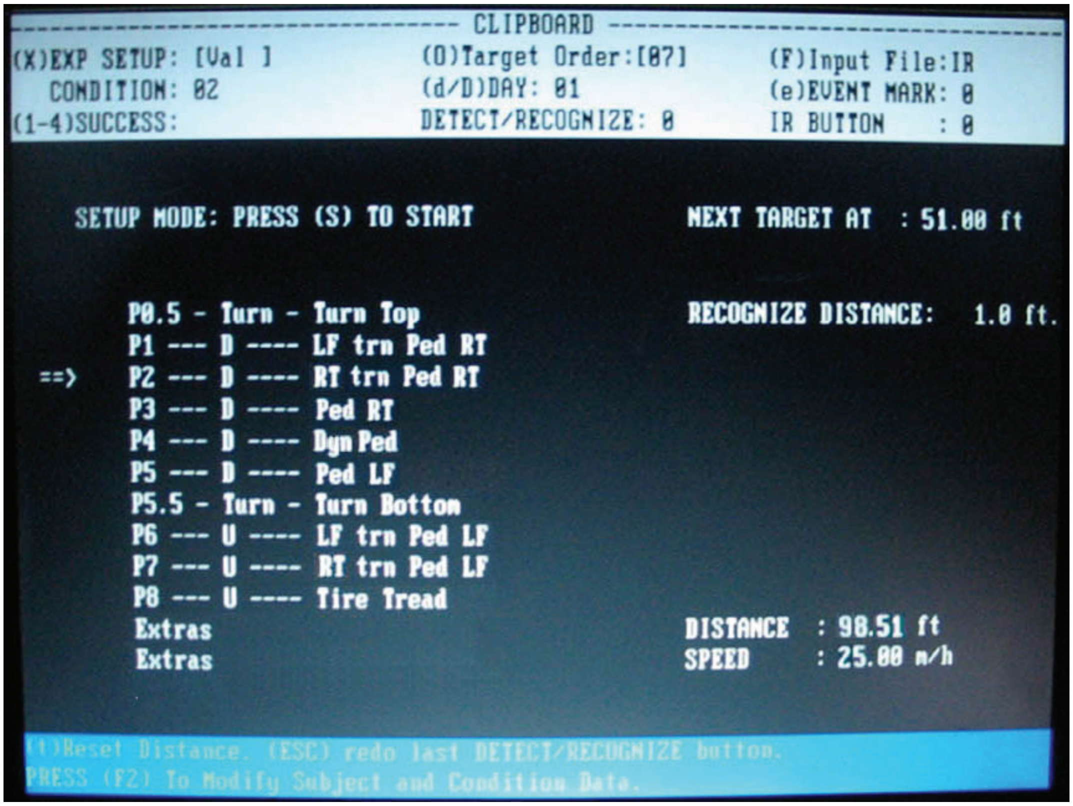


Figure 11. Photo. Data collection display screen.

Measurements of object detection and recognition distances were collected using two methods. When a participant detected an object, he or she would say the word "something." Then, when the participant could recognize the object, he or she would provide a verbal identification. At each of these utterances, the in-vehicle experimenter would press a button to flag the data. The in-vehicle experimenter pressed the spacebar when the bumper of the vehicle passed the object. The data flags generated by these button presses provided one method for collecting the distance measures. In addition, as the participant vehicle passed an object, the onroad crew transmitted the number of the object over the radio (inaudible to the participant), which was synchronized with the datastream. A video and audio recording of the participant orally stating detection and recognition, combined with the onroad crew's transmission from when the vehicle passed the object, provided a second method for identifying the distance measurements in the datastream.

Smart Road

The Virginia Smart Road (see figure 12) was used for the onroad study. Figure 13 presents a schematic of the Smart Road segment used in this study with examples of object locations.

Figure 12. Photo. Smart Road.

In this study, there were four object locations, two on each side of the road. Each lap included a blank (i.e., no object) at one of the locations. Figure 13 is a schematic of the Smart Road with the object locations.

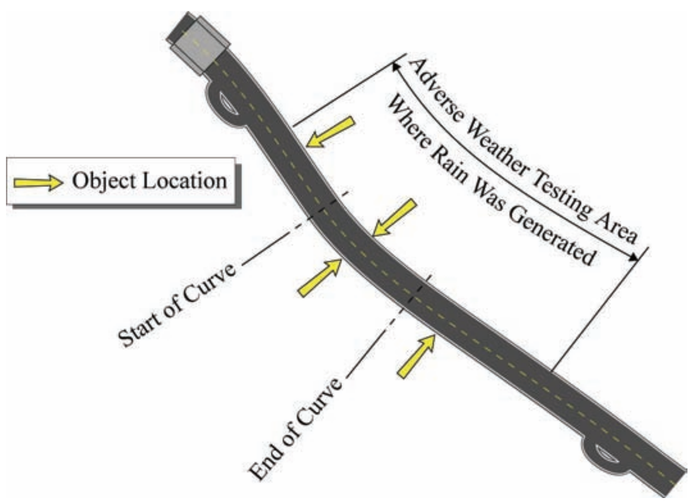


Figure 13. Diagram. Roadway layout.

All objects were presented in the all-weather testing portion of the Smart Road. Using the Smart Road pumping system, a constant water pressure was distributed to the 40 rain towers used for the experiment. The rain rate used for the investigation was 12.5 cm/hr (2.5 inches/hr), and the rain towers were located every 9.2 to 10.7 m (30 to 35 ft). The tower heads were positioned over the centerline of the westbound lane of the test facility. From this position, consistent rain was available only in this lane, which forced the participant to drive in the wrong lane when he or she was traveling the eastbound (downhill) leg of the test route.

The participant started each drive from the contractor building. One onroad experimenter was assigned to each participant; this experimenter was responsible for showing the participant where the different controls were and verifying that the correct VES configuration was being tested. Five onroad experimenters positioned tire treads, worked as pedestrians, and shuttled other onroad experimenters to different object locations during the session. A sixth onroad experimenter was responsible for presenting certain scenarios, preparing the next vehicle for the participant, and making measurements of the participant's eye position and instrument dimmer settings. The participant made two laps through the weather testing section in each of the four vehicles used for data collection. The participant experienced a different object order for each vehicle.

Headlamp and IR System Aiming

The HLB headlamps were mounted on a testing rack external to the experimental vehicle. This mounting, developed at the beginning of the ENV project, allowed different headlamps to be swapped on a single vehicle for each night of testing. An aiming procedure was developed to ensure that the headlamp condition was the same after every swap. The procedure was the same for all of the ENV testing. During the photometric characterization of the headlamps, it was discovered that the maximum intensity location of the HLB was aimed higher and more toward the left than typically specified. This aiming deviation likely increased detection and recognition distances for the HLB configuration. Details about the aiming procedure and the maximum intensity location are discussed in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

The headlamps on the FIR vehicle, NIR 2 vehicle, and NIR 1 vehicle were production headlamps. They were aimed before the study, and they did not require further aiming. The aiming of cameras and IR emitters on these vehicles was checked according to the procedures provided by the system manufacturers. When necessary, the aiming was further confirmed by comparing IR system images collected at the start of the study to new system images. The NIR 2 vehicle was the only IR system that required re-aiming during testing. This was because the adhesive tape used on the provided prototype system came unfastened between sessions of the experiment.

EXPERIMENTAL PROCEDURE

Participant Screening

The participants in this study had participated in the previous ENV IR study in clear conditions (ENV Volume XIII). Candidates were initially screened over the telephone (appendix A), and if a candidate qualified for the study, a time was scheduled for testing. Candidates were instructed to meet the experimenter at the contractor facility in Blacksburg, VA. After arriving, an overview of the study was presented to each candidate. Subsequently, each candidate was asked to complete the Informed Consent Form (appendix B) and take an informal vision test for acuity using a Snellen chart and a contrast sensitivity test (appendix C). The vision tests and predrive questionnaires from the clear weather study were used because each of the candidates had completed it recently. After the candidate qualified and these steps were completed, the participant began the training portion of the session.

Training

The participant was given an overview of the study indicating that it was similar to the previous study (ENV Volume XIII) during which the participant was provided with a definition of detection ("Detection is when you can just tell that something is ahead of you. You cannot tell what the object is, but you know something is there") and recognition ("Recognition is when you not only know something is there but you also know what it is"). The participant was instructed to say the word "something" when he or she detected an object, and then say what he or she saw when he or she could identify it. The participant was shown daytime photographs of each of the experiment objects similar to those in table 4.

The participant was then shown the questionnaire that would be administered after he or she drove each vehicle. The in-vehicle questionnaire included subjective questions rated on a seven-point Likert-type scale to record the participants' perceptions of the performance of the VES compared to his or her normal headlamps. Each statement was read aloud and the in-vehicle experimenter reviewed the scale. If the participant had no questions, the training was complete.

Vehicle Familiarization

Next, the experimenter took the participant to the first test vehicle. In this vehicle (as well as subsequent vehicles), the experimenter helped the participant adjust the seat, steering wheel, and instrument panel lighting. Where an in-vehicle display was present, the experimenter assisted the participant in achieving a clear view of the image and showed him or her how to adjust the brightness of the display. The participant was permitted to adjust the instrument panel and display brightness three times—before driving, halfway through the practice, and at the end of the practice drive. The brightness settings were recorded, and remained set throughout data collection. After the participant was ready, an onroad experimenter measured eye position in relation to landmarks on the door. When this was complete, to provide a reference for video data of driver glances (video was recording during this phase), the participant was asked to look at various locations in and around the vehicle while saying the location aloud. Where a display was present in the vehicle, the participant was instructed: “This system is not intended to be used alone. Instead, it is supposed to accompany your normal driving. Be sure to view the road as you normally do while also using the display.”

Driving and Practice Lap

The participant then drove a practice lap to become familiar with the vehicle, the objects, the road, and the procedure for calling out objects. During the driving portions of the study, the in-vehicle experimenter rode in the second-row passenger-side seat of the vehicle. The participant was reminded of the procedure and instructed not to drive faster than 10 mi/h (16 km/h) while in the rain section. After the practice lap was completed, the participant began the test drive. During the actual test drive, the in-vehicle experimenter configured and monitored the data collection system, recorded when the participant detected and recognized objects, gave guidance on where to make turns, checked speed, and, if necessary, advised the participant to maintain the 10 mi/h (16 km/h) speed limit.

General Onroad Procedure

While the participant drove the practice lap and the test drive, the onroad crew was responsible for presenting objects at different locations along the Smart Road according to the appropriate object order for each participant and VES. The participant had a different object order for each of the four vehicles he or she drove. Each time the bumper of the participant's vehicle passed the current object, an onroad experimenter transmitted its number by radio.

CHAPTER 3—RESULTS

To analyze the data, separate ANOVAs were conducted for each of the objects. For the pedestrians standing in turns, a between-subjects, one-way model for the four VES configurations was used. For each of the other objects, which included the pedestrians on the left and right of straight sections, the dynamic pedestrian, and the tire tread, a within-subjects, four (VES) by three (Age) mixed factorial model was used. This model was also used for the Likert scale ratings from the subjective questionnaire after the drive. In each of the models where main effects were found, Student-Newman-Keuls (SNK) tests were used to identify differences between VESs or age groups. Responses to open-ended questions were reviewed and tallied to identify emergent themes.

An $\alpha = 0.05$ level was used to identify statistically significant effects in this report. In main effects graphs, means with the same letter are not significantly different.

OBJECTIVE MEASURES

The results for the ANOVAs conducted on the objective measures of detection distance and recognition distance for the three groups of objects—obstacle (tire tread), pedestrians in straight roadway portions, and pedestrians in curves—are presented in the following paragraphs.

Tire Tread

The analysis for the tire tread was a four (VES) by three (Age) mixed factorial design. The analyses results for detection and recognition appear in table 5 and table 6; the results indicate no significant main effects (age or VES) or interactions.

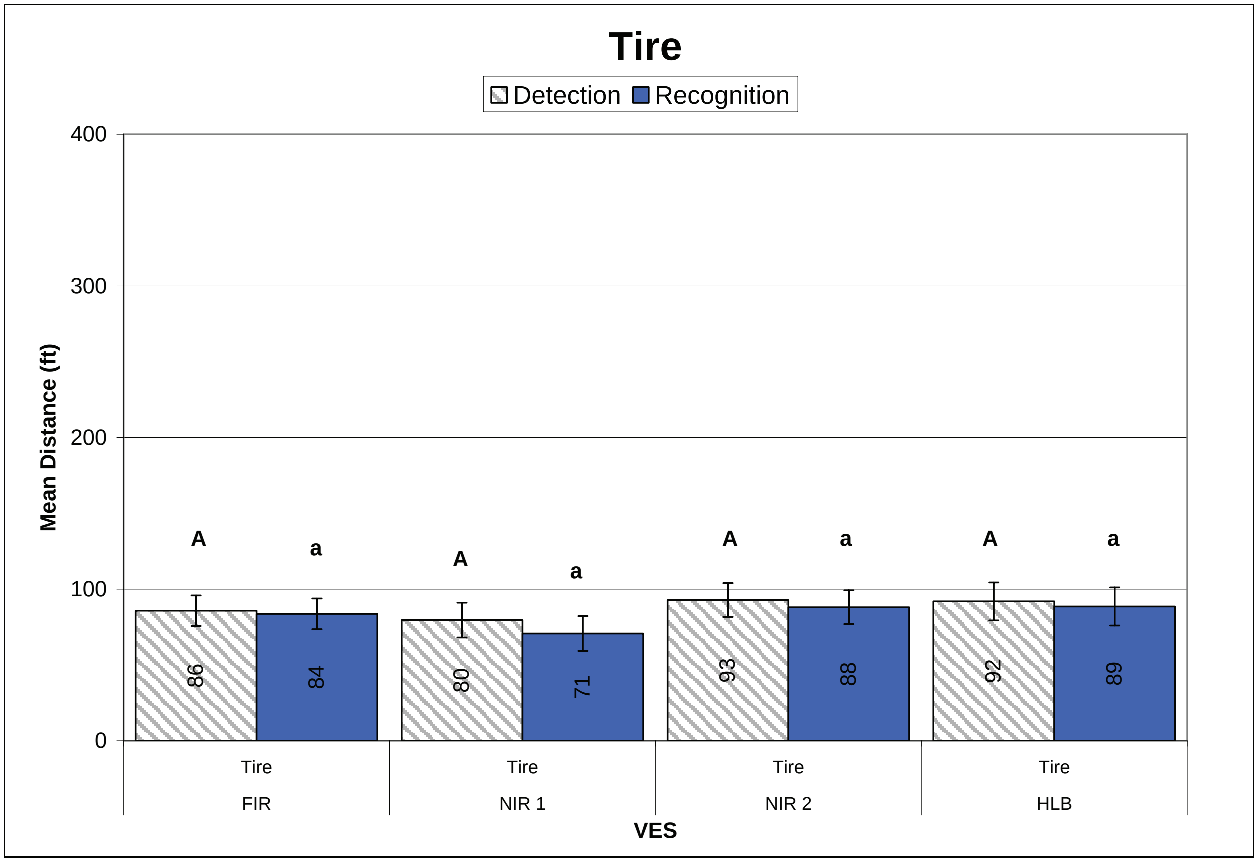
Table 5. Tire tread ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value
Between					
Age	2	12005.3	6002.7	1.81	0.205
Subject/Age	12	39720.6	3310.0		
Within					
VES	3	1691.8	563.9	0.37	0.7758
VES by Age	6	5362.6	893.8	0.58	0.7401
VES by Subject/Age	36	55022.0	1528.4		
TOTAL	59	113802.4			

Table 6. Tire tread ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value
Between					
Age	2	12813.2	6406.6	2.13	0.161
Subject/Age	12	36010.4	3000.9		
Within					
VES	3	3112.6	1037.5	0.69	0.5635
VES by Age	6	5254.9	875.8	0.58	0.7412
VES by Subject/Age	36	54050.5	1501.4		
TOTAL	59	111241.7			

There are no statistically significant differences between the VESs for detecting or recognizing the tire tread at the $\alpha = 0.05$ level. Figure 14 shows the mean detection and recognition distances for the tire; standard error bars are provided around the means.



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

Figure 14. Bar graph. Tire detection and recognition distances.

Pedestrians in Straight Sections

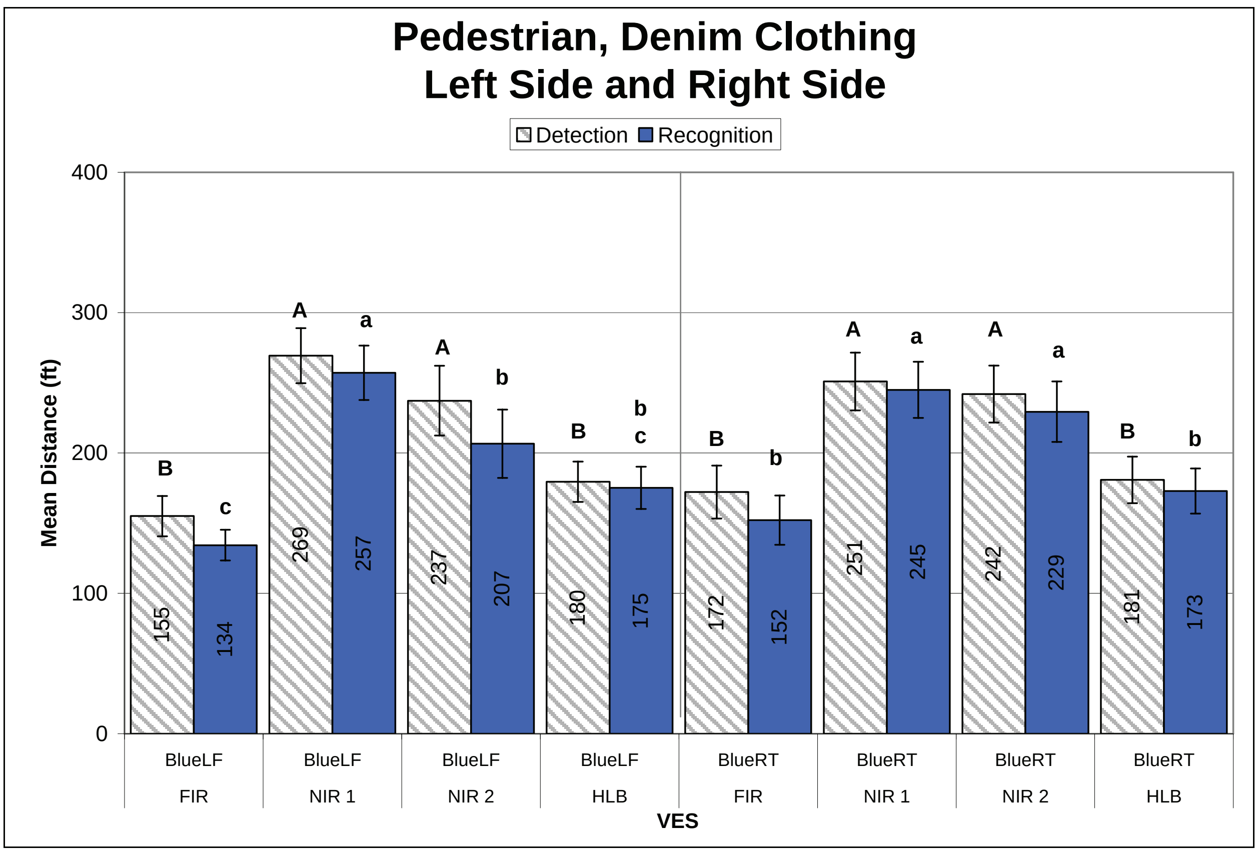
The analysis results for the dynamic pedestrian and pedestrians standing on the right and left sides of straight roadway sections were obtained using four (VES) by three (Age) mixed factorial designs. Complete ANOVA tables for these scenarios appear in appendix D.

Age Effects

The analysis of detection of pedestrians in straight roadway sections shows significant differences in VES performance. The differences resulted from the age factor for the pedestrian on the left side of the road (p = 0.0241) but not for the pedestrian on the right (p = 0.2223) or the dynamic pedestrian (p = 0.0668). In particular, the SNK results show that a significant difference exists between the overall detection distance means for the younger age group (18 to 25) and the older age group (over 65). The mean detection distances across all VESs are 75.6 m (248 ft) for the younger group and 51.2 m (168 ft) for the older group. In general (for all objects), it appears that typical age effects (decreases in detection distances with increases in age) may have been present, but they were not sufficiently strong to indicate statistical differences.

VES Effects

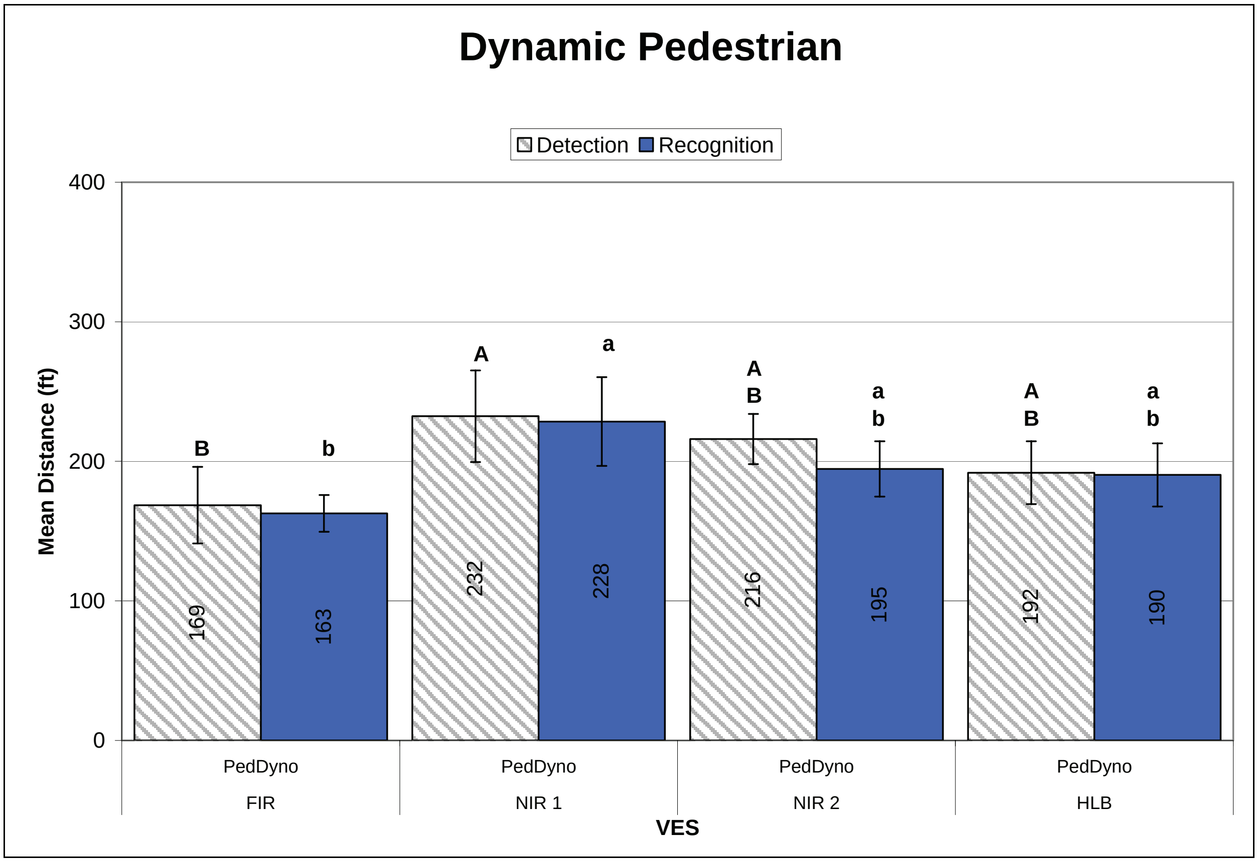
Figure 15 illustrates the significant differences in results when pedestrians stood stationary on the left or right side of a straight section of roadway. The NIR systems resulted in significantly longer detection distances than the HLB or the FIR system. The results of the NIR 1 system show significantly longer distances for recognizing the pedestrian on the left side of the road than the results for the other three systems (NIR 2, FIR, and HLB). Both the NIR systems resulted in significantly longer distances than the results for the other two VESs for recognizing the pedestrian on the right side of the road.



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

Figure 15. Bar graph. Blue-clothed pedestrian on straight: left and right side detection and recognition distances.

Figure 16 shows the results in the dynamic pedestrian scenario. The NIR 1 system produced significantly longer detection and recognition distances than the FIR system; otherwise, the systems were undistinguished from one another in detection or recognition distances.

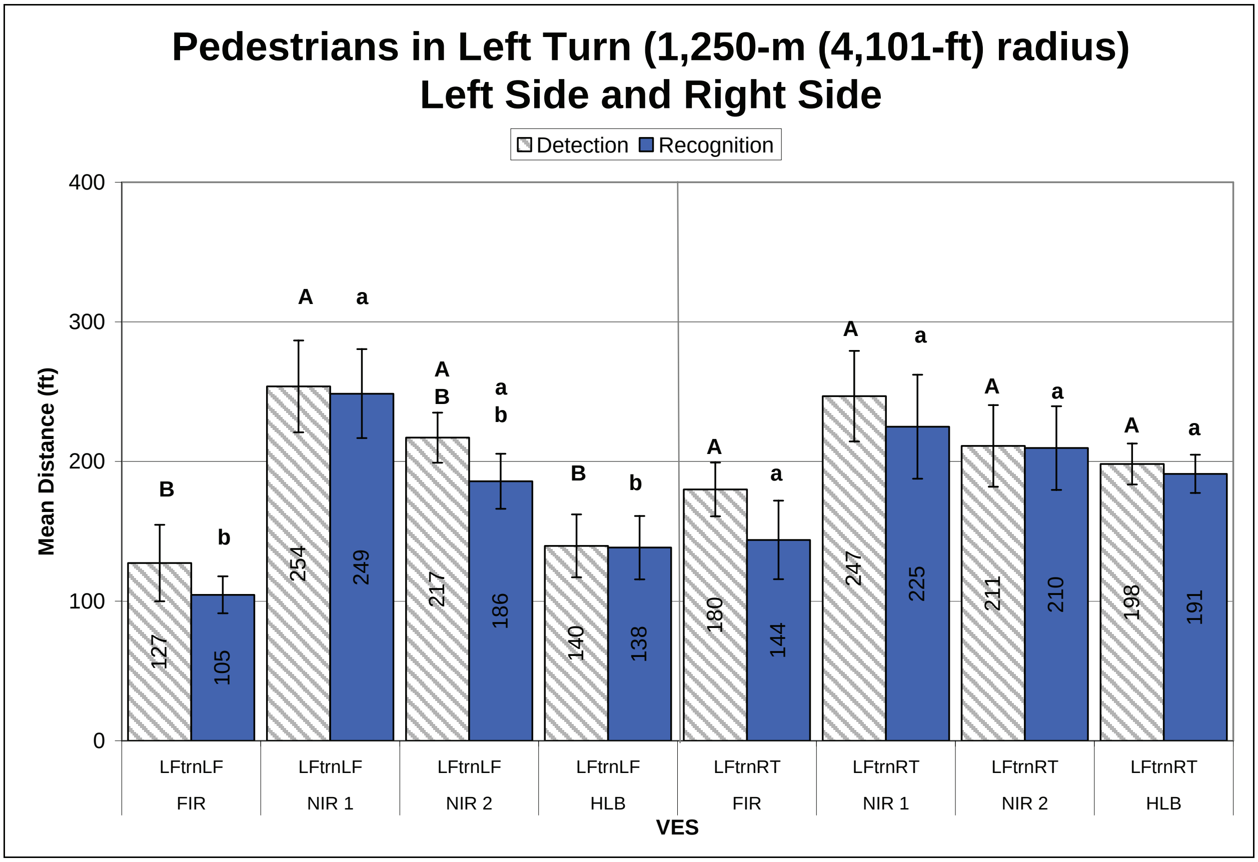


Means with the same letter are not significantly different.
1 ft = 0.305 m

Figure 16. Bar graph. Dynamic pedestrian on straight: detection and recognition distances.

Pedestrians in 1,250-m Radius Curves

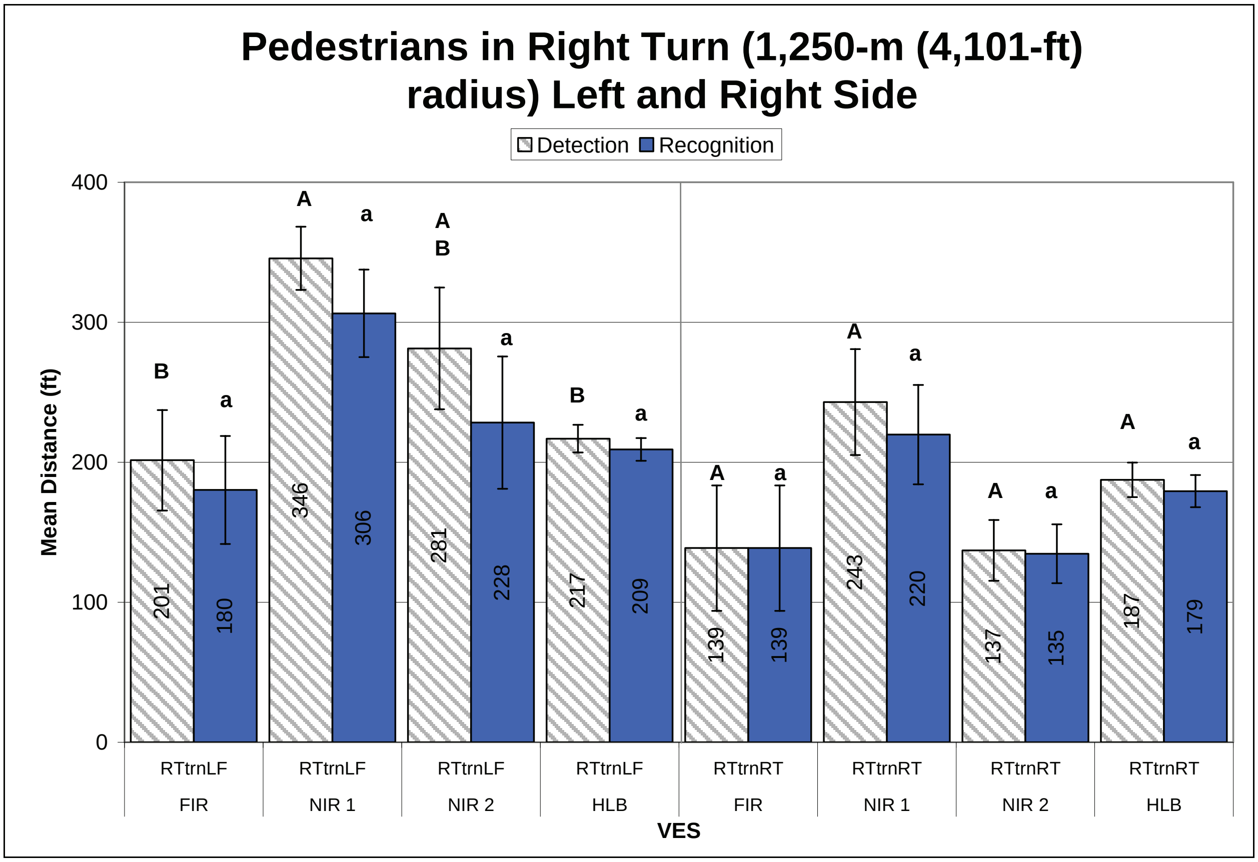
Each of the four pedestrian turn scenarios were analyzed using a one-way ANOVA for VES. The complete ANOVA tables for the scenarios appear in appendix E. Figure 17 presents the means and standard errors for the scenarios with a pedestrian standing on the left or right side of a left-hand turn (1,250-m (4,101-ft) radius), and figure 18 presents similar information for a right-hand turn (1,250-m (4,101-ft) radius).



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

Figure 17. Bar graph. Blue-clothed pedestrian in left turn: left and right side detection and recognition distances.

Figure 17 shows that in the scenario for a pedestrian on the left side of the left-hand turn, the NIR 1 system again performs significantly better (longer distance) for detection and recognition than the HLB or the FIR. When a pedestrian was on the right side of a left-hand turn, the detection and recognition distances for each of the systems were not significantly different from each other.



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

Figure 18. Bar graph. Blue-clothed pedestrian in right turn: left and right side detection and recognition distances.

Figure 18 shows that for detecting pedestrians standing on the left side of a right-hand turn (1,250-m (4,101-ft) radius), the NIR 1 system significantly outperforms the HLB and the FIR systems. Recognition distances were not statistically distinguishable between the systems. Also, in the scenario with a pedestrian on the right side of the road in a right-hand turn, the systems were not statistically distinguishable for results of either detection or recognition distance.

SUBJECTIVE MEASURES

Scaled Responses

ANOVAs were conducted on the participant responses for each of the Likert-type scale questions using the four (VES) by three (Age) mixed model described earlier. The ANOVA summary tables appear in appendix F. A significant main effect for VES ($\alpha = 0.05$) was found for three of the statements; significant main effects for age ($\alpha = 0.05$) were found for two of the statements (table 13). Statement 6, which dealt with signs in the ENV IR clear weather study (ENV Volume XIII), was absent from this study because signs were not included. To maintain consistency in statement content between the present study and the ENV IR clear weather study, statements 7 and 8 are not renumbered.

Table 7. Summary of significant main effects and interactions for the Likert-type scales.

Significance Summary per Statement

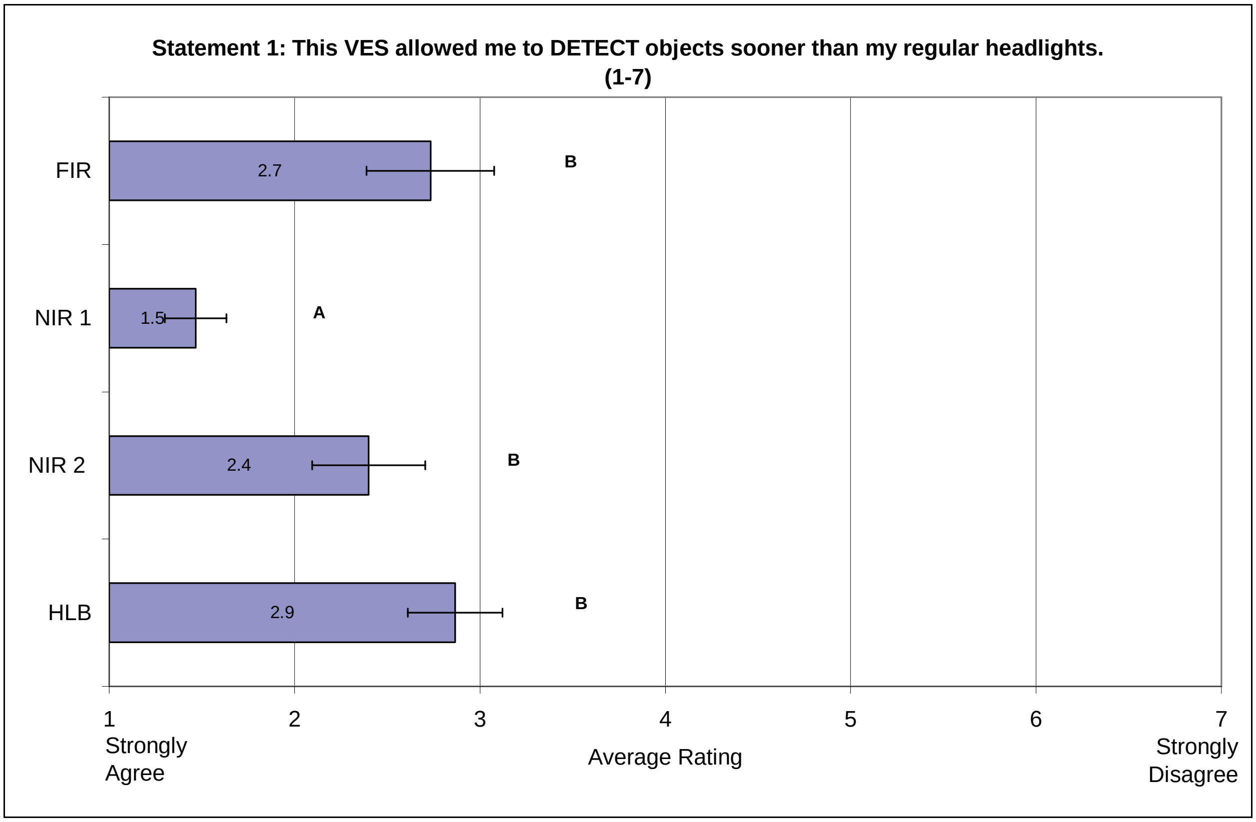
Source	**1**	**2**	**3**	**4**	**5**	**7**	**8**
Between							
Age			x	x			
Subject/Age							
Within							
VES	x	x			x		
VES by Age							
VES by Subject/Age							

Age Subjective Main Effects

In two of the statements (3 and 4), participants compared the ability of the VESs to help them stay on the road and know which direction the road was heading. It appears that the older age group gave more favorable evaluations for the VESs overall than the younger groups for these categories. In other words, older drivers tended to think that the systems tested were more advantageous than their own headlamps in helping to maintain location on the road and predicting road direction.

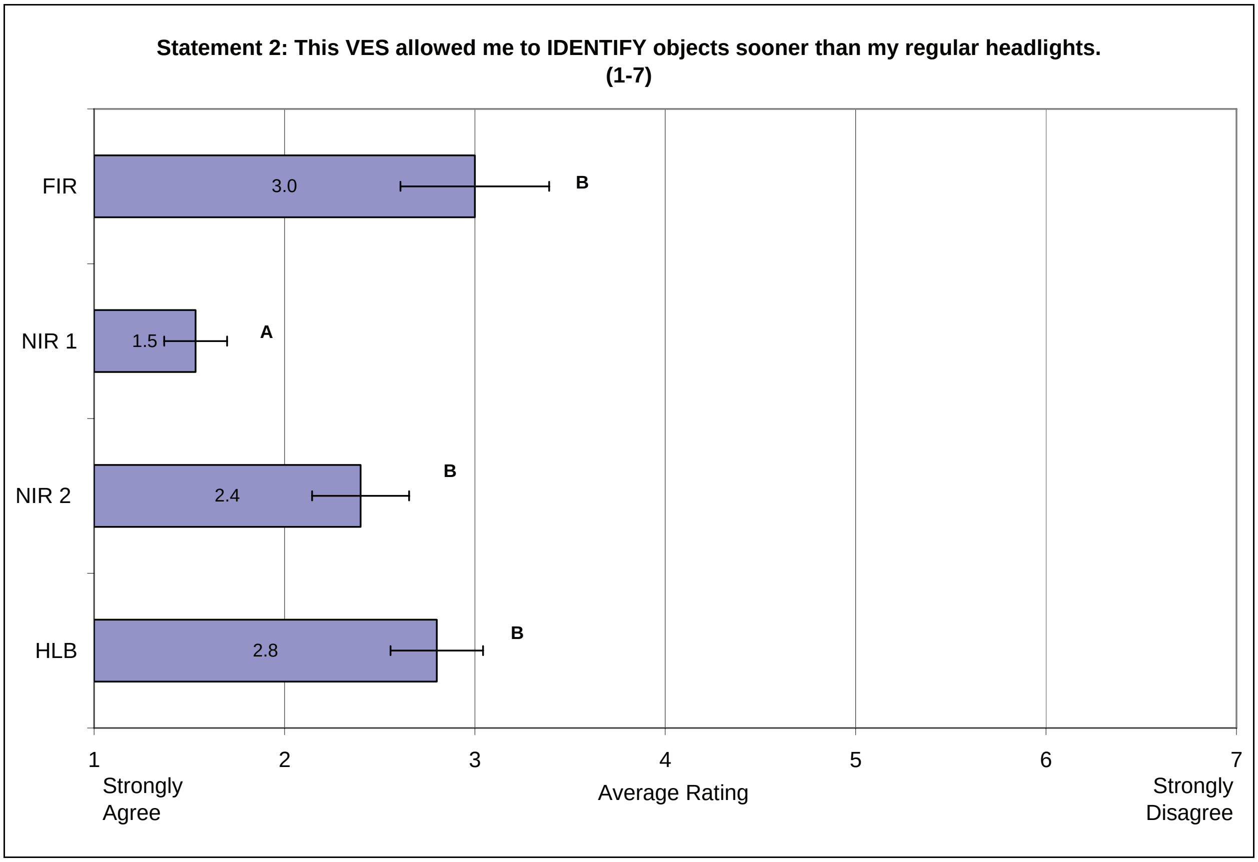
VES Subjective Main Effects

Results of the SNK analyses show that when asked which VES allowed them to detect objects sooner than their regular headlights (statement 1), participants indicated that the NIR 1 system was best with an average rating of 1.5. The remaining systems are above the average rating when compared to the participants' regular headlamps, but not statistically different from each other. Similar results were found in the subjective evaluation of identifying objects (statement 2). The NIR 1 system has the best evaluation, and the others are not statistically distinguishable from each other. Figure 19 and figure 20 depict the mean responses for the subjective evaluation of detection and identification, respectively, for the four VESs. Standard error bars, as well as the SNK groupings, are shown on these graphs.



Means with the same letter are not significantly different.

Figure 19. Bar graph. Mean subjective ratings by VES for statement 1: "This vision enhancement system allowed me to detect objects sooner than my regular headlights."

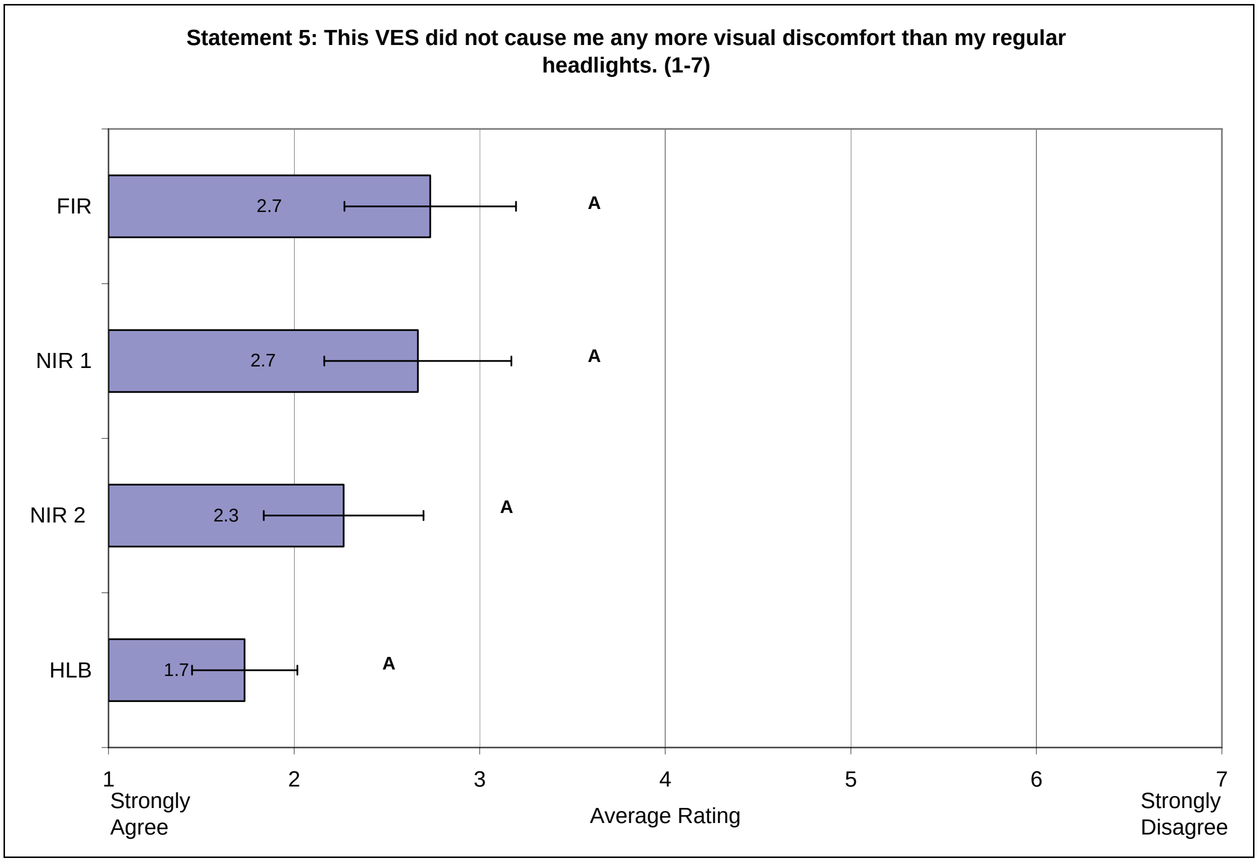


Means with the same letter are not significantly different.

Figure 20. Bar graph. Mean subjective ratings by VES for statement 2: "This vision enhancement system allowed me to identify objects sooner than my regular headlights."

No significant differences were found when participants evaluated which VES helped them stay on the road better, know which way the road was heading, or feel safer, or which they generally thought was better than their own headlamps.

When participants were asked to evaluate the visual discomfort from the VESs compared to their regular headlamps (statement 5), the results in the model indicate a main effect for VES, but the SNK analysis does not differentiate between the VESs. Figure 21 shows the means of these responses. The mean responses were all 2.7 or less, indicating that in general the participants agreed that the VESs tested did not cause them any more discomfort than their regular headlamps.



Means with the same letter are not significantly different.

Figure 21. Bar graph. Mean subjective ratings by VES for statement 5: "This vision enhancement system did not cause me any more visual discomfort than my regular headlights."

Open-Ended Responses

Following are summaries of the comments about specific VESs made by 2 or more of the 15 participants.

FIR:

- Image improvement: make clearer—can detect, but not identify (six participants).
- Image improvement: make wider (two participants).
- Hard to see in rain (lines, lanes, and/or tire) (two participants).

NIR 1:

- Distracting glare (six participants).

- Like it/good system (four participants).
- Hard to see in rain (reflection) (two participants).

NIR 2:

- The projector in the IR system gets in the way (three participants).
- Image improvement: make clearer—can detect, but not identify (two participants).
- Distracting glare (outweighs benefits) (two participants).
- Display should be larger (two participants).

HLB:

- No comment (seven participants).
- Like it/it is good (two participants).

CHAPTER 4—DISCUSSION

This chapter begins with an explanation of stopping distance and continues with the calculation of stopping distances for each VES at various speeds plus tabulated detection distances for each object. The discussion continues with a summary of the performance of each of the VESs and comparisons to both the baseline HLB VES (a readily available system) and the FIR VES (the system that outperformed the others in detecting pedestrians in the clear driving condition in the previous study (ENV Volume XIII). The summaries for the different VESs also contain more detailed observations about the performance of each VES. The chapter concludes with some general comments about results of the clear weather study versus results in the rainy weather study, and the results of the near (active) versus far (passive) IR systems.

As mentioned in chapter 2, the aiming protocol used for this study resulted in a deviation in the location of maximum intensity from where it typically is for the HLB VES. Details about this deviation are discussed in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*. As a result of the headlamp aiming, the detection and recognition distances likely increased for the HLB configuration. It is important to consider the results presented in this study in the context and conditions tested. If different halogen headlamps or aiming methods had been used, different results might have been obtained.

STOPPING DISTANCES

While these detection and recognition distances provide an indication of the advantages of one system over another, they fail to describe completely potential safety benefits or concerns based on VES use. With a limited number of assumptions, the VES-specific detection distances in rainy weather conditions can be compared with various speed-dependent stopping distances, which can help determine how easy it is to out-drive a system. In other words, when are the increased detection distance advantages of a particular system overridden by an increase in vehicle speed resulting from a driver's unfounded sense of security?

Collision-avoidance research dealing with different aspects of visibility suggests that time-to-collision is an important factor in enhancing driving safety.[9] For consistency, time-to-collision is presented as distance-to-collision (or stopping distance) for direct comparisons to the detection distances in this current study. Stopping distance is the sum of two components: (1) the distance needed for the braking reaction time (BRT) and (2) braking distance (table 8). Braking distance is the distance that a vehicle travels while slowing to a complete stop.[10] The results from driver braking performance studies suggest that the 95th percentile BRT to an unexpected object scenario in open-road conditions is about 2.5 s. (See references 11, 12, 13, and 14.) The braking distances in table 8 are calculated using the equation shown in figure 22.

$$\boldsymbol{d_{BD} = V^2/[2g(f+G)]}$$

Figure 22. Equation. Braking distance approximation.

The equation in figure 22 assumes an acceleration (g) of 9.8 m/s^2 (32.2 ft/s^2), a final speed of zero, a coefficient of friction (f) between the tire and the pavement of 0.35, and a straight, level roadway (gradient, G = 0 percent).

Table 8. Stopping distances needed for a wet roadway.

	25 mi/h	35 mi/h	45 mi/h	55 mi/h	65 mi/h	70 mi/h
Speed (ft/s)	37	51	66	81	95	103
BRT in terms of Distance (ft)	92	128	165	202	238	257
Braking Distance (ft)	60	117	193	289	403	468
Stopping Distance (ft)	**151**	**245**	**358**	**490**	**642**	**724**

1 ft = 0.305 m
1 mi/h = 1.6 km/h

The calculations shown in table 8 represent a simple and ideal condition, but they allow for some visualization of the capabilities of VESs. These stopping distances can be used as a measure of the capability of VESs to provide enough time to detect, react, and brake to a stop at different speeds, but with some caveats. First, in this study, distances were obtained while drivers were moving at approximately 16 km/h (10 mi/h), and their ability to detect objects will not necessarily remain the same as speeds increase. Second, systems that produce stopping distances close to those in table 8 or longer stopping distances could produce less effective results when conditions worsen (e.g., standing water, worn tires, or downhill condition).

Table 9 through table 12 present VES and object combinations with mean detection distances that might compromise sufficient stopping distances. (In these tables, an "X" means the stopping distance might be compromised). Note that the detection distances in tables 9 through 12 for each VES and object combination were collected while the drivers were traveling in a controlled manner (e.g., within a specified speed range) and thus assume that such distances translate to all of the speeds listed.

Table 9. Detection distances by types of object and potential detection inadequacy when compared to stopping distance at various speeds: FIR.

Type of Object	Detection (ft)	151 ft at 25 mi/h	245 ft at 35 mi/h	358 ft at 45 mi/h	490 ft at 55 mi/h	642 ft at 65 mi/h	724 ft at 70 mi/h
Pedestrian, Left, Denim Clothing	155		X	X	X	X	X
Pedestrian, Right, Denim Clothing	172		X	X	X	X	X
Pedestrian, Left Turn, Left	127	X	X	X	X	X	X
Pedestrian, Left Turn, Right	180		X	X	X	X	X
Pedestrian, Right Turn, Left	201		X	X	X	X	X
Pedestrian, Right Turn, Right	139	X	X	X	X	X	X
Pedestrian, Dynamic	169		X	X	X	X	X
Tire Tread	86	X	X	X	X	X	X

X = stopping distance might be compromised
1 ft = 0.305 m
1 mi = 1.6 km

Table 10. Detection distances by types of object and potential detection inadequacy when compared to stopping distance at various speeds: NIR 1.

Type of Object	Detection (ft)	151 ft at 25 mi/h	245 ft at 35 mi/h	358 ft at 45 mi/h	490 ft at 55 mi/h	642 ft at 65 mi/h	724 ft at 70 mi/h
Pedestrian, Left, Denim Clothing	269			X	X	X	X
Pedestrian, Right, Denim Clothing	251			X	X	X	X
Pedestrian, Left Turn, Left	254			X	X	X	X
Pedestrian, Left Turn, Right	247			X	X	X	X
Pedestrian, Right Turn, Left	346			X	X	X	X
Pedestrian, Right Turn, Right	243		X	X	X	X	X
Pedestrian, Dynamic	232		X	X	X	X	X
Tire Tread	80	X	X	X	X	X	X

X = stopping distance might be compromised
1 ft = 0.305 m
1 mi = 1.6 km

Table 11. Detection distances by types of object and potential detection inadequacy when compared to stopping distance at various speeds: NIR 2.

Type of Object	Detection (ft)	151 ft at 25 mi/h	245 ft at 35 mi/h	358 ft at 45 mi/h	490 ft at 55 mi/h	642 ft at 65 mi/h	724 ft at 70 mi/h
Pedestrian, Left, Denim Clothing	237		X	X	X	X	X
Pedestrian, Right, Denim Clothing	242		X	X	X	X	X
Pedestrian, Left Turn, Left	217		X	X	X	X	X
Pedestrian, Left Turn, Right	211		X	X	X	X	X
Pedestrian, Right Turn, Left	281			X	X	X	X
Pedestrian, Right Turn, Right	137	X	X	X	X	X	X
Pedestrian, Dynamic	216		X	X	X	X	X
Tire Tread	93	X	X	X	X	X	X

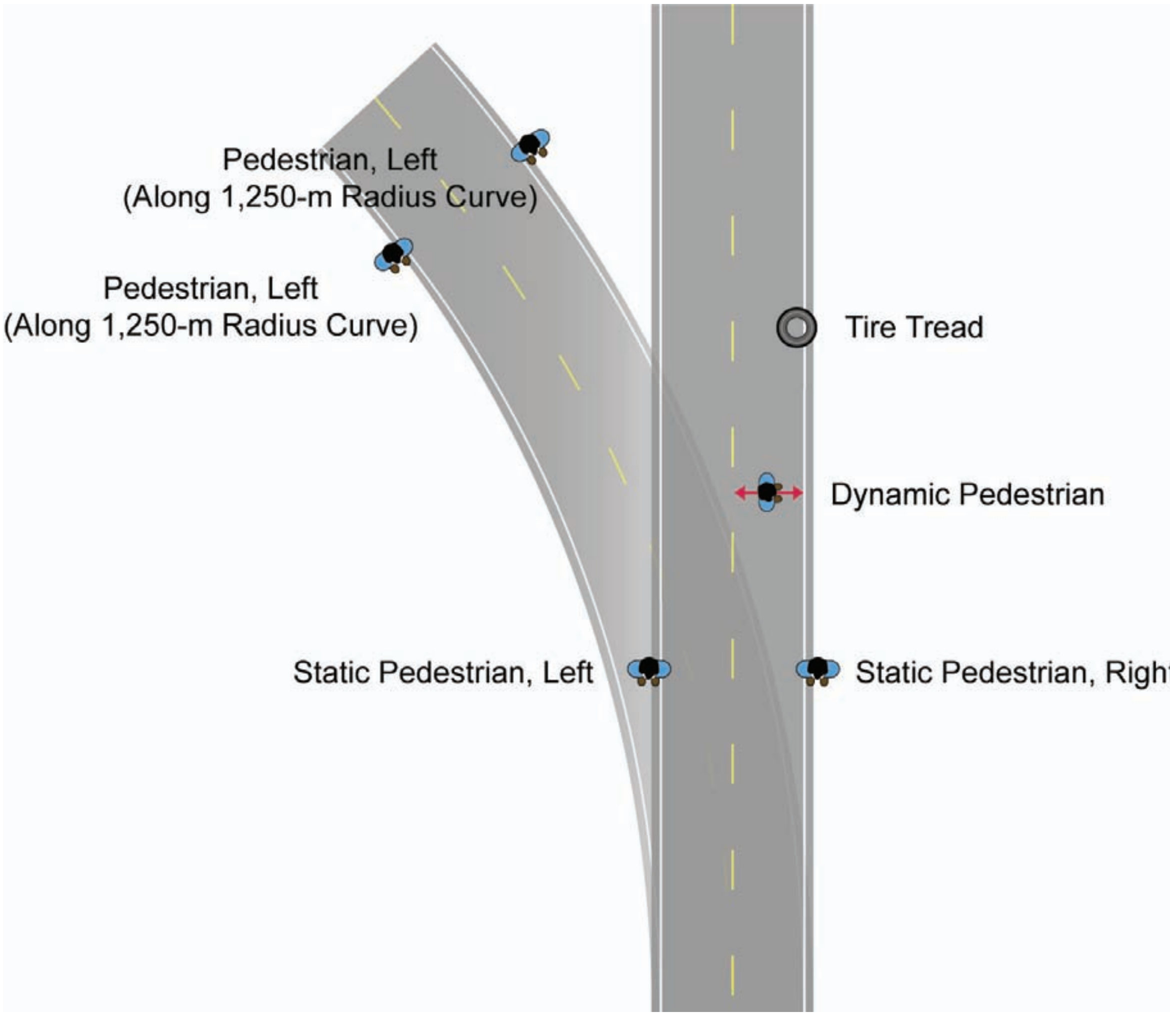
X = stopping distance might be compromised
1 ft = 0.305 m
1 mi = 1.6 km

Table 12. Detection distances by types of object and potential detection inadequacy when compared to stopping distance at various speeds: HLB.

Type of Object	Detection (ft)	151 ft at 25 mi/h	245 ft at 35 mi/h	358 ft at 45 mi/h	490 ft at 55 mi/h	642 ft at 65 mi/h	724 ft at 70 mi/h
Pedestrian, Left, Denim Clothing	180		X	X	X	X	X
Pedestrian, Right, Denim Clothing	181		X	X	X	X	X
Pedestrian, Left Turn, Left	140	X	X	X	X	X	X
Pedestrian, Left Turn, Right	198		X	X	X	X	X
Pedestrian, Right Turn, Left	217		X	X	X	X	X
Pedestrian, Right Turn, Right	187		X	X	X	X	X
Pedestrian, Dynamic	192		X	X	X	X	X
Tire Tread	92	X	X	X	X	X	X

X = stopping distance might be compromised
1 ft = 0.305 m
1 mi = 1.6 km

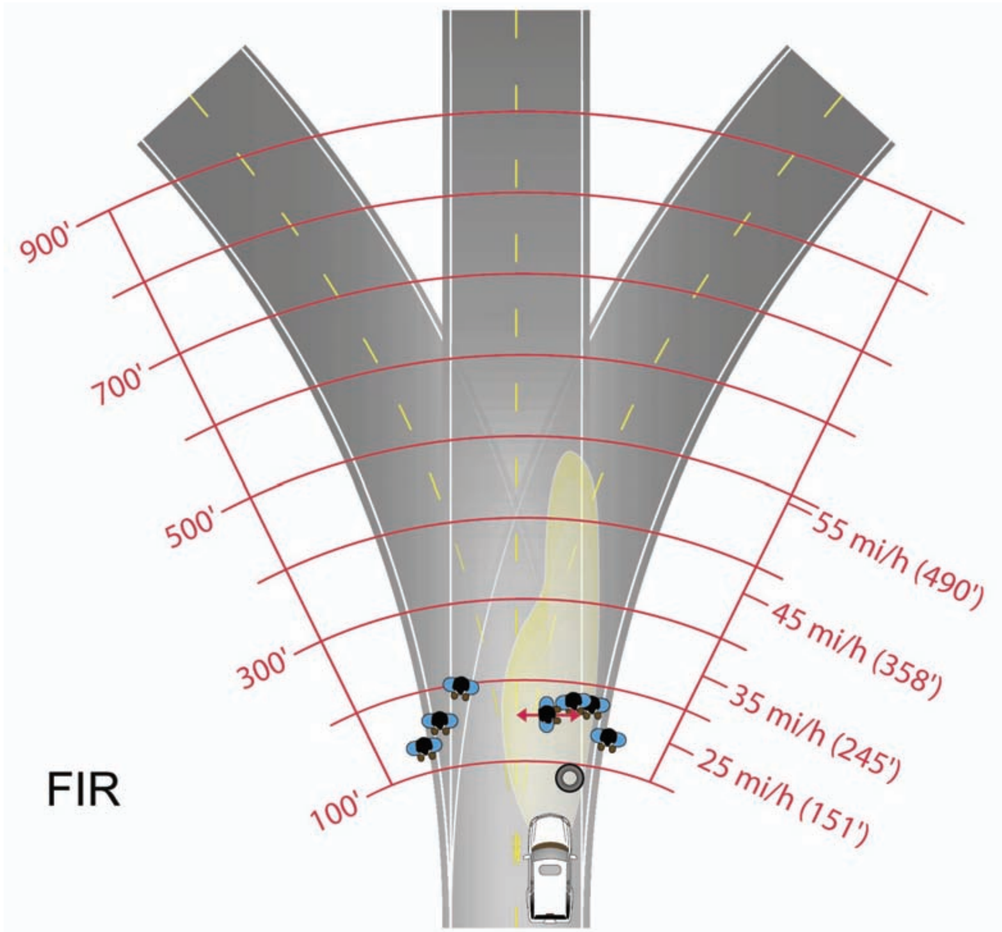
To provide an overview of each system's performance, graphics are provided for each VES. Figure 23 depicts some of the general graphics used in the representations of specific VESs. The VES-specific representations, figure 24 through figure 26, depict the detection performance for each of the pedestrian scenarios and the obstacle scenario (tire tread). Pedestrian icons facing straight down on the diagram (e.g., Static Pedestrian, Left) were presented on straight road segments. Pedestrian icons angled with the road (e.g., Pedestrian, Left) were presented on the curved road segment. Each graphic is intended to give an overall impression rather than precise comparisons.



1 m = 3.28 ft

Figure 23. Diagram. Graphics for detection distances.

Where patterns or items of interest are identified for specific VESs in figure 24 through figure 27, the reader is encouraged to refer to table 19 through table 24 (presented subsequently) to investigate the information in more detail. Additionally, while reading the following Discussion sections, the graphics provide a quick comparison of the discussed results. Each graphic includes an icon representing mean detection distance for a given scenario. The mean-detection-distance scale is located on the left side of the diagram. On the right side, the approximate stopping distance required for given speeds is shown. Where an icon is below a given speed, the stopping distance (where required) may be insufficient for the given speed.



1 ft = 0.305 m
1 mi/h = 1.6 km/h

Figure 24. Diagram. FIR mean detection distances.

In general, stopping distances are insufficient for the FIR system except at speeds less than 48 km/h (30 mi/h) for all objects. Stopping distances are compromised at speeds of only 40 km/h (25 mi/h) for the pedestrian on the left side of a left curve, the pedestrian on the right side of a right curve, and the tire tread. The FIR system produced detection distances similar to, but always less than, the HLB in all of the tested scenarios, though not significantly so. It follows that the FIR system also underperformed the NIR systems in all scenarios. The FIR detection distances were, in fact, significantly lower than those of the NIR 1 system for the detection of all pedestrian scenarios except the pedestrian on the right side of both the left and right curves (LFtrnRT and RTtrnRT). Note that detection distances were not significantly different for these two scenarios between any of the VESs. Table 13 and table 14 illustrate some of the differences between the FIR system results and those of the other VESs. These tables include information similar to that provided for the HLB baseline, but the percentage differences comparisons are made to the FIR system. (An asterisk indicates a significant difference.)

Table 13. Percentage differences from FIR: detection distances by VES and object.

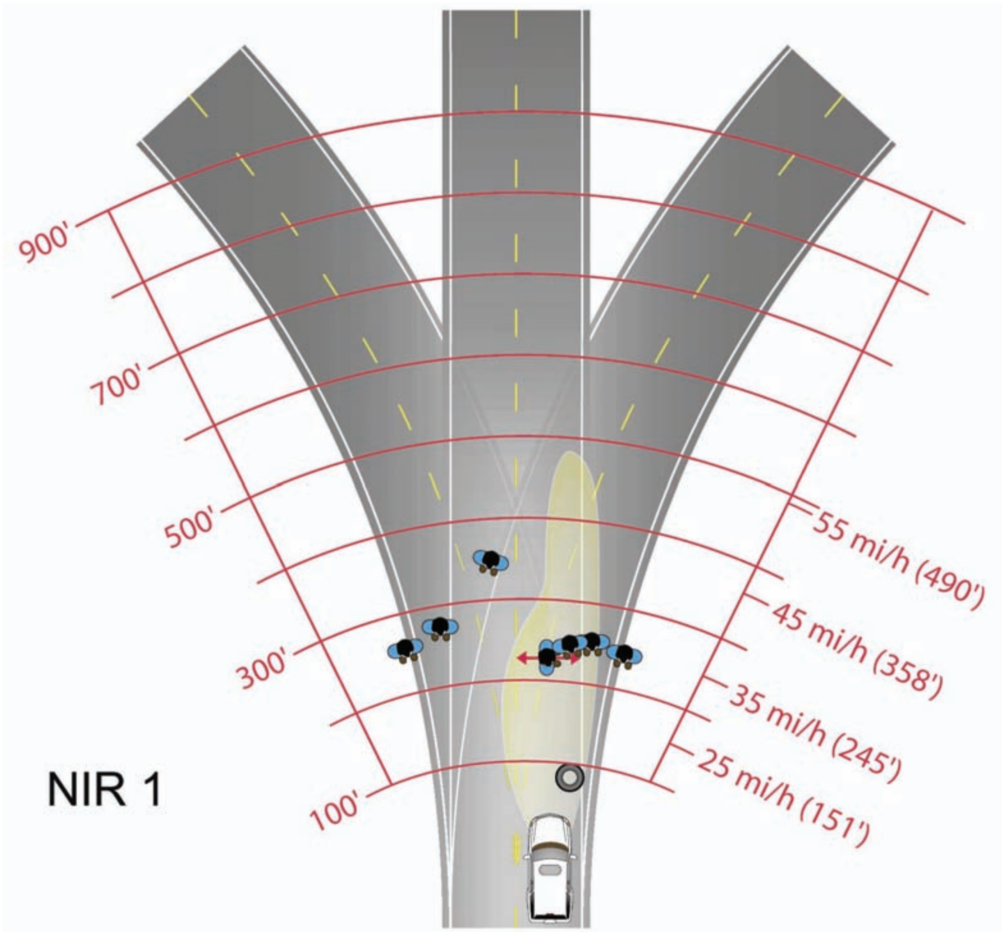
VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
NIR 1	* 74	* 46	* 38	* 99	37	* 72	75	−7
NIR 2	* 53	* 41	28	71	17	40	−1	8
HLB	16	5	14	10	10	8	35	7

* = significantly different from FIR

Table 14. Percentage differences from FIR: recognition distances by VES and object.

VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
NIR 1	* 91	* 61	* 40	* 138	56	70	58	−16
NIR 2	* 54	* 51	20	78	46	27	−3	5
HLB	30	14	17	32	33	16	29	6

* = significantly different from FIR



1 ft = 0.305 m
1 mi/h = 1.6 km/h

Figure 25. Diagram. NIR 1 mean detection distances.

For the NIR 1, all pedestrian scenarios were associated with detection distances close to or higher than required stopping distances at speeds in the 56 km/h (35 mi/h) range. Detection of one scenario, the pedestrian on the left side of a right curve, could allow sufficient stopping distance at a speed of nearly 72 km/h (45 mi/h). The NIR 1 system provided better overall performance (shorter detection distances) than the HLB and the FIR system in all scenarios except the tire tread scenario, when it performed worse (longer detection distances) than any other system, though not significantly. The NIR 1 also performed better than or similar to the NIR 2 system in several scenarios. The differences between the NIR 1 system and the HLB, as well as the FIR, are generally significant. The exceptions, as mentioned earlier, are the scenarios with pedestrians on the right side of curves, for which detection distances are longer for NIR 1, but not statistically significant. Table 15 and table 16 illustrate some of the differences between the NIR 1 system results and those of the other VESs. These tables include information similar to that provided for the HLB baseline, but the percentage differences comparisons are made to the NIR 1 system. (An asterisk indicates a significant difference.)

Table 15. Percentage differences from NIR 1: detection distances by VES and object.

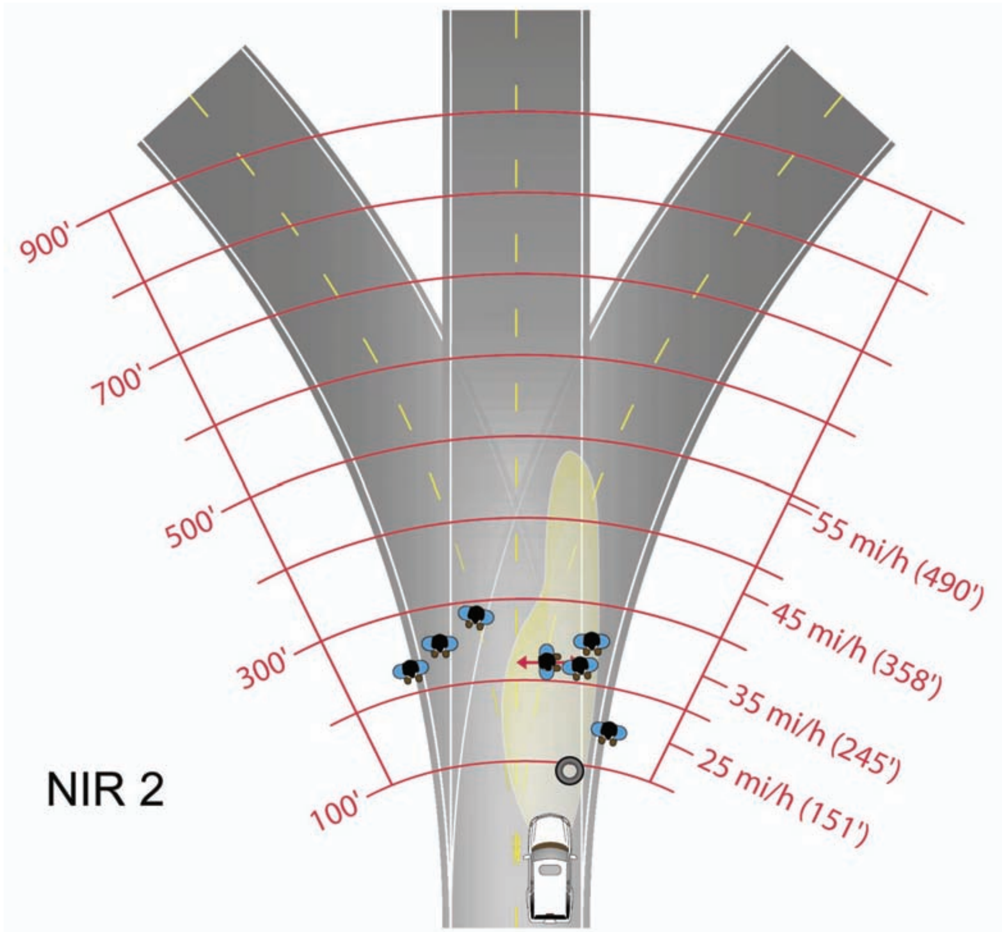
VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	* −42	* −31	* −27	* −50	−27	* −42	−43	8
NIR 2	−12	−4	−7	−14	−14	−19	−44	17
HLB	* −33	* −28	−17	* −45	−20	* −37	−23	15

* = significantly different from NIR 1

Table 16. Percentage differences from NIR 1: recognition distances by VES and object.

VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	* −48	* −38	* −29	* −58	−36	−41	−37	18
NIR 2	* −20	−6	−15	−25	−7	−25	−39	25
HLB	* −32	* −29	−17	* −44	−15	−32	−18	25

* = significantly different from NIR 1



1 ft = 0.305 m
1 mi/h = 1.6 km/h

Figure 26. Diagram. NIR 2 mean detection distances.

Similar to the NIR 1 system, pedestrian detection distances for NIR 2 were acceptable compared to required stopping distances at speeds in a range around 56 km/h (35 mi/h). The detection of some pedestrian scenarios allows adequate stopping distance up to slightly above 56 km/h (35 mi/h), and others are acceptable only at speeds slightly below 56 km/h (35 mi/h). The exception is the pedestrian on the right side of a right curve, which is not detected at an acceptable distance, even at a speed as low as 40 km/h (25 mi/h). Although similar to NIR 1 values, the NIR 2 system effectively decreases the allowable speed for adequate stopping distance for every pedestrian scenario, compared to the same scenarios using the NIR 1 system. With the exception of the tire tread, the NIR 2 tended to perform close to or below the NIR 1, but better than the other two systems. In ENV Volume XIII, the NIR 2 VES was found to have a generally lower performance than the other VESs in clear weather. Thus, the improvement in relative performance in this study indicates the potential benefits of NIR technology. Table 17 and table 18 illustrate some of the differences between the NIR 2 system results and those of the other VESs. These tables include information similar to that provided for the HLB baseline, but the percentage differences comparisons are made to the NIR 2 system. (An asterisk indicates a significant difference.)

Table 17. Percentage differences from NIR 2: detection distances by VES and object.

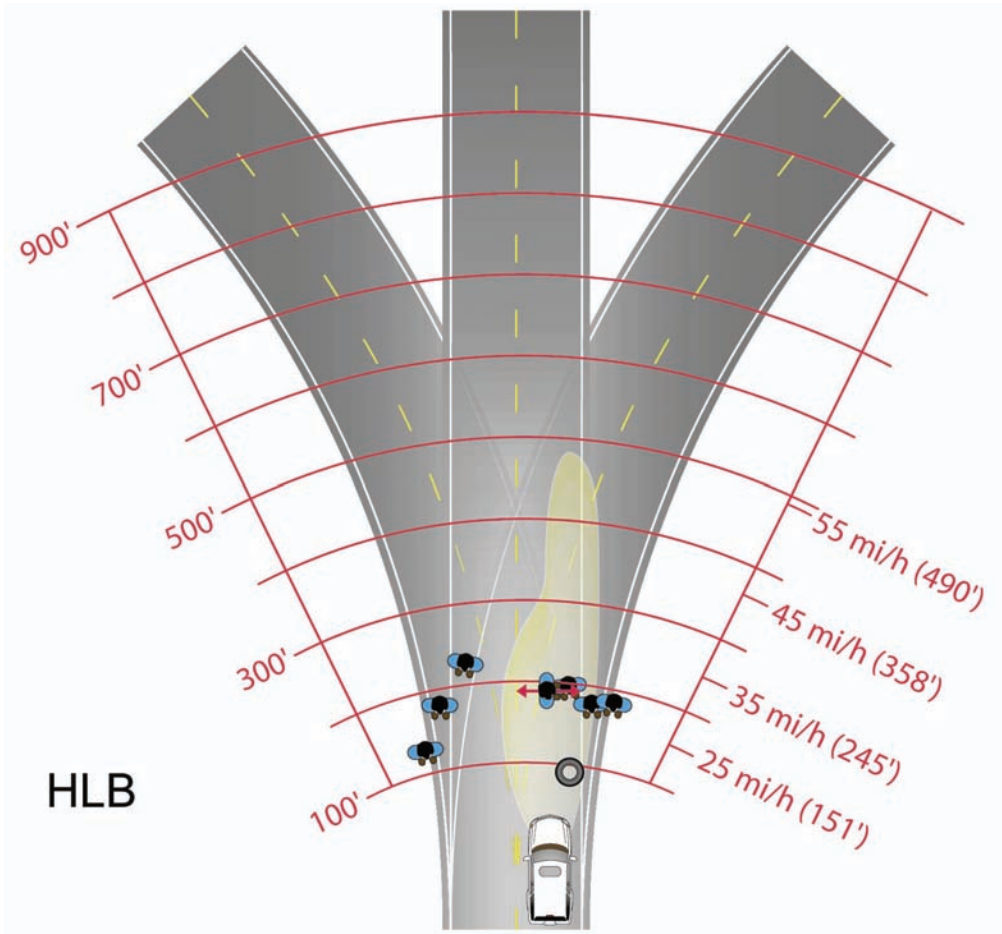
VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	* −35	* −29	−22	−41	−15	−28	1	−8
NIR 1	14	4	8	17	17	23	77	−14
HLB	* −24	* −25	−11	−36	−6	−23	37	−1

* = significantly different from NIR 2

Table 18. Percentage differences from NIR 2: recognition distances by VES and object.

VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	* −35	* −34	−16	−44	−31	−21	3	−5
NIR 1	* 24	7	17	34	7	34	63	−20
HLB	−15	* −24	−2	−26	−9	−8	33	1

* = significantly different from NIR 2



1 ft = 0.305 m
1 mi/h = 1.6 km/h

Figure 27. Diagram. HLB mean detection distances.

The HLB provided sufficient detection distances in relation to stopping distances only at low speeds (below 56 km/h (35 mi/h)) for all objects. For the pedestrian on the left side of a left curve and the tire tread, stopping distance could be compromised even at a speed as low as 40 km/h (25 mi/h). Unlike the clear weather performance found in the previous testing, the HLB was surpassed in most of the scenarios by the NIR systems tested. HLB, which was the baseline for the technologies tested, produced significantly lower detection distances than both NIR systems for the static pedestrians on the left and right sides of the straight road. The HLB also had significantly lower detection distances than the NIR 1 system for the pedestrian standing on the left side of both a left curve and a right curve (i.e., LFtrnLF and RTtrnLF). These findings are listed in table 19, which includes percentage differences from HLB detection distances for each of the other three VESs (an asterisk indicates a significant difference). Table 20 lists similar findings for the recognition distances.

Table 19. Percentage differences from HLB: detection distances by VES and object.

VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	−14	−5	−12	−9	−9	−7	−26	−7
NIR 1	* 50	* 39	21	* 82	25	* 59	30	−13
NIR 2	* 32	* 34	13	55	7	30	−27	1

* = significantly different from HLB

Table 20. Percentage differences from HLB: recognition distances by VES and object.

VES	BlueLF	BlueRT	PedDyno	LFtrnLF	LFtrnRT	RTtrnLF	RTtrnRT	Tire
FIR	−23	−12	−14	−24	−25	−14	−23	−5
NIR 1	* 47	* 42	20	* 80	18	46	23	−20
NIR 2	18	* 33	2	34	10	9	−25	−1

* = significantly different from HLB

COMPARISON OF RAIN AND CLEAR CONDITION DETECTION DISTANCES

The participants in this study also took part in the previous IR study in clear weather (ENV Volume XIII). Table 21 to table 27 provide the mean detection distance and standard error for each object in the rain and clear studies. The tables also provide the detection distances in the rain condition as a percentage of the detection distances in the clear condition. The only scenario in which a VES had a higher detection distance in the rain condition than in the clear condition was the FIR with the pedestrian on the left during a left turn (table 21). As discussed in the clear study, this pedestrian likely was not visible with the FIR because of the system’s field of view; therefore, this pedestrian likely was detected with headlamps alone in the clear study as well as in the rain study. The FIR system could not distinguish pedestrians in the rain; therefore, participants may have glanced at the FIR system less and the road more, resulting in slightly longer detection distances with this VES in the rain condition than in the clear condition, although these detection distances are not statistically different. In fact, after considering the relative detection distances of other objects in rain, it appears that detection with the FIR configuration actually was performed with the headlamps alone in the rain condition.

The potential merit of NIR in rain can be seen by further examination of the NIR 2 results in the clear and rain studies. The detection distances with the FIR in rain conditions ranged from

18 percent to 32 percent of the detection distances in the clear condition; however, for the pedestrian on the left in a left turn scenario, the NIR 2 system showed no detection decrement in rain and a 41 percent longer detection than the FIR. (Both the FIR and the NIR 2 were on the same SUV model and year with the same type of headlamps.) Assuming that the participants driving with the FIR system were using headlamps alone, this result could indicate a potential benefit of NIR. In the clear study, the NIR 2 system had the shortest detection distance for all the objects and VESs that were also included in the rain study (table 25 to table 31). In the rain study, the NIR 2 had the second greatest detection distance in six out of the seven pedestrian scenarios. Assuming that the FIR system provided only headlamps to detect pedestrians, the NIR 2 system indicated an average 30 percent benefit over headlamps alone for these six scenarios. In the remaining scenario, a pedestrian on the right in a right turn, it appears that drivers with the NIR 2 used headlamps only because the short detection distance of the VES was similar to the detection distance with the FIR (table 24). The pedestrian is this scenario may be outside the FOV of the NIR 2 system. (See ENV Volume XIII for further discussion.) The other NIR system, NIR 1, had the longest detection distance in all the pedestrian scenarios in rain conditions, further highlighting the potential benefit of near IR in rain conditions. The NIR 1 system had either the longest or the second longest detection distance for pedestrians in clear condition scenarios that were also included in the rain study.

The halogen lights showed a 50 to 70 percent decrement in detection distance in the rain condition when compared to the clear condition. This decrement, combined with the potential added detection benefit of the NIR system in rain conditions, indicates a possible added safety benefit from including a supplemental NIR system on a vehicle.

Table 21. Detection in rain compared to clear for a pedestrian on the left in a left turn.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	98	127	13	27	130
NIR 1	500	254	32	33	51
NIR 2	217	217	29	18	100
HLB	346	140	15	23	40

1 ft = 0.305 m

Table 22. Detection in rain compared to clear for a pedestrian on the left in a right turn.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	768	180	101	19	23
NIR 1	682	247	32	32	36
NIR 2	386	211	35	29	55
HLB	412	198	17	15	48

1 ft = 0.305 m

Table 23. Detection in rain compared to clear for a pedestrian on the right in a left turn.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	698	201	92	36	29
NIR 1	536	346	50	23	65
NIR 2	372	281	37	44	76
HLB	500	217	23	10	43

1 ft = 0.305 m

Table 24. Detection in rain compared to clear for a pedestrian on the right in a right turn.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	434	139	46	45	32
NIR 1	440	243	33	38	55
NIR 2	294	137	21	22	47
HLB	416	187	28	12	45

1 ft = 0.305 m

Table 25. Detection in rain compared to clear for a pedestrian on the left.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	851	155	101	14	18
NIR 1	707	269	59	20	38
NIR 2	409	237	64	25	58
HLB	452	180	35	14	40

1 ft = 0.305 m

Table 26. Detection in rain compared to clear for a pedestrian on the right.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	894	172	106	19	19
NIR 1	788	251	54	21	32
NIR 2	455	242	51	20	53
HLB	599	181	42	17	30

1 ft = 0.305 m

Table 27. Detection in rain compared to clear for a tire tread.

VES	Clear Mean (ft)	Rain Mean (ft)	Clear SE (ft)	Rain SE (ft)	Percentage
FIR	166	86	18	9	52
NIR 1	152	80	19	12	52
NIR 2	141	93	11	11	66
HLB	186	92	27	13	49

1 ft = 0.305 m

SUBJECTIVE RATINGS

The NIR 1 system received the most favorable ratings overall in the subjective scaled responses. With the exception of the statement “This VES did not cause me any more visual discomfort than my regular headlights,” the mean subjective statement responses for NIR 1 were the most favorable among the four VES configurations. In particular, the responses for statements 1 and 2, allowing detection and allowing recognition of objects compared to regular headlamps, were statistically greater for the NIR 1 system compared to the other three systems. These subjective results correspond to the objective results discussed previously, and they demonstrate that drivers subjectively felt the advantage of NIR in the detection and recognition of objects as well.

For the cases in which drivers felt better able to detect and recognize objects while using the NIR 1 system, there were no significant differences in ratings related to the age of the drivers. There was some evidence of more favorable ratings for older drivers when they asked whether systems aided in the determination of road direction (statement 4), but there was no significant difference in these ratings related to VES and no interaction of VES and age for this category.

CHAPTER 5—CONCLUSIONS

In general, in rainy weather driving conditions, the NIR systems were associated with longer detection distances than the baseline HLB and FIR systems for nearly all pedestrian detection scenarios. The only case in which either of the two NIR systems had shorter detection distances was for the pedestrian on the right side of a right curve. The NIR 2 had similar or slightly shorter detection distances for this scenario than both the HLB and the FIR systems, although the differences were not statistically significant. The difference likely results because the pedestrian in that scenario is outside the FOV of the NIR 2 system. All other mean detection distances in pedestrian scenarios for both NIR 1 and NIR 2 were longer than those of the HLB and FIR. Many of the differences, especially for the pedestrians on straight sections of road, were significantly different. Although there were some ranking differences between the VES detection distances for the remaining scenario, the tire tread, the fact that there were no differences between systems was significant. It appears from these results that there is no performance loss between the tested VESs for detecting and recognizing this type of obstacle (a small, low-contrast object). These objective findings are corroborated by the subjective responses of the drivers in this study, and they do not appear to be differentiated by age. Review of the open-ended comments could provide insight into further improvements of the NIR system, including glare reduction and display enhancement.

APPENDIX A—SCREENING QUESTIONNAIRE

Name ____Male/Female

Phone Numbers (Home)______________________(Work)______________________

Best Time to Call ____

Best Days to Participate__________________

DRIVER SCREENING AND DEMOGRAPHIC QUESTIONNAIRE: ENV-IR

Note to Screening Personnel

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

Introductory Statement

(Use the following script as a guideline in the screening interview.)

My name is _____ and I work ___________. I'm recruiting drivers for a study to evaluate new night vision enhancement systems for vehicles.

This study will involve you driving different vehicles instrumented with data collection equipment on the Smart Road at night and filling out questionnaires. Participants will come in for two separate driving sessions that will last approximately 3 hours each. We will pay you $20 per hour. The total amount will be given to you at the end of the second night. Would you like to participate in this study?

If the Participant Agrees

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

If the Participant Does Not Agree

Thanks for your time, would you like me to remove you from the database?

QUESTIONS

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

   Yes ______ No ______

2. How often do you drive each week?

   Every day _____ At least 2 times a week_____ Less than 2 times a week______

3. How old are you? _______

4. What is your date of birth?____________

5. Have you previously participated in any experiments at _________? If so, can you briefly describe the study?

   Yes ______
   Description:____
   No ______

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

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

   Yes ______ No ______

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

   Yes ______ ____
   No ______

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

   Yes ______ ____
   No ______

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

Heart condition	No_____	Yes____________________________
Heart attack	No_____	Yes____________________________
Stroke	No_____	Yes____________________________
Brain tumor	No_____	Yes____________________________
Head injury	No_____	Yes____________________________
Epileptic seizures	No_____	Yes____________________________
Respiratory disorders	No_____	Yes____________________________

Motion sickness	No____	Yes________________________________
Inner ear problems	No____	Yes________________________________
Dizziness, vertigo, or other balance problems	No____	Yes________________________________
Diabetes	No____	Yes________________________________
Migraine, tension headaches	No____	Yes________________________________

11. Have you ever had radial keratotomy (corrective eye surgery) or other eye surgeries? If so, please specify.

Yes _____ ____

No _____

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

Yes _____ No _____

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

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

Yes _____ ____

No _____

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

Yes _____

No _____ ____

CRITERIA FOR PARTICIPATION

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

9. Cannot have a history of heart condition or prior heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures within the last 12 months, lingering effects from respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.
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 (corrective eye surgery) or any other ophthalmic surgeries.

Accepted: ________

Rejected: ________ Reason:____

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

APPENDIX B—INFORMED CONSENT FORM

[Contractor Facility]
INFORMED CONSENT FOR PARTICIPANTS OF INVESTIGATIVE PROJECTS

Title of the Project: Enhanced Night Visibility—Evaluation of Infrared Systems in Rain Conditions

INVESTIGATORS

I. The Purpose of the Research

The purpose of this research is to gather information pertaining to different Night Vision Systems to be used to improve night driving conditions in rainy weather.

II. Procedures

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

1) Read and sign an Informed Consent Form.
2) Show a current driver's license.
3) Complete three vision tests.
4) Drive a vehicle on the Smart Road at 10 miles per hour in the rain, and notify the experimenter when you can detect and identify different objects along the roadway.
5) Complete questionnaires.
6) Listen to the instructions regarding any tasks you may perform.

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

III. Risks

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

1. The risk of an accident normally associated with driving an unfamiliar automobile at 10 miles per hour or less, on straight and slightly curved roadways in the rain.

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

The following precautions will be taken to ensure minimal risk to you.

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

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

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

IV. Benefits of this Project

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

V. Extent of Anonymity and Confidentiality

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

VI. Compensation

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

VII. Freedom to Withdraw

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

VIII. Approval of Research

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at [university and university transportation research center].

IX. Participant's Responsibilities

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

X. Participant's Permission

Check one of the following:

- ☐ [The contractor] **has my permission** to give the videotape including my image to the client who has sponsored this research. I understand that the client will only use the videotape for research purposes.

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

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

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

____ ________________________

Participant's Signature Date

Should I have any questions about this research or its conduct, I may contact:
(Name) (Phone)
(Name) (Phone)
(Name) (Phone)

______________________________________ ________________________

Experimenter's Signature Date

APPENDIX C—VISION TEST

PARTICIPANT NUMBER: __________

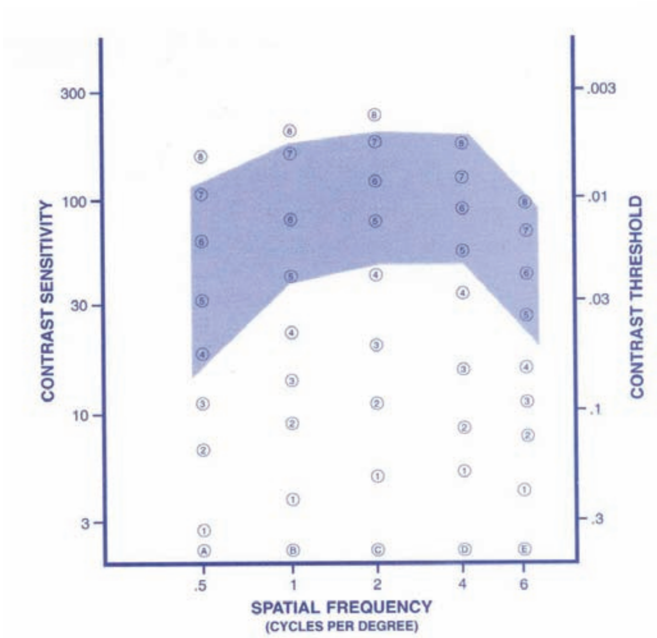
VISION TESTS

Acuity Test

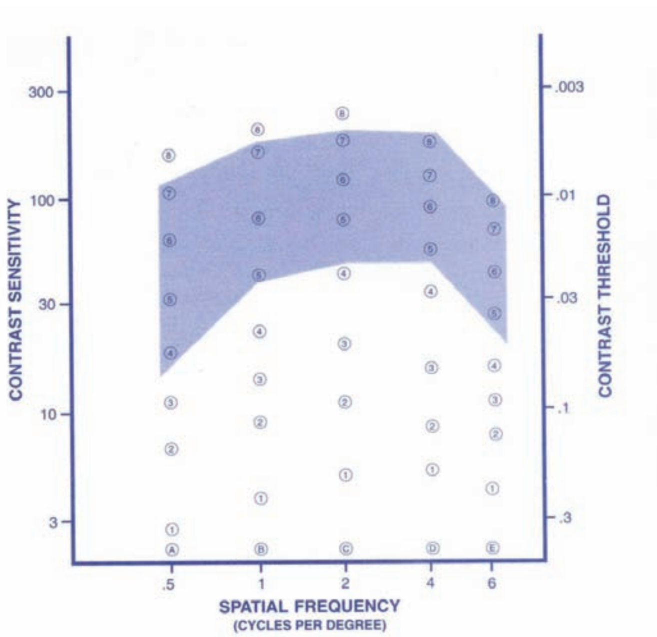
- Acuity Score:_________

Contrast Sensitivity Test

Left



Right



Ishihara Test for Color Blindness

1._____ 4._____ 7.____

2._____ 5._____

3._____ 6._____

Standing Height _________+ 20 inches _______________________

APPENDIX D—ANOVA TABLES FOR PEDESTRIANS IN STRAIGHT SECTIONS

Table 28. Pedestrian, denim clothing, left ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	65578.0	32789.0	5.16	0.0241	*
Subject/Age	12	76182.3	6348.5			
Within						
VES	3	123148.5	41049.5	10.31	<.0001	*
VES by Age	6	12584.8	2097.5	0.53	0.7842	
VES by Subject/Age	36	143367.8	3982.4			
TOTAL	59	420861.4				

* $p < 0.05$ (significant)

Table 29. Pedestrian, denim clothing, left ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	59180.7405	29590.3702	4.36	0.0377	*
Subject/Age	12	81444.2385	6787.0199			
Within						
VES	3	120891.2345	40297.0782	11.39	<.0001	*
VES by Age	6	7529.5261	1254.921	0.35	0.9025	
VES by Subject/Age	36	127417.0028	3539.3612			
TOTAL	59	396462.7				

* $p < 0.05$ (significant)

Table 30. Pedestrian, denim clothing, right ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	18484.9	9242.5	1.71	0.2223	
Subject/Age	12	64893.9	5407.8			
Within						
VES	3	77988.4	25996.1	5.36	0.0038	*
VES by Age	6	44679.6	7446.6	1.53	0.196	
VES by Subject/Age	35	169878.2	4853.7			
TOTAL	58	375924.9				

* $p < 0.05$ (significant)

Table 31. Pedestrian, denim clothing, right ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	22516.241	11258.1205	1.66	0.2308	
Subject/Age	12	81345.0437	6778.7536			
Within						
VES	3	89691.7849	29897.2616	6.64	0.0011	*
VES by Age	6	28013.5336	4668.9223	1.04	0.4186	
VES by Subject/Age	35	157646.2573	4504.1788			
TOTAL	58	379212.9				

* $p < 0.05$ (significant)

Table 32. Dynamic pedestrian ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	48397.1	24198.5	3.42	0.0668	
Subject/Age	12	84942.9	7078.6			
Within						
VES	3	35015.7	11671.9	3.17	0.0359	*
VES by Age	6	19818.6	3303.1	0.90	0.5076	
VES by Subject/Age	36	132555.8	3682.1			
TOTAL	59	320730.1				

* $p < 0.05$ (significant)

Table 33. Dynamic pedestrian ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	62528.3286	31264.1643	4.17	0.0421	*
Subject/Age	12	89950.6015	7495.8835			
Within						
VES	3	32769.8772	10923.2924	3.88	0.0169	*
VES by Age	6	27498.4954	4583.0826	1.63	0.1683	
VES by Subject/Age	36	101453.6729	2818.1576			
TOTAL	59	314201.0				

* $p < 0.05$ (significant)

APPENDIX E—ANOVA TABLES FOR PEDESTRIANS IN CURVES (TURNS)

Table 34. Pedestrian in left turn, left side ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
VES	3	84807.1349	28269.0450	5.48	0.0047	*
Error	26	134111.1436	5158.1209			
TOTAL	29	218918.2785				

* $p < 0.05$ (significant)

Table 35. Pedestrian in left turn, left side ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
VES	3	89200.49231	29733.49744	7.08	0.0012	*
Error	26	109248.6715	4201.8720			
TOTAL	29	198449.1638				

* $p < 0.05$ (significant)

Table 36. Pedestrian in left turn, right side ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value
Between					
VES	3	17586.70437	5862.23479	1.25	0.3107
Error	26	121571.1740	4675.8144		
TOTAL	29	139157.8783			

Table 37. Pedestrian in left turn, right side ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value
Between					
VES	3	28588.88483	9529.62828	1.54	0.2277
Error	26	160862.2159	6187.0083		
TOTAL	29	189451.1007			

Table 38. Pedestrian in right turn, left side ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
VES	3	110398.8699	36799.6233	5.06	0.0068	*
Error	26	189069.7959	7271.9152			
TOTAL	29	299468.6658				

* $p < 0.05$ (significant)

Table 39. Pedestrian in right turn, left side ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value
Between					
VES	3	77045.56589	25681.85530	2.71	0.0658
Error	26	246610.1002	9485.0039		
TOTAL	29	323655.6661			

Table 40. Pedestrian in right turn, right side ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
VES	3	48691.74861	16230.58287	3.17	0.0417	*
Error	25	127869.5356	5114.7814			
TOTAL	28	176561.2842				

* $p < 0.05$ (significant)

Table 41. Pedestrian in right turn, right side ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value
Between					
VES	3	31460.35105	10486.78368	2.20	0.1134
Error	25	119323.7248	4772.9490		
TOTAL	28	150784.0758			

APPENDIX F—ANOVA TABLES FOR POST-DRIVE QUESTIONNAIRE

Table 42. ANOVA summary table for the Likert-type scale on detection.

Statement 1: Detection						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	1.4	0.7	0.3	0.7487	
Subject/Age	12	29.0	2.4			
Within						
VES	3	17.9	6.0	7.63	0.0004	*
VES by Age	6	5.4	0.9	1.14	0.3585	
VES by Subject/Age	36	28.2	0.8			
TOTAL	59	81.9				

* $p < 0.05$ (significant)

Table 43. ANOVA summary table for the Likert-type scale on recognition.

Statement 2: Recognition						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	1.7	0.9	0.42	0.6636	
Subject/Age	12	24.5	2.0			
Within						
VES	3	19.0	6.3	7.06	0.0008	*
VES by Age	6	5.2	0.9	0.97	0.4619	
VES by Subject/Age	36	32.3	0.9			
TOTAL	59	82.7				

* $p < 0.05$ (significant)

Table 44. ANOVA summary table for the Likert-type scale on lane-keeping assistance.

Statement 3: Lane-keeping assistance						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	35.8	17.9	3.95	0.048	*
Subject/Age	12	54.4	4.5			
Within						
VES	3	6.3	2.1	2.11	0.1158	
VES by Age	6	3.6	0.6	0.61	0.7188	
VES by Subject/Age	36	35.6	1.0			
TOTAL	59	135.7				

* $p < 0.05$ (significant)

Table 45. ANOVA summary table for the Likert-type scale on roadway direction.

Statement 4: Roadway direction						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	30.8	15.4	5.29	0.0226	*
Subject/Age	12	35.0	2.9			
Within						
VES	3	6.3	2.1	2.01	0.1306	
VES by Age	6	4.6	0.8	0.74	0.6244	
VES by Subject/Age	36	37.8	1.1			
TOTAL	59	114.6				

* $p < 0.05$ (significant)

Table 46. ANOVA summary table for the Likert-type scale on visual discomfort.

Statement 5: Visual discomfort						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	3.6	1.8	0.21	0.8126	
Subject/Age	12	102.3	8.5			
Within						
VES	3	9.5	3.2	2.91	0.0479	*
VES by Age	6	8.9	1.5	1.36	0.2555	
VES by Subject/Age	36	39.3	1.1			
TOTAL	59	163.7				

* $p < 0.05$ (significant)

Table 47. ANOVA summary table for the Likert-type scale on overall safety rating.

Statement 7: Overall safety rating					
Source	**DF**	**SS**	**MS**	**F value**	**P value**
Between					
Age	2	3.7	1.9	0.28	0.7598
Subject/Age	12	79.7	6.6		
Within					
VES	3	6.9	2.3	1.75	0.1739
VES by Age	6	3.1	0.5	0.39	0.8822
VES by Subject/Age	36	47.5	1.3		
TOTAL	59	140.9			

Table 48. ANOVA summary table for the Likert-type scale on overall VES evaluation.

Statement 8: Overall VES evaluation (better than regular)					
Source	**DF**	**SS**	**MS**	**F value**	**P value**
Between					
Age	2	6.6	3.3	0.47	0.6374
Subject/Age	12	85.1	7.1		
Within					
VES	3	8.9	3.0	2.29	0.0953
VES by Age	6	4.2	0.7	0.53	0.7795
VES by Subject/Age	36	46.9	1.3		
TOTAL	59	151.7			

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