Volume 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

PUBLICATION NO. FHWA-HRT-04-144

DECEMBER 2005

U.S. Department of Transportation

Federal Highway Administration

Research, Development, and Technology
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FOREWORD

The overall goal of the Federal Highway Administration's (FHWA) Visibility Research Program is 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 clear weather using visual headlight 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 under various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume XIII. 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 those involved in headlamp and roadway specifications.

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-04-144	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Enhanced Night Visibility Series, Volume XIII: Phase III—Study 1: Comparison of Near Infrared, Far Infrared, High Intensity Discharge, and Halogen Headlamps on Object Detection in Nighttime Clear Weather		5. Report Date December 2005 6. Performing Organization Code
7. Author(s) Shane B. McLaughlin, Jonathan M. Hankey, Thomas A. Dingus		8. Performing Organization Report No.
9. Performing Organization Name and Address Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061		10. Work Unit No. 11. Contract or Grant No. DTFH61-98-C-00049
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code HRDS-05
15. Supplementary Notes Contracting Officer's Technical Representative (COTR): Carl Andersen, HRDS-05		

16. Abstract

Phase III—Study 1 was performed to further explore findings on far infrared (FIR) systems from Phase II, to investigate near infrared (NIR) and high intensity discharge (HID) technologies, and to investigate detection and recognition of retroreflective infrastructure components. The empirical testing for this study was performed at the Virginia Smart Road testing facility during clear weather conditions. A total of 18 participants were involved in the study. A 6 by 3 by 17 mixed-factorial design was used to investigate the effects of 6 different types of vision enhancement systems, 3 age groups, and 17 object presentations on detection and recognition distances; subjective evaluations were obtained for the different systems as well.

The results of the empirical testing suggest that infrared (IR) systems, when designed correctly, can provide pedestrian detection benefit in clear weather, particularly for pedestrians in dark clothing and veiled in the glare of oncoming headlamps. A wider field of view display appears to facilitate detection in curves of 1,250-m radius. Retroreflective objects may be detected earlier in an NIR display, but require direct visual observation to recognize the object or read signage. HID systems did not provide detection benefit over the baseline halogen headlamps tested.

17. Key Words Detection, Recognition, Night Vision, Visibility, Vision Enhancement System, Infrared, Headlamp, Pedestrian, High Intensity Discharge, Halogen		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 164	22. Price

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 13th 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
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XII	Enhanced Night Visibility Series: Overview of Phase II and Development of Phase III Experimental Plan	FHWA-HRT-04-143
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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
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LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

CAD ....computer-aided design
ENV ....Enhanced Night Visibility
FOV...................................field of view
HHD..................................high head down
HUD..................................heads-up display
IP ....instrument panel
IR.......................................infrared
OCH ....optical center height
OEM..................................original equipment manufacturers
SAE ....Society of Automotive Engineers
SUV...................................sport utility vehicle
UV–A ....ultraviolet A (wavelength 315 to 400 nanometers)
VES ....vision enhancement system
VOA ....visually optically aligned
VOL ....visually optically aligned left
VOR ....visually optically aligned right

Vision Enhancement Systems

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

Objects

BlackLF.............................pedestrian, black clothing, left
BlackRT ....pedestrian, black clothing, right
BloomLF............................bloom object, left (denim clothing)
BloomRT............................bloom object, right (denim clothing)
BlueLF ....pedestrian, denim clothing, left
BlueRT...............................pedestrian, denim clothing, right
FOALT...............................far off axis left (denim clothing)
FOART ....far off axis right (denim clothing)
LFtrnLF.............................pedestrian in left turn, left side (denim clothing)
LFtrnRT ....pedestrian in left turn, right side (denim clothing)
RRPM ....raised retroreflective pavement marker
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
SD ....standard deviation
SE.....................................standard error
SNK..................................Student-Newman-Keuls
SS ....sums of squares

Measurements

C.......................................Celsius
cm.....................................centimeters
F ....Fahrenheit
ft ....feet
ft/inches.............................feet per inches
h..hours
km ....kilometers
km/h ....kilometers per hour
m ....meters
m/cm ....meters per centimeter
mi ....miles
mi/h ....miles per hour
mm ....millimeters
s ....seconds

Stopping Distance

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

Contrast Sensitivity

cpd....................................cycles per degree
PCLA ....percentage of contrast left eye line A (line A represents 1.5 cpd)
PCLB.................................percentage of contrast left eye line B (line B represents 3.0 cpd)
PCLC.................................percentage of contrast left eye line C (line C represents 6.0 cpd)
PCLD ....percentage of contrast left eye line D (line D represents 12.0 cpd)
PCLE.................................percentage of contrast left eye line E (line E represents 18.0 cpd)

PCRA ....percentage of contrast right eye line A (line A represents 1.5 cpd)
PCRB ....percentage of contrast right eye line B (line B represents 3.0 cpd)
PCRC ....percentage of contrast right eye line C (line C represents 6.0 cpd)
PCRD ....percentage of contrast right eye line D (line D represents 12.0 cpd)
PCRE.................................percentage of contrast right eye line E (line E represents 18.0 cpd)

CHAPTER 1—INTRODUCTION

During Phase II of the Enhanced Nighttime Visibility (ENV) project, far infrared (FIR) systems showed promise for pedestrian-detection capabilities (ENV Volume III). These systems, which show warm-bodied objects as light silhouettes on a dark background, have been received with interest in the marketplace. FIR technology is present on production vehicles and remains a unique vision enhancement system because of its ability to present images based on the temperature differential between an object and its background. The images presented by FIR do not contain many details; for example, they do not show headlamp light, pavement markings, signs, or raised retroreflective pavement markers (RRPMs). Despite this lack of detail, FIR has been shown to potentially allow for the early detection of pedestrians, cyclists, or animals (i.e., objects generating heat) on the roadway.

Near infrared (NIR) systems have also gained interest from original equipment manufacturers (OEMs) and suppliers for possible future product offerings. NIR systems, which present features of the forward road scene with more picture-like quality, are a more recent addition to automotive-based vision enhancement systems (VESs). These systems use infrared (IR) emitters to act like IR headlamps when viewed through the IR camera and its associated display. Unlike FIR, NIR systems show many details of the forward roadway scene, including headlamp light, pavement markings, signs, and RRPMs. NIR success in maintaining a clear image in the presence of retroreflective objects and headlamps is negatively affected by bright halos, or "blooming." This area is currently being refined by system designers, with development of different methods to actively control blooming. While blooming of lights and retroreflective objects is an issue with NIR, these systems nevertheless have the potential to increase the visible distance ahead of the vehicle (when it is viewed through the in-vehicle displays) without blinding oncoming drivers.

This portion of the ENV project compared conventional tungsten-halogen (halogen), high intensity discharge (HID), and NIR and FIR night vision enhancement systems in a set of object detection scenarios. The VESs tested included the following configurations: two NIR systems (NIR 1 and NIR 2), two HID systems (HID 1 and HID 2), one FIR system, and one halogen system (HLB). Each of the systems was tested on a sport utility vehicle (SUV). The HLB headlamps tested are currently available on the market; therefore, they served as a baseline condition, allowing a comparison between readily available technologies and more advanced VES alternatives.

Discussion about the performance of HIDs has often involved discussion of the breadth of the beam pattern and performance in roadway curves. The two HID systems used in this study were selected to provide two different HID beam patterns: one with a shorter, wider pattern (HID 2) and one with a longer, narrower pattern (HID 1). The HID systems also provide a point of comparison between currently fielded technologies and the more advanced VESs. For more information on the headlamps, see the detailed technical specifications of each headlamp in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

Interest in this research also originated, in part, from the increasing number of IR systems on production vehicles. As more and more of these vehicle-based IR systems are introduced into the larger transportation system, it has become important to develop an understanding of the interactions between these systems, their users, other drivers, and the established components of the roadway system, including signage, roadway geometry, and roadway markers. With an infrastructure that has been carefully designed for specifics such as sight distances, visibility levels, and lighting methods, it is important to actively monitor and plan for the introduction of these new vision enhancement technologies. The experimental goal of this research was to investigate the performance of new VESs and develop an understanding of their interaction with the larger transportation system.

The IR systems tested in this phase of the research were provided by automotive manufacturers as well as suppliers of IR vision systems. The manufacturers and suppliers provided the contractor with the prototype systems installed on vehicles and the descriptive information about the specific implementation tested, such as IR emitter types and field of view. To protect proprietary characteristics of the systems, additional details beyond those the manufacturers and suppliers provided were not recorded. The headlamp systems tested were production headlamps purchased by the contractor.

CHAPTER 2—METHODS

PARTICIPANTS

Eighteen individuals participated in this study. The participants were divided into three different age categories: six participants were between the ages of 18 and 25 years (younger category of drivers), six were between the ages of 40 and 50 years (middle category of drivers), and six were over the age of 65 years (older category of drivers). There were three males and three females in each age category. Participation was allowed after a screening questionnaire was completed and only if the selection conditions were fulfilled (appendix A). Participants were required to sign an informed consent form (appendix B), present a valid driver's license, pass the visual acuity test (appendix C) with a score of 20/40 or better (as required by Virginia State law), and have no health conditions that made operating the research vehicles a risk.

Each participant was instructed about his or her right to freely withdraw from the research program at any time without penalty. Each participant was told that no one would try to make him or her participate if he or she chose at any time not to continue and that he or she would be paid for the amount of time of actual participation. All data gathered as part of this experiment were treated with complete anonymity. Participants received $20 per hour for their participation.

Each participant drove with six different VESs during two or three driving sessions (nights). Three of the participants drove in two separate experimental sessions that lasted approximately 4.5 h. Fifteen of the participants drove in three separate experimental sessions that lasted approximately 3 h. The first session included training, during which the study was described and the forms and questionnaires were completed (appendixes B, C, and D). Participants also completed a practice lap for each of the six VESs to familiarize themselves with the Smart Road and the experimental detection and recognition methods.

EXPERIMENTAL DESIGN

The study was a 6 by 3 by 17 mixed-factors design. There were three independent variables: (1) VES configuration, (2) age, and (3) type of object (including location). The between-subjects factor of the experiment was age, which had three levels (18 to 25 years, 40 to 50, and 65 and older). VES and object were within-subjects factors. There were six types of VESs tested: three were headlamp types, and three were IR-based systems with high head down (HHD) displays. There were 17 objects, including 12 pedestrians in various location scenarios, three retroreflective objects, and two obstacles. The VESs, age, and objects are described in more detail in the Independent Variables section.

For counterbalancing, six possible orders of object presentation were developed. These orders included all the test objects but differed in when the objects were presented, the required turnarounds, and confederate vehicle interactions. The confederate vehicle was an additional vehicle driven by an experimenter who executed planned scenarios near the participant, making the participant drive as if in the presence of other traffic. The participant was not informed that the confederate vehicle was involved in the study. This facilitated more real-world driving during object detection and recognition. Specific attention was paid to ensuring that the orders did not cause participants to expect or predict an upcoming object. The six orders were then treated as a block variable and held constant with order 1 always being presented first, order 2 presented second, and so on until all six orders were presented. The six VESs were counterbalanced using a balanced Latin square for each age group; therefore, each participant from an age group was assigned a unique VES presentation order, but all participants received the object presentation order sequentially from order 1 through order 6. Counterbalancing in this fashion reduced any systematic order biases that could have occurred for the VESs and age groups. An example is shown in table 1, where the first column, Order, indicates both the order in which the participant experienced the VES configurations and the object order that was presented for a given configuration; the objects tested are described in the Independent Variables section. The second column, VES, is the configuration that was tested. The third column, Vehicle, describes the vehicle that served as the platform for the VES.

Table 1. Example of the VES order for three participants.

	Order	VES	Vehicle
Participant 7, Night 1	1	NIR 2	SUV 1
	2	FIR	SUV 1
Participant 7, Night 2	3	HID 2	SUV 3
	4	NIR 1	SUV 2
Participant 7, Night 3	5	HID 1	SUV 3
	6	HLB	SUV 3
Participant 8, Night 1	1	FIR	SUV 1
	2	NIR 1	SUV 2
Participant 8, Night 2	3	NIR 2	SUV 1
	4	HLB	SUV 3
Participant 8, Night 3	5	HID 2	SUV 3
	6	HID 1	SUV 3
Participant 9, Night 1	1	NIR 1	SUV 2
	2	HLB	SUV 3
Participant 9, Night 2	3	FIR	SUV 1
	4	HID 1	SUV 3
Participant 9, Night 3	5	NIR 2	SUV 1
	6	HID 2	SUV 3

INDEPENDENT VARIABLES

VES configuration, age, and type of object were the independent variables used in the experiment. The age variable 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 (ENV Volume II) that suggest changes in vision during certain ages. (See references 1, 2, 3, 4, and 5.) Each age group was made up of three males and three females. Gender was matched across age groups.

Vision Enhancement Systems

Three IR VESs, two HID VESs, and one halogen VES were included in this study. The study used three types of SUVs because some VES systems were provided only on specific SUVs; the type of SUV never varied for a specific VES. Throughout this document, where an abbreviation is used to describe a VES (e.g., FIR), it refers to the system as well as the SUV type on which the system was tested. Note that there was an SUV 1 with an FIR system and SUV 1 with an NIR 2 system. These SUVs were not the same vehicle, but they were the same make, model, and year. The VES configurations (i.e., systems and vehicle types) for this study were defined as follows:

- FIR: prototype far infrared vision system on SUV 1.
- NIR 1: prototype near infrared vision system 1 on SUV 2.
- NIR 2: prototype near infrared vision system 2 on SUV 1.
- HLB: halogen (i.e., tungsten-halogen) low beam on SUV 3.
- HID 1: high intensity discharge 1 on SUV 3.
- HID 2: high intensity discharge 2 on SUV 3.

Participant eye positions for each VES can be found in appendix H. The following paragraphs further describe both the VESs and the vehicle platforms on which they were tested.

FIR—Prototype Far Infrared Vision System on SUV 1

A prototype FIR system was tested on SUV 1. The system display used a directly reflected virtual image with an 11.7° horizontal by 4° vertical field of view (FOV). The reflective mirror was located in an HHD position on centerline with the driver, directly on the instrument panel surface above the instrument cluster. The reported magnification at the eye was approximately 1:1. The headlamps used were the production halogen headlamps for this vehicle.

NIR 1—Prototype Near Infrared Vision System 1 on SUV 2

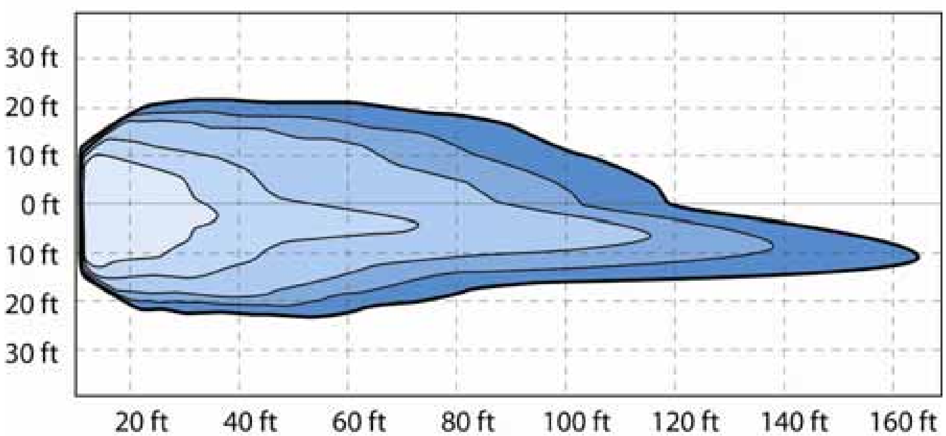
A prototype NIR system that used a laser IR emitter was tested on a second SUV (SUV 2). The system used a curved mirror display with an 18° horizontal by ~6° vertical FOV. The mirror was located in an HHD position on centerline with the driver, directly on the instrument panel surface above the instrument cluster. The reported minification was ~2:3 at the eye. The headlamps used were the production halogen headlamps for this vehicle.

NIR 2—Prototype Near Infrared Vision System 2 on SUV 1

A prototype NIR system that used halogen IR emitters was tested on SUV 1 (i.e., the same type of vehicle as the vehicle used for the FIR vehicle). The system display used a direct reflect virtual image with an 11.7° horizontal by 4° vertical FOV. The reflective mirror was located in an HHD position on centerline with the driver, directly on the instrument panel surface above the instrument cluster. The reported magnification at the eye was approximately 1:1. The headlamps used were the production halogen headlamps for this vehicle.

HID 1—High Intensity Discharge 1 on SUV 3

These HID headlamps were tested on a third type of SUV (SUV 3) using a light rack as described in the Apparatus and Materials section of this report. The headlamp beam profile (figure 1 and figure 2) was narrower than the beam profile of the other HID headlamp (i.e., HID 2) tested in the study.



1 ft = 0.305 m

Figure 1. Diagram. Bird's-eye view of beam pattern of HID 1.

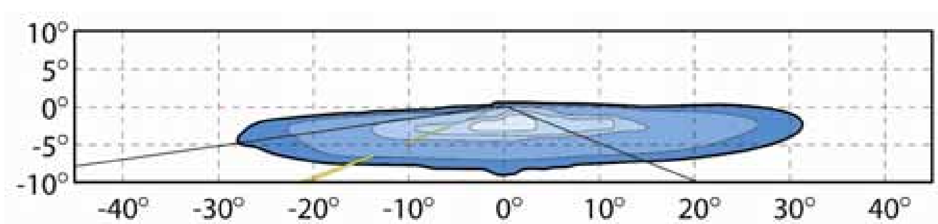
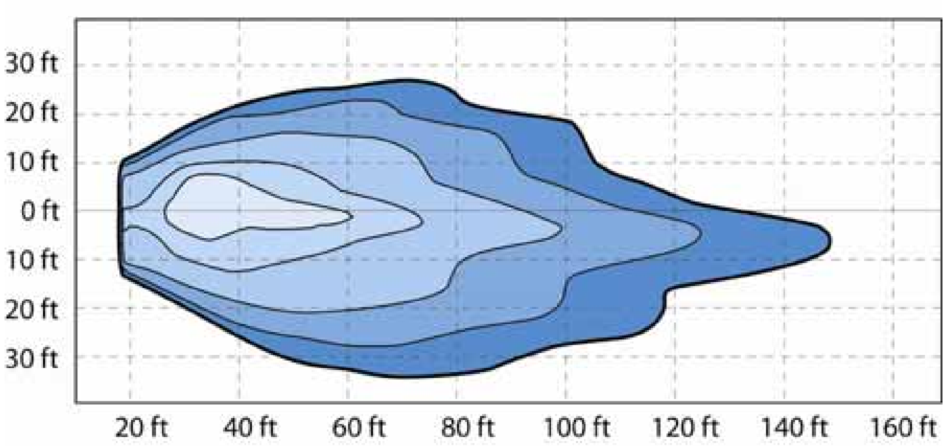


Figure 2. Diagram. Forward beam pattern of HID 1.

HID 2—High Intensity Discharge 2 on SUV 3

A second type of HID headlamp was also tested on SUV 3 using a light rack as described in the Apparatus and Materials section of this report. These headlamps have a wider lighting footprint than the previously discussed HID 1. Figure 3 and figure 4 illustrate the beam pattern of HID 2.



1 ft = 0.305 m

Figure 3. Diagram. Bird's-eye view of beam pattern of HID 2.

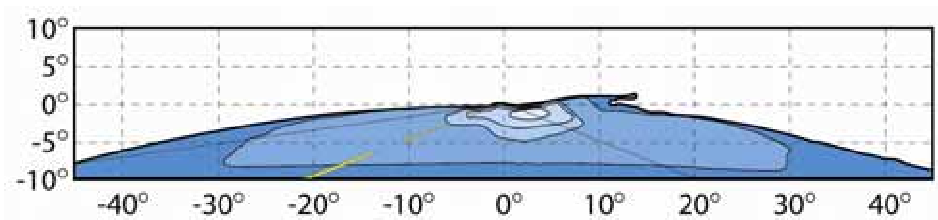


Figure 4. Diagram. Forward beam pattern of HID 2.

HLB—Halogen Low Beam on SUV 3

Halogen (i.e., tungsten-halogen) headlamps were tested on SUV 3 using a headlamp rack as described in the Apparatus and Materials section of this report. These headlamps were tested to provide a benchmark of headlamp performance and to provide a comparison point to previous studies.

VES Summary

Table 2 shows 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 size. Specification of displays, display FOVs, and image sizes were provided by the system engineers responsible for the systems. ENV Volume XVII provides a more indepth look at the technical specifications of each VES.

Table 2. VES configuration details.

Tested Technology	VES Abbreviation	Test Vehicle	Headlamps	Display	Display FOV	Image Size
HLB headlamps	HLB	SUV 3	tested HLB	None	n/a	n/a
HID headlamps	HID 1	SUV 3	tested HID 1	None	n/a	n/a
HID headlamps	HID 2	SUV 3	tested HID 2	None	n/a	n/a
Far IR	FIR	SUV 1	SUV 1 manufacturer HLB	direct reflect virtual image	11.7^{o} by 4^{o}	~1:1
Near IR with laser emitter	NIR 1	SUV 2	SUV 2 manufacturer HLB	curved mirror virtual image	18^{o} by ~6^{o}	minification ~2:3
Near IR with halogen emitters	NIR 2	SUV 1	SUV 1 manufacturer HLB	direct reflect virtual image	11.7^{o} by 4^{o}	~1:1

HLB headlamps are the most commonly available production VES; therefore, throughout this document, it is important to compare the results of other VESs to the results obtained for the HLB, thus making the HLB a baseline or benchmark measure.

Objects

Using the six VESs, detection and recognition distances of 17 different objects were measured. The objects selected for this study were static pedestrians (whose scenarios included appearing on the right side, the left side, or in the center of the road, appearing in turns, appearing off axis, and appearing in bloom scenarios), retroreflective signs, pavement markers and pavement markings, and static objects (see table 3). They can be grouped into three sets: (1) pedestrians, (2) retroreflective objects, and (3) obstacles. Each of the objects is discussed in the following paragraphs. Additional details about the objects are provided in table 4, along with photographs of the objects (figure 5 through figure 21).

Table 3. The 17 objects used in study.

	Object	Abbreviation
Pedestrian Group	Pedestrian, Black Clothing, Left	BlackLF
	Pedestrian, Black Clothing, Right	BlackRT
	Pedestrian, Denim Clothing, Left	BlueLF
	Pedestrian, Denim Clothing, Right	BlueRT
	Pedestrian in Left Turn, Left Side (Denim Clothing)	LFtrnLF
	Pedestrian in Left Turn, Right Side (Denim Clothing)	LFtrnRT
	Pedestrian in Right Turn, Left Side (Denim Clothing)	RTtrnLF
	Pedestrian in Right Turn, Right Side (Denim Clothing)	RTtrnRT
	Far Off Axis Left (Denim Clothing)	FOALT
	Far Off Axis Right (Denim Clothing)	FOART
	Bloom Object, Left (Denim Clothing)	BloomLF
	Bloom Object, Right (Denim Clothing)	BloomRT
Retroreflective Group	Raised Retroreflective Pavement Marking	RRPM
	Sign	Sign
	Turn Arrow	Arrow
Obstacle Group	Dog	Dog
	Tire Tread	Tire Tread

The main reason for including the pedestrians was because of the high crash fatality rates for these nonmotorists.[6,7] Although pedestrian mockups have been used in previous research of this type, actual pedestrians were used here to permit performance measurement of the FIR VES, which functions based on temperature characteristics of the object of interest.[8] Pedestrians were presented in several different positions in relation to the direction of the participant's approach.

Pedestrians were presented to the drivers at two different contrast levels: (1) with black clothing and (2) with blue denim clothing. Pedestrians in black clothing and denim clothing were presented on the straight segment of the road to permit this comparison. All other pedestrian scenarios used pedestrians dressed in denim. All the pedestrians were static and faced oncoming traffic. Their possible positions included the left and right shoulders of the road (relative to the driver), straight sections of the road, left and right curves of 1,250-m radius, and positions 9.5 m (31 ft) to the left and right (i.e., approximately 2.5 lane widths) of the centerline of the driver's lane.

The selected obstacles represented low contrast objects common in public roadways. A small stuffed dog was used to measure the VESs' ability to provide earlier detection of animals present in the roadway. This improved capability potentially would facilitate an appropriate response from the driver to this situation. Resistive electrical elements were used inside the body of the dog to simulate the warm-bodied characteristics of animals. The tire tread was selected because of its potential for very low detection distances, which often lead to last minute object-avoidance maneuvers. Because it was used in previous research, the tire tread also provided a point of comparison to preceding research (ENV Volumes III and IV).

Retroreflective devices were selected to duplicate those present on public roadways. Road signs, RRPMs, and a retroreflective pavement marking turn arrow were included in this study to provide a measure of the impact of the VESs on driver detection and recognition of these critical components of the nighttime driving scene. Performances of NIR in the presence of retroreflective materials, as well as the comparison of NIR to FIR systems with respect to retroreflective materials, were of particular interest to IR system designers, highway designers, and end users. An additional issue of interest was the interaction between emitted NIR, conventional retroreflective materials, NIR image processing, and the user.

Two sign configurations were used during the study. In one configuration, a stop sign was presented next to a speed limit sign. In another configuration, a yield sign was presented next to a speed limit sign. By using these different sign configurations, it was possible to measure both when the signs could first be detected and when the different types and significance of the signs were recognized.

The final object configuration of interest was the bloom scenario. This scenario was included to evaluate the possible improvements of new technologies over traditional technologies in the situation where a pedestrian has exited a vehicle with headlamps on (e.g., to change a tire). When viewed using traditional headlamp technology, the bloom scenario presents a pedestrian who is potentially veiled in the glare of the parked vehicle's headlamps while the participant vehicle approaches. FIR and NIR vision systems could reveal pedestrians to the driver in these situations. Because of its reception of light in the visible spectrum and the design variables involved, performance of NIR systems in this scenario is particularly informative.

Table 4, accompanied by figure 5 through figure 21, describes the objects used for the study as well as their locations; photographs in figures 5 through 21 were taken during daylight hours to demonstrate more clearly the appearance and position of the objects. Detailed descriptions of the objects appear in ENV Volume XVI.

Table 4. Object descriptions.

Object Description	Objects
Pedestrian wearing black 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. Pedestrians stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 5. Photo. Object: pedestrian, black clothing, left (BlackLF).**
Pedestrian wearing black 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-hand lane boundary on a straight segment of roadway. Pedestrians stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 6. Photo. Object: pedestrian, black clothing, right (BlackRT).**
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 7. Photo. Object: pedestrian, denim clothing, left (BlueLF).**

Table 4. Object descriptions. (continued)

Object Description	Objects
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-hand lane boundary on a straight segment of roadway. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 8. Photo. Object: pedestrian, denim clothing, right (BlueRT).**
In a 1,250-m 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 9. Photo. Object: pedestrian in left turn, left side (LFtrnLF).**
In a 1,250-m 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-hand lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 10. Photo. Object: pedestrian in left turn, right side (LFtrnRT).**

Table 4. Object descriptions. (continued)

Object Description	Objects
In a 1,250-m 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 11. Photo. Object: pedestrian in right turn, left side (RTtrnLF).**
In a 1,250-m 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-hand lane boundary. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 12. Photo. Object: pedestrian in right turn, right side (RTtrnRT).**
Pedestrian wearing blue denim scrubs stood on the left side of the road as viewed from the participant vehicle. Pedestrian stood 9.5 m (31 ft) to the left of the center of the participant's lane of travel. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 13. Photo. Object: far off axis, left (FOALT).**

Table 4. Object descriptions. (continued)

Object Description	Objects
Pedestrian wearing blue denim scrubs stood on the right side of the road as viewed from the participant vehicle. Pedestrian stood 9.5 m (31 ft) to the right of the center of the participant's lane of travel. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 14. Photo. Object: far off axis, right (FOART).**
With a vehicle parked with its headlamps on in the oncoming lane, 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 and in line with the rear wheels of the parked vehicle. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 15. Photo. Object: bloom object, left (BloomLF).**
With a vehicle parked with its headlamps on in the oncoming lane, 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-hand lane boundary and in line with the rear wheels of the parked vehicle. Pedestrian stood with arms down to the side and faced the oncoming test vehicle.	 **Figure 16. Photo. Object: bloom object, right (BloomRT).**

Table 4. Object descriptions. (continued)

Object Description	Objects
The dog mockup was placed on the centerline that divides the two lanes; the dog's head faced the participant's lane of travel. The dog had internal heating elements to warm the body. Surface temperature of the dog was 26.6–32.2 °C (80–90 °F).	 **Figure 17. Photo. Object: dog.**
A turn arrow made of retroreflective pavement tape was placed in the center of the participant's lane of travel. The arrow was pointed either right or left.	 **Figure 18. Photo. Object: pavement marking turn arrow.**
Two RRPMs were placed on the road, one before and one after a skip mark. The RRPMs were placed with the white reflective side facing the oncoming test vehicle.	 **Figure 19. Photo. Object: RRPMs.**

Table 4. Object descriptions. (continued)

Object Description	Objects
Signs were placed to the right of the participant’s right-hand lane boundary. Signs were placed with the lower edge approximately 2.1 m (7 ft) above the pavement, with the planes of the signs perpendicular to the lane of travel. A 60.9-cm by 60.9-cm (24-inch by 24-inch) stop sign and a 60.9-cm by 91.4-cm (24-inch by 36-inch) “SPEED LIMIT 55” sign were presented beside each other. In another scenario, a 60.9-cm by 60.9-cm (24-inch by 24-inch) yield sign and a 60.9-cm by 91.4-cm (24-inch by 36-inch) “SPEED LIMIT 30” sign were presented beside each other. The number height on the speed limit signs was 25.7 cm (10 inches). Signs were mounted on wooden supports, which were painted matte black. (Photo at right shows yield and speed limit sign.)	 **Figure 20. Photo. Object: sign.**
A tire tread was centered on the right boundary line of the participant’s lane of travel. The tire was kept outside during the day to maintain it at realistic outdoor temperatures.	 **Figure 21. Photo. Object: tire tread.**

OBJECTIVE DEPENDENT VARIABLES

Two objective performance measures were collected for the VESs: (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 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: "Recognition is when you not only know something is there, but you also know what it is." The method for determining detection and recognition distance measurements is described in the Apparatus and Materials section.

SUBJECTIVE RATINGS

Participants were asked to indicate their agreement or disagreement with a series of eight statements for each VES, using a seven-point Likert-type scale. The two anchor points of the scale were 1 (indicating "Strongly Agree") and 7 (indicating "Strongly Disagree"). The scale shown below (figure 22) was located on the instrument panel for the participant to refer to while responding to the statements.

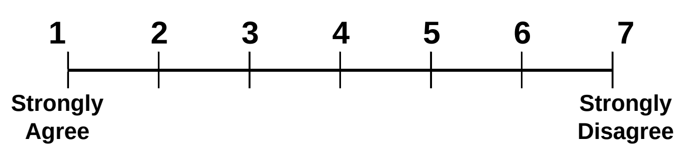


Figure 22. Diagram. Subjective ratings scale.

The statements were intended to address each participant's perception of improved vision, safety, and comfort after experiencing a particular VES. Participants were asked to compare each VES to their regular headlights (i.e., the headlights on their own vehicles). The assumption was made that the participants' own vehicles represented what they knew best and, therefore, were most comfortable using. The statements used for the questionnaire included the following (note that while the word "headlamp" is used throughout the ENV series, the subjective questionnaires posed to the participants used the synonymous word "headlight," as reflected below):

1. This VES allowed me to DETECT objects sooner than my regular headlights.
2. This VES allowed me to RECOGNIZE objects sooner than my regular headlights.

3. This VES helped me to stay on the road (not go over the lines) better than my regular headlights.
4. This VES allowed me to see which direction the road was heading (i.e., left, right, or straight) beyond my regular headlights.
5. This VES did not cause me any more visual discomfort than my regular headlights.
6. This VES allowed me to read signs beside the road sooner than my regular headlights.
7. This VES makes me feel safer when driving on the roadways at night than my regular headlights.
8. This is a better VES than my regular headlights.
9. If you could provide any advice to the manufacturer of this vision system, what would it be?
10. Anything else?

SAFETY PROCEDURES

Safety procedures were implemented as part of the instrumented vehicle system. These procedures were employed to minimize possible risks to participants during the experiment. The safety measures required that: (1) all data collection equipment had to be mounted such that, to the greatest extent possible, it did not pose a hazard to the driver in any foreseeable instance; (2) participants had to wear the seatbelt restraint system anytime the car was on the road; (3) none of the data collection equipment could interfere with any part of the driver's normal FOV; (4) a trained in-vehicle experimenter had to be in the vehicle at all times; and (5) an emergency protocol had to be established prior to testing. The participant was required to maintain 40 km/h (25 mi/h) during the drive. Two-way communications were maintained between the onroad crew and the in-vehicle experimenter to ensure that the onroad objects were ready and that the vehicle followed the expected path. Onroad pedestrians also visually monitored the approach of the participant vehicle and moved away from the lane boundary approximately 1.5 s before the vehicle reached them.

APPARATUS AND MATERIALS

Onroad driving was conducted using three types of SUVs. The 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. In addition, it prompted the experimenter with the appropriate object order for each participant and VES trial. The software was also the basis for detection and recognition distance collection. Figure 23 shows the screen used by the experimenters to provide turnaround guidance, to monitor object presentation orders, and to collect data.

Figure 23. Photo. Data collection display screen.

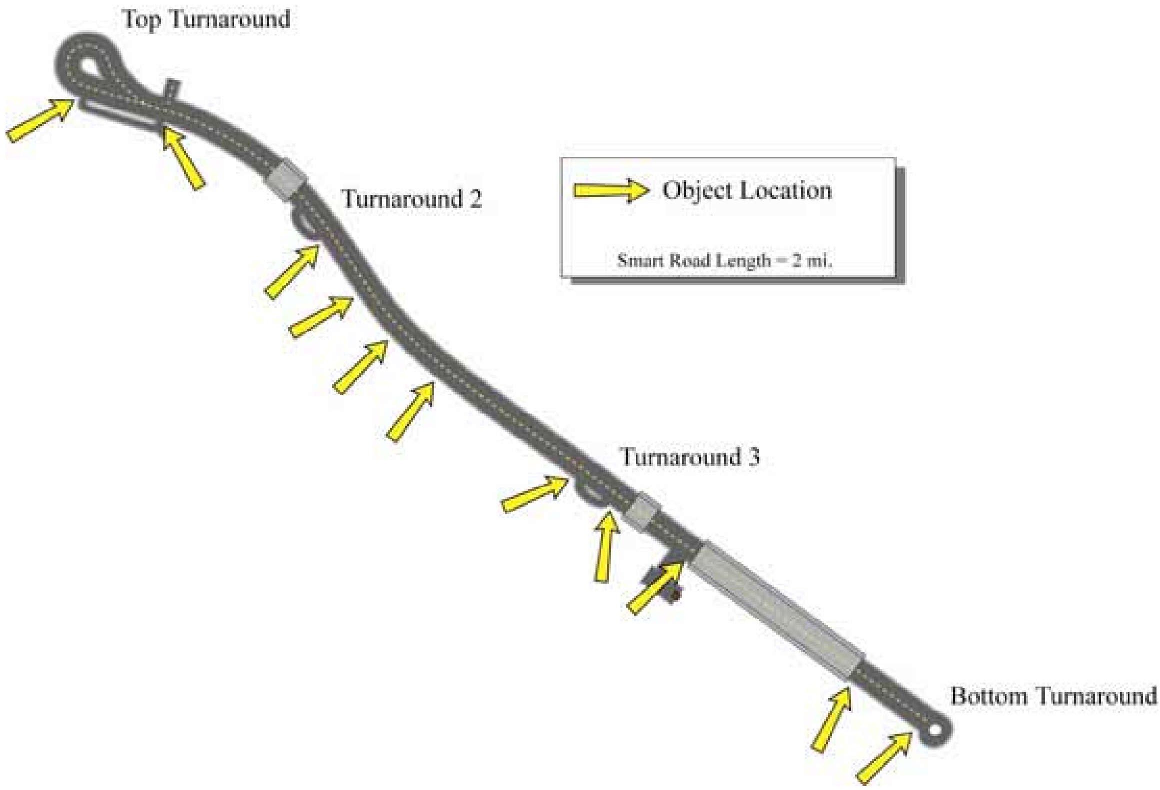
Measurements of object detection and recognition distances were collected using two methods. When a participant detected an object, he or she would say the word “something.” Then, when the participant could recognize the object, he or she would provide a verbal recognition. At each of these utterances, the in-vehicle experimenter would press a button to flag the data. The in-vehicle experimenter also pressed a button when the front 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. This transmission was also synchronized with the data stream. A video and audio recording of the participant verbally stating his or her detection and recognition, combined with the onroad crew’s transmission of the vehicle passing the object, provided a second method for identifying the distance measurements in the data stream. The participant was not able to hear the radio transmissions from onroad staff.

The HID 1 headlamps, the HID 2 headlamps, and the HLB headlamps were mounted on a testing rack on the front of SUV 3 during testing as shown in figure 24 below.

Figure 24. Photo. Headlamp testing rack.

Smart Road

The Virginia Smart Road was used for the onroad study. This roadway was designed according to United States Department of Transportation specifications for a two-lane undivided highway with a 104.7-km/h (65-mi/h) speed limit. Thirty-three object locations were used to present objects, with some locations being used for left, right, or center presentation of objects. Some locations were only acceptable for certain objects or for certain approach directions due to road geometry and the need for consistent ambient lighting (note that no overhead lighting was used on the road). Figure 25 presents a schematic of the Smart Road with examples of object locations.



1 mi = 1.6 km

Figure 25. Diagram. Smart Road layout with object locations.

The participants started each drive from an intersection entering the Smart Road. One in-vehicle experimenter was assigned to each participant; this experimenter was responsible for driving the participant to the first vehicle, showing the participant the location of the different controls, and verifying that the right VES configuration was being tested. Five onroad experimenters were present to position objects, stand as pedestrians, drive confederate vehicles, and shuttle other onroad experimenters to different object locations during the session. A sixth onroad experimenter was responsible for presenting certain objects, preparing the next vehicle for the participant, and making measurements of the participant's eye position and dimmer settings. Four paved turnaround areas on the road were used (top turnaround, turnaround 2, turnaround 3, and bottom turnaround) to vary the sequence in which a participant traversed the different segments of the road during the drive. Of the 33 possible locations, a subset of 17 was used for each vehicle. Object presentation is discussed in the General Onroad Procedure section of the Experimental Procedure.

Headlamp and IR System Aiming

The headlamps used for the HLB, HID 1, and HID 2 configurations were mounted on a testing rack that was external to the experimental vehicle. This mounting allowed the three 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 and was developed at the beginning of the ENV project.

In this investigation, the HLB headlamps were aimed as they were in the Phase II studies. During the photometric characterization of the headlamps, it was discovered that the position of the maximum intensity location of the HLB was aimed higher and more towards 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 HID 1 and HID 2 headlamps were visually optically aligned (VOA) systems. For these, the aiming points were selected based on the SAE requirements according to the height of the headlamps as mounted on the testing rack. For more information on the aiming of these headlamps refer to ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*. It should be noted that the headlamp height and approximate eye height were kept constant across the HLB, HID 1, and HID 2 VESs. Headlamp mounting height and driver seating position would be different in production for HID 1 and HID 2 since these VESs would be on a sedan, not an SUV. However, the testing method held constant (within intra-participant variability) the headlamp-to-eye angle and eye height for all three headlamp VESs.

Each light assembly transfer required a re-aiming process. The headlamps on the FIR vehicle, NIR 2 vehicle, and the NIR 1 vehicle were production headlamps. These headlamps were aimed prior to the study and did not require further aiming during the study. The IR systems on these vehicles were checked for aiming of cameras and IR emitters 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 because adhesive tape used on the provided prototype system became unfastened between experimental sessions.

EXPERIMENTAL PROCEDURE

Participant Screening

Participants were initially screened over the telephone (appendix A), and if a participant qualified for the study, a time was scheduled for testing. Participants were instructed to meet the experimenter at the testing facility in Blacksburg, VA. After arriving, an overview of the study was presented to each participant. Subsequently, each participant was asked to complete the informed consent form (appendix B) and to take an informal vision test for acuity using a Snellen chart and a contrast sensitivity test (appendix C). The vision tests were performed to ensure that all participants had at least 20/40 vision as well as to identify any type of vision disparity that might have influenced the results. After these steps were completed and if no problems were identified, the participant was taken through a set of measurements and predrive questionnaires. Participants were tested for color blindness using pseudo isochromatic plates, but they were not excluded based on the results (appendix C). The participant's standing height was also measured. The participant then completed a predrive questionnaire (appendix D) that documented frequency of night driving, any difficulties with overhead or oncoming vehicle lighting and weather, and any other concerns. The participant's own vehicle and eyewear used for night driving were also recorded. Once these steps were completed, the participant began the training portion of the session.

Training

On the first night, each participant was given an overview of the study and trained on how each of the sessions would be conducted. 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." The participant was also given the definition of 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 able to detect an object and to say what it was when able to recognize it. Daytime photographs, similar to those in table 4, were shown of each of the objects the participant would be exposed to during the drive.

The participant was then shown the questionnaire that would be administered after each vehicle was driven. The in-vehicle questionnaire included the eight 7-point Likert-type scale statements described previously, which investigated the participants' perception of the VES's performance as compared to their normal headlamps. Each statement was read aloud, and the scale was reviewed. Two open-ended questions were also reviewed. If there were no questions from the participant, the training was completed.

Vehicle Familiarization

Next, the experimenter drove the participant to the Smart Road, where the first test vehicle was waiting. For each vehicle, 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 how to adjust the brightness of the display. The participant was permitted to adjust the instrument panel and display brightness three times: once before driving, once halfway through the practice drive, and once at the end of the practice drive. The brightness settings were then kept the same for the remainder of the drive. The interested reader may refer to appendix E for a brief analysis of these brightness settings. When ready, the participant's eye position was measured in relation to landmarks on the door (appendix H). The participant was then 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 told: "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 was then asked to drive a practice lap to familiarize him or her with the vehicle, the objects, the road, and the procedure for calling out objects. This practice lap was performed at the start of the driving portion for each vehicle. The in-vehicle experimenter rode in the second-row, passenger-side seat of the vehicle. The participants were reminded of the procedure and were instructed not to drive faster than 40 km/h (25 mi/h) during the study. To help the participant learn the test objects during the practice drive, the experimenter indicated to the participant what the next practice object would be. The experimenter also pointed out objects on the road that would not be necessary to recognize (e.g., guardrails, cement blocks, reflector). At the end of the practice drive, the experimenter reviewed the questionnaire with the participant and gave a final opportunity to adjust the IR display's brightness settings. Once this practice was completed, the participant began the test drive. During the 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 turn around, checked speed, and advised the participant to maintain the 40 km/h (25 mi/h) speed limit, if necessary. Driving time in each vehicle was approximately 1 h.

General Onroad Procedure

While the participant drove on the practice drive and the test drive, an onroad crew was responsible for presenting objects at different locations along the Smart Road according to the object order assigned to the participant for the VES being driven. An onroad experimenter also transmitted the object number as the front bumper of the participant vehicle passed the object. Different turnarounds on the road were used to reverse direction, and different object locations were used on the road to produce six different object and route orders. Within this variation, object locations were frequently passed by the participant without an object being present. The participant had a different object order for each of the six vehicles driven.

Four confederate vehicle events occurred during each of the six VES drives. These events were included in the object orders to ensure consistent and balanced exposure, which was unpredictable to the participant. Table 5 provides descriptions and illustrations of the four confederate vehicle events. These events were included to encourage the participant to expect other vehicles on the road, to allow the participant to observe other vehicles with the VES, and to add credibility to the bloom scenario.

Table 5. Vehicle scenarios.

Description	Vehicle Scenario
An onroad vehicle entered the road ahead in the same direction as the participant vehicle. The onroad vehicle traveled at 40 km/h (25 mi/h) without using brakes until required to exit the road. Turn signals were used when exiting.	 **Figure 26. Photo. Slow lead vehicle.**
An onroad vehicle with its headlights on passed the test vehicle going in the opposite direction at 40 km/h (25 mi/h) on a straight section of road.	 **Figure 27. Photo. Pass participant vehicle.**
With its headlights on, the onroad vehicle drove from one side of the road to the other in front of the participant vehicle. Crossing distance was approximately 244 m (800 ft) ahead of the participant vehicle.	 **Figure 28. Photo. Crossing front vehicle.**
The onroad vehicle waited as the participant vehicle passed, at which time the onroad vehicle drove from one side of the road to the other, behind the participant vehicle, with the headlights on.	 **Figure 29. Photo. Crossing rear vehicle.**

DATA ANALYSIS

Because of the large number of objects tested, the first analysis combined the tested objects into three groups: pedestrians, retroreflective objects, and obstacles. The first group consisted of all the pedestrians, including the bloom scenarios, both black-clothed and denim-clothed pedestrians, pedestrians in turns, and far off axis pedestrians. The retroreflective object group included the turn arrow, the RRPMs, and the signs. The third object group included the dog and the tire tread. These two objects were both smaller, low contrast objects that extended into the lane of the participant vehicle. Table 6 identifies the grouping of the objects for this analysis.

Table 6. Grouping of objects and abbreviations used in this analysis.

	Object	Abbreviation
Pedestrian Group	Pedestrian, Black Clothing, Left	BlackLF
	Pedestrian, Black Clothing, Right	BlackRT
	Pedestrian, Denim Clothing, Left	BlueLF
	Pedestrian, Denim Clothing, Right	BlueRT
	Pedestrian in Left Turn, Left Side (Denim Clothing)	LFtrnLF
	Pedestrian in Left Turn, Right Side (Denim Clothing)	LFtrnRT
	Pedestrian in Right Turn, Left Side (Denim Clothing)	RTtrnLF
	Pedestrian in Right Turn, Right Side (Denim Clothing)	RTtrnRT
	Far Off Axis Left (Denim Clothing)	FOALT
	Far Off Axis Right (Denim Clothing)	FOART
	Bloom Object, Left (Denim Clothing)	BloomLF
	Bloom Object, Right (Denim Clothing)	BloomRT
Retroreflective Group	RRPM	RRPM
	Sign	Sign
	Turn Arrow	Arrow
Obstacle Group	Dog	Dog
	Tire Tread	Tire Tread

This grouping generated a statistical model for this analysis that was a 6 (VES) by 3 (Object Group) by 3 (Age) mixed factorial design. Where significance was found for an object group, which occurred for all three groups, subsequent statistical models were used to identify the specific objects and VESs creating the differences within each group. This analysis required statistical models for each object group, as listed below:

- A 6 (VES) by 12 (Pedestrian) by 3 (Age) mixed factorial design.
- A 6 (VES) by 3 (Retroreflective) by 3 (Age) mixed factorial design.
- A 6 (VES) by 2 (Obstacle) by 3 (Age) mixed factorial design.

By analyzing the data with these groupings, more detailed information about the independent variables could be determined. For example, the first analysis for the object group identified what general type of object a VES did well with. The second analysis determined if there were differences within an object group for the VESs. For example, did a VES do better with some pedestrian locations than others? In each of these models where main effects were found, Student-Newman-Keuls (SNK) tests were used to identify differences between VESs or age groups.

The Likert-type scale ratings from the post-drive questionnaires were analyzed using two-way ANOVAs to test the effects of VES and age as well as their interaction. Where main effects were found, SNK tests were also used to identify statistical differences between the VESs for each of the objects. Responses to open-ended questions were reviewed and tallied to identify emergent themes in the responses. For the Bloom Left, Blue Left, and Blue Right objects, the available sight distance may have restricted the maximum achievable measured detection distance for the FIR vehicle. Investigation of the measured detection distance values indicated that the effect of this possible restriction on the system's mean values would be minimal, so values were maintained as measured. In fact, the FIR statistically outperformed the other VESs for these objects even with the possible limitation.

CHAPTER 3—RESULTS

Results included in this report are based on statistically significant effects at an $\alpha = 0.05$ level except where otherwise stated. In main effect graphs, means with the same letter are not significantly different based on the SNK post hoc test. Bars above and below the means indicate standard error.

OBJECTIVE MEASURES

Table 7 shows the results for the 6 (VES) by 3 (Object) by 3 (Age) mixed factorial design ANOVA (i.e., object group ANOVA), which was conducted on the objective measures of detection distance for the three groups of objects (i.e., obstacles, pedestrians, and retroreflective). Significant age, VES, and object main effects were found along with a significant VES by Object Group interaction.

Table 8 shows results for the object group ANOVA on recognition. Table 9 shows significant VES and object group main effects along with a significant VES by Object interaction.

Table 7. Object group ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	5675797.6	2837898.8	4.64	0.027	*
Subject/Age	15	9175174.3	611678.3			
Within						
VES	5	12651827.2	2530365.4	23.76	<0.0001	*
VES by Age	10	1028099.1	102809.9	0.97	0.4804	
VES by Subject/Age	75	7986752.0	106490.0			
Object Group	2	531867870.5	265933935.2	1038.61	<0.0001	*
Object Group by Age	4	2677855.3	669463.8	2.61	0.0549	
Object Group by Subject/Age	30	7681454.0	256048.5			
VES by Object Group	10	50053432.0	5005343.2	40.51	<0.0001	*
VES by Object Group by Age	20	3180129.6	159006.5	1.29	0.1960	
VES by Object Group by Subject/Age	150	18534017.1	123560.1			
TOTAL	323	650512408.7				

* $p < 0.05$ (significant)

Table 8. Object group ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	4516545.624	2258272.812	2.08	0.1591	
Subject/Age	15	16264060.3	1084270.7			
Within						
VES	5	7017614.386	1403522.877	10.8	<0.0001	*
VES by Age	10	603581.26	60358.126	0.46	0.9077	
VES by Subject/Age	75	9746314	129950.9			
Object Group	2	331270458.6	165635229.3	277.43	<0.0001	*
Object Group by Age	4	3563344.7	890836.2	1.49	0.2295	
Object Group by Subject/Age	30	17911080.7	597036			
VES by Object Group	10	24746359.56	2474635.96	14.75	<0.0001	*
VES by Object Group by Age	20	2075484.13	103774.21	0.62	0.8943	
VES by Object Group by Subject/Age	150	25159462.5	167729.8			
TOTAL	323	442874305.8				

* $p < 0.05$ (significant)

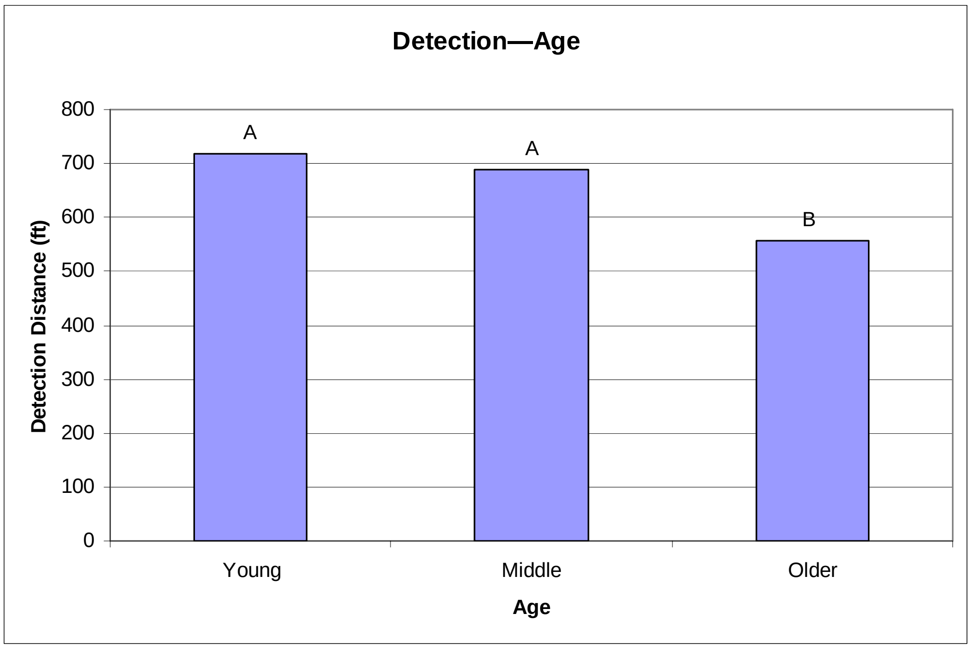
Table 9. Summary of significant main effects and interactions for object group analysis.

Source	Significant Detection	Significant Recognition
Between		
Age	x	
Subject/Age		
Within		
VES	x	x
VES by Age		
VES by Subject/Age		
Object Group	x	x
Object Group by Age		
Object Group by Subject/Age		
VES by Object Group	x	x
VES by Object Group by Age		
VES by Object Group by Subject/Age		

x = $p < 0.05$ (significant)

Age

The main effect of age was significant ($p < 0.05$) for object detection. For all the VESs and all the object groups, the younger and middle-aged groups detected objects at greater distances than did the older group. Figure 30 shows the object detection means for the three different age groups.



1 ft = 0.305 m

Figure 30. Bar graph. Object detection means for the three age groups.

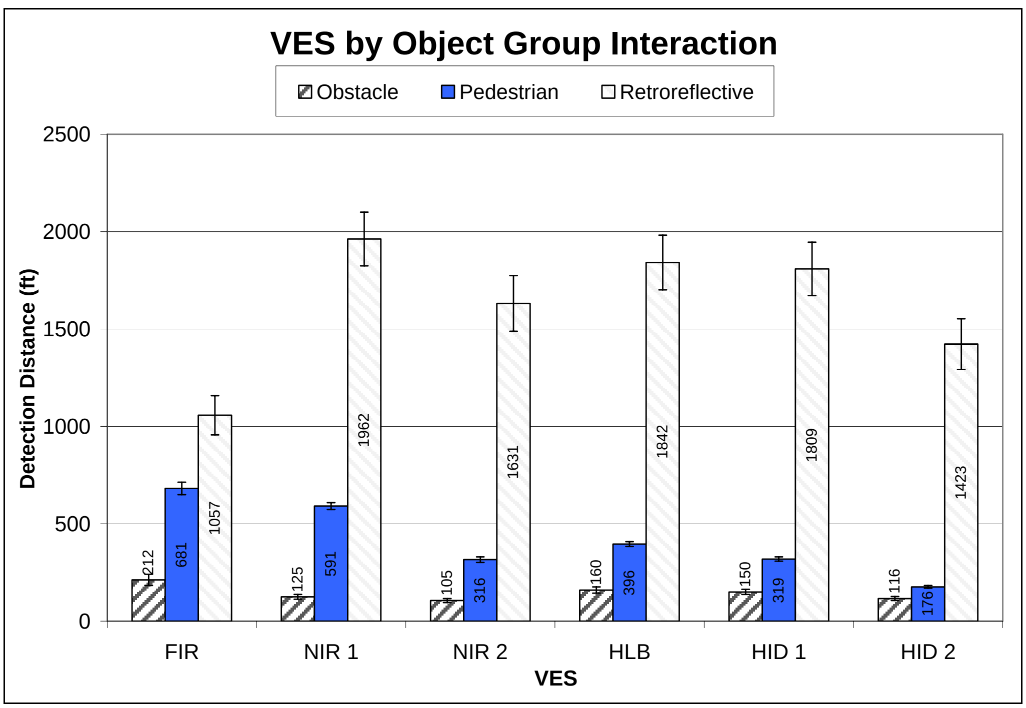
The Age by Object Group interaction *p* value of 0.0549 for detection distance is not significant at $p < 0.05$, but it indicates that further consideration of the effect of age is warranted. For this reason, age will continue to be included in subsequent analysis and discussion.

Object Group and VES Main Effects

The main effects of object group and VES were statistically significant ($p < 0.05$) in this model for object detection and recognition measurements. An object group main effect is expected because of the dramatic detection and recognition differences between a retroreflective object, for example, and a small, low-contrast obstacle such as a tire tread. The main effect of VES is similarly limited for interpretation at this object group level because the effect is influenced by the number of different objects selected for investigation. This summary effect could generate an advantage or disadvantage for a given system based on the type of experimental objects tested. Further description of this can be found in the beginning of the Obstacle Object Group Analysis section later in this report.

VES by Object Group Interaction

The VES by Object Group interaction was found to be significant ($p < 0.05$) for both the distance at which participants detected objects with a VES and the distance at which participants recognized an object with a VES. This interaction indicates that some VESs performed better with one object group than with another object group (i.e., type of object). For example, detection of pedestrians as a group and obstacles (i.e., tire and dog) using the FIR vehicle occurred earlier (i.e., at a greater distance) than detection of pedestrians or obstacles with any of the other VESs; however, the mean detection distance for retroreflective objects with the FIR vehicle was later (i.e., shorter distance) than for any of the other VESs. Figure 31 indicates the mean detection distance for each of the VESs for each of the three object groups. A standard error bar is included at the top of each mean bar.

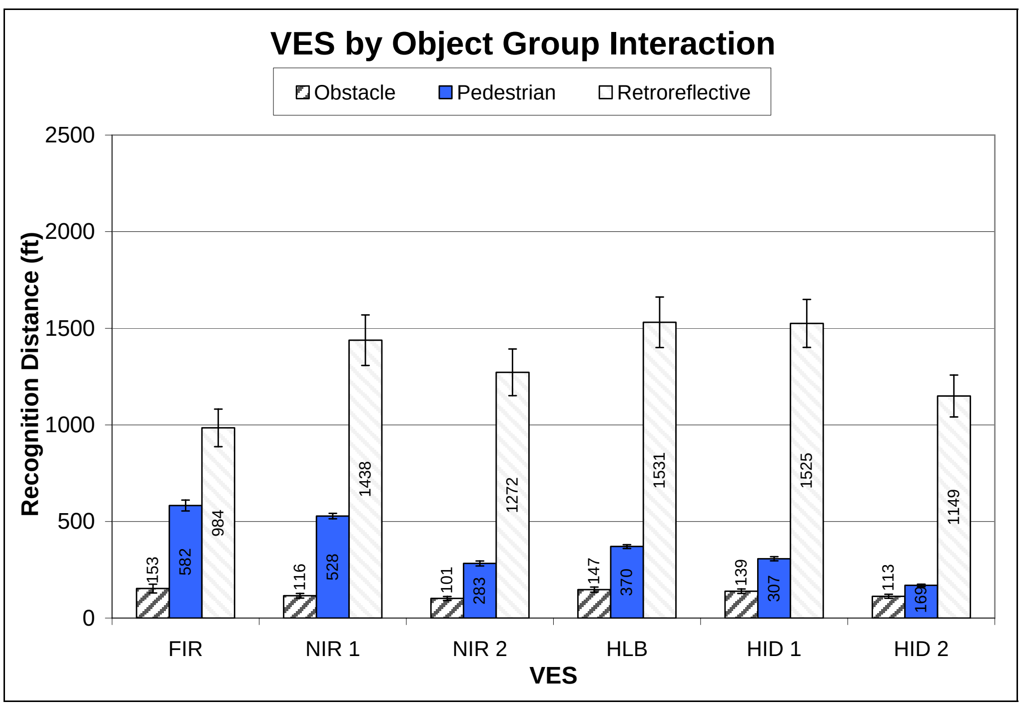


1 ft = 0.305 m

Figure 31. Bar graph. Mean detection values for each VES for each of the three object groups.

The NIR 1 configuration performed well detecting retroreflective objects and people; however, for detecting obstacles (i.e., dog and tire tread), it was surpassed by the better headlamp-based systems (i.e., HLB and HID 1). The HID 1 vehicle provided similar detection distances to the benchmark HLB vehicle for obstacles and retroreflective objects, but it had lower detection distances than the HLB vehicle for the pedestrian group overall. The HID 2 vehicle had the lowest mean detection distance of the VESs tested for pedestrians. For detecting obstacles, the HID 2 vehicle was surpassed by the other VESs, except for the NIR 2 and NIR 1 vehicles. For retroreflective objects, the HID 2 vehicle was surpassed by NIR 1, HLB, and HID 1 vehicles; however, the HID 2 vehicle had better mean detection distances for retroreflective objects than did the FIR vehicle.

Similar results were present when considering the mean recognition distances of the different VESs for the object types. Figure 32 indicates the mean recognition distances for each VES and object group.



1 ft = 0.305 m

Figure 32. Bar graph. Mean recognition distances for each VES for each of the three object groups.

The mean recognition distance for retroreflective objects with the FIR vehicle was shorter than that of all the other VESs except HID2; however, recognition of pedestrians with the FIR vehicle was the best of the VESs. When detecting obstacles, FIR had the longest mean detection distance of the VESs. In recognizing obstacles, that is, identifying the obstacle ahead, the FIR vehicle had results similar to the HLB and HID 1 vehicles. This same effect occurred with the NIR 1 vehicle in detecting and recognizing retroreflective objects. In detecting retroreflective objects, the NIR 1 had the longest mean distance; however, in recognizing the object as an RRPM, sign, or turn arrow, NIR 1 was similar to HLB and HID 1.

Obstacle Object Group Analysis

For the obstacle object group, which included the tire tread and dog, a 6 (VES) by 2 (Object) by 3 (Age) mixed factorial design was conducted. The results of this analysis are shown in table 10; they indicate significant main effects of age, VES, and object. A significant interaction between VES and object was also found.

Table 10. Obstacle group ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	129037.4	64518.7	3.97	0.0414	*
Subject/Age	15	243975.1	16265.0			
Within						
VES	5	270960.0	54192.0	7.95	<.0001	*
VES by Age	10	69654.8	6965.5	1.02	0.4337	
VES by Subject/Age	75	511294.5	6817.3			
Object	1	72816.6	72816.6	10.52	0.0055	*
Object by Age	2	28501.3	14250.7	2.06	0.1621	
Object by Subject/Age	15	103813.1	6920.9			
VES by Object	5	188522.9	37704.6	4.83	0.0007	*
VES by Object by Age	10	68043.9	6804.4	0.87	0.5624	
VES by Object by Subject/Age	74	577153.3	7799.4			
TOTAL	214	2263772.9				

* $p < 0.05$ (significant)

Table 11 indicates that for recognition distance of the two obstacles, there were statistically significant main effects of VES and object.

Table 11. Obstacle group ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	60231.55242	30115.77621	1.97	0.1734	
Subject/Age	15	228872.3114	15258.1541			
Within						
VES	5	77110.49642	15422.09928	2.66	0.0288	*
VES by Age	10	31662.52511	3166.25251	0.55	0.8519	
VES by Subject/Age	75	434969.4358	5799.5925			
Object	1	121761.6172	121761.6172	35.45	<.0001	*
Object by Age	2	11960.9061	5980.4531	1.74	0.2089	
Object by Subject/Age	15	51515.4452	3434.363			
VES by Object	5	45491.44406	9098.28881	1.58	0.1762	
VES by Object by Age	10	39240.80808	3924.08081	0.68	0.7382	
VES by Object by Subject/Age	74	426087.6993	5757.9419			
TOTAL	214	1528904.2				

* $p < 0.05$ (significant)

Table 12 provides a summary of the statistically significant main effects and interactions in the analysis of the obstacle object group.

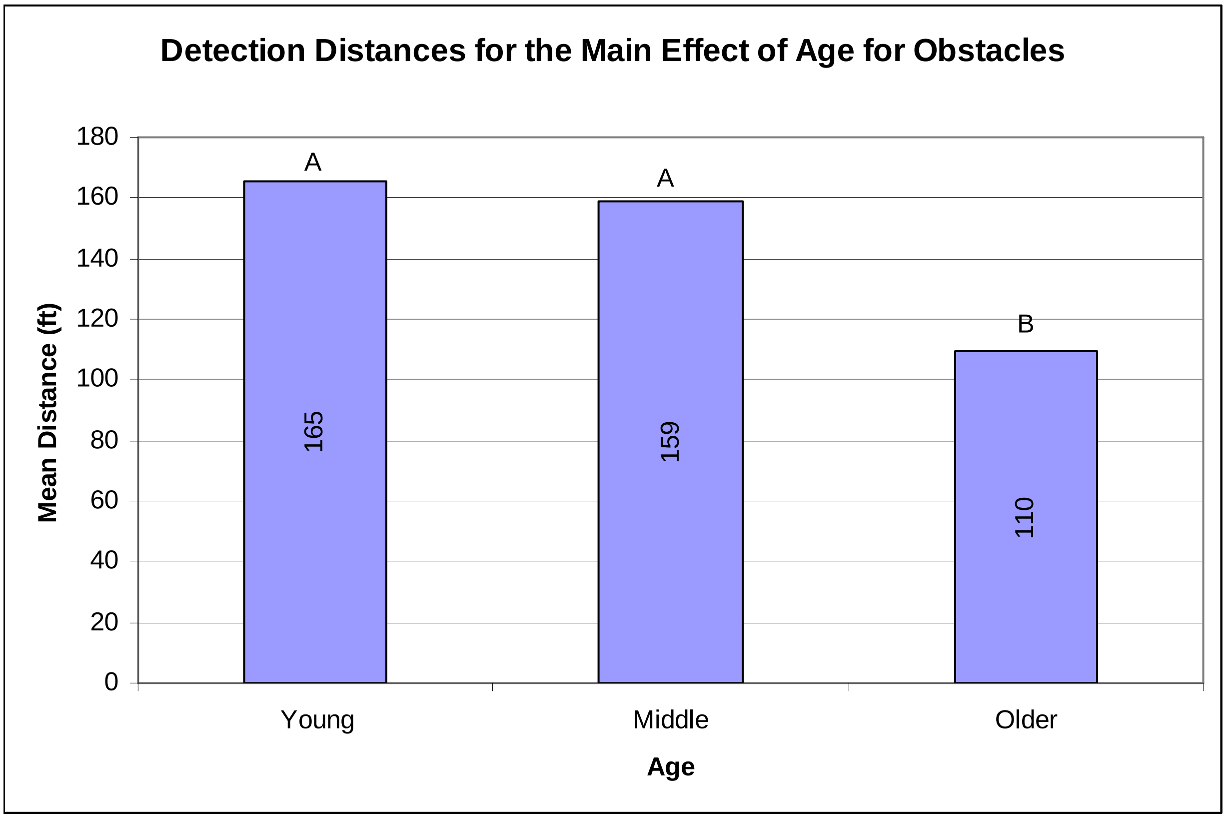
Table 12. Significant main effects and interactions summary for obstacle object group analysis.

Source	Significant Detection	Significant Recognition
Between		
Age	x	
Subject/Age		
Within		
VES	x	x
VES by Age		
VES by Subject/Age		
Object	x	x
Object by Age		
Object by Subject/Age		
VES by Object	x	
VES by Object by Age		
VES by Object by Subject/Age		

x = $p < 0.05$ (significant)

Age

The main effect of age that was identified in the object group model discussed previously was evident in the analysis of the obstacles object group as well. For the tire and dog, the mean detection distances were 50.3 m and 48.5 m (165 ft and 159 ft) for the young and middle-aged groups. For the older age group, the mean detection distance was 33.5 m (110 ft). SNK analysis indicates the older group had shorter detection distances than the middle and younger groups (figure 33).



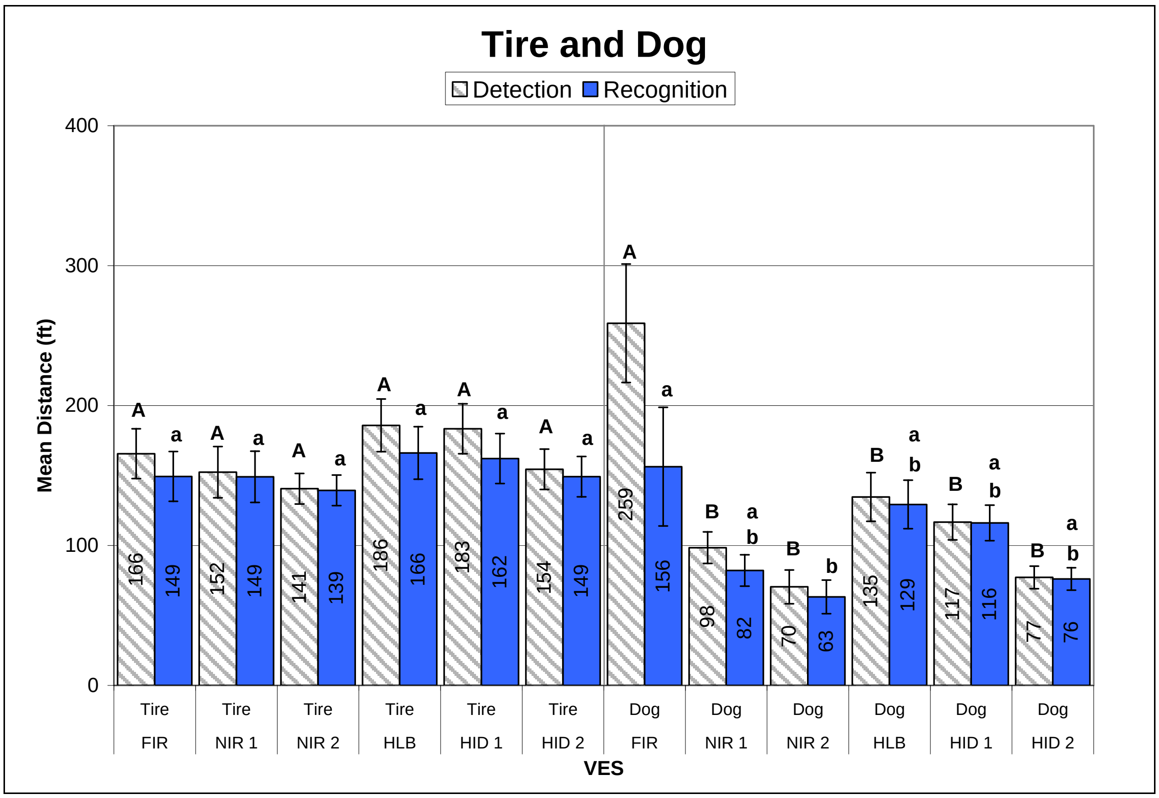
1 ft = 0.305 m

Figure 33. Bar graph. Mean detection distances for the age main effect for the obstacle group.

The main effect of object in this analysis describes differences in the detection distances of the dog versus the tire tread. The mean detection distance for the dog was 38.4 m (126 ft) and the mean detection distance for the tire tread was 50.0 m (164 ft). The main effect of VES is best understood by consideration of the VES by Object interaction, which is discussed next.

VES by Object Interaction

The ANOVA for the detection and recognition distances when approaching either the tire tread or the dog had a significant VES by Object interaction for detection distance. SNK tests performed on detection distances were used for the two obstacles to identify differences between the VESs for each object. In figure 34, SNK grouping for detection distance is shown with an uppercase letter. SNK grouping for recognition distance is shown with a lowercase letter. Bar height indicates the mean detection or recognition distance for a specific VES, with a tall bar being better than a short bar. SNK grouping applies only to a specific object, not to both objects shown on the chart together. Standard error bars are also included around the means to illustrate the associated variance.



1 ft = 0.305 m

Figure 34. Bar graph. Tire and dog mean detection and recognition distances by VES.

The mean distance at which participants were able to detect the tire with the different VESs ranged from 43.0 m to 56.7 m (141 ft to 186 ft). Recognition distances for the tire ranged from 45.4 m to 50.6 m (149 ft to 166 ft). There were no statistically significant differences at the

$\alpha = 0.05$ level between the VESs for detecting or recognizing the tire tread. The left side of figure 34 shows the mean detection and recognition distances for the tire, with standard error bars provided around the means.

When approaching the dog object, the FIR vehicle provided a mean detection distance of 78.9 m (259 ft). This was statistically different at the $\alpha = 0.05$ level from all of the other vehicles, which had mean detection distances ranging from 23.5 m to 41.1 m (77 ft to 135 ft). Recognition distances for the dog indicated differences between the FIR vehicle, with a mean recognition distance of 47.5 m (156 ft), and NIR 2, with a mean recognition distance of 19.2 m (63 ft). The mean recognition distances for the other four VESs fell between the means for the NIR 2 and the FIR and were not significantly different from these two vehicles.

Pedestrian Object Group Analysis

The next set of results is from the analysis of the pedestrian object group. This was a 6 (VES) by 12 (Object) by 3 (Age) mixed factorial design. In this analysis, the object variable is composed of the 12 pedestrian scenarios. As discussed in the Independent Variables section, these scenarios involved pedestrians standing in different locations in relation to the participant vehicle and wearing black or denim clothing.

Table 13 indicates that for detection distance within the pedestrian object group, all main effects and interactions were significant. Table 14 indicates that for recognition distance in the pedestrian object group, statistically significant main effects were found for age, VES, and object. Statistically significant interactions were found for Object by Age and VES by Object. Table 15 provides a summary of the statistically significant main effects and interactions in the analysis of the pedestrian object group.

Table 13. Pedestrian object group ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	5106529.9	2553265.0	5.30	0.0182	*
Subject/Age	15	7226283.5	481752.2			
Within						
VES	5	37856755.0	7571351.0	50.46	<.0001	*
VES by Age	10	3178104.1	317810.4	2.12	0.0331	*
VES by Subject/Age	75	11252753.1	150036.7			
Object	11	9169261.9	833569.3	28.11	<.0001	*
Object by Age	22	1323152.7	60143.3	2.03	0.0066	*
Object by Subject/Age	165	4893476.1	29657.4			
VES by Object	55	12450098.9	226365.4	7.47	<.0001	*
VES by Object by Subject/Age	110	4625001.0	42045.5	1.39	0.0080	*
VES by Object by Subject/Age	806	24419105.1	30296.7			
TOTAL	1276	121500521.1				

* $p < 0.05$ (significant)

Table 14. Pedestrian object group ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	4640310.902	2320155.451	4.78	0.0247	*
Subject/Age	15	7278259.15	485217.28			
Within						
VES	5	25849407.49	5169881.5	44.85	<.0001	*
VES by Age	10	1991478.05	199147.8	1.73	0.09	
VES by Subject/Age	75	8644631.59	115261.75			
Object	11	6180821.269	561892.843	26.18	<.0001	*
Object by Age	22	952324.79	43287.49	2.02	0.007	*
Object by Subject/Age	165	3541686.7	21464.77			
VES by Object	55	10829295.69	196896.29	9.15	<.0001	*
VES by Object by Age	110	2141637.54	19469.43	0.91	0.7411	
VES by Object by Subject/Age	806	17335080.69	21507.54			
TOTAL	1276	89384933.9				

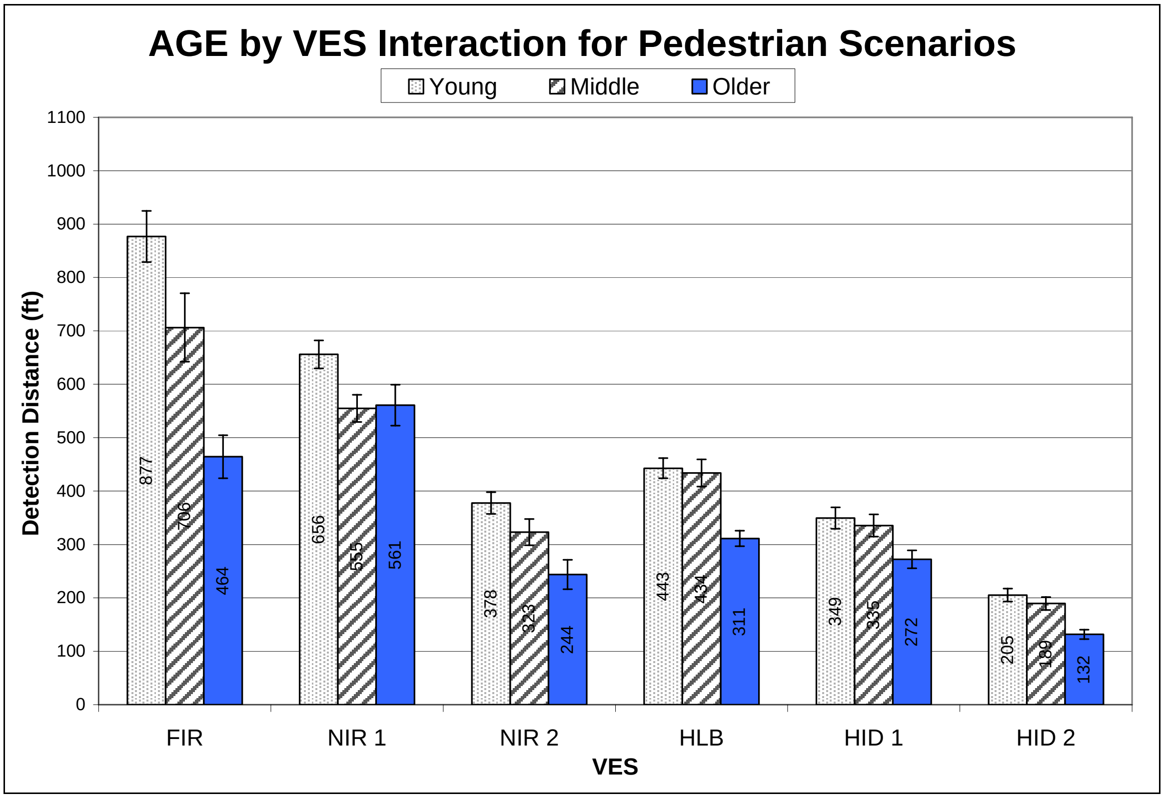
* $p < 0.05$ (significant)

Table 15. Summary of significant main effects and interactions for pedestrian group analysis.

Source	**Significant Detection**	**Significant Recognition**
Between		
Age	x	x
Subject/Age		
Within		
VES	x	x
VES by Age	x	
VES by Subject/Age		
Pedestrian	x	x
Pedestrian by Age	x	x
Pedestrian by Subject/Age		
VES by Pedestrian	x	x
VES by Pedestrian by Age	x	
VES by Pedestrian by Subject/Age		

x = $p < 0.05$, significant

Differences in performance due to age were evident in the distances at which participants detected pedestrians. The main effect of age indicated the younger participants were detecting pedestrians at longer distances than the older participants. The Age by VES interaction indicated differences in how the age groups performed with one VES versus another. This interaction is presented in figure 35.



1 ft = 0.305 m

Figure 35. Bar graph. Mean detection distances for the Age by VES interaction for pedestrian scenarios.

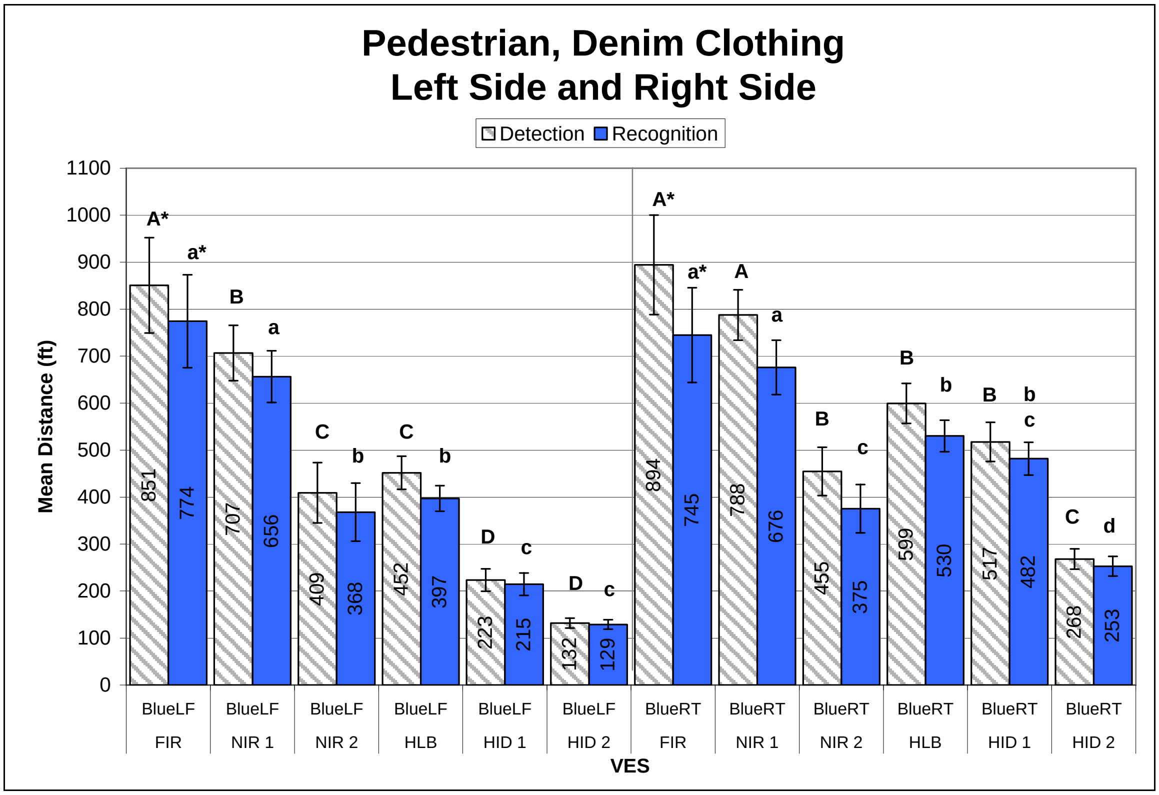
For the headlamp-based systems, the younger and middle-aged groups tended to be similar, while the older age group tended to have shorter detection distances. For the FIR and NIR 2 VESs, the younger group had longer detection distances than the older group, while the middle-aged group was somewhere between the other two. For the NIR 1 vehicle, there was no difference between the middle and older age groups. The older age group had longer detection distances for pedestrians with the NIR 1 vehicle than with the FIR or NIR 2 vehicles.

VES by Object Interaction and VES by Object by Age Interaction

The statistically significant VES by Object and VES by Object by Age interactions for the pedestrian scenarios indicate a large number of possible differences. Due to the number of interactions present and the interest in how all the VESs performed on each of the objects, separate Age by VES ANOVAs were conducted for each of the pedestrian scenarios. Only the main effect of VES for each of these objects is discussed, allowing the reader to evaluate the effect of every VES on each pedestrian individually. The Discussion section provides a comparison of the stopping distance achievable for each object for each VES; a separate discussion on the effect of age is also provided there.

Pedestrian, Denim Clothing

Mean detection and recognition distances for pedestrians wearing denim clothing and standing on the left and right side of a straight section of road are shown in figure 36.



1 ft = 0.305 m
* FIR means may be reduced due to limited sight distance

Figure 36. Bar graph. Mean detection and recognition distances for pedestrians in denim on straight—left and right side.

The FIR vehicle mean detection distance may have been limited by the available sight distance. (Further explanation appears in the Data Analysis section of this report.) When pedestrians were standing on the left side of a straight section of road, the FIR vehicle had the longest mean detection distance of 259.4 m (851 ft), followed by the NIR 1 vehicle, with a mean detection distance of 215.6 m (707 ft). The HLB vehicle and the NIR 2 vehicle were not statistically different from each other, with mean detection distances of 137.8 m and 124.7 m (452 ft and 409 ft), respectively. The HID 1 and the HID 2 vehicles had shorter detection distances than the other four vehicles; however, the HID 1 and the HID 2 vehicles were not statistically different from each other, with mean detection distances of 68.0 m and 40.2 m (223 ft and 132 ft), respectively.

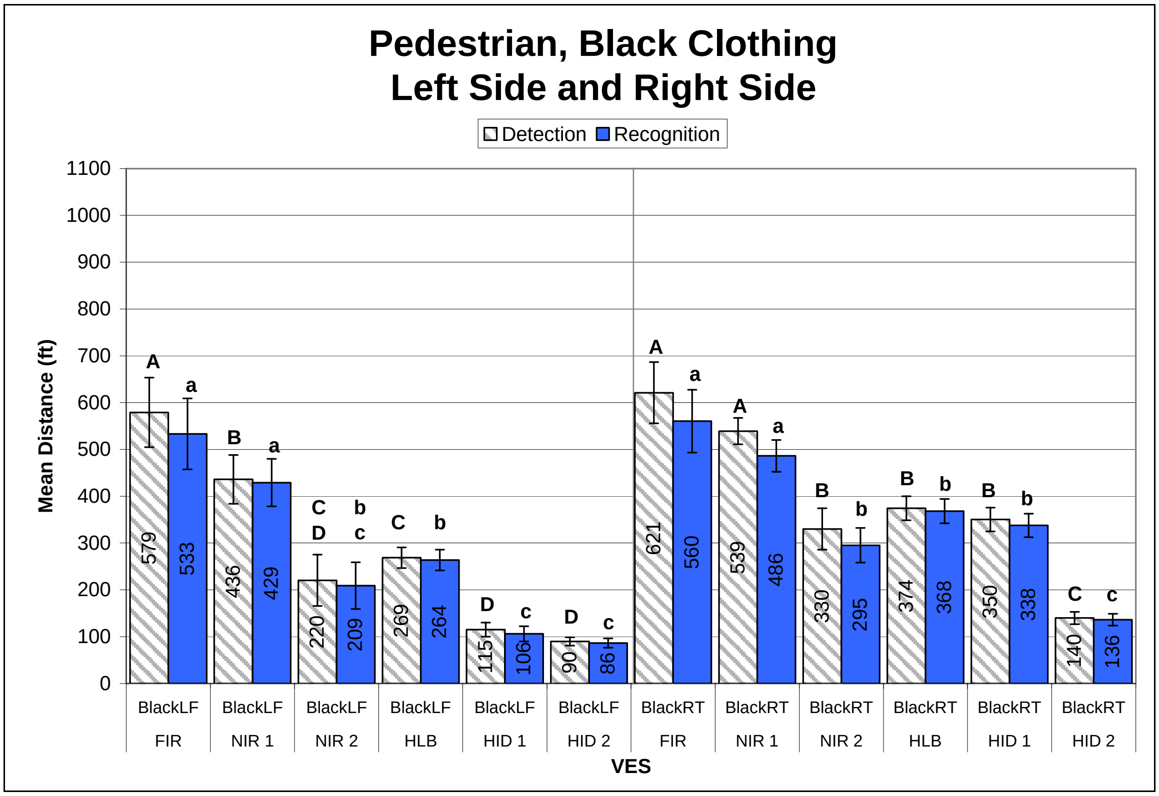
Mean recognition distances were longest for the FIR vehicle and the NIR 1 vehicle. The mean recognition distances were 235.9 m and 199.9 m (774 ft and 656 ft) for the FIR and the NIR 1, respectively. These two vehicles were not statistically different from each other. The next longest mean recognition distances were for the HLB and the NIR 2 vehicles. These distances were 121.0 m and 112.2 m (397 ft and 368 ft), respectively. The shortest mean recognition distances were for the HID 1 and the HID 2 vehicles, with mean recognition distances of 65.5 m and 39.3 m (215 ft and 129 ft), respectively. These distances were not statistically different from each other.

When pedestrians were standing on the right side of the road, the mean detection distances of 272.5 m (894 ft) for FIR and 240.2 m (788 ft) for NIR 1 were the longest of the VESs. Detection distances of 182.6 m (599 ft) for HLB, 157.6 m (517 ft) for HID 1, and 138.7 m (455 ft) for the NIR 2 were grouped together. Because of the limited available sight distance, the FIR mean detection distance may have been less than its full potential. The detection distance of 81.7 m (268 ft) for the HID 2 vehicle in this scenario was the shortest of the VESs.

Recognition distances for the FIR of 227.1 m (745 ft) and for the NIR 1 of 206.0 m (676 ft) were again the longest of the VESs. The HLB recognition distance of 161.5 m (530 ft) was longer than the 114.3 m (375 ft) for the NIR 2 vehicle and 77.1 m (253 ft) for the HID 2 vehicle. The HID 1 recognition distance of 146.9 m (482 ft) was not statistically different from the HLB or the NIR 2 vehicles. The HID 2 vehicle recognition distance was the shortest of all the VESs.

Pedestrian, Black Clothing

Mean detection and recognition distances for pedestrians wearing black clothing and standing on the left and right side of a straight section of road are shown in figure 37.



1 ft = 0.305 m

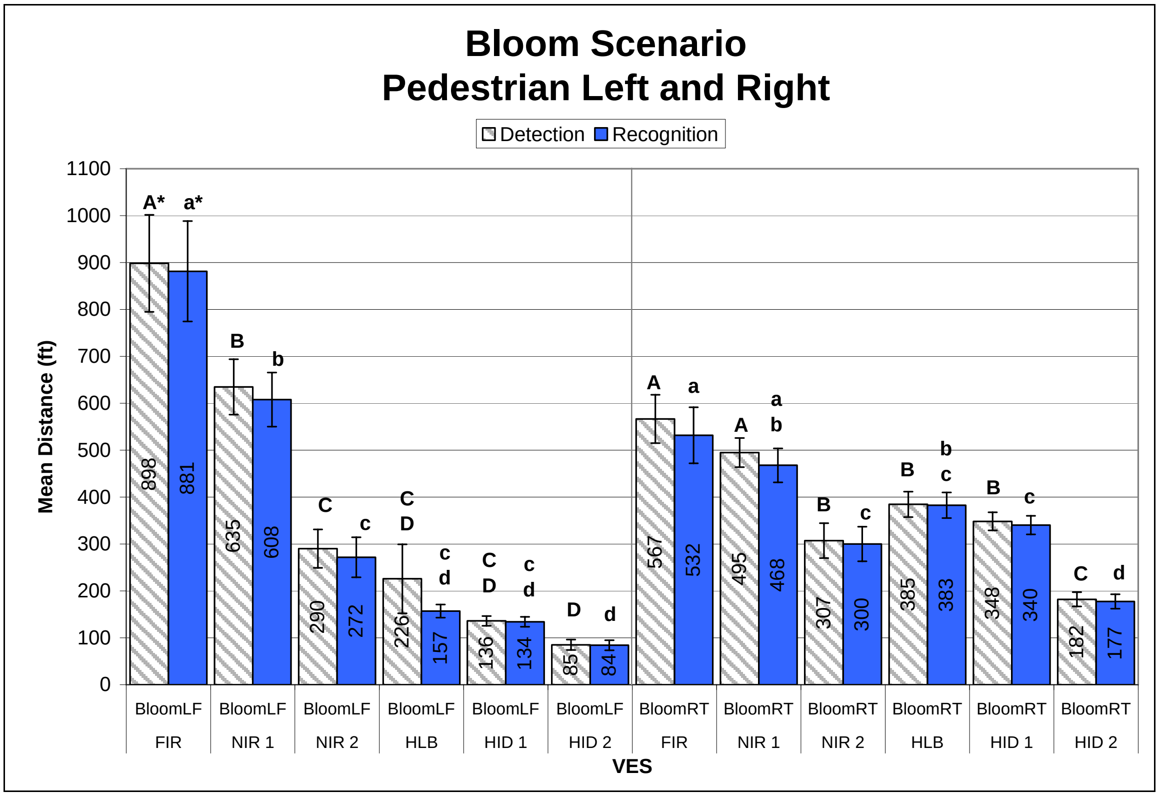
Figure 37. Bar graph. Mean detection and recognition distances for pedestrian in black on straight—left and right side.

When a pedestrian dressed in black appeared on the left side of a straight road section, the FIR vehicle had the longest mean detection distance measured at 176.48 m (579 ft). The NIR 1 vehicle had the next longest mean detection distance of 132.89 m (436 ft). The mean detection distance with the HLB vehicle of 82.0 m (269 ft) was not statistically different from the NIR 2 vehicle measurement of 67.1 m (220 ft). The mean detection distances of 35.1 m (115 ft) with the HID 1 vehicle and 27.4 m (90 ft) with the HID 2 vehicle were very similar and were not statistically different from NIR 2 VES. The FIR, the NIR 1, and the HLB vehicles all had longer mean detection distances than the HID VESs. Though the detection distance for the FIR and the NIR 1 vehicles were statistically different, the recognition distances of 162.5 m (533 ft) and 130.8 m (429 ft), respectively, did not show significant statistical differences. These were the longest mean recognition distances for the tested VESs. The HLB vehicle had a longer mean recognition distance (80.5 m (264 ft)) than both the HID 1 vehicle (32.3 m (106 ft)), and HID 2 vehicle (26.2 m (86 ft)). The NIR 2 vehicle (63.7 m (209 ft)) was not statistically different from the HID VESs or the HLB.

When a pedestrian dressed in black appeared on the right side of a straight road section, the FIR and the NIR 1 had the longest mean detection distances of 189.3 m and 161.2 m (621 ft and 529 ft), respectively. Recognition distances for these two VESs were 170.7 m and 148.1 m (560 ft and 486 ft), respectively. Neither the detection distances nor the recognition distances of the vehicles were statistically different from each other. In addition, the mean detection distances for the HLB (114.0 m (374 ft)), HID 1 (106.7 m (350 ft)), and the NIR 2 (100.6 m (330 ft)) were not statistically different from each other; nor were the recognition distances of 112.2 m, 103.0 m, and 89.9 m (368 ft, 338 ft, and 295 ft) for the same VESs, respectively. The HID 2 vehicle had the shortest mean detection (42.7 m (140 ft)) and recognition distances (41.5 m (136 ft)) of the VESs tested.

Pedestrian, Bloom Scenario

In the bloom scenarios, a pedestrian was standing next to a car with its headlamps on while the participant approached in the oncoming lane. Mean detection and recognition distances for these scenarios are shown in figure 38.



1 ft = 0.305 m
* FIR means may be reduced due to limited sight distance

Figure 38. Bar graph. Mean detection distances for bloom scenario, left and right side.

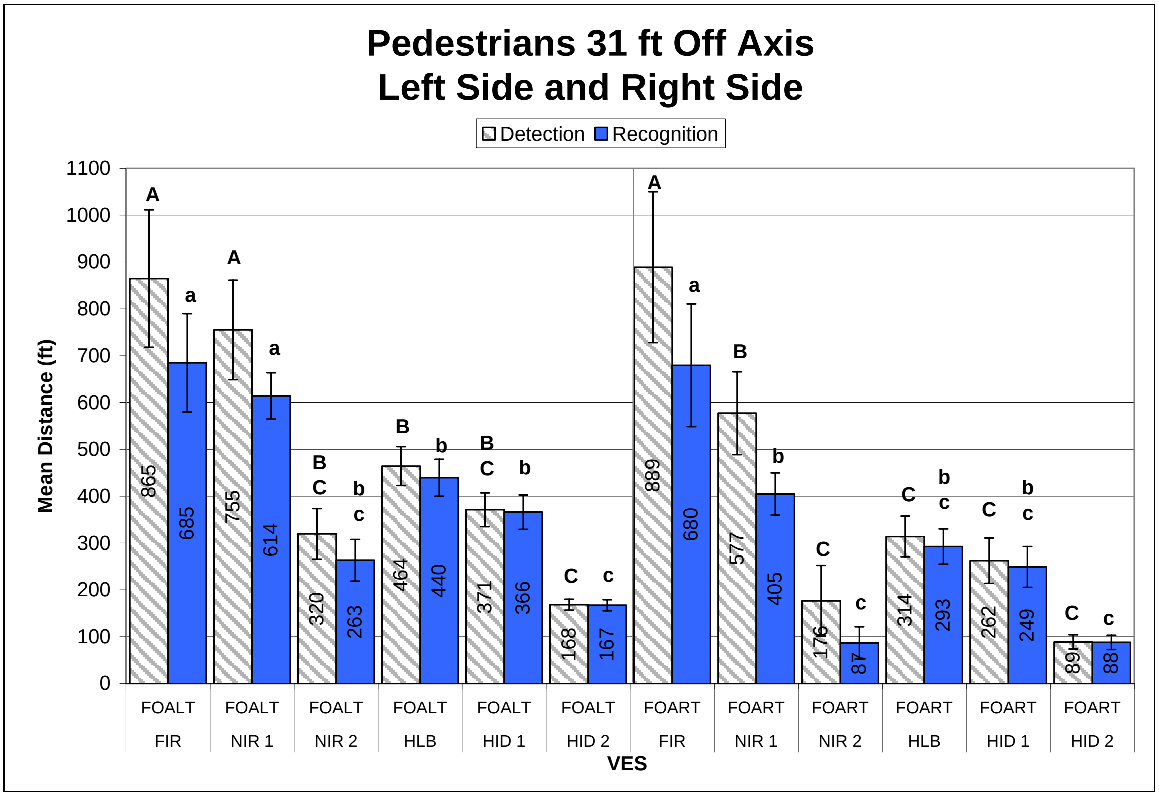
In the scenario in which the pedestrian was standing to the left of the participant vehicle, the mean detection distance was the longest when driving the FIR vehicle (273.7 m (898 ft)). Because the available sight distance was limited, this FIR mean detection distance may have been reduced in this scenario. The NIR 1 vehicle had the next longest mean detection distance in this scenario (193.6 m (635 ft)). The NIR 2 (88.4 m (290 ft)), the HLB (68.5 m (226 ft)), and the HID 1 (41.5 m (136 ft)) vehicles were not statistically different from each other. At 25.9 m (85 ft), the mean detection distance of the HID 2 vehicle was not statistically different from the HID 1 or the HLB vehicles; however, it was statistically shorter than both the NIR vehicles and the FIR vehicle.

Recognition distances for the different VESs followed the same pattern as the detection distances in this scenario. For example, the mean recognition distance for the FIR vehicle was the longest (268.5 m (881 ft)). The NIR 1 vehicle had the next longest mean recognition distance in this scenario (185.3 m (608 ft)). The NIR 2 (82.9 m (272 ft)), the HLB (47.9 m (157 ft)), and the HID 1 (40.8 m (134 ft)) were not statistically different from each other. The HID 2 mean recognition distance of 25.6 m (84 ft) was not statistically different from either the HID 1 or the HLB; however, it was statistically shorter than both the NIR vehicles and the FIR vehicle.

In general, in the bloom scenario, the performance of the VESs on the left side of the road ordered the VESs similarly as their performance on the right side of the road did. With the pedestrian on the right side of the road, however, the FIR system did not perform as well as it did on the left and so was more similar to the performance of the NIR 1 system. The headlamp-only VESs performed better on the right side than on the left due to more illuminance being provided toward the right than toward the left.

Pedestrian Off Axis

In the pedestrian off axis scenario, a pedestrian stood 9.4 m (31 ft) to the left or right of the participant vehicle centerline. Mean detection and recognition values for these scenarios are shown in figure 39.



1 ft = 0.305 m

Figure 39. Bar graph. Mean detection and recognition distances for pedestrian far off axis, left and right side.

When a pedestrian was located 9.5 m (31 ft) to the left, measured from the center of the participant vehicle's lane, the FIR vehicle and the NIR 1 vehicle were not statistically different in mean detection distance. The mean detection distances for the two vehicles were 263.7 m and 230.1 m (865 ft and 755 ft), respectively. These two vehicles had the longest mean detection distances of the group. The mean detection distances of the HLB vehicle (141.4 m (464 ft)), the HID 1 vehicle (113.1 m (371 ft)), and the NIR 2 vehicle (97.5 m (320 ft)) could not be statistically distinguished from one another. Moreover, at 51.2 m (168 ft), the mean detection distance for the HID 2 vehicle also was not statistically different from the NIR 2 vehicle or the HID 1 vehicle mean detection distances.

The FIR (208.9 m (685 ft)) and the NIR 1 (187.1 m (614 ft)) had the longest mean recognition distances of the group, and they were not statistically different from each other. The HLB mean recognition distance (134.1 m (440 ft)) was not statistically different from the HID 1 (111.6 m

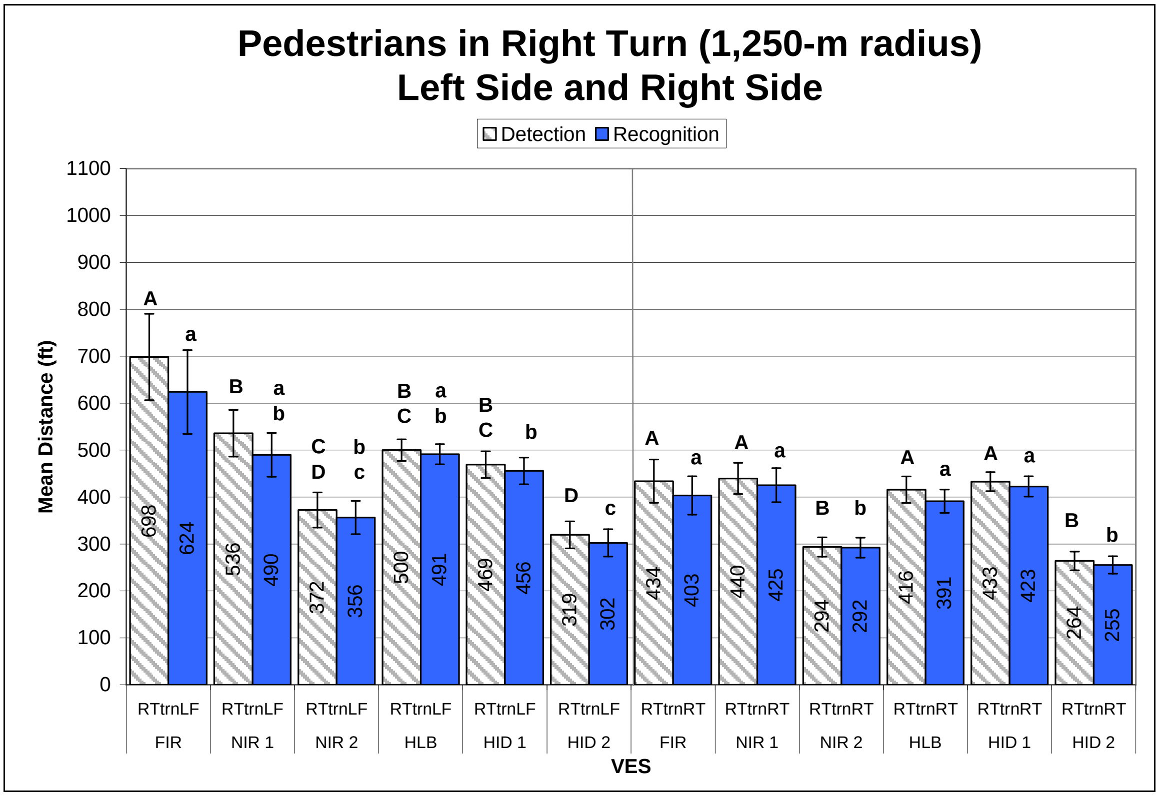
(366 ft)) or from the NIR 2 (80.2 m (263 ft)) but was statistically longer than the HID 2 (50.9 m (167 ft)). The HID 2 mean recognition distance was not statistically different from the NIR 2.

When the pedestrian was standing 9.5 m (31 ft) to the right of the center of the participant’s lane, the FIR vehicle mean detection distance of 271.0 m (889 ft) was the longest of the group, followed by the NIR 1 mean detection distance of 175.9 m (577 ft). The mean detection distances of the other four vehicles were not statistically different from each other: HLB (95.7 m (314 ft)), HID 1 (79.9 m (262 ft)), NIR 2 (53.6 m (176 ft)), and HID 2 (27.1 m (89 ft)).

At 185.3 m (680 ft), the mean recognition distance of the FIR vehicle was the longest of the group statistically. The mean recognition distance of the NIR 1 (123.4 m (405 ft)) was statistically longer than the NIR 2 (26.5 m (87 ft)) and the HID 2 (27.8 m (88 ft)); however, it was not statistically longer than the HLB (89.3 m (293 ft)) or the HID 1 (75.9 m (249 ft)) vehicles. The HLB, the HID 1, the NIR 2, and the HID 2 vehicles were not statistically different from each other in terms of mean recognition distances in this scenario.

Pedestrian in Right Turn

Mean detection and recognition distances for pedestrians wearing denim clothing and standing on the left and right side of a 1,250-m radius right turn are shown in figure 40.



1 ft = 0.305 m

Figure 40. Bar graph. Mean detection and recognition distances for pedestrian in denim in right turn, left and right side.

When detecting and recognizing pedestrians that were standing on the left side of a 1,250-m radius right-hand turn, the FIR vehicle had the longest mean detection distances, at 212.8 m (698 ft). The mean detection distance for the NIR 1 (163.4 m (536 ft)) was not statistically different from the HLB (152.4 m (500 ft)) or the HID 1 (143.0 m (469 ft)); however, the NIR 1 was statistically longer than the NIR 2 (113.4 m (372 ft)) and the HID 2 (97.3 m (319 ft)). The HLB (152.4 m (500 ft)) and the HID 1 (143.0 m (469 ft)) had statistically longer mean detection distances than the HID 2 (97.2 m (319 ft)), but they were grouped together with the NIR 2 (113.4 m (372 ft)) vehicle. The HID 2 had similar mean detection distances to the NIR 2.

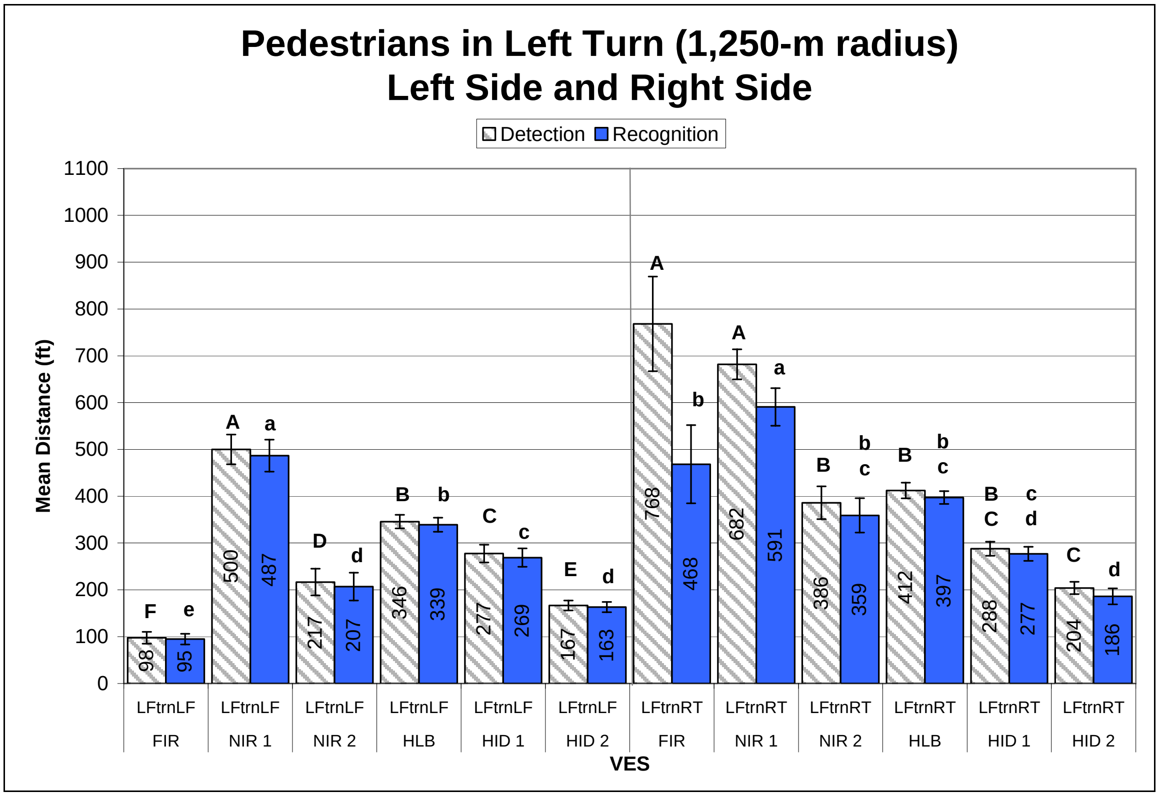
Recognition distances for the systems showed that the FIR (190.2 m (624 ft)), the NIR 1 (149.4 m (490 ft)), and the HLB (149.7 m (491 ft)) were grouped together. Recognition distances for the NIR 1 (149.4 m (490 ft)), HLB (149.7 m (491 ft)), HID 1 (139.0 m (456 ft)), and NIR 2 (108.5 m (356 ft)) were grouped together. At 92.0 m (302 ft), the mean recognition distance for the HID 2 vehicle was statistically shorter than for all the systems except the NIR 2.

Where pedestrians were standing on the right side of a 1,250-m radius right-hand turn, the six vehicles tested were separated into two groups based on detection performance. The mean detection distances of the NIR 1 (134.1 m (440 ft)), FIR (132.3 m (434 ft)), HID 1 (132.0 m (433 ft)), and HLB (126.8 m (416 ft)) placed them in the longer group. The mean detection distances of the NIR 2 (89.6 m (294 ft)) and the HID 2 (80.5 m (264 ft)) placed them in the group with shorter mean detection distances.

This same grouping occurred for recognition distances. The mean recognition distances for the NIR 1, FIR, HID 1, and HLB were 129.5 m, 122.8 m, 132.0 m, and 126.8 m (425 ft, 403 ft, 433 ft, and 416 ft), respectively. For the NIR 2 and HID 2, the mean recognition distances were 58.5 m (192 ft) and 77.7 m (255 ft), respectively, which placed them in a separate group from the other four VESs.

Pedestrian in Left Turn

Mean detection and recognition distances for pedestrians wearing denim clothing and standing on the left and right side of a 1,250-m radius left turn are shown in figure 41.



1 ft = 0.305 m

Figure 41. Bar graph. Mean detection and recognition distances for pedestrian in denim in left turn, left and right side.

When detecting pedestrians standing on the left side of a 1,250-m radius left-hand turn, the mean detection distances from longest to shortest were 152.4 m (500 ft) (NIR 1), 105.5 m (346 ft) (HLB), 84.4 m (277 ft) (HID 1), 66.1 m (217 ft) (NIR 2), 50.9 m (167 ft) (HID 2), and 29.9 m (98 ft) (FIR). Each of these mean detection distances was statistically different from all the other systems.

The recognition distances for the VESs followed a similar arrangement. The order of recognition distances was the same, except for the HID 2 and NIR 2. These VESs were grouped together with mean recognition distances of 49.7 m and 63.0 m (163 ft and 207 ft), respectively. Around these two, the mean recognition distances for the other four vehicles (from longest to shortest) were 148.4 m (487 ft) (NIR 1), 103.32 m (339 ft) (HLB), 82.0 m (269 ft) (HID 1), and 29.0 m (95 ft) (FIR). Each of these was statistically different from each other and from the two grouped VESs.

In the same left-hand 1,250-m curve, when looking at pedestrians standing on the right side of the road, the mean detection distance for the NIR 1 (207.9 m (682 ft)) was grouped with the FIR, (235.0 m (768 ft)). The next longest mean detection distances were for the HLB (125.6 m (412 ft)) and the NIR 2 (117.7 m (386 ft)). These two vehicles were grouped together statistically. The shortest mean detection distance for this scenario was 62.2 m (204 ft), from the HID 2 VES. The mean detection distance for the HID 1 (87.8 m (288 ft)) was not statistically different from the HLB, the NIR 2, or the HID 2 vehicles.

Recognition of the pedestrian standing to the right side of the left curve was longest for the NIR 1 (180.1 m (591 ft)). Mean recognition distances for the FIR (142.7 m (468 ft)), the HLB (121 m (397 ft)), and the NIR 2 (109.4 m (359 ft)) grouped together statistically. The mean recognition distance of the HID 1 (84.4 m (277 ft)) was statistically shorter than for the FIR and NIR 1, but it was not statistically different from the other three VESs. The HID 2 mean recognition distance (56.7 m (186 ft)) was not statistically different from the HID 1, but it was statistically shorter than the recognition distance for the other four VESs in this scenario.

Retroreflective Object Group Analysis

A VES by Retroreflective Object Group ANOVA was used to investigate the effect of the VESs on the detection of roadway guidance objects at night. This object group included the RRPMs, signs, and the turn arrow. Table 16 and table 17 indicate statistically significant main effects in detection and recognition for VES and object and a statistically significant interaction for VES by Object.

Table 16. Retroreflective group ANOVA summary table for the dependent measurement: detection distance.

Source	DF	SS	MS	F value	P value	
<u>Between</u>						
Age	2	4942689.2	2471344.6	3.30	0.0647	
Subject/Age	15	11221308.7	748087.2			
<u>Within</u>						
VES	5	30607560.5	6121512.1	30.55	<.0001	*
VES by Age	10	1143637.5	114363.8	0.57	0.8327	
VES by Subject/Age	75	15027402.4	200365.4			
Object	2	417139124.0	208569562.0	918.72	<.0001	*
Object by Age	4	1716496.4	429124.1	1.89	0.138	
Object by Subject/Age	30	6810669.5	227022.3			
VES by Object	10	13914411.4	1391441.1	8.45	<.0001	*
VES by Object by Age	20	3607852.1	180392.6	1.10	0.3601	
VES by Object by Subject/Age	149	24538876.1	164690.4			
TOTAL	322	530670027.8				

* $p < 0.05$ (significant)

Table 17. Retroreflective group ANOVA summary table for the dependent measurement: recognition distance.

Source	DF	SS	MS	F value	P value	
<u>Between</u>						
Age	2	5636728.812	2818364.406	2.31	0.1338	
Subject/Age	15	18321641.6	1221442.8			
<u>Within</u>						
VES	5	14875454.76	2975090.95	14.73	<.0001	*
VES by Age	10	1285201.86	128520.19	0.64	0.7783	
VES by Subject/Age	75	15149792.5	201997.2			
Object	2	272468249	136234124.5	182.41	<.0001	*
Object by Age	4	2091062.3	522765.6	0.70	0.5981	
Object by Subject/Age	30	22406260.6	746875.4			
VES by Object	10	8156580.822	815658.082	4.18	<.0001	*
VES by Object by Age	20	3127735.986	156386.799	0.8	0.71	
VES by Object by Subject/Age	149	29108561.7	195359.5			
TOTAL	322	392627269.9				

* $p < 0.05$ (significant)

Table 18 provides a summary of the statistically significant main effects and interactions found for the retroreflective object group.

Table 18. Summary of significant main effects and interactions for retroreflective group analysis.

Source	Significant Detection	Significant Recognition
Between		
Age		
Subject/Age		
Within		
VES	x	x
VES by Age		
VES by Subject/Age		
Object	x	x
Object by Age		
Object by Subject/Age		
VES by Object	x	x
VES by Object by Age		
VES by Object by Subject/Age		

x = $p < 0.05$, significant

As would be expected, the main effect of object indicates large differences in the detection and recognition distances for the different objects. The mean detection distance for the signs across all the VESs was 776.3 m (2,547 ft). For the RRPM, the mean detection distance was 349.6 m (1,147 ft), and for the turn arrow the mean detection distance was 69.8 m (229 ft). When considering recognition distances of the sign, the RRPMs, and the turn arrow, mean distances were 632.2 m, 273.1 m, and 65.2 m (2,074 ft, 896 ft, and 214 ft), respectively.

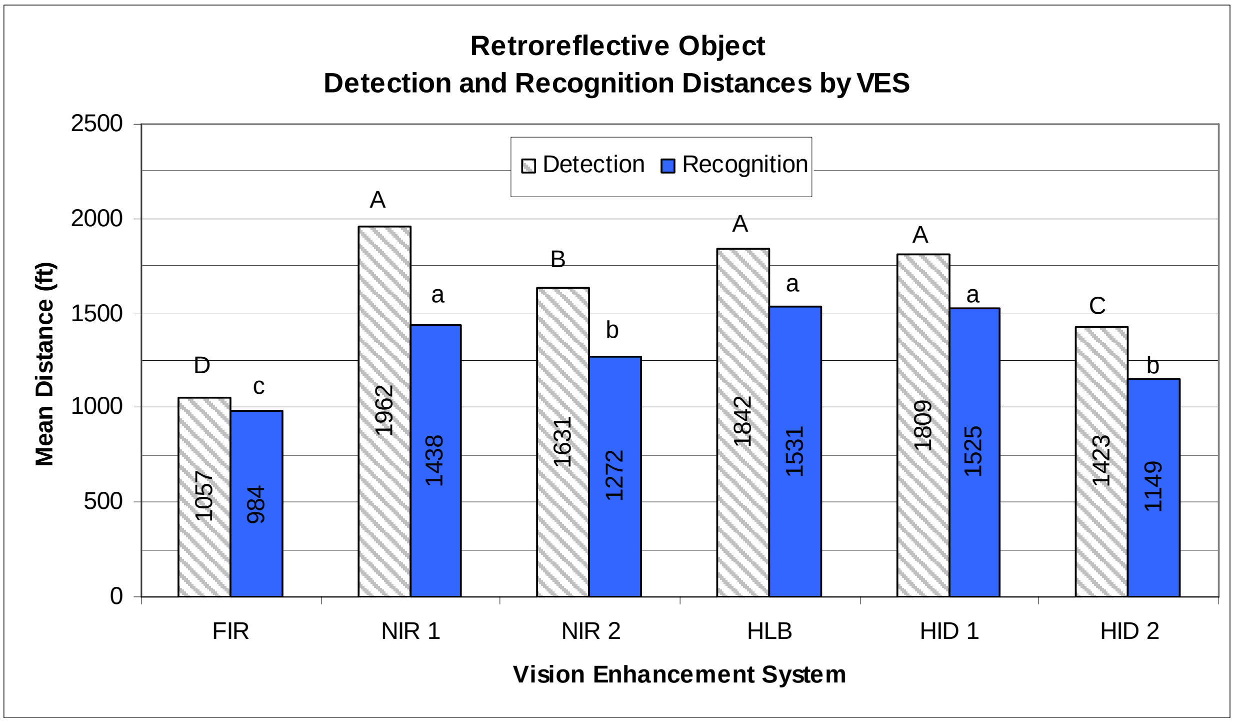
In the ANOVA for the retroreflective objects detection distances, the VES by Object interactions were statistically significant, as were the main effects of VES and object.

Object

The significant main effect of object indicates that the signs were detected and recognized at the greatest distances, followed by the RRPMs. The turn arrow was the retroreflective object with the shortest mean detection and recognition distances.

VES

The significant main effect of VES indicates differences between the VESs in both detection and recognition distances of retroreflective objects as a group (figure 42). The NIR 1, HLB, and HID 1 vehicles had the longest detection and recognition distances for retroreflective objects. The mean detection distances for these three vehicles were 598.0 m, 561.4 m, and 551.4 m (1,962 ft, 1,842 ft, and 1,809 ft), respectively. The mean recognition distances were 438.3 m, 466.7 m, and 464.8 m (1,438 ft, 1,531 ft, and 1,525 ft), respectively. The NIR 2 vehicle was the next longest with a mean detection distance of 497.1 m (1,631 ft), followed by the HID 2 (433.7 m (1,423 ft)) and the FIR (322.7 m (1,057 ft)) vehicle.



1 ft = 0.305 m

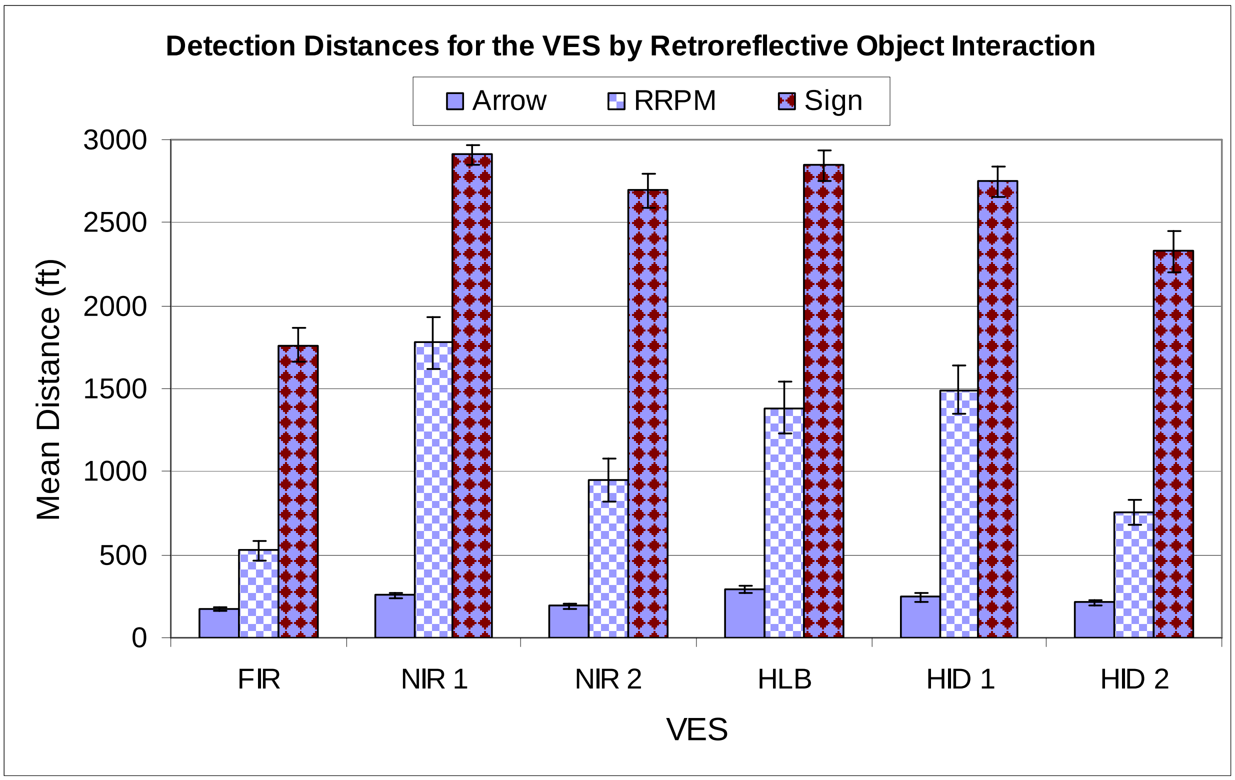
Figure 42. Bar graph. Mean detection and recognition distances for retroreflective object group by VES.

Mean recognition distances for retroreflective objects indicate that the NIR 2 (387.7 m (1,272 ft)) and the HID 2 (350.2 m (1,149 ft)) were similar. The mean recognition distance for retroreflective objects for the FIR was 299.9 m (984 ft), which was the shortest of the VESs. An analysis of the performance of the VESs on each object is provided in the following section.

VES by Object Interaction

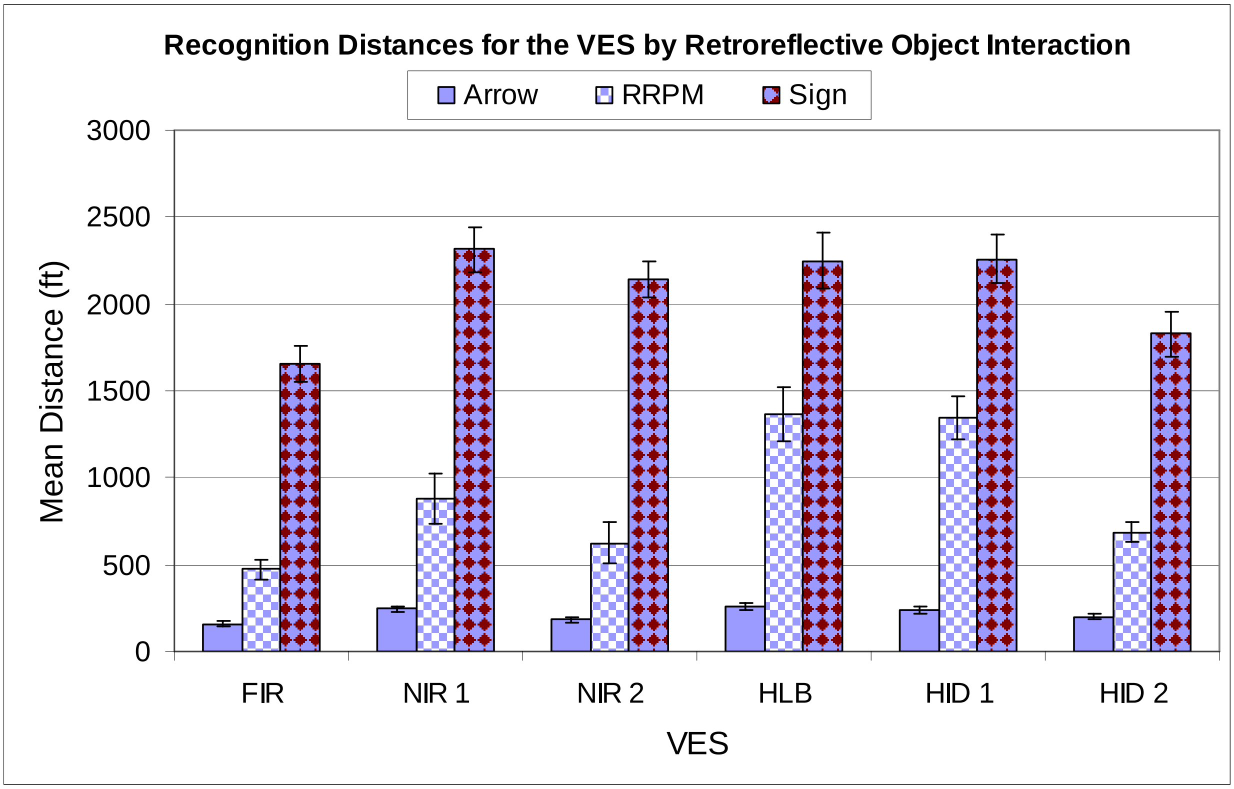
The significant VES by Object interaction for the detection distances of retroreflective objects indicates that certain VESs do well on some objects but not on others. The NIR 2 vehicle was comparable to the NIR 1, HLB, and HID 1 in detecting signs; however, for the turn arrow and RRPMs, the NIR 2 had lower performance than did these three other VESs. The NIR 1 vehicle outperformed the HLB benchmark on detecting RRPMs, but it was below the benchmark for the turn arrow.

For retroreflective object recognition, the NIR 1 had recognition distances that were similar to the HLB and HID 1 for the signs, but recognition distances for the RRPMs were shorter than for these two VESs. Figure 43 and figure 44 illustrate these interactions.



1 ft = 0.305 m

Figure 43. Bar graph. Mean detection distances for the VES by Object interaction for retroreflective group.



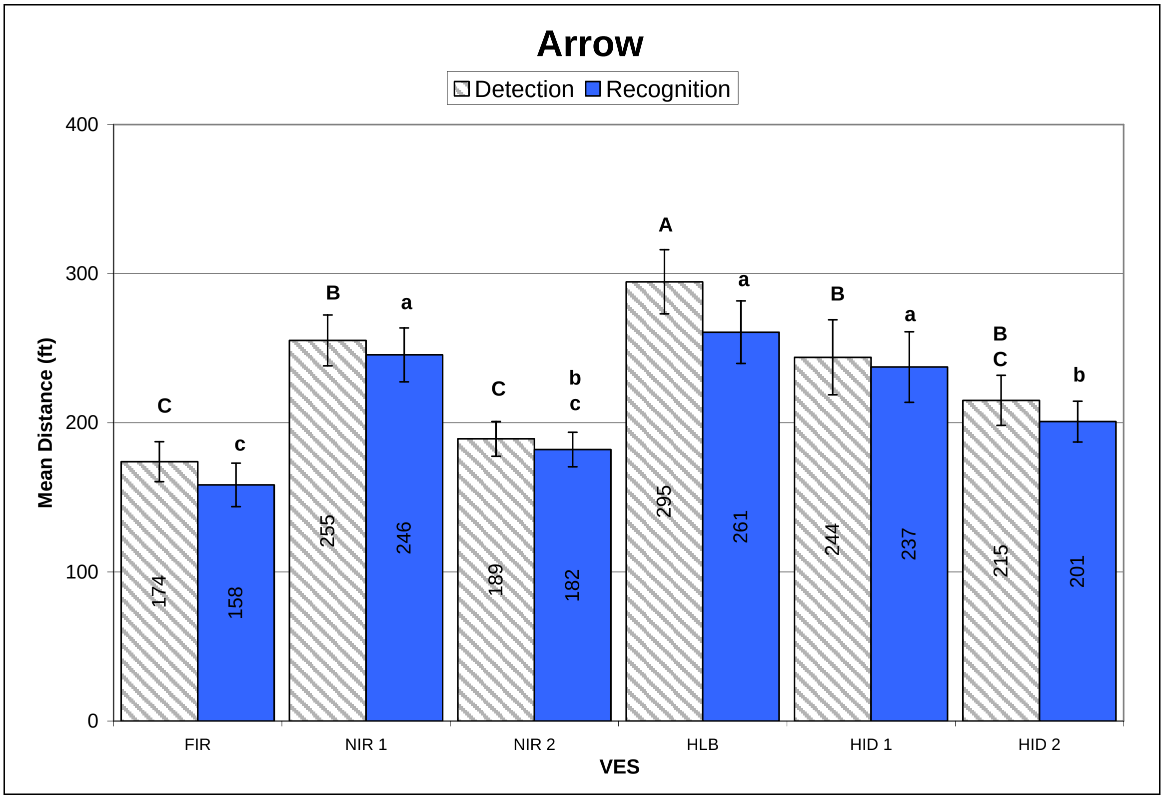
1 ft = 0.305 m

Figure 44. Bar graph. Mean recognition distances for VES by Object interaction for retroreflective group.

For more detailed comparison of the VESs on each of the retroreflective objects, the next sections report on their post hoc comparisons.

Turn Arrow

Mean detection and recognition distances for the six VESs when approaching the retroreflective pavement marking turn arrow are shown in figure 45.



1 ft = 0.305 m

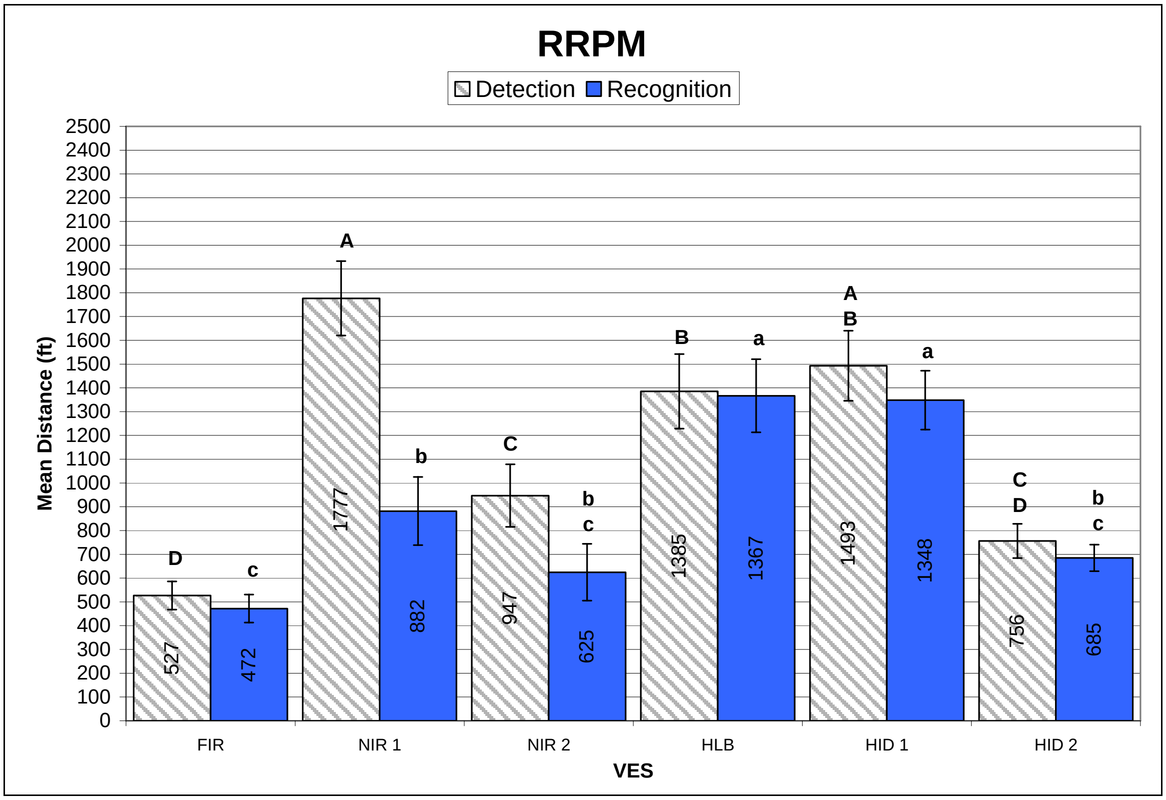
Figure 45. Bar graph. Arrow detection and recognition distances by VES.

When detecting the turn arrow, the HLB benchmark provided the longest mean detection distance at 89.2 m (295 ft). This was followed by the NIR 1 (77.7 m (255 ft)), the HID 1 (74.4 m (244 ft)), and the HID 2 (65.5 m (215 ft)). These means were not statistically different from each other. The mean detection distances for the FIR and the NIR 2 were 53.0 m (174 ft) and 57.6 m (189 ft), respectively, and were not statistically different from the HID 2 VES.

In comparing recognition distance, the HID 1, the NIR 1, and the HLB vehicles were grouped together, with mean recognition distances ranging from 72.2 m to 79.6 m (237 ft to 261 ft). These were the longest recognition distances for the six VESs. The HID 2 had the next longest mean recognition distance, at 61.3 m (201 ft). The FIR vehicle had the shortest mean recognition distance (48.2 m (158 ft)) for the turn arrow. The NIR 2 had a mean recognition distance of 55.5 m (182 ft), which was not statistically different from the HID 2 or the FIR vehicle.

RRPMs

Mean detection and recognition distances for the six VESs when approaching an RRPM are shown in figure 46.



1 ft = 0.305 m

Figure 46. Bar graph. RRPM detection and recognition distances by VES.

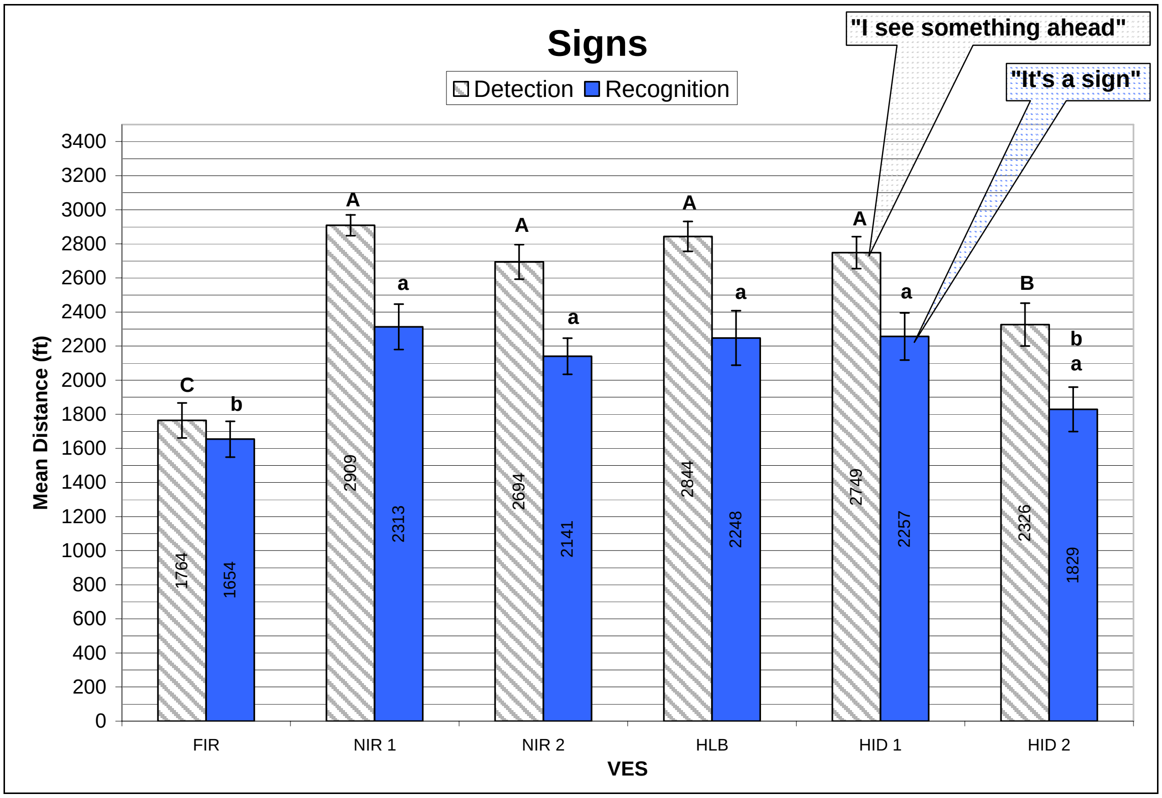
The detection distance provided by the NIR 1 of 541.6 m (1,777 ft) was statistically longer for the RRPMs than those of the HLB (422.2 m (1,385 ft)), the NIR 2 (288.7 m (947 ft)), the HID 2 (230.4 m (756 ft)), and the FIR (160.6 m (527 ft)). The HID 1 (455.1 m (1,493 ft)) and the HLB were not statistically different from each other, and the NIR 2 and the HID 2 were not statistically different from each other. In addition, the FIR was not statistically different from the HID 2; however, the NIR 2 had statistically longer detection distances than did the FIR.

When considering recognition distances for the RRPMs, HLB and HID 1 had the longest recognition distances at 416.7 m and 410.9 m (1,367 ft and 1,348 ft), respectively. The mean recognition distance of 268.8 m (882 ft) for the NIR 1 was statistically longer than the FIR of 143.9 m (472 ft). The mean recognition distances of 190.5 m (625 ft) for the NIR 2 and 208.8 m (685 ft) for HID 2 were not statistically different from those of the FIR or the NIR 1.

Signs

When detecting the signs ahead, the mean detection distances for HLB, NIR 1, HID 1, and NIR 2 were 866.9 m, 886.7 m, 837.9 m, and 821.1 m (2,844 ft, 2,909 ft, 2,749 ft, and 2,694 ft), respectively. These distances were not statistically different from each other. The FIR had the shortest mean detection distance (537.7 m (1,764 ft)). For signs, the HID 2 detection distance of (709.0 m) 2,326 ft was statistically shorter than that of the long-distance group, but longer than that of the FIR.

Mean recognition distance for the signs generated similar performance grouping. The mean recognition distances for the long-distance group ranged from 652.6 m to 705.0 m (2,141 ft to 2,313 ft). The FIR mean recognition distance was 504.1 m (1,654 ft). The HID 2 mean distance of 557.5 m (1,829 ft) was not statistically different from the others. Figure 47 shows the mean detection and recognition distances for signs, with standard error bars provided around the means.



1 ft = 0.305 m

Figure 47. Bar graph. Sign detection and recognition distances by VES.

Recognition of Sign Type

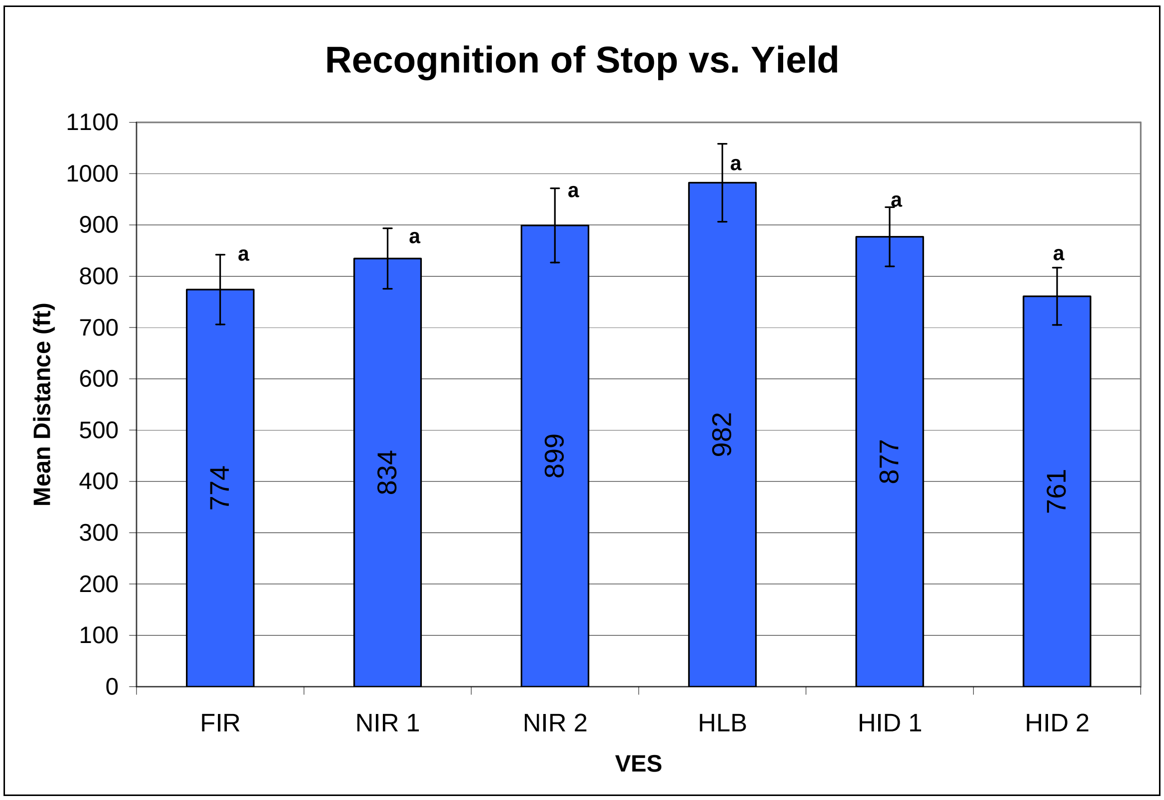
A 6 (VES) by 3 (Age) mixed factorial ANOVA was conducted to investigate differences in when the participants could recognize (i.e., discriminate between) a stop or a yield sign. Table 19 indicates that age was a statistically significant factor in distinguishing the stop sign from yield sign ($p = 0.0239$).

Table 19. ANOVA summary table for recognition of sign type (stop versus yield).

Source	DF	SS	MS	F value	P value	
Between						
Age	2	5533941.2	2766970.6	4.84	0.0239	*
Subject/Age	15	8575531.6	571702.1			
Within						
VES	5	1240877.9	248175.6	1.98	0.092	
VES by Age	10	465657.7	46565.8	0.37	0.9556	
VES by Subject/Age	75	9422647.3	125635.3			
TOTAL	107	25238655.8				

* $p < 0.05$ (significant)

At 327.1 m (1,073 ft), the mean detection distance for the younger group was longer than the mean distances for the middle (242.9 m) (797 ft) and older (211.5 m) (694 ft) groups. Analysis of the mean distance at which the participants could recognize a sign as either a stop sign or a yield sign did not indicate statistical differences among the VESs at the $\alpha < 0.05$ level ($p = 0.092$). The distances at which the participants recognized the sign type ranged from 232.0 m to 299.3 m (761 ft to 982 ft) across the VESs, with a mean of 260.6 m (855 ft). The mean distance for each of the VESs is presented in figure 48.



1 ft = 0.305 m

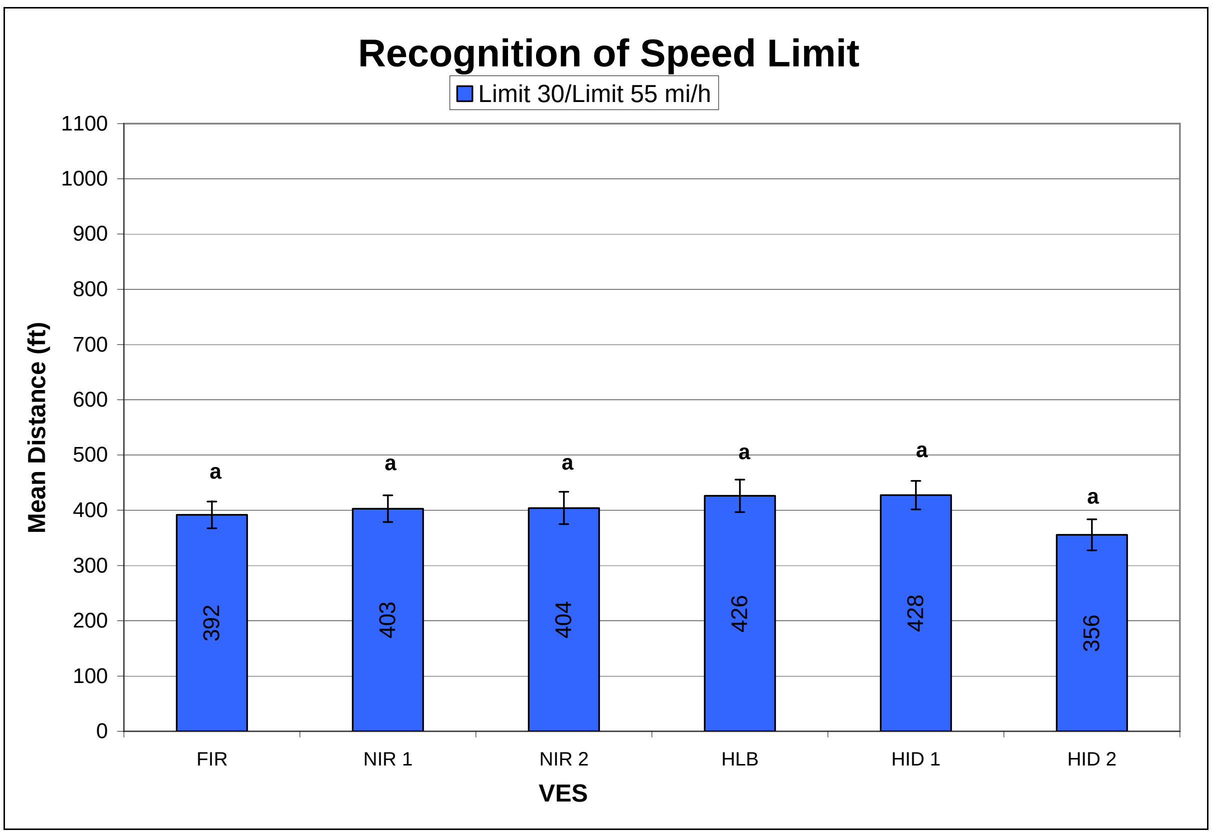
Figure 48. Bar graph. Sign recognition distances of stop versus yield sign by VES

A 6 (VES) by 3 (Age) mixed factorial ANOVA of when participants could read the speed limit shown on the speed limit sign also did not indicate differences between the systems. Table 20 shows the results of this ANOVA.

Table 20. ANOVA summary table for when participants could read speed limit.

Source	DF	SS	MS	F value	P value
Between					
Age	2	1056334.747	528167.373	3.64	0.0513
Subject/Age	15	2173934.533	144928.969		
Within					
VES	5	125850.2558	25170.0512	1.6	0.1696
VES by Age	10	61307.6299	6130.763	0.39	0.947
VES by Subject/Age	75	1177315.704	15697.543		
TOTAL	107	4594742.9			

Figure 49 provides the mean distances at which participants could read the speed limit signs for each of the VESs.

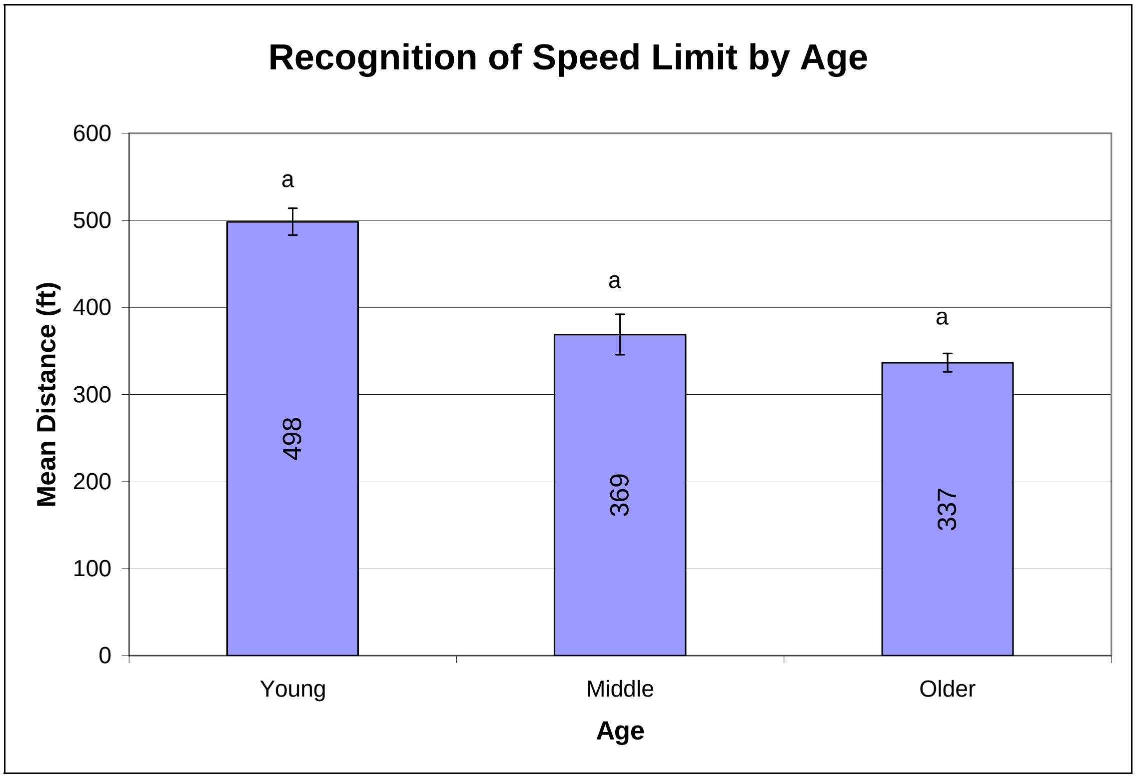


1 ft = 0.305 m

Figure 49. Bar graph. Mean distances at which speed limit signs were read.

Distances at which the signs could be read ranged from 108.5 m to 130.5 m (356 ft to 428 ft), with a mean of 122.2 m (401 ft). Using the 25.7-cm (10-inch) number height of the speed limit, a range from 4.2 m/cm to 5.1 m/cm with a mean of 4.8 m/cm (35 ft/inches to 42 ft/inches with a mean of 40 ft/inches) is obtained.

Though not statistically significant at the $\alpha = 0.05$, it appears that an age effect may occur for reading a speed limit sign. The mean distances at which the younger, middle, and older groups read the signs were 151.8 m, 112.5 m, and 102.7 m (498 ft, 369 ft, and 337 ft), respectively. Figure 50 provides the mean distances at which the different age groups could read the speed limit.



1 ft = 0.305 m

Figure 50. Bar graph. Mean distance at which speed limit signs were read by each age group.

SUBJECTIVE RATINGS

ANOVAs were conducted on the participant responses for each of the eight Likert-type scale statements presented below:

1. This VES allowed me to DETECT objects sooner than my regular headlights.
2. This VES allowed me to RECOGNIZE objects sooner than my regular headlights.

3. This VES helped me to stay on the road (not go over the lines) better than my regular headlights.
4. This VES allowed me to see which direction the road was heading (i.e., left, right, straight) beyond my regular headlights.
5. This VES did not cause me any more visual discomfort than my regular headlights.
6. This VES allowed me to read signs beside the road sooner than my regular headlights.
7. This VES makes me feel safer when driving on the roadways at night than my regular headlights.
8. This is a better VES than my regular headlights.

Participants were asked to indicate their agreement or disagreement on a seven-point scale ranging from "Strongly Agree" to "Strongly Disagree." ANOVA tables for the analyses of these responses are shown in appendix G.

Table 21 indicates significant main effects for VES ($\alpha < 0.05$) were found for participant responses to all of the statements except number 8, in which the participants indicated agreement with the statement "This is a better VES than my regular headlights." No other statistically significant main effects or interactions were found at the $\alpha < 0.05$ level.

Table 21. Summary of significant main effects and interactions for the Likert-type scales.

Source	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Between								
Age								
Subject/Age								
Within								
VES	x	x	x	x	x	x	x	
VES by Age								
VES by Subject/Age								

x = $p < 0.05$ (significant)

For those statements where a main effect of VES was found, SNK post hoc analyses were conducted to identify differences between the different VESs.

When participants were asked which VES allowed them to detect objects sooner than their regular headlights, they indicated that the NIR 1 VES was the best, with an average rating of

1.17 on a scale of 1 to 7 (1 representing “Strongly Agree” and 7 representing “Strongly Disagree”) (figure 51). Based on participant responses, the HID 2 VES faired worst, with an average rating of 3.67. The mean values of the remaining systems were between 2.06 and 2.61 on the same scale.

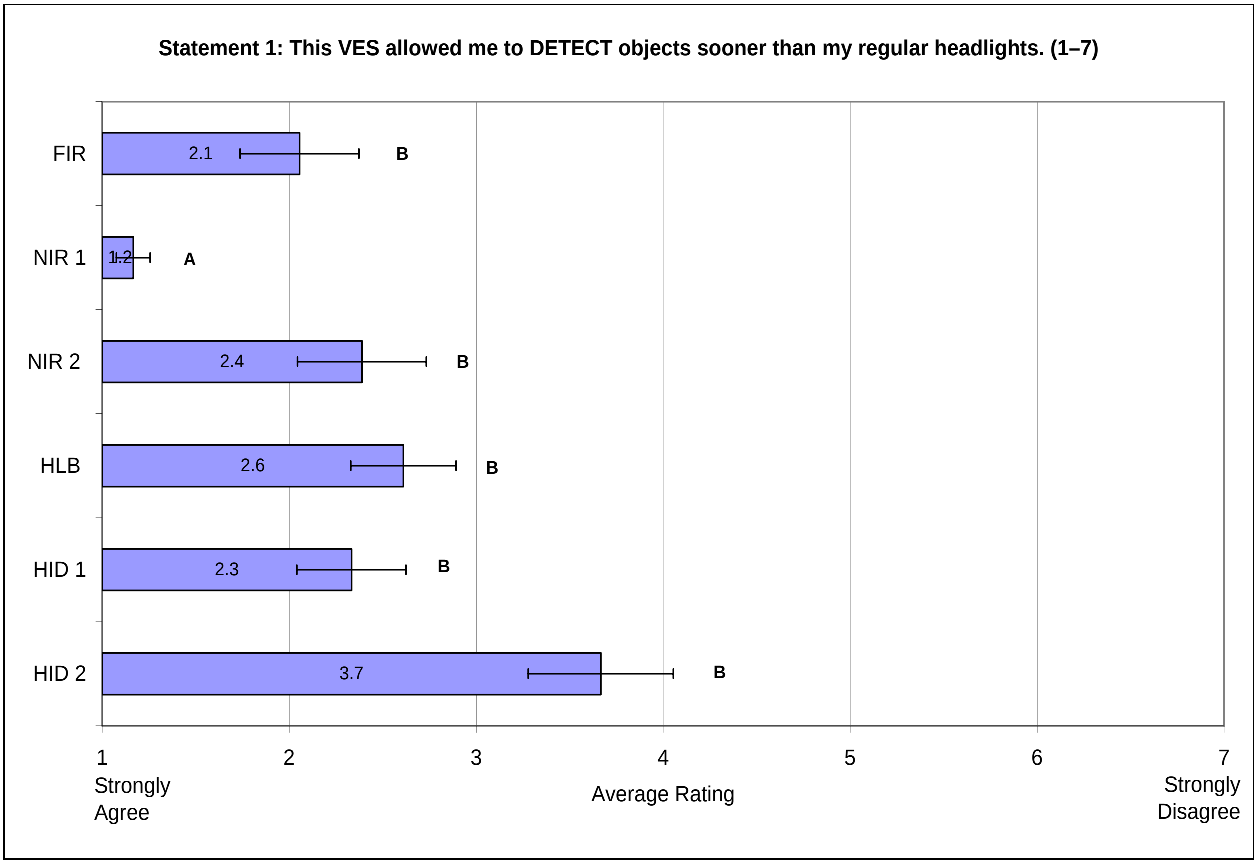


Figure 51. Bar graph. Mean subjective ratings by VES for statement 1: This vision enhancement system allowed me to detect objects sooner than my regular headlights.

With respect to recognition, participants responded that the NIR 1 VES allowed them to recognize objects sooner as compared to their regular headlights (figure 52). The average rating for the NIR 1 was 1.67 on a scale of 1 to 7 (1 representing “Strongly Agree” and 7 representing “Strongly Disagree”) ($\alpha = 0.05$). The FIR, HID 1, and the NIR 2 were not statistically different from the NIR 1 in this measure, with mean response ratings between 2.61 and 2.44. The HLB, with a mean rating of 2.83, was not statistically different from the previous three vehicles. The HID 2 VES received the lowest average rating, at 3.78.

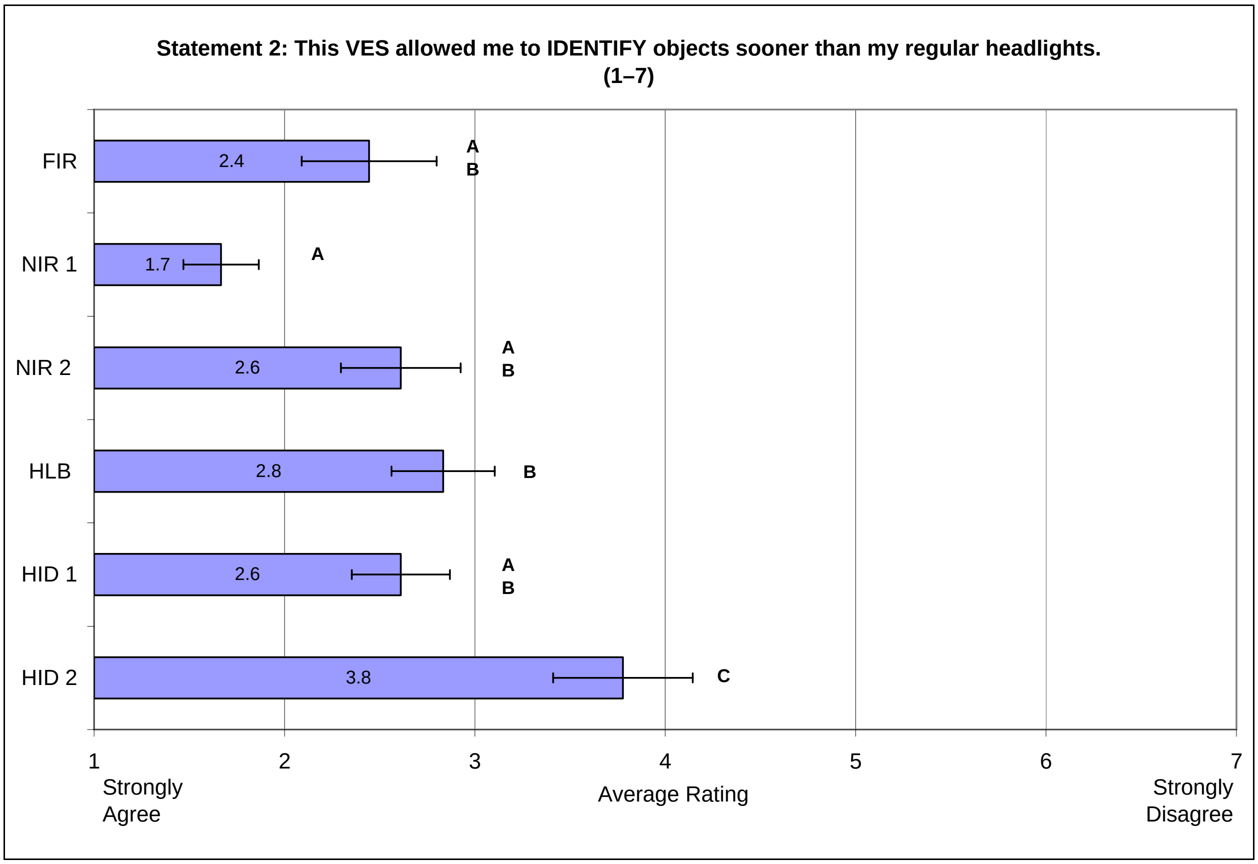


Figure 52. Bar graph. Mean subjective ratings by VES for statement 2: This vision enhancement system allowed me to recognize objects sooner than my regular headlights.

When asked which VES helped them to stay on the road better than their regular headlights, participant responses showed the HID 1 to be the most effective, with an average rating of 3.39 (α = 0.05). This vehicle was not statistically different from the HLB, the NIR 1, or the HID 2. The NIR 2 (mean 4.4) and the FIR (mean 4.7) had mean values on the "Disagree" side of the response scale, indicating that participants felt these systems were not as helpful in staying on the road as their regular headlamps (figure 53).

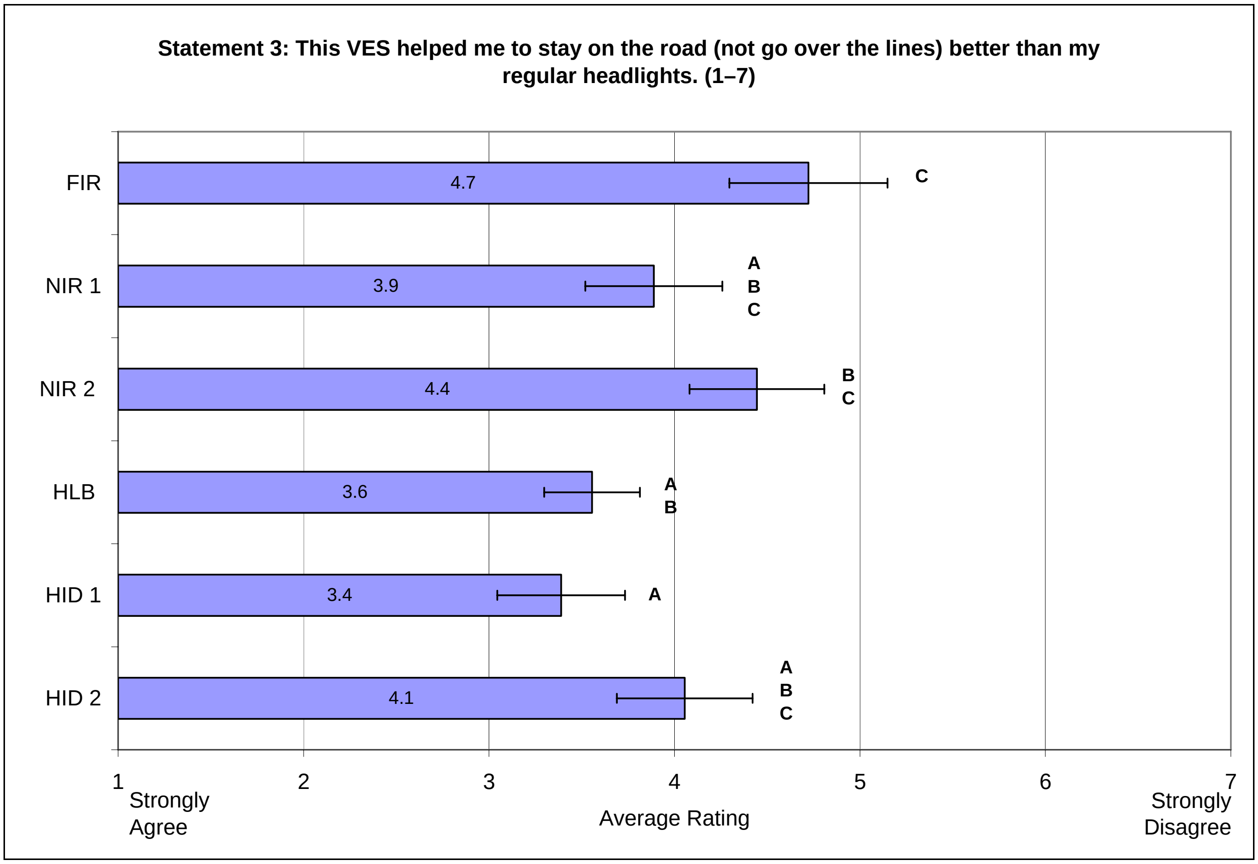


Figure 53. Bar graph. Mean subjective ratings by VES for statement 3: This vision enhancement system helped me to stay on the road (not go over the lines) better than my regular headlights.

When asked which VES allowed the driver to see which direction the road was heading beyond regular headlights, the NIR 1 received the most favorable average rating, at 2.33 (figure 54). The HID 2, with a wide beam profile, faired worst, with an average rating of 3.89. The remaining systems averaged between 2.72 and 3.67 on a 1–7 scale (1 representing “Strongly Agree” and 7 representing “Strongly Disagree”).

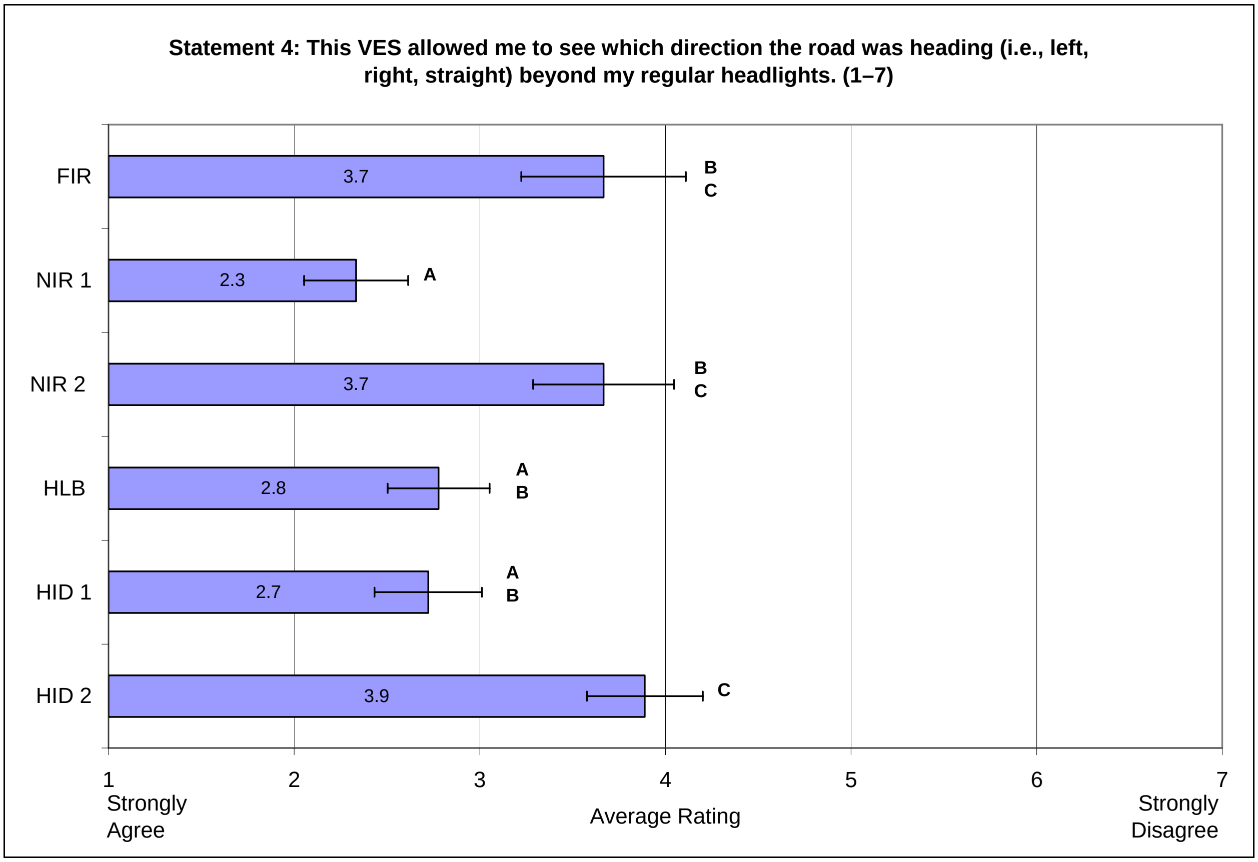


Figure 54. Bar graph. Mean subjective ratings by VES for statement 4: This vision enhancement system allowed me to see which direction the road was heading (i.e., left, right, straight) beyond my regular headlights.

The HID 1 VES was rated the best with respect to causing the least amount of visual discomfort in comparison to normal headlights. The NIR 2 VES received the lowest mean rating of 2.9. The remaining systems averaged between 1.9 and 2.7 on the same scale (figure 55).

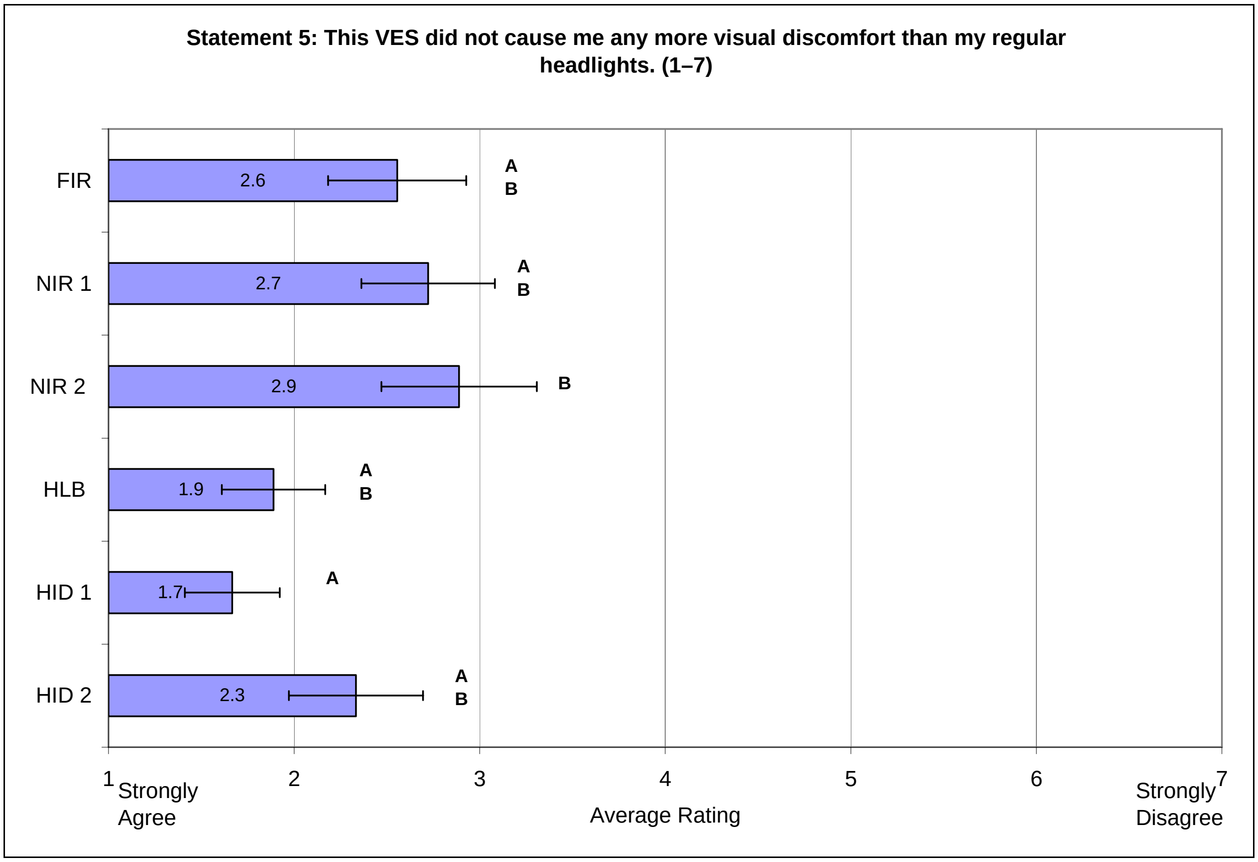


Figure 55. Bar graph. Mean subjective ratings by VES for statement 5: This vision enhancement system did not cause me any more visual discomfort than my regular headlights.

When asked which VES allowed the participant to read signs beside the road sooner than regular headlights, responses showed that participants felt that, overall, the tested headlamps were better than the IR vehicles (figure 56). Specifically, the HID 1 VES was rated best among the vehicles, with an average rating of 3.11 on a scale of 1 to 7 (1 representing "Strongly Agree" and 7 representing "Strongly Disagree").

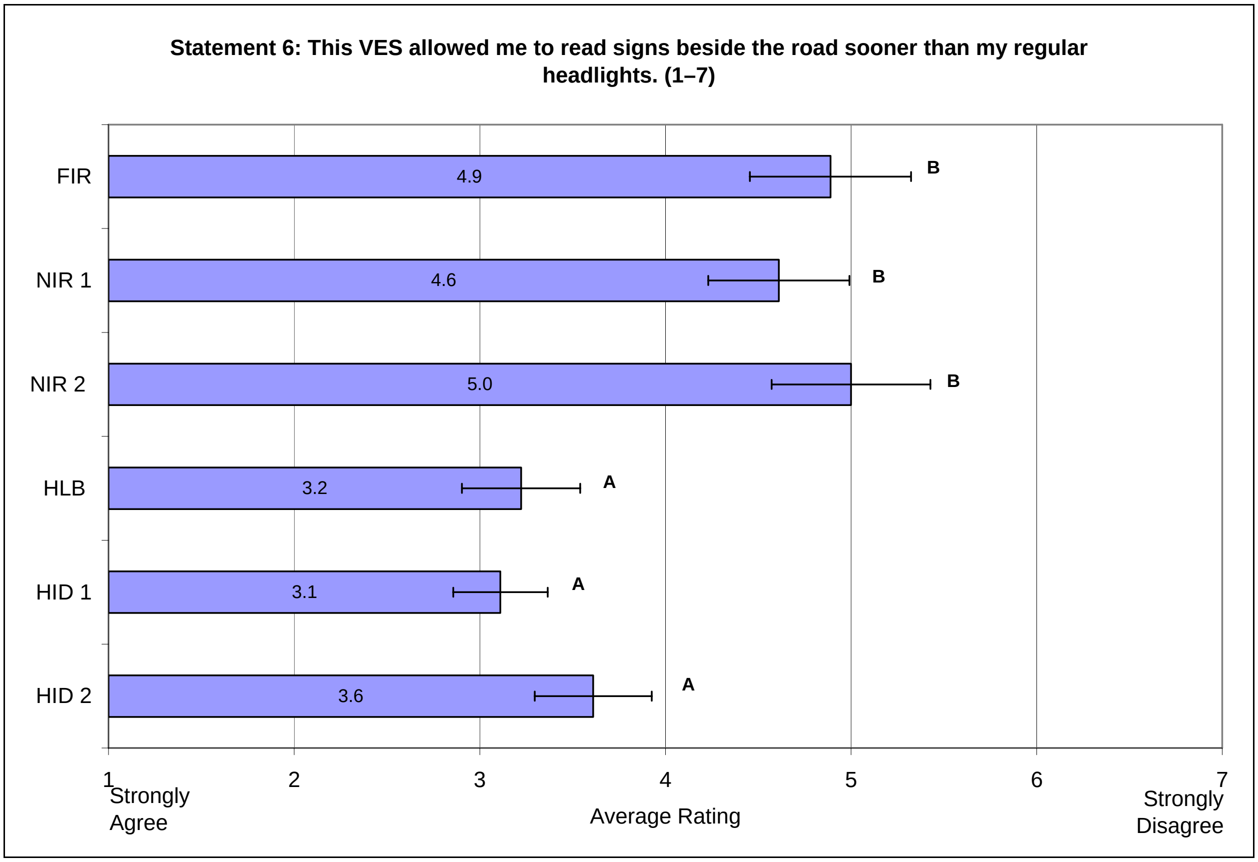


Figure 56. Bar graph. Mean subjective ratings by VES for statement 6: This vision enhancement system allowed me to read signs beside the road sooner than my regular headlights.

With respect to safety while driving at night, responses indicated that participants felt that the NIR 1 VES made them feel safer in relation to normal headlights, with an average rating of 2.2 on a scale of 1 to 7 (1 representing “Strongly Agree” and 7 representing “Strongly Disagree”). While still on the positive side of the scale, the HID 2 VES had the lowest mean rating of 3.7. The remaining systems received average ratings between 2.6 and 2.8 on the same scale (figure 57).

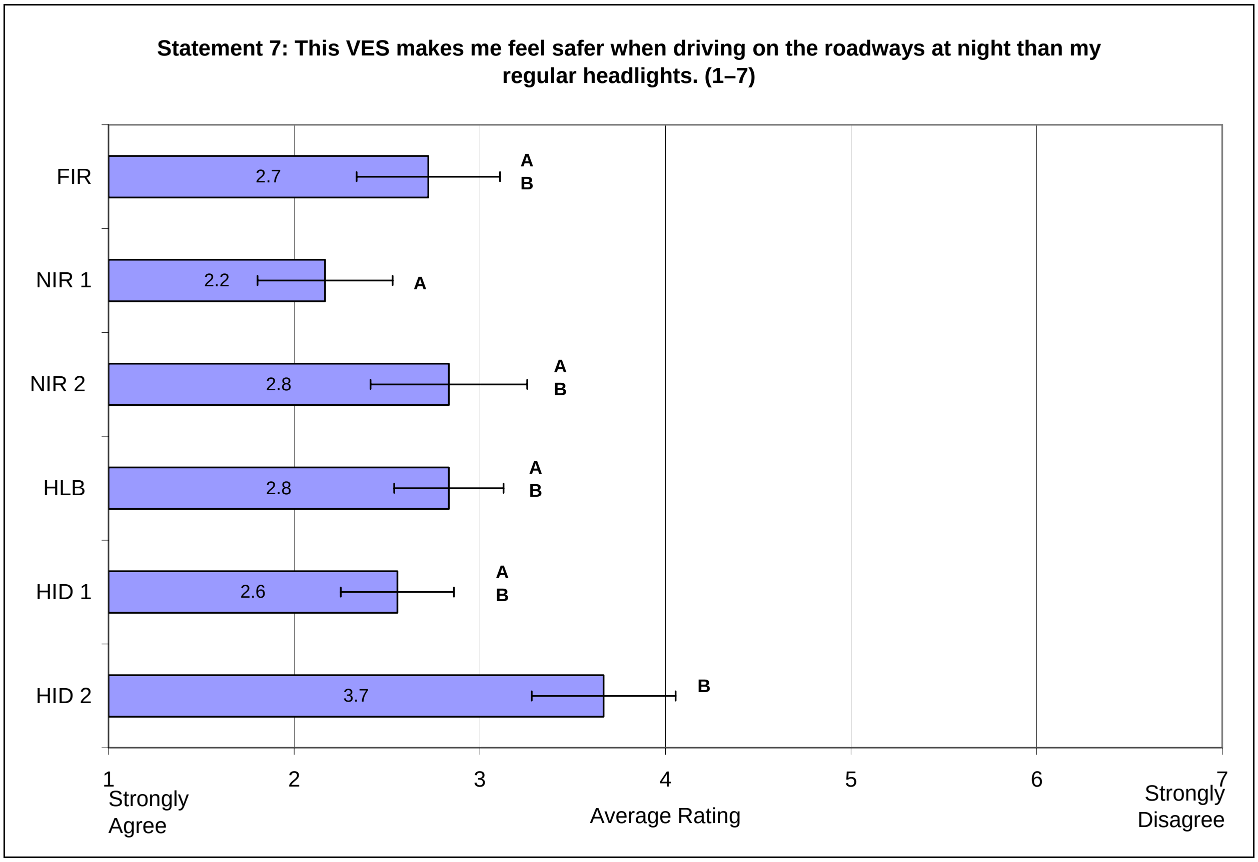


Figure 57. Bar graph. Mean subjective ratings by VES for statement 7: This vision enhancement system makes me feel safer when driving on the roadways at night than my regular headlights.

When asked to respond to the statement, “This is a better VES than my regular headlights,” no significant main effect was found for VES (p = 0.1061) (figure 58).

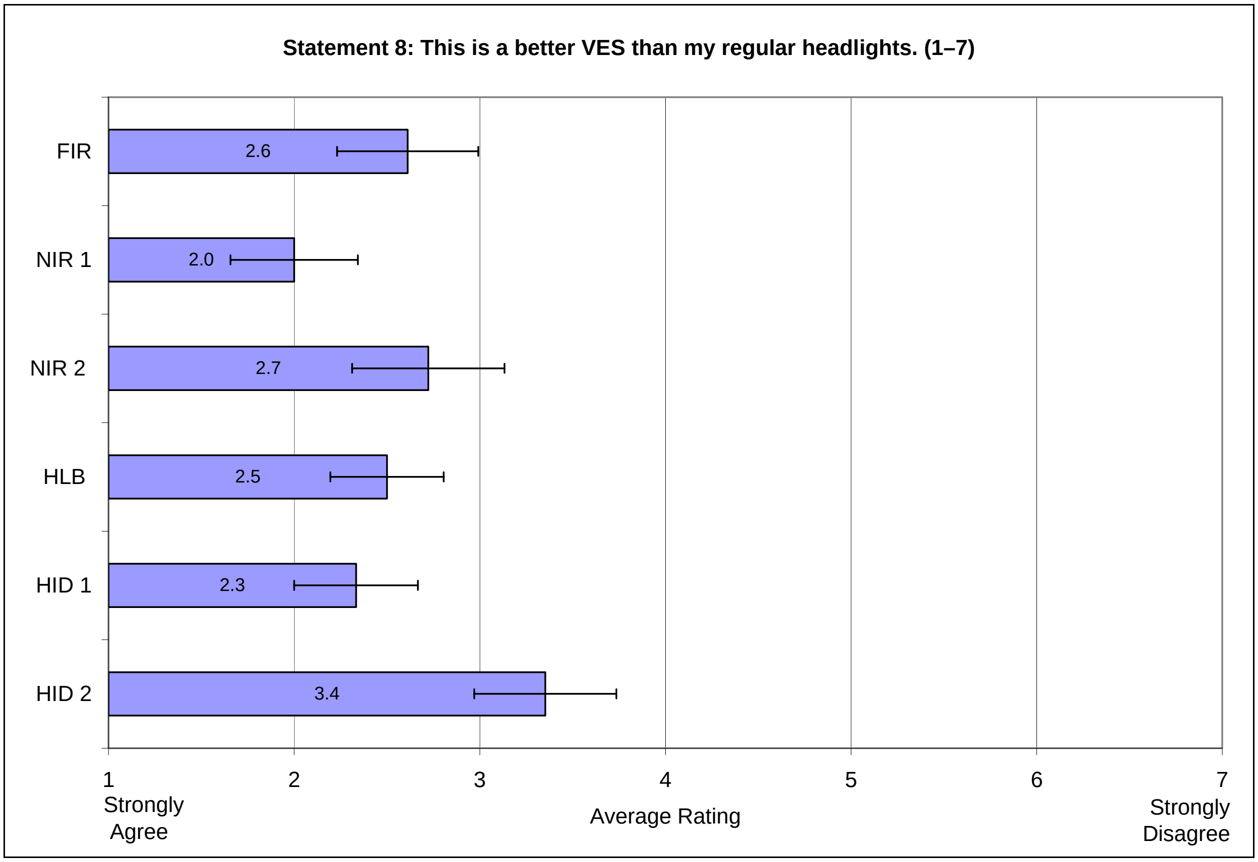


Figure 58. Bar graph. Mean subjective ratings by VES for statement 8: This is a better vision enhancement system than my regular headlights.

CHAPTER 4—DISCUSSION

Approximation of stopping distances provides a method of scaling detection and recognition distances according to what is necessary for nighttime driving. This section first presents approximation of stopping success for each of the scenarios across all of the VESs. The stopping distance approach used here is the same as was presented in ENV Volume III, *Visual Performance During Nighttime Driving in Clear Weather*. Next, a summary of the performance of each of the VESs is provided, with comparisons primarily to the baseline HLB VES. Following these summaries for the different VESs, a discussion is provided regarding areas of particular interest for each VES. This includes a more detailed discussion of points such as age-related findings and items specific to the IR vehicles.

As mentioned in the chapter 2, Methods, 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 baseline headlamp. 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 the detection and recognition distances discussed to this point provide an indication of the advantages of one vehicle over another, they fail to describe any potential safety benefits or concerns based on VES use; however, with a limited number of assumptions, the VES-specific detection distances in clear weather conditions can be compared against various speed-dependent stopping distances. For consistency, time-to-collision will be presented as “distance-to-collision,” or stopping distance, for direct comparisons to the detection distances from the 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 22). 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 in open road conditions is about 2.5 s. (See references 11, 12, 13, and 14.) The equation for braking distance (d_{BD}) is calculated in the equation in figure 59:

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

Figure 59. Equation. Braking distance approximation.

This equation 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 0.6, and a straight, level roadway (gradient G = 0 percent). The final equation appears in figure 60, including distance for brake reaction time and braking distance.

$$d = 2.5V+V^2/2gf$$

Figure 60. Equation. Distance for brake reaction time and braking distance.

Here, distance (d) is in meters or feet, velocity (V) is in m/s or ft/s, and acceleration (g) is in m/s^2 or ft/s^2. The coefficient of friction used for these calculations is based on Lindeburg (1992) [(15)] data for dry surface conditions. The data obtained from Lindeburg (1992) is comprehensive in terms of type of surface, condition of the tires, and speed. A mean value of 0.65 was obtained for the coefficient of friction for dry surfaces (across all dry conditions). To accommodate for most types of vehicles (braking capabilities), a conservative approach was taken, and 0.60 was used as the coefficient of friction for the calculations. Using this approach, stopping distances were calculated at a range of speeds (table 22).

Table 22. Stopping distances needed for a dry 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)	35	68	113	168	235	273
Stopping Distance (ft)	**126**	**197**	**278**	**370**	**474**	**529**

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

The calculations in table 22 represent a simple and ideal condition, but they allow for some visualization of the VESs' capabilities. These stopping distances can be used as a measure of the VESs' ability to provide enough time to detect, react, and brake to a stop at different speeds, but only with some caveats. First, in this study, distances were obtained while drivers were moving at approximately 40 km/h (25 mi/h), and their ability to detect objects will not necessarily remain the same as speeds increase. Second, systems that are currently close to the stopping distance or that need a larger stopping distance might quickly become less effective when conditions such as wet pavement, worn tires, and downhill slope worsen. Third, drivers in this study were alert and looking for a known set of possible objects in the roadway. Table 23 through table 28 present VES and object combinations with mean detection distances that might compromise sufficient stopping distances (shown by an "X").

Table 23. Approximation of stopping success for each object for FIR and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	579						
Pedestrian, Right, Black Clothing	621						
Pedestrian, Left, Denim Clothing	851						
Pedestrian, Right, Denim Clothing	894						
Pedestrian, Left Turn, Left	98	X	X	X	X	X	X
Pedestrian, Left Turn, Right	768						
Pedestrian, Right Turn, Left	698						
Pedestrian, Right Turn, Right	434					X	X
Far off axis, Left	865						
Far off axis, Right	889						
Bloom, Left	898						
Bloom, Right	567						
Dog	259			X	X	X	X
Arrow	174		X	X	X	X	X
RRPM	527						X
Sign	1,764						
Tire Tread	166		X	X	X	X	X

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

Table 24. Approximation of stopping success for each object for NIR 1 and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	436					X	X
Pedestrian, Right, Black Clothing	539						
Pedestrian, Left, Denim Clothing	707						
Pedestrian, Right, Denim Clothing	788						
Pedestrian, Left Turn, Left	500						X
Pedestrian, Left Turn, Right	682						
Pedestrian, Right Turn, Left	536						
Pedestrian, Right Turn, Right	440					X	X
Far off axis, Left	755						
Far off axis, Right	577						
Bloom, Left	635						
Bloom, Right	495						X
Dog	98	X	X	X	X	X	X
Arrow	255			X	X	X	X
RRPM	1,777						
Sign	2,909						
Tire Tread	152		X	X	X	X	X

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

Table 25. Approximation of stopping success for each object for NIR 2 and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	220			X	X	X	X
Pedestrian, Right, Black Clothing	330				X	X	X
Pedestrian, Left, Denim Clothing	409					X	X
Pedestrian, Right, Denim Clothing	455					X	X
Pedestrian, Left Turn, Left	217			X	X	X	X
Pedestrian, Left Turn, Right	386					X	X
Pedestrian, Right Turn, Left	372					X	X
Pedestrian, Right Turn, Right	294				X	X	X
Far off axis, Left	320				X	X	X
Far off axis, Right	177		X	X	X	X	X
Bloom, Left	290				X	X	X
Bloom, Right	307				X	X	X
Dog	70	X	X	X	X	X	X
Arrow	189		X	X	X	X	X
RRPM	947						
Sign	2,694						
Tire Tread	141		X	X	X	X	X

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

Table 26. Approximation of stopping success for each object for HLB and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	269			X	X	X	X
Pedestrian, Right, Black Clothing	374					X	X
Pedestrian, Left, Denim Clothing	452					X	X
Pedestrian, Right, Denim Clothing	599						
Pedestrian, Left Turn, Left	346				X	X	X
Pedestrian, Left Turn, Right	412					X	X
Pedestrian, Right Turn, Left	500						X
Pedestrian, Right Turn, Right	416					X	X
Far off axis, Left	464					X	X
Far off axis, Right	314				X	X	X
Bloom, Left	226			X	X	X	X
Bloom, Right	385					X	X
Dog	135		X	X	X	X	X
Arrow	295				X	X	X
RRPM	1,385						
Sign	2,844						
Tire Tread	186		X	X	X	X	X

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

Table 27. Approximation of stopping success for each object for HID 1 and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	115	X	X	X	X	X	X
Pedestrian, Right, Black Clothing	350				X	X	X
Pedestrian, Left, Denim Clothing	223			X	X	X	X
Pedestrian, Right, Denim Clothing	517						X
Pedestrian, Left Turn, Left	277			X	X	X	X
Pedestrian, Left Turn, Right	288				X	X	X
Pedestrian, Right Turn, Left	469					X	X
Pedestrian, Right Turn, Right	433					X	X
Far off axis, Left	371					X	X
Far off axis, Right	262			X	X	X	X
Bloom, Left	136		X	X	X	X	X
Bloom, Right	348				X	X	X
Dog	117	X	X	X	X	X	X
Arrow	244			X	X	X	X
RRPM	1,493						
Sign	2,749						
Tire Tread	183		X	X	X	X	X

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

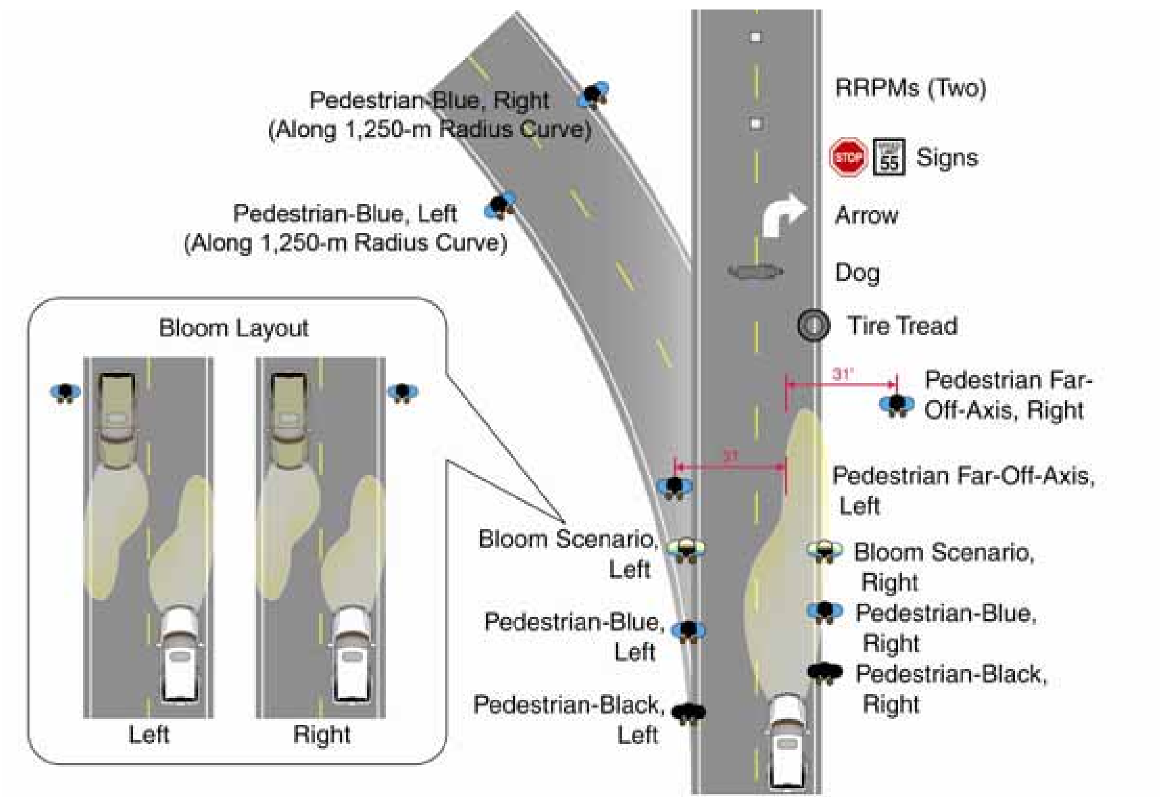
Table 28. Approximation of stopping success for each object for HID 2 and potential detection inadequacy when compared to stopping distance at various speeds.

Type of Object	Detection (ft)	126 ft at 25 mi/h	197 ft at 35 mi/h	278 ft at 45 mi/h	370 ft at 55 mi/h	474 ft at 65 mi/h	529 ft at 70 mi/h
Pedestrian, Left, Black Clothing	90	X	X	X	X	X	X
Pedestrian, Right, Black Clothing	140		X	X	X	X	X
Pedestrian, Left, Denim Clothing	132		X	X	X	X	X
Pedestrian, Right, Denim Clothing	268			X	X	X	X
Pedestrian, Left Turn, Left	167		X	X	X	X	X
Pedestrian, Left Turn, Right	204			X	X	X	X
Pedestrian, Right Turn, Left	319				X	X	X
Pedestrian, Right Turn, Right	264			X	X	X	X
Far off axis, Left	168		X	X	X	X	X
Far off axis, Right	89	X	X	X	X	X	X
Bloom, Left	85	X	X	X	X	X	X
Bloom, Right	182		X	X	X	X	X
Dog	77	X	X	X	X	X	X
Arrow	215			X	X	X	X
RRPM	756						
Sign	2,326						
Tire Tread	154		X	X	X	X	X

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

DETECTION AND RECOGNITION CAPABILITIES SUMMARY

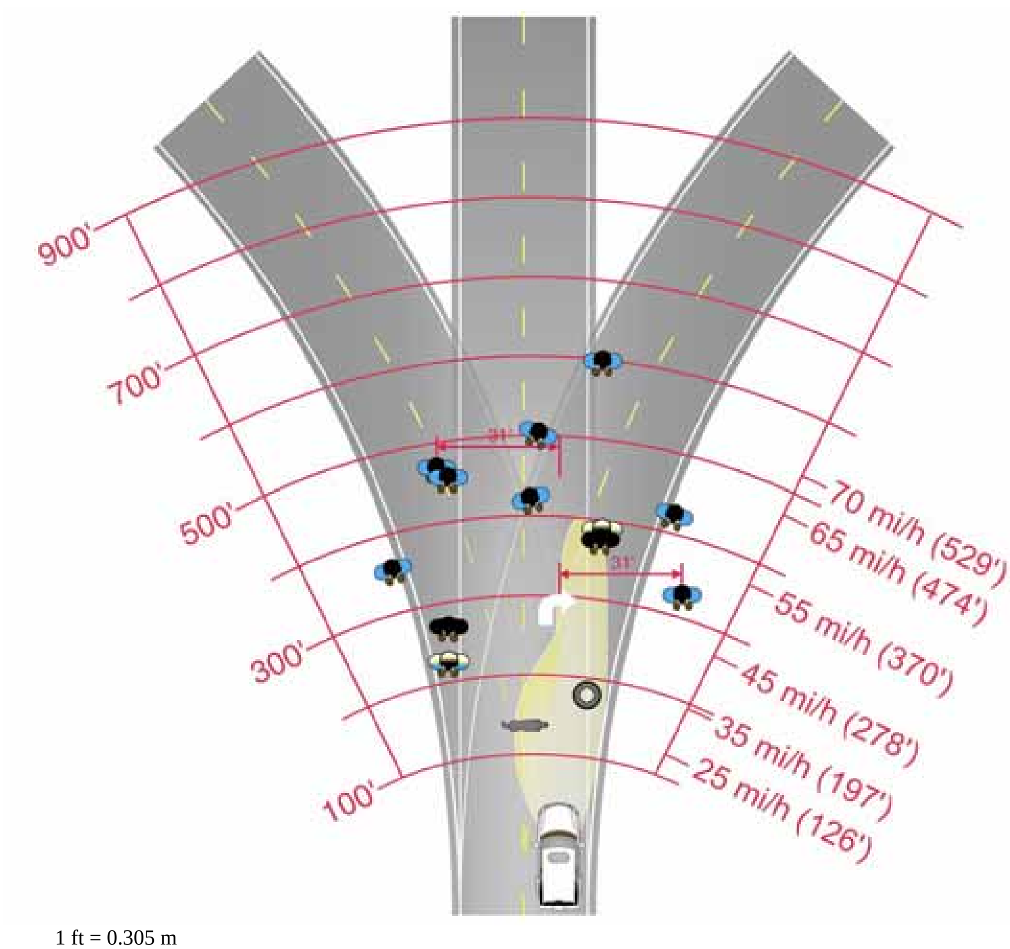
To provide an overall look at the individual performance, graphics are provided for each VES. These graphics depict the detection performance for each of the pedestrian scenarios, the obstacle scenarios (i.e., dog and tire tread), and the turn arrow. Pedestrian icons facing straight down on the diagram were presented on straight road segments. Pedestrian icons angled with the road were presented on the curved road segment. Each graphic is intended to give an overall impression rather than precise comparisons. Additional details are given in the Results section on patterns or items of interest identified in the graphics. In addition, the following Discussion sections use the graphics to provide a quick comparison of the results. Each graphic includes an icon representing mean detection distance for a given object (figure 61). The mean detection distance scale appears on the left side of the diagram. The approximate stopping distance required for given speeds appears on the right side of the diagram. Where an icon is below a given speed, the stopping distance (where required) may be insufficient for the given speed. Stopping distance approximations are discussed in more detail in the Stopping Distance section.



1 ft = 0.305 m
Right curve scenarios mirror left curve

Figure 61. Diagram. Detection distance diagram key.

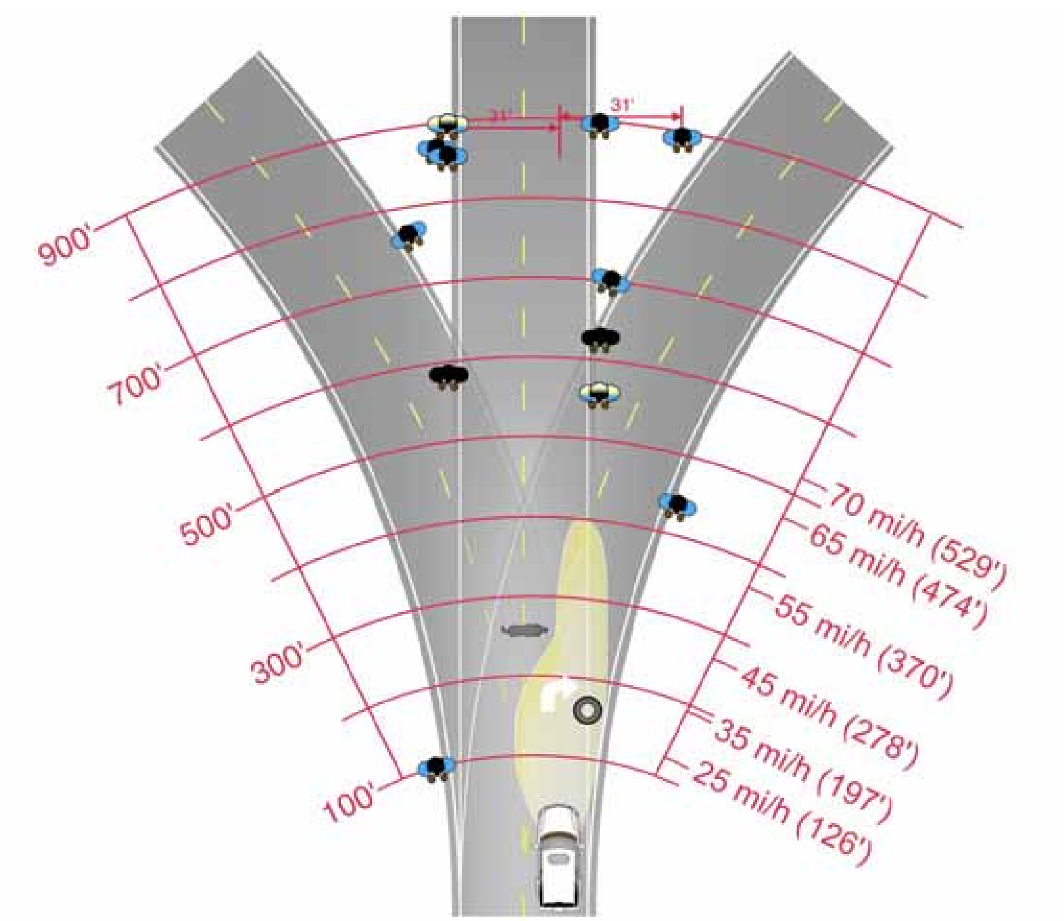
As was found in previous research and likely resulting in part from the alignment protocol used, HLB provided good detection and recognition as compared to the other systems tested. The HLB, which was the baseline for the technologies tested, was better than or equal to the HID vehicles in every scenario tested. The HLB was also better than or equal to the NIR 2 vehicle in every scenario tested. In the pedestrian scenarios tested, the HLB lamps provided sufficient detection distances up to 89 km/h (55 mi/h) for all but the far off axis pedestrian to the right, the pedestrian dressed in black to the left side of the road, and the left-hand bloom pedestrian. The HLB was the best for detecting the turn arrow of any of the vehicles tested. It was surpassed only by the FIR for detecting the dog, and it was equaled only by the HID 1 in detecting the tire tread. Figure 62 indicates the mean detection distances provided by the HLB for all of the tested objects, except RRPMs and signs.



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

Figure 62. Diagram. HLB mean detection distances.

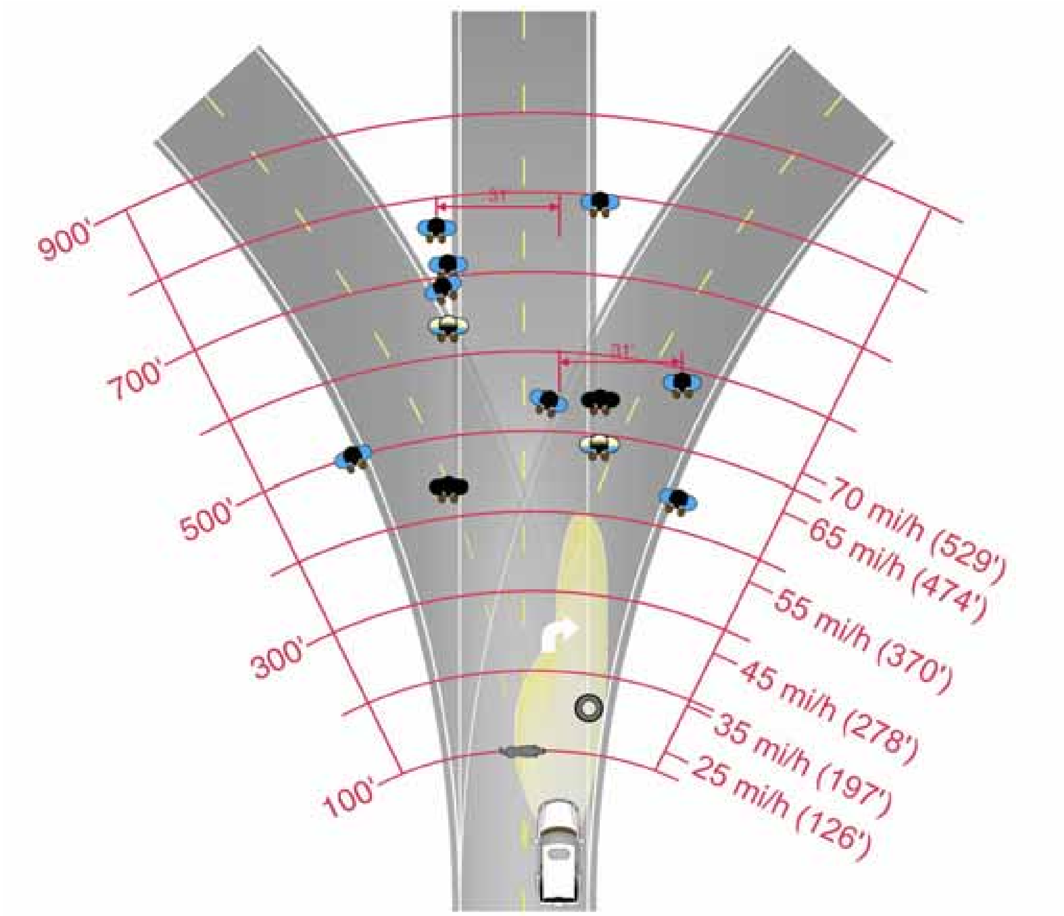
As shown in figure 63, the FIR provided excellent detection of warm-bodied obstacles, was approximately equivalent to the baseline on detecting the tire tread, and had shorter detection distances for retroreflective objects. The distances for the RRPMs and signage appear to be sufficient for normal use. Road markings similar to the turn arrow may be an issue if stopping is required at speeds of 56 km/h (35 mi/h) or more. This is approximately 16 km/h (10 mi/h) lower than speeds possible with the baseline. The FIR provided better detection of pedestrians than did the baseline for all scenarios except for the pedestrian on the right side of the right-hand turn, which was similar to the baseline, and for the pedestrian on the left side of the left-hand turn, which was surpassed by the baseline. The uncharacteristically short mean detection distance for the pedestrian on the left side of a left-hand turn appears to indicate that a wider FOV may be beneficial. This finding is discussed in more detail in the Field of View section of this report.



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

Figure 63. Diagram. FIR mean detection distances.

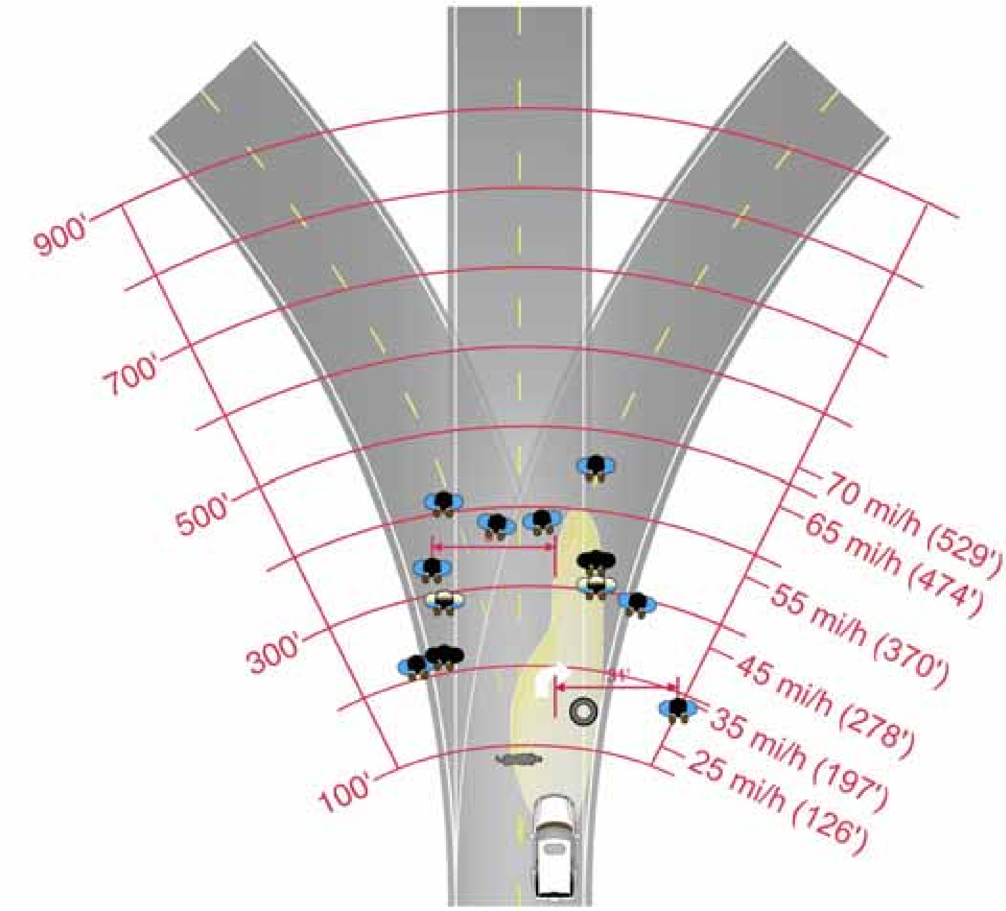
The NIR 1 vehicle provided good overall performance, providing benefits in pedestrian detection over the baseline for all of the pedestrian scenarios except for the two right-hand turn scenarios (figure 64). In these scenarios, the NIR 1 was comparable to the baseline; however, in the dog and turn arrow scenarios, the baseline vehicle gave an approximate 16-km/h (10-mi/h) advantage.



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

Figure 64. Diagram. NIR 1 mean detection distances.

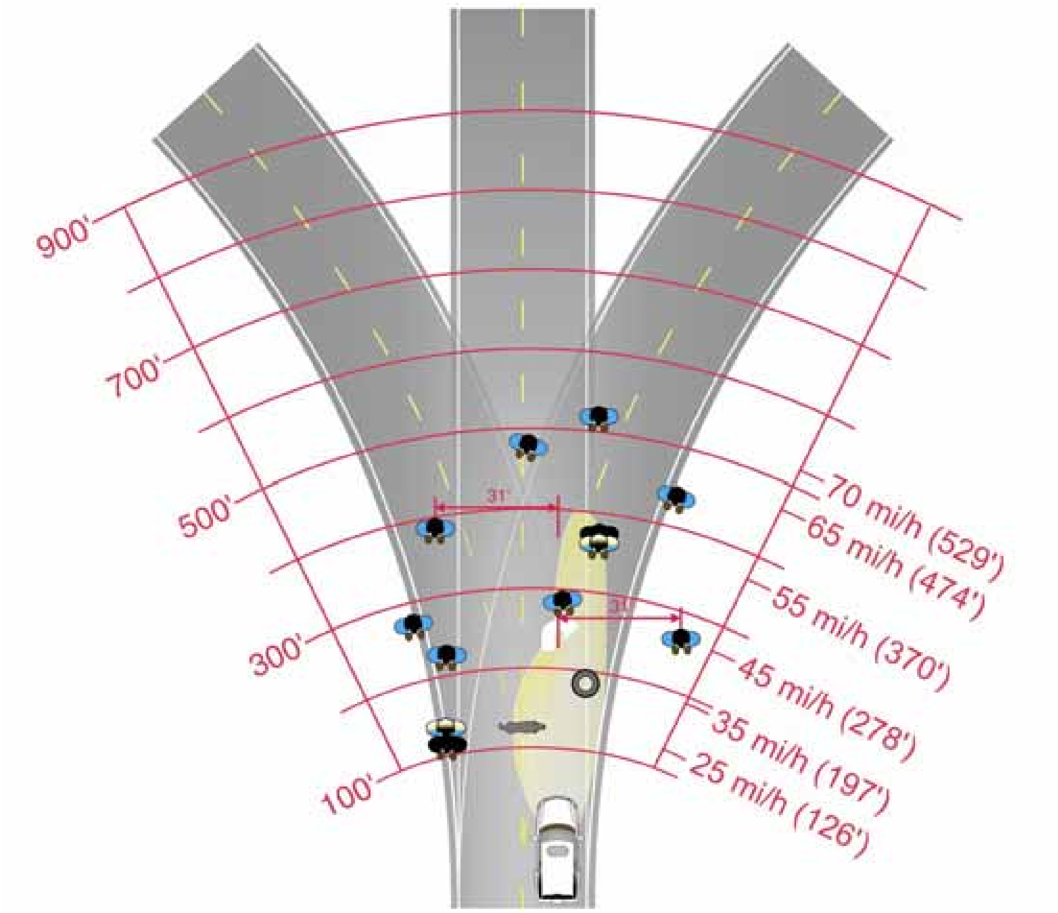
The NIR 2 did not surpass the baseline HLB in any of the scenarios tested. In fact, in 2 of the 12 pedestrian scenarios, in which a pedestrian was on the left side of a left-hand turn and a pedestrian was on the right side of a right-hand turn, it statistically underperformed the baseline. The NIR 2 VES did not perform better than the baseline in the bloom scenarios. For road markings similar to the turn arrow, speeds at or above 56 km/h (35 mi/h) may be excessive if stopping is a necessary response (figure 65). This is approximately 16 km/h (10 mi/h) lower than the baseline.



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

Figure 65. Diagram. NIR 2 mean detection distances.

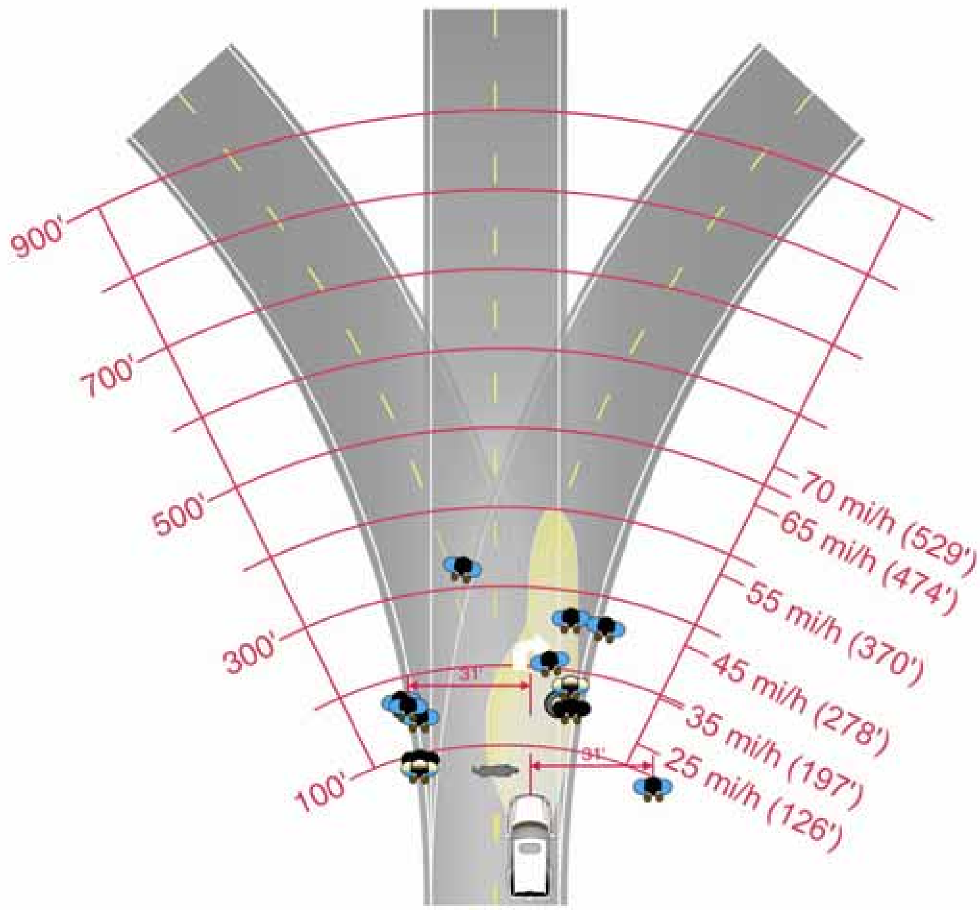
The HID 1 vehicle did not surpass the baseline HLB vehicle in any of the scenarios tested. The HID 1 vehicle had statistically shorter detection distances than the baseline where a pedestrian was on the left side of a left curve and the left side of a straight section in both black clothing and blue clothing. The detection distance for the turn arrow was also statistically shorter than the baseline. This indicates HID 1 would require speeds roughly 16 km/h to 32 km/h (10 mi/h to 20 mi/h) lower than HLB's speeds to stop in response to the pedestrians on the left (figure 66).



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

Figure 66. Diagram. HID 1 mean detection distances.

The HID 2 VES underperformed the baseline in all of the tested scenarios in which the pedestrian was on the left (except for the left-hand bloom scenario), the pedestrian far off axis to the right scenario, and the tire tread. Based on stopping distance approximations, if complete stopping was necessary, the HID 2 VES appears to provide insufficient detection distances for responding to any of the pedestrian scenarios at speeds of 89 km/h (55 mi/h) or greater. For all of these pedestrian scenarios in which a pedestrian was on the right side of the road, nearest to the driver's lane of travel, speeds of 72 km/h (45 mi/h) or greater appear to be too fast when stopping is required (figure 67).



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

Figure 67. Diagram. HID 2 mean detection distances.

AGE EFFECTS ON DETECTION AND RECOGNITION

Of the three types of objects tested—pedestrians, obstacles, and retroreflective objects—only the pedestrian scenarios indicated age-related differences due to VES (i.e., Age by VES interactions). All of the age groups did better overall in detecting pedestrians with the NIR 1 and the FIR than with the other VESs.

General age effects, regardless of VES, indicated that age was a factor in both detecting objects and differentiating signs. From the object group analysis, it appears that the older group (65 years and older) had shorter detection distances overall, and the younger (18 to 25 years) and middle groups (40 to 50 years) were similar for obstacle detection; however, the younger group performed better than the middle group when detecting pedestrians. When differentiating a stop sign from a yield sign, the younger group had significantly longer distances than did the middle and older groups. Differentiation occurred for the younger group at approximately 335.3 m (1,100 ft), while the differentiation for the middle and older groups occurred at approximately 213.4 m to 243.8 m (700 ft to 800 ft). The p value for this age effect when reading a speed limit sign was 0.0513, which does not meet the $p < 0.05$ criteria; however, this finding probably agrees with an expected lower visual acuity found in older age groups.

AGE AND VES INTERACTIONS

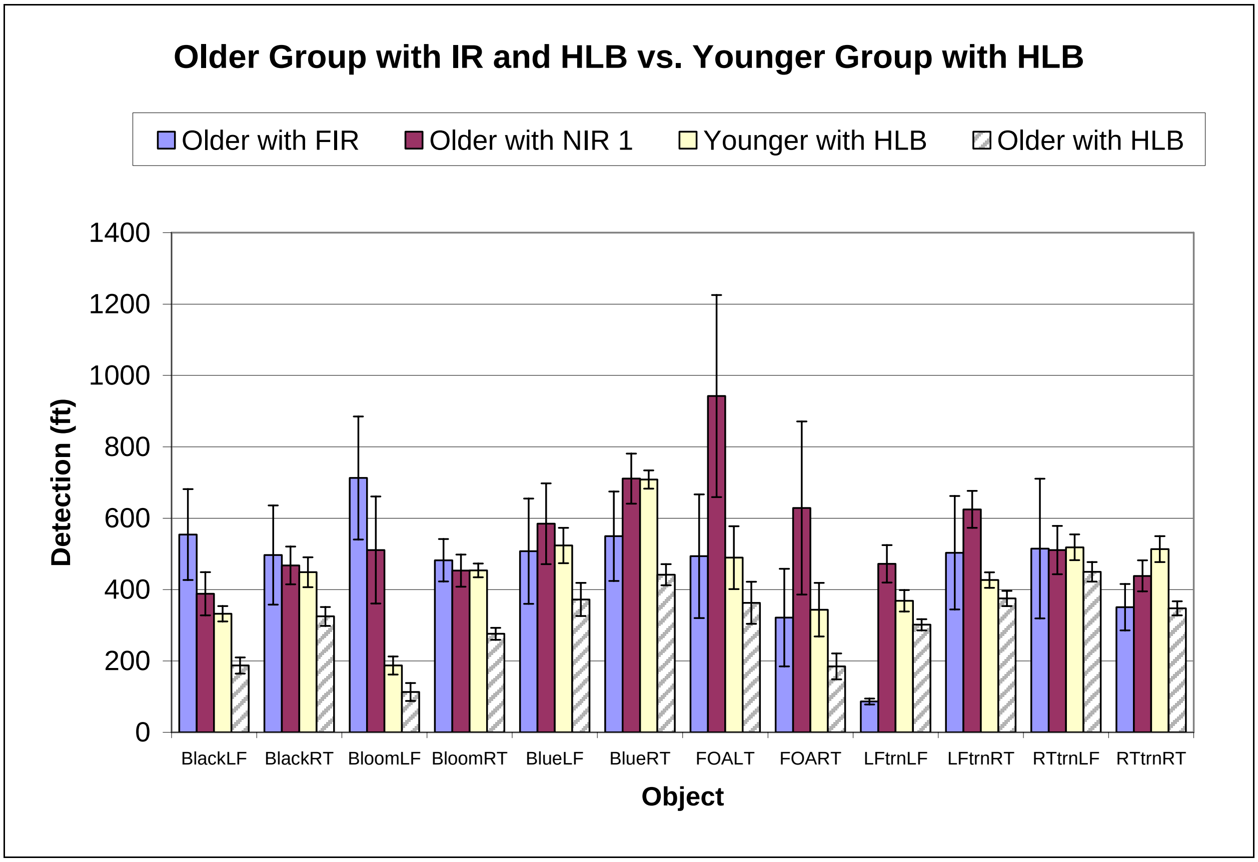
Although all subjects appeared to benefit from the IR VESs, the older subjects appeared to benefit more from the NIR 1 than the FIR. The opposite was true for the younger and middle-aged groups. It is somewhat surprising that the older subjects were not able to obtain the same benefit from the FIR as they did from the NIR. It appears that the older age group may not have experienced the same benefits as the younger and middle-aged participants in detecting pedestrians with the FIR vehicle. That is to say, for the younger group and the middle group, in many pedestrian detection scenarios, the FIR had longer detection distances than the NIR 1. In several cases, the NIR 1 appeared to give an advantage to the older group as compared to the FIR system. These cases and a comparison of the systems are provided below.

As is true for all of the age groups combined, specific comparison of older drivers with an IR system to older drivers with the benchmark indicates greater performance with the IR systems.

To characterize the extent of IR technology's benefits for older users further, the older group's performance with the two leading IR VESs was first compared to that group's performance with the benchmark HLB VES. Figure 68 portrays the values used in this comparison.

With the NIR 1 VES, the older group performed better than with the benchmark in 11 of the 12 pedestrian scenarios. In the right turn scenario with a pedestrian on the left side of the road, the older group's NIR 1 performance was essentially equivalent to the HLB. Again for the older group, when comparing the FIR to the HLB, the performance with the FIR VES was better in 4 of the 12 pedestrian scenarios (pedestrians dressed in black on straight segments and the bloom scenarios). The older group's performance on the left turn with a pedestrian on the left scenario was better with the HLB than with the FIR VES. Note that this lower performance of the FIR VES in this scenario was present for the younger and middle-aged groups as well. For the remaining seven scenarios, the performance with the FIR VES was similar to the performance with the HLB. From the comparisons of these IR vehicles to the HLB vehicle, it is clear that the IR provides benefits in the tested scenarios.

Next, the performance of the younger group with the HLB was used as a comparison point for the older group's performance with the IR vehicles. The nighttime detection and recognition capabilities of the older drivers are in general lower than the capabilities of younger drivers. Through comparison of younger drivers with the HLB benchmark to older drivers with an IR system, it is possible to estimate the extent to which an older user might benefit from the use of an IR vehicle. Figure 68 provides a performance comparison of the younger participants using the HLB to the older participants using the FIR and NIR 1 VESs. It appears that the participants 65 years and older driving with the NIR 1 were able to detect pedestrians about as well as the 18-to-25-year-old participants driving the vehicle with HLB. Where this comparison indicates underperformance of the older group using an IR vehicle, it is important to remember that this is a comparison of the older group to the younger group. In almost every scenario, the older group using an IR vehicle outperformed itself using the HLB.



1 ft = 0.305 m

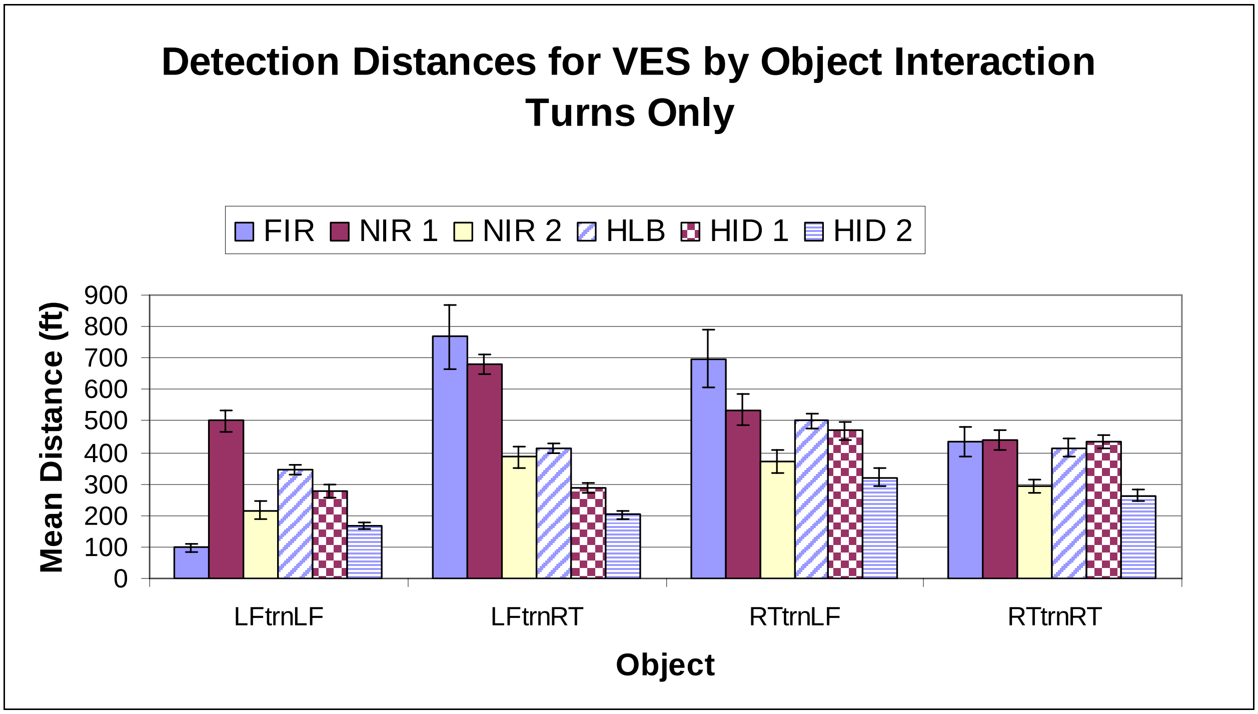
Figure 68. Bar graph. Mean detection distances of pedestrians for older group with IR versus younger group with HLB.

The older group with the NIR 1 outperformed the younger group with HLB on 4 of the 12 scenarios, performed similarly for 7 scenarios, and underperformed the younger group with the HLB on only 1 scenario. When the older group using the FIR was compared to the younger group using HLB, the older group outperformed the younger on 2 of the 12 scenarios, performed similarly on 7 scenarios, and underperformed the younger group on 3 of the scenarios.

PERFORMANCE IN CURVES FOR ALL VISION ENHANCEMENT SYSTEMS

The most critical curve scenario, making a right turn with a pedestrian standing on the right side of the road, is discussed first. In this scenario, most systems were similar to each other, with detection distances between 126.5 m (415 ft) and 131.1 m (430 ft). This group includes the HLB, HID 1, NIR 1, and the FIR vehicles. Detection distances in this scenario were shorter for the NIR 2 and the HID 2, with means approximately 30 percent shorter than the other systems.

Figure 69 indicates the mean detection distance for each of the VESs for pedestrian detection in curves.



1 ft = 0.305 m

Figure 69. Bar graph. Mean detection distances for VES by Object (people) interaction, turns only.

In the next most critical scenario, where a pedestrian is standing on the right side of a left-hand curve, both the FIR and NIR 1 VESs allowed for detection of the pedestrian earlier than all of the headlamp-only systems. The NIR 2 vehicle was comparable to the HLB vehicle in this scenario. It appears that with the clear view into the turn as the driver looks across the oncoming lane, the FIR and NIR 1 vehicles were able to present the pedestrian earlier. For headlamp systems with an extended beam pattern in the right lane, sufficient light reaches a pedestrian on the left later when making this same turn. This is particularly true when there is a distinct cutoff in the beam pattern, such as with the HID 1; however, in right turns the display-based systems and the headlamp systems are similar; the extended beam pattern to the right permits detection of the pedestrian at a distance that is essentially the same as when the pedestrian becomes visible on the IR display.

When comparing the headlamp-based vehicles to each other for turns, the HID 2 vehicle underperformed both the HLB and HID 1 vehicles in all scenarios. The HID 1 VES is comparable to the baseline HLB in right turns with the pedestrian on either the side of the road; however, in the turn to the left, the HID 1 had significantly shorter detection distances than the HLB when the pedestrian was on the left side of the road. This characteristic of lower performance to the left agrees with the performance findings in the straight road pedestrian scenarios as well.

Performance of the FIR and NIR 1 vehicles varied with curve and pedestrian location. In left turns, these systems appeared to provide advantages where FOV was sufficient. It appears that with the IR-based VESs with an 11.7° FOV, a pedestrian standing on the left side of the road in a left-hand, 1,250-m curve may not have entered the view of the IR system. The reader is referred to the Field of View section of this report for further discussion.

CLOTHING COLOR

While the effect of blue clothing versus black clothing on nighttime visibility seemed clear for traditional halogen lamps, it was not certain what the outcome would be for IR-based vehicles. The two pedestrian scenarios conducted on straight segments permitted a comparison of the effect of blue clothing versus black clothing on detection distances.

All of the VESs demonstrated longer detection distances for pedestrians dressed in blue clothing than for pedestrians dressed in black clothing. The FIR vehicle had the lowest differences. This is to be expected because the FIR is based on thermal differences between the object and the background rather than on differences in the visible spectrum; however, it is still surprising that blue had longer detection and recognition distances than black for this system. There are a few possible explanations for this result:

- The blue denim clothing may have exhibited temperature behavior that made it more visible than the black. The denim cloth was thicker than the black cloth and a different blend. The denim may retain heat within the material making it a distinct thermal object. The black may have allowed body heat to mix with the cooler ambient air more randomly or conversely, providing a thermal barrier that obscured the body temperatures while reflecting the cooler ambient temperatures. Either condition would make the black a less distinct thermal outline in the display and possibly to the IR sensor itself.

- Participants, in general, may have seen the blue earlier using visible light rather than solely through the IR system.

- Some participants may have waited to announce their detection of an object until they could confirm the presence of an object visually, and blue objects become visible earlier (at greater distance) than do black objects. This would increase the overall mean for the combination.

Whether in black clothing or denim, pedestrians on the left were more difficult to detect than pedestrians on the right. This pattern was present in the recognition distances as well.

The comparison of HID headlamps to halogen headlamps was also of interest in relation to clothing color. The HID 1 VES had the most similar overall detection and recognition distances to the HLB VES and so can be used to investigate relationships between headlamp type (i.e., beam patterns between the two types of headlamps make this relationship difficult to determine clearly. Table 29 shows a percentage improvement in detection distance for each of the systems for the two comparable pedestrian scenarios.

Table 29. Percentage improvements in detection distance for two comparable pedestrian scenarios.

	Black Left Side (ft)	Blue Left Side (ft)	Blue Percentage Longer, Left Side	Black Right Side (ft)	Blue Right Side (ft)	Blue Percentage Longer, Right Side	Overall Blue Percentage Longer
FIR	579	851	47	621	894	44	45
NIR 1	436	707	62	539	788	46	54
NIR 2	220	409	86	330	455	38	62
HLB	269	452	68	374	599	60	64
HID 1	115	223	94	350	517	48	71
HID 2	90	132	46	140	268	92	69

1 ft = 0.305 m

The overall benefit obtained from the blue clothing over the black clothing for the HLB was 64 percent. The improvement for the HID 1 was 71 percent. Comparing the differences between left and right indicates possible differences between the two because of the beam pattern. With the HID 1, pedestrians in blue on the left side of the road were detected 94 percent farther away than those in black on the same side. With the HLB, the pedestrians in blue were detected only 68 percent farther away than black. Looking now at the right side of the road, which was more highlighted by the beam patterns, the advantage of blue clothing drops to 48 percent longer detections for the HID 1, and it drops to only 60 percent for the HLB. It appears that the more diffuse beam pattern of the HLB may be generating similar left-right values, while the more discrete pattern of the HID 1 makes the blue clothing have more of an advantage on the left side than on the right. The aiming pattern of the HLB also likely influenced this finding.

SUBJECTIVE MEASURES

Participant Acceptance

To evaluate users' acceptance of the VESs, the subjective ratings provided after driving with each system can be used. In particular, three statements that required the participant to evaluate the VES in comparison to his or her own headlamps provide insight into customer acceptance. One statement required the participants to indicate if the VES was better than their regular headlamps, and the other asked them to indicate if the VES made them feel safer. In terms of better performance, no differences were found between the VESs. In terms of feeling safer, NIR 1 received a higher rating than HID 2; the others were not distinguishable. All responses were above neutral.

The NIR 1 had the most positive participant indications for providing detection and recognition benefits over normal headlamps. HID 2 had the worst evaluation.

When asked if the VES helped them stay on the road better than their regular headlamps, participants did not score the VESs far from the neutral rating overall; however, it appears that the participants' perception is that the NIR 1, the HLB, and the HID 1 provide some advantage in seeing where the road is heading, while responses indicate that the HID 2 provided the least advantage in terms of seeing the road's direction.

Participant responses indicated that the IR VESs did not allow them to read roadside signs sooner than regular headlamps, whereas the headlamp systems did. When indicating if the VES allowed them to read signs beside the road sooner than regular headlamps, responses for the IR systems indicated disagreement with the statement, while responses for the headlamp systems indicated agreement.

As was expected, the participants' subjective responses do not necessarily reflect their performance differences between the VESs. This may occur for several reasons. A new technology may be thought of as better when compared to a familiar technology. Also, people may not be good judges of their performance. Greater light in the foreground may give the perception of better visibility while actual detection capabilities may not be better. Examples where subjective measures did not reflect actual performance can be seen when comparing HID 1 to the baseline halogen headlamps. In the subjective ratings, while the HID 1 VES was not statistically different from the baseline in any of the statement responses, it frequently had higher ratings (lower numerical scores) than the HLB VES; however, in the detection measures, the HID 1 demonstrated lower capabilities in some scenarios.

The HID 2 VES scored below the baseline on subjective evaluations of detecting and recognizing objects, seeing where the road was heading, and feeling safer. The NIR 1 surpassed the baseline on the evaluation of its ability to detect objects sooner than regular headlamps. As with the other IR vehicles, it was less helpful in reading signs than regular headlamps.

Open-Ended Comments on VESs

Comments about a specific VES that occurred with 2 or more out of the 18 participants were as follows:

FIR

- Can't read signs. Would like to be able to. (6 participants)
- Good. (4 participants)
- Not wide enough view. (4 participants)
- Not a lot of help. (3 participants)
- Wish display would show road line. (3 participants)
- Reflections of mirror obtrusive/too bright. (2 participants)

NIR 1

- Annoying reflection of display in windshield. (5 participants)
- Signs are too bright and blurry/can't read. (5 participants)
- Good. (5 participants)
- Glare when passing guardrails. (2 participants)

NIR 2

- Needs to be clearer, sharper, brighter, bigger. (7 participants)
- Sign has too much glare. Can't read. (4 participants)
- Seems fine. (3 participants)
- Need to increase width to the left on inside of curve. (2 participants)
- When road is rough, display is blurry. (2 participants)
- Need to be able to see farther/no more depth than regular headlamps. (2 participants)
- Liked FIR better. (2 participants)

HLB

- Couldn't tell difference between these lights and regular lights. (3 participants)
- Well done. (3 participants)
- Lights should provide wider field. (2 participants)

HID 1

- Good. (5 participants)
- Lights should be higher—more depth, farther down road. (2 participants)
- Hard to see with oncoming headlights. Can see better than regular headlights, but not much differently than high beams. (2 participants)

HID 2

- Beams need to be higher. (3 participants)

IR TECHNOLOGIES PERFORMANCE SUMMARY

Active IR versus Passive IR

Consideration of selected objects can provide some insight into the performance comparison between NIR (active) and FIR (passive) technologies. For this comparison, the results from the FIR and the NIR 1 will be used. Analysis of the pedestrians on the right side of the straight road segments provides a method for minimizing the effects of FOV between the NIR and FIR systems tested in this study; therefore, the pedestrian in black on the right, the bloom scenario with a pedestrian on the right, and the pedestrian in denim on the right will be used for this analysis.

Pedestrians in black on the right side of the road were detected roughly 24.4 m (80 ft) (13 percent) farther, on average, with the FIR vehicle than with the NIR 1 vehicle. Pedestrians in denim clothing on the right side of the road were detected approximately 30.5 m (100 ft) (12 percent) farther, on average, with the FIR than the NIR 1. In the bloom scenario, the pedestrian on the right was detected approximately 21.3 m (70 ft) (13 percent) farther with the FIR than the NIR 1. It appears that the FIR VES drew attention to the presence of (i.e., detected) pedestrians 21.3 m to 30.5 m (70 ft to 100 ft) earlier than the NIR 1 VES. It is important to note that the shortest of the measures found with IR vehicles for each of these pedestrian-on-the-right scenarios were well past the best detection range for any of the headlamps in the same scenario. This finding indicates that the differences between the FIR and NIR VESs being discussed are due to the IR systems rather than to headlamp differences on the platform vehicles. Comparison of the dog and the tire tread provide additional insight into the performance of these two VESs. For both FIR and NIR 1, detection and recognition of the dog and tire tread occurred at less than 79.3 m (260 ft), so differences in the vehicle platforms headlamp could be involved.

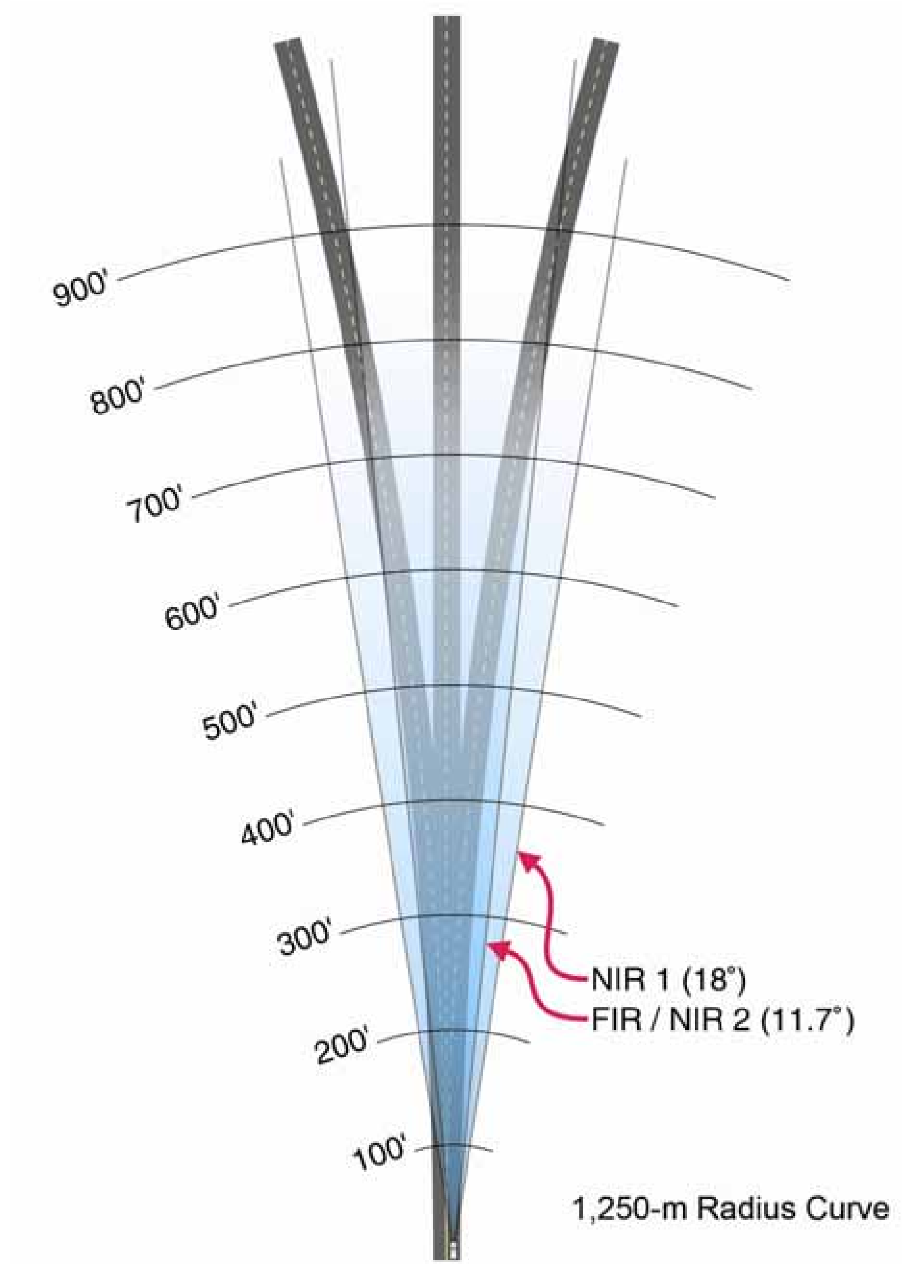
For the tire tread, the mean detection distances were essentially the same for the FIR and NIR 1 (less than 4.6 m (15 ft) mean difference); however, for the dog, the detection distance with the FIR VES was 78.9 m (259 ft), which was 48.8 m (160 ft) earlier than with the NIR 1 VES. These detection distances indicate that the FIR may support sufficient stopping distances up to approximately 64.4 km/h (40 mi/h) in this scenario, while the NIR may be limited to approximately 32.2 km/h (20 mi/h). The less visually conspicuous warm-bodied objects, similar to the dog, require faster response times. It also appears that the additional time an FIR system provides for detection of these smaller warm-bodied objects could be used by the driver. Using the tested systems as general approximations in terms of sensing and display capabilities of the technology types (i.e., FIR or NIR), it appears that an FIR system provides detection benefit over an NIR system in detecting warm objects. Both types of system appear to provide detection in time for stopping at typical driving speeds.

For signs and RRPMs, the NIR 1 vehicle outperformed the FIR vehicle. Though detection with the NIR vehicle was 335 m (1,100 ft) farther than with the FIR vehicle, detection distances for both vehicles were more than 520 m (1,700 ft), well within the necessary distances for responding to signage. The mean detection distance for the RRPMs with the FIR was 160.6 m (527 ft), which is at the stopping limits for speeds above 113 km/h (70 mi/h). This speed drops to 56 km/h (35 mi/h) for the turn arrow for both the NIR 1 and FIR VESs. The mean detection distances for the turn arrow and the tire tread were similar to each other for the FIR vehicle.

Field of View

The FIR system was better at detecting pedestrians on the left side of the road than was the NIR 1 in most cases, but they were similar for pedestrians on the right. This holds true for the pedestrians in black on a straight section and pedestrians in blue on a straight section, in a right turn, and in the bloom scenario. Two explanations are proposed for this difference: (1) the amount of NIR light hitting pedestrians on the right side of the road was more than on the left and (2) differences in FOV make objects in the center more conspicuous for the narrow FOV system (FIR) than for the wide FOV system (NIR 1). To evaluate whether FOV affected performance at various angular distances from the vehicle longitudinal axis, detection distances for the pedestrians in denim at the far off axis location and turn locations may be compared to the pedestrians in denim on the straight sections. Discussion here will simply determine if the vehicles performed sufficiently well. In terms of performance at freeway speeds, the FIR VES, with a narrower FOV (11.7°), had insufficient approximated stopping distances throughout the speed range when a pedestrian was standing on the left side of a left-hand turn. The wider-angle NIR 1 VES (18°) had longer mean detection distances and therefore acceptable stopping distances for this scenario. As mentioned previously, the detection distance in this scenario was uncharacteristically short for the FIR system.

For a possible explanation of these findings, an analysis of the road geometry and FOV was performed. The analysis involved a review of the systems' FOVs on the curve used in the study, as well as a re-creation of the scenario based on computer-aided design (CAD) (figure 70). Review of the system display with a pedestrian on the road at the position tested in this scenario indicated that the pedestrian on the left in the left turn was not visible in the 11.7° system; however, the driver's track in the lane could vary the outcome of this test somewhat. The diagram in figure 70 illustrates the CAD-based analysis that was also conducted. The analysis indicates that a pedestrian in this position would probably appear just outside the view of the 11.7° FOV system. The pedestrian stood on the inside of the left-hand curve 1 ft (0.305 m) to the outside of the lane. In this position, the pedestrian is either outside or on the edge of the 11.7° FOV. On the right-hand curve, the 11.7° FOV encompasses much more of the side of the road. The 18° FOV extends farther beyond the road edge on both sides.



1 ft = 0.305 m

Figure 70. Diagram. Comparison of 11.7° and 18° field of view.

Participants appeared to be sensitive to the two systems' fields of view. In the open-ended questions following drives with the VESs, 4 of 18 participants indicated that they would like the FOV in the 11.7° FOV FIR system to be wider, and two indicated the same for the 11.7° FOV NIR VES. Comments included "not wide enough," with two people indicating "especially to the left" and one saying "especially on inside of curves." No comments related to FOV were made about the 18° FOV system (NIR 1).

Presence of Display

When introducing a vision system, it is important to compare performance without the system to performance with the system to determine if any losses in performance occur. In this study, it is not possible to directly compare one vehicle with a display-based vision system to the identical vehicle without the display-based vision system. However, the pedestrian standing on the left side of a left-hand curve scenario tested in this study may provide a similar comparison to the "with-and-without" comparison just described. In this scenario, the FIR vehicle provided the data for a pedestrian standing on the left side of a left-hand curve. It is important to recognize that the FIR vehicle may be used as an example of this issue because of its higher performance in the other pedestrian detection scenarios. Where the pedestrian was standing on the left side of the road in the left-hand curve, the FIR vehicle had the shortest mean detection distance (29.9 m) (98 ft) of the VESs tested. The mean detection distance in this scenario included two cases of a participant completely missing the pedestrian. These are the only complete misses that occurred for this scenario. The mean detection distance stands in contrast to the fact that the FIR had the longest mean detection distance for all of the other pedestrian scenarios. Mean detection distance when the pedestrian was on the left in a left-hand curve was shorter for the FIR than for the shortest headlamp-based VES. This distance for detecting a pedestrian dressed in denim was shorter than the mean distance for detecting a tire tread on the road (50.6 m) (166 ft). The NIR 2 vehicle, which had the same pillar, glass geometry, and headlamps as the FIR vehicle but a generally lower-performing display-based system, had a mean detection distance of 66.2 m (217 ft), which was twice that of the FIR vehicle in the same scenario.

A comparison of the visibility level of the pedestrian in this scenario was also conducted. The visibility level value is based on photometric data, observation time, object size, and contrast values between the object (pedestrian) and the background when illuminated by the vehicle's headlamps and results in a unitless value. The visibility level was calculated based on the method presented in Illuminating Engineering Society of America Recommended Practice #8 (2000) where visibility levels of 2.6 to 4.9 are considered sufficient for detection and are used for the design of roadway lighting installations.[16] The calculated visibility level of the pedestrian, provided by the vehicle headlights, at the mean detection distance for the FIR vehicle was 106 at 29.9 m (98 ft). The visibility level at detection for the other vehicles ranged from 9 to 49. The

NIR 2 vehicle, which had the same headlamps as the FIR vehicle, had a visibility level of 33 at 66.2 m (217 ft). This indicates that illumination from the vehicle headlamps was sufficient to detect the pedestrian much earlier than when detection actually occurred. Based on this information, it appears that when objects are not presented in a vision system display, detection distances may be reduced below those found with headlamps alone.

As introduced earlier, one question to consider is why the NIR 2 VES, with the same FOV as the FIR, did not have the same low mean detection distance for this scenario. It is believed that the lower overall usability of the NIR 2 display may provide some explanation for this difference. The lower usability of the display by the participants may reduce the amount of attention or visual sampling allocated to the display, thereby increasing the opportunity to observe the pedestrian directly with just headlamps.

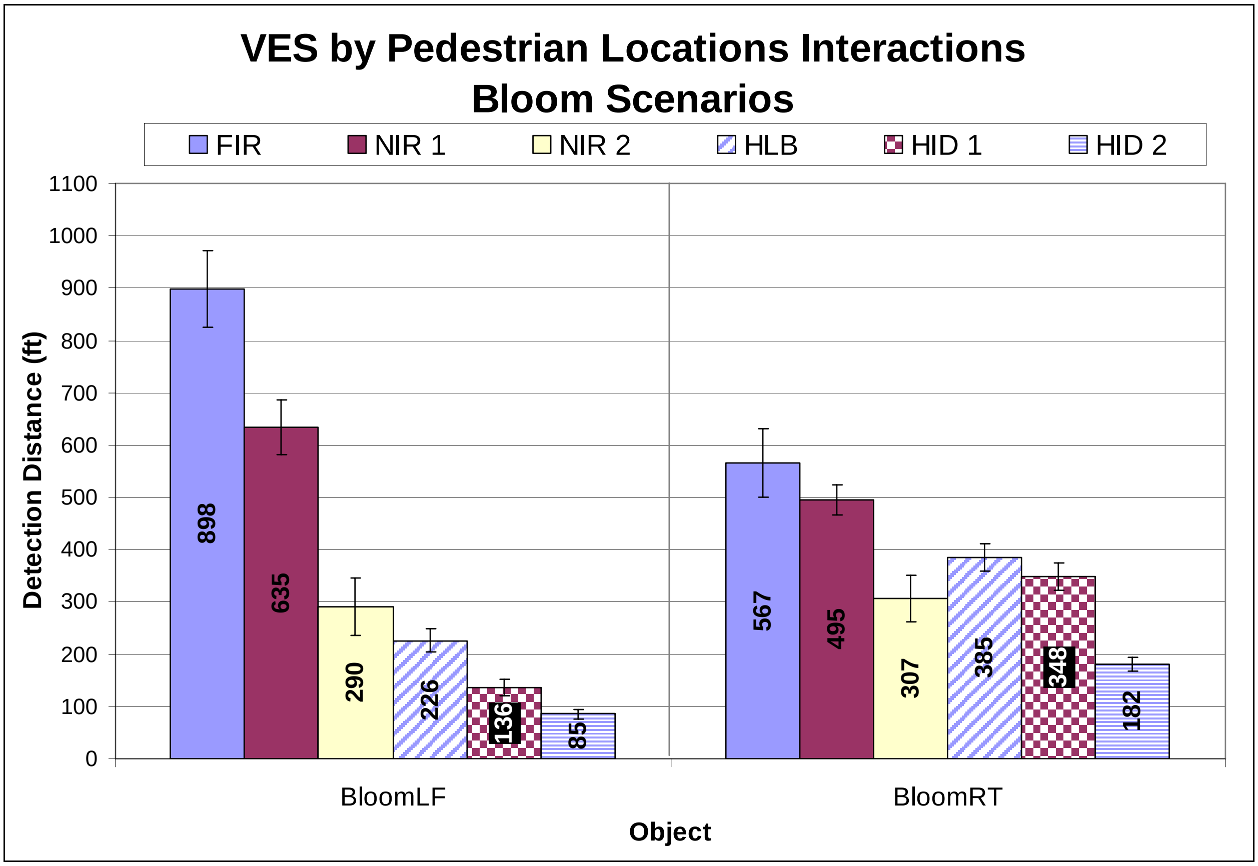
As mentioned previously, because a vehicle was not available with the same headlamps but without a vision enhancement system, and because of the singular scenario available in this test framework to test this FOV, it is difficult to determine definitively if the presence of the VES reduced detection distances below what they would be had no VES been present. Headlamp performance, frequency of thermal objects in study, a conscious decision of users to use FIR for distance detection and rely on headlamps for near detection, or system novelty/experimental situation must also be considered as possible factors in this finding. The combination of indicators does imply that further analysis is warranted. Further descriptions of the factors involved are given in ENV Volume XVI, where the objects are described in more detail and visibility measurements are provided.

Bloom Scenario

The better IR VESs (FIR and NIR 1) revealed a pedestrian veiled by oncoming headlights on either side of the road earlier than any of the headlamp-based systems. Where the pedestrian was standing on the left side of the road near a car parked in that lane, the IR VESs (FIR and NIR 1) showed the most benefit over the HLB and HID vehicles. The mean detection distance for the FIR (273.7 m) (898 ft) in this pedestrian-on-the-left bloom scenario was almost four times the mean detection distance of the HLB (68.9 m) (226 ft), and the mean detection distance of the NIR 1 (193.6 m) (635 ft) was almost three times that of the HLB. There may have been some slight reduction in the mean detection distance of the FIR because of the limited sight distance available for some presentations of the scenario.

A comparison of when a given vehicle type (IR or headlamp) revealed a pedestrian on the right in glare versus when it revealed a pedestrian on the left in glare indicated opposite results between the IR VESs and the headlamp-based systems. In the bloom scenario, for all of the headlamp-based systems, the pedestrian on the right, closer to the driving lane, was detected at longer distances than the pedestrian on the left. This probably resulted from the emphasis on the right side of the road in the beam pattern of the headlamps; however, the reverse was true for the IR VESs. With the IR VESs, the pedestrian on the left side of the road, closer to the glaring headlamps, was detected earlier than the pedestrian on the right side of the road. With the NIR systems, this probably resulted from the image processing used to reveal objects behind the glaring headlights. With the FIR system, this may have resulted from attention being drawn to the vehicle on the left with a visibly warm engine block, or it may be due to an overall warmer field to the left than to the right.

Looking specifically at the headlamp technologies, the HLB had significantly longer detection distances than either of the HID headlamps when the pedestrian was on the left side of the road, near the oncoming headlamps. When the pedestrian was on the right side of the road, the HLB and the HID 1 VESs were not significantly different from each other, but the HID 2 was shorter than the others. Figure 71 illustrates these differences.

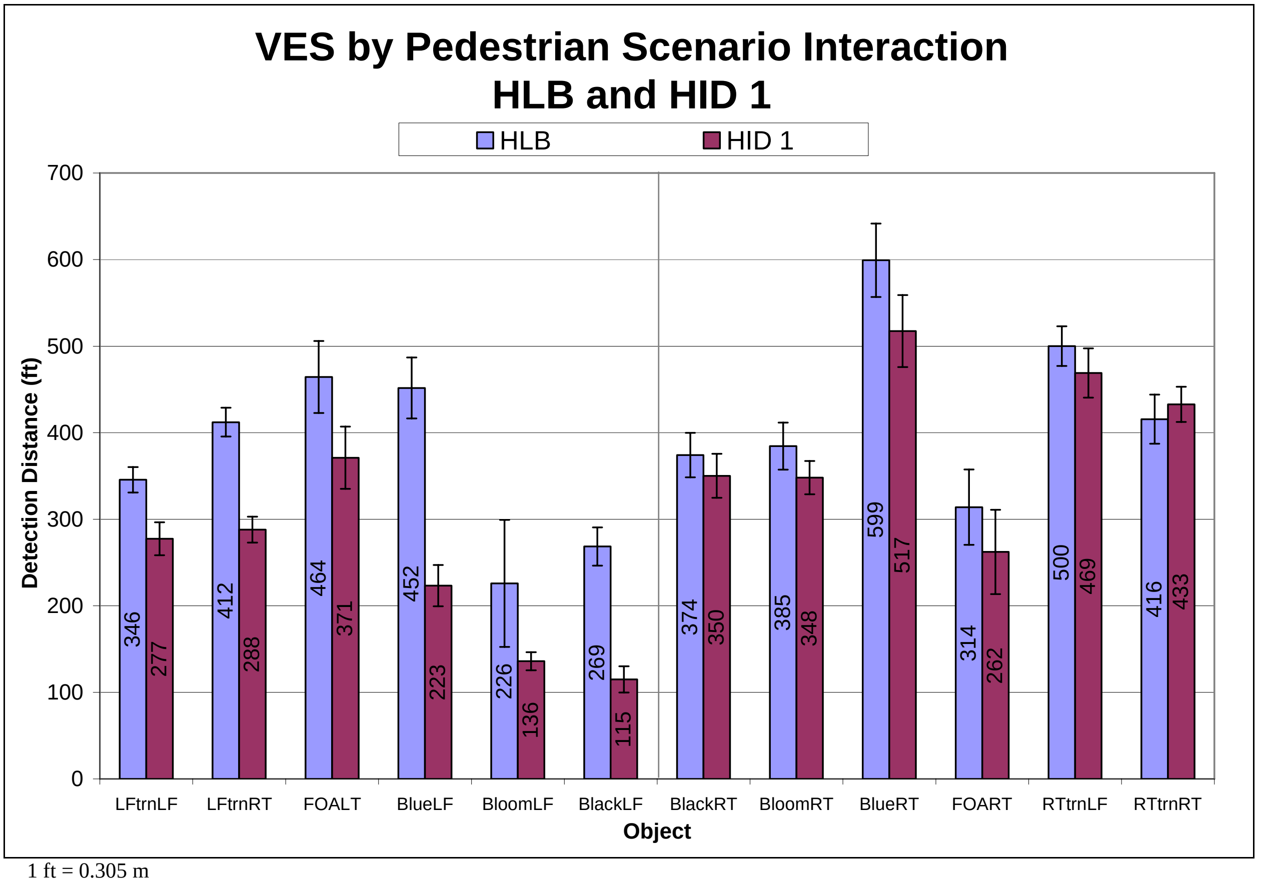


1 ft = 0.305 m

Figure 71. Bar graph. Detection distances for VES by Pedestrian Locations interaction, bloom scenarios only.

HID TECHNOLOGIES PERFORMANCE SUMMARY

As a rule, in the driving scenarios tested in this study, HIDs did not have better performance qualities than halogen lamps. The HID 2 detection and recognition distances were lower than the benchmark HLB distances in all of the tested scenarios. The HID 1 was more comparable to the HLB; in the tested scenarios, it was either not statistically different from the benchmark or it had lower performance. The pedestrian scenarios in which the pedestrian was on the left side of the road showed lower performance with the HID 1 than with the HLB. The performance of the two systems was approximately equal when the pedestrian was on the right side of the road.
Figure 72 shows the comparison of these two VESs. It is important to note that the results described in this section could have been affected by the alignment protocol used for the HLB configuration.



1 ft = 0.305 m

Figure 72. Bar graph. Detection distances for VES by Pedestrian Scenario interactions: HLB versus HID 1.

COMPARISON TO PHASE II

Comparison of this research to the previous ENV Phase II research can be made using the pedestrian dressed in black on the right side of the road and the tire tread, as well as with the HLB and FIR VESs; however, certain caveats must be made. In Phase II, the pedestrian dressed in black was moving, while in this research the pedestrian was stationary. In comparing the FIR used in this research to Phase II, it is important to realize that the prototype reflective mirror display system used here was different than the see-through projected display used in Phase II, and the FIR vehicle platform used here was a SUV, while the FIR platform used in Phase II was a sedan. A comparison of the detection distance values from Phase II to those in this research are shown in table 30.

Table 30. Comparison of mean detection distances from Phase II to Phase III (current study).

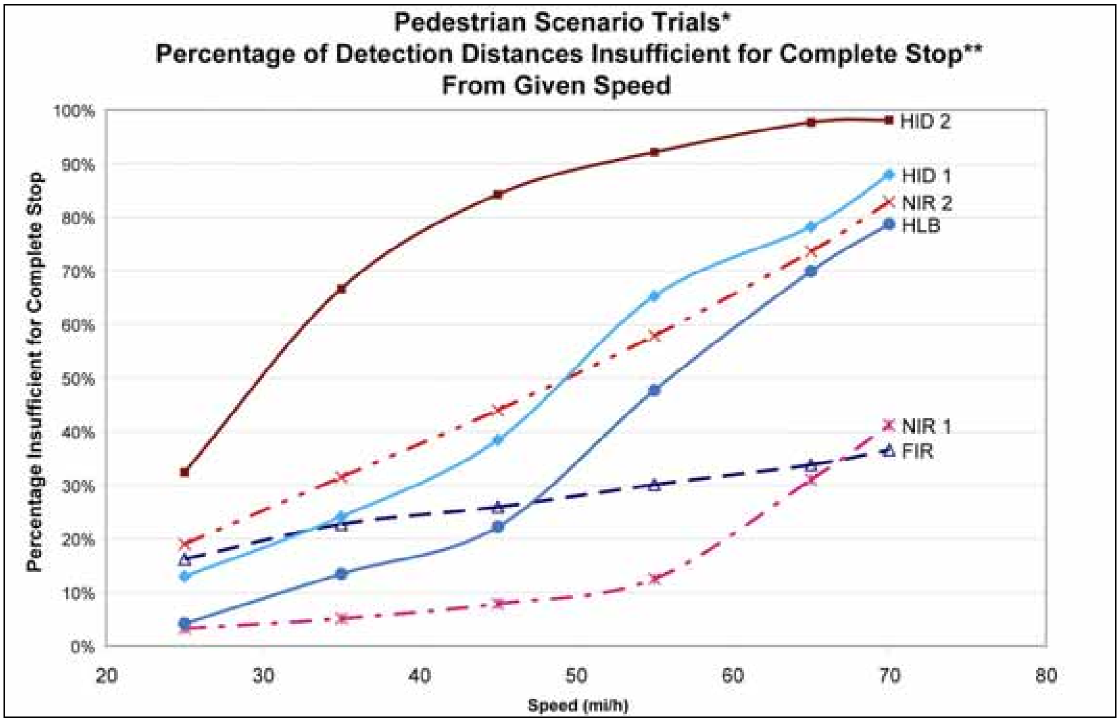
	FIR Phase II (ft)	FIR Phase III (ft)	HLB Phase II (ft)	HLB Phase III (ft)
Pedestrian on Right in Black	662	621	386	374
Tire Tread	172	166	240	186

1 ft = 0.305 m

The mean detection distance for pedestrians in black on the right appears to have approximately a 6 percent difference between the two phases of research for the FIR vehicles and approximately a 3 percent difference for the HLB vehicle. The tire tread with the FIR also had a detection distance difference of 3 percent from Phase II to the current research. With the HLB VES, the difference was 23 percent, with the current research having a shorter detection distance. Overall, this appears to indicate agreement in results of the two studies. The differences for the tire tread with HLB may have resulted from the types of objects used and participant expectations while scanning the roadway. The current research used a larger number of target objects in more locations than Phase II. In addition, nearly all of the target objects tested in this research were more visible to the participant than the tire tread.

FREQUENCY ANALYSIS

Discussion to this point has described the headlamps using means for all of the participants. This approach used alone has the potential of masking situations where a few participants had problems with a VES. A comparison of the frequency of short detection distances was made to address this possibility. Using the stopping distance approximation described previously, each pedestrian detection was grouped according to highest speed at which the participant could theoretically have stopped before reaching the pedestrian. Several caveats should be considered in this analysis. First, stopping distances for speeds up to 113 km/h (70 mi/h) are approximated, although the participant was driving 40 km/h (25 mi/h). Second, the pedestrian scenarios varied in their degree of criticality. For example, pedestrians on the left side of the road or 9.5 m (31 ft) from it are less critical than a pedestrian on the right side of the road. Third, stopping completely probably would not be required for most of these pedestrian scenarios in the real world. Fourth, the pedestrian scenarios tested were selected to explore a range of possible locations and are not indicative of the frequency with which pedestrians appear on the roadway. With these caveats in mind, it is possible to compare the VESs using the 12 pedestrian scenarios as a broad representation of possible pedestrian locations with respect to approaching vehicles. Figure 73 portrays the percentage of all of the pedestrian scenario trials where a complete stop may not have been possible at a given speed.



10 mi/h = 16.1 km/h
* Scenario trials and locations not indicative of frequency of occurrences while driving.
** Complete stop not necessarily required in real driving situations.

Figure 73. Line graph. Percentage of detection distances insufficient for complete stop for pedestrian scenarios.

As illustrated in figure 73, the NIR 1 VES had the lowest percentage of trials that may have had insufficient stopping distances at speeds up to 89 km/h (55 mi/h). At speeds up to 72 km/h (45 mi/h), the FIR VES had a higher percentage of the theoretical insufficient stopping distance trials than the NIR 1 and the HLB. These are essentially very late detections, which make the FIR percentage higher from the start (it should be noted that these late detections are not solely due to the pedestrian standing on the left side in a left-hand turn). At higher speeds (greater than 72 km/h (45 mi/h)), FIR shows advantages over the HLB, indicating fewer trials with insufficient detection distances. The HLB is similar to NIR 1 at low speeds, but as speeds increase, a greater number of insufficient detection distances may occur with the HLB. The HLB tested had fewer occasions of possible insufficient stopping distances than HID 1, NIR 2, and HID 2 throughout the speeds approximated. HID 2 had the highest number of trials with detection distances that may have been insufficient for complete stopping.

CHAPTER 5—CONCLUSIONS

OVERALL

Following is a summary list of the overall conclusions in Phase III—Study 1:

- In the clear weather scenarios tested, both active and passive IR systems, if designed correctly, appear to provide pedestrian detection benefit over headlamps.
- Older people detect pedestrians later and recognize sign types later.
- IR systems may help offset the reduced visual performance of older drivers.
- Pedestrians in blue denim were detected earlier than pedestrians in black cloth for all of the VESs.
- When comparing VESs, drivers gave similar or more positive subjective evaluations to the HID headlamps, although objective measures showed similar or negative results.
- There were no differences between VESs in recognition of sign meanings.

IR-SPECIFIC CONCLUSIONS

IR vision systems provide the potential for earlier detection of objects; however, some question remains regarding the effect on the driver of when objects are not presented in a display. The following items outline IR-related findings based on the tested systems:

- The FIR and the NIR 1 provided pedestrian detection benefit in clear weather over headlamps.

- In all but one pedestrian scenario tested, detection distance was acceptable for 89 km/h (55 mi/h) driving.

- Presence of an IR system alone will not increase detection distances. Differences in implementation are important.

- Pedestrians in blue denim were detected 45 percent farther away than pedestrians in black cloth for FIR. Color differences were expected to have a minimal effect on an FIR vehicle. These differences could be explained by thicker denim cloth that may have held heat better than thinner black cloth. Also, some participants may have waited for visual confirmation (through the windshield) before "detecting" a pedestrian.

- An older group using the IR systems had similar performance to a younger group using HLB headlamps.
- Older people may have improved performance with the NIR 1 over FIR.
- IR systems can reveal pedestrians in glare earlier than headlamp-based systems.
- People with an IR system may have reduced detection distances for objects that are not shown in the system display. The FIR had the shortest detection of pedestrians on the left in a left turn scenario and the shortest detection and recognition of retroreflective objects; however, it is not clear if this was the result of headlamp performance, presence of FIR system, frequency of thermal objects in study, or system novelty and experimental situation.
- Some participants indicated they would like the display systems to show sign information.
- For most of the pedestrian scenarios tested, the FIR implementation appeared to provide a 21.3-m to 30.5-m (70-ft to 100-ft) detection advantage over the NIR 1 implementation.
- The wider FOV system (18°) tested appears to have had beneficial effects in detecting pedestrians to the side.
- The wider FOV (18°) appears sufficient for presenting pedestrians on the curve tested (radius of 1,250 m), for pedestrians located 9.45 m (31 ft) from the lane center, and for pedestrians along the sides of road. A narrower FOV (11.7°) may not present objects on curves with radii of 1,250 m or less.

From this research, development of recommendations for future direction in display-based nighttime VES systems is possible. System engineers should pursue a display that is located as close to the forward road scene as possible, using HHD- or Heads-Up Display-type (HUD) technology. Possible objects should be called out clearly in a display to minimize the need for a driver to spend time visually scanning a display. At the same time, it is not desirable for drivers to have the perception that they could drive solely by using a display. Ideally, an interface that attracts the driver's attention when necessary but that would not otherwise require glances is preferable. This might include HUD technology, auditory warnings when a possible object is present, or activating the display only when possible objects are present. When a display is visually interrogated by the driver, the required glance time should be minimized. This might be accomplished by presenting objects in high contrast or, as enabling technology becomes feasible, by augmenting the scene with distinctive graphics to call out possible objects.

ADDITIONAL QUESTIONS

The possibility of users missing objects that were not presented on displays should be investigated further. If users are allocating attention to a display rather than to the forward road scene, what variables influence this behavior? For example, would a less realistic display increase or decrease this level of attention? Would a symbolic format or a HUD presentation eliminate this effect?

How wide an FOV is wide enough? Investigation of the performance of VESs should be undertaken to develop guidelines regarding appropriate fields of view in more severe road geometries such as on secondary roads and in neighborhoods.

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 at the [contractor]. *I'm recruiting drivers for a study to evaluate new night vision enhancement systems for vehicles.*

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

If they agree:

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

If they do not agree:

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

****

Questions

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

   Yes _____ No _____

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

3. How old are you? ______

4. What is your date of birth?__________

5. Have you previously participated in any experiments at the [contractor]? 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's university] Informed Consent for Participants of Investigative Projects

TITLE OF THE PROJECT: EVALUATION OF IN-VEHICLE NEW TECHNOLOGIES

INVESTIGATORS: [names of 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

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 25 miles per hour, and notify the experimenter when you can detect and identify different objects along the roadway.
5. Complete questionnaires
6. Listen to the instructions regarding any tasks you may perform.

It is important for you to understand that we are evaluating the technology 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 25 miles per hour or less, on straight and slightly curved roadways.
2. Possible fatigue due to the length of the experiment. However, you will be given the option to take breaks when you choose.
3. Discomfort caused by the glare of a vehicle parked in the oncoming lane.

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

1. The in-vehicle experimenter will monitor participants driving and will ask you to stop if he/she feel 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. The headlights of oncoming vehicles are production headlights and meet all the legal requirements for passenger vehicles in the state of Virginia.
6. 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.
7. 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.
8. None of the data collection equipment or the display technology interferes with any part of the driver's normal field of view present in the automobile.
9. The in-vehicle experimenters are aware of the location of other test vehicles on the road, and maintain radio contact with each other.
10. 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.
11. 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
12. When oncoming traffic is presented, participants will be driving at 25 mi/h or less on the Smart Road, which was designed to Department of Transportation specifications for two-lane divided highways with a 65 mi/h speed limit.

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 $1,000,000. 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, workers 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 videotape 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 videotape 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 FORM

PARTICIPANT NUMBER: __________

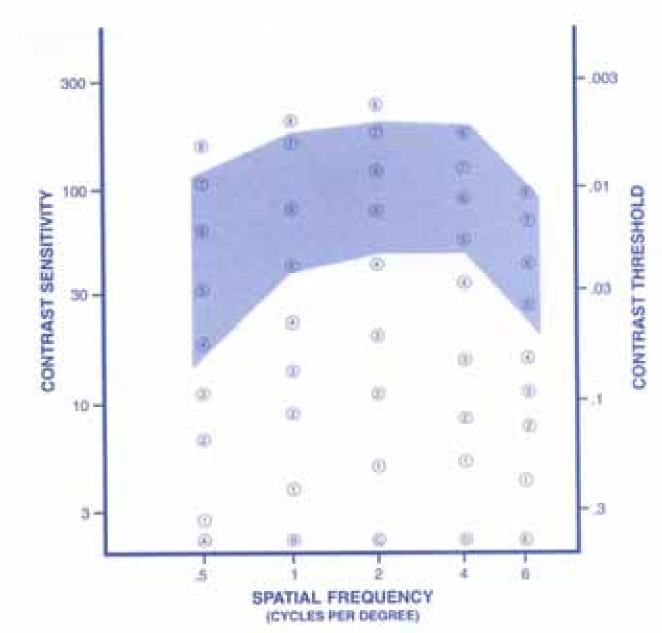
VISION TESTS

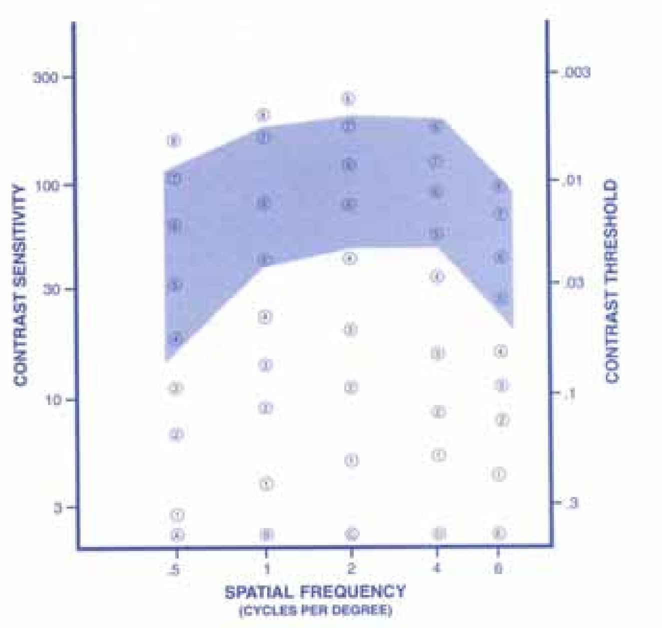
Acuity Test

- 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—PREDRIVE QUESTIONNAIRE

1. Please indicate approximately how often you drive at night *(Please check only one)*

O Every night

O Three times per week

O Once per week

O Less often that one time per week

2. When driving at night, do you mostly wear… *(Please check only one)*

O Single vision eyeglasses

O Bifocal eyeglasses

O Trifocal eyeglasses

O Contact lenses

O Do not wear corrective lenses when driving

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

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

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

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

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

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

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

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

7. **What vehicle do you most often drive at night?**

Make _______________

Model _______________

Year _____________

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

APPENDIX E—VISION TEST RESULTS

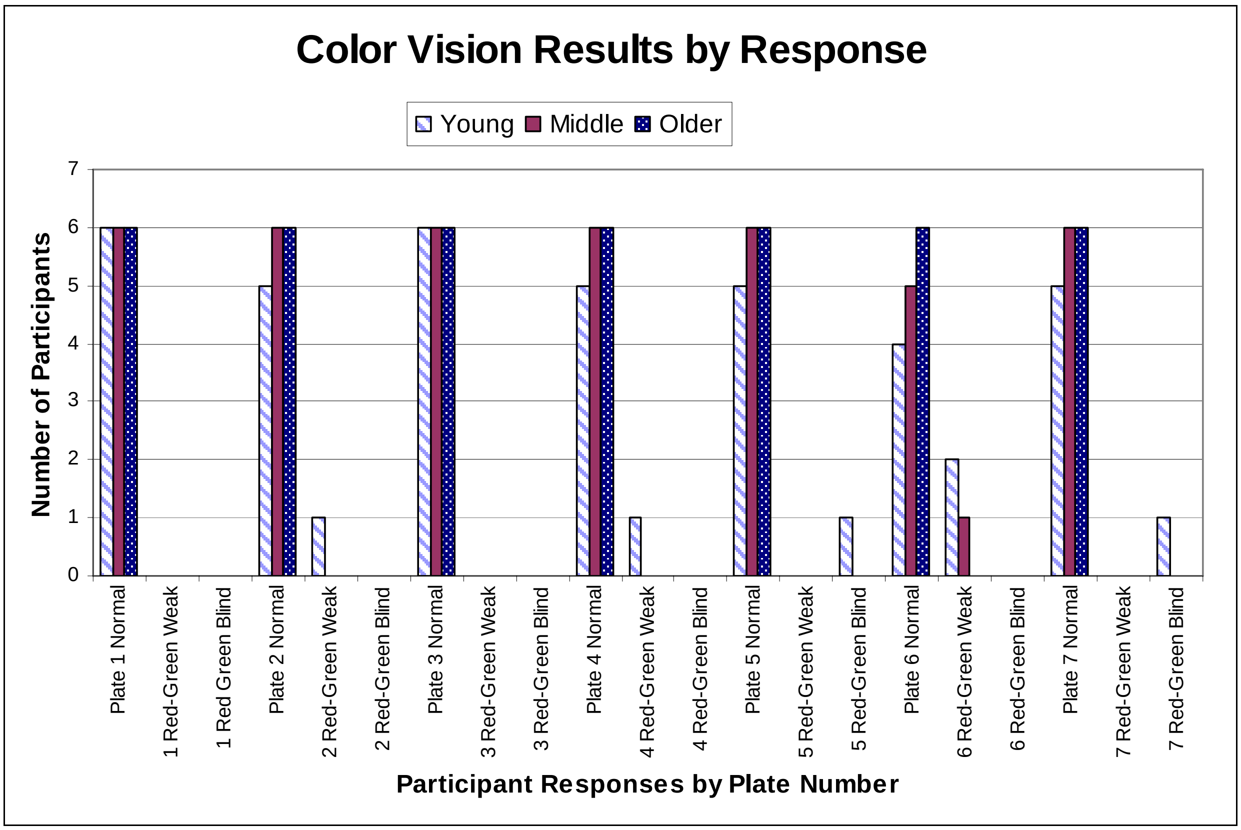


Figure 74. Bar graph. Color vision results for the three age groups by response.

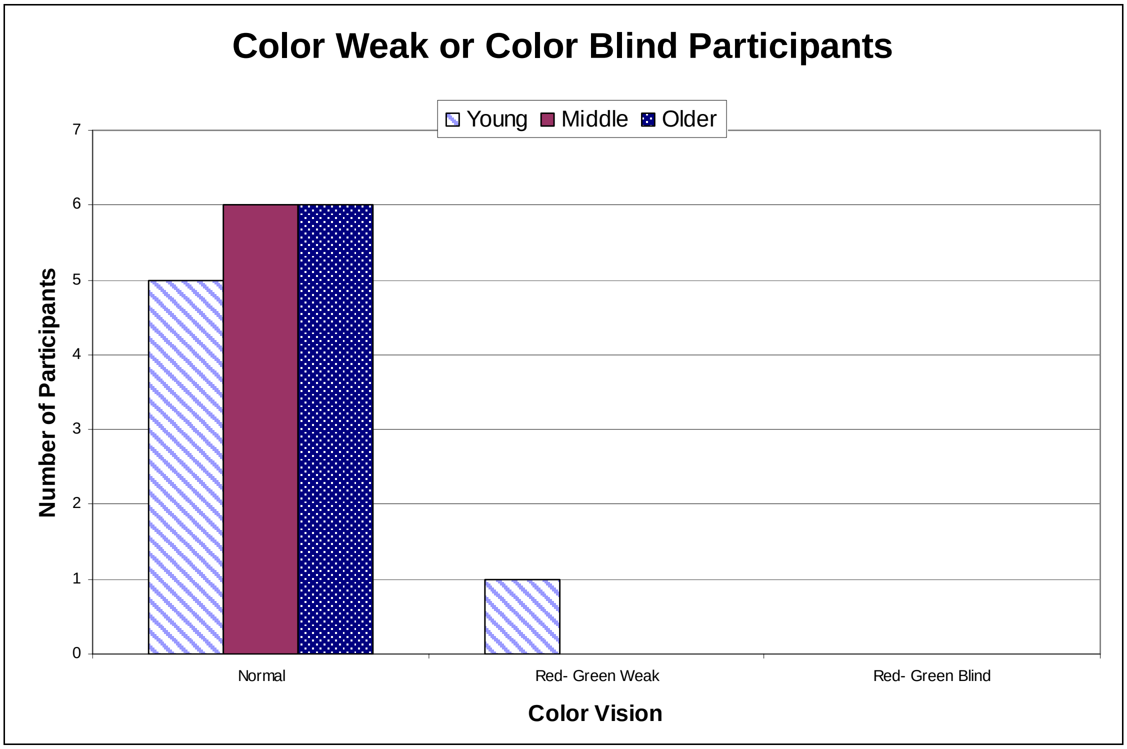


Figure 75. Bar graph. Color weak or color blind participants per age group.

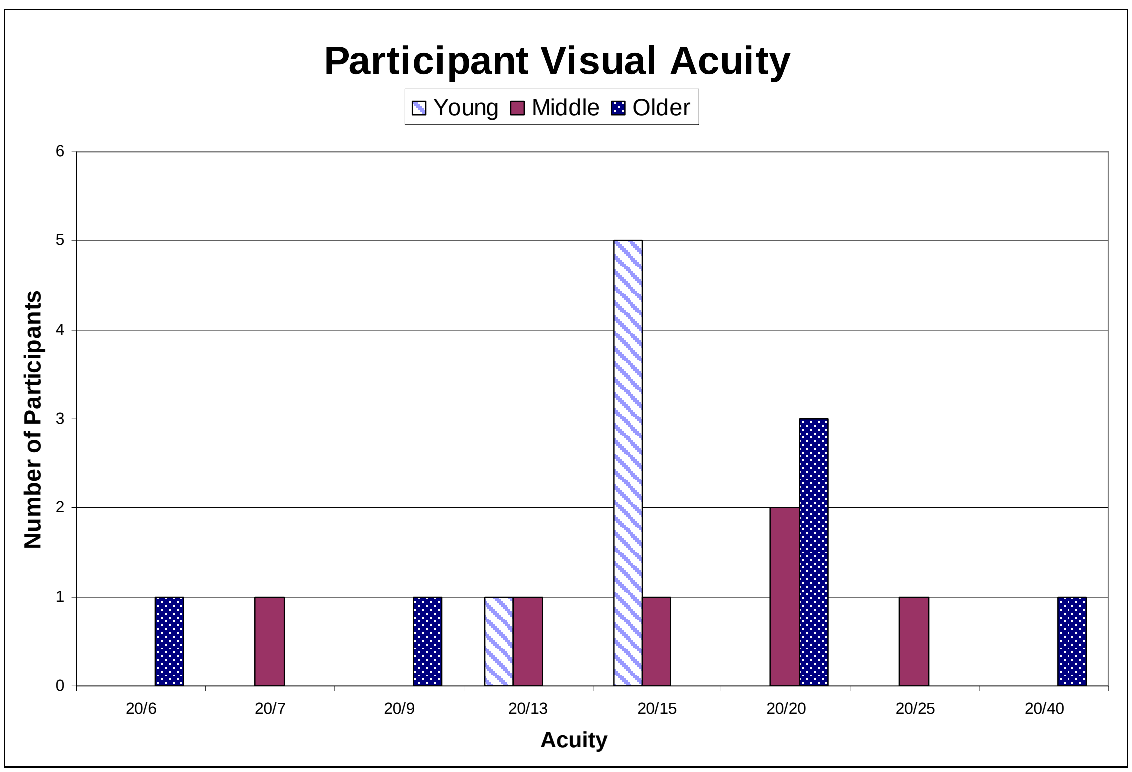


Figure 76. Bar graph. Participant visual acuity per age group.

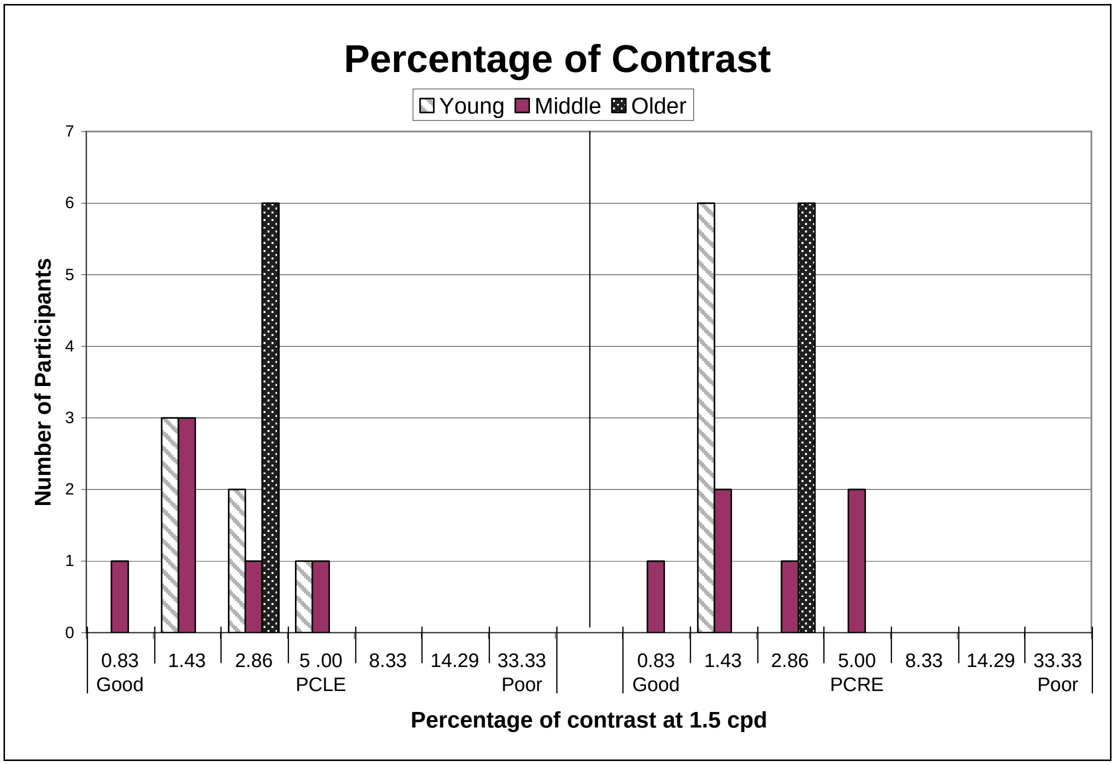


Figure 77. Bar graph. Percentage of contrast for left eye (PCLE) and percentage of contrast for right eye (PCRE) at 1.5 cycles per degree (cpd) per age group.

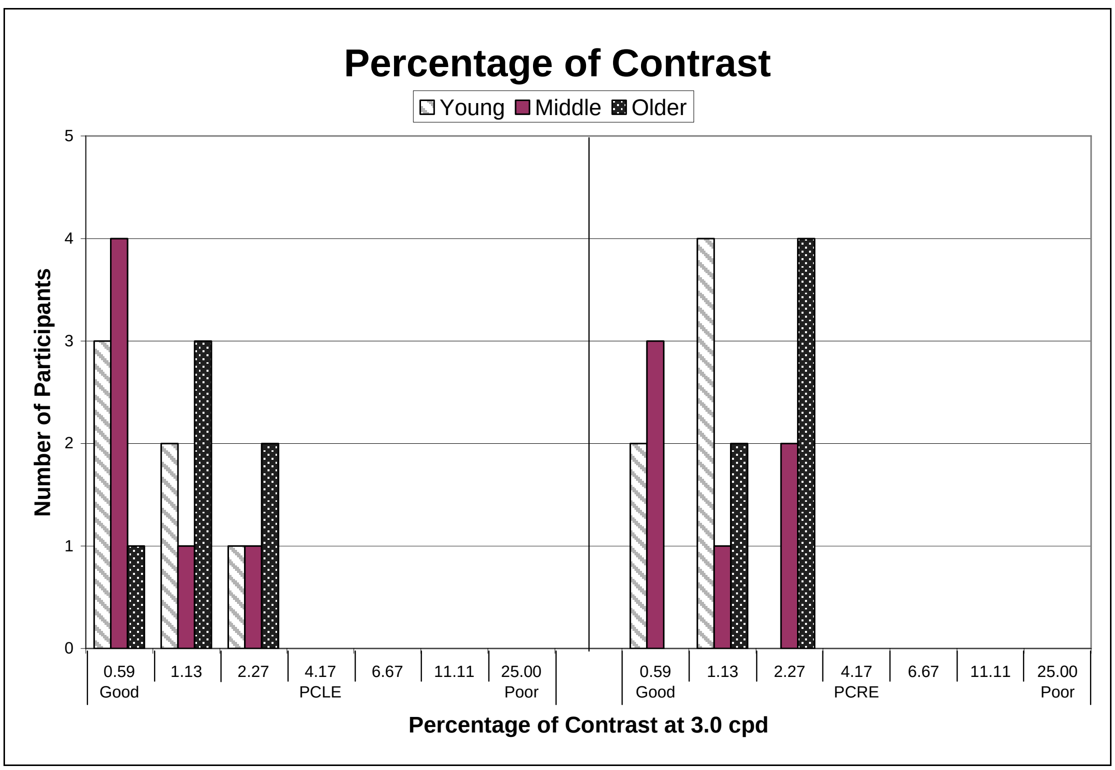


Figure 78. Bar graph. Percentage of contrast at 3.0 cpd per age group.

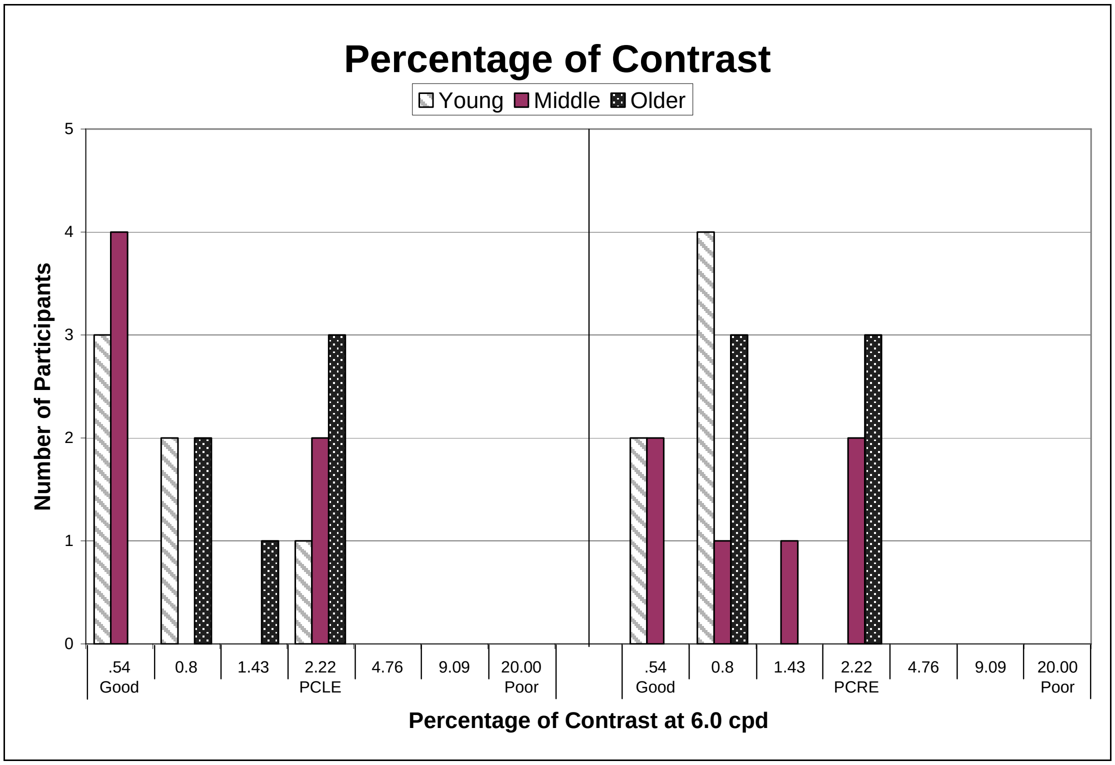


Figure 79. Bar graph. Percentage of contrast at 6.0 cpd per age group.

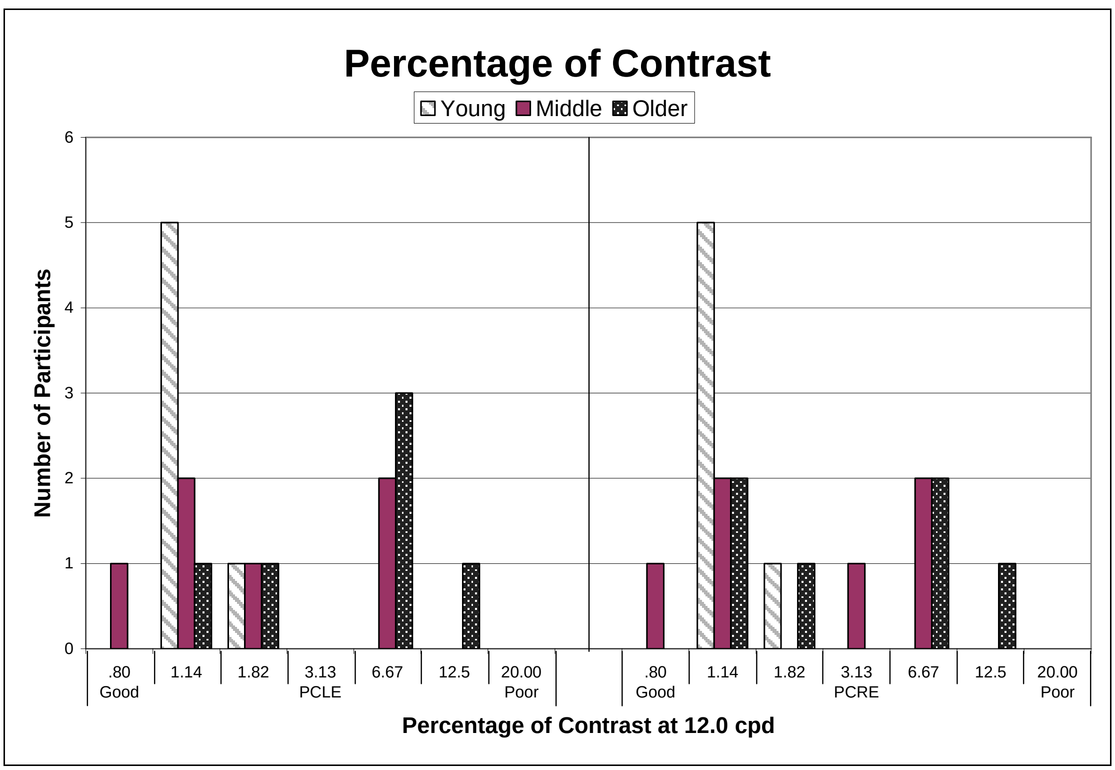


Figure 80. Bar graph. Percentage of contrast at 12.0 cpd per age group.

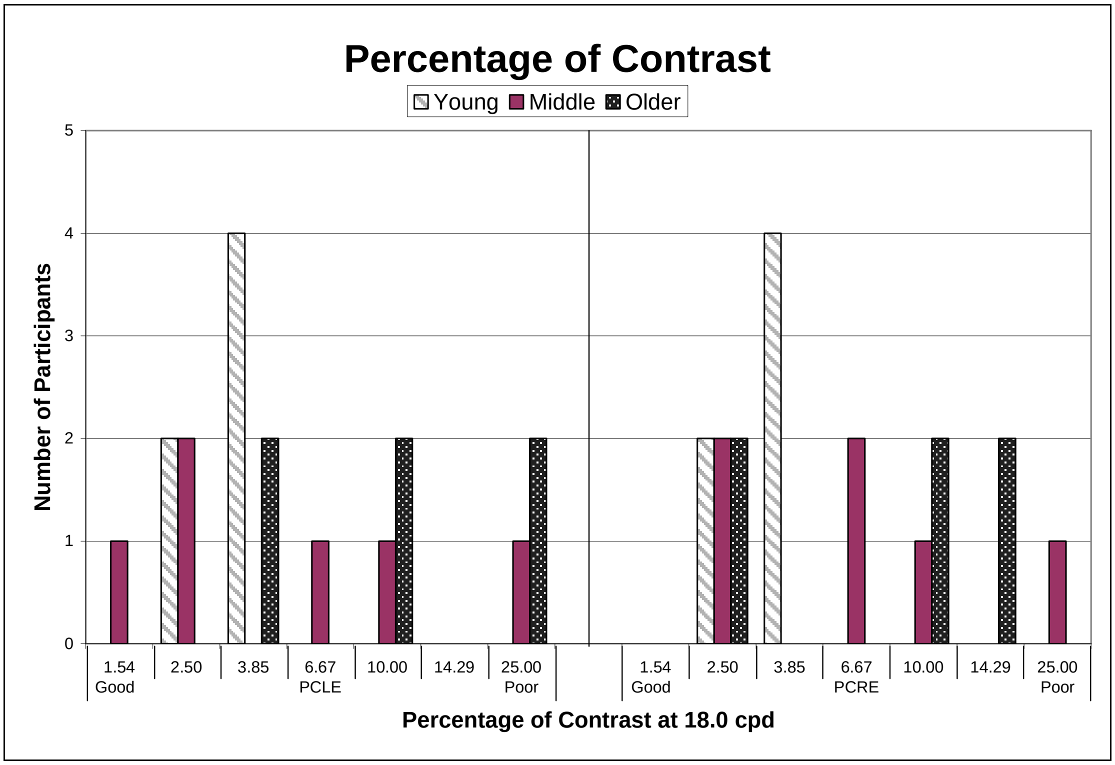


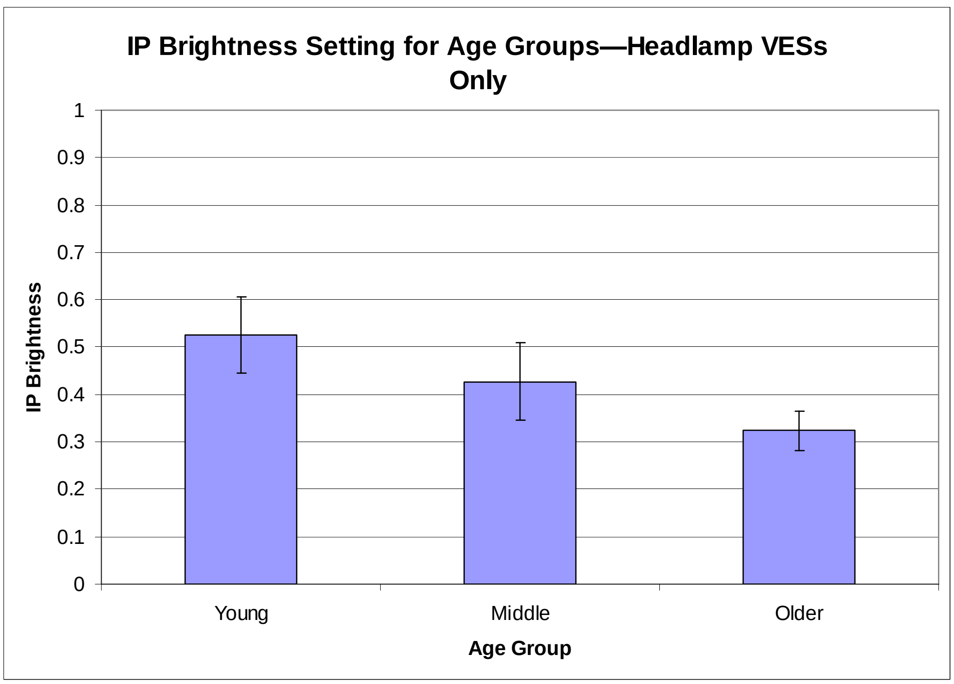
Figure 81. Bar graph. Percentage of contrast at 18.0 cpd per age group.

Table 31. Participant height.

Participant	Standing Height (mm)
1	1,664
2	1,867
3	1,778
4	1,575
5	1,829
6	1,676
7	1,715
8	1,918
9	1,803
10	1,676
11	1,765
12	1,600
13	1,905
14	1,740
15	1,791
16	1,613
17	1,727
18	1,588
	Mean = 1,735
	SD = 106

APPENDIX F—BRIGHTNESS SETTINGS

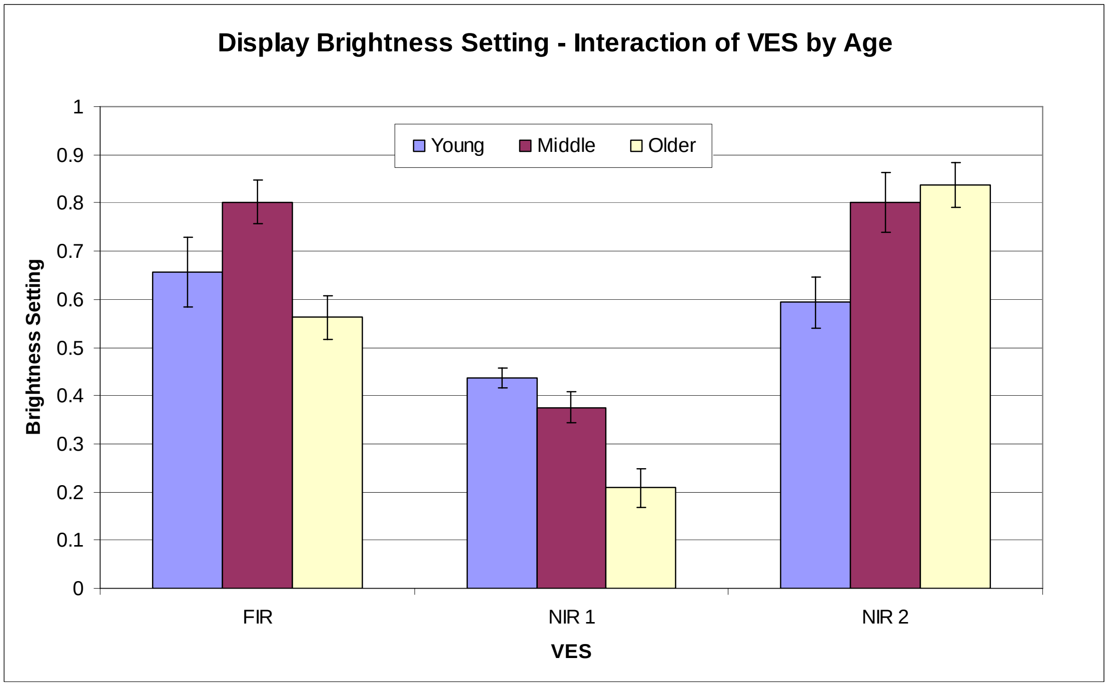
For comparison of brightness settings across the different age groups, instrument panel (IP) (dashboard) brightness settings in the vehicles were recorded using the control setting selected by the participants. Absolute measures of brightness for the different vehicle and systems were not collected. Measures were made by dividing the range of each vehicle's IP physical adjustment range approximately into eighths. The final position of the control as set by the participant was recorded within this range. Due to different controls in each vehicle, only the settings for SUV 3 are used here for comparison of IP brightness across the age groups. Figure 82 indicates the mean setting of the IP brightness control and standard error for each of the age groups.



Not statistically different ($p = 0.57$)

Figure 82. Bar graph. Instrument panel brightness setting by age group (headlamp VESs only).

Similarly, in-vehicle display brightness settings were recorded by dividing each vehicle's in-vehicle display physical adjustment range approximately into eighths. The final position of the control within this range— as set by the participant was recorded. Figure 83 indicates the mean in-vehicle display brightness setting and standard error for each of the age groups in each vehicle. Due to different controls in each vehicle and different gain on the controls, comparison is not possible from vehicle to vehicle.



Settings across VESs not comparable
Interaction $p = 0.0924$

Figure 83. Bar graph. VES by Age interaction for display brightness setting.

APPENDIX G—ANOVA SUMMARY TABLES FOR SUBJECTIVE RATINGS

Table 32. ANOVA summary table for the Likert-type scale on detection.

Statement 1: Detection						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	1.7	0.8	0.23	0.7936	
Subject/Age	15	53.8	3.6			
Within						
VES	5	59.2	11.8	9.6	<0.0001	*
VES by Age	10	18.0	1.8	1.46	0.1724	
VES by Subject/Age	75	92.5	1.2			
TOTAL	107	225.2				

* $p < 0.05$ (significant)

Table 33. ANOVA summary table for the Likert-type scale on recognition.

Statement 2: Recognition						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	0.2	0.1	0.03	0.9677	
Subject/Age	15	54.9	3.7			
Within						
VES	5	41.7	8.3	6.3	<0.0001	*
VES by Age	10	10.2	1.0	0.77	0.6559	
VES by Subject/Age	75	99.3	1.3			
TOTAL	107	206.3				

* $p < 0.05$ (significant)

Table 34. 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	21.7	10.8	1.42	0.2713	
Subject/Age	15	114.1	7.6			
Within						
VES	5	23.5	4.7	4.14	0.0022	*
VES by Age	10	14.6	1.5	1.29	0.2505	
VES by Subject/Age	75	85.0	1.1			
TOTAL	107	259.0				

* $p < 0.05$ (significant)

Table 35. 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	6.9	3.5	0.68	0.5204	
Subject/Age	15	75.9	5.1			
Within						
VES	5	37.2	7.4	5.25	0.0003	*
VES by Age	10	17.4	1.7	1.23	0.2862	
VES by Subject/Age	75	106.3	1.4			
TOTAL	107	243.7				

* $p < 0.05$ (significant)

Table 36. 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	0.8	0.4	0.05	0.948	
Subject/Age	15	111.4	7.4			
Within						
VES	5	20.7	4.1	3.12	0.0129	*
VES by Age	10	8.0	0.8	0.6	0.8075	
VES by Subject/Age	75	99.5	1.3			
TOTAL	107	240.3				

* $p < 0.05$ (significant)

Table 37. ANOVA summary table for the Likert-type scale on reading signs sooner.

Statement 6: Read signs sooner						
Source	**DF**	**SS**	**MS**	**F value**	**P value**	
Between						
Age	2	15.4	7.7	1.54	0.2463	
Subject/Age	15	75.0	5.0			
Within						
VES	5	66.2	13.2	8.07	<0.0001	*
VES by Age	10	25.8	2.6	1.57	0.131	
VES by Subject/Age	75	123.0	1.6			
TOTAL	107	305.4				

* $p < 0.05$ (significant)

Table 38. 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	0.9	0.5	0.06	0.9426	
Subject/Age	15	114.6	7.6			
Within						
VES	5	22.0	4.4	2.88	0.0197	*
VES by Age	10	11.6	1.2	0.76	0.6627	
VES by Subject/Age	75	114.4	1.5			
TOTAL	107	263.5				

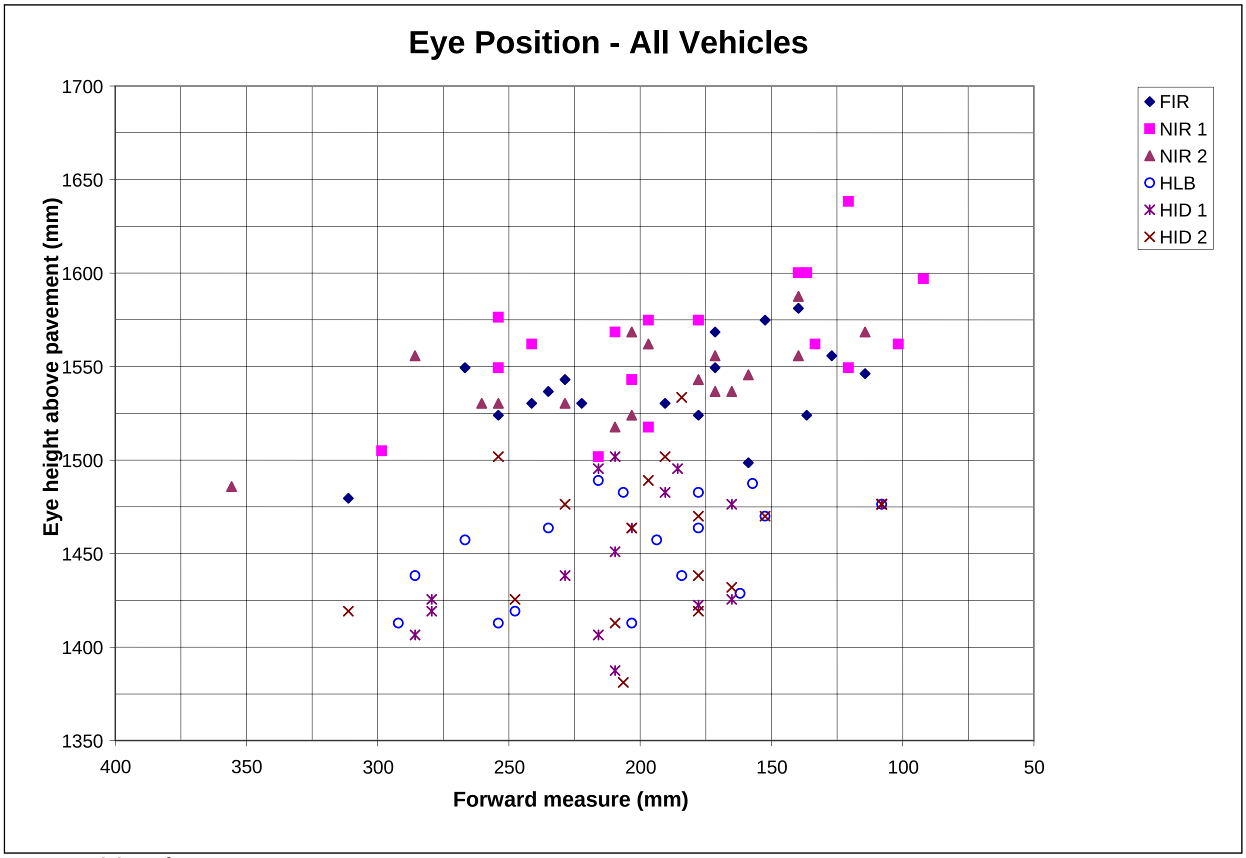
* *p* < 0.05 (significant)

Table 39. 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	1.0	0.5	0.07	0.9299
Subject/Age	15	104.6	7.0		
Within					
VES	5	15.0	3.0	1.89	0.1061
VES by Age	10	12.3	1.2	0.77	0.6532
VES by Subject/Age	74	117.6	1.6		
TOTAL	106	250.5			

* *p* < 0.05 (significant)

APPENDIX H—PARTICIPANT EYE HEIGHT



1 mm = 0.04 inches

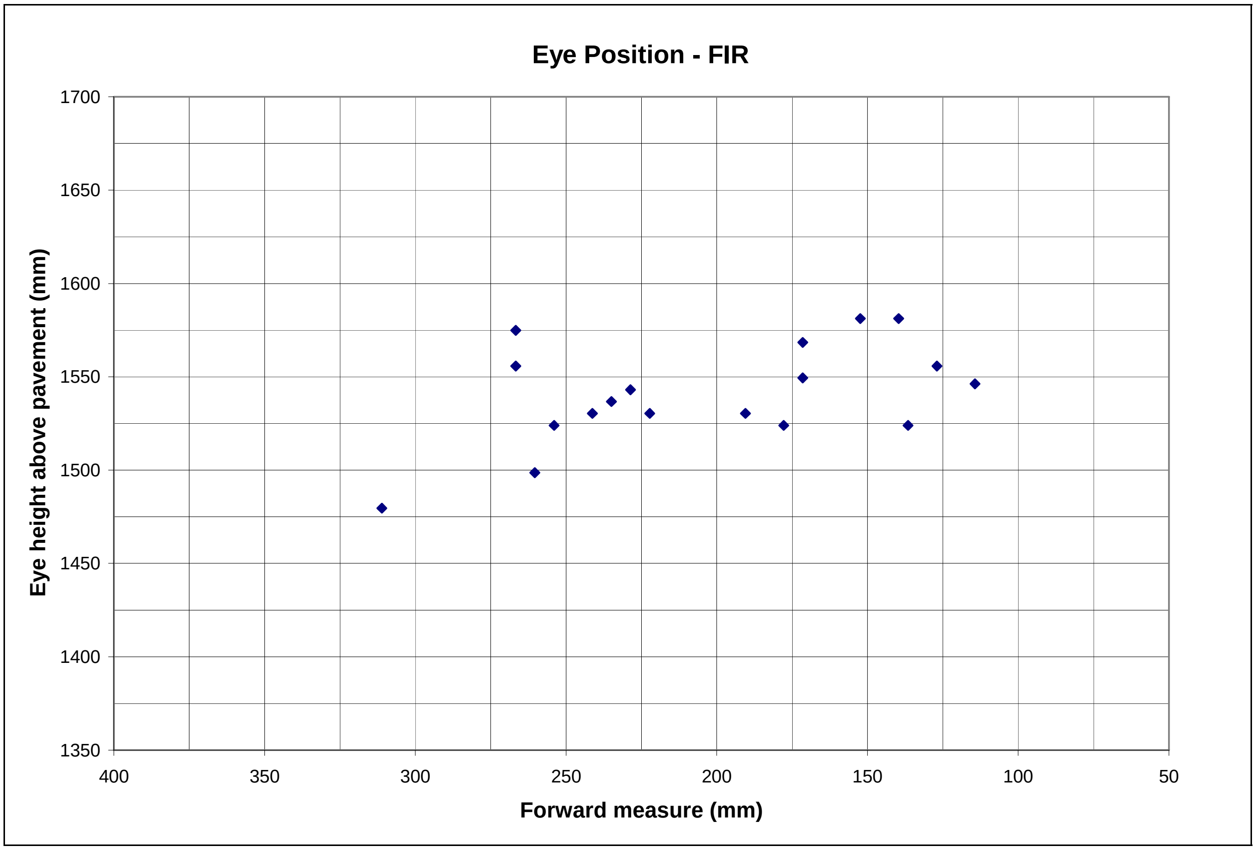
Figure 84. Scatter plot. Participant eye position for all vehicles.

Figure 85. Diagram. Eye position measurement locations for all experimental vehicles (forward measure taken from leading edge of B-pillar weather seal).

Table 40. Horizontal distances from headlamps for each VES vehicle.

VES	Distance from optical center of headlamp to B-pillar (inches)	Distance from optical center of headlamp to ground (inches)
FIR	95	37
NIR 1	97	37
NIR 2	95	37
HLB	93	33
HID 1	103	33
HID 2	103	33

1 inch = 2.54 cm = 25.4 mm



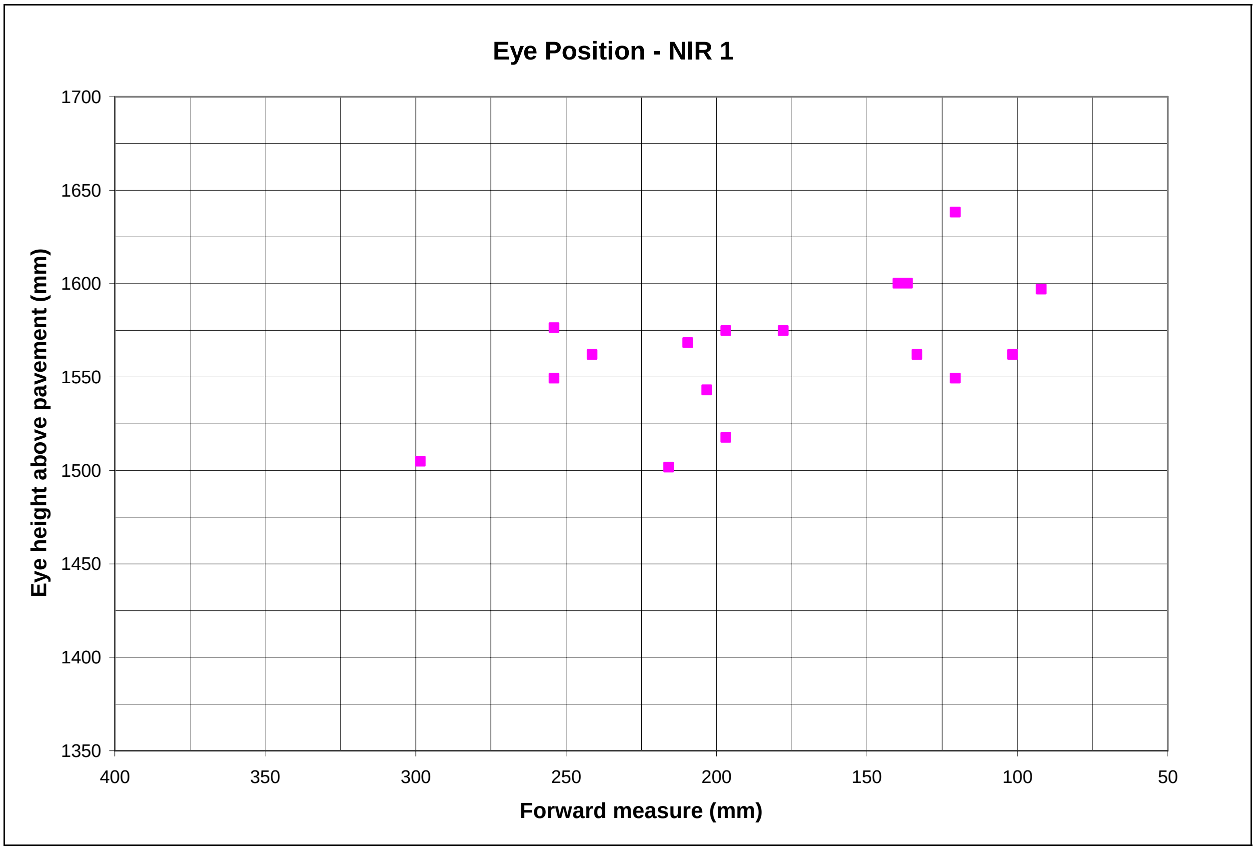
1 mm = 0.04 inches

Figure 86. Scatter plot. Participant eye position for FIR.

Table 41. FIR eye position measurements.

Participant	Forward (inches)	Height (inches)
1	10.5	14.25
2	6.75	14
3	5.5	12.25
4	10.5	13.5
5	5.5	14.5
6	7	12.25
7	7.5	12.5
8	4.5	13.25
9	6.75	13.25
10	9	13
11	6	14.5
12	10	12.25
13	5	13.5
14	8.75	12.5
15	9.25	12.75
16	9.5	12.5
17	6.25	11.25
18	12.25	10.5

1 inch = 2.54 cm = 25.4 mm



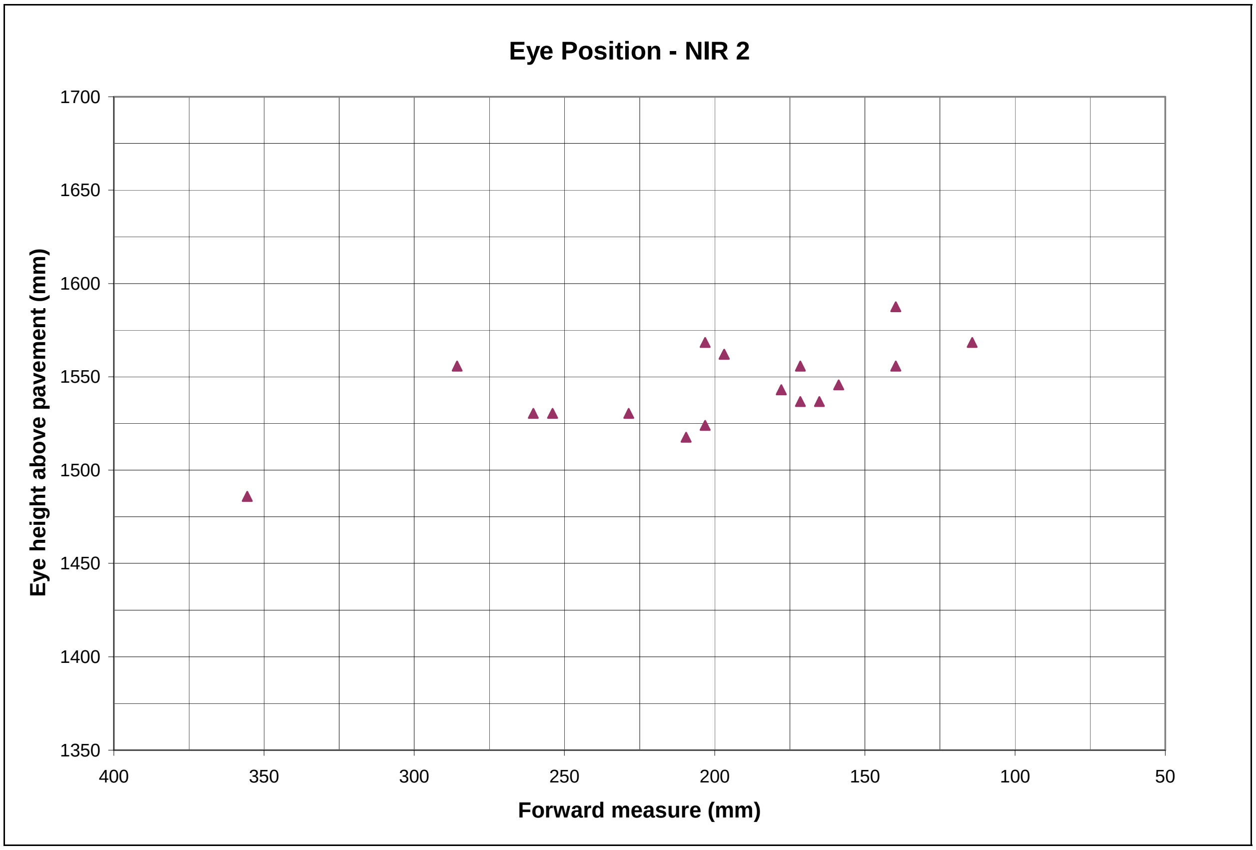
1 mm = 0.04 inches

Figure 87. Scatter plot. Participant eye position for NIR 1.

Table 42. NIR 1 eye position measurements.

Participant	Forward (inches)	Height (inches)
1	6.75	14.5
2	5.25	14
3	4.75	13.5
4	8.5	11.75
5	5.5	15.5
6	7	14.5
7	8.25	14.25
8	3.75	15.5
9	7.75	14.5
10	10	14.5
11	5.5	15.5
12	10	13.5
13	4.75	17
14	4	14
15	9.5	14
16	7.75	12.25
17	8	13.25
18	11.75	11.75

1 inch = 2.54 cm = 25.4 mm



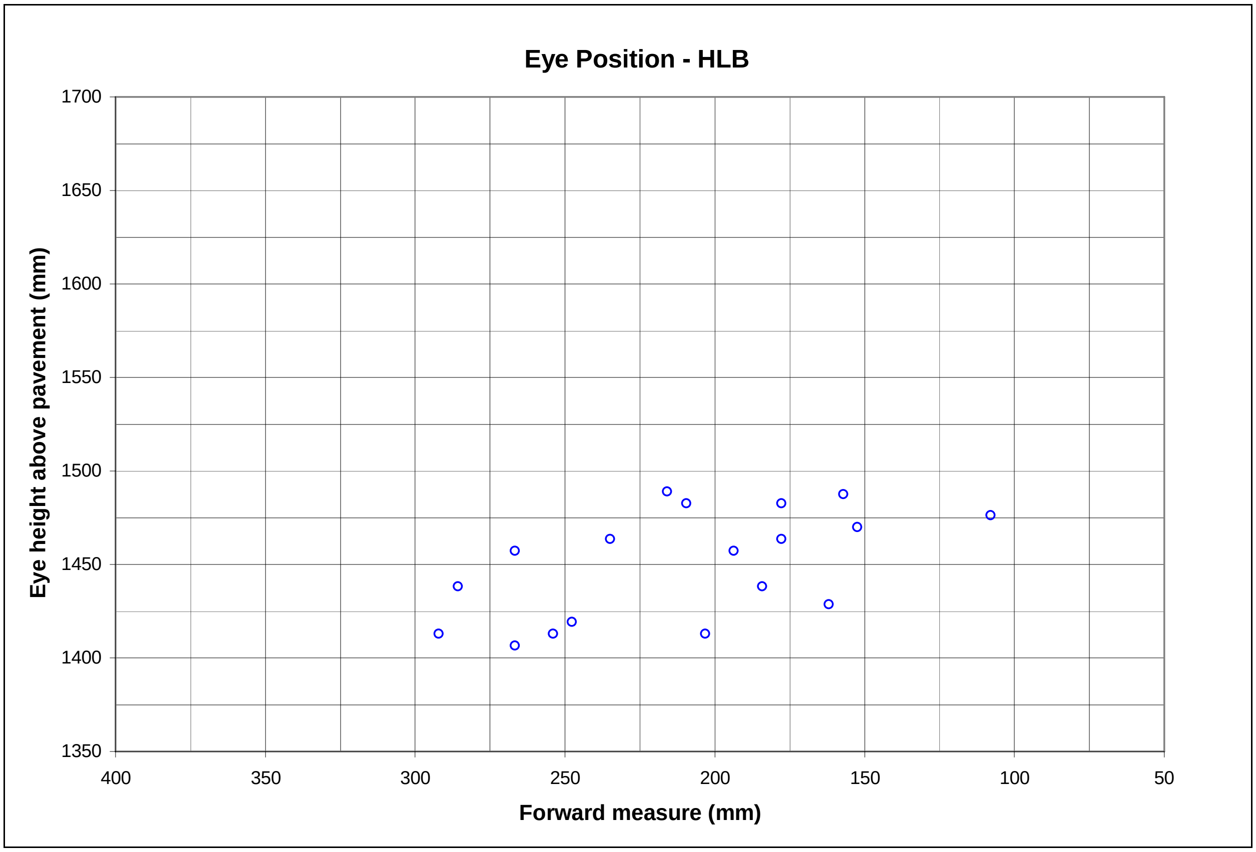
1 mm = 0.04 inches

Figure 88. Scatter plot. Participant eye position for NIR 2.

Table 43. NIR 2 eye position measurements.

Participant	Forward (inches)	Height (inches)
1	7.75	13.75
2	4.5	14
3	6.75	12.75
4	11.25	13.5
5	6.75	13.5
6	8	12.25
7	7	13
8	5.5	14.75
9	6.5	12.75
10	9	12.5
11	6.25	13.1
12	10	12.5
13	5.5	13.5
14	8	14
15	7.75	13.75
16	10.25	12.5
17	8.25	12
18	14	10.75

1 inch = 2.54 cm = 25.4 mm



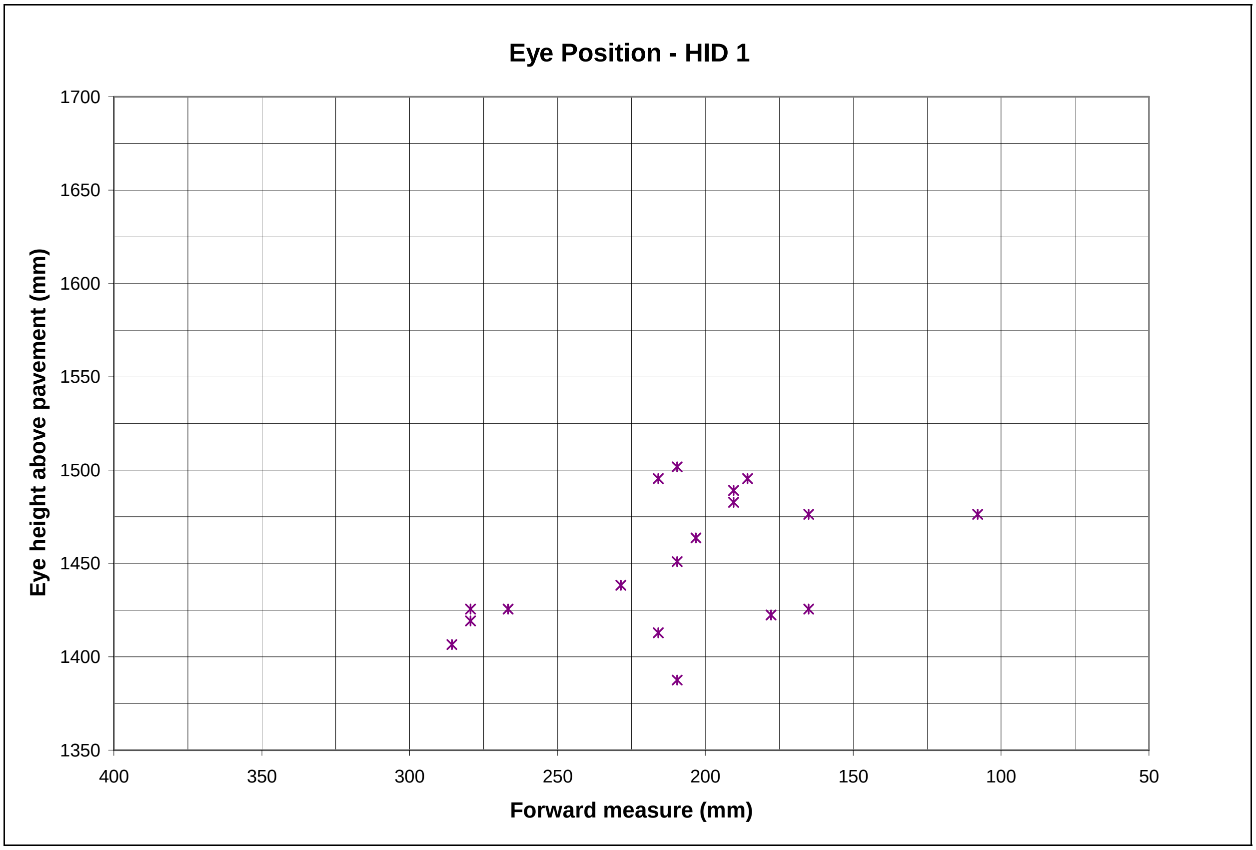
1 mm = 0.04 inches

Figure 89. Scatter plot. Participant eye position for HLB.

Table 44. HLB eye position measurements.

Participant	Forward (inches)	Height (inches)
1	10.5	12.25
2	6	14.75
3	6.5	13.25
4	9.75	12.75
5	7	15.25
6	8	12.5
7	10.5	14.25
8	8.25	15.25
9	7	14.5
10	7.75	14.25
11	8.25	15.25
12	11.5	12.5
13	6.25	15.5
14	8.5	15.5
15	9.25	14.5
16	10	12.5
17	7.25	13.5
18	11.25	13.5

1 inch = 2.54 cm = 25.4 mm



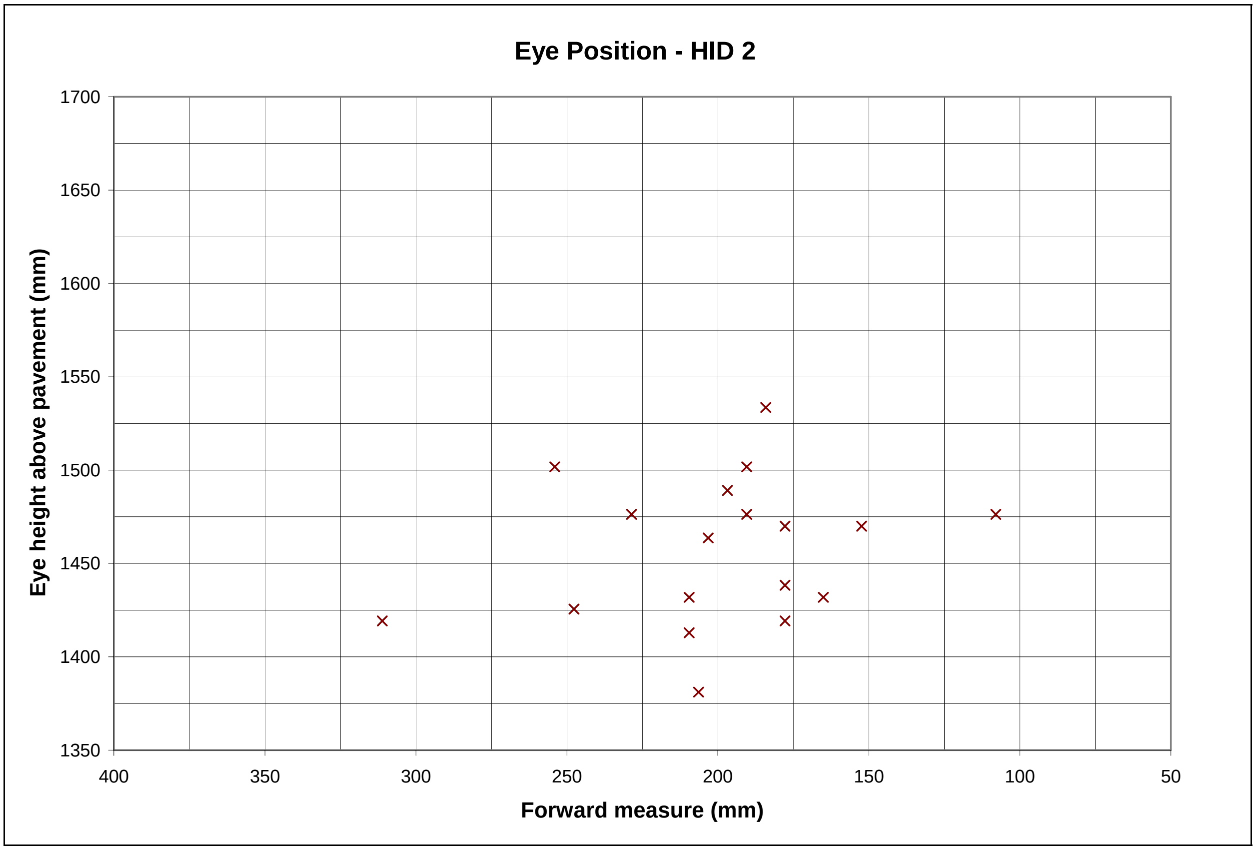
1 mm = 0.04 inches

Figure 90. Scatter plot. Participant eye position for HID 1.

Table 45. HID 1 eye position measurements.

Participant	Forward (inches)	Height (inches)
1	10.5	13
2	6.5	15
3	7	12.75
4	11	12.75
5	8.25	16
6	8.5	12.5
7	11	13
8	4.25	15
9	7.5	15.5
10	8	14.5
11	8.25	14
12	9	13.5
13	7.5	15.75
14	7.5	15.25
15	8.5	15.75
16	8.25	11.5
17	6.5	13
18	11.25	12.25

1 inch = 2.54 cm = 25.4 mm



1 mm = 0.04 inches

Figure 91. Scatter plot. Participant eye position for HID 2.

Table 46. HID 2 eye position measurements.

Participant	Forward (inches)	Height (inches)
1	8.25	13.25
2	6	14.75
3	7	13.5
4	8.25	11.25
5	7.5	16
6	7	12.75
7	8	14.5
8	4.25	15
9	7.5	15
10	9	15
11	7.75	15.5
12	8.25	12.5
13	7.25	17.25
14	7	14.75
15	10	16
16	9.75	13
17	6.5	13.25
18	12.25	12.75

1 inch = 2.54 cm = 25.4 mm

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