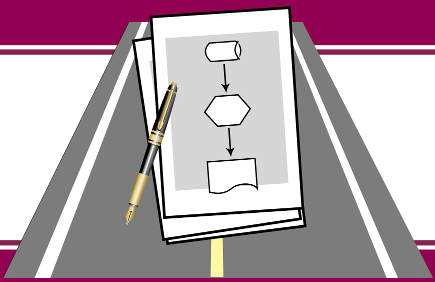

ENV

Volume XII

Enhanced Night Visibility Series: Overview of Phase II and Development of Phase III Experimental Plan

PUBLICATION NO. FHWA-HRT-04-143

DECEMBER 2005

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
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FOREWORD

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

The following document provides an overview of the series of studies conducted under Phase II of the Enhanced Night Visibility (ENV) project and the development of the Phase III experimental plan. The ENV project provided a comprehensive evaluation of evolving and proposed headlamp technologies in various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume XII. It is anticipated that the reader will select those volumes that provide information of specific interest.

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

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

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This volume provides an overview of the six studies that compose Phase II of the Enhanced Night Visibility project and the experimental plan for its third and final portion, Phase III. The Phase II studies evaluated up to 12 vision enhancement systems in terms of drivers' ability to detect and recognize objects, visibility of pavement markings, and discomfort caused by glare from oncoming headlamps. Drivers' ability to detect and recognize objects was assessed in clear, rain, fog, and snow conditions. The results indicated that supplemental ultraviolet headlamps do not provide sufficient benefit to justify further testing. The performance of supplemental infrared (IR) vision enhancement systems, on the other hand, was robust enough to suggest further investigation. As a result, additional IR testing, disability glare testing, and off-axis object detection on the Virginia Smart Road were proposed as a replacement for public road Phase III testing with UV–A. The details of the experimental plan for each of these testing areas are provided in the Phase III portion of this report.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

ENHANCED NIGHT VISIBILITY PROJECT REPORT SERIES

This volume is the 12th of 18 volumes in this research report series. Each volume is a different study or summary, and any reference to a report volume in this series will be referenced in the text as "ENV Volume I," "ENV Volume II," and so forth. A list of the report volumes follows:

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

General Terms

ENV ....Enhanced Night Visibility
OEM.................................original equipment manufacturer
SUV..................................sport utility vehicle
TCD..................................traffic control device
UV–A ....ultraviolet A (wavelength 315 to 400 nanometers)
VES ....vision enhancement system

Vision Enhancement Systems

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

Measurements

km/h ....kilometers per hour
lx ....lux
m ....meters
nm ....nanometers

CHAPTER 1—INTRODUCTION

The three-phase Enhanced Night Visibility (ENV) project studied the potential for implementing supplemental ultraviolet A (UV–A) headlamps and supporting infrastructure to improve onroad night visibility. Phase I of the project is detailed in ENV Volume II, *Overview of Phase I and Development of Phase II Experimental Plan*. The focus of the Phase I effort was on the establishment of performance and design objectives to facilitate the deployment of UV–A headlamps. Phase II of the project included the initial studies that were conducted to support the establishment of these performance and design objectives. The marginal performance benefits of the UV–A headlamps found in Phase II dictated a change in direction for the Phase III portion of this research. This report provides an overview of the studies accomplished in Phase II and the experimental plan that was developed for Phase III.

CHAPTER 2—PHASE II STUDIES

Phase II of the ENV project included six studies. Four studies evaluated 12 different vision enhancement systems (VESs) on their ability to assist drivers in detecting and recognizing objects and pedestrians at night in clear and inclement weather. The other two studies evaluated 11 of these VESs in the areas of pavement marking detection and discomfort glare. This chapter summarizes the independent variables, dependent variables, and key results of the six studies conducted in Phase II. The following nine ENV reports provide the full details of all Phase II efforts:

- Volume III: Study 1: Visual Performance During Nighttime Driving in Clear Weather (FHWA-HRT-04-134)
- Volume IV: Study 2: Visual Performance During Nighttime Driving in Rain (FHWA-HRT-04-135)
- Volume V: Study 3: Visual Performance During Nighttime Driving in Snow (FHWA-HRT-04-136)
- Volume VI: Study 4: Visual Performance During Nighttime Driving in Fog (FHWA-HRT-04-137)
- Volume VII: Study 5: Evaluation of Discomfort Glare During Nighttime Driving in Clear Weather (FHWA-HRT-04-138)
- Volume VIII: Study 6: Detection of Pavement Markings During Nighttime Driving in Clear Weather (FHWA-HRT-04-139)
- Volume IX: Characterization of Experimental Objects (FHWA-HRT-04-140)
- Volume X: Visual Performance Simulation Software for Objects and Traffic Control Devices (FHWA-HRT-04-141)
- Volume XI: Cost-Benefit Analysis (FHWA-HRT-04-142)

Volume III through Volume VIII provide the detailed methodologies, protocols, and results for each of the six studies. Volume IX describes the methodology and results of a subsequent analysis that characterized the luminance of the objects with each VES used in the detection and recognition testing except for the infrared thermal imaging system (IR–TIS). Volume X describes the visual performance simulation software developed to evaluate the visibility of objects and traffic control devices with various headlamps. Volume XI describes the cost-benefit analysis that evaluated the performance of the UV–A headlamps.

In addition, Volume XVII—*Characterization of Experimental Vision Enhancement Systems* (FHWA-HRT-04-148)—details the characterization of the VESs used in this phase.

VISUAL PERFORMANCE STUDIES

Independent Variables

Vision Enhancement Systems

The term "VES" encompasses the combination of headlamps, supplemental lighting, and/or imaging system used on each vehicle. The VESs for the conditions of clear weather (ENV Volume III), rain (ENV Volume IV), snow (ENV Volume V), and fog (ENV Volume VI) included the following technologies:

- Halogen (i.e., tungsten-halogen) low beam (HLB).
- Halogen (i.e., tungsten-halogen) high beam (HHB).
- High intensity discharge (HID).
- High output halogen (HOH).
- Ultraviolet light band A (UV–A) with minimal visible-band light.
- Hybrid UV–A, which includes both UV–A and visible-band light.
- Infrared thermal imaging system (IR–TIS).

As a VES, UV–A is not designed to function without visible light, and it should be thought of as a supplemental visibility system. This research used the following three UV–A configurations: two hybrid UV–A lamps (hybrid UV–A), so called because of their significant visible light component; three UV–A lamps (three UV–A) that had a minimal visible light component; and five of these lamps (five UV−A). Each of the UV–A configurations was paired with two HLB baseline headlamps and, separately, two HID baseline headlamps. Table 1 presents these six UV–A configurations as well as the other six VES configurations used throughout the visual performance studies. An "X" in this table indicates that the VES configuration was used in the corresponding study. The clear and rain studies included all 12 VESs. The fog and snow studies reduced the VESs to the subset with the most potential to perform well in inclement weather.

Table 1. VESs in each Phase II study.

VES	Clear	Rain	Snow	Fog
HLB	X	X	X	X
Hybrid UV–A + HLB	X	X	X	X
Three UV–A + HLB	X	X		
Five UV–A + HLB	X	X	X	X
HLB–LP	X	X		X
HHB	X	X		
HOH	X	X		
HID	X	X	X	X
Hybrid UV–A + HID	X	X		
Three UV–A + HID	X	X		
Five UV–A + HID	X	X		
IR–TIS	X	X		X

HLB = halogen low beam
UV–A = ultraviolet A
HLB–LP = halogen low beam at a lower profile
HHB = halogen high beam
HOH = high output halogen
HID = high intensity discharge
IR–TIS = infrared thermal imaging system

Most of the configurations were installed on high-profile vehicles, including sport utility vehicles (SUVs) and pickup trucks. The IR–TIS was part of an original equipment manufacturer (OEM) package on a sedan that used halogen headlamps. This was the only sedan included in the study, so the headlamps were defined as halogen low beam, low profile (HLB–LP). These HLB–LP headlamps were tested alone and in conjunction with the IR–TIS. The prototype HOH lamp, which was designed to produce more visible light, was installed in the same type of housing as the HLB–LP but placed on a pickup rather than a sedan. The HHB lamp was in the same housing as the HOH lamp but in the high-beam lamp position.

The headlamps used for the HLB, HID, HOH, HHB, and UV–A configurations were located on external light bars. To change from one configuration to another, researchers moved the HLB and HID headlamps between vehicles. Each light assembly movement necessitated a re-aiming process, which took place before starting the experimental session each night. During the photometric characterization of the headlamps, it was discovered that the position of the maximum intensity location of the HLB, HOH, and HHB configurations was aimed higher and more toward the left than typically specified. This aiming deviation likely increased detection and recognition distances for the HLB and HOH configurations and likely decreased them for the HHB configuration. Details about the aiming procedure and the maximum intensity location are discussed in ENV Volume XVII.

Age

Each of the studies except for the snow study used three age groups: younger participants (18 to 25 years), middle-aged participants (40 to 50 years), and older participants (65 years or older). For the snow condition, the older group was excluded for safety reasons. The participants were required to get in and out of the experimental vehicles multiples times throughout the night on a potentially icy road surface. Therefore, the risk for a slip and fall, although unlikely, was deemed too great to allow older drivers to participate.

Objects

Table 2 and figure 1 through figure 6 show the objects used in the clear, rain, snow, and fog studies. ENV Volume IX provides detailed characterization of each of these objects. Parallel pedestrians continuously walked back and forth along a portion of the right side of the road on the shoulder side of the edgeline. The pedestrian walked 10 paces forward followed by 10 paces backward, always facing the oncoming vehicle for safety reasons. Perpendicular pedestrians continuously walked from the right edgeline of the road to the centerline and back. Cyclists continuously rode from one edgeline to the other. The static pedestrian, tire tread, and child’s bicycle were on the right edgeline.

The clear study used all the objects. In the snow study, the cyclist was removed for the safety of the cyclist and because it is unlikely that a cyclist would be present in an actual snowstorm. The tire tread and the child’s bicycle were also removed because they were rapidly covered with snow. In the fog study, variable wind and temperature conditions made it challenging to maintain consistent fog density across runs. To more accurately assess object visibility independent of fluctuations in fog density, the study used only the white-clothed perpendicular pedestrian, but it used this object multiple times to provide a better estimate of detection distance.

Table 2. Objects used in each Phase II study.

Object	Clear	Rain	Snow	Fog
Parallel Pedestrian, Black Clothing	X	X		
Perpendicular Pedestrian, Black Clothing	X	X	X	
Parallel Pedestrian, White Clothing	X	X	X	
Perpendicular Pedestrian, White Clothing	X	X	X	X
Cyclist, Black Clothing	X			
Cyclist, White Clothing	X	X		
Static Pedestrian, White Clothing	X			
Tire Tread	X	X		
Child's Bicycle	X	X		

Figure 1. Photo. Pedestrian in black clothing.

Figure 2. Photo. Pedestrian in white clothing.

Figure 3. Photo. Cyclist in black clothing.

Figure 4. Photo. Cyclist in white clothing.

Figure 5. Photo. Tire tread.

Figure 6. Photo. Child's bicycle.

Dependent Variables

The primary performance variables used in the clear, rain, snow, and fog studies were detection and recognition distance. Detection was explained to participants as follows: "Detection is when you can just tell that something is on the road in front of you. You cannot tell what the object is, but you know something is there." Recognition was explained as follows: "Recognition is when you not only know something is there, but you also know what it is."

During training and practice, the participants pressed a button on a hand-held wand when they could detect an object on the road. The participants performed a second button press when they could recognize the object. The in-vehicle experimenter pressed another button the moment the participant drove past the object. Detection and recognition distances were calculated from distance data collected at these three points.

The dependent variables also included subjective ratings. Participants were asked to evaluate a series of seven 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 statements addressed each participant's perception of improved vision, safety, and comfort after experiencing a particular VES. Participants were asked to compare each VES with their own vehicle's regular headlights. Following is a list of the statements on the questionnaire:

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

Experimental Design

Each of the visual performance studies used a mixed-factor experimental design. VES and object were both within-subject variables, and age was the between-subjects variable for each of the studies.

Key Findings

The following are the key findings in the clear, rain, snow, and fog object detection and recognition studies. ENV Volumes III, IV, V, and VI, respectively, contain the full findings for these studies.

Supplemental UV–A

In general, the supplemental UV–A did not provide sufficient improvement over the baseline HID and HLB headlamps to justify additional research in this area. As expected, the UV–A produced longer detection distances for the scenarios with the white-clothed pedestrian in the clear, rain, fog, and snow conditions relative to the baseline headlamps alone. For comparison purposes, the detection results for the baseline headlamps with five UV–A—the configurations with the most supplemental UV–A—and for the perpendicular pedestrian dressed in white—the object most likely to have its visibility enhanced by UV–A—are shown in table 3. Note that these combinations had the greatest potential to show a benefit of UV–A. In inclement weather, the five UV–A configuration allowed an approximately 10-m (32-ft) greater detection distance than the HLB baseline headlamps. In the clear condition, the five UV–A showed the greatest improvement, with a 25-m (83-ft) greater detection distance than HLB alone and an approximately 40-m (132-ft) greater detection distance than HID alone. In rain, the five UV–A detection distance improvement was approximately 18 m (60 ft) greater than HID alone; however, when the results of five UV–A are compared for all the objects (table 4), it can be seen that the supplemental UV–A increased detection distance by approximately 7 m (23 ft). The exceptions to this is the fog condition, which used only the white-clothed pedestrian (the object most likely to have its visibility enhanced by UV–A), and the clear condition with HID, which had a 16-m (52-ft) detection distance improvement.

It is important to recognize that the five UV–A headlamp configuration was included to provide a proof-of-concept by evaluating the maximum potential benefits of a UV–A supplemental headlamp system. As described in detail in ENV Volume XVII, the configuration used five large, high-wattage lamps designed for use on snowplows in Norway. Thus, barring significant advances in technology (such as UV–A light-emitting diodes), providing this much UV–A light is not practical for installation on automobiles at this time for reasons of cost, power consumption, and size.

Table 3. Mean detection distances with five UV–A of the perpendicular pedestrian dressed in white for the different weather conditions.

Weather Condition	HLB (m)	Five UV–A + HLB (m)	HID (m)	Five UV–A + HID (m)
Clear	253	278	224	264
Rain	81	91	67	86
Snow	71	80	58	NA
Fog	47	57	51	NA

NA = data not available
1 m = 3.28 ft

Table 4. Mean detection distances with five UV–A for all objects in the different weather conditions.

Weather Condition	HLB (m)	Five UV–A + HLB (m)	HID (m)	Five UV–A + HID (m)
Clear	184	191	154	170
Rain*	60	67	55	61
Snow*	59	66	51	NA
Fog*	47	57	51	NA

NA = data not available
1 m = 3.28 ft
*Subset of objects; refer to table 1 for details.

Supplemental Infrared System

The IR–TIS was included because of its ability to present the driver with images of the environment based on the temperature differential of objects. This approach has the potential to allow for very early detection of pedestrians, cyclists, animals (i.e., objects generating heat) or infrastructure objects that shed heat (e.g., guard rails, light posts) on the roadway.

Table 5 compares mean detection distances with HLB–LP and IR–TIS (recall that these two VESs were always paired) for the perpendicular pedestrian dressed in white, the only object used in clear, rain, and fog conditions. The IR–TIS was not used during the snow condition because the camera became blocked by snow. Heavy rain negatively affected the image presented to the drivers from the IR–TIS in the rain condition. In the fog condition, IR−TIS provided the longest detection distances and was rated as the most helpful for detection. In the clear condition, IR–TIS was superior to all other VESs for pedestrian detection, especially for detection of low-contrast pedestrians.

Table 5. Mean detection distances with HLB–LP and IR–TIS for the perpendicular pedestrian dressed in white clothing for the different weather conditions.

Weather Condition	HLB–LP (m)	IR–TIS (m)
Clear	237	292
Rain	72	66
Fog	46	58

1 m = 3.28 ft

Table 6 illustrates the mean detection distances for the perpendicular pedestrians dressed in white and in black clothes for IR–TIS and HLB–LP in the clear condition. The pedestrian dressed in white was detected more than 50 m (164 ft) farther when IR–TIS was available than with the headlamps alone. For the pedestrian dressed in black, detection occurred more than 100 m (328 ft) farther with the IR−TIS, potentially allowing a driver twice the time to avoid such a pedestrian than would be provided by headlamps alone. Because it is atypical for pedestrians to wear high-luminance or highly reflective clothing,(1) this type of technology has the potential to reduce pedestrian crashes and should be evaluated further.

Table 6. Mean detection distances with HLB–LP and IR–TIS for the perpendicular pedestrians dressed in white and in black clothing for the clear weather condition.

Clothing Color	HLB–LP (m)	IR–TIS (m)
White	237	292
Black	99	201

1 m = 3.28 ft

Age

In the clear condition, older drivers had shorter detection distances on average than the younger and middle-aged drivers, especially with low-contrast objects; the differences were smaller with the IR–TIS. However, in the rain and snow conditions, age made little difference; the precipitation reduced visibility levels so drastically that it effectively leveled the playing field for all ages. Surprisingly, the younger participants had shorter detection distances than the other participants in the fog condition.

Objects

In the clear and rain conditions, clothing contrast, rather than object motion, appears to have been responsible for the differences observed between the different types of pedestrians and cyclists. Not surprisingly, pedestrians dressed in white were detected farther away than pedestrians dressed in black, regardless of the VES used.

Subjective Ratings

The drivers' subjective evaluations suggest that they thought HID helped them the most to detect and recognize the different objects. This finding conflicts with the objective data. For example, in the rain condition, although the HLB supplemented with UV–A allowed pedestrians and cyclists in white clothing to be detected farther away, the drivers' subjective evaluation indicated that HID was more helpful in object detection.

DISCOMFORT GLARE STUDY

The primary focus of the discomfort glare study (ENV Volume VII) was to determine the degree of driver discomfort caused by oncoming supplemental UV–A headlamps. The study included all VESs (table 1) except IR–TIS because glare is not an issue with IR technology. This study was conducted on the Smart Road using 60 participants split equally among 3 age groups: younger participants (18 to 25 years), middle-aged participants (40 to 50 years), and older participants (60 years or older). Participants drove toward a fixed glare source and rated it twice using the deBoer discomfort rating scale.[(2)] The first rating represented the discomfort the participant experienced at an approximate range of 396 to 305 m (1,300 to 1,000 ft) away from the opposing headlamps.

The second rating reflected the discomfort felt in the approximate range of 137 to 46 m (450 to 150 ft).

The results indicated that the amount of visible light (maximum illumination) directed toward the observer's eye by the opposing headlamps was the overriding factor contributing to the reported discomfort sensation. The spectral distribution of the light did not appear to have an effect. The hybrid UV–A lamps appeared to add discomfort glare (recall that this lamp had a larger visible light component), but the other UV–A lamps did not. The HLB headlamps selected for this testing produced more discomfort glare than did the HID headlamps tested. This result may have been caused by the aiming strategy used for the HLB headlamps; however, a subsequent study could not confirm that the aiming strategy made a difference.

Finally, modifications of the Schmidt-Clausen and Bindels equation were made to allow the maximum level or last experienced level of illuminance at the driver's eye to be used in predicting ratings of discomfort glare.(3) This may provide headlamp designers with insight into discomfort glare of proposed headlamps early in the design process.

PAVEMENT MARKINGS

The pavement marking study (ENV Volume VIII) focused on the visibility of three pavement marking materials: a liquid system, fluorescent thermoplastic, and fluorescent paint. The liquid system was chosen because it has approximately twice the retroreflectivity of conventional patterned tape markings. Fluorescent pigments were added to the other two pavement markings to evaluate the potential benefit of UV–A in these materials. The pavement markings were applied to three separate sections of the Smart Road with a blank section (i.e., no pavement marking) before and after each type of marking. As in the discomfort glare study, the pavement markings study used all the VESs (table 1) except for IR–TIS because that technology was not designed to facilitate pavement-marking visibility. Thirty participants, 10 from each of the 3 age groups (18 to 25 years, 40 to 50 years, and 60 years or older), completed the study.

While driving, the participants indicated when they could first detect the beginning of a pavement marking section by pressing a hand-held pushbutton. They pressed the pushbutton a second time when they could detect the end of a pavement marking section. Each participant performed this detection activity for each marking type using each of the VESs. The two baseline VESs, HLB and HID, were compared both individually and in combination with three levels of UV–A to each other and three other headlamps (see table 1).

The results indicated that all the VESs provided adequate minimal visibility distances for all of the pavement markings at the 40-km/h (25-mi/h) speed driven. It is likely that visibility would be adequate at much higher speeds, but additional research would be required to verify this. The supplemental UV–A did not improve detection distances for either the HID or the HLB headlamps. This effect likely was caused by the significant and rapid degradation of the fluorescent pigments in the pavement marking materials. Nothing in this study supported the additional cost of adding fluorescent material to pavement markings. In fact, no VES and pavement marking pair outperformed other pairs to the extent that a combination of VES and pavement marking could be recommended. Both the liquid system and fluorescent thermoplastic pavement markings outperformed the fluorescent paint. As expected, younger drivers attained the longest detection distances, which likely can be attributed in part to their faster reaction times and increased contrast sensitivity.

CONCLUSIONS

The results of the Phase II research indicated that supplemental UV–A did not provide sufficient improvement in visibility to justify conducting the onroad field study planned for Phase III; however, the IR–TIS technology in clear conditions did show a meaningful improvement in visibility of pedestrians (especially pedestrians in low-contrast clothing) over headlamps alone. IR–TIS also improved visibility in the fog condition but not in rain.

The maximum illumination directed toward the driver's eye by the opposing headlamps was the overriding factor contributing to the reported discomfort sensation. Based on these results, modifications to the Schmidt-Clausen and Bindels equation were made to allow the maximum level or last experienced level of illuminance at the driver's eye to be used in predicting ratings of discomfort glare.[3] This equation could potentially help headlamp designers early in the design process. Because the UV–A sources used in the study did not produce much visible light, the addition of the UV–A did not substantially increase discomfort glare ratings.

No VES and pavement marking pair outperformed other pairs enough to merit recommendation. An unfortunate side effect of providing UV–A-sensitive marking materials is that the fluorescent properties fade rapidly because of the lack of UV protection from the sun. This was clearly a factor in these results; however, because there is no known practical method for alleviating this issue, no additional testing was warranted.

CHAPTER 3—PHASE III DEVELOPMENT

Not one of the vision enhancement system configurations evaluated in the Phase II studies was clearly beneficial across all of the conditions tested; therefore, at this stage of the project, an onroad field study using a given configuration would have been premature. As a result, the implementation portion of the Phase I work plan (activity 5) was eliminated along with the following activities:

- Specifying photometric characteristics of fluorescent traffic control devices (TCDs) when illuminated with UV–A headlamps as compared to conventional TCDs illuminated with standard halogen headlamps in rain and fog.
- Comparing the beam pattern of the UV–A headlamp to safety standards.
- Evaluating the potential for driver overconfidence with UV–A headlamps and the degree of crash reduction.

Additional Smart Road testing was recommended rather than conducting an onroad field study. Ongoing changes in night vision enhancement technology presented new opportunities to gain valuable information from expanded testing focusing on comparisons between conditions that were tested in Phase II and new VESs. Thus, the Phase III work plan was developed with the primary objective of improving visibility of the road environment. The Phase III work plan added the following four activities, detailed in this chapter and labeled 6 through 9 for consistency, to replace the eliminated tasks from the revised statement of work:

- Activity 6: Expand evaluation of headlamp technology.
- Activity 7: Expand infrared technology evaluation.
- Activity 8: Evaluate disability glare.
- Activity 9: Evaluate off-axis benefits of HID headlamps.

ACTIVITY 6: EXPAND EVALUATION OF HEADLAMP TECHNOLOGIES

Background and Problem Statement

During the last 10 years, significant advancements have been made in new headlamp technologies that provide greater visibility than traditional halogen headlamps. This was evident in the results of Phase II of this research effort. Some other advantages of these newer headlamps (e.g., HID) include a greater beam-spread, which may not only use the available light more efficiently but may also increase the visibility of objects in the roadway periphery. Some disadvantages of these lights may include discomfort and disability glare effects for oncoming drivers. Empirical studies designed to investigate possible advantages and disadvantages of headlight technology often do not occur until after the technology has appeared on U.S. roadways. A more proactive approach involving communication between researchers and car manufacturers is needed to initiate testing on what may be available in the near future.

New Headlamp Technology Search

It was proposed that up to three new VESs—differing with respect to technology, spectrum, and beam pattern—be tested as part of the protocols suggested in activities 8 and 9. The experimental designs used in the Phase II Smart Road studies had sufficient flexibility to allow these technologies to be evaluated and compared to other technologies tested in Phase II. The goal was an advanced evaluation of technologies that automotive manufacturers were considering for implementation in the near future, as well as a better understanding of their possible advantages (visibility of objects in the periphery) and disadvantages (disability glare effects).

In the first portion of the investigation, the contractor identified and contacted automotive manufacturers and headlamp suppliers who had innovative headlamp technologies intended for market distribution in the near future. The criteria for selection of the new technologies were the following: (1) the new technologies should be different from the technologies that had already been tested, and (2) these new technologies should be testable at the Smart Road testing facility.

Three HID headlamps were selected for inclusion in the disability glare study (activity 8), and two of these headlamps were selected for object detection and recognition testing in clear weather as well as for potential off-axis benefits (activity 9).

ACTIVITY 7: EXPAND INFRARED TECHNOLOGY EVALUATION

Background and Problem Statement

The research in Phase II aided in the understanding of VESs such as UV–A, HLB, HID, and hybrid headlamps as well as other technologies including IR–TIS. The IR–TIS showed significant benefits in Phase II for detecting pedestrians in clear weather conditions. Recall that IR–TIS uses the difference between the thermal signature of objects and that of the surrounding driving environment to aid in object detection. Several OEMs and suppliers are developing IR−TISs as well as near IR (i.e., active IR) technologies, which both have potential to greatly improve visibility during nighttime driving. The newer IR–TISs may be more sensitive to temperature differences, making it possible to detect and identify more objects (e.g., pedestrians) or to detect objects at greater distance. Several OEMs and suppliers are also developing near IR to provide a more detailed view of the driving environment including lane markings. These systems use IR emitters to act similarly to headlamps when viewed through the IR camera and its associated display. Unlike IR–TISs, near IR systems show many details of the forward roadway scene such as headlamp light, pavement markings, and signs. Because IR will not generate glare, near IR systems have the potential to increase visibility distances beyond those of conventional headlamps without negative effects for oncoming traffic.

Infrared Systems Comparison

Using methodology similar to the headlamp search described in activity 6, the researchers contacted OEMs and suppliers to determine which systems were going to be available in the near future. Three IR systems were selected for additional testing: two prototype near IR systems and the same IR–TIS from the Phase II studies. At the time, no new IR–TISs could be obtained. All three systems obtained were to be placed on SUVs.

The testing methodology for this activity was designed to determine if the evolving IR technologies further improve detection and recognition of objects in the roadway and what could be done to the roadway infrastructure to provide the greatest possible integration and benefit from these systems. To determine possible detection and recognition benefits, the IR technologies were to be tested using a methodology similar to that used in Phase II. Development work was required to determine how to provide infrastructure that would benefit from these systems. Roadway infrastructure components designed for integration with IR VESs do not currently exist; however, as IR systems become more prevalent in the marketplace, these components could be designed to increase driving safety by providing more information from the infrastructure to the driver. For example, heat-retaining roadway delineators might be visible at greater distances, potentially improving the ability of the driver to reconcile the view through the IR system (enhanced view) with the forward scene from the windshield. Materials such as route management signage, temporary road markings, and safety vests should be capable of reflecting emitted IR as well as visible light to ensure that information remains conspicuous in both formats. In critical roadway sections (e.g., crosswalks, complex intersections, and roadway areas during incident management), roadway IR emitters could be used to increase conspicuity.

This activity devoted a great deal of effort to investigating infrastructure alternatives both by designing potential prototypes and contacting suppliers. After substantial pilot testing, it was determined that resources would be better spent determining how well existing infrastructure interacted with IR systems. During the pilot testing, it was determined that the near IR appeared to have some potential problems with blooming when exposed to certain road signs. On the other hand, it also showed promise in providing drivers forewarning of a traffic sign. As a result, it was determined that assessing existing signage and road markings would provide the most benefit because this infrastructure is already in place and will likely remain for a significant period of time.

During the pilot testing, it appeared there was sufficient time to include activity 9 (off-axis testing) in this study using the same test participants. The purpose of activity 9 is described in more detail in the activity 9 section. Combining these studies would provide several advantages:

- Allowing direct comparisons between the IR systems and additional headlamps for both object and infrastructure detection and recognition.
- Determining how well the IR system performed when objects were off axis.
- Providing objects in addition to off-axis objects so that the participants in activity 9 would not modify their normal visual scanning behavior (i.e., to avoid oversampling the sides of the road).

A methodology similar to what was used in the Phase II object detection and recognition studies was planned for this activity. Initially, a clear-condition study was planned using a 6 (VES) by 3 (Age) by 17 (Object) mixed-factor design. VES, a within-subject factor, was to include the HLB headlamp used in the Phase II studies, the three IR systems (i.e., one IR–TIS and two near IRs), and two HIDs. Age was to be the only between-subjects factor. Phase III was also to use the same gender-balanced age group criteria used in the Phase II visual performance studies. For the objects within-subject factor, a total of 17 different objects were to be presented, including signs, directional markings, and some of the objects used in Phase II (e.g., pedestrian dressed in black and the tire tread). Phase III was also to use pedestrians in curves and off-axis positions. After completion of the clear study, a rain study was to be conducted with a subset of the objects to determine the merit of the Phase III systems in rain.

ACTIVITY 8: EVALUATION OF DISABILITY GLARE

Background and Problem Statement

Public concern and press coverage about glare associated with new headlamps has been an increasingly prevalent topic in recent years, especially since the introduction of HID headlights.[4] HID headlamps provide more luminous flux than conventional HLB headlamps. This trait has made them excellent candidates for vehicular applications, and they have already been implemented as standard components in some automobiles; however, limited research exists on the possible negative effects of these headlights on the vision of oncoming drivers.

Public opinion about the glare problem has revolved around drivers' perceived increase in discomfort glare when approaching a vehicle equipped with HIDs. Although driver comfort is very important and may ultimately decide whether or not a new technology is universally adopted, disability glare is more likely to affect safety.

Disability glare is a result of light scattering in the ocular media. Light from a glare source, such as the headlights of an oncoming vehicle, enters the eye and scatters, creating a uniform luminance, or veiling luminance, over the retina. Regardless of whether an object is brighter or darker than its background, veiling luminance will decrease the contrast of the object. As a result, the object is less likely to be seen.

Recall that Phase II of the ENV project included a discomfort glare evaluation of 11 different headlamp configurations, including HLB, HID, and UV–A headlamps (ENV Volume VII). The primary focus of this Phase II study was on rating the discomfort glare of UV–A as compared to other VESs. However, it is difficult to fully understand the effects of these VESs on safety without a direct disability glare evaluation. The two types of glare have different physiological origins, and factors that affect one type often do not affect the other;[5] therefore, a disability glare evaluation in combination with a discomfort glare evaluation was needed to determine what effect the newer headlight technologies have on oncoming drivers. As part of this evaluation, a literature review was to be conducted and included in the report.

Disability Glare Study

The disability glare study was planned as a 5 (VES) by 2 (Driver's Adaptation Level) by 2 (Pedestrian Location) by 3 (Age) mixed-factor design. As mentioned in activity 6, three additional HID headlamps were selected for comparison to the baseline HLB and HID headlamps used in the Phase II studies. This provided the following headlamp intensities and patterns of oncoming glare:

- High/narrow: higher intensity with narrow beam pattern (HID).
- High/wide: higher intensity with wide beam pattern (HID).
- Low/wide: lower intensity with wide beam pattern (baseline HID).
- Medium/medium: mid-level intensity with medium beam pattern (HID).
- Low/narrow: low intensity with narrow beam pattern (baseline HLB).

Driver age was the only between-subjects variable. It included the same three gender-balanced age ranges used in the majority of Phase II studies: a younger group (18 to 25 years old), a middle-aged group (40 to 50 years old), and an older group (65 years and older).

At night, a driver's eye will adapt to the ambient lighting condition. This adaptation level will change the ability of the driver to perceive objects as well as the driver's glare sensitivity. For this study, driver light adaptation level was a within-subjects variable including a low level of 0.15 lux (lx) and a high level of 0.45 lx. A dimmable light source inside the vehicle (on top of the instrumentation panel) was to allow experimenters to control the driver's light adaptation level.

Pedestrian location was also a within-subjects variable. The location of pedestrians in the roadway significantly affects their visibility to drivers in the presence of glare. Two locations were chosen for this study, one near the centerline and the other near the right edgeline. Both locations were set 15.2 m (50 ft) behind the oncoming glare headlamps, and both pedestrians were to wear white clothing and stand facing the glare vehicle.

ACTIVITY 9: EVALUATE OFF-AXIS BENEFITS OF HID HEADLAMPS

Background and Problem Statement

The human visual system consists of two types of photoreceptors: rods and cones. These two photoreceptor types have different characteristics and different visual functions. Cones, mostly located in the fovea of the eye, are sensitive to higher (photopic) lighting conditions. They provide the finest detail of visual acuity as well as perception of color. The periphery of the eye has very few cones. Rods, entirely located in the periphery of the eye, are sensitive during lower (scotopic) lighting conditions. They provide most of the detection of motion and objects but very little acuity. At the extremes of lighting conditions (photopic and scotopic), either rods or cones are active; but at the lighting levels used for roadways, both rods and cones are active, which is called mesopic vision. Because the sensitivity and effectiveness of the peripheral visual field is affected by the photoreceptor in use, the adapted luminance level influences the ability to perceive objects. Typically, the lower the adaptation luminance level the lower the visibility of objects.

Another aspect of rod photoreceptors is their difference in spectral sensitivity. Cone sensitivity is characterized by the photopic sensitivity function, shown in a bell-shaped sensitivity curve peaking at 555 nanometers (nm). Rods sensitivity is characterized by the scotopic sensitivity function, a bell-shaped curve peaking at 507 nm. This means that at night, the peak eye sensitivity changes from green toward blue colors.

HID lamps have a greater blue spectral component, which is more closely related to the scotopic sensitivity of the human peripheral visual field. Some HID headlamps also have a wider beam-spread than conventional halogen headlamps. These characteristics can effectively increase the visibility of objects that are eccentric to the drivers' line of sight. This increased visibility creates a potential safety benefit by allowing earlier detection of pedestrians, animals, and other objects that could enter the roadway.

Investigate HID Performance in Off-Axis Pedestrian Detection

While the Phase II studies evaluated detection and recognition of objects in the roadway including the edgelines, this portion of the Phase III testing was intended to focus on establishing the benefit of headlamps with wider beam-spreads for the visibility of pedestrians beyond the roadway edge. This testing was to be accomplished by presenting off-axis objects to drivers and recording their visual performance by measuring detection distance (as previously defined for Phase II studies). Recall that this study was to be conducted in activity 7, the IR evaluation, in which pedestrians were to be positioned 9.5 m (31 ft) to the left or the right of the travel lane. Pedestrians were also to be positioned either to the left or right of the road in a curve to the left or a curve to the right. These pedestrians were to be included in the counterbalance of the 17 objects tested in activity 7 studies to avoid having participants anticipate the next-appearing object.

REFERENCES

1. Blomberg, R.D., & Cleven, A.M. (2000). *Development, Implementation and Evaluation of a Countermeasure Program for Alcohol-Involved Pedestrian Crashes* (DTNH22-91-C-07202). Retrieved on November 9, 2005, from http://www.nhtsa.dot.gov/people/injury/alcohol/PedestrianAccident/DocHeader.html
2. deBoer, J.B., & Schreuder, D.A. (1967). “Glare as a Criterion for Quality in Street Lighting.” *Transactions of the Illuminating Engineering Society*, *32*, 117–135.
3. Schmidt-Clausen, H.J., & Bindels, J.T.H. (1974). “Assessment of Discomfort Glare in Motor Vehicle Lighting.” *Lighting Research and Technology*, *6*(2), 79–88.
4. Singh, S., & Perel, M. (2004). *Drivers’ Perceptions of Headlight Glare from Oncoming and Following Vehicles* (DOT HS 809 669). Available at http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/Rpts/2003/809-669/images/GLARE_PERCEP.pdf
5. Fry, G.A. and King, V.M. (July 1975). “The Pupillary Response and Discomfort Glare.” *Journal of Illuminating Engineering Society*, *4*, 307.

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