Volume I

Enhanced Night Visibility Series: Executive Summary

PUBLICATION NO. FHWA-HRT-04-132

DECEMBER 2005

U.S. Department of Transportation

Federal Highway Administration

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

FOREWORD

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

The following document summarizes the results of a series of studies conducted under the Enhanced Night Visibility (ENV) project. 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 I. 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

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HRT-04-132		

4. Title and Subtitle Enhanced Night Visibility Series, Volume I: Executive Summary	5. Report Date December 2005
	6. Performing Organization Code:
7. Author(s) Jonathan M. Hankey, Myra Blanco, Ronald B. Gibbons, Shane B. McLaughlin, and 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
This volume, an executive summary of the Enhanced Night Visibility project, is the first of 18 volumes that report on the project's evaluation of the merit of implementing supplemental ultraviolet headlamps, supplemental infrared systems, and other vision enhancement systems (VESs) to enhance drivers' nighttime roadway safety. The entire project evaluated 18 VESs in terms of their ability to provide object detection and recognition. Objects included scenarios with pedestrians standing or walking in different locations on the roadway. Pedestrians were dressed in black, white, or blue clothing to produce varying levels of contrast with their surroundings. Detection and recognition testing took place in clear weather, rain, snow, and fog conditions. Project research also evaluated a subset of the VESs for their effect on drivers' disability and discomfort glare. The VESs were also tested for their value in facilitating drivers' detection of pavement markings and other traffic control devices. The results indicated that supplemental ultraviolet headlamps do not provide sufficient benefit to justify further testing; however, supplemental infrared vision enhancement systems do offer an improvement over headlamps alone for detection of pedestrians. Near infrared systems have the potential to provide an added benefit in detecting pedestrians in inclement weather, but the implementation of NIR technology is the key to achieving this benefit.

17. Key Words	18. Distribution Statement
Age, Cyclist, Detection, Fog, Halogen, Headlamp, High Intensity Discharge (HID), Infrared, Night Vision, Nighttime, Pavement Markings, Pedestrian, Rain, Recognition, Snow, Traffic Control Devices, Ultraviolet, Vision Enhancement System, Weather	No restrictions. This document is available through the National Technical Information Service; Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	27	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

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

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

TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

ENV ....Enhanced Night Visibility
IR......................................infrared
RRPM ....raised retroreflective pavement marker
UV–A................................ultraviolet A (wavelength 315 to 400 nanometers)
VES..................................vision enhancement system

Vision Enhancement Systems

FIR ....far infrared
five UV–A.........................five UV–A headlamps
HID ....high intensity discharge
HLB...................................halogen (i.e., tungsten-halogen) low beam
HOH..................................high output halogen
hybrid UV–A ....hybrid UV–A/visible output
IR–TIS..............................infrared thermal imaging system
NIR....................................near infrared
three UV–A.......................three UV–A headlamps

Measurements

ft ....feet
km/h ....kilometers per hour
lux lx
m ....meters
mi/h ....miles per hour

CHAPTER 1—INTRODUCTION

Timely detection of traffic control devices and hazards on the roadway is an essential part of safe driving at night. There is general agreement that automobile low-beam headlamps provide, at best, marginal visibility for low-contrast objects such as pedestrians.[1] Therefore, alternative systems that enhance night visibility are needed, especially systems that enhance pedestrian detection. Preliminary studies have indicated that prototype UV–A headlamps significantly improve visibility for fluorescent traffic control devices and for pedestrians.[2,3,4]

The purpose of the Enhanced Night Visibility (ENV) project was to study supplemental ultraviolet A (UV–A) headlamps, supplemental infrared (IR) systems, various headlamp technologies, and supporting infrastructure to improve drivers' ability to detect and recognize objects and pedestrians at night. The project 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.

The project initially focused on the potential for implementing UV–A and its supporting infrastructure. Phase I established the plan to facilitate implementation of UV–A headlamps. Phase II was a series of six studies with the primary objective of facilitating the implementation of UV–A technology. Four of the studies were object detection and recognition studies (i.e., visual performance studies) that separately examined visibility in clear weather (ENV Volume III), rain (ENV Volume IV), snow (ENV Volume V), and fog (ENV Volume VI). Another study was conducted to assess oncoming drivers' level of discomfort glare caused by UV–A headlamps relative to other vision enhancement systems (VESs) (ENV Volume VII). The sixth study conducted in Phase II evaluated the visibility of 3 different pavement markings in combination with 11 VESs (ENV Volume VIII). VESs in Phase II of the ENV project included headlamps alone or headlamps in combination with a supplemental system such as UV–A or infrared thermal imaging system (IR−TIS).

Originally Phase III was planned to be a public-road study to further assess the benefit of supplemental UV–A; however, the results of the Phase II testing indicated that supplemental UV–A did not produce sufficient improvement to justify further testing. On the other hand, IR−TIS did show sufficient benefit to be tested further. Phase III of this project shifted the emphasis from supplemental UV–A to supplemental IR. Three studies were conducted in this phase. Two visual performance studies, one in clear weather (ENV Volume XIII) and one in rain (ENV Volume XIV), tested both IR–TIS and near IR systems as well as headlamps alone. The third study (ENV Volume XV) assessed the discomfort glare and disability glare of five different headlamp systems.

In total, the ENV project included 6 studies of visual performance, in terms of object detection and recognition, while using 18 different VESs ranging from halogen (i.e., tungsten-halogen) to UV–A and IR technology. All of the VESs were tested in clear weather conditions, and subsets of the VESs were tested in adverse weather conditions, including rain, fog, and snow. Subsequent analyses characterized the luminance of the objects for each VES used in the visual performance studies (i.e., detection and recognition testing) (ENV Volumes IX and XVI) and characterized the VESs (ENV Volume XVII). Two studies evaluated discomfort glare to oncoming drivers from 14 of the VESs and disability glare to oncoming drivers from 5 of the VESs. An additional study assessed pavement marking detection using 11 of the VESs.

CHAPTER 2—PHASE I PLANNING

The planning for this project, detailed in ENV Volume II, included the following five activities:

1. Development of UV–A headlamp specification.
2. Evaluation of fluorescent infrastructure materials.
3. Quantification of glare and photobiological risks.
4. Expanded cost-benefit analysis.
5. Demonstration and implementation.

Although the primary focus of this phase was on planning for the Phase II and Phase III activities, significant time was devoted to working with automotive and lighting manufacturers. It became apparent early in the project that the automotive manufacturers would need to fully understand the costs and benefits of UV–A technology before they would embrace it. Significant time was also spent working with infrastructure suppliers to determine their interest in being a project partner and the feasibility of obtaining fluorescent materials for evaluation that represented realistic alternatives for roadway infrastructure.

Because even prototype UV–A headlamps were not readily available, a great deal of effort was devoted to developing and researching pre-prototype headlamps that could be combined to produce varying levels of UV–A. It was decided that as many as five pre-prototype headlamps were needed to provide a high-output UV–A VES and that both high- and low-output UV–A VESs would be required for testing.

Finally, a literature review was conducted to further refine the planned Phase II research.

CHAPTER 3—PHASES II AND III VISUAL PERFORMANCE STUDIES

METHODS

To measure drivers' visual performance using different types of VESs, nighttime experiments required volunteer participants to drive various types of vehicles outfitted with a variety of headlamps and combinations of headlamps with supplemental UV–A or IR technology. The various VESs tested were obtained either through coordination with potential manufacturers and suppliers or by purchasing and combining off-the-shelf components. The participants were asked to report when they could detect, and then recognize, different objects placed on or near the roadway. Test vehicles were instrumented to record the distance to the object at the moment of detection and recognition. The testing was conducted on the Virginia Smart Road, 3.2 km (2 mi) of two lanes of roadway (closed to public traffic) that includes weather-making capability. Separate studies tested object detection and recognition in clear and adverse weather conditions—rain, snow, and fog.

INDEPENDENT VARIABLES

The visual performance studies included three independent variables: VES, age, and object. The VES variable included different types of headlamps as well as headlamps combined with supplemental UV–A or IR systems. The age variable grouped participants into three age groups. The object variable included various roadway objects and pedestrians that participants were required to detect and recognize.

Vision Enhancement Systems

The VESs used for the visual performance studies included several different technologies. The studies reported in ENV Volume III (clear weather), ENV Volume IV (rain), ENV Volume V (snow), and ENV Volume VI (fog) included the following VESs:

- Halogen (i.e., tungsten-halogen) low beam (HLB).
- Halogen high beam (HHB).
- High intensity discharge (HID).
- High output halogen (HOH).

- Ultraviolet band, including wavelengths from 315 to 400 nanometers, with minimal visible-band light (UV–A).
- UV–A and visible-band light (hybrid UV–A).
- Infrared thermal imaging (IR–TIS).

The studies reported in ENV Volume XIII (clear weather) and ENV Volume XIV (rain) included these VESs:

- HLB.
- HID.
- IR–TIS.
- Near infrared (NIR).

The Phase II 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 in conjunction with the UV–A component; three UV–A lamps (three UV–A) that had a minimal visible light component; and five of these UV–A lamps (five UV−A). It is important to recognize that the five UV–A headlamp configuration was included to provide a proof-of-concept, 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 because of the UV–A headlamps' cost, power consumption, and size.

Each of the UV–A configurations was paired with halogen headlamps and, separately, with HID headlamps.

The research in Phase III evaluated two NIR systems, which used IR emitters in combination with a camera sensitive to the near IR spectrum. Both Phases II and III evaluated an IR–TIS system, which used a camera sensitive to thermal contrast between objects and surroundings. A display located just above the instrument panel presented images from these systems. Because NIR and IR–TIS are supplemental visibility systems not designed to be used without visible light in vehicular applications, each system was paired with halogen headlamps provided by the IR system suppliers; these halogen headlamps were different from the halogen headlamps paired with the UV–A headlamps.

Headlamps were aimed before starting the experiment's session each night. At the beginning of the project, a headlamp aiming device was not available to the contractor, so an aiming protocol was developed with the help of experts in the field. 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 typical. 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, *Characterization of Experimental Vision Enhancement Systems*.

Age

All 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). The older group was excluded from the snow condition because the participants were required to get in and out of the experimental vehicles multiple times throughout the night on a potentially icy road surface. The risk for a slip and fall, although unlikely, was deemed too great to allow older drivers to participate.

Objects

The objects used for these studies were selected to represent a variety of potential roadway obstacles and pedestrian scenarios. Table 1 shows all the objects included in this project as well as the weather conditions and phase of the project in which they were used. All the objects were static with the exception of the parallel pedestrians, perpendicular pedestrians, and cyclists. Parallel pedestrians continuously walked back and forth along the shoulder next to the road's right edgeline. Perpendicular pedestrians continuously walked from the right edgeline of the road to the centerline and back. Cyclists continuously rode from one side of the road to the other. All other objects were statically positioned on the side of the road near the edgeline or, in the case of the far off axis pedestrians, 9.4 m (31 ft) to the left or right of the centerline. "Bloom" pedestrians stood beside a car parked in the oncoming lane with its headlamps on. In this configuration, the glare from the oncoming vehicle had the potential to overload the NIR camera. This caused the image in the system display to be washed out with a bloom of light and caused the pedestrian to be nonvisible in the display.

This project used real people for the pedestrians to allow for movement and to give the IR–TIS system a realistic heat differential. The dog was an internally heated, stuffed model of a Scottish terrier.

Table 1. Objects used in studies.

Object	Clear	Rain	Snow	Fog	Phase
Parallel Pedestrian, Black Clothing*	X	X			II
Perpendicular Pedestrian, Black Clothing*	X	X	X		II
Parallel Pedestrian, White Clothing*	X	X	X		II
Perpendicular Pedestrian, White Clothing*	X	X	X	X	II
Perpendicular Pedestrian, Blue Clothing*		X			III
Cyclist, Black Clothing*	X				II
Cyclist, White Clothing*	X	X			II
Static Pedestrian, White Clothing	X				II
Tire Tread	X	X			II, III
Child's Bicycle	X	X			II
Pedestrian, Black Clothing, Left	X				III
Pedestrian, Black Clothing, Right	X				III
Pedestrian, Blue Clothing, Left	X	X			III
Pedestrian, Blue Clothing, Right	X	X			III
Pedestrian in Left Turn, Left Side, Blue Clothing	X	X			III
Pedestrian in Left Turn, Right Side, Blue Clothing	X	X			III
Pedestrian in Right Turn, Left Side, Blue Clothing	X	X			III
Pedestrian in Right Turn, Right Side, Blue Clothing	X	X			III
Pedestrian Far Off Axis Left, Blue Clothing	X				III
Pedestrian Far Off Axis Right, Blue Clothing	X				III
Bloom Pedestrian, Left, Blue Clothing	X				III
Bloom Pedestrian, Right, Blue Clothing	X				III
Raised Retroreflective Pavement Marking (RRPM)	X				III
Sign	X				III
Turn Arrow on Pavement	X				III
Dog	X				III

* Object was moving.

DEPENDENT VARIABLES

The primary performance variables were the distance at which participants detected an object and the distance at which they recognized an object. Detection was explained to the 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." Later, participants were also asked to indicate their degree of agreement with a series of statements that addressed their perceptions of improved vision, safety, and comfort after using each VES. Participants rated their agreement to these questions using a seven-point Likert-type scale with anchor points at "1," indicating "Strongly Agree," and "7," indicating "Strongly Disagree."

KEY FINDINGS

Supplemental UV–A

The Phase II results indicate that VESs with supplemental UV–A generally did not provide sufficient improvement over the tested HID and HLB headlamps to justify additional research in this area. As expected, the UV–A produced longer detection distances of the pedestrian dressed in white for the clear, rain, fog, and snow conditions than did the HID or HLB headlamps tested alone. The UV–A also provided longer detection distances of all the objects on average; however, even five UV–A, the most powerful UV–A configuration, provided improvements ranging from only 7 m (23 ft) in adverse weather to 16 m (52 ft) in clear conditions. Given these small benefits combined with the current impracticality of producing this much UV−A with a vehicle, the UV–A conditions were excluded from the Phase III research.

Supplemental IR System

The Phase II experiments showed that for the pedestrian dressed in white in adverse weather, IR–TIS showed a 12-m (39-ft) improvement over the baseline HLB headlamps in fog, but in heavy rain it showed a 6-m (20-ft) decrement; the system was not used in the snow condition because snow buildup would have blocked the camera. In the Phase II clear condition research comparing the headlamps supplemented with IR–TIS to the headlamps alone (ENV Volume III), the supplemental IR–TIS showed an approximately 55-m (181-ft) greater detection distance for the pedestrian dressed in white and a more than 100-m (328-ft) greater detection distance for the pedestrian dressed in black. This latter finding was important because pedestrians often wear low-contrast, nonreflective clothing.[(5)] The overall Phase II results show that IR technology has the potential to reduce pedestrian crashes by increasing detection and recognition distances; therefore, the emphasis for this project was shifted from testing UV–A to testing IR technology and other headlamps more thoroughly in Phase III. As the Phase II research came to an end, automobile manufacturers became more interested in near IR, which has the potential to greatly increase detection distance in inclement weather. For this reason, the Phase III testing included the IR−TIS system as well as two prototype NIR systems.

The overall Phase III results indicated that both the IR–TIS and one of the NIR systems could outperform headlamps alone in pedestrian detection (ENV Volume XIII). For most of the pedestrian scenarios, the IR–TIS implementation provided a 20- to 30-m (66-ft to 98-ft) detection advantage over the best NIR implementation. The second NIR system did not perform as well as the other two IR systems or even some of the headlamps, illustrating that implementation is the key to a successful enhanced night vision system. Both NIR and IR–TIS improved detection distance of pedestrians, compared to visible headlamp systems, when a glare source was present.

In general, in rainy driving conditions (ENV Volume XIV), both NIR systems had longer detection distances than the HLB and the IR–TIS system for nearly all pedestrian detection scenarios. This is a particularly interesting finding because even the NIR system that did not perform well in the clear condition outperformed the other systems in adverse weather. These objective findings do not appear to be differentiated by age and are corroborated by the subjective responses of the drivers in this study.

Age

In the Phase II clear condition study (ENV Volume III), older drivers had shorter detection distances on average than the younger and middle-aged drivers, especially with low-contrast objects, but the differences were smaller with the IR–TIS. Supplemental IR showed this benefit for older participants in Phase III also (ENV Volume XIII). A more detailed analysis of this

Phase III data showed that the older participants using the IR systems performed similarly to the younger participants using the best of the three headlamp systems, indicating that these IR systems could be used to reduce an age-related decrement in object detection.

Objects

In the Phase II clear and rain conditions (ENV Volumes III and IV), clothing contrast rather than object motion appears to have been responsible for differences in detection distances 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.

In the Phase III clear condition study (ENV Volume XIII), on average the VESs demonstrated longer detection distances of pedestrians dressed in blue clothing than of pedestrians dressed in black clothing by 60 percent. Although this result was not surprising for most of the VESs, the 83-m (273-ft) greater detection distance for blue clothing when using an IR–TIS system was greater than expected. IR–TIS imaging is based on thermal differences between the object and the background rather than differences in the visible spectrum, so theoretically there should have been no difference in pedestrian detection because of clothing color. The observed difference could have been the result of the thicker blue cloth retaining more of the pedestrians' body heat than the thinner black cloth, or perhaps some participants waited for visual confirmation (through the windshield) before declaring detection of a pedestrian.

Subjective Ratings

In Phase II, the drivers' subjective evaluations suggest that they thought HID helped them detect and recognize the different objects from farther away than did the other VESs. This finding conflicts with the objective data, which show shorter detection and recognition distances with HID. This conflict indicates that collecting subjective data alone for this type of research is not sufficient.

CHAPTER 4—PHASES II AND III GLARE STUDIES

Glare studies were conducted in Phase II and Phase III of this project. In Phase II, a discomfort glare study evaluated 11 different headlamp configurations by rating the driver's discomfort glare caused by oncoming UV–A VESs as compared to other VESs (ENV Volume VII). To more fully understand the effects of glare on vehicle safety, a disability glare evaluation in combination with a discomfort glare evaluation was conducted as part of Phase III (ENV Volume XV). In addition to discomfort glare ratings, this study measured driver detection distances of pedestrians in the glare of various oncoming HID and halogen headlamps.

PHASE II DISCOMFORT GLARE STUDY

The primary focus of the Phase II 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 of the UV–A configurations from the visual performance studies and the two baseline headlamps types (HLB and HID) assessed alone. Three additional headlamp-only systems were also included for a total of 11 VES configurations. The discomfort glare study was conducted on the Smart Road using 60 participants split equally among three age groups: younger participants (18 to 25 years), middle-aged participants (40 to 50 years), and older participants (60 years or older). Participants drove at 40 km/h (25 mi/h) toward a fixed glare source (i.e., each VES) and rated it twice using the deBoer discomfort rating scale.[6] The first rating represented the discomfort the participant experienced from a range of approximately 396 to 305 m (1,300 to 1,000 ft) away from the opposing headlamps. The second rating reflected the discomfort experienced in the range of approximately 137 to 46 m (450 to 150 ft).

The hybrid UV–A headlamps appeared to have added discomfort glare relative to the baseline headlamps (recall that hybrid UV–A headlamps had a significant visible light component), but the other UV–A headlamps did not. The halogen headlamps selected for this testing produced more discomfort glare than did the high intensity discharge headlamps tested. This result may have been caused by the aiming strategy used for the halogen headlamps; however, a subsequent study could not confirm that the aiming strategy made a difference. Analysis of illuminance measurements taken at the approximate driver's eye position during testing indicated that the amount of visible light (i.e., maximum illumination) directed toward the driver's eye by the opposing headlamps was the overriding factor contributing to the reported discomfort sensation; the spectral distribution of the headlamp light source did not appear to have an effect.

PHASE III DISCOMFORT AND DISABILITY GLARE STUDY

The purpose of the discomfort and disability glare study (ENV Volume XV) was to determine the effect of beam intensity and pattern on disability glare, defined here as detriment to pedestrian detection, and to determine any relationship between disability glare and discomfort glare.

The discomfort and disability glare study used the baseline headlamps from the Phase II discomfort glare study and three additional HID headlamps. These five VESs allowed comparison of different combinations of beam intensities and patterns:

- 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-width beam pattern (HID).
- Low/narrow: low intensity with narrow beam pattern (baseline HLB).

To study the effect of environmental light on discomfort and disability glare, a dashboard light source mounted in the experimental vehicles produced two driver light adaptation levels, 0.15 lux (lx) and 0.45 lx at the driver's eye level. The disability glare study used two pedestrians in white clothing as objects, differing only in their locations relative to their glare sources; both pedestrians stood 15.2 m (50 ft) behind their glare source, one pedestrian on the centerline and the other on the right edgeline. Thirty participants were again divided equally into three age groups—younger (18 to 25 years), middle-aged (40 to 50 years), and older (65 years or older).

During the study, the participants drove toward the glare sources, which were positioned on a static frame simulating an oncoming vehicle. During the disability glare assessment portion, participants indicated when they could detect the pedestrian as they approached the glare sources. During the discomfort glare portion, participants were asked to rate the discomfort experienced (using the deBoer scale) over an approximately 305-m (1,000-ft) approach toward the glare source.

Three dependent variables were collected during this study: pedestrian detection distance, the deBoer scale rating of discomfort glare, and driver illumination level (i.e., illuminance at the driver's approximate eye position.)

The results indicated that beam intensity (i.e., maximum light output) affected disability and discomfort glare more than beam pattern did. Specifically, VESs with higher maximum output had shorter pedestrian detection distances and were rated as more discomforting. In general, the results showed that discomfort glare corresponded to disability glare; oncoming VESs that were rated as more discomforting were the same VESs that restricted detection distances.

CHAPTER 5—PAVEMENT MARKINGS

The pavement marking study (ENV Volume VIII) focused on the detection distances 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 study included all of the visual performance studies' UV–A configurations and the two baseline headlamps types (HLB and HID) assessed alone. Three additional headlamp-only systems were also included for a total of 11 VES configurations. Thirty participants were divided equally among three age groups: younger (18 to 25 years), middle-aged (40 to 50 years), and older (60 years or older). While driving, the participants indicated when they could first detect the beginning of a pavement marking section after a blank section and when they could detect the end of a pavement marking section before a blank section. The participants performed this detection activity for each marking type using each of the VESs.

The results indicated that all the VESs provided adequate detection distance, but no pairing of VES and pavement marking outperformed the others enough to merit recommendation. The supplemental UV–A did not improve detection distances when paired with the HID or the HLB headlamps. This effect was likely caused by significant degradation of the fluorescent pigments in a short time period. None of the results of this study supported the additional cost of adding fluorescent material to pavement markings.

CHAPTER 6—CONCLUSIONS

The results indicated that UV–A does have the potential to allow greater detection of pedestrians dressed in clothing with fluorescent properties. This potential exists in clear as well as inclement weather. Additional glare from oncoming UV–A sources does not appear to create additional discomfort glare to other drivers. Adding fluorescent pigment to pavement markings appears to have no benefit. Overall, due to the cost, power consumption, and size, supplemental UV–A is not sufficiently beneficial at enhancing night visibility to justify additional research in this area. If improvements to UV–A technology were to overcome these barriers, further research may be worth considering again.

The current supplemental IR systems, on the other hand, have the potential to greatly enhance pedestrian detection and safety. This is particularly true for pedestrians dressed in nonreflective, dark clothing. Near IR systems, specifically, have the potential to improve pedestrian visibility in adverse weather conditions.

It is important to note that this research did not assess how attention to an IR display of the forward road scene may distract drivers from other driving activities or at least create a time-sharing dilemma. There was some indication that, for objects not presented in the IR display, the object detection distances were shorter for participants driving with the IR display than for those driving without a display. Future research should evaluate methods to alert the driver when an important object is present, and these methods should not rely on the driver noticing the object through normal scanning of the display. Such an alert could potentially highlight objects on the display or eliminate the display entirely and use another mechanism to alert drivers.

Perhaps the most important lesson to be derived from this research is that a well-designed implementation, not just the use of a technology, is a key to a successful enhanced night visibility system. For example, claiming that all HID headlamps significantly improve visibility but also significantly increase glare is oversimplified; in this research, there were HID headlamps that did not significantly improve visibility and HID lamps that did not cause significantly worse glare. In addition, one NIR system in the clear weather condition outperformed headlamps, but another NIR system performed worse than headlamps. In general, different implementations of a given technology may yield significantly different performances. Results should not be generalized across a technology but should be tied to the particular implementation of that technology.

REFERENCES

1. Sivak, M., & Olson, P.L. (1984). *Nighttime Visual Problems of Elderly Drivers* (UMTRI 70665). Ann Arbor, MI: University of Michigan Transportation Research Institute.
2. Fast, P.T. (1994). "Field Test of UV-Headlamps at a 100-km Test Site." *Towards an Intelligent Transportation System, Proceedings of the Fifth World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems*, *4*, 2172–2179.
3. Fast, P.T., & Ricksand, A. (1993). *Safer Nighttime Driving: UV-Headlamps Improve Visibility Of Pedestrians*. Paper presented at SIA 8th Congrès Mondial, Paris.
4. Mahach, K.R., Knoblauch, R.L., Simmons, C.J., Nitzburg, M., Arens, J., & Tignor, S.C. (1997). *A Preliminary Field Evaluation of Ultraviolet-Activated Fluorescent Roadway Delineation* (Technical Report FHWA-RD-97-082). Washington, DC: U.S. Department of Transportation, FHWA.
5. 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
6. 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.