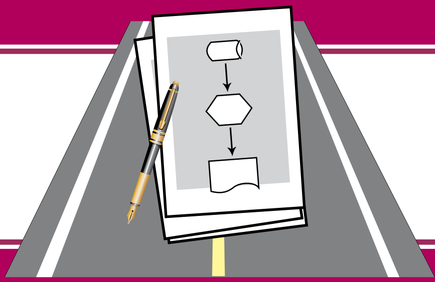


Volume II

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

PUBLICATION NO. FHWA-HRT-04-133

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 provides an overview of the initial series of studies conducted in Phase I of the Enhanced Night Visibility (ENV) project, and the development of the Phase II plan for the experiment. 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 II. 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-04-133		

4. Title and Subtitle	5. Report Date
Enhanced Night Visibility Series, Volume II: Overview of Phase I and Development of Phase II Experimental Plan	December 2005
	6. Performing Organization Code:

7. Author(s)	8. Performing Organization Report No.
Thomas A. Dingus, Gary R. Allen, Stephen C. Brich, Vicki L. Neale, Aaron D. Schroeder, Myra Blanco, Thomas Schnell, James S. Gillespie, Tracey Talley Schroeder, Carole J. Simmons, and Jonathan M. Hankey	

9. Performing Organization Name and Address	10. Work Unit No.
Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061	11. Contract or Grant No. DTFH61-98-C-00049

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	Final Report
	14. Sponsoring Agency Code HRDS-05

15. Supplementary Notes

Contracting Officer's Technical Representative (COTR): Carl Andersen, HRDS-05

16. Abstract

The focus of the Phase I effort was on the establishment of performance and design objectives to facilitate the deployment of ultraviolet A (UV–A) headlamps. This report describes the plan to develop UV–A headlamp specifications, evaluate fluorescent infrastructure materials, quantify glare and photobiological risks, expand the cost/benefit analysis, and demonstrate and implement the UV–A technology. It also includes a literature review that was conducted before the Phase II studies. As is often the case in large projects, some of the planned work eventually changed or was replaced to address more pressing issues. The later volumes of this report series detail what research occurred and why.

17. Key Words	18. Distribution Statement
Age, Detection, Halogen, Headlamp, High Intensity Discharge (HID), Infrared, Pedestrian, Night Vision, Nighttime, Recognition, Stakeholder, Ultraviolet, Visibility, Vision Enhancement System	No restrictions. This document is available to the public 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	95	

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

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

Organizations

ASTM ....American Society of Testing and Materials
CFAR ....Center for Applied Research
FHWA............Federal Highway Administration
NHTSA ....National Highway Traffic Safety Administration
TFHRC............Turner-Fairbank Highway Research Center
USCAR ....United States Council for Automotive Research
VDOT ....Virginia Department of Transportation
VTCTR ....Virginia Tech Center for Transportation Research
VTRC.............Virginia Transportation Research Council
VTTI ....Virginia Tech Transportation Institute

General Terms

ENV ....Enhanced Night Visibility
GPS ....global positioning system
HD...................head-down
HID ....high intensity discharge
HUD................heads-up display
IR.....................infrared
IR–TIS............infrared thermal imaging system
ISIS ....in-vehicle signing information system
SPD ....spectral power distribution
TCD.................traffic control device
UV–A.............ultraviolet A (wavelength 315 to 400 nanometers)
VES.................vision enhancement system
VMT................vehicle miles traveled

Measurements and Scientific Abbreviations

cd.....................candelas
cm....................centimeters
h.......................hours
H......................horizontal
Hz....................Hertz
km ....kilometers
L ....luminance
lm ....lumens
m ....meters
mi ....miles
min ....minutes
mm ....millimeters
nm ....nanometers
R_A ....coefficient of retroreflection
R_L ....retroreflected luminance
s ....seconds
V......................vertical
W.....................watts

CHAPTER 1—PURPOSE

INTRODUCTION

This section describes the activities that occurred during the first phase of the Enhanced Night Visibility (ENV) project. The priority for this initial phase was to make significant progress toward the first milestone outlined in the original contract: establishment of performance and design objectives to facilitate the deployment of ultraviolet A (UV–A) headlamps. This phase involved the following tasks:

- Establish stakeholder teams to move the technology forward on all fronts toward potential deployment.
- Determine the current state of knowledge of UV costs and benefits.
- Develop an evaluation plan to fill gaps in the current state of knowledge necessary to establish not only realistic performance and design objectives but also quantitative and comprehensive benefits and costs.
- Develop materials, methods, and partnerships to enable performance of the required evaluations, beginning on a relatively small scale and culminating in a larger-scale demonstration.

This volume describes the efforts of researchers at the Virginia Tech Transportation Institute (VTTI) (formerly known as the Virginia Tech Center for Transportation Research or VTCTR), the Virginia Transportation Research Council (VTRC), the Virginia Department of Transportation (VDOT), and the University of Iowa to develop the groundwork necessary to support the subsequent research. In the interest of demonstrating this process, the initial approaches, plans, and goals of the researchers are presented as they were established at the time, regardless of their actual outcomes. Much of this volume comes from an unpublished workplan developed in Phase I of this project for the Federal Highway Administration (FHWA). Many of these tasks came to full fruition, some were implemented with minor changes, and some were completely redesigned. Several new tasks were added. The actual outcomes are detailed in ENV Volumes III through XVIII covering Phase II and Phase III of this project.

TEAM APPROACH

To achieve the first milestone, establishment of performance and design objectives to facilitate the deployment of ultraviolet (UV–A) headlamps, four research teams were created:

- Vehicle team: Headlamp specification and development issues.
- Driver/pedestrian team: Driver performance and headlamp safety issues.
- Infrastructure team: Specification, fabrication, installation, and evaluation of pavement markings and delineators.
- Implementation team: Development of public and private partnerships needed for eventual deployment.

Early in the project, the teams focused on making the final team member selections, clarifying team member roles, and refining the research questions for Phase I.

Two of the major tasks in Phase I of the project were identifying and procuring infrastructure materials and headlamps. As such, the teams worked with lighting and infrastructure manufacturers to develop products for testing. The following paragraphs summarize the results of these efforts.

Infrastructure Materials Development

Infrastructure materials suppliers showed interested in participating in the project. The following suppliers were involved to varying degrees:

- 3M™
- Carsonite International
- Cataphote®
- Potters Industries
- PrecisionScan LLC®
- Flint Trading Company™
- Cleanosol
- DayGlo®

The level of participation varied among these organizations from providing the use of equipment and testing facilities to providing certain types of materials for evaluation and testing. The companies that manufactured fluorescent pigments, glass beads, and pavement markings (both paint and thermoplastic material) were interested in having their products evaluated. These same companies expressed a willingness to join the project team to refine their products, if necessary, for the planned deployment phase of the project.

The companies that manufacture sign sheetings were more reluctant to invest significant research and development funding until the UV–A and fluorescent technology proved itself more and a market for such technology developed.

Headlamp Development

Research and development of UV–A (the "A" stands for the portion of the UV band from 315 to 400 nanometers (nm)) and fluorescent technology began in Sweden in the late 1980s. European companies have largely abandoned production and testing of the technology because of a perceived lack of market size in Europe. During the first year of the ENV project, the research team made considerable effort to locate headlamps and other necessary products for testing. Although this work was difficult, several avenues appeared promising. The team proposed that the United States Council for Automotive Research (USCAR) participate in the project and contribute financial support to leverage project and other funds aimed at accelerating headlamp development. In addition, Labino AB, a European lighting manufacturer, appeared willing and able to supply the project with all of the UV–A headlamps necessary for the testing and demonstration activities.

PHASE I: GENERAL APPROACH

Part of Phase I determined the current state of knowledge of UV–A and fluorescent technology. The results revealed a need to conduct analytical and empirical research to better understand this technology. By filling the gaps in the state of knowledge at that time, the research team hoped to establish achievable performance and design objectives as well as quantitative and comprehensive analyses of the benefits and costs associated with UV–A and fluorescent technology. The research team also hoped that such an effort eventually would culminate in a demonstration of the technology and lead to full-scale implementation. To effectively undertake this effort, the research team developed five activity areas to establish UV–A and fluorescent technology design and performance objectives and provide a catalyst for eventual deployment:

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

In each activity area, the research team identified a number of performance and design issues to resolve before the potential wide-scale deployment of UV–A technologies. Table 1 lists these primary issues and identifies which activity areas were to address them. The following sections describe Phase II activity areas and specific performance and design objectives as well as the plans for conducting these analyses and studies.

Table 1. Issues to be addressed by the ENV workplan.

Issues	Applicable Activity Area				
	1	2	3	4	5
Locate suppliers	X	X			
Construct preprototype	X				
Obtain USCAR's assistance	X				X
Determine the required distribution of UV–A radiant intensities	X				
Determine the desired spectral power distribution	X				
Determine the upper and lower cutoffs for filtering	X				
Determine aiming test points	X				
Obtain assistance from industry with research and development	X				
Ascertain photometric characteristics of fluorescent traffic control devices (TCDs)		X			
Determine durability of fluorescent TCDs		X			
Solve installation issues for fluorescent TCDs		X			
Explore potential environmental concerns related to fluorescent TCDs		X			
Set criteria for acceptance or rejection of UV–A and fluorescent technology		X			
Consider driver safety (and photobiological risk)			X		
Consider pedestrian safety (and photobiological risk)			X		
Consider age and acceptance			X		
Consider eye disease and acceptance			X		
Assess headlamp compliance to safety standards			X		
Consider rearview mirror reflection			X		
Consider fluorescent clothing distraction			X		
Calculate costs associated with UV–A and fluorescent technology				X	
Determine deterioration rate of fluorescent TCDs				X	
Calculate cost of making and installing UV–A headlamps				X	
Calculate maintenance costs of UV–A headlamps				X	
Calculate potential effect of UV–A headlamps on accident costs				X	
Calculate potential effect of fluorescent TCDs on accident costs				X	
Assess degree UV–A and fluorescent technology enhances visibility				X	
Assess potential for driver overconfidence with UV–A and fluorescent technology				X	
Calculate degree of crash reduction				X	
Obtain VDOT's assistance					X
Obtain automotive lighting manufacturers' assistance					X
Establish implementation network					X
Analyze stakeholders					X
Formulate strategic planning					X
Manage stakeholder interests					X

CHAPTER 2—ACTIVITY 1. DEVELOP UV–A HEADLAMP SPECIFICATION

Research and development of the UV–A and fluorescent technology began in Sweden in the late 1980s. Saab and Volvo® formed a joint venture called Ultralux® to develop and promote the technology. Prototype UV–A headlamps were manufactured and used in field tests and demonstrations. These headlamps incorporated components from a number of European manufacturers: 50-watt (W) high intensity discharge (HID) lamps with enhanced UV–A output from Philips®, reflectors and housings from Hella® and Valeo, filters from Schott, and ballasts from Hughes Power Products®. In the end, though, this technology was not adopted in Europe, largely because of a perceived lack of market; by the late 1990s, the European UV–A effort had been largely abandoned. The situation required that a major activity area of the ENV project be the fabrication and assembly of UV–A headlamps to help develop a UV–A headlamp specification.

Before commercial UV–A headlamps could become a reality, specifications would need to be developed by the Society of Automotive Engineers, approved by the National Highway Traffic Safety Administration (NHTSA), and incorporated in Federal Motor Vehicle Safety Standards (49 CFR 571.108), as is the case for conventional headlamps. The specification parameters need to differentiate UV–A headlamp performance from that of conventional headlamps. Because UV–A radiation is not visible, it cannot be measured by the usual photometric equipment in units of luminous flux (such as candela per square meter (cd/m^2) at a specified distance). Instead, it must be measured by UV–A-sensitive radiometric equipment in terms of radiant flux (such as microwatts per square centimeter (cm^2) at a specified distance). Equally critical, the spectral characteristics of UV–A headlamps must be specified.

Research was needed to determine the following minimum specifications:

- Required distribution of UV–A radiant intensities (isowatt/steradian diagrams).
- Desired spectral power distribution, including peak wavelength, of the headlamp output.
- Upper and lower cutoffs for filtering the UV–A.
- Aiming test points and procedures for UV–A headlamps.
- Operational design constraints and guidelines that ensure there is no potential biohazard (e.g., no UV–A radiation when the vehicle is traveling at less than 42 km/h).

Obviously, these would concern vehicle manufacturers, but some additional design and safety considerations also required resolution. Only industry could undertake the research and development necessary to address these issues because they were beyond the direct scope of the analytical and empirical research to be conducted as part of the contract. Nonetheless, it was hoped that the ENV project, through its work with stakeholders, would help foster and coordinate these proprietary efforts:

- UV–A headlamp efficiency needs to be maximized to provide the required UV−A output while minimizing power requirements.

- UV–A headlamp optics require materials that transmit rather than screen out UV–A, while allowing styling flexibility.

- Auxiliary UV–A high beam use may allow the Society of Automotive Engineers to adopt the sharp cutoff low-beam pattern used by the Economic Commission for Europe. This would yield safety benefits (resulting from lower glare to oncoming traffic) and also offer manufacturers greater economy of scale.

- UV–A headlamp safety needs to be addressed and resolved for manufacturers' liability concerns.

- UV–A headlamps must be capable of being frequently turned off and on (e.g., when vehicle is going slow or is stopped) without significantly shortening the life of the lamp.

- UV–A headlamps in normal use would supplement conventional low beams; however, for use in fog or mist conditions, the benefits of UV–A (absence of backscatter) may be substantially reduced if a conventional low beam is also on. Yet if only the UV–A headlamps are on, the vehicle would not be adequately visible to oncoming traffic, and the driver would not be able to see the road surface. Therefore, appropriate visible-light fog lamps need to be developed to enhance the visibility of the UV–A vehicle without creating undue backscatter.

TASK 1.1: FABRICATE/ASSEMBLE UV–A HEADLAMP UNITS FOR TESTS

From the outset of the ENV project it was clear that obtaining appropriate UV–A headlamps would be a critical issue. Early in the process the research team contacted vehicle and headlamp manufacturers, only to discover that there was no source for readymade UV–A headlamps; the Ultralux prototype components were no longer available, and the headlamps from North American Lighting® had much lower UV–A output. Fortunately, Labino AB manufactured UV–A lighting for other applications. Thus, bulbs, ballasts, and filters were readily available to support the testing and demonstration activities.

Project requirements for UV–A headlamps were considered in the following phases:

- Year 2: To carry out tests of the UV–A and fluorescent technology on the Virginia Smart Road (appendix A), the project needed to assemble or fabricate a small number of UV–A headlamps. These headlamps would be considered preprototypes rather than true prototypes in the sense of a product being readied for market. The team planned to use the Labino high-output UV–A 35-W bulbs and ballasts. If necessary, as many as four to six UV–A sources may have been placed on a vehicle to attain a high UV–A condition. A high-beam reflector (such as for a halogen (i.e., tungsten-halogen) headlamp) would be needed, and it might have required customization to handle the UV–A bulbs. The Labino Trac-Pack housing may have been appropriate, but the housings may have required fabrication by VTTI. The Schott filters used in the Ultralux units worked well, and the team planned to obtain more of these and use the Labino lamps. The protective front glass needed to transmit UV–A.

- Years 3 and 4: The research team expected that for more extensive and naturalistic testing and demonstration using privately-owned vehicles, only two (or possibly three) prototype UV–A headlamps with sufficient output would be required per vehicle. These headlamps could still be attached as add-ons, so they would not need dynamic styling. Ideally, these headlamps would have been developed and assembled for the project with the help of USCAR, Labino, or another private industry.

TASK 1.2: DEVELOP UV–A HEADLAMP SPECIFICATION

Establishing a basis for UV–A headlamp specifications required both analytical and empirical research. A limited number of field studies with UV technology in Sweden and the United States had demonstrated the potential for large gains in nighttime visibility; however, these were not parametric studies because the levels of UV–A output, fluorescent efficiency, and resulting luminance were not measured and specified as independent variables.

The performance of the UV–A and fluorescent technology as a system depends on the combined performance of the headlamps and the fluorescent materials. Until the UV–A output is fully specified, it is not possible to say what level of fluorescent efficiency is required of the materials to yield a given increase in luminance and visibility distance. Likewise, without knowing the fluorescent performance characteristics of the materials, a headlamp designer would not know how much UV–A is enough.

To address these issues, the research team planned a two-stage approach. The first stage included development and implementation of a computerized visibility model supplemented by measurements of prototype headlamps and materials to analytically test various hypothetical UV–A headlamps in concert with various hypothetical materials. The second stage included field studies to empirically verify results of the model and test proposed specifications for UV–A headlamps and fluorescent materials.

Procedures and Methods

UV–A Headlamp Measurements

Samples of prototype UV–A headlamps were to be obtained and measured, including the Ultralux, Labino, and North American Lighting units and unassembled components (lamps, lenses, filters) as they became available. The FHWA's Photometric and Visibility Laboratory at the Turner-Fairbank Highway Research Center (TFHRC) was to make measurements according to the following plan:

- UV–A beam pattern: The unfiltered, UV–A-enhanced HID headlamp would be affixed to a computer-controlled, three-axis goniometer. A complete set of luminous intensity measurements would be made at a standard array of geometries (about 1,200 readings), and isocandela diagrams would be generated. The UV–A filter would then be put in place, and a spectroradiometer would measure the UV–A output in the direction that yielded the highest photometric reading. A conversion factor would then be applied to scale the photometric readings into radiometric estimates of UV–A output, and isowatt diagrams would be generated.

- Relative spectral power distribution (SPD): The relative SPD of the UV–A headlamps would be measured with a spectroradiometer.

- Spectral transmissivity of the lens and the UV–A filter: These would be measured with a spectroradiometer.

Measurement of Fluorescent Materials

The evaluation of fluorescent infrastructure materials is described in chapter 3, activity 2.

Model Pavement Marking Visibility

A computerized model of visibility for retroreflective pavement markings was to be developed to predict the visibility of retroreflective and fluorescent pavement markings in halogen low beams, HID, and low beams supplemented with UV–A headlamps. The model was to serve as a tool to determine target visibility over a wide spectrum of parameters with relative ease. One major advantage of the computer model would be its ability to examine headlamp and pavement-marking scenarios that were unavailable for field evaluation.

The proposed computer model was to provide the following outputs: pavement marking luminance, road surface luminance, luminance contrast, threshold contrast, and visibility distances. The user would be able to specify the following input parameters: driver age, exposure time, probability of detection, ambient sky luminance, headlamp intensity distribution (for low-beam, HID, and UV−A headlamps), and pavement marking material retroreflectivity and fluorescent efficiency. The user could also vary the spectral composition of the headlamps and the spectral response of the fluorescent markings. Headlamps, observer, and pavement markings would have been implemented in three degrees of freedom only (translation only). The model would handle any number of headlamps attached to the vehicle at any location (three translation degrees of freedom).

The model was to be implemented in MATLAB® and C++ for Microsoft® Windows® (Microsoft Windows 95, Microsoft Windows 98, and Microsoft Windows NT®). The preliminary design stage was to include definition and documentation of the required mathematical equations, definition and documentation of a thesaurus for the data structures and functions, development of an overall (global) data structure and function structure, and definition of the input and output data formats. The main design stage was to accomplish refinement of the overall design of the individual functions and local data structures. Modeling of fluorescent pavement markings was to include the spectral sensitivity. A brief final report describing the Phase I model and the results of the test scenarios were to be submitted.

Issues Addressed

The researchers planned to use the model to seek preliminary answers to several issues raised by the vehicle team:

- The required distribution of UV–A radiant intensities: UV–A radiant intensity distributions (isowatt/steradian diagrams) for all available UV–A prototype headlamps were to be entered into data matrices. A particular prototype would then be selected as an input parameter, which could be multiplied by a scalar vector to increase or decrease the UV–A output. First, the model would position and aim each prototype to maximize pavement marking visibility. Each prototype would be subjected to a sensitivity analysis to determine the lowest scalar multiple of its UV–A output that would achieve a criterion for adequate driver preview time.

- The desired spectral power distribution, including peak wavelength, of the UV–A headlamp output and the upper and lower cutoffs for filtering: The desired spectral power distribution would be determined in part by the action spectra of available fluorescent materials because the fluorescent efficiency of a material depends on how well the action spectrum of a given material matches the spectral output of the UV–A headlamp. In addition, the wavelength cutoffs for filtering are affected by the biohazard potential at the lower wavelength end and the potential for creating glare at the upper wavelength end. The model would make it possible to easily examine what effect these spectral parameters had on pavement marking luminance and preview times. Specifically, the model would run sensitivity analyses using the spectral power distributions from the available UV–A bulbs; action spectra from all available fluorescent materials; 320, 330, or 340 nm as a lower bound; and 370, 380, or 390 nm as an upper bound.

Limitations

This model would be limited to straight and level roadway situations. Only the visibility of pavement markings was to be predicted. Glare and backscatter caused by fog was not to be considered. Because these are significant limitations, the research team recommended that the model eventually be enhanced to allow for the following additional analyses:

- Visibility and legibility of TCDs at various levels of fluorescence in various illumination conditions.
- Visibility of pedestrians with clothing at various levels of fluorescence in various illumination conditions.
- Effectiveness of UV–A headlamps in various ambient illumination conditions.
- Effectiveness of UV–A headlamps in various glare conditions.
- Effectiveness of UV–A headlamps in various levels of fog. It should be noted that existing visibility models consider only the extinction part of fog. Attempts would be made to accurately model the effects of backscatter (veiling luminance) caused by fog as well.

The Model

Work on the model began in January 1999. A limited working prototype of the model was to be released to the project team as soon as practicable to allow for feedback from the model users. Availability of fluorescent pavement-marking data was not critical for the development of the computer model itself; the development could use hypothetical pavement marking fluorescence efficiency matrices for the time being; however, such data would be necessary for the final validation of the model and for performing the model runs. Both the final validation and the model runs were to occur when pavement marking fluorescent-efficiency data became available.

Field Tests

Field testing was to be conducted on the Smart Road and developed in coordination with the driver/pedestrian and infrastructure teams. Visibility measures were to be made for various headlamp and TCD conditions. The prototype UV–A headlamp with the highest radiant output was to be used. It was desirable that visibility be tested with at least two levels of UV–A intensity. Because the UV–A output of the preprototype headlamps might be less than optimal, a high-UV–A-output condition was to be achieved by using up to six of these headlamps per vehicle. The low-UV–A-output condition was to be implemented using fewer of these headlamps.

Equally important was the issue of what standard headlamps to use for the field tests. Until the time of the project, it had been appropriate to use a common tungsten-halogen headlamp. In view of the increased visibility claimed for the newly-developed metal halide, HID headlamps, it seemed important to include these as a basis for comparison. The use of a high-beam condition for comparison against the UV–A condition was also considered. While it would have been of interest to know how well the UV–A headlamps compared to a visible high beam, this comparison did not translate to a real-world option. That is, even if a visible high beam could outperform a UV–A system, drivers would simply be unable to make use of these high beams in the real world in most driving situations because of the presence of other traffic. The research team proposed that the field testing include the following six headlamp conditions:

- Tungsten-halogen low beam alone.
- Tungsten-halogen low beam with auxiliary high-UV–A-output headlamps.
- Tungsten-halogen low beam with auxiliary low-UV–A-output headlamps.
- HID low beam alone.
- HID low beam supplemented with auxiliary high-UV–A-output headlamps.
- HID low beam supplemented with auxiliary low-UV–A-output headlamps.

Comparisons of visibility distances, subjective ratings, and measurement of glare in these six conditions (as part of activity 4) were planned to help answer the following questions:

- How do these dependent measures vary as a function of the UV–A output?
- Does UV–A-enhanced lighting offer advantages over HID and tungsten-halogen alone?
- How do field data compare with predictions from the visibility model? (The model could have been recalibrated, allowing more accurate predictions for a wider range of conditions than could have been field tested.)
- How do the glare measures of the six headlamp conditions compare? In particular, do participants experience increased discomfort or disability glare in the UV–A conditions? If so, this may indicate a need to lower the upper-wavelength bounds for the UV–A headlamp filter.

CHAPTER 3—ACTIVITY 2. EVALUATION OF FLUORESCENT INFRASTRUCTURE MATERIALS

Past research on UV–A headlamps and fluorescent TCDs found that they increased nighttime driving visibility distance. Further, pedestrian visibility increased by as much as 117 percent.[1] Based on the results of this previous research, this technology might increase visibility in adverse weather such as fog, rain, and snow.

Much of the past research took no photometric measurements of the fluorescent TCDs to compare the effects of the UV–A and fluorescent technology with those of the halogen headlamps and marking systems currently in place. Much of the research had also been conducted in ideal nighttime conditions, and the true potential of the system during adverse weather conditions had yet to be quantified.

Therefore, there was a need to objectively measure the increased visibility that can be achieved with UV–A headlamps and fluorescent TCDs. These measurements needed to be performed not only during darkness but also during fog, rain, and snow. These measurements were necessary to enable the research team to quantify differences, if any, from the halogen headlamps and TCDs currently in use. The results would provide the data necessary for the subsequent economic analysis.

The project was to be conducted in two phases. The initial testing was to be conducted on the Smart Road with a variety of prototype UV–A headlamps and fluorescent TCDs. This was intended to allow researchers to identify the combinations of headlamps and TCD materials that held the most promise for wide-scale deployment. After the design parameters had been determined, the headlamps and fluorescent TCDs were to be readied for deployment and testing on up to 160 km (99 mi) of Virginia’s roadways.

To meet the objectives of this study, several questions had to be answered by the infrastructure team. Those questions are addressed in the tasks described on the following pages.

TASK 2.1: COMPARE FLUORESCENT TCDS AND UV–A HEADLAMPS WITH CONVENTIONAL TCDS AND HEADLAMPS

In task 2.1, the researchers were asked to specify photometric characteristics of fluorescent TCDs illuminated with UV–A headlamps as compared to conventional TCDs illuminated with standard headlamps. To address this question, a three-phase approach was planned: an analytical evaluation, preliminary field testing on the Smart Road, and onroad testing. In Phase I, the analytical evaluation was intended to predict the visibility of prototype fluorescent and conventional materials to be tested on the Smart Road. This evaluation would allow researchers to determine and model the characteristics of the fluorescent materials in the illumination of various headlamps (e.g., UV of varying wavelengths and HID headlamps). This evaluation would help identify critical design parameters of the headlamps and TCDs requiring further development and refinement. The results were expected to provide TCD action spectra that closely matched those of headlamps. The vehicle team, with input from fluorescent TCD manufacturers, was to coordinate this portion of the research.

Phase II, the preliminary Smart Road field testing, was envisioned to consist of several combinations of the various TCDs and headlamps to quantitatively determine the increased visibility of fluorescent TCDs when illuminated with UV–A headlamps over conventional TCDs with tungsten-halogen and HID headlamps. This portion of the research was to allow experimentation with various combinations of headlamp sources and fluorescent and nonfluorescent TCDs in varying visibility conditions in a controlled, real-world setting. The most promising combinations of UV–A headlamps and fluorescent TCDs were to be selected for onroad testing in Phase III.

Phase III, critical to the overall success of the project, was to be designed with significant input from the driver/pedestrian team, vehicle team, and manufacturers. This phase was to provide researchers with a keen insight into how the UV–A headlamps and fluorescent TCDs perform in real-world traffic conditions using private citizens as the driving participants. It was thought that the participants would drive their own personal automobiles retrofitted with the prototype UV–A headlamps. In this phase, up to 160 km (99 mi) of roadways were to be marked with fluorescent TCDs.

Experimental Design

The design of the experiment for each phase would depend on the number of headlamp sources and the number and types of fluorescent and nonfluorescent TCDs to be evaluated.

Apparatus

Following is a list of the apparatus needed for the Phase I analytic evaluation tasks:

- Goniometer: apparatus to manipulate the TCDs to measure retroreflectivity.
- UV–A light source.
- Light tunnel (VDOT, TFHRC, or 3M).

Following is a list of the apparatus needed for the Phase II and Phase III preliminary field testing on the Smart Road and onroad testing:

- Portable UV–A irradiance meter to measure the amount of UV–A radiation reaching the same region of the TCD where the luminance is being measured.
- Portable telephotometer to capture the luminance values for each TCD evaluated.
- Portable retroreflectometer to obtain retroreflectivity measurements for each type of TCD tested. The retroreflectometer for the pavement marking measurements uses 30-m geometry.
- Vehicles outfitted with standard tungsten-halogen, HID, and prototype UV–A headlamps.
- Segments of roadway installed with conventional and fluorescent TCDs.
- Smart Road's all-weather testing equipment.

Procedures

Phase I

Following is a list of procedures that were to be used in Phase I:

- Pavement markings: Samples of pavement markings were to be applied to metal plates and placed on the goniometer. These samples were to be illuminated by halogen low beams and then by the UV–A headlamps. The luminance values for both conditions were to be summed to represent the luminance when both sources are used together. The corresponding illuminances or irradiances were to be measured. A ratio of luminance in UV–A to irradiance from UV–A was to be computed to yield the fluorescent efficiency of the material. Also to be determined were the action spectra of materials.

- Sign sheeting: This testing was contingent on obtaining UV–A-activated retroreflective sheeting samples. Two series of sign luminance measurements were to be made at a set of predetermined entrance and observation angles, one series in halogen low beams and one series in UV–A headlamps. These two luminances were to be summed to represent the luminance when both sources are used together. The corresponding illuminances or irradiances were to be measured. A ratio of luminance in UV–A to irradiance from UV−A was to be computed to yield the fluorescent efficiency of the material.

Phases II and III

Preliminary combinations of materials and headlamps that were to be used in Phases II and III are listed in table 2. Luminance measurements of both conventional and fluorescent TCDs were to be made using halogen low beams, halogen high beams, HID, and halogen low beams supplemented with prototype UV–A headlamps. The luminance measurements were to be taken using a portable telephotometer at select distances from the light source (see figure 1). It was envisioned that the distance between intervals would be determined during the initial testing on the Smart Road and in conjunction with computer modeling of visibility.

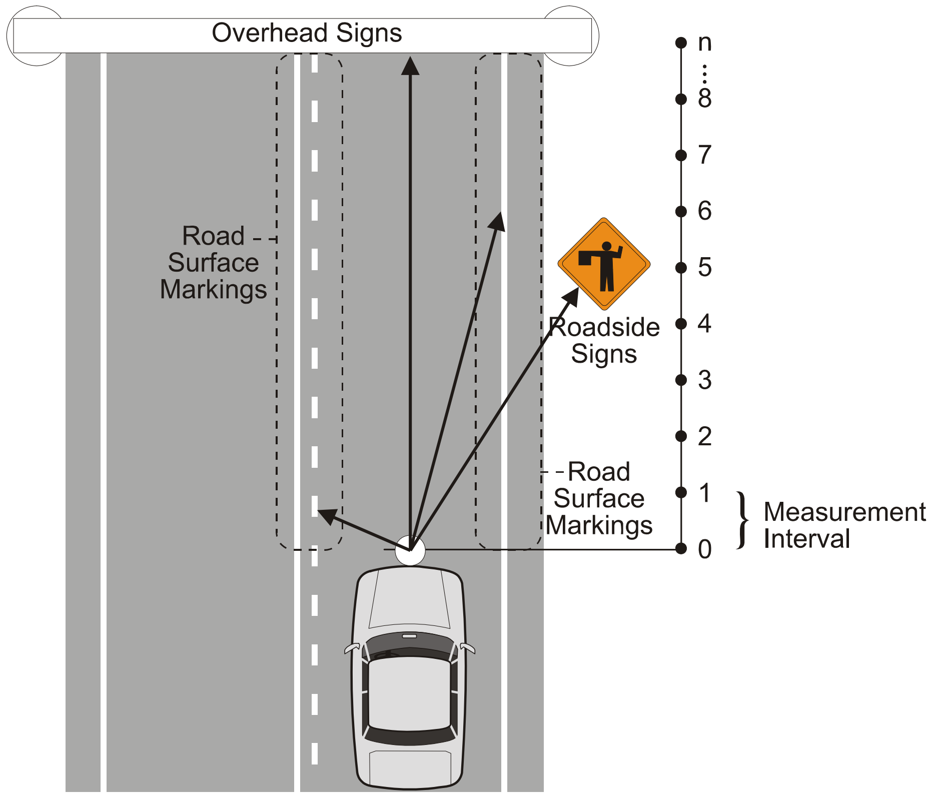


Figure 1. Diagram. TCD evaluation intervals.

Photometric measurements of TCDs were to be made in ideal daytime and nighttime conditions as well as during rain, fog, and snow. These measurements were to include luminance, luminance contrast, retroreflectivity, fluorescent efficiency, color, and daytime reflectivity. (See List of Key Performance Measures for detailed definitions and their respective measures.) These measures were to enable researchers to quantify the added visibility of this technology in all conditions. The actual methods were to be tested and likely refined on the Smart Road. In addition, the TCDs were to be measured at the initial installation and subsequently once every 2 months for 2 years (years 2 and 3 of the project) in similar types of environmental conditions (weather permitting). This would allow researchers to better understand the effects that the environment has on these devices when compared to conventional, nonfluorescent devices.

Table 2 depicts the combinations of pavement marking type and headlamp type to be analyzed. The pavement markings listed were to be tested as the right edgeline (white), white lane line (or yellow centerline where applicable), and yellow edgelines. Other types of pavement markings (e.g., stop bars) might have been tested on the Smart Road to determine whether deployment was recommended. Photometric measurements were to be made of each type of pavement marking using the appropriate instrument. Durability of the markings was to be tested using applicable American Society of Testing and Materials (ASTM) standards D713-90 and D913-88.[2,3]

Table 2. Pavement marking and headlamp combinations for testing.

Pavement Marking Type	Halogen Low Beam	Halogen High Beam	HID	Low Beam with UV–A
Conventional paint w/nonfluorescent beads	X	X	X	
Conventional paint w/fluorescent beads	X	X	X	X
Fluorescent paint w/nonfluorescent beads	X	X	X	X
Fluorescent paint w/fluorescent beads	X	X	X	X
Conventional thermoplastic w/nonfluorescent beads	X	X	X	
Conventional thermoplastic w/fluorescent beads	X	X	X	X
Fluorescent thermoplastic w/nonfluorescent beads	X	X	X	X
Fluorescent thermoplastic w/fluorescent beads	X	X	X	X
Conventional preformed tape	X	X	X	

Fluorescent and nonfluorescent ground-mounted post delineators were to be tested using the applicable measures previously discussed. The delineators were to be installed on both sides of the road. The nonfluorescent delineators were to be compared to fluorescent delineators using halogen low beams, HID, and halogen low beams supplemented with the prototype UV–A headlamps.

Testing of signs was contingent on obtaining UV–A-activated retroreflective sheeting samples. The number of potential sign types and colors to be studied was quite large. It was envisioned that only right shoulder-mounted signs would be evaluated. As for sign colors, the research team decided to limit the possible number of sign colors to be studied. Initial colors to be considered were white (regulatory), red (stop and yield), yellow (warning), and green (guidance). All of these signs were to be mounted as permanent signs. Construction zone signs (fluorescent orange) were also considered for study. These could have been temporary signs (rigid signs placed in sign stands) or permanent sign installations (rigid signs on wood posts). The actual type and color of signs to be tested would be determined after the applicable sheeting manufacturers had been identified and the sign sheeting colors had been made available.

As with the pavement markings and the delineators, the fluorescent signs (if available) were to be compared to their nonfluorescent counterparts using halogen low beams, halogen high beams, HID, and halogen low beams supplemented with UV–A headlamps.

It was envisioned that the results of the individual comparisons of the pavement markings, delineators, and signs (if available) tested on the Smart Road could be combined to convey the magnitude of driving environment visibility enhancement achievable with supplemental UV–A headlamps.

Testing Facility

As noted previously, Phase I of the testing was to take place in the laboratory and light tunnel using equipment from VDOT, TFHRC, and 3M. Phase II was to take place on the Smart Road.

Phase III was to take place on various, yet-to-be determined sections of Virginia's roadways, including Afton Mountain. These sections of roadway, to be selected during the initial testing on the Smart Road, were to use fluorescent TCDs. After the proposed test sites were selected, their characteristics were to be forwarded to FHWA for review and approval. The selected sites were to depend on the test participants, who would have been using their personal vehicles. This was to ensure that a large population of drivers outfitted with the prototype UV–A headlamps would traverse sections of roadway that had been marked with the fluorescent TCDs and with conventional TCDs. The testing scenarios developed in Phase II were to be refined and used in this phase.

Several criteria were to be used in the site selection process to ensure that this research examined a cross section of roadways:

- Type of roadway: two-lane rural roads, two-lane suburban roads, two-lane urban roads, four-lane divided roadways, and four-lane urban roads.
- Traffic density.
- Operating speeds: less than 72 km/h (45 mi/h) and above 72 km/h (45 mi/h).
- High accident rates resulting from adverse weather or nighttime conditions.
- Frequent occurrences of fog and smoke.

- Locations with limited visibility.
- Pedestrian activity.

Stratification of test roadways was to afford researchers the opportunity to determine which installations garner the highest returns on the investment. The findings were intended to provide guidelines for future installations of fluorescent TCDs.

The existing conventional markings on Afton Mountain were not to be eradicated. Instead, the new fluorescent markings were to be installed alongside the existing markings, allowing for a direct comparison between them in daytime, nighttime, and adverse weather conditions including rain, snow, and especially fog.

List of Key Performance Measures

During the planning stage, the research team agreed to the following minimum key performance measures, but the team also anticipated that additional measures would develop as the study progressed:

- Luminance (cd/m^2): Luminous flux in a beam emanating from a surface in a given direction, per unit of projected area of the surface as viewed from that direction, per unit solid area. This may be thought of as a measure of how bright the object appears to the driver.

- Luminous contrast: The degree of dissimilarity of the luminance of two areas, expressed as a number (see figure 2). Contrast tells how clearly a target stands out from its background.

$$\text{Luminous contrast} = [(L_{max} - L_{min})/L_{max}]$$

Figure 2. Equation. Luminous contrast.

Where

L_{max} = maximum luminance

L_{min} = minimum luminance

- Coefficient of retroreflection, R_A (cd/lux/m^2): The ratio of the coefficient of luminous intensity of a plane's retroreflecting surface to its area. Essentially, this coefficient is a measure of the device's ability to return light back to its source.

- Coefficient of retroreflected luminance, R_L (cd/m^2/lux): The ratio of the luminance of a projected surface to the illuminance at the surface on a plane normal to the incident light.

- Fluorescent efficiency (cd/W): A measure of a material's ability to convert a given amount of UV–A radiation to visible light. It will vary depending on the spectral composition of the incident UV–A.

TASK 2.2: DETERMINE DURABILITY OF FLUORESCENT TCDS COMPARED TO CONVENTIONAL TCDS

Durability of TCDs is of concern to people responsible for installing and maintaining the infrastructure. Departments of transportation currently have a good understanding of the durability of various types of conventional, nonfluorescent TCDs. The addition of fluorescent pigments is of concern; they have a potentially short useful life because of their daily exposure to natural UV–A light. In this project, these effects were to be examined by placing both fluorescent and nonfluorescent pavement markings, as shown in table 2, on the Smart Road and assessing their changes over time.

Apparatus

Following is a list of the apparatus needed in this task:

- Visual inspection.
- Retroreflectometer (pavement markings were to be measured using a 30-m geometry device).
- Telephotometer.
- Vehicle outfitted with UV–A headlamps.
- Daytime color measurement device.

Procedure

Pavement marking durability was to be conducted according to ASTM D713-90 and D913-88.[2,3] Both fluorescent and conventional pavement markings (including those markings with fluorescent glass beads) were to be analyzed. Background data on conventional, nonfluorescent pavement marking information were also to be reviewed.

Luminance measurements were to be made using the low beams of the vehicle supplemented by the UV–A headlamp.

List of Key Performance Measures

During the planning stage, the research team agreed to the following minimum key performance measures, but the team also anticipated that additional measures would develop as the study progressed:

- Durability: A material's resistance to wear and loss of adhesion to the pavement's surface over time. A material's durability might vary depending on the type of pavement where it has been installed.

- Glass bead retention: The ability of fluorescent pavement markings to ensure proper bonding of the binder with the glass beads and to maintain long-term glass bead retention.

- Color retention: The ability of a marking to retain its color under normal wear and in a variety of environmental conditions. The color of the material was to be measured to determine if the material undergoes any color shift when activated by UV–A light. (This measurement could be performed in the laboratory.) This performance measure was also to be used to determine if the material discolors over time.

TASK 2.3: DETERMINE ANY SPECIAL FLUORESCENT TCD INSTALLATION AND/OR REMOVAL PROCEDURES

Task 2.3 asked the researchers to determine if fluorescent TCDs require any special installation and/or removal procedures when compared to their nonfluorescent counterparts. The infrastructure team was to rely on the applicable vendor or manufacturer to supply the installation and removal specifications. (It was envisioned that this task would be aimed at the pavement marking more so than any of the other TCDs.) The manufacturer was also to provide a list of VDOT-approved companies for the installation of their respective TCDs. Notes regarding any deviation from standard installations or removals were to be taken. A cost associated with these deviations was to be generated and used in subsequent economic analyses. These deviations were to be discussed in detail, as were their implications to departments of transportation. Members of the infrastructure team were to carry out this task with close coordination from the manufacturers, vendors, and installers.

Apparatus

Following is a list of the apparatus needed in this task:

- Pavement marking vehicles.
- Visual inspections.
- Written specifications.
- Smart Road.
- Video recorder and 35-mm camera.

Procedure

The installation and removal requirements of the fluorescent pavement markings were to be compared to those of the nonfluorescent markings. Staff from VTRC and VDOT were to inspect the installation of the markings on the Smart Road (Phase II), as well as the installation during the deployment phase (Phase III). Notes regarding the installation process were to be taken, and any deviation from existing practices was to be highlighted and further discussed. Special attention was to be given to the surface preparation required for proper adhesion to the pavement. Again, instances where the procedure deviated from standard practice were to be noted.

In addition to installation requirements, the requirements of removing the pavement markings were to be evaluated, project duration permitting. As with the installation requirements, instances where the procedure deviated from standard practice were to be noted.

The handling, fabrication, and installation requirements for delineators and signs (if available) likely would be identical to those of their nonfluorescent counterparts. VDOT likely would have fabricated the signs in its sign shops, provided the shops had the necessary equipment. Staff from VTRC and VDOT were to be onsite during the installation of these devices to monitor and record the installation practices.

TASK 2.4: DETERMINE ANY FLUORESCENT TCD ENVIRONMENTAL CONCERNS

The infrastructure team was to rely on the manufacturers of the TCDs to supply the material safety data sheets and comply with existing Environmental Protection Agency regulations relating to pavement markings during installation, disposal, and eradication.

CHAPTER 4—ACTIVITY 3. QUANTIFICATION OF GLARE AND PHOTOBIOLOGICAL RISK

Guidelines for human exposure to ultraviolet radiant energy have been promulgated by the International Commission on Non-Ionizing Radiation Protection and the American Conference of Governmental Industrial Hygienists. In addition, the American National Standards Institute and the Illuminating Engineering Society of North America Standard RP27.1 also applies to the photobiological safety of lamps and lighting systems.[(4)] These guidelines and standards are compatible; however, not all materials have been tested to verify that they fall within the standards.

The eye's response to illumination from near-UV–A light varies greatly with age. The causes of this change are the eye's crystalline lens absorption of these wavelengths increasing from infancy onward and the lens's increased fluorescence of chromophores with age. As individuals age, less energy reaches the retina; however, older individuals may still sense discomfort with greater fluorescence. Some cataractous and precataractous lenses will demonstrate increased fluorescence as well as greater light scatter. Although these effects have been documented in the laboratory, it is not clear whether these effects will be of concern to drivers and pedestrians. The range of individual responses at a given age level is unknown. The windshields of all United States motor vehicles have UV–A absorbers, which should eliminate this concern for oncoming drivers. Side and rear windows, however, often do not have this feature; hence, these conditions must be studied in night driving conditions. The following tasks address these issues.

TASK 3.1: EVALUATE APPEARANCE OF UV–A HEADLAMPS

The proposed approach was to evaluate the subjective visual responses of pedestrians and the driving public to UV–A headlamp illumination using a cross section of individuals of varying age.

Experimental Design

The experiment was to use a 6 (Age Groups: children, adolescents, young adults, middle-aged, elderly, and elderly with diagnosed early cataract) by 3 (Exposure Condition: pedestrian in front of standing vehicle, pedestrian with pass-by, and driver viewing from rearview mirror) by 2

(UV–A Spectral Cutoff) design. The primary measures of discomfort were to be answers to a short questionnaire indicating discomfort or disability glare level. Some early pilot testing was to determine the final test design and also indicate whether an objective glare-card reading test would be required for some phases of this study.

The same population recruited to serve as drivers in other human factors studies were to be asked to participate in this experiment immediately following their drive test. Elderly participants with early diagnosed cataracts were to be recruited separately from children.

Apparatus

Following is a list of the apparatus needed in this task:

- Instrumented vehicle with installed UV–A headlamps.
- Two intensities (or spectral distributions) of UV–A.
- A second test vehicle for the second driver.

TASK 3.2: COMPARE HEADLAMP BEAM CONFIGURATIONS TO SAFETY STANDARDS

The proposed approach was to evaluate the headlamp beam characteristics relative to current national and international safety standards and guidelines. Initial safety measurements were to be taken in the laboratory after initial receipt of the headlamps or at the time of installation in the test vehicles. These measurements were to be conducted before participants in the experiment were involved in onroad testing.

Experimental Design

The design of the experiment was to include UV–A irradiance measurements as a function of beam angle and distance from the headlamp. Intrabeam photographs of the source were also to be taken to determine the retinal image size for retinal safety studies. Some early testing was to be done to ensure safety before beginning the tests with participants. A followup series of measurements was to determine if changes in UV–A output were significant during the test. The final test design may also have included an intermediate check test.

Apparatus

Following is a list of the apparatus needed in this task:

- Instrumented vehicle with installed UV–A headlamps.
- Two intensities (or spectral distributions) of UV–A.
- A sampling of vehicles to measure spectral transmission of windows.
- International Light UV–A safety meter.
- Spectroradiometer.

CHAPTER 5—ACTIVITY 4. EXPANDED COST-BENEFIT ANALYSIS

A thorough economic analysis of UV–A and fluorescent technology is greatly needed. Analyses conducted to date, although valuable, have not considered all the variables that can affect a cost-benefit outcome. For example, the Center for Applied Research®, Inc. (CFAR) performed an analysis that focused on the percentage reduction in crashes required to recover the increased cost of fluorescent roadway delineation and auxiliary UV–A headlamps.[1] CFAR computed estimated costs of implementing the UV–A and fluorescent technology and compared them to potential cost reductions from crashes avoided by using UV–A and fluorescent technology. CFAR did not consider all variables associated with a crash such as visibility condition, road type, driver age, and rural versus urban driving conditions. Without examining these factors, it is not possible to accurately determine which accidents could be avoided with the UV–A fluorescent technology and which would be unavoidable regardless of the technology.

The research team planned to conduct a thorough economic analysis of UV–A and fluorescent technology. This was to occur through nine tasks conducted as part of five major analyses:

- Complete a database analysis of crashes that considered all variables affecting the occurrence of the crash, including weather (visibility) condition, driver age, and so forth. The research team's work was to expand on that of CFAR to incorporate all variables that affect visibility.

- Determine the costs associated with UV–A headlamps and fluorescent materials.

- Determine the visibility of TCDs and pedestrians with UV–A headlamp technology from the other tasks. This was intended to allow estimation of whether accidents recorded in the database could have been avoided with the UV–A and fluorescent technology.

- Evaluate driver overconfidence with UV–A and fluorescent technology. This was to determine negative consequences that potentially could increase the number of crashes.

- Estimate crash reduction with UV–A and fluorescent technology. Data generated from the other tasks would have been used to determine the degree of effect that UV−A headlamps and fluorescent TCDs would have on driving safety.

TASK 4.1: CONDUCT DATABASE ANALYSES TO ESTIMATE THE CURRENT COST OF CRASHES

The purpose of this analysis was to classify the types of crashes whose frequency and severity could be reduced by the use of UV–A headlamps and fluorescent markings. The team was to examine national crash databases to identify these crash types. The first phase of this analysis was to involve developing a list of variables available from the databases. These variables were to be used to define relevant crash types. The list included, but was not limited to, the following variables:

- Crash configuration (e.g., head-on collision or roadway departure involving a single vehicle).
- Visibility conditions (i.e., light conditions).
- Driver age.
- Road type.
- Weather conditions.
- Involvement of pedestrians or bicyclists.
- Road class (interstate versus rural).

Some potential crash types include the following variables:

- Crashes that occur during fog or rain conditions, or both.
- Pedestrian or bicyclist crashes.
- Head-on collisions.
- Side impact collisions.
- Single-vehicle roadway departure crashes.
- Crashes involving older drivers.
- Crashes that occur in low light conditions or at night.

During this phase, it would be necessary to conduct some exploratory analyses to determine if there were sufficient crashes to analyze for each crash type. This would have affected the identification of crash types and determined how many years of data should have been used from each database.

After all of the relevant crash types were identified, the process of estimating the cost of these types of motor-vehicle crashes was to begin. The cost would be defined in terms of injury incidence and severity, vehicle damage, and other relevant factors (e.g., the number of working days lost, type and length of medical care, and so on). These cost-determining factors were to be extracted from both nonfatal and fatal motor-vehicle crashes.

The results of the database analysis were to determine the cost of motor vehicle crashes. This information was to be incorporated into data reflecting the cost of installing and maintaining UV–A and fluorescent technology. These cost data were to be compared to the calculated benefit data to determine the cost-benefit ratio of UV–A and fluorescent technology.

TASK 4.2: DETERMINE UV–A HEADLAMP UNIT, OPERATING, AND MAINTENANCE COSTS

Task 4.2 asked the researchers to determine the unit cost of making and installing UV–A headlamps in new vehicles, the unit cost of retrofitting existing vehicles, and the additional operating and maintenance costs (if any) that UV–A headlamps will impose on the automobile owner-operator. This task was to use information from activity 1. Initial answers to this task were to depend on engineering estimates from the headlamp manufacturers. The experience that the vehicle team was to derive from installing the experimental UV–A headlamps in the cars of 100 volunteers was to enable the team to refine the engineering estimates. The possible measures of a headlamp’s continuing effectiveness included power output (over the relevant part of the spectrum), energy efficiency, and physical integrity.

TASK 4.3: DETERMINE FLUORESCENT TCD DETERIORATION RATE AND ITS FACTORS

The goal of task 4.3 was to determine the rate at which fluorescent TCDs deteriorate over time and the factors that influence that rate. It would have been necessary to estimate the service life of each type of fluorescent TCD in order to estimate the frequency with which it would need replacing, and hence, to compute its unit life cycle cost. This task was to use data from task 2 of activity 2. The research team was to place the TCDs in a variety of locations to expose them to as many natural and artificial fluorescence-deteriorating factors as possible; it was hoped that this would produce numerous independent (i.e., uncorrelated) variations. Following is a list of factors that might have influenced the rate of deterioration (or frequency of failure):

- Meteorological conditions (e.g., sunlight, extreme temperatures).
- Chemical pollutant concentrations (e.g., diesel exhaust).
- Mechanical damage (e.g., tire contact, snow removal, accident damage).

The useful life of a TCD may be modeled either as a steady, more or less predictable deterioration in its effectiveness or as the cumulative probability of its failure in a given time. The continuing effectiveness of a TCD would be indicated by one or more of the following measures:

- Luminance.
- Retroreflectivity.
- Luminance contrast.
- Fluorescent efficiency.
- Physical integrity.

Fluorescent TCDs were to undergo field tests, first in controlled conditions on the Smart Road (as described in activity 2) in Blacksburg, VA, and later on selected segments of public roads in Albemarle and Montgomery Counties, VA. The rate of deterioration (or the frequency of failure) was to be monitored for the duration of the study.

TASK 4.4: DETERMINE FLUORESCENT AND CONVENTIONAL TCD UNIT COSTS

Task 4.4 was to determine material and installation unit costs associated with the fluorescent and comparable conventional TCDs. The unit costs associated with each type of TCD were to be determined in task 3 of activity 2. In addition, the research team envisioned that much of this information would be readily available from the material suppliers or the manufacturers. The costs were to be disaggregated by type of TCD (i.e., pavement marking, delineator, and sign) and whether it was a conventional device or a fluorescent device. The cost for the material itself was to be obtained along with the total cost (material plus installation). The unit costs associated with the fluorescent devices were to be scrutinized to ensure that what was used in a subsequent economic analysis would be representative of what VDOT or another state department of transportation would encounter if this particular device were procured for statewide deployment. This scrutiny was to ensure that the fluorescent TCD costs were being evaluated similarly to those of the more readily available conventional devices.

TASK 4.5: DETERMINE UV–A HEADLAMP AND FLUORESCEN TCD EFFECT ON ACCIDENT COSTS

Task 4.5 was to determine the effect that UV–A headlamps in a given percentage of the motor vehicle fleet would have on accident costs, the effect of fluorescent TCDs on accident costs for a given percentage of the State's centerline miles, and any additional effect of an interaction of UV–A headlamps and fluorescent TCDs on accident costs. This task would depend on the findings of the driver/pedestrian team and published research on accident costs. The findings were to be largely a synthesis of the team's original research (concerning the driver's perception of and response to fluorescent TCDs and other fluorescent objects such as pedestrians' clothing) with published research concerning the cost and probability of accidents.

The expected costs associated with accidents can be broken into two components: the expected cost per accident of each type and the expected number of accidents per million vehicle miles traveled (VMT). Points of comparison between the results of the studies, envisioned as part of this project, and the extant literature relating accident rates to characteristics of the vehicle, the roadway, the driver, and the weather were to form the basis for estimating the effect of UV–A headlamps and fluorescent TCDs on the expected number of accidents, all other things being equal.

TASK 4.6: DETERMINE EFFECT OF UV–A HEADLAMPS AND FLUORESCENT TCDS ON OTHER ROAD USER COSTS AND POLLUTION EMISSIONS

The goal of task 4.6 was to determine the effect on other road user costs and on pollution emissions of UV–A headlamps in a given percentage of the motor vehicle fleet and fluorescent TCDs on a given percentage of the State's centerline miles. In addition to an effect on safety, the UV–A and fluorescent technology conceivably may alleviate or aggravate certain other costs borne either by the motorist or by third parties including the following possibilities:

- UV–A headlamps and fluorescent TCDs could improve visibility and sense of safety, and hence, induce motorists to drive faster. This increase in the effective capacity of roads equipped with fluorescent TCDs could in turn bring additional traffic volume (i.e., latent demand). The impact of this mechanism on travel time cost, vehicle operating cost, and pollutant emissions, as well as its secondary effect on accident cost, must be estimated. Established road-user cost methodology permits an estimate of the savings in travel time (and possibly vehicle operating costs and pollutant emissions), priced in dollars. The accident-cost literature also may warrant a secondary adjustment to the accident-cost calculations.

- UV–A light at the frequency and intensity proposed for the study may have an effect on the health of drivers and pedestrians.

- UV–A headlamps and fluorescent paints and sign materials are not known to emit pollutants, and the price of any quantifiable effect is unknown.

TASK 4.7: DETERMINE ENHANCED VISIBILITY PROVIDEDBY UV–A HEADLAMPS

Task 4.7 was to determine the degree of enhanced visibility of TCDs and pedestrians illuminated by UV–A headlamps for various ambient lighting conditions. The proposed approach began by specifying the UV–A system parameters of interest. This task likely would be performed by the driver/pedestrian team in conjunction with the vehicle and infrastructure teams. A decision was to be made regarding whether to test available systems that were not necessarily optimal (e.g., a system that required more power than a car manufacturer might deem acceptable) or to specify systems that would require prototyping. It was anticipated that six headlamp configurations would be tested.

The ambient visibility conditions of interest were in snow, rain, fog, and clear night.

To determine the distance at which drivers can detect the TCDs, drivers were to drive an instrumented vehicle on the Smart Road and inform the experimenter when the TCDs were detectable and recognizable. The experiment was to consist of two segments: one to evaluate the visibility of pavement markings and marking posts and a second to determine the visibility of pedestrians.

Evaluation of the Visibility of TCDs

Experimental Design

The experiment was to use a 2 (Age: young, old) by 3 (Visibility Condition: between subjects; clear, rain, fog) by 6 (Headlamp Type: within subject) by 4 (TCDs: within subject) mixed-factor design. The snow visibility condition was excluded because snow would have covered the TCDs. The dependent variables were to be the participant's detection of the end of pavement markings and the visibility distance of marking posts.

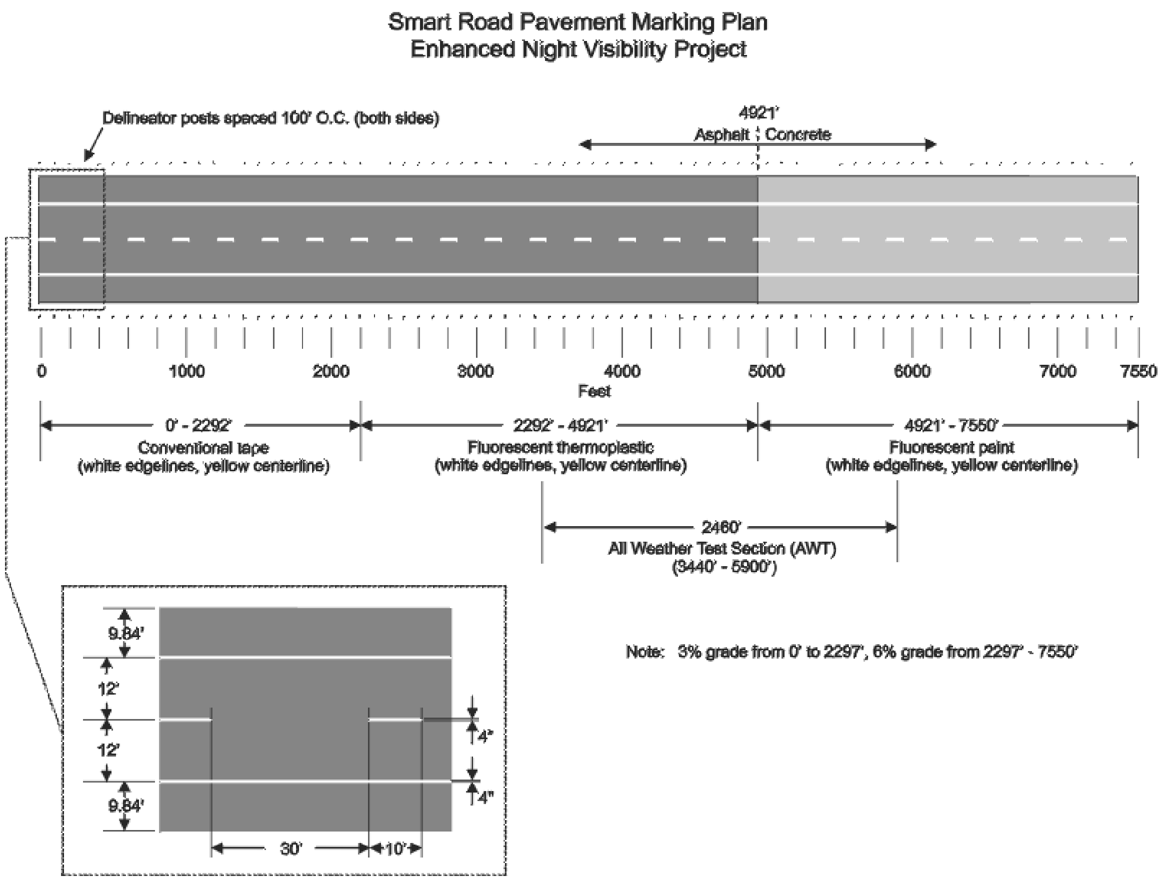
The drivers (60 divided into 30 younger and 30 older) were to be recruited from Blacksburg, VA, and the surrounding communities. All drivers were to possess a current, valid Virginia State driver's license. In addition, they were to have successfully completed a health screening questionnaire. Visual tests for acuity, contrast sensitivity, and color vision were to be administered. Drivers were to be paid for their participation.

Apparatus

This study was to use instrumented vehicles outfitted with halogen, HID, and UV–A headlamps. The beam configuration for the UV–A headlamps was to have an elliptical shape. At 90 percent of maximum intensity, the beam was to be aimed approximately 0.5° vertically (V) and 2° horizontally (H). At 50 percent, the beam configuration was to be approximately 1.5° V and

4° H. At 10 percent, the beam shape was to be approximately 4° V and 10° H. The aim was to be straight forward vertically and horizontally. In addition, in-vehicle instrumentation to collect distance traveled was to be installed.

The pavement marking types to be tested were conventional tape, florescent paint with fluorescent glass beads, and fluorescent thermoplastic with fluorescent glass beads. The location of the pavement markings as applied to the Smart Road is shown in figure 3. Along the solid edgeline, reflective tags (similar to raised pavement markers) were to be placed every 5 m (16 ft) to determine the distance viewed down the edgeline. Marking posts were to be located both inside and outside the all-weather test section of the facility.



1 ft = 0.305 m

Figure 3. Diagram. Smart Road pavement marking plan.

Procedure

Drivers were to be met at the VTCTR to read and sign an informed consent form, complete a brief vision and hearing exam, and read an introduction to the study. Afterward, drivers were to be taken to the Smart Road test facility.

To ensure that participants had the same viewing perspective as they would when driving, the participants were to sit in the driver's seat and operate the vehicle. The experimenter was to sit in the front passenger seat and record the participants' comments, tell participants where to drive for each test, and flag the datastream to indicate when participants had detected the end of the pavement marking. In the sections with marking posts, participants were to report the number of marking posts they could detect. Visibility in the rain condition was to be tested in the all-weather portion of the Smart Road. This procedure was to be followed for each of the weather conditions.

Evaluation of Pedestrian and Object Visibility

Experimental Design

The experiment was to use a 2 (Age: young, old) by 4 (Visibility Condition: clear, rain, fog, and snow) by 6 (Headlamp Type) mixed-factor design. The dependent variable was to be the distance at which mock pedestrians can be detected.

Drivers (24 divided into 12 younger and 12 older) were to be recruited from Blacksburg, VA, and the surrounding communities. These participants likely would have been the same as those in the previously defined experiment. All drivers were to possess a current, valid Virginia State driver's license. In addition, they were to successfully complete a health screening questionnaire. Visual tests for acuity, contrast sensitivity, and color vision were to be administered. Drivers were to be paid for their participation.

Apparatus

This study was to use instrumented vehicles outfitted with halogen, HID, and UV–A headlamps. The beam configuration for the UV–A headlamps was to be an elliptical shape. At 90 percent of maximum intensity, the beam was to be approximately 0.5° V and 2° H. At 50 percent, the beam configuration was to be approximately 1.5° V and 4° H. At 10 percent, the beam shape was to be approximately 4° V and 10° H. The aim was to be straight forward both vertically and horizontally. In addition, in-vehicle instrumentation to collect distance traveled was to be installed along with an incident button to flag the datastream.

The following mockups were to be installed on the Smart Road test facility:

- Two mockups of a person changing a car tire on the right side of the roadway (static pose).
- Two mockups of a person jogging on the right side of the roadway (static pose).
- Two mockups of a road maintenance worker on the left side of the roadway (static pose).
- A dynamic object entering the roadway from the left side.

One possible dynamic object was a barrel sent into the roadway down a ramp on the side of the road. The pedestrians were to be dressed with light and dark machine-laundered clothing (i.e., clothing with varying levels of fluorescent properties). The mockups were to be placed both within and outside of the all-weather testing area.

Procedure

Drivers were to be met at the VTCTR to read and sign an informed consent form, complete a brief vision and hearing exam, and read an introduction to the study. Afterward, participants were to be taken to the Smart Road test facility.

To make this experiment as realistic as possible, the participants were to drive the vehicle and maintain a speed of 16 km/h (10 mi/h) while scanning the roadway for potential hazards. Participants also were to state when they noticed anything out of the ordinary in the roadway scene (detected an object). Then, after detecting an object, they were to tell the experimenter when they could recognize the object. The experimenter, sitting in the front passenger seat, was to flag the datastream when the participant announced detection and recognition of the object. Two pedestrian mockups were to be tested using halogen headlamps, two were to be tested with HID headlamps, and two were to be tested with UV–A headlamps. This procedure was to be followed for each of the weather conditions.

TASK 4.8: EVALUATE POTENTIAL FOR DRIVER OVERCONFIDENCE WHEN USING UV–A HEADLAMPS

Past research has shown that the highest potential payoff of the UV–A and fluorescent technology is in areas where there is little roadside artificial light such as in rural areas. Other research has shown that fluorescent traffic control devices provide added visibility in fog, smoke, dusk, dawn, or wet conditions. On the other hand, pavement markings that greatly enhance the distance at which drivers can see the roadway in front of them may lead to increased driving speeds. For example, it has been suggested that on Interstate 64 (I–64) across Afton Mountain in Virginia, drivers' speed increased after embedded pavement lights were installed to increase visibility in this heavy fog area. The purpose of this task was to evaluate the effects of UV–A and fluorescent technology on long-term driving behavior. This was to be accomplished by installing instrumentation in privately owned vehicles to determine vehicle position (i.e., global positioning system or GPS), speed, and visibility condition. The GPS was to be used to indicate when the vehicle was traveling on a designated section of the roadway, which would trigger recording of vehicle speed and visibility condition during this time. This information was to be used to determine effects on long-term driving behavior.

Experimental Design

The experiment was to use a 3 (Age) by 2 (UV–A) design. The driving behavior of three participant age groups—younger (18 to 25 years old), middle-aged (35 to 45), and older (60 and over)—was to be measured in driving situations with and without the use of UV–A headlamps. Both genders were to be equally represented. Visibility conditions including rain, fog, and time of day were to be analyzed later. In addition, data on road type including interstate roadways, primary roads, secondary roads, and rural roads were to be analyzed later.

It was anticipated that 60 drivers as described above would be recruited for this study. Drivers were to be selected based on their frequency of driving the designated routes; that is, drivers who used the designated highways as part of their daily commute would have been preferable because such participants would have contributed more data to the study. All drivers were to hold a valid driver's license and pass a vision and hearing screening test. Recruiting was to have been through local newspaper advertisements and posted fliers. Drivers were to be paid for participation in the study.

The study was to be implemented in the rural areas of Montgomery and Albemarle Counties, VA. The study was to begin 5 months before fluorescent TCDs were installed to provide baseline data and was to continue for 5 months after the fluorescent TCD installation.

Apparatus

Drivers were to use one of four specially instrumented vehicles (or instrumentation packages in their own vehicles) for a period of up to 2 weeks each. To make the instrumentation of 12 vehicles feasible, only those subsystems required to answer the questions in the experiment were to be installed. Instrumentation was to include a GPS device, speed recording hardware, accelerometers, brake-activation recording hardware, and a video camera to record visibility outside the windshield. Data recording was to occur only when data from the GPS indicated that the driver was traveling on designated roadways, that is, roadways with installed fluorescent TCDs. Data recording was to occur at a rate of 1 Hertz (Hz). The resolution was set low to allow data collection for several weeks before downloading became necessary.

TASK 4.9: ESTIMATE DEGREE OF CRASH REDUCTION

It was considered important to collect objective performance data to determine the safety benefits of UV−A-equipped vehicles. The collection of objective performance data would have required an innovative approach. The fundamental concept was to use trigger criteria to determine the onset of critical incidents and accidents that occur while driving instrumented vehicles. With proper instrumentation, including video, the research team’s experience had shown that it was possible to detect the occurrence of up to 90 percent of incidents for subsequent recording. This instrumentation could be installed in personal vehicles in addition to research vehicles.

After a trigger had been exceeded, the driver performance measures surrounding the occurrence of a critical incident would be saved for future analysis. Through analysis of these data, it was anticipated that critical incidents related to issues of visibility both with and without UV–A headlamps could be used to estimate safety benefits.

The four systems to be used in task 4.8 were also to be used to collect critical incident data for analysis.

Experimental Design

The experiment was to use a 2 (Gender) by 2 (Location) by 3 (Age) full-factor between-subjects design. Five participants were to be recruited for each gender and age group for a total of 60 drivers. Note that these 60 drivers were to be the same drivers as described in task 4.8. Of the drivers selected, 30 were to be selected from the rural areas surrounding Blacksburg, VA, and 30 were to be selected from the urban areas of northern Virginia. Drivers were to represent younger (18 to 25 years), middle-aged (35 to 45 years), and older (60 years and older) driving populations, and both genders were to be represented. All drivers were to hold a valid driver's license and pass a vision and hearing screening test. Recruiting was to have been through local newspaper advertisements and posted fliers. Drivers were to be paid for participation in the study.

Apparatus

The hardware systems available for this research were previously described in task 4.8. The video and data collection systems were to save event-triggered data. The video image was to pass through a computer-controlled video titler to stamp a frame number on the video for synchronization with an electronic data file. This multiplexed video signal was then to be passed to a bank of video cassette recorders that would record data at 1 Hz.

Each time an event was detected by the data collection system, the electronic data and real-time video would mark the event on the videotape. In addition to the video data, a variety of driver performance measures were to be collected. A power inverter was to be used to supply the data collection equipment with power from the car battery. The total system would require less than 150 W of power, and it was not to draw enough current to damage or drain the batteries, even if the vehicle was shut off. No additional power sources (e.g., generators) were to be required as part of the data collection hardware.

The entire data collection system fit into a unit the size of a briefcase. All of the sensor mountings to the vehicles were temporary, resulting in no damage to the vehicle. The camera was to be mounted in a duplicate rearview mirror purchased for the experiment, which was to be replaced with the original mirror after the study was completed.

Procedure

By using the selection criteria described earlier whenever possible, it was anticipated that a minimum of 48,280 km (about 30,000 mi) of data could be collected. Based on previous experiences, this amount of data was expected to result in roughly 500 to 1,000 critical incidents for analysis.

After the data were collected, the driver error and critical incident data could be analyzed to help determine the relative safety of UV–A and fluorescent technology. The researchers considered accomplishing this by comparing a baseline condition of no UV–A headlamps or fluorescent TCDs to the experimental condition with these technologies.

The study was to be implemented in Montgomery and Albemarle Counties, VA. The study was to begin 5 months before fluorescent TCDs were installed to provide baseline data and was to continue for 5 months after the fluorescent TCD installation.

CHAPTER 6—ACTIVITY 5. DEMONSTRATION/IMPLEMENTATION

To achieve successful, full deployment of the technologies being researched, each level of the research process needed input from the stakeholders who would have a crucial role in the final deployment. Although the real-world implementation of the technology was a separate project milestone, it was a vital part of the research throughout the project. Stakeholders were accorded a much higher degree of ownership in the process than is typical of basic research.

For the first year of the project, the implementation team was charged with the fulfillment of two objectives:

- Initiate primary stakeholder involvement through the team's research advisory board.
- Produce a detailed plan for the construction of a larger UV–A and fluorescent implementation network.

OBJECTIVE 1

The first implementation team objective for milestone 1, Performance of Design Objectives, in year 1 was to initiate primary stakeholder involvement through the research advisory board and begin disseminating information regarding the project's purpose and goals as well as any preliminary results. It was hoped that this process would guide the performance and design objectives toward the needs of applicable Federal and State agencies and especially the automotive industry. Indeed, eventual commercial deployment of UV–A and fluorescent technologies had become the project's focus so much so that the research team did some major rethinking regarding the state of current UV–A technology as applied to automotive lighting systems. The automotive and lighting manufacturers gave impetus to this repositioning, which called for reconceptualization of the project. This was not seen as a setback. Indeed, such a refocusing was exactly the purpose of the implementation team: to focus the project on the necessary precursors to actual market deployment of UV–A and fluorescent technologies. In other words, if certain aspects of the project had to change, it was because input from the potential commercial market indicated that such change was necessary.

As mentioned, automotive and lighting stakeholders, as well as VDOT, played a key role in decisionmaking in the first year of this project. To that point, the following major stakeholder groups were incorporated in the evolving approach:

- The three major American automakers, represented by USCAR.
- Major national and international automotive lighting manufacturers.
- State departments of transportation as represented by VDOT.

The research team determined that the foremost problem in getting UV–A headlamps incorporated into passenger cars would be acceptance from automobile manufacturers. The eventual successful deployment of this technology would depend largely on the automotive manufacturers' perception of the potential benefits and costs (in terms of the automotive manufacturing process, electrical system impact) of this technology. With this in mind, even though original plans for the first year called only for detailing how the project team would go about making contacts with the automotive industry, the project team started building such connections early in the process. The importance of automotive manufacturer support for the team's design of the experiment was simply too great to address later in the project. The team conducted many phone conversations with both automotive industry and lighting industry executives. In addition, the team traveled to Detroit to discuss in detail the purpose and structure of the project with USCAR. The input from USCAR was significant, and resource support for this project from USCAR seemed likely.

It also became apparent during the first year of this project that the major lighting manufacturers would also play a key role in any successful deployment attempt; it is the lighting manufacturers who must decide that the potential benefits of producing this technology for the automotive industry is worth the cost and risk of major factory retooling and manufacturing process reengineering. Given that these lighting manufacturers rely heavily on input received from the major automakers, the project team decided that both of these stakeholder groups must be approached and worked with in tandem. To that point, the approach proved fruitful. The project team believed that UV–A headlamp fixtures would be produced for project testing. Support for this production would come from both the original project budget and, potentially, resources from USCAR.

OBJECTIVE 2

The implementation team's second Phase I objective was to produce a detailed plan for the construction of a larger UV–A and fluorescent implementation network—a stakeholder network of industry representatives, government representatives (Federal, State, and municipal), and nongovernment organizations such as public safety interest groups (e.g., Insurance Institute for Highway Safety, American Association of State Highway and Transportation Officials, Mothers Against Drunk Driving, and the American Association of Retired Persons) focused on successful deployment of UV–A and fluorescent technologies. The following paragraphs describe the plan for extending the existing network. While the plan called for full development of an implementation network during the remainder of the study, the implementation team was to focus on completing just task 5.1; tasks 5.2 to 5.4 were to be completed in a follow-on effort.

TASK 5.1: ASSESSING POTENTIAL SUPPORT NETWORK FOR NATIONWIDE DEPLOYMENT

Network Market Assessment

The implementation team was to assess potential economic support from a possible system of stakeholders and the implementation network. Support—monetary or willingness to actively participate in the network—could come from key organizations.

The implementation team was to conduct a first-level assessment of the potential network market using a modified Delphi technique. Participants were to be existing research board members and representatives from already established stakeholder groups (automotive and lighting manufacturers). The results of this technique were to give the team an initial read on where the network stood and what actions would best expand it.

Following this initial assessment, secondary resources were to be studied, including printed and electronic reports, articles, books, dissertations, and other sources that could be analyzed to discern the probable position of potential stakeholders before communication with those stakeholders was initiated. Much indirect research had already been conducted, and a list of potential stakeholders to be contacted had been produced and made available on the project team's Web site. Organizations on that list and the assessment of individual stakeholder organizations were to grow and become more detailed following initial assessment and more indirect research.

Following these first two steps of the network market analysis, the implementation team was to begin direct research, including directed individual interviews (semisurvey type), close-ended surveys, and, if appropriate, focus group interviews.

Finally, all qualitative and quantitative information was to be synthesized to produce a single comprehensive assessment of the potential avenues to pursue to maximize likely support, and therefore, success of an ENV implementation network. This assessment was to give the team a good first look at the panoply of stakeholders who might have been involved in the deployment efforts over the following decade or so. From this assessment, the team was to take its direction for expansion of the existing core set of stakeholders.

Stakeholder Analysis

To address the technical questions relating to the effective identification and management of relevant stakeholders in the ENV project, the implementation team was to identify all potential stakeholders who might have had a vested interest in the development and deployment of UV–A headlamps and related technologies. This database, already under development, was to be compiled using Web-based research, literature searches, and interviews with project members. This stakeholder database was to contain the following information about the potential stakeholders:

- Web page address.
- Contact person.
- Relationship to project goals (Y/N).
- Description of the relationship.
- Contact phone number.

Each potential stakeholder was to be analyzed and categorized as either having or not having power, legitimacy, or urgency. After this preliminary determination, an overall assessment was to be made classifying the stakeholder based on its combination of characteristics.[5]

The power dimension is based on the probability that the stakeholder would have influence on another agent. The legitimacy dimension is defined as a generalized perception or assumption that the stakeholder has a right to participate and is relevant. The urgency dimension is related to time sensitivity and criticality of the stakeholder.

A stakeholder judged to have all three characteristics would have been classified as a definitive or primary stakeholder. Dominant stakeholders would have been those considered powerful and legitimate. Dependent stakeholders would have been both urgent and legitimate. Dangerous stakeholders would have had both the urgent and powerful attributes. Classifying stakeholders as dangerous would not automatically imply that they should be excluded from the process; some dangerous stakeholders were to be critical to the process. How and when these types of stakeholders would be included ultimately would depend on the needs and the stage of implementation. Dormant stakeholders would score only in the power dimension. Discretionary stakeholders would score on legitimacy only. Demanding stakeholders would have been those who were neither powerful nor legitimate but perceived a deep sense of urgency about a particular issue.

TASK 5.2: BUILDING THE NETWORK

Building the right network structure was an important aspect of this project. Based on an assessment of a stakeholder's willingness to cooperate and its potential to become a threat to the organization, there were four categories or types of stakeholders, which can explain and deepen the discussion of primary and secondary stakeholders (see table 3 and table 4).[6]

Table 3. Diagnostic typology for stakeholders.

	High Stakeholder Threat to Organization	Low Stakeholder Threat to Organization
High Stakeholder Potential for Cooperation	Type 4 MIXED BLESSING Strategy: COLLABORATE	Type 1 SUPPORTIVE Strategy: INVOLVE
Low Stakeholder Potential for Cooperation	Type 3 NONSUPPORTIVE Strategy: DEFEND/CO-OPT	Type 2 MARGINAL Strategy: MONITOR

Table 4. Factors affecting stakeholders' potentials for threat and cooperation.

Stakeholder Attributes	Stakeholder's Potential for Threat	Stakeholder's Potential for Cooperation
Stakeholder controls key resources (needed by organization)	Increases	Increases
Stakeholder does not control key resources	Decreases	Either
Stakeholder more powerful than organization	Increases	Either
Stakeholder as powerful as organization	Either	Either
Stakeholder less powerful than organization	Decreases	Increases
Stakeholder likely to take action (supportive of the organization)	Decreases	Increases
Stakeholder likely to take nonsupportive action	Increases	Decreases
Stakeholder unlikely to take any action	Decreases	Decreases
Stakeholder likely to form coalition with other stakeholders	Increases	Either
Stakeholder likely to form coalition with organization	Decreases	Increases
Stakeholder unlikely to form coalition	Decreases	Decreases

A stakeholder scoring high on potential for cooperation and low on potential for threat would be a supportive stakeholder. The team's strategy was to involve these stakeholders in the network's activities. A stakeholder scoring high on potential for threat and low on potential for cooperation would have been a nonsupportive stakeholder. With these stakeholders, the team was to take a defensive stance or attempt to move these stakeholders' positions toward the network (this would have been especially true of those stakeholders who ranked as both definitive and nonsupportive). Stakeholders who scored low on both potential cooperation and threat would have been marginal stakeholders. The team was to monitor these stakeholders for any changes. Mixed-blessing stakeholders would have scored high on both potential for threat and potential for cooperation. The most appropriate strategy in these cases was to solicit collaboration with the stakeholder.

The potential primary, cooperative stakeholders identified in step one were to be contacted and invited to participate in the project. Depending on the relationship that the implementation team had with the particular stakeholder, one of three approaches was to be used to make initial contact:

- Informal approach—to be taken when the stakeholder was one with whom the implementation team had already established a working relationship. Because a formal introduction was not necessary with such a stakeholder, the initial contact was to be made by phone. After the researchers reached the stakeholder, they were to explain the reason for the contact and ask the stakeholder a series of nonthreatening questions exploring the stakeholder's potential economic and political interests in the project. These interests may have been both internal and external to their organization (i.e., how they perceived the role of other stakeholders in the network). These questions were to lay the foundation for the development of the implementation network.

- Formal approach—to be taken with affiliates when the implementation team did not have a working relationship with the potential stakeholder, yet the stakeholder had a working relationship with an affiliated member of the ENV project team. The implementation team was to ask the affiliate to facilitate the initial contact, meaning that the affiliate was to make the stakeholder aware of the project and interests of the implementation team member who was to be in contact with them. After the liaison had introduced the stakeholder to the project, the implementation team was to formally contact the stakeholder. This formal contact was to be made in person, preferably, or over the phone if necessary. After the contact was made, the researchers were to provide the stakeholder with an overview of the project, explain the reason for the contact, and ask the stakeholder a series of questions including questions assessing interest in the project.

- Formal approach—to be taken when the stakeholder had no relationship with the implementation team or the project team. It would have been necessary to identify the appropriate contact in the organization and request a face-to-face meeting with that individual. When this meeting occurred, the researchers were to provide the stakeholder with an overview of the project, explain the reason for the contact, and ask the stakeholder a series of questions.

TASK 5.3: NETWORK FACILITATION I—ESTABLISHING GOAL-SETTING NETWORK THROUGH STRATEGIC PLANNING

Contacting primary stakeholders and inviting their participation was an essential first step to bring together primary, cooperative stakeholders. This was the level where initial decisions needed to be made about how to develop and promote this technology.[7] At this goal-setting level of network development, it was critical that the stakeholder representatives who were invited to participate had autonomous decisionmaking authority in their organizations.

Demonstration of Concept

In the research team's experience, the tool most effective at stimulating participation from top-level individuals in an implementation network was the prototype demonstration with sample real-world data and reactions. Accordingly, three demonstrations or field tests were planned. Two of these field tests were to be conducted in Montgomery and Albemarle Counties, VA. These two tests were to give the team real-world data on the effects of UV–A lighting on nighttime driving in rural, mountainous, and foggy conditions. These findings were to supplement the findings from controlled testing conducted on the Smart Road.

In addition, the project team had planned a demonstration-of-concept field test in the Northern Virginia metropolitan area, most likely to follow the two other field tests. While this demonstration was to enhance the data collection efforts by providing some data on real-world urban driving effects, the overriding value of this demonstration was to be the ability of major project stakeholders, many of whom resided in the greater Washington, DC, area, to see a live, working prototype of the system under study. Having access to the information provided by a live demonstration, these major stakeholders would have had the ability, and hopefully the inclination, to participate more fully in the implementation network.

Strategic Planning Session

After the participation of the goal-setting network was secured, stakeholder involvement in a strategic planning session was to be requested and coordinated. The goal-setting stakeholder was to be invited along with a member of his or her organization who represents the program level. Goal and program were matched to ensure that after a goal was set, there was someone from each organization who would then be in charge of carrying that goal out at the program level. Here was the first link from the goal-setting network to the program-level network discussed in the next section.

In preparation for this strategic planning session, the implementation team members were to formulate preliminary questions designed to stimulate and facilitate the discussion. These questions included, among others: What is the goal of the project? What tasks and resources are necessary to reach this goal? Who will be responsible for supplying the resources and carrying out the tasks? These questions were to provide a framework for the discussion but were not to stifle the energy and ideas that evolved from the participants. The vision and action plan that was to emerge from such a strategic planning session needed to be owned and supported by the stakeholder representatives because they were the individuals who were to champion the vision in their own organizations.

During the ENV strategic planning session, stakeholders at the goal-setting and program levels of their organizations were to begin formulating goals for the implementation of ENV technology. The group was to accomplish the following tasks:

- Develop and clarify a goal (or vision) for the project.
- Identify the barriers and opportunities in the path to this goal.
- Formulate strategic action steps for how to reach the goal (i.e., how to overcome the barriers and take advantage of the opportunities).
- Identify resources necessary to complete each action step.

- Explore and clarify roles and responsibilities of the individual and organizations involved.
- Develop a timeline for the project in general and for each of the next steps in particular (i.e., who is responsible for what by when).

Each issue covered during the session was to be captured and recorded on flip charts and in meeting minutes. The minutes were then to be circulated to every participant. It was very important at this point in the process to create a joint vision and action plan and then to provide the group with a written record of their contribution and commitment to that plan.

After the strategic planning session, members of the implementation team were to synthesize its results, from which they were to formulate a proposal for implementation.

TASK 5.4: NETWORK FACILITATION II—ESTABLISHING PROGRAM-LEVEL NETWORK BY TRANSLATING GOALS INTO ACTIONS

This stage of network facilitation involved the creation of program and operating plans designed to reach the goals established at the goal-setting-level strategic planning session and outlined in the proposal. The participation of a program-level representative in the strategic planning session is essential; although goal setters set the vision for the project, the program representatives likely do the daily work toward goal realization. The implementation team was to ensure that participation and understanding at the program level was secured from the beginning.

This program-level network was to be larger than the goal-setting network and require more time and resources to develop. This phase was to involve working out the details among the goal setters and determining how the goals translate in terms of time, staff, and resources into actions at the program level. This program level development was to involve obtaining formal commitments of resources from the various organizations. After resources were committed, the project team was to educate the program-level network about the project and define how they and the resources they oversee fit into it. This effort was anticipated to be time consuming but essential to successful implementation.

When the program gained more detailed definition, the implementation team was to reflect on and evaluate the process to determine if any necessary organization had been excluded. The team considered that partnership or collaboration with another organization would enable them to carry out an action more efficiently or effectively. The process was intended to be a continual cycle of planning, acting, reflecting, and adjusting the plan to ensure that the set goal is realized.

TASK 5.5: NETWORK FACILITATION III—ESTABLISHING OPERATIONAL NETWORK THROUGH IMPLEMENTATION OF THE ACTION PLANS

The operational network was to perform the various procedures and routines for deployment, dissemination of information, and client monitoring. Participants at this level were to synthesize development and planning from the goal-setting and program network developments and could have worked iteratively with a number of agents from either network to further define how they should put into operation the tasks handed down to them. This stage was to address line-level implementation issues and allot resources to carry out each task.

TASK 5.6: DETERMINE SCENARIOS FOR ADOPTION OR REJECTION OF UV–A AND FLUORESCENT TECHNOLOGY

Task 5.6 was to determine the plausible scenarios and key events that will allow for adoption or rejection of the UV–A and fluorescent technology. To address this task, the expanded cost-benefit analysis needed to be addressed first. In addition, the finding was to depend on published studies on the introduction of innovations such as seat belts and air bags, car manufacturers' estimates of the market response, and a survey of state highway agencies. The findings were to be applied considering that the necessary changes were made to predict the rate of acceptance of UV–A and fluorescent technology given the costs and benefits estimated previously.

Some of the team felt much uncertainty about the rate of public acceptance of UV–A headlamps in the marketplace, and a certain amount of uncertainty also surrounded the rate of political acceptance of fluorescent pavement markings and delineation systems among State and local highway agencies. It was assumed to be most useful to model the introduction of UV–A and fluorescent technology over time as a stochastic process whose ultimate cost-benefit outcome depended on a sequence of intermediate outcomes that were unknown at the start. Also, it was considered useful to identify the indicators that were to provide the earliest news of those future outcomes.

CHAPTER 7—LITERATURE REVIEW

Before beginning the studies in Phase II, the research team conducted a literature review on nighttime driving with an emphasis on vision, age, nighttime driving, object detection and recognition, different types of vision enhancement systems, and driving in adverse weather conditions.

VISION

Vision begins with light, but before this light is seen, it must be transformed into electrical energy by the receptors of the eye. This electrical energy must travel a long and complex path to the visual cortex and beyond.[8] Visible light, the band of electromagnetic energy with a wavelength between 380 and 720 nm, is the stimulus for vision. Light can be perceived by looking directly at the source that emits these wavelengths, such as the sun or a light bulb; however, most perceived light is reflected into the eyes from objects in the environment. That reflection provides information about the nature of these objects.

Photopic and Scotopic Vision

As light enters the eye, the process of vision begins. The first step is focusing light onto the receptors of the retina, done by the cornea and lens. Electrical signals generated in the receptors pass through the retina in the first neural network on the way to the brain. Rods and cones are the two basic receptor types. In essence, these receptors create a mosaic on the retina. Rods (responsible for scotopic vision) and cones (responsible for photopic vision) differ in a number of areas (table 5).

Table 5. Properties of photopic (cone) and scotopic (rod) vision of humans.[9]

	Photopic	Scotopic
Receptor	Cones (~7 million)	Rods (~125 million)
Retinal Location	Concentration in Fovea	Peripheral Retina
Functional Luminance Level	Daylight	Night Light
Peak Wavelength	555 nm	505 nm
Color Vision	Trichromatic	Achromatic
Dark Adaptation	Rapid (~5 min)	Slow (~30 min)
Temporal Resolution	Fast Reacting	Slow Reacting
Spatial Resolution	High Acuity, Low Sensitivity	Low Acuity, High Sensitivity

Only all-cone foveal vision enables the detection of small details, which explains why nighttime drivers might not be able to identify details in a scene. Scotopic vision tends to allow object detection until the object is illuminated by the vehicle's headlamps and the identification of more details is possible through photopic vision.

Visual Acuity and Contrast Sensitivity Testing

Testing of visual acuity, which is typically measured using high-contrast stimuli, indicates the visual system's capacity to resolve fine detail in optimum conditions. Contrast sensitivity testing measures detection abilities in different contrast levels and corresponds to how well the person can perform common, everyday visual tasks such as detecting and identifying a road sign at dusk. Many people have good acuity, even 20/20, but they still have problems seeing in conditions of decreased contrast, such as in rain or at night. By analogy, the Snellen acuity test evaluates vision quantity, whereas the contrast sensitivity test evaluates vision quality. When the contrast between an object and its background is low (i.e., low quality), the object must be larger (i.e., increased quantity) for it to be discriminated equivalently as a smaller object with greater contrast (i.e., higher quality).

Contrast has many definitions including modulation contrast, luminous contrast, and luminance ratio. The formulas for these three definitions are shown in the equations in figure 4 through figure 6.

$$\text{Modulation Contrast} = (L_{max} - L_{min}) / (L_{max} + L_{min})$$

Figure 4. Equation. Modulation contrast.

$$\text{Luminous Contrast} = (L_{max} - L_{min}) / L_{max}$$

Figure 5. Equation. Luminous contrast.

$$\text{Luminance Ratio} = L_{max} / L_{min}$$

Figure 6. Equation. Luminance ratio.

Where

L_{max} = maximum luminance

L_{min} = minimum luminance

Luminous contrast has been used previously to measure objects for object detection and discrimination in transportation-related research.[10,11]

Various characteristics of the environment and the individual are known to affect acuity and contrast sensitivity. Increased levels of light or background luminance increase acuity and contrast sensitivity. Higher levels of light activate the cones, resulting in higher acuity and sensitivity.[12] Visual acuity and contrast sensitivity decline with age. The movement of an object or the observer (or both) decreases visual acuity. The ability to visually discriminate in these circumstances (e.g., looking at objects on the side of the road while driving) is called “dynamic visual acuity.” Burg states that acuity deteriorates with increased relative motion.[13] Scialfa et al. suggest that static and dynamic visual acuity may be moderately correlated.[14] Therefore, testing a driver’s static acuity might provide an indication of dynamic acuity.

AGE

By the year 2020, it is anticipated that 17 percent of the United States population will be 65 or older, resulting in more than 50 million eligible older drivers.[15] These drivers may be more likely to suffer a crash. Many studies have examined traffic crashes involving drivers aged 65 and older, researching these drivers’ physical, mental, and psychomotor skills as a potential cause of crashes. (See references 16, 17, 18, 19, and 20.) Accident analyses have shown that crash patterns and older drivers’ accident maneuvers are similar in many motorized countries, regardless of the different traffic environments and rules.[17,21,22] Deficiencies in physical and mental functions of older drivers are said to play a major role in crash occurrence; however, an exact cause-and-effect relationship between crash occurrence and the possible deficiencies of older drivers has not been determined.

When calculating crash rates based on the number of licensed drivers, crash rates for older drivers are lower than for younger drivers.[23] If crash rates are computed with an estimated distance traveled, overall crash rates are higher for drivers age 65 and older, with a steep rise at age 75. (See references 20, 24, 25, and 26.)

As mentioned previously, visual acuity and contrast sensitivity decline with age. The decline generally begins slowly after the age of 40, followed by an accelerated decline after age

60.[27,28,29] Lens opacity increases and the pupil diameter decreases with age. The maximum area of the iris in eyes of people aged 60 is about half that of those aged 20. These factors allow less light to reach the retina in older persons.[30] Weale determined that there is a 50 percent reduction in retinal illumination at age 50 compared to age 20, and this reduction increases to 66 percent at age 60.[31] Hills and Burg indicated no significant correlation between vision measures and crash data for participants under the age of 54, but for those 54 and older, acuity showed significant correlations with crash data.[32]

NIGHTTIME DRIVING

Depending on the complexity of the required tasks, the ability to see is degraded when illumination is reduced below certain levels. Nighttime driving is one such task in which the ability to see is often inadequate and frequently exposes road users to high levels of risk.

The traffic volume at night is much lower than during daytime (20 percent and 80 percent, respectively); however, the fatality rate for nighttime driving in the United States is about two to four times the daytime rate when the factor of VMT is considered.[33] In an interesting analysis of traffic crashes, Vanstrum and Landen showed that, after removing the effects of alcohol in drivers, there were 1.21 and 2.79 fatalities per hundred million miles of exposure in the day and night, respectively.[34] Thus, the risk of a fatality at night among drivers not impaired by alcohol is about 2.3 times higher than in daytime.

It is difficult to properly account for all of the variables that can affect traffic fatalities, but clearly the most dramatic difference between day and night driving is the large reduction in visibility because of the decreased levels of illumination, particularly when drivers are dependent solely on headlamps, and the increased glare from other illumination sources including other vehicles.

Past analyses point to the continued need to improve the visibility of salient objects at night by using fixed lighting, better and consistent roadway delineations, reflective traffic signs, and increased reflectivity of pedestrian and cyclist clothing. Such improvements are necessary in clear atmospheric conditions, but they are essential in adverse weather conditions; fatality rates for adverse weather conditions during nighttime driving are more than 25 percent greater than for daytime driving.[35] While vehicle headlamps can improve, it will be difficult to make significant advances in their effectiveness unless radically new concepts are developed. Furthermore, many current automobile designs reduce the visibility of drivers because of lower eye heights, lower headlamp mounting, and more raked windshields. The introduction of sport utility vehicles represents an alternative for higher eye height and headlamp mounting, but these vehicles tend to create a glare problem for drivers of oncoming, lower-profile vehicles.

Reduced visibility poses a serious problem to driving because both longitudinal and lateral control are based on environmental references.[36] Most drivers reduce their speed when confronted with sight restrictions, but these speed reductions are usually insufficient when considering sight distance.[37,38] Reduced visibility may also disturb drivers' lateral control by forcing them to adjust their lateral position based on a small number of close and rapidly changing visual cues. Thus, in conditions of reduced visibility, lateral control will probably be more erratic without speed reductions. Tenkink demonstrated that the amount of lateral variation in lane position increased with decreasing sight distance when the speed level was held constant, whereas in free-speed conditions both speed and lateral variance decreased.[39] The speed difference between a straight road and a curved road was found to be smaller for short sight distances than for longer ones, and drivers' lateral stability in curves differed between sight conditions. Both findings indicate that drivers' lateral control was affected by restricted sight.

OBJECT DETECTION

The results of Chrysler, Danielson, and Kirby show that when regular low-beam headlamps are used in clear conditions, younger drivers are able to detect "small road hazards" at longer distances than older drivers.[40] The younger group detected a static object (18 cm tall and 33 cm wide) at an average of 89.9 m, and the older group did so at an average of 70.1 m. When a mannequin 107 cm tall (simulating a children or static pedestrian) was presented to the participants, age was also a significant factor. The older group's mean detection distance for the mannequin was 80.8 m and the younger group's mean was 109.7 m. This research effort simulated adverse weather conditions by having participants wear blurred plastic visors that reduced the contrast of the scene. During simulated adverse weather conditions, the same age trend continued, but the detection distance for the static objects had an average reduction of

51 percent when compared to the clear condition. A detection distance reduction of 37 percent occurred for the small pedestrian objects during the adverse weather simulation.

There is general agreement that automobile low-beam headlamps provide, at best, marginal visibility for low-contrast objects such as pedestrians.[(41)] Furthermore, it is well known that pedestrians tend to overestimate their own nighttime visibility.[(42)] This combination of these two factors is especially critical for older drivers because of their generally impaired vision.

When doing roadway object visibility research, both detection and recognition distances have often been collected to analyze the degree to which the different vision enhancement system (VES) configurations enhanced nighttime visibility while driving. (See references 43, 44, 45, 46, and 47.)

VISION ENHANCEMENT SYSTEMS

Timely detection of traffic control devices and hazards on the roadway is an essential part of safe driving. As mentioned previously, most drivers tend to over-drive their low-beam headlamps and operate at very short preview times at night, which could explain the high rates of nighttime crashes.[(48)] Therefore, alternative systems that enhance night visibility are needed.

If reduced visibility is one of the primary direct causes of increased crash risk at night, are there technologies that can reduce crash risk by providing enhanced visual cues to drivers? Various VESs that are said to accomplish this are currently in development by original equipment manufacturers and tier-one suppliers. Some of the VESs discussed in this section are currently commercially available, while others remain in prototype testing. These systems differ in various aspects, including cost and spectral distribution (figure 7 and figure 8).

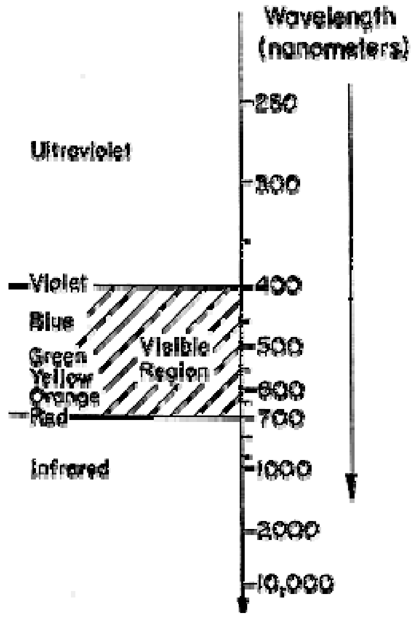


Figure 7. Diagram. Electromagnetic spectrum.

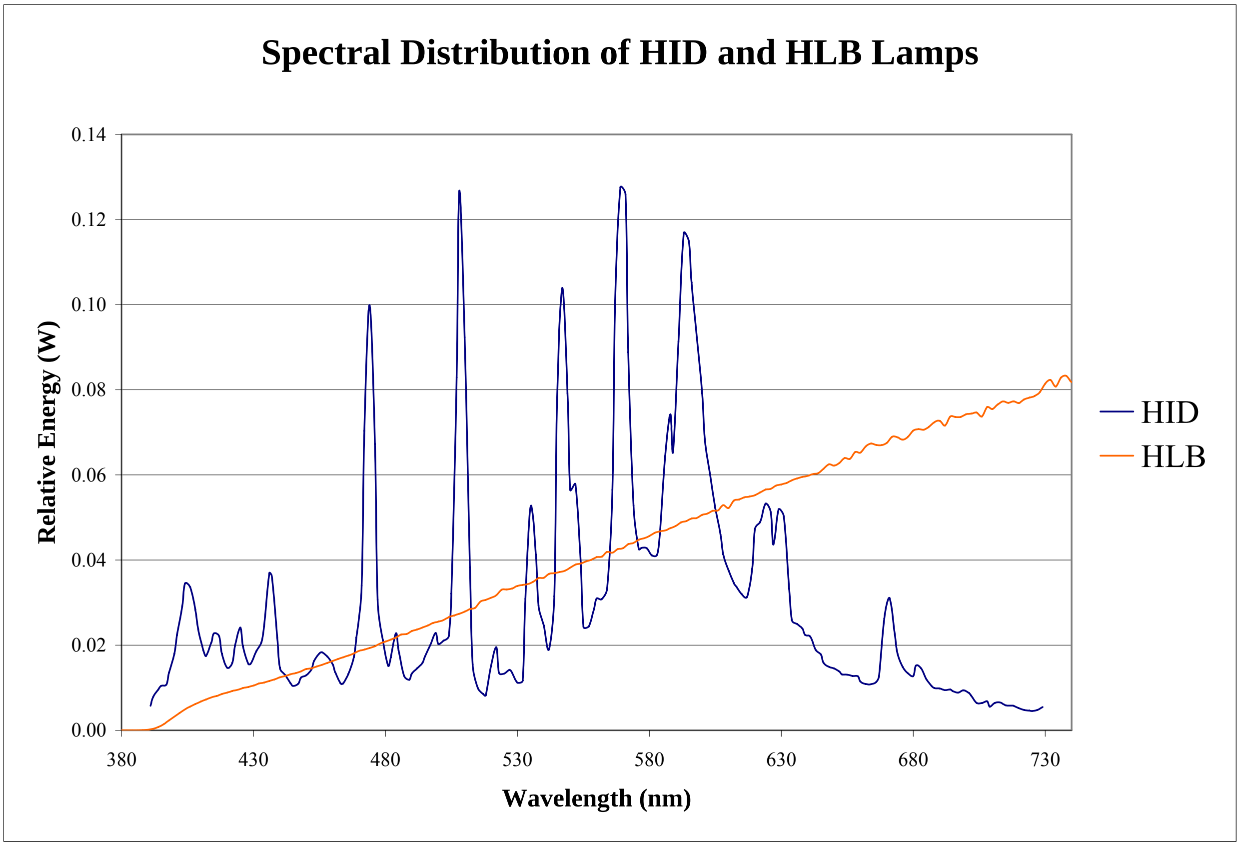


Figure 8. Line graph. Characteristics of available and prototype vision enhancement systems.

Halogen Headlamps

Although the development of lighting technology was quite advanced in the 1970s, government restrictions prohibited halogen headlamps in the United States until the early 1980s. Until that time, traditional headlamps were incandescent sealed beams, which gave off a lot of heat and required great power, drawbacks that halogen headlamps reduced. A conventional incandescent bulb generates 16 to 18 lumens (lm) of light per W compared to 20 to 22 or more lm/W for a standard halogen bulb or 28 to 33 lm/W for some high output halogen bulbs. Currently, halogens are the standard headlamps for vehicles in the United States.

Halogen systems provide illumination by routing electricity through a high-resistance tungsten filament surrounded by halogen gas. The glowing tungsten filament produces visible-spectrum light of greater luminance than that of the conventional filament. Luminous flux measures of 200 to 300 lm are typical of halogen bulbs. Combined with sophisticated reflectors and lenses, today's halogen bulbs can provide a low-beam output of 500 or even up to 1,000 lm.[49] Halogen lighting systems usually cost between $40 and $100 per vehicle.[50]

Unfortunately, about 80 percent of the output of halogen headlamp systems is wasted as heat in the infrared spectrum.[50,51] Furthermore, the filament oxidizes and erodes over time, resulting in light with a yellowish hue. The filament is also susceptible to damage from shock, vibration, or impact, limiting its useful lifespan.

High Intensity Discharge Lamps

HID systems represent a major breakthrough in headlamp technology. Unlike halogen lamps, HID systems produce light in a gas discharge lamp by ionization rather than by a glowing tungsten filament. The arc tube used in the system is composed of a quartz glass envelope that surrounds two electrodes. Inside the tube are pressurized xenon and mercury gases and metal-halide salts. The system applies a very high voltage between the electrodes that results in an arc, which in turn creates visible light.[50,52] This process usually takes a few minutes to stabilize, although current designs allow the process to be sufficiently complete within seconds. The HID lamp can provide an output varying between 1,000 and 3,000 lm at the bulb.

HID lighting systems are more efficient than standard halogen headlamps, producing about 75 lm/W. The relative high efficacy of HID headlamps permits the use of a lower wattage lamp, while still producing at least 70 percent more light than traditional halogen lamps, and with less heat. In contrast to a halogen bulb, an HID bulb produces a brighter, blue-white hue, which improves visibility distance by more than 50 percent compared to traditional headlamps, and it enhances reflective features of road signs and lane markers.(50,52) Furthermore, the no-filament design allows a system life up to six times longer than the life of a halogen bulb.(53) The system also provides more flexibility in headlamp design and allows breakage-resistant polycarbonate plastic to be used as the cover lens material.

Despite its promising features, HID technology has not been implemented widely for several reasons. The system is relatively expensive—roughly \$800 to \$2,000 per vehicle—and therefore, it is currently available in only a few luxury car models. NHTSA requires complete replacement of the system if a component fails, increasing service costs.(52) Furthermore, the technology requires a complex sensor system in the vehicle to maintain proper aiming; poorly aimed HID light results in glare for the oncoming driver.(51) In addition, as is often the case with new technology, the increased viewing distance provided by HID headlamps may create a false sense of security when driving at night.

Another major drawback of HID headlamps is that they offer relatively low color rendering capabilities. The perceived color of an object depends on the spectral power distribution of the light source used to illuminate the object and the spectral reflectance of the object. Unlike the continuous spectral power distributions of daylight or halogen lamps, HID lamps have high concentrations of energy at several narrow-band wavelength regions, while at other regions they have little or no energy. Thus, not all spectral frequencies will be reflected back to the driver, affecting the driver's color perception. The primary concern with this low color rendering has been with the color perception of traffic signs, especially red signs (such as stop signs), because most HID lamps are deficient at the long-wavelength end of the visible spectrum. Sivak and Flannagan present an extensive summary of research that relates to this matter.(54) These authors state that there are two fundamental issues that have not yet been addressed in past HID research: how important is color (in addition to other dimensions such as shape and legend content) in achieving conspicuity and comprehension of traffic signs in general and red signs in particular, and if color is important, how large a decrement in color rendition is acceptable from a safety point of view? Empirical evidence addressing these two issues does not yet exist.

Ultraviolet Headlamps

Researchers have investigated various methods of making objects and pedestrians more visible at night, thus increasing the reaction time for drivers. One of these methods uses UV light as an auxiliary technology to more traditional headlamp systems (e.g., halogen or HID). Although the concept of UV headlamps has existed for some time, a new UV lamp technology developed in Sweden has given researchers fresh insights into the possibilities of its use. These prototype UV headlamps are aimed similarly to high-beam headlamps. They are intended for use with fluorescent TCDs. The headlamps emit UV radiation in the spectral range of 320 to 380 nm, which is invisible to the human eye. The short-wavelength light emitted by the UV headlamps reacts with the fluorescent properties of objects that it contacts to produce visible light. These UV headlamps potentially could offer high-beam performance without glare to oncoming drivers; however, because most objects in roadways are not fluorescent, UV headlamps would always be used with low- or high-beam headlamps.

To date, a number of European and United States studies have begun establishing the technical feasibility of the Swedish approach. Field studies show that prototype UV–A headlamps significantly improve visibility for pedestrians and fluorescent TCDs. (See references 47, 55, 56, and 57.) Analysis of the spectrophotometric output of the UV–A headlamps shows them to be safe and suitable.[(58)]

Mahach et al. and Nitzburg, Seifert, Knoblauch, and Turner suggest in their research that UV–A headlamps could improve visibility distances.[(1,57)] Nitzburg performed a pedestrian visibility study in a static environment (i.e., the car's transmission was in the "park" position) with the participant in the passenger side of the vehicle. Between detection and recognition trials, the vehicle advanced on the pedestrian in increments of 30.5 m. The study used a windshield shutter to limit the time available for visual search, giving a 2-s stimulus exposure time after each 30.5-m advancement. Results suggested an improvement on visibility distances of more than 200 percent when the detection distances of halogen headlamps supplemented with UV–A headlamps were compared to those of halogen headlamps alone.

Several issues regarding UV headlamps remain unaddressed, and it is essential to identify any unintended adverse effects of UV technology that could block implementation, even if these systems improve object detection distances. First, the appearance of UV headlamps to oncoming drivers might be considered unacceptable. Studies conducted to date have, for the most part, evaluated only the appearance of the roadway and pedestrians as seen by the driver of the UV-equipped vehicle. While it is true that the eye is insensitive to optical radiation below 400 nm, it is not completely precise to say that UV–A light is invisible to the normal eye. The UV–A light causes some fluorescence to occur within the ocular media, particularly the lens, and thus observers—oncoming drivers, potentially—experience the headlamps as shimmering, purplish-blue light. When viewed through a windshield, this fluorescence is lessened because much of the UV–A radiation is absorbed, but pedestrians and motorcyclists do not have this advantage.

As stated earlier, the second UV headlamp issue that needs to be addressed before implementation is the possibility of driver adaptation or overconfidence. UV–A headlamps can increase the visibility distance for fluorescent roadway delineation and other fluorescent objects such as pedestrians who are wearing light-colored or fluorescent clothing. Visibility of dark, nonfluorescent objects does not increase in UV–A illumination. Will drivers adapt to improved roadway visibility by driving faster, and therefore detecting dark roadway hazards or pedestrians at shorter distances? Such an argument could be made by opponents of this technology, and while a counterargument exists in principle (e.g., reliance on retroreflective TCDs involves a similar risk), the issue needs to be evaluated empirically. If driver adaptation or overconfidence does increase the risk of crashes with roadway objects and especially darkly clad pedestrians, these issues need to be considered in a detailed human-factors analysis.

There is also a need to accurately assess the benefits of this technology in adverse weather conditions because this could be an area where UV headlamps offer substantial performance advantages compared to other systems. While the potential for increasing pedestrian safety in these circumstances certainly exists for this VES, the system remains untested in adverse weather conditions.

Infrared Thermal Imaging Systems

Infrared thermal imaging systems (IR–TIS) are already in production, and they are optional in several high-end luxury cars as additions to halogen headlamps. This type of system is composed of an infrared (IR) camera and a heads-up display (HUD). IR cameras sense infrared energy to see in the dark. Because IR energy is emitted proportionally to the temperature of an object, the warmer the object, the more energy it emits and the more visible it is. The image obtained from an IR camera provides a thermal signature of the scene. This image can be stored or displayed on a standard video monitor. The IR system presents objects that exhibit temperature differentials when compared to the environment (e.g., pedestrians, cyclists, animals) as an image in different shades of gray. IR systems do not enhance the environment as seen by the driver but instead display an alternative version of the environment that contains additional information not available from the areas illuminated by the traditional headlamp system.

The research of Barham, Oxley, and Ayala on a prototype IR system found that participants using the prototype were able to spot pedestrians 89.9 to 100 m away, providing the driver with 5 s to react if driving at 72.4 km/h or 20.1 m/s (45 mi/h or 66 ft/s).[(43)] This research was performed statically, and motion likely would decrease these detection distances. Because IR systems display information on a HUD, they also impose a secondary task to the driver: monitoring the images on the HUD while driving. Secondary tasks while driving can be causes of driver distraction, which can lead to driving performance degradation.

An HUD is a logical alternative for presenting the type of information provided by IR−TIS. While the use of IR–TIS HUDs in passenger cars is relatively new, car manufacturers have used HUDs to visually present other information through the windshield to the driver since 1988.[(59)] An HUD allows the driver to access visually displayed information in closer proximity to forward scene events than does a conventional head-down (HD) instrument panel display. Heads-up information traditionally includes digital speed, high-beam indicator, and master and specific warnings. In most driving conditions, only the speedometer is shown on the HUD, which is translucent and either blue- or yellow-green. In addition, HUD information is redundantly displayed at conventional HD locations, and the driver can dim the HUD or turn it off.

GM production HUDs are positioned at a nominal 4° look-down angle, centerline to the driver, and at front bumper distance (about 2.4 m or 7.9 ft). The Nissan and Toyota production HUDs are positioned at a nominal 7° look-down angle, 8° to 11° from driver centerline, and at image distances ranging from about 0.9 to 2.1 m (3 to 6.9 ft).[60,61] HUD look-down angle settings vary somewhat across drivers, depending on each driver's eye position and preference. The owner's manuals of HUD-equipped vehicles advise drivers to adjust the HUD as low as possible in the field of view, with the entire HUD image remaining fully visible (i.e., so the HUD appears just above the vehicle's hood).

The next generation of HUDs may include information not redundantly displayed at traditional HD locations, provided technological advances can ensure HUD image visibility comparable to HD displays in a range of conditions. These advances involve increasing image source luminance and HUD optical system efficiency. Assuming this technological challenge can be overcome, automotive HUDs have potential to improve the driver-vehicle interface, present information that could not be effectively communicated on an HD display, and increase display space and interface design flexibility. In addition, future HUDs may include more advanced content such as navigation guidance, headway (car-following) aid, intelligent cruise control, forward collision warning, lane maintenance aid, infrared night vision displays, and roadway-to-vehicle communication information.[62] These relatively unexplored areas may yield the greatest potential benefits of HUD technology.

Driving Performance With VESs

There are numerous concerns regarding the overall benefit of VESs because of potential adverse effects on driving performance and behavior.[63] Increased speeds because of increased driving confidence and comfort, degraded depth perception, degraded object recognition, and missed peripheral targets because of attention tunneling and restricted display field of view are among the problems that may be linked to VES use.

There is currently no consensus regarding net VES benefits because there are certain aspects of performance and behavior that are improved and others that are degraded when using particular VESs. (See references 46, 47, 64, 65, and 66.) Using a prototype VES with a conformal HUD, Barham, Oxley, and Alexander determined that the detection distance to pedestrian and child dummy objects increased by 39 and 18 m (128 and 59 ft), respectively, when compared to existing halogen headlamps.[64] The system provided no benefit to the legibility of road signs. This study is particularly noteworthy because it used a sample of older drivers aged 65 to 80. Replicating the Barham, Oxley, and Alexander findings using a prototype VES in a controlled field experiment, Stahl et al. demonstrated enhanced visibility of pedestrian (47.9-m increase) and child objects (63.1-m or 207-ft increase) compared to halogen headlamps, but no benefit for legibility of road signs.[47] Nilsson and Alm reported improvements in detection performance in simulated fog conditions in a driving simulator; however, lane deviations and speed increased.[46] Despite generalization concerns caused by the use of a simulator, the Nilsson and Alm findings suggest that studies must include multiple dependent variables to obtain a more complete picture of the overall effectiveness of VESs.

Incorporating measures of mental workload, speed choice, and pedestrian detections, Ward, Stapleton, and Parkes showed that speed reductions had no effect on pedestrian detections in the presence of VESs among drivers using a prototype VES on a closed test track.[66] The authors attributed the drivers' decision to reduce their speed to increased workload imposed by the VES. The lack of an effect on pedestrian detection was not explained, although it is plausible that workload could explain the lack of a detection distance benefit.

To determine how to evaluate the potential benefits or limitations of VESs, Gish, Staplin, and Perel performed a small-scale investigation of driver performance and behavior using a mockup VES.[67] Four younger (26 to 36 years) and four older (56 to 70 years) participants drove an instrumented vehicle and orally reported the detection and recognition of targets placed along a predefined route while performing speed monitoring and navigation tasks. Although the mockup VES provided drivers with longer preview distances than low-beam headlamps alone, results suggested that drivers could not always take full advantage of this enhancement because of the visual, scanning, and cognitive demands of the driving tasks. Also, older drivers were less willing to use the mockup VES. Based on oral reports, the consensus among all observers was that the VES increased curve detection distances relative to low-beam headlamps alone.

Other researchers have focused on the potential of VESs in automotive applications to improve peripheral detection. For example, Bossi used a combination of infrared sensor and HUD technologies to research the effect of VES on driver peripheral visual performance.[68] To investigate unwanted effects on peripheral detection performance, Bossi, Ward, and Parkes studied the effect of a simulated VES on detection performance in dark and dusk viewing conditions.[65] The authors reported some degradation in peripheral target detection and recognition performance. Although this can be attributed to the presence of the simulated VES, it could also be attributed to sensory factors, eye scanning patterns, or attention factors. It is important to determine the reason for the peripheral performance degradation, if it exists, in order to recommend a VES design to overcome this problem.

Comparisons among these studies are complicated because the technical approaches ranged from using simulated VESs (e.g., a monochrome monitor displaying the same road scene as the forward screen) in a laboratory setting to actual dynamic viewing conditions using prototype VESs along a closed test track. Although enhanced performance is certainly a necessary condition for a net VES benefit, the effectiveness of supplemental VESs as night driving crash countermeasures cannot be determined from previous research.

DRIVING IN ADVERSE WEATHER CONDITIONS

The driving task involves performing a number of functions, the most important of which is guiding the vehicle within the roadway geometrics and TCDs while detecting other vehicles and nonmotorists and judging their speed, position, and possible behavior. Driving is largely a visual task; therefore, poor visibility conditions such as rain, fog, or snow may impose severe demands on drivers because their ability to collect necessary visual information is markedly degraded. The driving task becomes even more complex when such weather-related conditions of reduced visibility are accompanied by wet surfaces and darkness. The effect of these conditions on driver behavior has been a matter of concern for many years and the subject of past research.

Collins, Neale, and Dingus studied several factors that can affect the visibility and conspicuity of road signs, taking into consideration participant age (younger and older), weather (clear and rain), time of day (day and night), and in-vehicle signing information system (ISIS) use (ISIS and no ISIS).[69] Khattak, Kantor, and Council analyzed the impacts of adverse weather interactions with driver and roadway characteristics on occurrence and injury severity of selected crash types.[70] Another example of adverse weather research is the DRIVE II project ROSES, which dealt with improving traffic safety in adverse weather conditions.[71] The ROSES system consists of in-vehicle safety monitoring and driver support equipment and an infrastructure-based central monitoring system that combines inputs on road and weather conditions from various sources to derive the current and predicted safety level and recommended maximum speed. Khattak, Koppelman, and Schofer developed a conceptual framework to assess the impact of adverse weather on travel behavior.[72] The framework was used to evaluate the effects of weather and traffic information, individual attributes, and situational factors on drivers' willingness to change normal travel patterns. Similarly, Vos presented a traffic simulation model based on literature sources and model analysis.[73] This model incorporates the influences of reduced friction and visibility. Simulation of a sudden visibility reduction shows that road capacity and traffic safety both decrease in such conditions. The gamut of these research topics represents the variety of adverse weather driving situations or conditions.

PHASE II EXPERIMENTAL ISSUES

The literature review illustrates the need to research enhanced night visibility for driving. Following is a list of the primary issues from the literature review that were considered for the Phase II studies:

- Both the stakeholders and the literature search indicated technologies that should be tested in addition to the UV–A headlamps. These VESs include halogen, HID, and IR–TIS.
- Based on the vision changes suggested by this literature review, three age groups should be used in this research: younger participants (18 to 25 years), middle-aged participants (40 to 50 years), and older participants (65 years or older).
- The potential of these VESs to increase visibility in adverse weather justifies the inclusion of adverse weather conditions in the original plan of the experiment.
- Both acuity and contrast sensitivity should be assessed for all participants in these studies.
- Both object detection and recognition distances should be collected to assess object visibility in enhanced night visibility research.

CHAPTER 8—CONCLUSIONS

On its inception, the ENV project was envisioned as a study with a wide scope that included research on various headlamp technologies, pavement markings, roadway infrastructures, roadway objects, and roadway conditions as well as a cost-benefit analysis. This volume describes an enormous amount of planned literature review, experimentation, and industry outreach. The plan would have required the collaboration of four organizations: the Virginia Tech Transportation Institute, the Virginia Transportation Research Council, the Virginia Department of Transportation, and the University of Iowa.

As is often the case in large projects, some of the planned work changed or was replaced to address more pressing issues. The Phase II effort addressed here led to a series of pavement marking, object, and pedestrian detection studies using not only the UV–A technology that was the initial focus of the project but also other new technologies such as the passive infrared detection systems discussed in the literature review. As in the original plan, the object and pedestrian testing was performed in clear, rain, fog, and snow conditions. Discomfort glare from the VESs was also tested with adults as described in this report, but no children participated. Pavement markings were tested not only with UV–A but also with other vision enhancement systems. The plan of the experiment and results of the Phase II testing are summarized in ENV Volume XII, *Overview of Phase II and Development of Phase III Experimental Plan*.

APPENDIX A—SMART ROAD

Figure 9. Photo. Smart Road testing facility.

The Virginia Smart Road (figure 9) is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of Intelligent Transportation Systems (ITS) concepts, technologies, and products. It is the first facility of its kind to be built from the ground up with its research infrastructure incorporated into a section of public roadway. Originating in Blacksburg, VA, the Smart Road presently consists of 3.2 km (2 mi) of two lanes of roadway, which are closed to public traffic and are designated a controlled test facility. When completed, the Smart Road will be a 9.6-km (6-mi) long, four-lane section of the U.S. Interstate system, connecting Blacksburg, VA with U.S. I–81. This connection will serve an important role in the I−81 and I–73 transportation corridor. After completion, provisions will be made to route traffic around controlled test zones on the Smart Road to allow for ongoing testing.

Construction of the Smart Road project was made possible through a cooperative effort of several Federal and State organizations, including VTTI, VDOT, VTRC, FHWA, and Virginia Tech.

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

- All-weather testing facility.
- Variable lighting test bed.
- UV pavement markings.

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

REFERENCES

1. Nitzburg, M., Seifert, R., Knoblauch, R., & Turner, D. (1999). *A Safety Evaluation of UVA Vehicle Headlights*. (FHWA-RD-99-074). Washington, DC: Federal Highway Administration.
2. ASTM International. (1998). *Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials* (D713-90). West Conshohocken, PA: Author.
3. ASTM International. (1993). *Standard Test Method for Evaluating Degree of Resistance to Wear of Traffic Paint* (D913-88). West Conshohocken, PA: Author.
4. American National Standards Institute (ANSI) & The Illuminating Engineering Society of North America (IESNA). (1996). *Photobiological Safety of Lamps and Lamp Systems-General Requirements* (standard RP27.1-96). Washington, DC: ANSI. New York, NY: IESNA.
5. Mitchell, R.K., Agle, B.R., & Wood, D.J. (1997). "Toward a Theory of Stake Holder Identification and Salience: Defining the Principle of Who or What Really Counts." *Academy of Management Review, 22*(4), 853–886.
6. Blair, J.D., & Whitehead, C.J. (1988). "Too Many on the Seesaw: Stakeholder Diagnosis and Management For Hospitals." *Hospital and Health Services Administration, 33*(2), 153–166.
7. O'Toole, L.J., Hanf, K.I., & Hupe, P.L. (1997). "Managing Implementation Processes in Networks." In W.J.M. Kikert, E.H. Klijn, & J.F.M. Koppenjan (Eds.), *Managing Complex Networks: Strategies for the Public Sector* (pp. 224–248). Thousand Oaks, CA: Sage Publications.
8. Goldstein, E.B. (1989). *Sensation and Perception* (3rd ed). Belmont, CA: Wadsworth Publishing Company.
9. Schiffman, H.R. (1990). *Sensation and Perception: An Integrated Approach* (3rd ed). New York, NY: John Wiley & Sons.
10. Vincent, A., & Lemay, P. (1997). *The Effect of Image Size and Luminance Contrast on Object Detection and Discrimination in Cross View Mirrors* (SAE Paper 970232). Warrendale, PA: Society of Automotive Engineers.
11. Zwahlen, H.T., & Schnell, T. (1999). "Visual Target Detection Models for Civil Twilight and Night Driving Conditions." *Transportation Research Record*, 1692, 49–65.

12. Sanders, M.S., & McCormick, E.J. (1993). *Human Factors in Engineering and Design* (7th ed.). New York: McGraw-Hill, Inc.
13. Burg, A. (1966). "Visual Acuity as Measured by Static and Dynamic Tests: A Comparative Evaluation." *Journal of Applied Psychology*, 50, 460–466.
14. Scialfa, C., Garvey, P., Gish, K., Deering, L., Leibowitz, H., & Goebel, C. (1988). "Relationships Among Measures of Static and Dynamic Visual Sensitivity." *Human Factors*, *30*(6), 677–687.
15. Bishu, R.B., Foster, B., & McCoy, P.T. (1991). "Driving Habits of the Elderly—A Survey." In *Proceedings of the Human Factors Society 35th Annual Meeting*, 1134–1138.
16. Brendemuhl, D., Schmidt, U., & Schenk, N. (1988). "Driving Behaviour of Elderly Motorists in Standardized Test Runs under Road Traffic Conditions." In J.A. Rothengatter & R.A. de Bruin (Eds.), *Road User Behaviour: Theory and Research* (pp. 310–318). Wolfeboror, NH: Van Gorcum.
17. Ichikawa, K. (1996). "Characteristics of Fatal Accidents Involving Older Drivers according to Vehicle Type." *Reports of the National Research Institute of Police Science*, *37*(1), 31–39.
18. Mtsui, T. (1995). "Relationship between Elderly Persons' Physical Performance and Fatal Traffic Accidents." *Reports of the National Research Institute of Police Science*, *36*(1), 58–69.
19. Schlag, B. (1993). "Elderly Drivers in Germany - Fitness and Driving Behavior." *Accident Analysis and Prevention*, 25, 47–55.
20. Wouters, P., & Welleman, T. (1988). "Growing Old Safely." In J.A. Rothengatter and R.A. de Bruin (Eds.), *Road User Behavior: Theory and Research* (pp. 332–340). Wolfeboror, NH: Van Gorcum.
21. Hakamies-Blomqvist, L.E. (1993). "Fatal Accidents of Older Drivers." *Accident Analysis and Prevention*, *25*, 19–27.
22. Simoes, A, (1996). "A Training Program to Improve the Driving Performance of Elderly Drivers." *Handbook of International Conference on Traffic and Transport Psychology* (pp. 235–240). Valencia: INTRAS, University of Valencia.
23. Mortimer, R.G., & Fell, J.C. (1989). "Older Drivers: Their Night Fatal Crash Involvement and Risk." *Accident Analysis and Prevention*, *21*(3), 273–282.

24. Evans, L. (1991). “Older-Driver Risks to Themselves and to Other Road Users.” *Transportation Research Record*, *1325*, 34–41.
25. Oxley, P.R. (1996). “Elderly Drivers and Safety when Using IT Systems.” *IATSS Research*, *20*(1), 102–110.
26. Stutts, J.C., & Martell, C. (1992). “Older Driver Population and Crash Involvement Trends, 1974–1988.” *Accident Analysis and Prevention*, *24*(4), 317–327.
27. Richards, O.W. (1966). “Vision at Levels of Night Road Illumination: XII Changes of Acuity and Contrast Sensitivity with Age.” American Journal of Optometry/Archives of the American Academy of Optometry, 43.
28. Richards, O.W. (1972). “Some Seeing Problems: Spectacles, Color Driving and Decline from Age and Poor Lighting.” American Journal of Optometry/Archives of the American Academy of Optometry, 49.
29. Weymouth, F.W. (1960). “Effects of Age on Visual Acuity.” In M.I. Hirsch & R.E. Wick (Eds.), Vision of the Aging Patient (pp. 37–62). Philadelphia, PA: Chilton.
30. Mortimer, R.G. (1989). “Older Drivers’ Visibility and Comfort in Night Driving: Vehicle Design Factors.” In *Proceedings of the Human Factors Society 33rd Annual Meeting*, 154–158.
31. Weale, R. (1961). “Retinal Illumination and Age.” Transactions of the Illuminating Engineering Society, 26, 95.
32. Hills, B.L., & Burg, A. (1977). *A Reanalysis of California Driver Vision Data: General Findings*. Crowthorne, England: Transport and Road Research Laboratory.
33. Mortimer, R.G. (1986). “Night Driving.” In A.G. Gale, M.H. Freeman, C.M. Haslegrave, P. Smith, & S.P. Taylor (Eds.), *Vision in Vehicles* (pp. 373–374). Amsterdam, the Netherlands: Elsevier Science.
34. Vanstrum, R.C., & Landen, J.C. (1984). “The Dark Side of Driving.” *Transportation Quarterly*, *38*(4), 491–505.
35. Blanco, M., Hankey, J.M., & Dingus, T.A. (2001). “Detection and Recognition of Non-Motorists and Objects Using New Technologies to Enhance Night Vision.” In *Proceedings of the Intelligent Transportation Society of America’s 11th Annual Meeting and Exposition*. Washington, DC: Intelligent Transportation Society of America.

36. Harms, L. (1993). "The Influence of Sight Distance on Subjects' Lateral Control: A Study of Simulated Driving in Fog." In A.G. Gale, I.D. Brown, C.M. Haslegrave, H.W. Kruysse, & S.P. Taylor (Eds.), *Vision in Vehicles IV* (pp. 109–116). Amsterdam, the Netherlands: Elsevier Science.
37. Hills, B.L. (1980). "Vision Visibility and Perception in Driving." *Perception*, *9*, 183–216.
38. Hawkins, R.K. (1988). "Motorway Traffic Behavior in Reduced Visibility Conditions." In A.G. Gale, M.H. Freeman, C.M. Haslegrave, P. Smith, & S.P. Taylor (Eds.), *Vision in Vehicles II*. Amsterdam, the Netherlands: Elsevier Science.
39. Tenkink, E. (1988). "Lane Keeping and Speed Choice with Restricted Sight Distance." In J.A. Rothengatter & R.A. de Bruin (Eds.), *Road User Behavior: Theory and Research*. Wolfeboror, NH: Van Gorcum.
40. Chrysler, S.T., Danielson, S.M., & Kirby, V.M. (1997). "Age Differences in Visual Abilities in Nighttime Driving Field Conditions." In W.A. Rogers (Ed.), *Designing for an Aging Population: Ten Years of Human Factors/Ergonomics Research*. Santa Monica, CA: Human Factors and Ergonomics Society.
41. Sivak, M., & Olson, P.L. (1984). *Nighttime Visual Problems of Elderly Drivers* (UMTRI 70665). Ann Arbor, MI: University of Michigan Transportation Research Institute.
42. Allen, M.J., Hazlett, R.D., Tracker, H.L., & Graham, B.V. (1970). "Actual Pedestrian Visibility and the Pedestrian's Estimate of His Own Visibility." *American Journal of Optometry and Archives of American Society of Optometry*, *47*(1), 44–49.
43. Barham, P., Oxley, P., & Ayala, B. (1998). "Evaluation of Jaguar's First Prototype Near Infrared Night Vision System and Its Potential Contribution to Road Safety." In A.G. Gale, I.D. Brown, C.M. Haslegrave, & S.P. Taylor (Eds.), Vision in Vehicles VI (pp. 203–211). Amsterdam: Elsevier Science.
44. Hodge, A.R., & Rutley, K.S. (1978). A Comparison of Changeable Message Signals for Motorways (Report No. TRRL Supplementary Report 380). Crowthorne, England: Transport and Road Research Laboratory.
45. Lunenfeld, H., & Stephens, B.W. (1991). "Human Factors Consideration in the Development of an IVHS System: Night Vision Enhancement." ITE 1991 Compendium of Technical Papers, 120–124.

46. Nilsson, L., & Alm, H. (1996) "Effect of a Vision Enhancement System on Drivers' Ability to Drive Safely in Fog." In A.G. Gale (Ed.), Vision in Vehicles V (pp. 263–271). Amsterdam: North-Holland/Elsevier.

47. Stahl, A., Oxley, P., Berntman, M., & Lind, L. (1998). "The Use of Vision Enhancements to Assist Elderly Drivers." Paper presented at Premier Congres Mondial sur les Application Telematiques aux Transports, Paris, France.

48. Zwahlen, H.T., & Schnell, T. (1997). "Driver Eye-Scanning Behavior as Function of Pavement Marking Configuration." *Transportation Research Record*, *1605*, 62–72.

49. Hogrefe, H., Neuman, R., & Huhn, W. (1997). "Improving Safety through Adaptive Forward Lighting." *Automotive Engineering*, *10*, 47–51.

50. Zino, K. (1995, August). "Technology Update: On the Beam." *Road and Track*, 134–138.

51. McCosh, D. (1990, May). "High Intensity Headlights: Safety Meets Style in Mini-Arc Lamps." *Popular Science*, *236*(5), 90–93.

52. Jost, K. (1995). "High-Intensity Discharge Lamp." *Automotive Engineering*, *11*, 38–42.

53. Siuru, B. (1991). "Lighting Up the Road of Tomorrow." *Mechanical Engineering*, *113*, 64–67.

54. Sivak, M., & Flannagan, M. (1993). "Vehicle Headlamps and Signal Lamps Design." In B. Peacock & W. Karwowski (Eds.), *Automotive Ergonomics* (pp. 185–204). London: Taylor & Francis.

55. 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.

56. Fast, P.T., & Ricksand, A. (1993). *Safer Nighttime Driving: UV-Headlamps Improve Visibility Of Pedestrians*. Paper presented at SIA 8th Congres Mondial, Paris.

57. 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.

58. Sliney, D.H., Fast, P.T., & Ricksand, A. (1995). "Optical Radiation Hazards Analysis of Ultraviolet Headlamps." *Applied Optics*, *34*(22), 4912–4922.

59. Weihrauch, M., Meloeny, G.G., & Goesch, T.C. (1989). *The First Head-Up Display Introduced by General Motors* (SAE Paper 890288). Warrendale, PA: Society of Automotive Engineers.

60. Kato, H., Ito, H., Shima, J., Imaizumi, M., & Shibata, H. (1992). *Development of Hologram Head-Up Display* (SAE Paper 92060). Warrendale, PA: Society of Automotive Engineers.

61. Obayashi, S., Sakata, M., Furukawa, M., Fukano, J., Daidoji, S., Hashimoto, C., & Ishikawa, T. (1989). *Development of Practical Head-Up Display for Production Vehicle Applications* (SAE Paper 890559). Warrendale, PA: Society of Automotive Engineers.

62. Grant, B.S., Kiefer, R.J., Wierwille, W.W., & Beyerlein, D.G. (1995). "Exploring Applications for Automotive HUDs through Ergonomic Research: Telltale Warning and Beyond." In *Proceedings of Associazione Technica Dell' Automobile 3rd International Conference of Vehicle Comfort and Ergonomics*.

63. Mortimer, R.G. (1997). "Some Errors in the Application of Human Factors Data in Traffic Safety: Actual and Potential Problems." In *Proceedings of the 41st Annual Meeting of the Association for the Advancement of Automotive Medicine*, 185–198.

64. Barham, P., Oxley, P., & Alexander, J. (1998). "Evaluation of the Human Factors Implications of Jaguar's First Prototype Near Infrared Night Vision System." In *Proceedings of the International Conference on Traffic and Transport Psychology*, 167–171.

65. Bossi, L., Ward, N., & Parkes, A. (1994). "The Effect of Simulated Vision Enhancement Systems on Driver Peripheral Target Detection and Identification." In *Proceedings of the 12th Triennial Congress of the International Ergonomics Association*, 192–195.

66. Ward, N., Stapleton, L., & Parkes, A. (1994). *Behavioral and Cognitive Impact of Nighttime Driving with HUD Contact Analogue Infrared Imaging* (Paper No. 94-S2-0-04). Paper presented at the XIVth International Technical Conference on the Enhanced Safety of Vehicles.

67. Gish, K.W., Staplin, L.K., & Perel, M. (1999). "Human Factors Issues Related to the Use of Vision Enhancement Systems." In *Proceedings of the 78th Annual Meeting of the Transportation Research Board*. Washington, DC: Transportation Research Board.

68. Bossi, L. (1997). “The Effect of Vision Enhancement Systems on Driver Peripheral Visual Performance.” *Ergonomics and Safety of Intelligent Driver Interfaces*. Mahwah, NJ: Lawrence Erlbaum Associates.
69. Collins, D.J., Neale, V.L., & Dingus, T.A. (1999). “Driver Performance when Using an In-Vehicle Signing Information System Considering Adverse Weather, Visibility Condition, and Age.” In *Proceedings of the 9th ITS America Meeting*. Washington, DC: ITSA.
70. Khattak, A.J., Kantor, P., & Council, F.M. (1998). “The Role of Adverse Weather in Key Crash Types on Limited Access Roadways: Implications for Advanced Weather Systems (Paper No. 981132).” In *Proceedings of the 77th Annual Meeting of the Transportation Research Board*. Washington, DC: Transportation Research Board.
71. de Vos, A.P. (1994). “A Comprehensive Approach of Traffic Safety in Adverse Weather and Road Conditions.” In *Towards an Intelligent Transport System, Proceedings of the World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems*, *3*, 1081–1088.
72. Khattak, A.J., Koppelman, F.S., & Schofer, J.L. (1993). “Automobile Commuters’ Response to Adverse Weather: Effect of Weather and Traffic Information and Implications for Information Systems (Paper No. 930049).” In *Proceedings of the 72nd annual meeting of the Transportation Research Board*. Washington, DC: Transportation Research Board.
73. de Vos, A.P. (1992). “Driver Behavior under Bad Weather.” In *Proceedings of the 25th International Symposium on Automotive Technology and Automation: Dedicated Conference on Road Transport Informatics/Intelligent Vehicle Highway Systems*, 427–434.

Recycled
Recyclable

HRDS-05/12-05(WEB)E