A Safety Evaluation of UVA Vehicle Headlights

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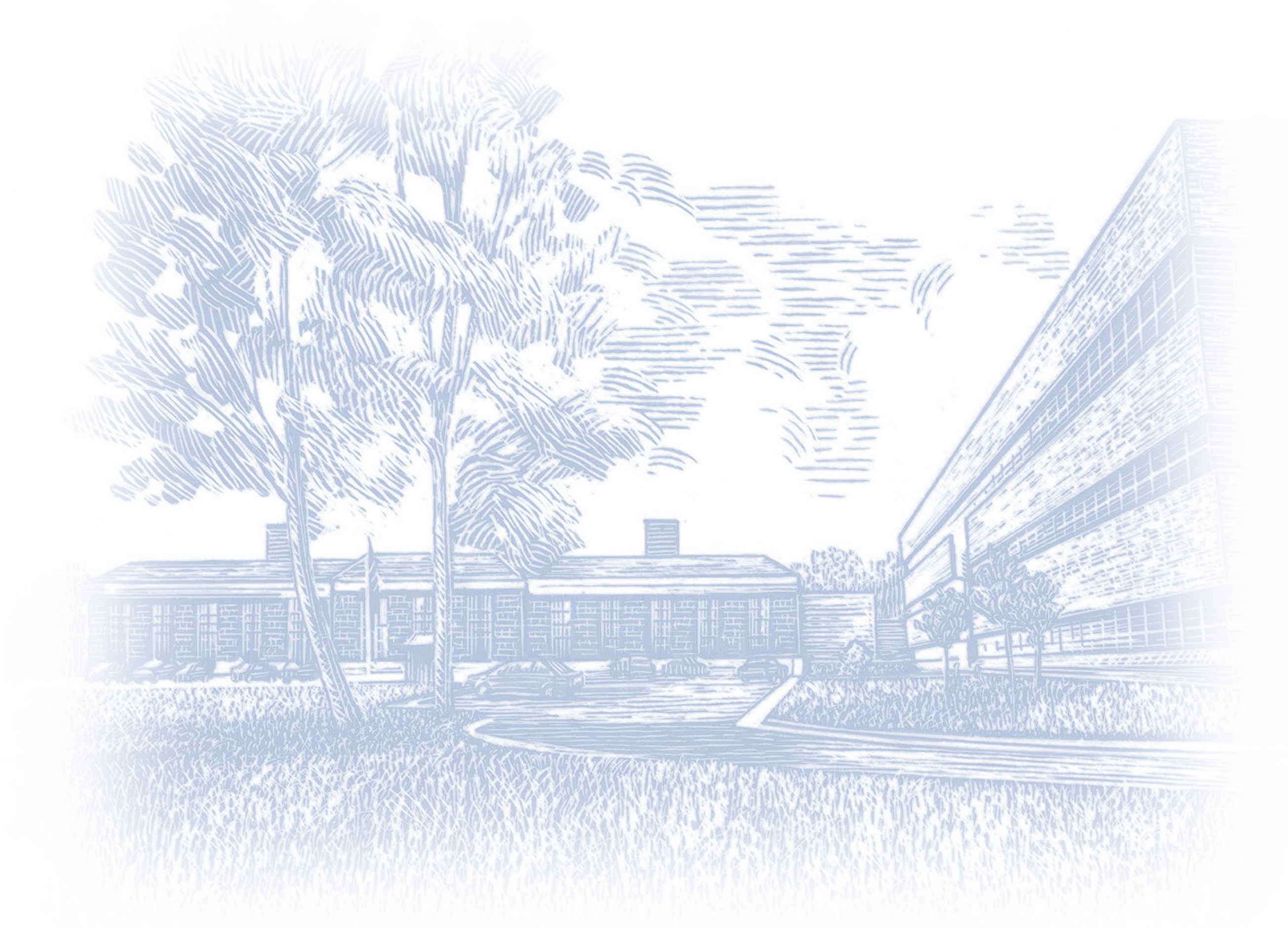

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Federal Highway Administration

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Foreword

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NOTICE

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16. Abstract
The objective of this report was to determine if driver performance can be improved through the use of fluorescent roadway delineation and auxiliary ultraviolet (UVA) vehicle headlights. Additionally, cost/benefit analyses were to be conducted to determine if UVA fluorescent technology may be an economical means of increasing highway safety.
The literature review found several Swedish studies indicating sizeable increases (approximately 200%) in visibility distances for fluorescent roadway markings. Also, the literature review found no evidence of potentially harmful effects from the ultraviolet radiation emitted by the UVA headlight systems.
An extensive field study was conducted to determine the effects of UVA/fluorescent technology on visibility distances and driver behavior. Using an instrumented vehicle, no differences were found in vehicle speed, lateral placement, throttle position, steering wheel reversals, or brake applications. However, there were sizeable (up to 50%) improvements in the detection and recognition distances of a variety of roadway delineations. Even larger (300%) increases in detection distances of fluorescent objects, such as a bicycle and traffic cones, were found. Drivers' subjective ratings of UVA/fluorescent technology were very favorable.
The cost/benefit analysis indicated that very favorable cost/benefit ratios were associated with relatively modest reductions in relevant nighttime crashes and pedestrian crashes.

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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2

yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
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

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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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	02.225	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)

Table of Contents

Foreword ... 3
NOTICE ... 3
Technical Report Documentation Page ... 4
List of Tables ... 10
Introduction ... 11
CONTRACT OBJECTIVE ... 11
SCOPE OF WORK ... 11
Literature Review ... 12
BACKGROUND ... 12
HEADLAMPS AND VISIBILITY ... 12
THE USE OF UVA HEADLAMPS TO ENHANCE NIGHTTIME VISIBILITY ... 13
SAFETY ISSUES OF UVA LIGHTING ... 15
CONSPICUITY AND VISUAL SEARCH ... 17
OTHER RELATED RESEARCH ... 18
SUMMARY ... 19
Field Study ... 20
INTRODUCTION ... 20
EXPERIMENTAL TEST SITES ... 20
TESTING EQUIPMENT ... 21
Vehicles ... 21
Windshield Shutter ... 23
Lane Aligner ... 24
TEST SUBJECTS ... 25
RESEARCH PERSONNEL ... 25
TESTING PROCEDURES ... 26
Roadway Delineation Visibility Study ... 26
Static Pedestrian Visibility Studies (Two Scenes) ... 26
Left-Curve Delineation Visibility Study (With and Without Oncoming Headlight Glare) ... 27
Dynamic Pedestrian Visibility Study ... 28
Disabled Vehicle Visibility Study ... 29
Loop Ride Study - Subjective Ratings ... 29
DASCAR Drive Study - Driver Performance and Subjective Ratings ... 29
Static Testing - Visibility Distances and Subjective Ratings ... 30

RESULTS 30
Detection and Recognition Distance 30
Static Testing 40
Subjective Ratings 40
Driver Performance Measures - DASCAR 41
Subjective Ratings 43
Age Effects 44
Cost/Benefit Analysis 46
INTERVENTION COSTS 46
Crash Costs 47
Incidence 47
RESULTS 48
References 50

Figure 1. Test track layout. 20
Figure 2. UVA headlight configuration on the Taurus test vehicle. 22
Figure 3. UVA headlight configuration on the Volvo test vehicle. 23
Figure. Down or Closed Position.. 24
Figure 4. Windshield shutter installed on the Taurus test vehicle (Up or Open Position). 25
Figure. Pedestrian Visibility Study. 27
Figure 5. Stimulus configurations: static pedestrian visibility studies and disabled vehicle visibility study (DISABLED VEHICLE SCENE). 28
Figure 6. Roadway Delineation - Detection Distances Graph. 31
Figure 7. Roadway delineation — recognition distances. 32
Figure 8. Roadway Scenes - Detection Distances Graph. 34
Figure 9. Roadway Scenes - Recognition Distances Graph. 35
Figure 10. Disabled vehicle scene shown with standard U.S. low beams (above) and standard U.S. low beams with UVA (below). 36
Figure 11. Pedestrian Scenes - Detection Distances Graph. 37
Figure 12. Pedestrian Scenes - Recognition Distances Graph. 38
Figure 13. Pedestrian crosswalk scene shown with standard U.S. low beams (above) and standard U.S. low beams with UVA (below). 39

List of Tables

Approximate Conversions to SI Units 5
Table. Roadway delineation — detection distances. 31
Table. Roadway delineation — recognition distances. 32
Table. Roadway scenes — detection distances. 34
Table. Roadway scenes — recognition distances. 35
Table. Pedestrian scenes — detection distances. 37
Table. Pedestrian scenes — recognition distances. 38
Table 1. Visibility distances: static testing. 40
Table 2. Subjective ratings: static testing. 40
Table 4. DASCAR data: vehicle lateral placement. 42
Table 5. Subjective ratings: how headlights compare to what you generally see......................... 43
Table 6. Subjective ratings: how UVA headlights compare to U.S. headlights. 44
Table 7. Age and headlight condition: 2x2 analyses of variance. 45
Table 8. Costs for fluorescent lane striping and UVA headlights. 47
Table 9. Crash costs by crash geometry.*.. 48
Table 10. Benefit/cost ratio for UVA headlights by percentage of reductions in nighttime pedestrian crashes. 49
Table 11. Benefit/cost ratio for UVA headlights and fluorescent striping by percentage of reduction in nighttime crashes.* 49

Introduction

This report describes the work performed under Contract DTFH61-95-C-00093, Safety Evaluation of Ultraviolet (UVA)-Activated Fluorescent Roadway Delineation. The objective and scope of the contract were as follows:

CONTRACT OBJECTIVE

The objective of this contract was to determine whether driver performance could be improved using auxiliary UVA vehicle headlighting and candidate fluorescent traffic control devices. In addition, safety and cost/benefit analyses were to be performed to determine if UVA/fluorescent technology offered an economical means of increasing highway safety.

SCOPE OF WORK

The research was designed to investigate the safety and cost/benefits possible from the use of UVA/fluorescent technology. The major project activities involved determining changes in driver performance, and visibility of roadway delineation and pedestrians, as well as assessing the effects on safety. Additionally, the project was to conduct a cost/benefit analysis comparing the expense of installing and maintaining fluorescent materials to any savings achieved from the reduction in highway crashes.

The first project activity involved conducting a preliminary field assessment of the effects of fluorescent/UVA technology on driver performance. The results of that initial research effort were reported earlier ("A Preliminary Field Evaluation of Ultraviolet-Activated Fluorescent Roadway Delineation," Karen R. Mahach, Richard L. Knoblauch, Carole J. Simmons, Marsha Nitzburg, John B. Arens, and Samuel J. Tignor, Public Roads, July/August 1997, Vol. 61, No. 1).

The second project activity involved conducting a critical review of a selected number of relevant references related to nighttime driving and visibility, use of UVA headlamps to enhance nighttime visibility, safety issues associated with UVA lighting, conspicuity and visual search, and other related research.

The third project activity involved designing and conducting a field evaluation to quantify the benefits associated with the use of UVA/fluorescent technology. Procedures were developed and implemented to measure changes in roadway delineation visibility, visibility of static and dynamic pedestrians, and driver performance. In addition, subjective ratings of UVA headlighting systems were made.

The final project activity involved conducting a cost/benefit analysis. This analysis consisted of preparing an estimate of the expense of installing and maintaining the UVA/fluorescent technology and comparing the costs involved to the potential cost savings resulting from the reduction of crashes attributable to UVA/fluorescent technology.

Literature Review

BACKGROUND

Nighttime driving is one of the motorist's most difficult tasks. The risks of having a nighttime accident on the road is 2 to 3 times greater than during the daytime. Since the basic difference between night and day driving is the absence of light at night, the increase in the accident rate in periods of darkness can be mainly attributed to poor visibility conditions. During nighttime driving, the visibility distance largely depends upon the availability of artificial light, the source of light being the vehicle headlamps or fixed overhead lighting. High object visibility is an essential characteristic of traffic control devices and a significant factor in highway safety. Researchers have studied this problem, looking for ways of making objects and pedestrians more visible at night. The use of ultraviolet (UVA) headlamps combined with low beams has been suggested as a promising solution to this problem.

The purpose of this literature review was to identify information that might document how UVA headlamps can enhance nighttime visibility. A comprehensive search was made of journals and reports in appropriate subject areas, and a listing was made of articles and reports with potential relevance to this project. Emphasis was placed on the application of UVA technology for highway visibility enhancements. Because this is a recent technology, the amount of existing research was limited. Nevertheless, a number of significant articles and papers have been written on the subject. This section highlights the most relevant sources.

HEADLAMPS AND VISIBILITY

The vehicle's headlamps are by far the main source of illumination available to the driver. The condition and potency of these lamps will directly impact the driver's ability to see objects at night.

The main factors that play a role in nighttime accidents and fatalities were examined by Vanstrum et al. The study revealed that those which predominate at night are alcohol, inadequate visibility, and driver fatigue. Of those factors, the one that can be enhanced through safety engineering is visibility.

Olson et al. studied the effect of headlamps on nighttime visibility. The study concluded that low beams do not provide adequate visibility under many driving conditions. The major limitations to improved headlamp design are due to certain characteristics of the human vision system as well as practical problems associated with headlamp mounting and conditions of use. Limitations arising from the human visual system are related to problems of brightness contrast detection at night, problems of glare, sharpness of central vs. peripheral vision, and the sensitivity of the eye to a broad range of lighting conditions.

Vaswani, for example, concluded that inadequate visibility of road signs and pavement markings at night contributed to wrong-way driving. He described a concept termed the "keg of legibility," which delineates the limits of nighttime visibility under low-beam headlights. The application of the keg-of-legibility concept to the placement of signs, markings, and additional devices that help guide the motorist through the intersection of a four-lane divided highway and another road was discussed.

THE USE OF UVA HEADLAMPS TO ENHANCE NIGHTTIME VISIBILITY

Ultraviolet light has a shorter wavelength than ordinary light and is invisible to the human eye. However, when ultraviolet light is reflected in certain materials, it is returned on longer wavelengths and becomes visible. This phenomenon, known as fluorescence, makes objects more visible and therefore offers a large potential for improving safety.

Most of the research in the application of UVA headlamps for enhancing highway visibility has been conducted in Europe, particularly by the Swedish National Road Administration under the ARENA Program.

ARENA is a Swedish National Road Administration (SNRA) project that uses field tests to ascertain how road traffic and safety can be improved by advanced technology. The project, based in Gothenburg in 1992, carries out field tests with the cooperation of industry and other organizations. Under the area of traffic safety, a project called UV Light was conducted. UVA headlamps, with emission spectra between 320 nm and 400 nm, and fluorescent road markings were used to create a full light effect in conditions of poor visibility without blinding the oncoming traffic. Pedestrians were seen much more clearly and the path of the roadway could be seen far beyond oncoming vehicles. This work has been documented in various papers.

Barrie described the Swedish trials on UVA vehicle headlamps. The ultraviolet light alone did not enable drivers to see where they were going. However, they were able to highlight anything that contained fluorescent pigments. These included road signs, road markings, and protective clothing. They greatly improved visibility, allowing drivers to identify objects 200 m (656 ft) away, compared with a low-beam range of 50 m (164 ft). They also worked well in fog.

UVA lamps are currently being tested by Saab and Volvo on various cars and a bus. Since 1990, these Swedish car manufacturers have been involved in a joint development company called Ultralux. Work on the dangers and problems of ultraviolet light are being carried out by the Swedish Road and Traffic Research Institute. They have found that UVA beams from headlamps do not constitute any health hazard. By using the filters, all the harmful UVB and UVR rays are eliminated. The remaining UVA intensity is very low compared with normal daylight. Because of the filters, the lamps appear black in the daylight and glow faintly blue when switched on in the dark. Saab, Volvo, and Philips are responsible for the technical development of a viable lamp. In the United States, the Ford Motor Company, in its Contour concept car, has incorporated prototypes of a High-Intensity Discharge (HID) lighting system. This system, scheduled to be in production in about 2 years, also emits UVA light.

In addition to the use of filters, the Swedish Road and Traffic Research Institute has proposed that sensors be placed in the cars to determine when the car is moving at speeds in excess of 48 km/h (30 mi/h). The UVA lighting system will be designed to operate only at speeds greater than 48 km/h (30 mi/h) to minimize the health threat to pedestrians.

Ultralux states that fluorescent road markings can be seen at a distance of 150 m (492 ft) with UVA light, compared with 60 m to 70 m (197 ft to 230 ft) with low beams. The corresponding visibility distance for roadside posts was even better. The posts were visible at more than 200 m (656 ft) with UVA light.

The percentage improvement in safety as a result of greater visibility varies between different studies. According to Road Transport Research, Organization of Economic Cooperation and Development (OECD), the percentage reduction in accidents associated with improved lighting is 20 percent on average. In some cases, the number of accidents is reduced by up to 56 percent.

Behavioral changes at higher speeds and with more aggressive driving is minimal, according to the same source.

Ultralux also found that pedestrians and other unprotected road users can be seen more easily when they are illuminated by UVA lighting. Different clothes, depending on the material and color, have different levels of fluorescence. Jeans could be seen at approximately 100 m (328 ft), for example, while white cotton clothes and synthetic fabrics could be seen at even greater distances. Dark clothes such as black wool, however, were no more visible with UV light than with normal low beams. They also found that washing can improve the fluorescent properties of garments due to the optical whiteners present in many detergents.

The detergents used for washing dishes and clothing generally have a number of additives—for example, bleaches, brighteners, and abrasives. Bleaches whiten fabrics by destroying dirt and colors. Brighteners are chemicals that convert normally invisible ultraviolet light into visible light. Because of the brighteners, additional light reflects back from the fabric, making it seem more vivid, or "whiter."

An important finding in this study was that, when combined with low beams, UVA light gives a unique possibility of increasing the visibility of fluorescent objects on the road without dazzling drivers in oncoming cars. Even fabrics of relatively low fluorescent efficiency, such as jeans, could be detected at a distance of about 100 m (328 ft), even in the presence of dazzling lights from oncoming cars.

When there was no dazzling light to reduce the visibility, detection distances of more than 150 m (492 ft) were achieved, even for clothes with low fluorescent efficiency. Since UV light is invisible to the eye, drivers in oncoming cars did not become dazzled.

Ultralux also studied how motorists experience UV light in traffic. The National Swedish Road Administration has equipped some 100 km (62 mi) of road with fluorescent properties. Some 40 drivers were interviewed after driving cars with UVA lamps on public roads and on test tracks. The results provided an "extremely positive picture of the effect UVA light has on driving in the dark." They found that the visibility of road markings more than doubled using UVA light. The test drivers found that the fluorescent markings improved visibility by more than 40 percent when driving with low beams only. UVA beams in combination with low beams received a higher rating than low beams alone in all cases. The drivers experienced a greater improvement in visibility on freeways and main roads than in city traffic with street lighting.

No fewer than 78 percent of the drivers in the Ultralux survey found that the new road markings could be seen more easily in the daylight.

Ultralux's Peder T. Fast also documented how with supplementary high-beam near-ultraviolet headlamps, fluorescent road markings and clothes could be seen at much greater distances. He utilized the 100-km (62-mi) road equipped by the Swedish National Road Administration with fluorescent road markings and delineator posts for his study. The headlamp system design is presented briefly in his paper, which also described the tests run to evaluate the headlamps. Some of these were on open roads and some were on a closed test circuit. The test methods used and the visibility ratings recorded are presented and discussed.

One of the most comprehensive studies of detection distances to obstacles on the road when using UVA headlights was done by Helmers et al. The study investigated whether low-beam illumination supplemented by UVA headlamps could provide long and safe detection distances. The detection distances were measured in a full-scale simulated opposing situation between two vehicles on a straight, level, two-lane road closed to traffic. The opposing car was stationary in the lane for opposing traffic. The subject's car was driven in the driving lane towards the stationary car. The task of the subject, as well as the driver, was to detect obstacles to the right in the driving lane. Upon detection, they were immediately to push a silent handheld switch. The obstacles were flat plates in the form of a square with a side of 0.4

m (1.3 ft). They were covered with cloth and had three reflectances: black, light gray, and white. The result showed a non-detectable or minor increase in the detection distances for the black and the light gray targets. However, the detection distances for the white targets were twice as long when the ordinary low-beam illumination was supplemented by UVA lighting. The relationship between the reflectance of clothes and the power to emit visible light in UVA light was also studied. The increase in luminance related to the increase in whiteness of the garments was found to be approximately 30 times greater in UVA lighting than in ordinary headlight illumination. Measurements showed a relatively strong positive connection and, furthermore, the ability to emit visible light in UVA lighting increased much more rapidly than the ability to reflect ordinary light when the reflectance of the clothes increased.

A positive effect on the visibility of pedestrians and on road design elements was demonstrated by Staehl et al., who tested two systems developed to enhance visibility during nighttime driving (the Volvo ultraviolet light system and the Jaguar night-vision system). It was apparent that using these systems would give older drivers more confidence when driving at night and should improve both their own safety and that of other vulnerable road users such as pedestrians.

The function and types of application of headlamps were described by Schoon et al. Subsequently, the technical lighting aspects of HID lamps, which have an influence on road safety, were described. Due to the intense light produced by HID lamps and the presence of ultraviolet radiation, two possible areas of application are described: (1) polarized light, and (2) the use of fluorescent material to enhance the visibility of objects. The health hazard presented by UV radiation is not ignored, however. The light emission of a low beam as stipulated by Economic Commission for Europe (ECE) regulation R20 is dealt with extensively. The paper also presents the results of study into HID lamps in the United States and by European research through EUREKA "VEDELIS." It is concluded that: (1) the proposed light emission of the low beam for HID lamps is higher than the current ECE standard for virtually all measurement parameters, and (2) the orientation of the light-beam emission should pay greater attention to the position of vulnerable road users.

The IIT Research Institute conducted a research study to develop a state-of-the-art assessment of current technology to produce fluorescent pigments suitable for use in retroreflective traffic control devices. In the study, Kozak identified materials likely to produce stable, long-life devices and what specific problems must be addressed before any implementation is undertaken. He determined that two distinct classes of materials would satisfy the base criteria for traffic control devices and allow for their use with retroreflectors: organic dyes and lanthanide-doped glasses. Toxicity and carcinogenicity were examined for the selected materials. A model was produced to demonstrate how UVA-activated fluorescent traffic controls might appear to the eye.

SAFETY ISSUES OF UVA LIGHTING

Only recently have scientists begun to understand the full effects of ultraviolet light on living organisms. Human exposure to longer wavelength ultraviolet radiation is necessary for the production within the body of vitamin D, a substance that helps promote and maintain proper bone development. Ultraviolet radiation also causes the production of melanin in skin cells, resulting in a suntan. However, scientists have established a strong correlation between exposure to shorter wavelength ultraviolet radiation, genetic mutation in basal skin cells, and skin cancer. It is common today for sunbathers to apply special lotions that block or absorb the high-energy and harmful portions of ultraviolet light.

Fortunately, the shortest wavelengths of ultraviolet radiation are absorbed by gases such as ozone in the Earth's atmosphere. This ionizing radiation has the potential to cause serious tissue damage to many life forms. The effects of chemical pollution on the gases in the ozone layer are being closely monitored in an attempt to preserve these protective layers. The blocking effects of the atmosphere are crucial to the survival of many organisms.

In general, small objects can be seen most clearly when wavelengths of light as small as or smaller than the objects themselves are reflected from them. Since ultraviolet wavelengths are extremely small, objects not readily seen in visible light can be more easily and clearly detected.

The work summarized in the previous sections seems to indicate that ultraviolet lighting has an enormous potential to enhance nighttime driving visibility. The one issue that remains is the safety issue. How harmful is the exposure to ultraviolet radiation (UVR)?

Ultraviolet radiation can produce direct and indirect effects upon the human body. The direct effects are limited to the surface skin because the rays have low penetrating power. Direct effects include sunburn, suntan, and progressive adaptation to heavier doses. Ultraviolet burns can be mild, causing only redness and tenderness, or they can be so severe as to produce blisters, swelling, seepage of fluid, and sloughing of the outer skin. The blood capillaries, which are tiny blood vessels, in the skin dilate with groups of red and white blood cells to produce the red coloration. A suntan occurs when the pigments in cells in the deeper, tissue portion of the skin are activated by ultraviolet radiation, and the cells migrate to the surface of the skin. When these cells die, the pigmentation disappears. The degree of pigmentation is directly related to the length of ultraviolet exposure and the body's inherent ability to produce pigments. Tanning is a body's natural defense to help protect the skin from further injury.

Frequent overexposure to sunlight induces thickening of the skin, more rapid skin aging, and a much higher frequency of skin disorders, including cancer, particularly in persons with fair skin. There is an increase in skin temperature, skin respiration, and skin cholesterol after ultraviolet radiation. Similarly, there is a decrease in pain sensitivity, perspiration, and mineral levels in the body's tissues.

The indirect effects of ultraviolet radiation are, for the most part, caused when the damaged skin cells release histamine, causing swelling. The respiratory tract becomes more vulnerable to bronchitis and pneumonia, and calcified scar tissue may form in the lungs after overexposure to ultraviolet radiation. Histamine stimulates the stomach to produce more secretions and a stronger acid concentration than normal; this, in turn, can lead to inflammation of the stomach lining, or ulcers.

Furthermore, there is usually a fall in blood pressure, but an increase in the quantity of red blood cells, white blood cells, and clotting proteins. There may be loss of weight, an increase in appetite, and a reduction in the respiration rate. Despite all of these harmful effects, ultraviolet radiation is generally not lethal to the human body, but it can kill individual tissue cells and such organisms as bacteria.

Two main papers have studied the safety issue. One evaluated the risks from unintentional exposure to UVR, while the other analyzed the safety aspects of UVA headlamps.

Sliney's work applied to acute exposure to ultraviolet radiation. It should be indicated that the amount of radiation emitted by UVA headlamps is far from acute. Ultraviolet radiation is present in sunlight, so we are all exposed to it. The question then is "how much is safe?" He states that occupational exposure limits (ELs) do exist for acute exposure to ultraviolet radiation, but that they may not be sufficient to ensure total protection from the delayed effects of chronic, repeated exposure to ultraviolet radiation. Sliney states that the development of realistic guidelines for chronic exposure would present a challenge for many reasons. According to Sliney, safety standards for ultraviolet radiation emitted by lamps have not been developed, mainly because they have been used for generations with few serious injuries being reported.

He provides a good summary of ultraviolet lighting's known biological hazards (adverse effects) to the eye and skin, which have been considered in the development of ELs:

- Skin: Erythema (sunburn), accelerated aging of the skin, and photocarcinogenesis (skin cancer) are initiated by ultraviolet photochemical effects.
- Eye: Photokeratoconjunctivitis (acute inflammation of the cornea and conjunctiva as in "welder's flash") has been demonstrated for wavelengths from 200 nm to 400 nm and cataractogenesis

(lens cataract) has been demonstrated principally in the wavelength range from 290 nm to 320 nm, and perhaps occurs at greater wavelengths.

Sliney goes on to describe the concept of "threshold," which involves the development of exposure limits below which an adverse effect does not occur. He states that all the aforementioned biological effects, except for carcinogenesis, are acute effects and are also generally considered to have a threshold, although the threshold would vary depending on skin pigmentation and other factors. Finally, Sliney discusses the importance of the geometry of exposure.

Sliney and Fast documented the safety aspects of UVA headlamps using the prototype headlamps of the Swedish program. They stated that most individuals do not experience a strong visual stimulus from the UVA light, unless standing directly in front of the source, so they investigated whether direct exposure to ultraviolet radiant energy was potentially dangerous to the eye or skin, even at close range.

They mention that only one group, the American Conference of Governmental Hygienists (ACGIH), has recommended ELs for visible radiation (i.e., light). The ACGIH refers to its ELs as "Threshold Limit Values," or TLVs, and these are issued yearly, so there's an opportunity for revision. The current ACGIH TLVs to protect the cornea and skin (180 nm to 400 nm) and aphakic retina (310 nm to 760 nm) from UVR have been largely unchanged. The TLVs have an underlying assumption that outdoor environmental exposure to visible radiant energy are normally not hazardous to the eye except in very unusual environments, such as snow fields and deserts.

They state that, at the time of the study, there were no device-specific ultraviolet safety standards for ultraviolet lamps or illumination systems, except for sunlamps and tanning beds. They also provide equations to compute permissible exposure duration.

After studying the results of their testing, they recommended the following safety requirements to limit potentially hazardous exposure:

- Limit on emission duration when auto is stopped,
- Disable the UV light emission automatically if protective features (outer envelope of a sealed-beam lamp or filter in a projection system) are damaged,
- Filter out shortest wavelengths (below 330 nm), and
- Maximize retinal image size.

Sliney and Fast et al. concluded that risk to the eye or skin does not exist. Indeed, the UVR exposures from the UVA prototype headlamp were "virtually the same" as that experienced when exposed to a conventional white-light headlamp.

CONSPICUITY AND VISUAL SEARCH

It was the goal of the research to measure the increased detectability and recognizability of roadway markings and pedestrian conditions using the UVA headlamps. The task was determined to be somewhat an issue of conspicuity. Webster defines the term "conspicuous" as: (1) obvious to the sight or mind, manifest; (2) attracting attention, striking. There are a number of operational definitions of conspicuity. Engel views conspicuity as that combination of properties of a visible object in its background by which it attracts attention. Cole and Jenkins define a conspicuous object as one that will be seen with certainty for a given background within a short observation time (250 msec), regardless of the location of the object in relation to the line of sight. For this particular study, the concept of a short observation time was used to give an indication of the conspicuity of the roadway markings and pedestrian scenes.

The task of detecting pedestrians and roadway markings at night was observed to be more than just an issue of conspicuity. The task of detecting a right curve, for instance, requires inputs from a variety of locations, such as the center lines and edge lines both near and far, as opposed to a single point. The pedestrian scenes were also complex in nature and required a visual search to discern the stimulus. Therefore, it was decided that a search time of greater than 250 msec, as recommended by Cole and Jenkins, would be required. The task would then be somewhat of a tradeoff between conspicuity and visual search.

Some preliminary pilot work was done using 35-mm slides projected from a xenon source in a laboratory setting. Slides of pedestrian scenes similar to the ones used in the field experiment were presented to three subjects using various exposure times. An exposure time of 2 sec was found to produce data in a meaningful range. The exposure time was then used in the pilot testing for the field experiment. Analysis of the pilot data indicated that the data was not clustered at the farthest distance nor close to the stimulus. It was concluded, therefore, that the exposure time of 2 sec would be adequate.

A review of the literature was done to determine if a similar exposure time had been used in previous research. Zwahlen and Schnell conducted a detection and recognition task dealing with fluorescent targets at various peripheral angles. The subjects in the study were seated in a stationary vehicle, and the targets were displayed for 2 sec. Although the study was done during the daytime, the author agreed that the same should work for the nighttime static situation.

The Ford visibility model assumed that 2 sec of visual input was required in a driving situation. The sources of information for the model agreed that driver performance did not change appreciably when a preview time of more than about 2 sec is provided.

Zwahlen and Schnell collected spatial driver eye-scanning behavior and driving speeds along four rural two-lane road test sites under low-beam conditions at night. The study compared the eye-scanning behavior for two conditions, the first with low-visibility temporary pavement markings and the second with new fully restored markings. The 50-percentile preview time ranged from 0.8 sec to 1.2 sec for the first condition and 1.2 sec to 1.8 sec for the second condition.

The existing research showed that the 2 sec had worked in a previous study. The past research also showed that drivers generally use a preview time of about 2 sec when driving at night, which can be related to the shutter exposure time. Based on the pilot testing and the information from past research, a shutter timing of 2 sec was deemed adequate.

OTHER RELATED RESEARCH

Quality and durability are always important aspects in the development of automotive components. Consumer expectations and competitive pressures require reliable and rapid testing to determine end-use performance. One of the most important areas of test development is in exterior durability predictions for polymeric materials.

Fischer used Spearman's rank correlation coefficients to determine the ability of several accelerated testing devices to predict the weathering performance of flexible polymer films used in exterior automotive graphic design. Commonly used cycles in carbon arc and fluorescent ultraviolet-condensation test equipment exhibited generally unacceptable correlation levels for these materials. Three causes for this poor correlation were identified: (1) test device variability can be a significant problem and certain precautions have to be taken to ensure uniform environmental stress application to all test specimens; (2) similar predetermined exposure periods for all samples have proven to be misleading—there is an optimum exposure period for best correlation for each material and each cycle; and (3) for maximum correlation, the stresses induced by the accelerated testing device should be characteristic of the natural environment—the effect on correlation by varying these stresses (UV spectral distribution and condensation-cycle duration) can be significant.

Rokosz discussed two methods for extinguishing a lamp's arc tube when the outer envelope is broken. One method utilized a mechanical switch, and the other method utilized an oxidizable fuse. It was felt that the mechanical switch approach was the more reliable method because it extinguished the arc immediately when the bulb was removed. The design does not depend on the electrical characteristics of the arc tube or ballasts, has no effect on the lamp characteristics, and is probably the least expensive approach.

McNaught et al. evaluated beads under field conditions on longitudinal paint stripes applied by a standard state paint truck and crew. Types tested were the state's standard bead, uniformly graded flotation beads, state standard beads with flotation treatment, and polyester beads with and without anti-ultraviolet light treatment. All were applied at three different rates to both asphalt and portland cement concrete pavements. Performance was rated using a vehicle-mounted photocell device, subjective visual ratings, and close-up photography until substantial failure occurred after 3 months. The uniform gradation flotation beads were found to be brighter than the others tested, having about the same brightness at a 0.5-kg/L (4-lb/gal) application rate as the New York standard beads applied at 0.7 kg/L (6 lb/gal). All other types have less, but essentially similar, brightness. The application rate did not appear to influence brightness to the degree expected, but this was attributed to bead distribution problems caused by a poorly designed dispenser.

Arens et al. assessed the possible improvement in driver recognition of traffic sign colors to be achieved by changing from the Federal Highway Administration (FHWA) highway colors to the American National Standards Institute (ANSI) safety colors. Sign color appearance under daylight and various nighttime viewing conditions was investigated. Although some conditions increased correct color recognition when viewing the ANSI safety colors, these improvements were marginal and applied only to some of the signing material colors and types.

The legibility of retroreflective road markings and, in particular, of signs depends on many parameters, notably the luminance contrast between the message and the background of the sign. For a given level of illumination, the luminance contrast itself depends on the retroreflection coefficients (R') of the materials used. There are a number of retroreflective products that have different values of R'. Colomb et al. studied how variations in R' affect visibility distance (d) at night for a driver at the wheel of his vehicle, the headlights of which illuminate the sign. In the first stage, a small-scale experiment (approximately 1/10th scale) was conducted in the laboratory to identify the variables. Legibility thresholds were determined by presenting different combinations of the alphabets and colors used on road signs to observers at different luminance contrast levels. In the second stage, working from these results, simulations were carried out to quantify the influence of the various parameters, in particular R' and d. It was found that R' is only one of the parameters that affect d. Most often, multiplying R' by 3 increases d by only 30 percent. But the dimensions of the letters used for the messages play a preponderant and limiting role because of their direct relationship to visual acuity. According to earlier experiments, other parameters that are harder to quantify (incident illumination of the signs by vehicle headlamps; dirt on the headlamps, signs, and windscreens; and weather conditions) are important and may require a correction of d ranging from 0 to 100 percent.

SUMMARY

The majority of the studies and research described above indicate that UVA headlamps can considerably increase detection distances, particularly those to pedestrians, compared with the use of only ordinary low beams. Even with clothes of relatively low fluorescent efficiency, the detection distance may increase from 50 m (164 ft) to approximately 100 m (328 ft) in the presence of glare from oncoming cars, as demonstrated by Fast et al.

Those findings lead to the conclusion that the use of UVA headlamps in automobiles may significantly increase highway safety by increasing detection distances, even in the presence of glare from oncoming cars.

Field Study

INTRODUCTION

The field evaluation of ultraviolet (UVA) headlamps and fluorescent traffic control devices (TCDs) involved eight experimental procedures designed to determine the effectiveness of UVA technology. The procedures were conducted on a closed series of roadways and involved objective and subjective methods. The visibility of roadway delineation and staged roadway scenes depicting pedestrians, bicycles, and disabled vehicles was compared using standard U.S. headlights, European specification (ECE) headlights, and UVA headlights. This section will describe the experimental methodology in detail. The following topics will be addressed:

EXPERIMENTAL TEST SITES

The various procedures were conducted at one of two sites located on the grounds of the Federal Bureau of Investigation (FBI) Training Academy driver training facility in Quantico, Virginia. New pavement-marking thermoplastic with UVA-activated fluorescent pigment and glass beads provided by Cleanosol were installed at both sites in November 1996. Testing began in May 1997 when the markings were about 6 months old. The layout of the roadways at both sites is shown in Figure 1.

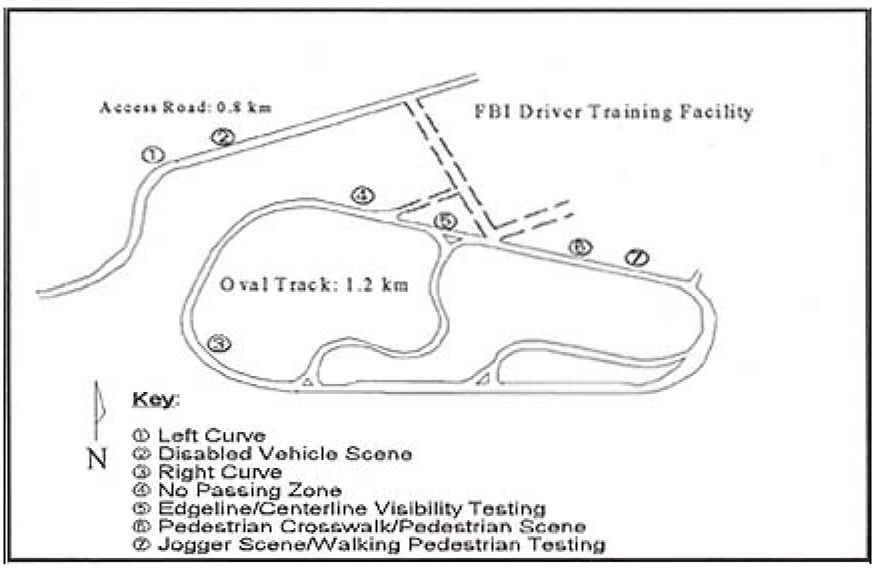

Figure 1. Test track layout.

The test track location consisted of a 1.6-km (1.1-mi) oval test track that was primarily a two-lane roadway. The pavement markings included white solid edge lines and double solid yellow center lines. The track widened to four lanes on the southern side of the course. There was no overhead lighting. On the northern side of the course and within the primary test track, there was a straight and level segment of roadway that was striped as a passing zone with a yellow dashed center line. A standard parallel pedestrian crosswalk was installed on the straight and level segment.

Fluorescent post-mounted delineators were installed on both sides of the curve on the northwest corner of the track. They were positioned 2.4 m (8 ft) from the paved roadway. The posts were made of heavyduty plastic and appear yellow in daylight and fluorescent green under UVA light. The other three curves on the course did not have post-mounted delineators.

Near the middle of the test track a narrow reverse curve segment of roadway connected the north and south sides of the test track. Only white UVA-activated fluorescent edge line markings were installed on the reverse curve. Another connecting road with a blind curve was near the southeast corner of the track. This segment of roadway was also striped with white UVA-activated fluorescent paint edge lines.

The access road, located about 0.8 km (0.5 mi) from the test track, was 1.3 km (0.8 mi) in length and ended at a closed gate. White UVA-activated fluorescent edge lines and double solid yellow UVA-activated fluorescent center lines were installed. The access road had two unsigned curves and one sharp curve signed with an advisory curve turn arrow and marked for 32.3 km/h (20 mi/h). Guardrails were installed at a location near one of the unsigned curves. Guardrails with one amber reflector marker attached on each end were located near one of the unsigned curves. An unpaved gravel shoulder lined both sides of the roadway. There was no overhead lighting.

Six fluorescent post-mounted delineators were installed near the right lane on the outside of the left curve. They were positioned 1.2 m (4 ft) from the paved roadway. The advisory curve turn sign, previously installed in advance of the left curve, was covered with a black painted plywood cover during the Left Curve Delineation Visibility Study and the Disabled Vehicle Visibility Study and left uncovered during the DASCAR Drive Study.

TESTING EQUIPMENT

The testing equipment included two specially equipped research vehicles. Both vehicles were fitted with UVA headlight units from Ultralux, a windshield shutter, and a lane aligner. A third vehicle, also equipped with a lane aligner, was used to simulate the headlight glare from an oncoming vehicle.

Vehicles

One of the vehicles used was a 1994 Ford Taurus station wagon. The Taurus was equipped with the DASCAR (Data Acquisition System for Crash Avoidance Research) instrumentation package developed by the National Highway Traffic Safety Administration (NHTSA). DASCAR can record up to 33 experimental parameters. Driver inputs such as steering, braking and accelerator, and GPS (Global Positioning System) inputs are recorded at a rate of 30 data points per second by a hard drive located in the rear of the vehicle. In addition, four video cameras are available to record two views of the driver as well as front and rear view out of the vehicles. Because all of the testing was done at night and because both test sites had no overhead lighting, the video cameras were not used. Although DASCAR has the capability of recording 33 different parameters, not all of these were relevant to a study of headlight effectiveness. It was hypothesized that improved vehicle lighting might produce changes in driver lane tracking and speed selection. For this reason, the following parameters were used: vehicle speed, braking applications, steering inputs (amplitude and direction), and vehicle lateral placement in the traffic lane.

The Taurus was also equipped with a custom steel rack fabricated by Kropp Tool Co., Berlin, Pennsylvania, to support the headlight units. A total of seven headlight units were installed on this rack:

- 3 Ultralux UVA headlights,
- 2 U.S. specification headlights (H6054 sealed beams), and
- 2 European specification headlights (ECE with H-4 elements).

As shown in Figure 2, the UVA units were installed in a triangular configuration; two were just above the bumper in the center of the vehicle and the third was just above the lower two. The U.S. and ECE headlights were also installed just above the bumper along side the UVA units, in the same horizontal and vertical plane as the Taurus headlights. Since the test headlights were installed directly in front of the standard Taurus headlights, the standard Taurus headlights were not used. The U.S., ECE, and UVA headlights were controlled by switches mounted on the dash.

Figure 2. UVA headlight configuration on the Taurus test vehicle.

The Taurus was used for the driver performance testing and two of the static tests and the subjective ratings.

The second experimental vehicle was a 1993 Volvo 960. The Volvo also had three Ultralux UVA headlight units. These units were mounted on a steel framework in front of the grille and on top of the bumper. The configuration of the UVA lamps on the Volvo test vehicle is shown in Figure 3. This test vehicle is the same vehicle used in a previous FHWA study (Mahach, Knoblauch, Simmons, Nitzburg, Arens, and Tignor, 1997), and was leased from Volvo of America. The Volvo had Society of Automotive Engineers (SAE) specification composite headlight units with standard H-4 Halogen elements that were used for the standard U.S. low-beam testing condition. Like the Taurus, the Volvo was equipped with switches so that the UVA units could be activated from the cabin, independently of the regular headlights.

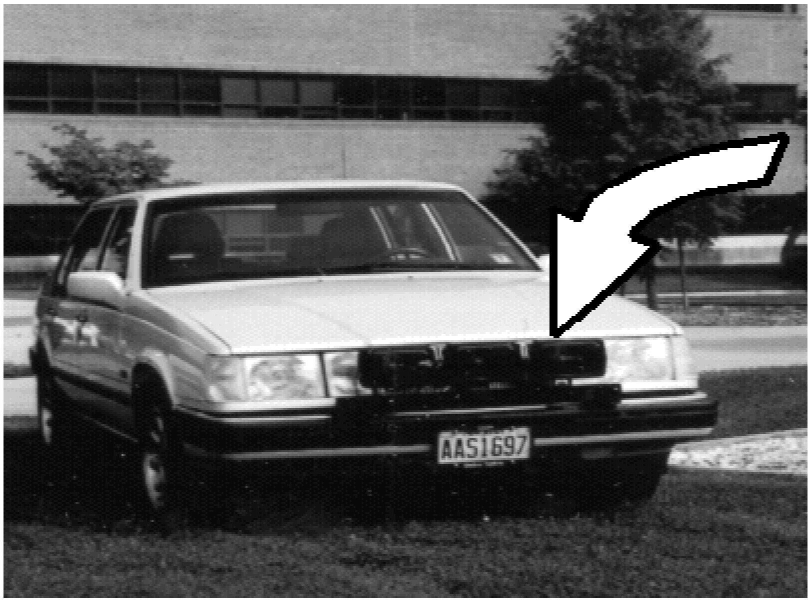

Figure 3. UVA headlight configuration on the Volvo test vehicle.

The Volvo was used for six of the static tests and the subjective rating procedure.

For all testing, the UVA headlight units were used as a supplement to either the U.S. or the European specification headlight. No testing was done with the UVA units alone. Throughout this report, "UVA" headlights will refer to the lighting conditions provided by two U.S. specification headlight sealed beams (H6054) and the three Ultralux supplemental UVA headlight units. In those testing situations where the UVA headlights were combined with the European specification headlights, the headlight condition will be described as Euro/UVA.

Two of the experimental procedures involved simulating glare from an oncoming vehicle. A 1990 Ford Tempo with standard composite U.S. headlights and H-4 elements was used for these procedures.

Windshield Shutter

The purpose of some of the field testing was to determine the effect of UVA headlights on the conspicuity of various visual stimuli at different distances. To do this, it is appropriate to limit the time available for visual search (Cole & Jenkins, 1980). This was done by using a windshield shutter to limit the exposure time of the subjects to the roadway scenes at each of the test distances. The shutter was a 304.8-mm by 533.4-mm (12-in by 21-in) flat panel that was lifted from the windshield surface by a rotational solenoid connected to a 12V power source. The shutter assembly was mounted on the outside of the passenger-side windshield with rubber suction cups. Photographs of the windshield shutter (closed position and open position) installed on the Taurus Test vehicle are shown in Figure 4. The shutter was positioned so that each subject could see a distance of 30 m (98.4 ft) in front of the vehicle when the shutter was closed. This 30-m (98.4-ft) distance allowed the subjects to retain their adaption to pavement luminance and reduced the amount of refocusing needed to detect the experimental stimuli. The experimenter controlled the shutter from the driver's seat by pushing a button that activated an adjustable timer controlling the amount of time the shutter was open. Based on previous human factors research and initial pilot testing, it was determined that a 2-sec stimulus exposure time was appropriate. The windshield shutter was used for six of the experiments.

Lane Aligner

In order to properly conduct the experiments, it was essential that the orientation of the test vehicles be the same in each trial. Having the vehicles' headlights pointing either to the left or to the right could seriously affect the conspicuity of the stimuli. In order to ensure an identical lane position from trial to trial, each vehicle was equipped with a lane aligner. The lane aligner was a custom-fabricated telescoping outrigger that was installed under the left side of both the front and rear of each vehicle. At the start of each testing session, the outriggers would be extended a predetermined distance from the side of each vehicle.

A small downward-facing light at the end of each outrigger could be activated by the experimenter. By positioning these lights directly over the center line of the roadway, the experimenter could consistently position the experimental vehicle within the travel lane in each trial.

Figure. Down or Closed Position

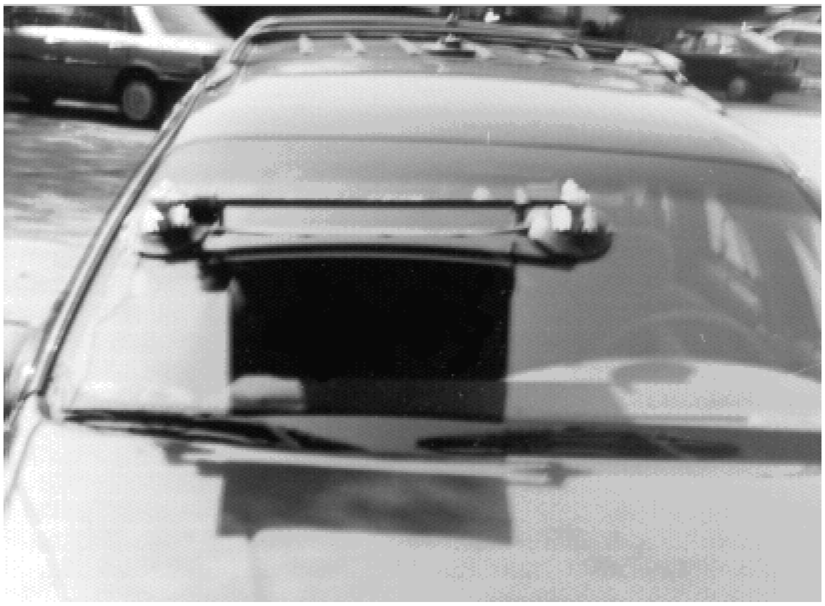

Figure 4. Windshield shutter installed on the Taurus test vehicle (Up or Open Position).

TEST SUBJECTS

Subjects were recruited from the northern and central Virginia regions through classified ads in local papers. Several prescreening meetings were held at local hotels and community centers. Each potential subject was given a test for visual acuity and color vision. A questionnaire was administered that included a self-assessment of driving abilities, day and night driving frequency, questions about headlight glare, and a general biographical inventory. After presenting a valid U.S. driver's license, subjects read the informed consent form and were scheduled for participation.

A total of 38 subjects ranging in age from 18 to 76 were tested. The mean age was 40.5 years. Ten of the subjects were age 55 years or older. A discussion of age effects is included in a later section. There were 16 males and 22 females. Two subjects were tested each evening, starting when it became dark. Testing typically started between 9:00 p.m. and 9:30 p.m. and concluded between 11:30 p.m. and midnight. Because access to the test facility was limited to two evenings per week, only four subjects per week could be tested. The field effort began in May 1997 and concluded in August 1997.

RESEARCH PERSONNEL

Two research teams, consisting of two individuals each, conducted all nine of the experiments. Each team was responsible for all of the experiments that were conducted at one of the two sites. The team that used the Volvo conducted five of the experiments, and the team that used DASCAR conducted four of the experiments.

Each experimenter had their own responsibilities that remained constant from night to night. Certain experimenters worked directly with the subjects and others recorded data, controlled the headlight glare vehicle, set the roadway scenes, and served as the staged walking pedestrian.

The experiments were designed so that each team tested one of two subjects for 75 minutes. After a 15-minute break, the subjects switched locations (and teams) and some of the same experiments were repeated. Half of all the subjects took part in the Dynamic Pedestrian Visibility Study and half took part in the Disabled Vehicle Visibility study. This schedule was necessary because some of the experiments were more time-consuming than others.

TESTING PROCEDURES

Nine distinct research procedures were designed to assess the effectiveness of UVA lighting and fluorescent traffic control devices. The procedures determined detection distances, recognition distances, and subjective ratings, as well as driver performance measures. Each of the following research procedures will be described:

Roadway Delineation Visibility Study

The roadway delineation visibility tests were conducted with the subject in the right front passenger seat of the Volvo. During pilot testing, the point where each target stimuli could not be seen using any of the test headlights was determined. This location served as the first station for each of the testing scenarios. Starting at the first station, the experimenter moved progressively closer to the stimulus, stopping at stations every 30.5 m (100 ft). The subjects were told that they were looking for a specific stimulus—either the end of a no-passing zone, a right curve, or a crosswalk. At each station, the subject was asked to indicate whether he or she "can't" see the stimulus, "thinks" he or she sees the stimulus, or is "absolutely sure" that he or she sees the stimulus. The windshield shutter was used to limit the subject's visual exposure to the stimulus to 2 sec. Headlight conditions tested were U.S. and UVA. Three pavement marking conditions on the oval test track were used as stimuli. A no-passing zone was located at the end of the long tangent section on the north side of the track. The first station was 274.5 m (900 ft) from the start of the double yellow lines. The right curve was located on the southwest corner of the track. The first station was 335.5 m (1,100 ft) from the start of the curve. The crosswalk was located on the tangent section on the north side of the track. The first station was 274.5 m (900 ft) from the crosswalk. The order of presentation of the headlight condition was counterbalanced. A second observer in the backseat recorded the subject's responses on a data collection form.

Static Pedestrian Visibility Studies (Two Scenes)

These static tests used a procedure similar to the Roadway Delineation Visibility Study. Subjects, starting beyond the point where the stimuli were visible, were moved progressively closer in 30.5-m (100-ft) intervals. When the windshield shutter was raised, they were instructed to indicate what they thought they could see and, when they were more certain, what they were sure they could see. Their responses were tape recorded. The tapes were transcribed and coded. Coding criteria were developed so that responses could be categorized as "I think I see..." and "I'm sure I see..." for each of the target stimuli. The subjects were given no indication as to the type of stimuli being presented.

Distances at which subjects indicated that they thought they saw something were tabulated as the detection distances. Distances at which subjects indicated they were sure they saw a specific stimuli were tabulated as recognition distances.

Two different roadway scenes were set up on the tangent section of the oval track. The layout of the two scenes is shown in Figure 5. Life-size silhouettes of pedestrians were cut out of 6-mm-thick (¼-in-thick) plywood. The pedestrian dummies were clothed in garments that had been washed once in a commonly used laundry detergent. The pedestrian dummies were used to create two different roadway scenes. The first scene consisted of a small child in a lavender skirt and a 51-cm (20-in) child's bicycle (painted with fluorescent yellowish-green spray paint) in the left lane. A second adult-size pedestrian cutout wearing khaki pants and a medium- to light-colored polyester shirt was located on the right edge line. Both cutouts were in the crosswalk. The second scene had a pedestrian cutout, with a light-grey cotton shirt and shorts, in the right lane approximately 20 m (65.6 ft) beyond the crosswalk. The pedestrian cutout appeared to be jogging across the roadway. The order of presentation of the two headlight conditions were counterbalanced.

Left-Curve Delineation Visibility Study (With and Without Oncoming Headlight Glare)

This study was a static test of the visibility distance of a left curve in the roadway. Like some of the previous tests, the vehicle, with the subject in the right front passenger seat, moved progressively closer to the stimuli in 30.4-m (100-ft) intervals until it was positively identified. The Taurus, with the windshield shutter in position, served as the test vehicle. The Tempo, driven by the second experimenter, was positioned in the opposing lane 60.8 m (200 ft) in front of the test vehicle with the headlights (low beams) turned on to simulate oncoming headlight glare. Two orders of presentation of headlight condition (U.S. or UVA) were used, first without oncoming headlight glare and then with oncoming headlight glare. Unlike some of the previous tests, the subjects were told that they were looking for a left curve in the road ahead. Hence, no detection distance measures were taken and only a recognition distance measure is reported in the results section. They were simply asked if they could see the left curve ahead when the windshield shutter was raised. Their responses were tape recorded.

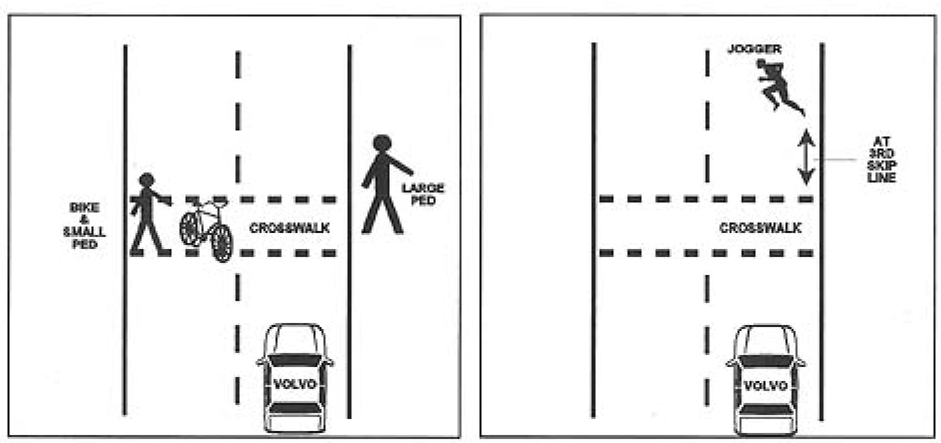

Figure. Pedestrian Visibility Study.

PEDESTRIAN/BIKE SCENE JOGGER SCENE

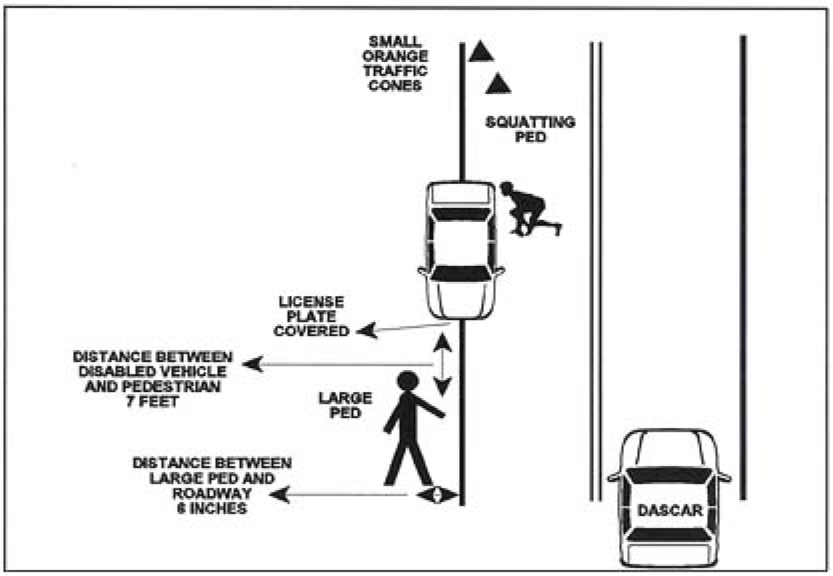

Figure 5. Stimulus configurations: static pedestrian visibility studies and disabled vehicle visibility study (DISABLED VEHICLE SCENE).

Dynamic Pedestrian Visibility Study

This study used a procedure similar to that used for the Static Pedestrian Visibility Studies; however, the stimuli and the subject response codes were different. Because a moving pedestrian (especially with the UVA headlights on) is very easy to recognize, it was decided to create a more challenging visual task—one involving headlight glare from a stationary oncoming vehicle. The 1990 Ford Tempo was positioned in the approaching (left) travel lane with the low-beam headlights on. On cue from the experimenter in the Volvo, a second experimenter (wearing light upper clothing and jeans) began walking across the right lane 10 m (30 ft) to the rear of the Tempo and directly in front of the subjects in the test vehicle. The windshield shutter was raised and the subject indicated whether or not he saw a pedestrian. The subjects were instructed to respond in one of three ways:

- Did not see a pedestrian,
- Thought I saw a pedestrian, or
- Absolutely sure I saw a pedestrian.
-

There were two trials at each station; one where there was a pedestrian and one where there was no pedestrian. The order of presentation of the stimulus (pedestrian or no pedestrian) was counterbalanced. All subjects were first tested with the U.S. headlights, followed by the UVA headlights.

Disabled Vehicle Visibility Study

This study was a static test of the visibility of a disabled vehicle scene. The test subject was in the right front passenger seat of the Taurus with the windshield shutter in position. A disabled vehicle roadway scene was created using a parked vehicle (1995 blue Toyota Celica, with the reflective license plate covered) on the shoulder of the opposing lane. The layout of the disabled vehicle scene is shown in Figure 5. A plywood cutout of a kneeling pedestrian, wearing pants and a white long-sleeved shirt, was located near the vehicle's left rear tire. A second plywood cutout of an adult pedestrian, wearing dark navy-colored pants and a medium dark blue shirt, was located 2.1 m (7 ft) in front of the disabled vehicle and 152 mm (6 in) to the outside of the left edge line. In addition, two orange fluorescent traffic cones, measuring 0.6 m (2 ft) in height, were located near the kneeling pedestrian and the left rear tire. The subjects were asked to indicate what they could see when the windshield shutter was raised. Their responses were tape recorded. The tapes were transcribed and coded. Responses were categorized to identify detection ("I can see something") and recognition ("I can see a car and people") distances.

Loop Ride Study - Subjective Ratings

The loop ride was a dynamic test with the subject riding in the right front passenger seat of the Volvo. Site 1, the 1.6-km (1.1-mi) oval test track, was used. The procedure began with one experimenter reading the script that instructs the subjects to observe the roadway markings and headlights and provide subjective comparisons with what they generally see when driving at night. The subjects were first given an acclimation loop, always with the U.S. headlights. They were then driven on two additional loops with the U.S. headlights and the UVA headlights. Two different orders of presentation were used: U.S./UVA and UVA/U.S. After the second and third loops, the subjects were also asked to provide subjective comparisons with the headlights used in the previous loop. A second researcher, riding in the back seat, recorded the subjects' responses.

DASCAR Drive Study - Driver Performance and Subjective Ratings

During the DASCAR Drive Study, the subjects drove the Taurus with the DASCAR instrumentation package on five round trips of the access road (Site 2). The access road consisted of two straight tangent sections, two right curves, and two left curves. After a short period of time in order to become acclimated to the vehicle and to adjust the seat, controls, mirrors, etc., the subjects were given a brief description of the course. They were told that there would be an oncoming car driven by a research team member. They were told that the road was closed to all other traffic. They were told that after each run, they would be asked two questions about the headlights and the roadway markings. They were told to drive at a safe and comfortable speed, but not to exceed 48 km/h (30 mi/h). They were *not* told that the vehicle was fully instrumented and would be recording their driving behavior. Each subject made five round trips or loops. The first loop was described as a practice run and all subjects made the loop using U.S. low-beam headlights. Four additional loops were made using four different headlight conditions: Euro low beams; Euro low beams with UVA; U.S. low beams; and U.S. low beams with UVA. The stationary Ford Tempo with low-beam headlights was positioned using the lane aligner in the oncoming lane, on the tangent section in the middle of the loop. The Tempo was kept out of sight and moved into position just prior to the subject's return drive through the tangent section. At the end of each loop, the subject was told to stop the vehicle and was asked the following:

1. How well did the headlights and roadway markings work for you compared to what you generally see when you drive your car? Response choices were: (a) not as good as; (b) as good as; or (c) better than.
2. And, on the second and subsequent loops:
3. Compared to the last ride down to the gate and back, how well did these headlights and roadway markings work for helping you see where to steer the car? Response choices were: (a) not as good as; (b) as good as; or (c) better than.

Static Testing - Visibility Distances and Subjective Ratings

This procedure was a replication of tests conducted on the Clara Barton Parkway (near Washington, DC) in 1996 that was described in Mahach, Knoblauch, Simmons, Nitzburg, Arens, and Tignor (1997).

The Clara Barton procedure was a static test with the subject sitting in the right front passenger seat. No windshield shutter was used. The experimenter parked the Volvo, using the lane aligner, at a fixed point on the straight two-lane section of Site 1. Traffic cones with reflective collars were set up at 50-m (150-ft) intervals, 3 m (9 ft) to the right of the right edge line. The first part of the testing always used the U.S. headlights. The subjects were asked:

1. How many centerline skip marks (dashed lines) they could count.
2. How far they could see the right edge line (using the traffic cones as a point of reference).
3. To rate (on a five-point scale) the overall visibility of the roadway markings.

The UVA headlights were then turned on and the subject was asked the same three questions. The experimenter recorded the subjects responses on a data form using a low-intensity penlight for illumination.

RESULTS

As previously described, the field study used a variety of experimental procedures to quantify the effectiveness of UVA/fluorescent technology. The results of the field study will be presented in this section. The discussion will be organized according to the measure of effectiveness (MOE) that was quantified. The following will be discussed:

Detection and Recognition Distance

Detection and recognition distances were measured using static testing scenarios in which the subject was moved progressively closer to the stimuli and a windshield shutter was used to limit exposure time. The results are being presented according to the nature of the stimuli. Three categories of stimuli will be discussed:

Roadway Delineation

Detection distance measuring procedures were developed for three different types of roadway delineation: right curve, start of a no-passing zone, and a pedestrian crosswalk. In these procedures, detection distance was defined as the point where the subjects indicated that they thought they could see the specific target ahead, but could not positively identify it as such (e.g., "I think I can see the crosswalk").

The results of the detection distance measuring procedures for the roadway delineation scenes are shown in Figure 6.

The UVA headlights outperformed the U.S. headlights for all roadway delineation scenarios. The percentage of improvement ranged from 53.6 percent for the pedestrian crosswalk to 32.3 percent for the no-passing zone to 6.1 percent for the right turn. While the differences for both the crosswalk and the no-passing zone were highly significant (0.000), the results for the right curve were not quite significant (0.074). The right-curve scene was on a slight downhill section that resulted in very long—more than

213.5 m (700 ft)—detection distances for both the UVA and the U.S. headlights and the UVA headlights appeared to offer somewhat less of an advantage in that situation.

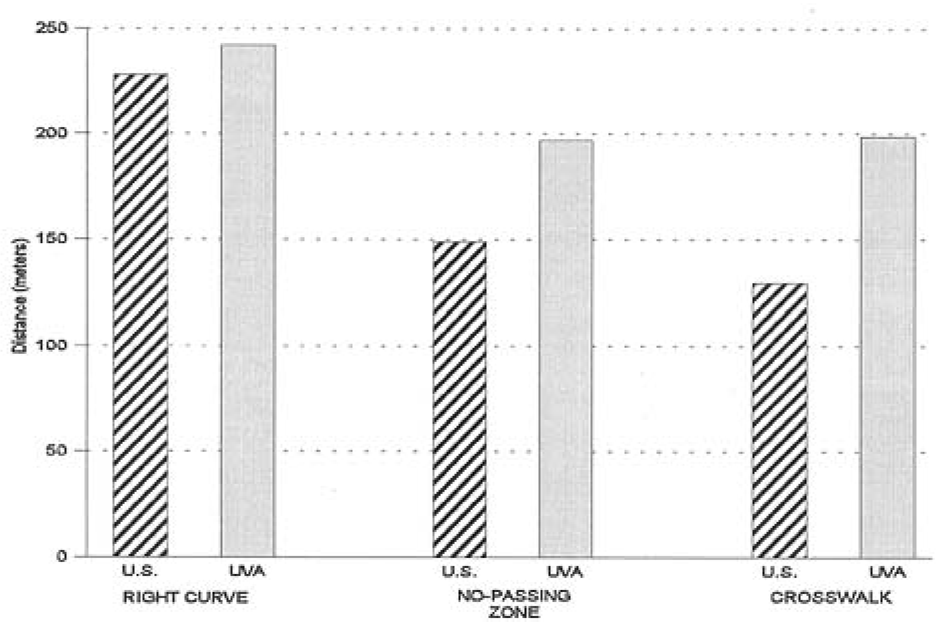

Figure 6. Roadway Delineation - Detection Distances Graph.

Table. Roadway delineation — detection distances.

	Right Curve		No-Passing Zone		Crosswalk	
	U.S.	**UVA**	**U.S.**	**UVA**	**U.S.**	**UVA**
Mean	228.3	242.2	148.8	196.9	129.4	198.7
No.	33	33	33	33	33	33
Std. Dev.	57.1	36.5	49.3	45.2	38.9	41.1
t	-1.844		-4.881		-9.193	
Signif.	0.074		0.000		0.000	

In these procedures, recognition distances were defined as the point where the subjects were "absolutely sure" that they could see the target stimulus. The results of these recognition distance measurements are shown in Figure 7. The percentage of improvement was computed by dividing the increase in recognition distance associated with the UVA headlights by the recognition distance associated with the U.S. headlights. The percentage of improvement in recognition distances with UVA headlights are as follows:

Delineation	***Percent Improvement***
No-Passing Zone	48.4%
Crosswalk	48.4%
Left Curve, With Glare	40.0%

Left Curve, No Glare	21.4%
Right Curve	13.9%

All of these differences were significant at the 0.001 level or better. It should be noted that the left-curve scene was not included in the previous discussion of detection distances because the experimental protocol limited the subjects to a simple "yes" or "no" response. They were not instructed to indicate when they "thought" they saw the stimulus as was the case with the procedure used for the no-passing zone, the crosswalk, and the right turn. It should be noted that in the left-curve visibility test, the UVA headlights were more effective when glare from an oncoming vehicle was present (40.0 percent) than when no such glare was present (21.4 percent).

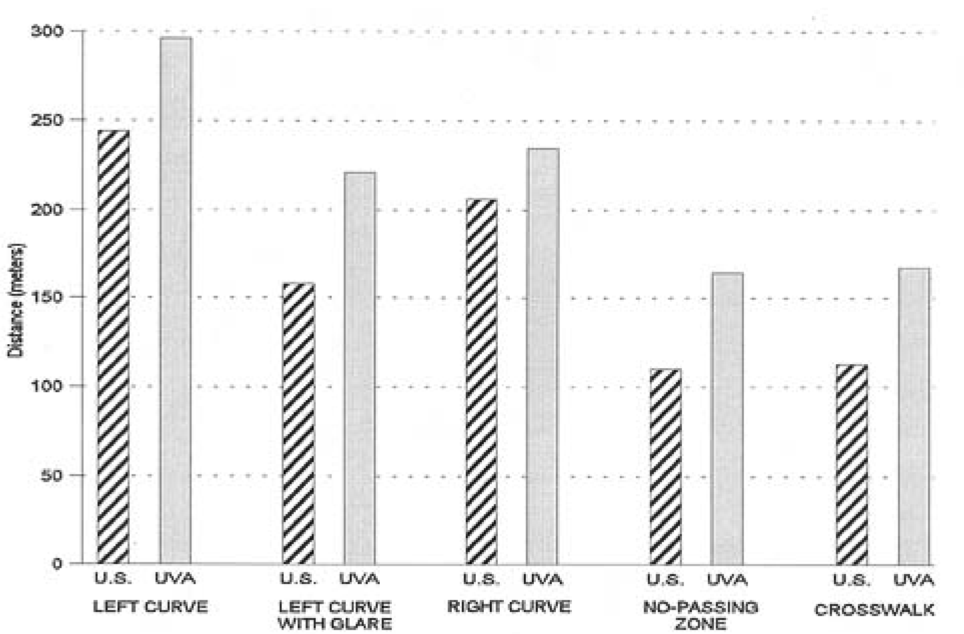

Figure 7. Roadway delineation — recognition distances.

Table. Roadway delineation — recognition distances.

	Left Curve		Left Curve With Glare		Right Curve		No-Passing Zone		Crosswalk	
	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA
Mean	244.0	296.3	157.9	221.1	206.1	234.8	110.0	164.5	112.8	167.3
No.	28	28	28	28	33	33	33	33	33	33
Std. Dev.	65.9	41.4	124.0	74.5	55.0	33.7	29.0	44.0	34.5	39.7
t	-5.645		-3.533		-3.881		7.408		-8.807	
Signif.	0.000		0.001		0.000		0.000		0.000	

Roadway Scenes

Detection distances were determined for the following roadway scenes: a disabled vehicle, a fluorescent bicycle, and fluorescent traffic cones. The results of the detection distance measurements ("I think I see a ___") are shown in Figure 8. Visibility improvements with the UVA lighting are very impressive. The percentage of improvements for the three scenes are:

Scene	***Percent Improvement***
Disabled Vehicle	27.1%
Bicycle	283.6%
Traffic Cones	372.7%

Although these improvements are very dramatic, it should be noted that both the bicycle and the traffic cones did not have a retroreflective component. The differences between U.S. and UVA headlights were significant for both the bicycle and the traffic cones, but not for the disabled vehicle. This is possibly because of the intrinsic differences between the test scenes. Both the bicycle (part of one of the pedestrian scenes with the child pedestrian) and the traffic cones (part of the disabled vehicle scene) were fluorescent and, therefore, detectable at relatively long distances with the UVA headlights. Except for the fluorescent traffic cones, the disabled vehicle scene was created to be a worse-case scenario. The disabled vehicle was dark colored with no fluorescent or retroreflective component. The tall standing pedestrian cutout had very dark clothing, making it difficult to see. Only the squatting pedestrian had a light-colored shirt that provided some visual cues to the subject relative to shape and positioning. In addition, given that the visual exposure was limited by the windshield shutter, the subject may not have had enough time to focus on both the fluorescent traffic cones and the disabled scene components. The detection distance differences demonstrate that UVA/fluorescent technology does not work as well in some situations as it does in others.

Pedestrian Scenes

Recognition distances were determined for the same three roadway scenes as well as the dynamic walking pedestrian scenario. Since the protocol restricted subjects to "pedestrian" or "no pedestrian" responses, only recognition distance measurements were reported for the walking pedestrian scenario.

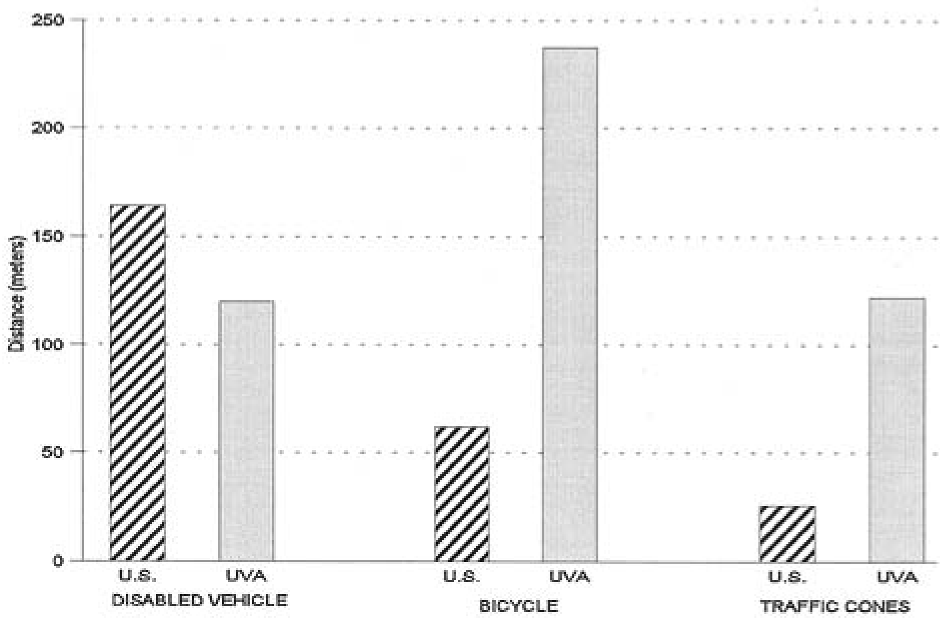

Figure 8. Roadway Scenes - Detection Distances Graph.

Table. Roadway scenes — detection distances.

	Disabled Vehicle		Bicycle		Traffic Cones	
	U.S.	**UVA**	**U.S.**	**UVA**	**U.S.**	**UVA**
Mean	164.2	120.0	62.0	237.9	25.8	122.0
No.	13	13	30	30	13	13
Std. Dev.	77.3	70.9	42.0	37.9	58.2	68.3
t	1.536		-18.857		-4.306	
Signif.	0.150		0.000		0.001	

Improvements in recognition distances were very dramatic in three of the four scenarios (Figure 9). The walking pedestrian was visible at 152.5 m (500.00 ft) with the UVA headlights and only at 610 m (200.00 ft) with the U.S. headlights—a 150-percent increase. The fluorescent bicycle was recognizable at 123.02 m (403.33 ft) with the UVA headlights and at 38.63 m (126.67 ft) with U.S. headlights—a 218.4-percent improvement. The fluorescent traffic cones were recognizable at 91.50 m (300.00 ft) with UVA headlights and at 11.73 m (38.46 ft) with U.S. headlights—a very dramatic 679.7-percent improvement. All three of these differences were very significant (0.000 level). Although the more visually complex disabled vehicle scene was recognized 32.84 m (107.69 ft) sooner with the U.S. headlights compared to the UVA headlights, this 29.8-percent increase was not statistically significant. Photographs of the disabled vehicle scene illuminated by regular low beams and by regular low beams and UVA headlights are shown in Figure 10.

Detection and recognition distances were determined for five different pedestrian cutouts. As shown in Figure 11, improvement in detection distances with the UVA headlights ranged from 20.33 m to 139.88 m (66.66 ft to 458.62 ft). The percentage of improvement varied from 33.64 percent to 117.18 percent. Four of the five differences were significant at the 0.004 level or better. Figure 12 depicts the recognition distances for the pedestrian scenes. Again, four of the five pedestrian cutouts were seen for significantly greater distances with the UVA headlights. These distances were for 15.25 m (50.00 ft) to 58.89 m (193.08 ft) more and represent a 37.50-percent to 67.87-percent improvement. Photographs of one of the pedestrian scenes illuminated by regular low beams and UVA headlights are shown in Figure 13.

The fluorescent painted bicycle was so highly visible with the UVA headlights that the subjects may have been distracted by its presence long after they positively identified it as a bicycle. The high visibility of the bicycle in the scene may have distracted from the other objects in the scene—specifically, the child pedestrian that was located nearby. This would explain the relatively short detection and recognition distances reported for the child pedestrian.

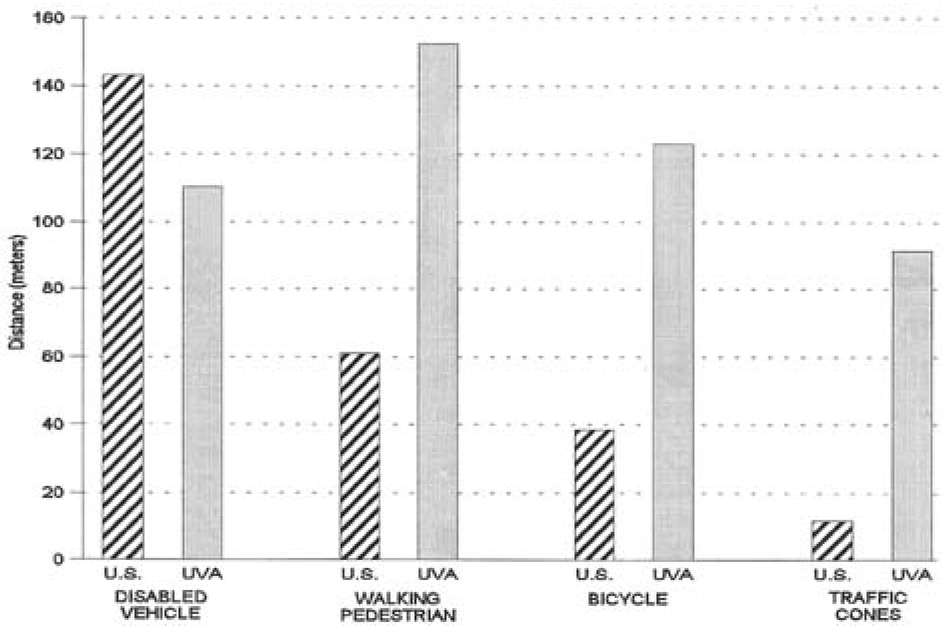

Figure 9. Roadway Scenes - Recognition Distances Graph.

Table. Roadway scenes — recognition distances.

	Disabled Vehicle		Walking Pedestrian		Bicycle		Traffic Cones	
	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA
Mean	143.1	110.3	61.0	152.5	38.6	123.0	11.7	91.5
No.	13	13	15	15	30	30	13	13
Std. Dev.	71.9	65.3	23.1	36.5	15.9	42.0	15.5	57.1
t	1.244		-7.685		-9.942		-5.226	
Signif.	0.237		0.000		0.000		0.000	

Standard U.S. Low Beams

Standard U.S. Low Beams With UVA

Figure 10. Disabled vehicle scene shown with standard U.S. low beams (above) and standard U.S. low beams with UVA (below).

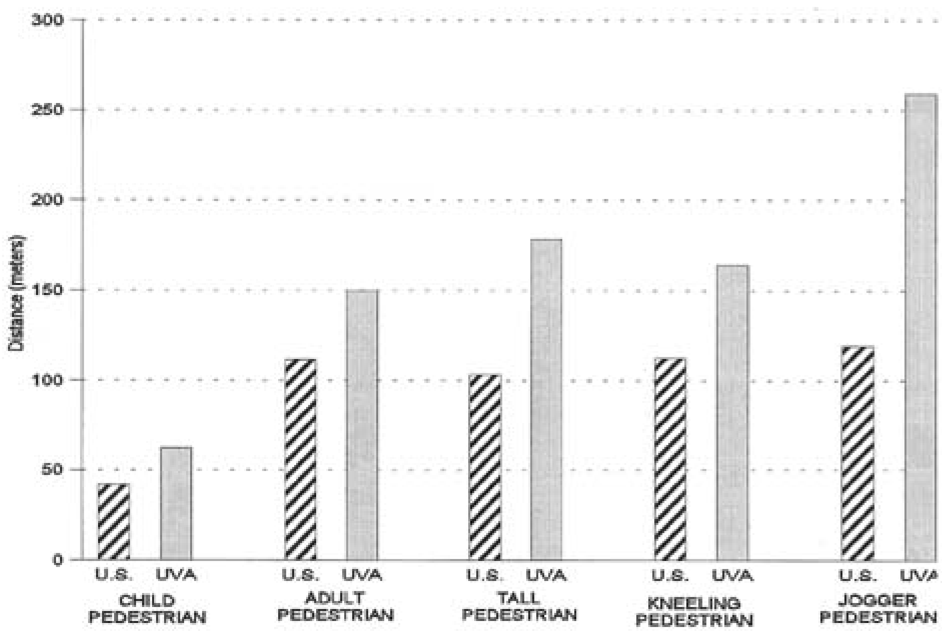

Figure 11. Pedestrian Scenes - Detection Distances Graph.

Table. Pedestrian scenes — detection distances.

	Child Pedestrian		Adult Pedestrian		Tall Pedestrian		Kneeling Pedestrian		Jogger Pedestrian	
	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA
Mean	41.7	62.0	111.8	149.5	103.2	178.3	112.6	164.2	119.4	259.3
No.	30	30	30	30	13	13	13	13	29	29
Std. Dev.	17.0	31.5	41.9	51.5	52.1	58.2	51.9	73.2	39.5	39.1
t	-3.162		-3.479		-4.064		-1.821		-19.474	
Signif.	0.004		0.002		0.002		0.094		0.000	

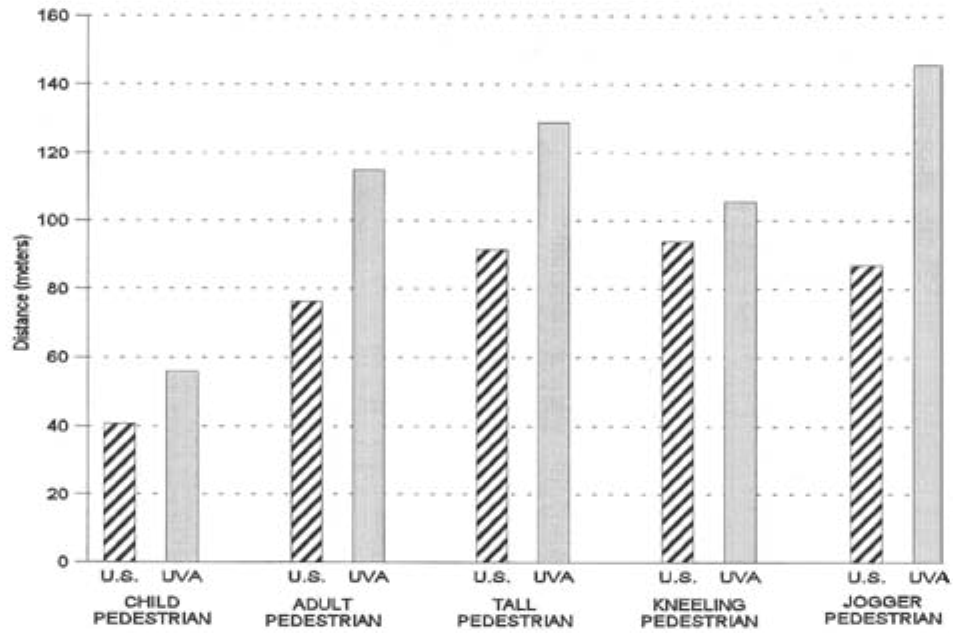

Figure 12. Pedestrian Scenes - Recognition Distances Graph.

Table. Pedestrian scenes — recognition distances.

	Child Pedestrian		Adult Pedestrian		Tall Pedestrian		Kneeling Pedestrian		Jogger Pedestrian	
	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA	U.S.	UVA
Mean	40.7	55.9	76.3	114.9	91.5	129.0	93.8	105.6	86.8	145.7
No.	30	30	30	30	13	13	13	13	29	29
Std. Dev.	16.7	26.7	22.3	38.1	32.9	55.9	54.9	65.4	31.9	63.6
t	-2.475		-5.517		-2.704		-0.440		-5.741	
Signif.	0.019		0.000		0.019		0.668		0.000	

Standard U.S. Low Beams

Standard U.S. Low Beams With UVA

Figure 13. Pedestrian crosswalk scene shown with standard U.S. low beams (above) and standard U.S. low beams with UVA (below).

Static Testing

Visibility Distances

The static testing procedure had subjects indicate how far away they could see the right edge line and the center lane skip lines. The results are shown in Table 1. With the UVA headlights, the edge line was visible 28.9 m (94.71 ft), or 14.46 percent, farther away than with the U.S. headlights. The centerline with the UVA headlights was visible 27.67 m (90.71 ft), or 49.35 percent, farther away. Both of these differences are very significant. The original Clara Barton Parkway study (Mahach, Knoblauch, Simmons, Nitzburg, Arens, and Tignor, 1997) found similar improvements—specifically, a 35.59-m (116.7-ft), or 24.71-percent, increase in edge line visibility and a 28.95-percent increase in centerline visibility.

Table 1. Visibility distances: static testing.

Delineation/Headlights	Mean (m)	No.	Std. Dev.	t	Signif.
Right Edge Line — U.S.	199.7	38	46.6	-5.456	0.000
Right Edge Line — UVA	228.6	38	33.2		
Skip Lines in Meters — U.S.	56.1	38	12.3	-14.250	0.000
Skip Lines in Meters — UVA	83.7	38	16.6		
1 m = 3.28 ft					

Subjective Ratings

The subjects in the Clara Barton Parkway study were also asked to rate, using a five-point scale, how visible the pavement delineation was with the U.S. and the UVA headlights. The results of these ratings are shown in Table 2. While 60.5 percent of the subjects rated the UVA headlights as excellent, only 7.9 percent said the U.S. headlights were excellent. This compares favorably with the original Clara Barton Parkway study where 75 percent of the subjects rated the UVA headlights as excellent and 8 percent of the subjects rated the U.S. headlights similarly.

Table 2. Subjective ratings: static testing.

Headlight Condition	No.	Percentage of Subjects Rating Visibility of Roadway Markings as				
		1 Poor	2	3	4	5 Excellent
U.S.	38	0	13.2	57.9	21.1	7.9
UVA	38	0	5.3	7.9	26.3	60.5

Driver Performance Measures - DASCAR

The DASCAR instrumentation in one of the UVA-equipped experimental vehicles allowed several driver performance measures to be monitored. It was hypothesized that improved headlighting/roadway delineation might result in increased vehicle mean speed and reduced speed and lateral placement variances.

The DASCAR collected data every 1/30th of a second. This included data on speed, left-lane lateral placement, right-lane lateral placement, throttle position, hard wheel data from string pot, lateral acceleration, longitudinal acceleration, yaw rate, and braking. For each subject, the number of times the brake was applied, and means and standard deviations for the remaining variables were computed for each of the eight segments for each of the last four laps and across the eight segments for each of the last four laps. The brake number and the means and standard deviations constituted the data set that was used to compare the four different headlights.

The use of parametric statistics for data analysis assumes that variables have normal distributions in the population. Since this could not be assumed for the data, non-parametric statistics for related samples were used. Comparisons between all four headlights were made using the Friedman two-way analysis of variance by rank test. Comparisons between the U.S. and U.S./UV headlights were made using the Wilcoxon signed-rank test. Each of the 8 segments and across all segments were analyzed for headlight differences for 17 variables:

(1) mean and (2) standard deviation of speed
(3) mean and (4) standard deviation of left-lane lateral placement
(5) mean and (6) standard deviation of right-lane lateral placement
(7) mean and (8) standard deviation of throttle position
(9) mean and (10) standard deviation of hand wheel
(11) mean and (12) standard deviation of lateral acceleration
(13) mean and (14) standard deviation of longitudinal acceleration
(15) mean and (16) standard deviation of yaw rate
(17) number of times brake was applied

Significance level was set at p=0.05. Given the large number of statistical tests, it would be expected that 5 percent of these tests would show significant headlight differences by chance. The number of tests with significant differences barely exceeded this level.

Speed

The DASCAR vehicle speed data is shown in Table 3. Although the mean speeds varied 41.81 km/h (25.97 mi/h) for the U.S. headlights to 42.36 km/h (26.31 mi/h) for the UVA headlights, these differences are quite small and not significant. The standard deviations of vehicle speed were also nearly identical—4.72 km/hr (2.97 mi/h) to 4.91 km/h (3.05 mi/h) across the four headlight conditions.

Table 3. DASCAR data: speed.

Measure/Headlight Condition	Mean	No.	Std. Dev.	Friedman Signif.
Speed — Average **(km/h)**				
Euro				0.300
U.S.	42.02	18	4.83	
Euro/UVA	41.81	18	4.06	
UVA	41.89	18	5.12	
Speed — Standard Deviation **(km/h)**	42.36	18	4.94	
Euro				
U.S.				

Euro/UVA UVA	 4.78 4.78 4.70 4.91	 18 18 18 18	 0.98 0.77 0.89 0.68	 0.801
1 km/h = 0.621 mi/h				

Lateral Placement

The DASCAR lateral placement data is shown in Table 4. The values shown are the distance (in centimeters) from the left side of the vehicle to the roadway centerline. Although a difference in the average lateral placement value was not expected, it has been suggested that better lighting/delineation might help drivers do a better job of tracking within the lane and, therefore, result in reduced lateral placement variance. As shown, the standard deviation values for the four headlight conditions are nearly identical, and not statistically different.

Table 4. DASCAR data: vehicle lateral placement.

Measure/Headlight Condition	Mean	No.	Std. Dev.	Friedman Signif.
***Lateral Placement — Average* (km/h)** Euro U.S. Euro/UVA UVA ***Lateral Placement — Standard Deviation* (km/h)** Euro U.S. Euro/UVA UVA	88.39 89.85 89.97 90.30 12.35 12.04 12.32 12.36	18 18 18 18 18 18 18 18	6.20 6.17 5.43 5.38 2.62 2.40 2.61 2.96	 0.371 0.595
1 km/h = 0.621 mi/h				

The DASCAR data for brake applications and steering input (amplitude and direction) were also analyzed, but no significant effects were found.

Apparently, the dramatic increases in detection and recognition distances associated with the UVA headlights do not translate to a measurable change in the driver performance measures examined. This was probably because the relatively new delineation in combination with any of the headlights tested was more than adequate to optimize driver speed maintenance and lane tracking.

Subjective Ratings

Part of the experimental procedure involved having the experimental subjects provide a subjective rating of the performance of the various headlights being tested. They were asked to observe the headlights and roadway markings and were asked two questions:

1. How do the headlights and roadway markings work compared to those you generally see when driving at night?
2. How well did these headlights and roadway markings work for helping you see where to steer the car?

The results of these subjective evaluations are presented in Tables 5 and 6. Table 5 shows the responses to the first question, "How do the headlights compare to what you generally see?" The DASCAR vehicle had four different headlight configurations. The UVA headlights with U.S. low beams were rated as "better than" what they generally see by 76.5 percent of the subjects. The next best headlight condition was the Euro low beams with the UVA headlights. They were rated "better than" by 65.6 percent of the drivers. Interestingly, the Euro low beams (without the UVA headlights) were rated as "better than" by 50.0 percent of the drivers, while the U.S. headlights alone were the most poorly rated, only 32.4 percent of the drivers thought they were better than what they generally see. The Volvo used for the Loops Drive portion of the study had two sets of headlights—regular low beams and the UVA headlights. The differences in subjective ratings are very dramatic. While 73.0 percent of the subjects rated the combined U.S./UVA headlights as "better than," only 43.2 percent rated the U.S. low beams alone as "better than."

Table 5. Subjective ratings: how headlights compare to what you generally see.

Headlight Condition	No.	Percentage of Subjects Rating Headlights/Delineation		
		Not As Good As	As Good As	Better Than
***DASCAR* (Subject as Driver)**				
Euro	32	3.1	46.9	50.0
U.S.	34	8.8	58.8	32.4
Euro/UVA	32	15.6	18.8	65.6
U.S./UVA	34	14.7	8.8	76.5
***Loops Drive* (Subject as Passenger)**				
U.S.	37	10.8	45.9	43.2
U.S./UVA	37	10.8	16.2	73.0

The subjective ratings in response to the second question—"How do the headlights compare to those used on the previous trial?"—are presented in Table 6. Our major interest is in the comparisons between the regular U.S. headlights and the U.S. headlights supplemented with the UVA headlights. Therefore, the responses have been sorted so that subjective comparisons to regular U.S. low beams are shown. The order of presentation was counterbalanced. On the DASCAR drive, 67.6 percent of the drivers said that the combined U.S./UVA headlights were "better than" the U.S. headlights alone. On the loops drive, on the inner test track, 56.8 percent of the subjects indicated that the U.S./UVA headlights were "better than" the U.S. headlights alone.

Table 6. Subjective ratings: how UVA headlights compare to U.S. headlights.

Test Scenario	No.	Percentage of Subjects Rating UVA Headlights Relative to U.S. Headlights		
		Not As Good As	As Good As	Better Than
DASCAR Drive **(Subject as Driver)** U.S./UVA	34	23.5	8.8	67.6
Loops Ride **(Subject as Passenger)** U.S./UVA	37	13.5	29.7	56.8

Age Effects

It is generally acknowledged that older drivers do not have as good visual acuity, especially at night, as younger drivers. During subject recruiting, every effort was made to recruit older drivers as experimental subjects. This was done so that we could determine if UVA/fluorescent technology would be beneficial to older drivers. Participation involved driving to the remotely located test facility during twilight and taking part in a procedure that typically lasted until 12:00 a.m. to 12:30 a.m. and then driving home. In spite of the generous incentive ($50), finding older drivers was difficult. A total of 10 of the 38 subjects were age 55 or older.

In order to determine if age had a significant impact on detection and recognition distances, a 2x2 analysis of variance with repeated measures on the second factor was performed on dependent variables. The first factor was age (18-54, 55-76) and the second factor was headlight condition (U.S., UVA).

Analyses of variance were performed on all 20 dependent variables. Significant main effects of age were found for the following 10 dependent variables:

1. Right curve — detection distance
2. Right curve — recognition distance
3. Left curve — visibility distance
4. No-passing zone — detection distance
5. No-passing zone — recognition distance
6. Centerline — visibility distance
7. Jogger pedestrian — detection distance

8. Jogger pedestrian — recognition distance
9. Adult pedestrian — detection distance
10. Bike — recognition distance

No significant differences were found for the remaining 10 dependent variables.

The results of the analyses of variance for the 10 dependent variables found to have significant main effects for age are shown in Table 7. Right-curve detection distances, for example, with U.S. headlights were 238.4 m (781.5 ft) for younger drivers and 183.0 m (600.0 ft) for the older drivers. The difference is 55.4 m (181.7 ft). With UVA headlights, the distances were 250.8 m (822.8 ft) for younger drivers and 203.3 m (667.0 ft) for older drivers, a difference of 47.5 m (155.8 ft). The F values for age effects and the resulting significance levels for each dependent variable are also shown. For the right-curve detection distance, the F value for age is 8.807 and the significance level is 0.006.

It is not known why there were significant main effects of age for 10 of the 20 dependent variables examined. Significant main effects were found for some measures that showed very large overall effects (e.g., bike: recognition distance) and relatively small overall effects (e.g., right-curve detection distance), so it does not appear that the older drivers performed worse on the harder tasks or did better on the easier tasks.

The significance levels for the differences between the U.S. headlights and the UVA headlights were found to be consistent with the t-test results discussed earlier. Most importantly, analysis for possible interactions between age and headlight condition (U.S./UVA) found no significant difference. Thus, UVA headlights helped younger drivers and older drivers equally. They do not help older drivers more than they help younger drivers. Although it might have been encouraging to find that older drivers, who did not do as well in 10 of the 20 tests, were helped more by the UVA headlights, such was not the case.

Table 7. Age and headlight condition: 2x2 analyses of variance.

DEPENDENT VARIABLE	DISTANCE (m)			
	U.S. Headlights		UVA Headlights	
	Age 18-54	Age 55-76	Age 18-54	Age 55-76
Right Curve: Detection Distance	238.4	183.0	250.8	203.3
F (Age) Significance	8.807 0.006			
Right Curve: Recognition Distance	214.6	167.8	243.0	198.3
F (Age) Significance	7.609 0.010			
Left Curve: Visibility Distance	184.4	61.0	234.3	172.8
F (Age) Significance	5.759 0.024			
No-Passing Zone: Detection Distance	152.5	132.2	205.6	157.6
F (Age) Significance	4.425 0.044			
No-Passing Zone: Recognition Distance	116.4	81.3	169.5	143.0

F (Age) Significance	5.976 0.020			
Centerline: Visibility Distance	58.7	48.7	86.6	75.3
F (Age) Significance	5.026 0.031			
Jogger Pedestrian: Detection Distance	129.3	81.3	268.5	223.7
F (Age) Significance	12.275 0.002			
Jogger Pedestrian: Recognition Distance	90.8	71.2	159.8	91.5
F (Age) Significance	6.169 0.020			
Adult Pedestrian: Detection Distance	120.7	76.3	160.1	106.8
F (Age) Significance	11.930 0.002			
Bike: Recognition Distance	68.6	35.6	242.7	218.6
F (Age) Significance	4.665 0.040			

Cost/Benefit Analysis

This analysis will focus on the percentage reduction in crashes required to recover the increased cost of fluorescent roadway delineation and auxiliary ultraviolet (UVA) headlights. There are currently no studies of crash reductions due to UVA vehicle headlights that would allow us to compute a "true" cost/benefit ratio. Instead, we computed the estimated costs of implementing UVA /fluorescent technology and compared these to the costs of crashes that could potentially be reduced using this technology. We then computed the reduction in crashes needed to pay for the intervention costs, what we call the "break-even point."

INTERVENTION COSTS

This analysis used costs for UVA/fluorescent devices provided by the Federal Highway Administration (FHWA). Highway striping paint costs are $0.36/m ($0.11/ft) for regular paint and $0.49/m ($0.15/ft) for fluorescent paint. UVA headlights would be an additional $50 per vehicle. The number of vehicle registrations were obtained from Highway Statistics 1994 (FHWA).

The miles striped were computed using data for U.S. lane miles and U.S. road miles, excluding local roads (FHWA). The combination of these will give us the total line miles to be striped. This includes lane markings and centerline markings. We computed total relevant U.S. line miles, which includes lane lines and centerlines, to be 1,753,815 km (1,089,800 mi).

Table 8 summarizes the intervention costs of UVA/fluorescent technology using the above estimates.

Table 8. Costs for fluorescent lane striping and UVA headlights.

Incremental Costs for Fluorescent Striping Paint:	$0.13/m/year ($0.04/ft/year) x 1000 m/km (5280 ft/mi) = $131.00/km ($211.00/mi)
U.S. Line Miles, excluding local roads:	1,753,815 km (1,089,800 mi)
Total added cost of highway paint striping with fluorescent paint:	$230 million
Headlight Costs for Fluorescent Headlights: Annualized over an 8-year period:	$50.00 $ 7.14/year
Number of Vehicles:	189,500,000
Annualized Headlight Costs for All Vehicles:	$1,327 million
Cost of Headlights + Striping:	$1,557 million

Crash Costs

Incidence

We identified crash geometries where the use of UVA headlights might reduce the frequency or severity. Because UVA headlights will not reduce daylight crashes, they were excluded from our analysis. The lighting conditions included were dark; dark, but lighted; dusk; and dawn. We found six crash types that would potentially benefit from the use of UVA headlights at night. These crash geometries included: (1) crashes where a pedestrian or bicyclist was involved; (2) crashes occurring in a construction or maintenance zone; (3) crashes occurring on entrance and exit ramps of interstates; (4) single-vehicle roadway-departure crashes; (5) two-vehicle opposite-direction crashes where collisions include head-on and offset frontal; and (6) sideswipe crashes with both vehicle traveling straight, where a driver fails to hold his/her lane.

To estimate injury incidence, we followed the procedure in Miller, Lestina, and Spicer (1998), which is similar to Blincoe and Faigin (1992), Miller and Blincoe (1994), Miller, Galbraith et al. (1995), and Blincoe (1996). We began with a sample of nonfatal motor vehicle-related injury counts of relevant crashes by sampling strata and police-reported injury severity from NHTSA's 1996 General Estimates System (GES) (NHTSA, 1994). GES does not contain the information on body region injured and Maximum Abbreviated Injury Scale (MAIS) needed to apply costs. NHTSA's Crashworthiness Data System (CDS) (NHTSA, 1995) and National Accident Sampling System (NASS) (since renamed the National Automotive Sampling System, NHTSA, 1987) describe these crash injury details. We used 1988-1991 CDS for the description of injuries to passenger vehicle occupants involved in tow-away crashes. The most recent medical description available of non-CDS nonfatal crash victims (passengers of vehicles other than towed passenger vehicles) came from 1982-1986 NASS. Multi-year data were needed to obtain large enough samples of injury victims by body region and MAIS severity to accurately determine the incidence of rare injuries such as paralyzing spinal cord injuries. We used 1996 GES data to weight CDS and NASS data so that they would represent the 1996 nonfatal injury total. Since the years the CDS and NASS data were collected, many changes have come about to influence passenger and non-occupant traffic safety, such as airbags and increased seat-belt use. In developing GES weights to apply to these data, we controlled for police-reported injury severity, age of the victim, and restraint use (belted, unbelted, unknown, in a child seat). Thereby, we had a hybrid CDS/NASS file with weights that summed to estimated annual GES nonfatal incidence by police-reported injury severity, restraint use, and vehicle type. Fatality counts came from the 1996 Fatal Analysis Reporting System (FARS) (NHTSA, 1994).

We then estimated the total cost of these crashes. Costs per crash-involved person by MAIS and body region were merged in the file. The crash costs used are described in Miller et al. (1997), Miller (1997), and Blincoe (1996). Total crash costs include direct costs, which are actual dollar expenditures related to crash injury and damage. Direct costs include amounts spent for hospital, physician, rehabilitation, prescriptions, and related medical costs. Also included in direct costs are short-term work loss, employer productivity loss, travel delay, and cost to repair or replace damaged vehicles and property. Also included are the costs attributed to quality-adjusted life years (QALYs) lost. Table 9 presents total crash cost by crash geometry.

Table 9. Crash costs by crash geometry.*

Crash Geometry	Total Crash Costs (in 1995 $)
Pedestrian Crashes	$13.9 million
Single-Vehicle Road Departure	$27.8 million
Opposite-Direction Crashes	$8.8 million
Interstate, on/off ramp	$1.3 million
Work-Zone Crashes	$.7 million
Sideswipe, vehicle straight	$.6 million
All Crashes	$53.2 million

* Crashes include those in lighting conditions other than daylight.

RESULTS

Only UVA headlights would be required in order to increase the visibility of pedestrians and possibly reduce crashes. We found that a 9.6-percent reduction in nighttime pedestrian crashes will pay for the additional headlight costs. Alternatively, a 3-percent reduction in all relevant nighttime crashes will pay for the costs of UVA headlights and fluorescent highway paint combined. We also looked at other combinations and found that a 5.5-percent reduction in nighttime pedestrian crashes and a 2-percent reduction in the remaining relevant nighttime crashes will pay for the costs of UVA headlights and fluorescent highway paint. At effectiveness levels above the break-even point, the benefit/cost ratio rises linearly with effectiveness. For example, a 6-percent effectiveness of UVA /fluorescent technology corresponds to a benefit/cost ratio of 2, while a 9-percent effectiveness level results in a benefit/cost ratio of 3.

The evaluation of UVA/fluorescent technology found that detection and recognition distances of pedestrians and bicyclists increased by 33 percent to 117 percent. Unfortunately, in the current literature, a relationship between increased detection and recognition distances and crash reduction is not shown. However, if we assume that pedestrian crashes are reduced by 17 percent (half of the value of the lowest recognition improvement, i.e., 33 percent), we would achieve a benefit/cost ratio of 1.8 for UVA headlights. Table 10 presents the benefit/cost ratio for nighttime pedestrian crash reductions between 10 percent and 50 percent.

Table 10. Benefit/cost ratio for UVA headlights by percentage of reductions in nighttime pedestrian crashes.

Reduction	Benefit/Cost Ratios
10%	1.01
15%	1.57
17%	1.78
20%	2.09
25%	2.62
50%	5.24

Improvements in detection and recognition were also found for roadway delineation. These improvements ranged from 14 percent for right-curve delineation to 48 percent for a no-passing zone. Again, a literature search for the crash effects of improved delineation detection found nothing. If we assume that nighttime crashes, including incidents where pedestrians are involved, are reduced by 7 percent (half of the value of the lowest recognition, i.e., 14 percent) we would achieve a benefit/cost ratio of 2.4 for UVA headlights and fluorescent striping. Table 11 presents the benefit/cost ratio for the different scenarios of reductions in nighttime crashes.

Table 11. Benefit/cost ratio for UVA headlights and fluorescent striping by percentage of reduction in nighttime crashes.*

% Reduction in Pedestrian Crashes	% Reduction in Other Relevant Nighttime Crashes				
	3%	7%	10%	15%	25%
10%	1.6	2.6	3.4	4.6	7.2
15%	2.1	3.1	3.9	5.1	7.6
17%	2.3	3.3	4.0	5.3	7.8
20%	2.5	3.6	4.3	5.6	8.1
25%	3.0	4.0	4.8	6.0	8.5
50%	5.2	6.2	7.0	8.2	10.8

* Crashes include those in lighting conditions other than daylight.

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