Volume VIII

Enhanced Night Visibility Series: Phase II–Study 6: Detection of Pavement Markings During Nighttime Driving in Clear Weather

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

FOREWORD

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

The following document summarizes the results of a study on the detection of pavement markings using various headlamp systems during nighttime driving in clear weather. The study was conducted under Phase II of the Enhanced Night Visibility (ENV) project, a comprehensive evaluation of evolving and proposed headlamp technologies under various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume VIII. It is anticipated that the reader will select those volumes that provide information of specific interest.

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

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

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16. Abstract
Phase II—Study 6 was part of the Enhanced Night Visibility project, a larger research effort investigating drivers' visual performance during nighttime driving. Study 6 evaluated the possibility of improving the detection distances of pavement markings through the use of fluorescent materials, combined with augmentation of vehicle headlamps with UV–A sources. Three different pavement marking materials and 11 headlamp configurations,—vision enhancement systems (VESs)—were evaluated. The VESs studied included halogen low beam (HLB), high intensity discharge (HID), halogen high beam (HHB), and high output halogen (HOH) sources. Both the HLB and HID configurations were used in the systems augmented with UV–A sources. The pavement marking materials included fluorescent paint, fluorescent thermoplastic, and a two-component liquid system.

Thirty participants from three age groups (young, middle-aged, and older) participated in the study. The results indicated that all of the VESs provided adequate minimal visibility distances for all of the pavement markings at the 40-km/h (25-mi/h) speed driven and that the supplemental UV–A did not improve the detection distances obtained with either the HID or the HLB headlamps. The liquid system and thermoplastic pavement markings outperformed the fluorescent paint. The report discusses the results and implications for both headlamp type and the pavement marking materials.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

ENHANCED NIGHT VISIBILITY PROJECT REPORT SERIES

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

Volume	Title	Report Number
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II	Enhanced Night Visibility Series: Overview of Phase I and Development of Phase II Experimental Plan	FHWA-HRT-04-133
III	Enhanced Night Visibility Series: Phase II—Study 1: Visual Performance During Nighttime Driving in Clear Weather	FHWA-HRT-04-134
IV	Enhanced Night Visibility Series: Phase II—Study 2: Visual Performance During Nighttime Driving in Rain	FHWA-HRT-04-135
V	Enhanced Night Visibility Series: Phase II—Study 3: Visual Performance During Nighttime Driving in Snow	FHWA-HRT-04-136
VI	Enhanced Night Visibility Series: Phase II—Study 4: Visual Performance During Nighttime Driving in Fog	FHWA-HRT-04-137
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XIV	Enhanced Night Visibility Series: Phase III—Study 2: Comparison of Near Infrared, Far Infrared, and Halogen Headlamps on Object Detection in Nighttime Rain	FHWA-HRT-04-145
XV	Enhanced Night Visibility Series: Phase III—Study 3: Influence of Beam Characteristics on Discomfort and Disability Glare	FHWA-HRT-04-146
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LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

C .... contrast
DMI .... distance measuring instrument
ENV .... Enhanced Night Visibility
FHWA .... Federal Highway Administration
GPS .... Global Positioning System
ITS .... Intelligent Transportation Systems
L_B .... pavement luminance
L_T .... marking luminance
SUV .... sport utility vehicle
VDOT .... Virginia Department of Transportation
VTRC .... Virginia Transportation Research Council
UV .... ultraviolet
UV–A .... ultraviolet A (wavelength 315 to 400 nanometers)

Vision Enhancement Systems

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

Statistical Terms

ANOVA .... analysis of variance
DF .... degrees of freedom
F value .... F-ratio
GLM .... general linear model
MS .... mean square
P value .... statistical significance
SE .... standard error
SNK .... Student-Neuman-Keuls
SS .... sums of squares

Measurements

cm .... centimeters
ft .... feet

gal......................................gallons
h...hours
kg/L ....kilograms per liter
km/h ....kilometers per hour
lb ....pounds
m ....meters
mi/h ....miles per hour
mm ....millimeters
s...seconds

CHAPTER 1—INTRODUCTION

This study is part of the Enhanced Night Visibility (ENV) project sponsored by the Federal Highway Administration. This report summarizes an investigation into the visibility of pavement markings in different vehicle lighting conditions. Of particular interest in this study is the effect of different vehicle vision enhancement systems (VESs) on the visibility of various pavement marking materials. For example, some of the pavement marking materials were fluorescent, and some of the vehicle lighting included an ultraviolet (UV–A) component.

This research evaluated the effects of 3 pavement marking materials and 11 VES technologies across three age groups of drivers: young (aged 18 to 25), middle-aged (aged 40 to 50), and older (aged 60 and over). The research focused on measuring the pavement marking visibility for each combination of pavement marking material and VES.

The research was conducted on a special research facility roadway under controlled conditions. The pavement marking visibility was assessed by evaluating the distances at which the participants were able to see the beginning and the end of a series of pavement markings in each experimental road section.

PAVEMENT MARKINGS

Pavement markings provide essential tracking and guidance information to drivers at night. In addition, pavement markings provide essential reference points so that drivers can maintain proper vehicle position.(1) For example, Fitzpatrick, Lance, and Lienau implemented lane drop pavement markings that indicated when a lane terminated on a highway exit.(2) The researchers found that driver behavior was modified such that with the addition of the markings, drivers were inclined to be more proactive and make less erratic maneuvers compared to a baseline of no such markings.

For pavement markings to be effective, it is suggested that they provide the driver with a 3.65-s preview time.(3) To attain that level of conspicuity, the pavement markings must provide adequate contrast with the pavement and draw the attention of the driver.(4) Contrast (C) is dependent on the luminance or lightness of both the marking (L_T) and the pavement (L_B) as calculated in the equation in figure 1.(5)

$$C = \frac{L_T - L_B}{L_B}$$

Figure 1. Equation. Contrast ratio.

Overall, materials differ in the amount of contrast they provide. Turner, Nitzburg, and Knoblauch investigated differences between pavement marking materials with a specific focus on new paint, worn paint, new thermoplastic, and fluorescent thermoplastic.[(6)] The fluorescent thermoplastic was found to be the most visible when viewed with both halogen and UV–A headlamps. Other pavement marking materials were not as visible as the fluorescent thermoplastic.

Pavement marking visibility is affected by the retroreflectivity of the material. The coefficient of retroreflected luminance is a measure of the amount of headlamp illumination that the pavement marking material reflects back to the driver, resulting in the level of marking luminance (L_T). (Note that in keeping with common usage, the terms “reflective” and “reflectance” may be used in place of “retroreflective” and “retroreflectance.”) Zwahlen and Schnell observed that if the reflectance of pavement markings was high, drivers modified their visual search.[(3)] Drivers exhibited increased longitudinal visual search and greater fixation durations. Increased viewing distances allow a potential increase in safety by providing drivers with longer viewing times of the upcoming roadway; however, these potential safety benefits also depend on vehicle speed.

When compared to the visibility from a stationary position, one researcher found a 40 percent decline in pavement marking visibility while driving at 24 km/h, or 15 mi/h.[(7)] Jacobs et al. argued that higher speeds would create an even greater decline in visibility, thus increasing the need for highly visible pavement markings. Therefore, determining the distance at which pavement markings are visible to a driver when a vehicle is moving is an important aspect to the research on the performance of alternative pavement markings.

To measure the effectiveness of pavement marking materials, it is necessary to consider both vehicle speed and headlamp systems. For example, Zwahlen and Schnell measured the effect of different headlamps on the visibility of roadway markings.[(3)] The researchers found that highly reflective pavement marking materials paired with low-beam headlamps compensated for medium reflective pavement marking materials paired with high-beam headlamps. The authors concluded that the reflectivity of the pavement markings was considered more important in pavement marking detection than the headlamp configurations; however, the researchers evaluated only two types of headlamps, suggesting that other types of headlamp or VES configurations may be beneficial when identifying pavement markings.

HEADLAMP TECHNOLOGIES

VESs serve two purposes in low ambient illumination conditions—to illuminate pavement markings and illuminate obstacles.[8] Many headlamp technologies have been developed over the past 80 years to assist drivers with detecting and recognizing obstacles and pavement markings. The following paragraphs summarize the technologies evaluated with the pavement marking materials in this investigation. Headlamp specifications appear in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

Halogen Low Beam

The tungsten-halogen (halogen) headlamp is currently the most common headlamp available for vehicles in the United Stated and Europe, so the low-beam setting of halogen headlamps (HLB) was used as the baseline condition for the ENV studies.

Halogen High Beam

The high-beam setting of a halogen headlamp (HHB) typically provides drivers with an increased area of illumination. The increased area is achieved through increasing the output of the lamp and also raising the angle of output. The result is that light is projected farther down the roadway, providing greater visual distance.

High Intensity Discharge Headlamps

High intensity discharge headlamps (HID) use a compact metal-halide arc lamp with high luminous efficiency and output, which makes them good candidates for vehicular applications.[9] These types of headlamps are becoming standard on some vehicles; however, there has been little direct research measuring the effects of HID headlamps on pavement marking visibility.

Ultraviolet A Headlamps

UV–A radiation, with wavelengths between 320 and 400 nanometers, is outside of the visible light spectrum. Researchers have determined that, with a combination of appropriate filters and minimized stationary exposure, UV–A headlamps do not pose a safety threat.[10] UV–A headlamps have shown potential for increasing visibility when illuminating objects with fluorescent properties. Mahach, Knoblauch, Simmons, Nitzburg, and Tignor implemented both dynamic and static testing to determine the enhanced visibility of fluorescent pavement markings when viewed with a UV–A headlamp.[11] Overall, a significant improvement was found with the UV–A headlamp configurations when compared to the non-UV–A headlamp setups.

High Output Halogen

High output halogen lamps are being evaluated as potential replacements for standard tungsten-halogen lamps in headlamp applications. For this investigation, the HOH conditions used prototype lamps to provide higher light output at the same power consumption, with an expectation of increased visibility.

AGE

When reviewing visibility issues concerned with both VES technologies and an assortment of pavement marking materials, it was found that driver age is also an important factor. Currently, the percentage of older drivers continuing to drive is increasing as the population grows older.[12] In 2002 there were 19.9 million older licensed drivers, which represented 10 percent of all drivers.[13] When driving at night, older drivers require increased levels of illumination, highly visible pavement markings, and reduced exposure to glare.[3,12,14]

As people age, their vision naturally declines for various reasons. Older drivers exhibit both reduced detection ability and reduced contrast sensitivity.[14,15] The latter may affect older drivers' abilities to detect pavement markings at night. Zwahlen and Schnell compared the detection distances of pavement markings for both young and old drivers.[16] The older drivers were found to have a 55 percent decrease in detection distances from the detection distances of younger drivers. The decrease in detection distance with age may place older drivers at a large disadvantage for navigating the roadways safely at night.

With various age-related factors, all drivers are likely to benefit from increased visibility at night provided by different VESs and enhanced pavement marking materials. In an effort to investigate the effect of these technologies on visibility, the current research study evaluated 11 different VESs in conjunction with 3 types of pavement marking materials.

CHAPTER 2—METHODS

EXPERIMENTAL DESIGN

This study was a mixed-factor design with three independent variables: VES (11 levels), pavement marking (3 levels), and age (3 levels). The VES configurations and pavement markings were the within-subjects factors; age was the between-subjects factor. Table 1 shows the experimental variables used for this study.

Table 1. Experimental variables: 11 (VES) by 3 (Pavement Marking) by 3 (Age) mixed-factor design.

VES Variable	HLB
	HID
	Hybrid UV–A + HLB
	Three UV–A + HLB
	Five UV–A + HLB
	Hybrid UV–A + HID
	Three UV–A + HID
	Five UV–A + HID
	HOH
	HHB
	HLB–LP
Age Variable	Young
	Middle
	Older
Pavement Marking Variable	Fluorescent paint
	Fluorescent thermoplastic
	Liquid system

INDEPENDENT VARIABLES

VES Configuration

The 11 VESs tested in this study were selected based on several considerations. HLB headlamps are the most common for vehicles in the United States and Europe, and they provide a baseline against which other systems can be measured. The use of HIDs is increasing. An earlier study indicated that UV–A headlamps would provide a number of potential improvements in nighttime driving.(6) Ultraviolet radiation, which is outside the visible light spectrum, has the potential benefit of reducing discomfort and disability glare caused by oncoming vehicles compared to other types of headlamps.(8) As a result of these findings, both an HLB and an HID headlamp were tested alone and in combination with three different configurations of UV–A. An HOH, HHB, and a low-profile HLB on a sedan (HLB–LP) comprised the remaining VESs. The HLB–LP was the only VES not tested on an SUV or pickup. Note, the term “HLB configurations” means all of the VESs using the HLB: HLB, hybrid UV–A + HLB, three UV–A + HLB, and five UV–A + HLB. The term “HLB with UV–A” indicates the hybrid UV–A + HLB, three UV–A + HLB, and five UV–A + HLB VESs. The same concept can be used to discuss the various VESs using HID systems.

Table 2 lists the VESs used in the present study with their headlamp description, beam pattern, and vehicle/headlamp profile (high versus low). ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*, contains details on the various VESs.

Table 2. VES configurations.

VES	Description	Beam Pattern (non-UV–A only)	Vehicle Profile
HLB	Baseline halogen available from an automobile manufacturer	Standard, straight-ahead pattern	High profile (SUV)
Hybrid UV–A + HLB	Two hybrid UV–A lamps (emitting some visible light in addition to UV-A) paired with the HLB baseline	Standard, straight-ahead pattern	High profile (SUV)
Three UV–A + HLB	Three UV–A lamps paired with the HLB baseline	Standard, straight-ahead pattern	High profile (SUV)
Five UV–A + HLB	Five UV–A lamps paired with the HLB baseline	Standard, straight-ahead pattern	High profile (SUV)
HID	Baseline high intensity discharge available from an automobile manufacturer	Sharp cutoff, wider pattern	High profile (SUV)
Hybrid UV–A + HID	Two hybrid UV–A lamps (emitting some visible light in addition to UV-A) paired with HID	Sharp cutoff, wider pattern	High profile (SUV)
Three UV–A + HID	Three UV–A lamps paired with HID	Sharp cutoff, wider pattern	High profile (SUV)
Five UV–A + HID	Five UV–A lamps paired with HID	Sharp cutoff, wider pattern	High profile (SUV)
HOH	Nonbaseline halogen, representative of an available after-market headlamp type	Standard, straight-ahead pattern	High profile (pickup)
HHB	Nonbaseline halogen, representative of the high beam option on all vehicles	Standard, straight-ahead pattern	High profile (pickup)
HLB–LP	Nonbaseline halogen, the only low-profile headlamp	Standard, straight-ahead pattern	Low profile (sedan)

Pavement Markings

Three pavement marking materials were used in this study: a two-component liquid system, fluorescent thermoplastic, and fluorescent paint. The two-component liquid system had not been investigated previously. The fluorescent paint and fluorescent thermoplastic both contain phosphorescent materials, but they were applied differently. The fluorescent paint was sprayed on, similar to standard acrylic pavement marking paint, whereas the fluorescent thermoplastic was applied as a ribbon of molten material that was then allowed to cool.

For each material, both the yellow dashed centerline and the white edgeline were installed. The beginning and the end of the sections of white and yellow lines were coincident.

Liquid System

The liquid system was selected for application because it exhibited nearly twice the retroreflectivity of conventional patterned tape markings. The liquid system was applied on an asphalt section of the roadway.

The material uses a polyurea binder to allow for installation and quick drying. The equipment used for installation consisted of a mobile truck-mounted, self-contained pavement marking machine specifically designed to apply the two-component liquid material (figure 2). The liquid system was applied over a 2-day period.

Figure 2. Photo. Application of the liquid system pavement marking.

Retroreflection was provided by both glass beads and proprietary ceramic retroreflective elements. Application was performed at a speed ranging from 10 to 13 km/h (6 to 8 mi/h) using a vehicle specifically designed for this material.

Fluorescent Thermoplastic

The fluorescent thermoplastic was installed on a section of road with an all-asphalt surface. The pavement marking material, both yellow and white, was manufactured using a hydrocarbon resin base with a 40 percent clear glass bead intermix.

The material was applied using a handcart (gravity extrusion) for each color (figure 3). The thermoplastic was applied at a 90-mm (0.39-inch) thickness followed by drop-on beads at a rate of approximately 3.2 kg per 9.29 m^2 (7 lb per 100 ft^2) of thermoplastic. Fluorescent white glass beads were used on the white edgelines, and fluorescent yellow glass beads were used on the yellow center skip lines.

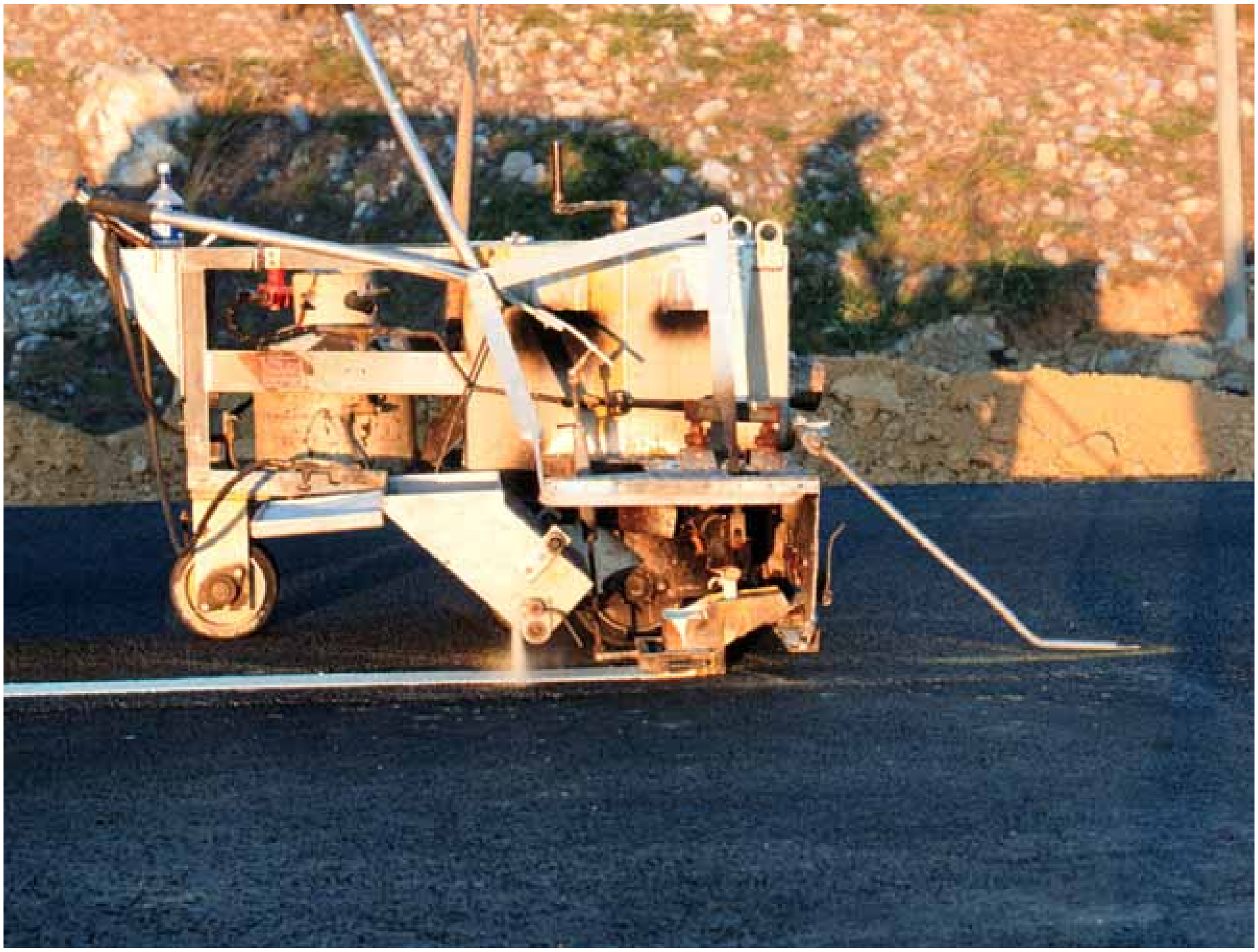


Figure 3. Photo. Application of the fluorescent thermoplastic pavement marking system.

Fluorescent Paint

The final section of roadway, which consisted of tined hydraulic cement concrete, had the fluorescent paint applied to it. Both colors were a waterborne, flat acrylic-based fluorescent road-marking paint. Fluorescent white and yellow glass beads, as appropriate, were used with the paint.

Before the application of the yellow centerlines, the concrete surface, which was fully cured and more than 30 days old, was swept with a broom tractor. Test strips were used to verify correct line width (10.16 cm or 4 inches) application, thickness (15 mm or 0.59 inch), and bead drop-on rate (6 lb/gal or 2.7 kg/L). The process was repeated using the white paint mixture for the roadway edgelines. Personnel from the State department of transportation applied these pavement markings to the road surface using a long-line truck (figure 4).

Figure 4. Photo. Application of the fluorescent pavement markings using the long-line truck.

Age

The age variable had three levels: young drivers (18 to 25 years old), middle-aged drivers (40 to 50 years old), and older drivers (60 years or older).

Age is an important factor when considering the risks of nighttime driving. These age groupings are based on common age ranges that have increased crash risk or represent a substantial portion of the driving population. For example, young drivers are often overrepresented in fatal collisions. Middle-aged drivers represent the largest portion of the driving population.(17) Older drivers have difficulty detecting low-contrast objects and report discomfort glare as a major problem with nighttime driving.(12,18) Older drivers exhibit different nighttime driving performance than the other age groups in part because vision degradation has a significant effect on driving performance.(12) Research has shown that enhanced visibility potentially could reduce the number of deaths each year.(14)

DEPENDENT VARIABLES

Detection distances of the beginning and end of the pavement markings were used as two dependent variables. During each session, participants were asked to indicate when they first saw the pavement marking ("beginning detection distance") and when they detected the end of the pavement marking ("ending detection distance"). The pavement marking detection distances determined which of the three pavement marking materials and which of the 11 VESs provided the greatest pavement marking visibility for drivers at night. Because the center and edgelines used the same pavement marking technology within each section and the covering of the center and edgelines was coincident, the participants were not instructed to look at one line or the other. Consequently, beginning and ending distances refer to both lines.

PARTICIPANTS

The 30 participants in the study were divided into the three different age categories: 10 participants were between the ages of 18 and 25 (young drivers), 10 were between the ages of 40 and 50 (middle-aged drivers), and 10 were aged 60 and over (older drivers). Gender was balanced in each age group—five male and five female participants.

Candidates were screened using a preliminary screening questionnaire. They were considered eligible if the selection conditions were fulfilled (appendix A). Before participation in the study, candidates were required to sign an informed consent form (appendix B), present a valid driver's license, pass the visual acuity test (appendix C) with a score of 20/40 or better (as required by Virginia State law), and have no health conditions that made operating the research vehicles a risk.

After candidates met the eligibility requirements, they were scheduled to participate in the study for two consecutive nights. Participants were informed about their right to freely withdraw at any time and told they would be remunerated at a rate of $20 per hour for the time they participated.

APPARATUS AND MATERIALS

Vehicles

Four vehicles were used for the onroad study (figure 5 through figure 8). Three of the vehicles were high profile (two sport utility vehicles and one pickup).

Figure 5. Photo. SUV 1 with hybrid UV–A + HID.

Figure 6. Photo. SUV 2 with three or five UV–A and HLB or HID.

Figure 7. Photo. Pickup with HOH and HHB.

Figure 8. Photo. Sedan with HLB–LP.

SUV 1 was equipped with two hybrid UV–A headlamps, and it was configured to interchange the HLB and HID VESs. The HID and the HLB headlamps were mounted on a light bar so the VESs could be positioned directly in front of the factory headlamps. The hybrid UV–A headlamps were permanently mounted on a bar in the front grill of the vehicle. The HLB and the HID headlamps were exchanged between data collection sessions so that each VES was paired with the hybrid UV–A headlamps.

SUV 2 was similar to SUV 1. It was equipped with five UV–A headlamps, and it was configured to interchange the HLB and HID VESs. Five UV–A headlamps were mounted on the light bar in front of the vehicle grill. The configuration with the three UV–A headlamps used the top three

UV–A spotlights (figure 6). The configuration with the five UV–A headlamps used the bottom two spotlights in combination with the top three spotlights. Between data collection sessions, the HLB and the HID VESs were exchanged so that both were paired with the three and five UV–A headlamps.

The pickup was equipped with HOH and HHB lamps located in the same housing; the HOH lamp replaced the standard low-beam lamp.

The sedan was equipped with halogen headlamps that were original equipment for this model vehicle. Because this vehicle was a sedan and had a lower profile than the other vehicles used, the headlamps were categorized as halogen low beam—low profile (HLB–LP).

Headlamp Aiming

The headlamps used for the HLB, HID, HOH, HHB, and UV–A configurations were located on external light bars. To accommodate changes from one configuration to another, the HLB and HID headlamps were moved onto, off of, and between vehicles. Each light assembly movement required a re-aiming process before the experiment session each night. An aiming protocol was developed with the help of experts in the field. (See references 19, 20, 21, and 22.) During the photometric characterization of the headlamps, it was discovered that the position of the maximum intensity location of the HLB, HOH, and HHB configurations was aimed higher and more toward the left than typically specified. This aiming deviation likely increased detection distances for the HLB and HOH configurations and likely decreased the detection distances for the HHB configuration. Details about the aiming procedure and the maximum intensity location appear in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*.

In-Vehicle Data Collection System

All vehicles were equipped with an electronic odometer or distance measuring instrument (DMI), a laptop computer, and a hand-held pushbutton wand. The DMI unit and the pushbutton were connected to the laptop computer through serial ports, which allowed data input from both the in-vehicle experimenter and the participant.

During the data collection, the participant pressed the pushbutton when he or she saw the beginning and ending pavement marking in each section. When the vehicle reached the end of the each pavement section, the in-vehicle experimenter pressed the space bar to provide a reference point for the detection distance. In each pavement marking section, three measurements were recorded: two button presses, which represented when the participant saw the beginning and the ending pavement marking in each section, and one space bar press, which represented when the vehicle passed the last pavement marking in each section. Every time the participant pressed the button or the in-vehicle experimenter pressed the spacebar on the laptop computer, the laptop recorded the corresponding distance from the DMI. These three measurements provided a complete set of distance data.

The software, created specifically by the contractor for the ENV research project to allow such data extraction, enabled the in-vehicle experimenter to enter information such as participant number, age, gender, VES, and data collection night (first or second).

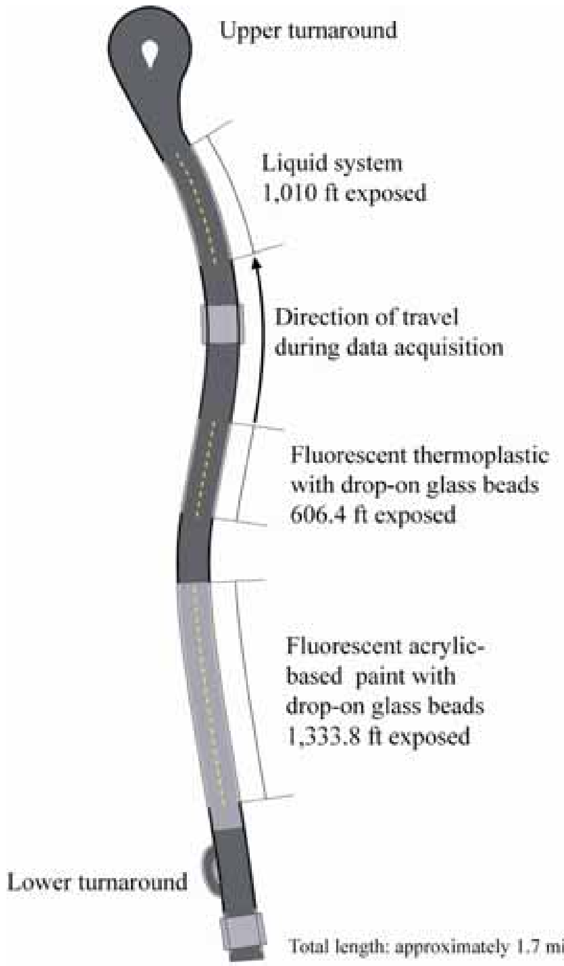
Test Facility

The Virginia Smart Road (figure 9) provided a closed-course segment to maximize safety for the participants and experimenters. The secluded roadway allowed customization of the road for the study; overhead lighting was turned off, and ambient lighting was adequately controlled to decrease the variability of the data. Appendix G gives more information on the Smart Road.

Figure 9. Photo. Smart Road.

A confound arose in study, however, because the different pavement types—concrete and asphalt—on the Smart Road created variations in contrast between the different pavement marking materials. The fluorescent paint was on concrete pavement; the fluorescent thermoplastic and liquid system pavement markings were on asphalt pavement. Concrete pavement is much lighter, so it had less contrast with the pavement marking. This paving material confound, which is discussed later, was taken into consideration when interpreting the data.

The sections of different pavement marking materials were defined by hiding pavement markings with black masking tape before and after each section, making gaps where no pavement markings were visible (see figure 10).



1 ft = 0.305 m
1 mi = 1.6 km

Figure 10. Diagram. Pavement marking material setup.

EXPERIMENTAL PROCEDURE

All participants drove at night and in clear weather. If rain, snow, or fog was present, the sessions that night were rescheduled. Clear weather was imperative because precipitation would have altered the retroreflectivity of pavement markings, thus altering the study's results. In addition, moisture in the air can affect the transmissivity of the atmosphere, which also can alter visibility and glare.(1)

Two in-vehicle experimenters and two onroad experimenters were required for each data collection session. The in-vehicle experimenters conducted vision tests, helped familiarize participants to the Smart Road and the study, recorded data, and answered questions from participants throughout the study (appendix D). The in-vehicle experimenters were with the participants at all times. The onroad experimenters prepared the road and vehicles and oriented participants to the vehicles (appendix E). Each evening, two participant vehicles were run through the pavement marking visibility testing. Two experimental sessions per participant were required for each participant to experience all the VESs and pavement markings.

VES Counterbalancing

The VESs presented in the same night were grouped together based on the placement of the HLB and HID headlamps on either the vehicle with hybrid UV–A headlamps or the vehicle with the five UV–A headlamps. Table 3 shows the two VES configuration groups. To evaluate the other headlamps, the HOH and the HHB were included in group A, and the HLB–LP was included in group B.

Table 3. VES configuration groups.

Group A	HLB Hybrid UV–A + HLB Three UV–A + HID Five UV–A + HID HHB HOH
Group B	HID Hybrid UV–A + HID Three UV–A + HLB Five UV–A + HLB HLB–LP

The VES groupings remained constant throughout the evaluation; however, the night (first or second) they were presented alternated. In other words, on the first night, half of the participants were presented with the group A VESs while the other half was presented with the group B VESs. On the second night, the order was switched. Within each group, the VESs were counterbalanced to avoid order effects (appendix F and appendix H). Thirty different presentation orders, one for each participant, were selected from a list of randomized orders; thus, each participant was exposed to the VES configurations in a unique order. Because of the

VES vehicle setup, two participants could not run the same VESs at the same time. To avoid this conflict, compatible orders were conducted together.

Participant Screening

Candidates were screened initially over the telephone (appendix A). Candidates who met the eligibility criteria were scheduled to come in for two separate sessions on two separate evenings. Two candidates were scheduled for each session. When the candidates arrived, the experimenters reviewed the informed consent form (appendix B) and asked each candidate to present a valid driver's license. After candidates completed the informed consent form, the experimenters administered a series of three vision tests (appendix C). The vision tests included an informal test for acuity using a Snellen chart, a contrast sensitivity test, and a color vision test. The acuity test was performed to ensure that all participants had at least 20/40 vision, corrected or uncorrected, as required by Virginia State law. Results for the contrast sensitivity test and color vision test were recorded, but the results were not used to determine eligibility for participation in the study. A detailed experimenter protocol for the vision testing appears in appendix D.

Familiarization and Practice

Because four different vehicles were used during the study, the onroad experimenters oriented the participants to the different vehicles as encountered on the order sheets. At the upper Smart Road turnaround (see figure 10), an onroad experimenter escorted a participant to the experimental vehicle according to the predetermined order sheet for that participant. The participant was asked to adjust the seat, steering wheel, and climate controls for his or her comfort.

Then the in-vehicle experimenter reviewed the experiment procedures. The experimenter explained the pavement marking detection task, showed the participant the handheld button, and used a diagram of the Smart Road to show the separation of the pavement marking sections. After all the participant's questions were answered, the in-vehicle experimenter instructed the participant to drive down the road at 40 km/h (25 mi/h). The purpose of this drive was to familiarize the participant to the Smart Road and ensure comfortable driving on the road at night in the absence of ambient lighting. No tasks were performed during this initial run.

Practice Run

The experimental task was performed in only one direction on the road; participants began the task at the lower turnaround shown in figure 10. The first drive up the road was a practice run. The in-vehicle experimenter gave the participant the handheld button and instructed him or her to proceed up the road at 40 km/h (25 mi/h). The experimenter instructed the participant to press the pushbutton when he or she detected the beginning of the pavement marking and press it again when he or she detected the end of the pavement marking in a section.

Anomalies in the vertical curvature of the pavement caused the pavement markings in a 3.3-m (11-ft) section of road to temporarily disappear from the driver’s view. A white cone was placed to mark this area, and the in-vehicle experimenter pointed this out to the participant during the practice run. After the practice run was complete and all the participant’s questions were answered, data collection began.

General Procedure for Data Collection

The two onroad experimenters met the two participants for that run when they arrived at the upper turnaround. The onroad experimenters escorted each participant to the appropriate experimental vehicle. While the onroad experimenter oriented the participant to the vehicle, the in-vehicle experimenter turned on the appropriate VES. The participant then drove the vehicle with the in-vehicle experimenter in the front passenger seat down the road to prepare for the detection task.

At the lower turnaround, the participant was instructed to drive up the road in the right-hand lane at 40 km/h (25 mi/h) and press the button when he or she was able to detect the beginning or end of the pavement marking in each of three road sections. The participants were not instructed as to which line to watch (edge or center). To provide a reference point to calculate the detection distances from the participant’s button press, the in-vehicle experimenter pressed the space bar when the vehicle was even with the end of the pavement marking in each section.

If the participant said he or she did not accurately indicate either the beginning or end of the pavement marking, the lap was taken again. Each participant completed the pavement marking detection task for all 11 VES configurations in all three pavement marking sections.

At no time during the pavement marking detection task did the participant vehicles directly face each other. Furthermore, all mirrors on the vehicles were covered to reduce the effect of glare from the other vehicle's headlamps.

The participant repeated the procedure for either five or six VESs on the first night (see table 3), and then he or she returned a second night to complete the procedure for the remaining VESs. Before the data collection began on the second night, the in-vehicle experimenter reviewed the protocol with the participant and answered any questions.

DATA ANALYSES

All data collected for the 30 participants were merged into a single database. An analysis of variance (ANOVA) was performed using a general linear model (GLM) procedure in SAS®. An alpha level of 0.05 was selected to indicate significance. A post hoc Student-Neuman-Keuls (SNK) test was conducted on significant main effects to determine the levels of the independent variables that were significantly different.

The ANOVA evaluated whether there were significant differences among the 3 pavement markings (designated "Pvt. Mrkg."), 11 VES configurations (designated "VES"), and 3 age groups (designated "Age") with respect to both beginning and ending detection distances. A VES by Pavement Marking by Age mixed model was used with age as the between-subjects factor (table 4). The results of these analyses were used to answer the following research questions:

- Which VES provided the longest beginning and ending detection distances?
- Which pavement marking material was the most visible with all the VESs?
- Does the addition of UV–A headlamps to the baseline headlamps affect pavement marking visibility?

Table 4. Model for the experimental design.

Source
Between
AGE
SUBJECT(AGE)
Within
VES
AGE by VES
VES by SUBJECT(AGE)
PVT. MRKG.
AGE by PVT. MRKG.
PVT. MRKG. by SUBJECT(AGE)
PVT. MRKG. by VES
AGE by PVT. MRKG. by VES
VES by PVT. MRKG. by SUBJECT(AGE)

CHAPTER 3—RESULTS

To measure the effect of pavement marking material and VES on pavement marking detection, data on two measures were collected. The first measure was the beginning detection distance, defined as the point where participants indicated first seeing the pavement markings in each section. The second measure was the ending detection distance, when the participants indicated seeing the end of the pavement marking in each section. A series of ANOVAs were conducted to look at the main effects and interactions of pavement marking material, VES, and age for both the beginning and the ending detection distances.

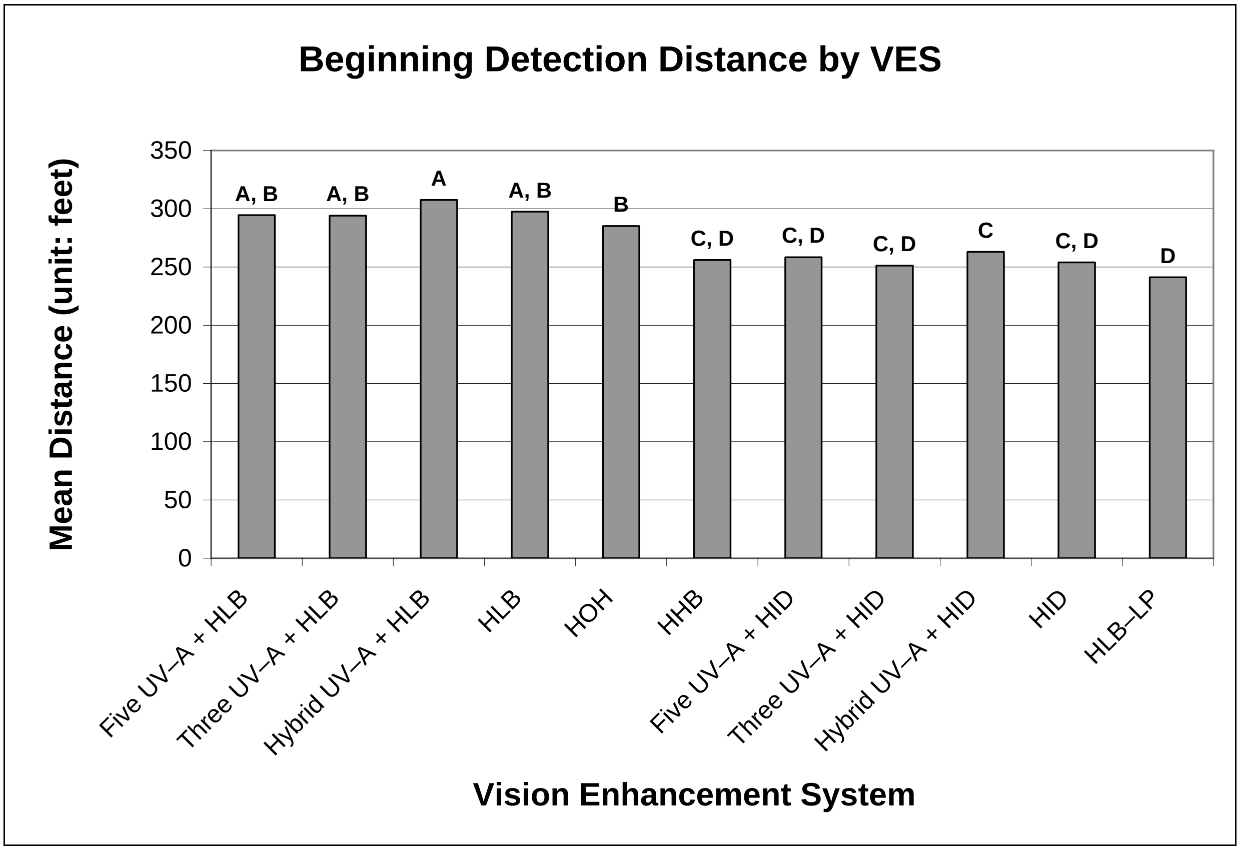
Table 5 represents the results of the ANOVA of the beginning detection distance for VES and pavement marking material. The main effects of VES and pavement marking as well as their interactions were significant ($p < 0.05$). The post hoc results for the significant main effects and interactions were graphed (figure 11 through figure 14). Means with the same letter (i.e., SNK grouping) are not significantly different.

Table 5. ANOVA table for the beginning detection distance for VES configuration and pavement marking.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	411512.9	205756.5	3.31	0.0518	
Subject/Age	27	1678307.5	62159.5			
Within						
VES	10	470638.2	47063.8	25.03	<.0001	*
Age by VES	20	41143.3	2057.2	1.09	0.3551	
VES by Subject/Age	270	507631.0	1880.1			
Pvt. Mrkg.	2	442806.9	221403.5	28.73	<.0001	*
Age by Pvt. Mrkg.	4	3462.5	865.6	0.11	0.9777	
Pvt. Mrkg. by Subject/Age	54	416132.0	7706.1			
VES by Pvt. Mrkg.	20	17849.5	8912.5	6.62	<.0001	*
Age by VES by Pvt.Mrkg.	40	55268.2	1381.7	1.03	0.4292	
VES by Pvt. Mrkg. by Subject/Age	532	717617.5	1346.4			
TOTAL	981	4915550.3	5005.7			

*$p < 0.05$ (significant)

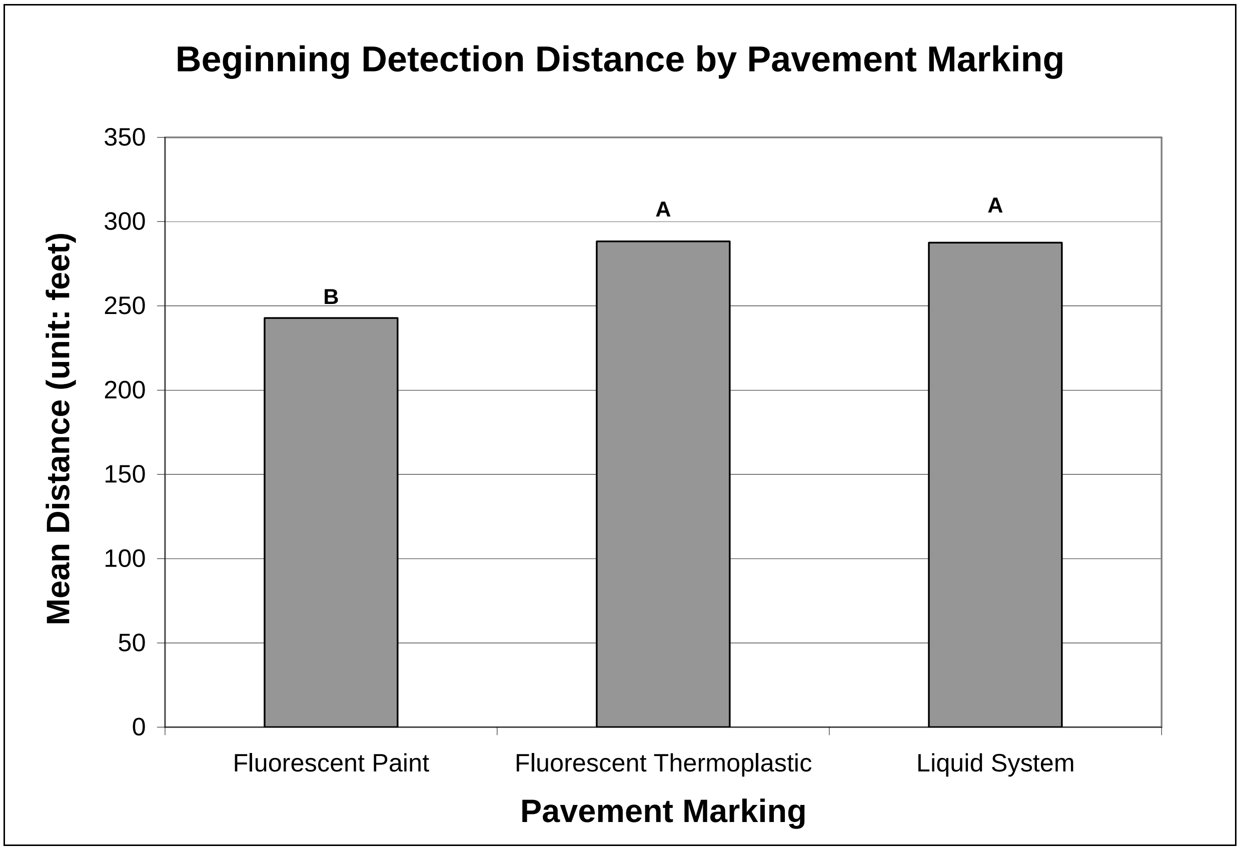
Figure 11 shows the SNK results on beginning detection distance for each VES. The HLB configurations (i.e., HLB, hybrid UV–A + HLB, three UV–A + HLB, and five UV–A + HLB) and HOH provided the longest beginning detection distances, and they were significantly different from the HID configurations, the HHB, and HLB–LP. Appendix I shows these results side-by-side with results for the ending distances by VES.



1 ft = 0.305 m

Figure 11. Bar graph. SNK post hoc results on beginning detection distance for the main effect: VES.

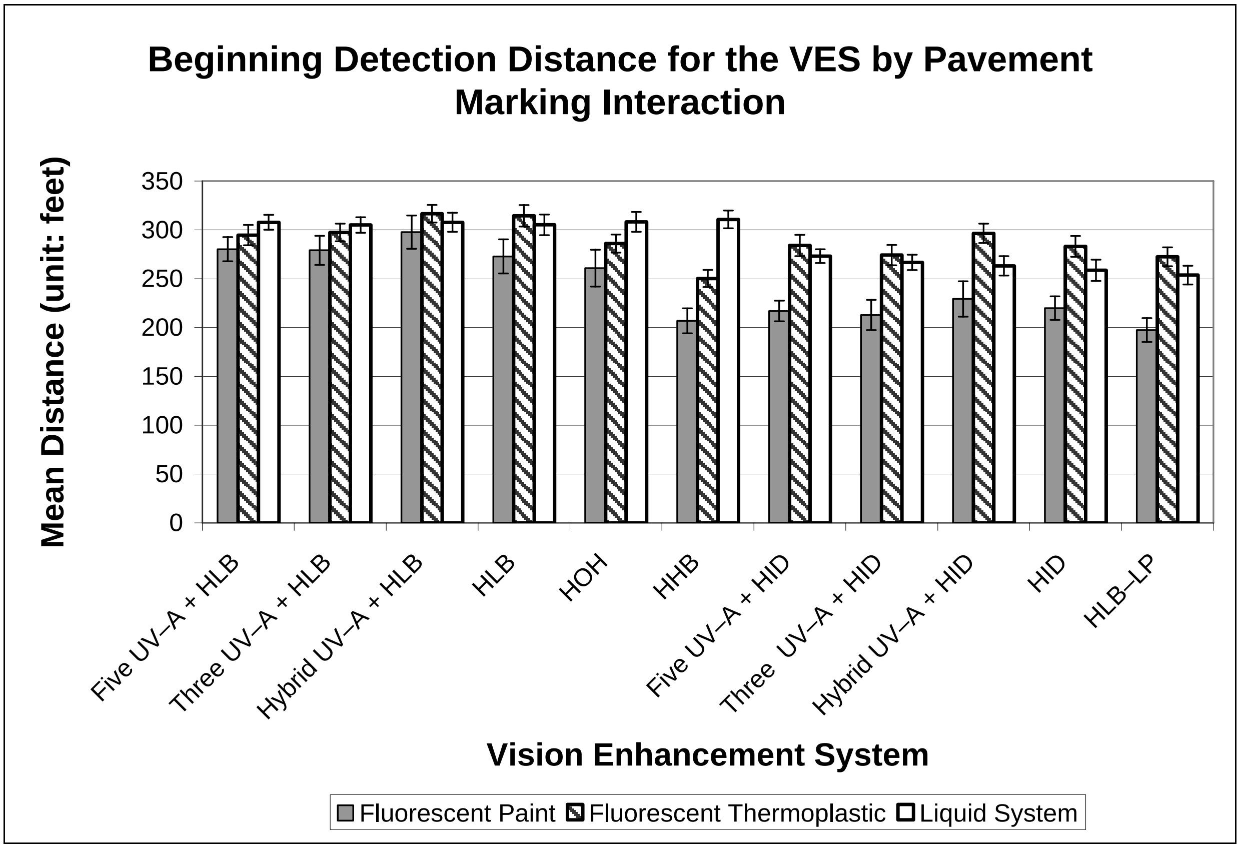
Figure 12 shows the SNK results on beginning detection distance for each pavement marking material. The fluorescent paint was statistically different from the fluorescent thermoplastic and the liquid system, and it provided the lowest beginning detection distance of the three.



1 ft = 0.305 m

Figure 12. Bar graph. SNK post hoc results on beginning detection distance for the main effect: pavement marking.

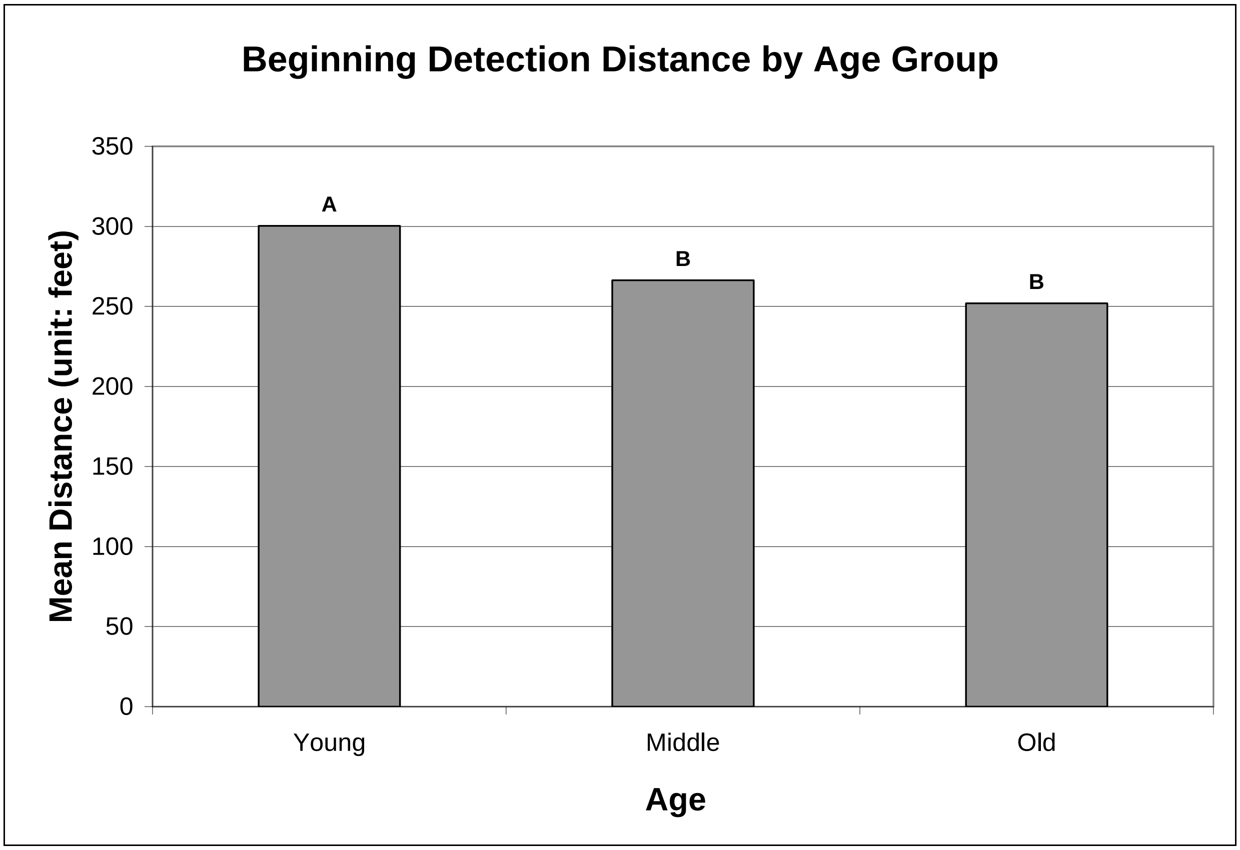
Figure 13 shows the interaction between pavement marking and VES for beginning detection distance. The fluorescent paint, the thermoplastic, and the liquid system appeared to perform comparably in conjunction with HLB, HLB with UV–A, and HOH. The beginning detection distance for the fluorescent paint diminished compared to the thermoplastic and liquid system when viewed with HHB, HLB–LP, and the HID configurations.



1 ft = 0.305 m

Figure 13. Bar graph. Results on beginning detection distance for the interaction: VES by Pavement Marking.

A marginal effect was found for age and beginning detection distance. A post hoc SNK (figure 14) indicates that the young age group attained the highest detection distance, which was significantly different from both the middle and older age groups.



1 ft = 0.305 m

Figure 14. Bar graph. SNK post hoc results for beginning detection distance for the main effect: age.

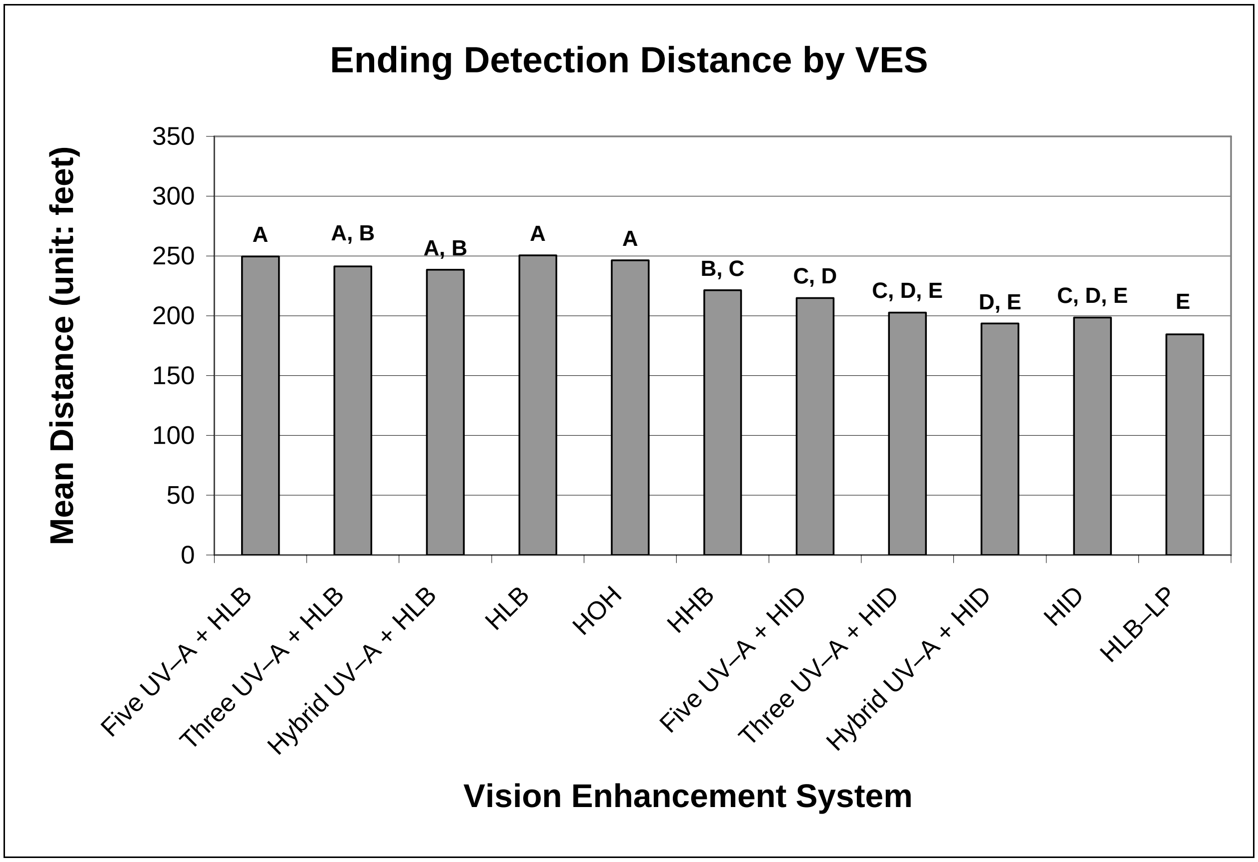
Table 6 outlines the results for the ending detection distance. The main effects of VES configuration, pavement marking, and age were significant ($p < 0.05$). The interaction between VES and pavement marking was also significant ($p < 0.05$). Figure 15 through figure 18 illustrate the post hoc results for the significant main effects and interactions.

Table 6. ANOVA table for the ending detection distance for VES configuration and pavement marking.

Source	DF	SS	MS	F value	P value	
Between						
Age	2	912646.0	456323.0	3.75	0.0367	*
Subject/Age	27	3213675.7	119025.0			
Within						
VES	10	529420.3	52942.0	13.70	<.0001	*
Age by VES	20	133691.3	6684.6	3.13	0.6665	
VES by Subject/Age	270	1052452.9	3898.0			
Pvt. Mrkg.	2	138943.0	69471.5	5.12	0.0092	*
Age by Pvt. Mrkg.	4	31107.1	7776.8	0.57	0.6831	
Pvt. Mrkg. by Subject/Age	54	732624.6	13567.1			
VES by Pvt. Mrkg.	20	121992.7	6099.6	3.08	<.0001	*
Age by VES by Pvt. Mrkg.	40	63765.6	1594.1	0.75	0.8735	
VES by Pvt. Mrkg. by Subject/Age	532	1140971.0	2136.7			
TOTAL	981	8092123.1				

*$p < 0.05$ (significant)

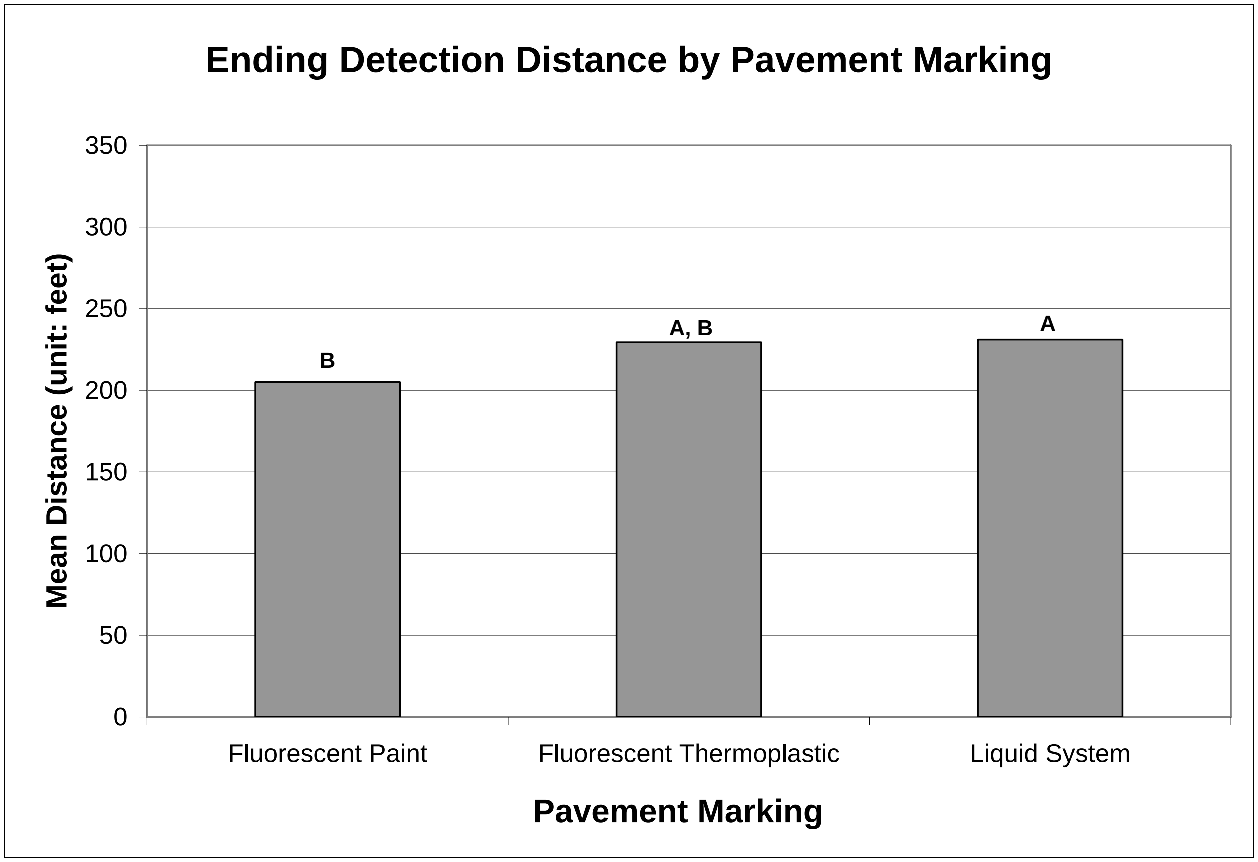
Figure 15 shows the SNK results on ending detection distance for each VES. For this evaluation, the HLB configurations and HOH provided the highest ending detection distances, and the results were significantly different from those of the HID configurations, HHB, and HLB–LP. Appendix I shows these results side-by-side with results for the beginning distances by VES.



1 ft = 0.305 m

Figure 15. Bar graph. SNK post hoc results on ending detection distance for the main effect: VES.

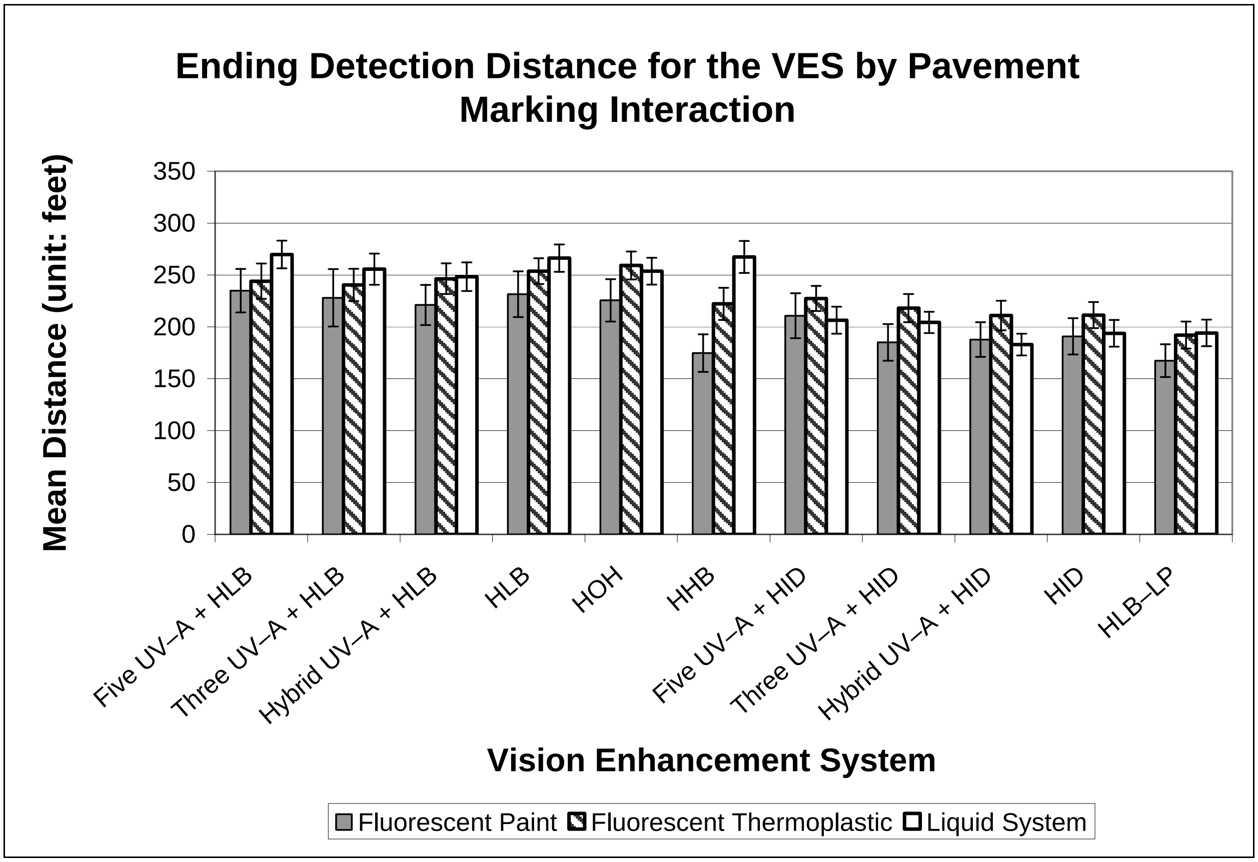
Figure 16 shows the SNK results on ending detection distance for each pavement marking material. For this evaluation, the liquid system and fluorescent thermoplastic were the most visible, but the fluorescent thermoplastic was not significantly different from the fluorescent paint.



1 ft = 0.305 m

Figure 16. Bar graph. SNK post hoc results on ending detection distance for the main effect: pavement marking.

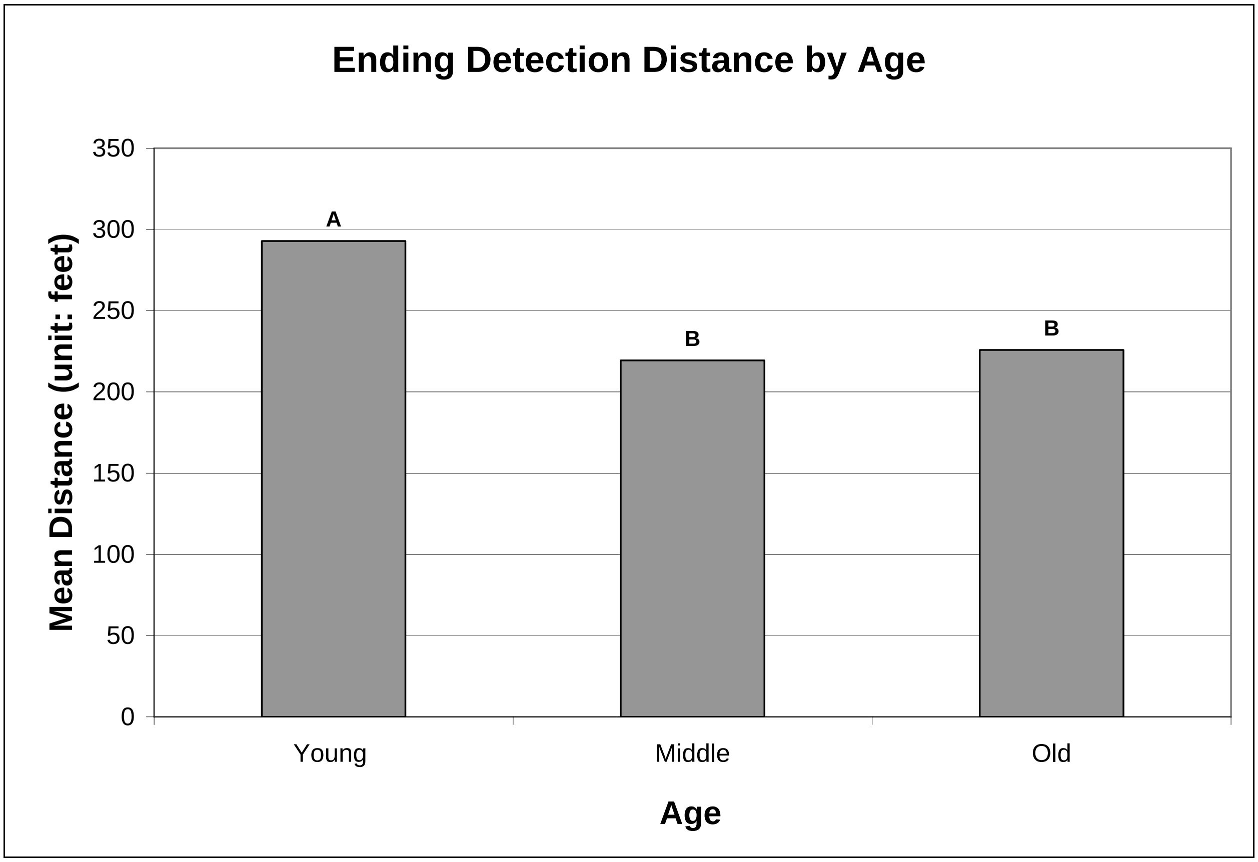
Figure 17 represents the interaction between pavement marking and VES for ending detection distance. Ending detection distances were higher for HLB configurations and HOH in conjunction with all three pavement marking materials. Both the thermoplastic and liquid system had high detection distances with HHB, but the fluorescent paint did not perform as well.



1 ft = 0.305 m

Figure 17. Bar graph. Results on ending detection distance for the VES by Pavement Marking interaction.

Figure 18 represents the SNK results on ending detection distance for age. Young drivers had significantly longer detection distances compared to the other two age groups.



1 ft = 0.305 m

Figure 18. Bar graph. SNK post hoc results on ending detection distance for the main effect of age.

CHAPTER 4—DISCUSSION AND CONCLUSIONS

For this research, a series of questions was established to evaluate VES types and pavement markings. First, which VES from the 11 chosen provided the longest pavement marking detection distances? Second, which pavement marking material was the most visible with all the VESs? Third, does the addition of UV–A headlamps to the baseline headlamps affect pavement marking visibility?

As mentioned in chapter 2, Methods, of this study, the aiming protocol used resulted in a deviation in the maximum intensity location from where it typically is for some headlamp types. Details about this deviation are discussed in ENV Volume XVII, *Characterization of Experimental Vision Enhancement Systems*. As a result of the headlamp aiming, it is likely that the detection distances increased for the HLB configurations and HOH and decreased for the HHB VES. It is important to consider the results presented in this study in the context and conditions tested. If different halogen headlamps or aiming methods had been used, different results might have been obtained.

VES

The first research question in this study evaluated which of the VESs offered the greatest beginning and ending detection distances.

For the beginning detection distance only, the hybrid UV–A + HLB provided the longest detection distance. In addition, HLB, three UV–A + HLB, five UV–A + HLB, and HOH had longer detection distances compared to the HID, HID + UV–A configurations, HHB, and HLB–LP. The shortest beginning detection distance was obtained by the HLB–LP, a common sedan headlamp configuration.

The five UV–A + HLB had the longest ending detection distance overall; however, it was not significantly different than the HLB, hybrid UV–A + HLB, three UV–A + HLB, or HOH VESs, all of which had significantly longer ending detection distances when compared to the other VESs. The poorest performing VES with the shortest ending detection distance was again the HLB–LP, or common sedan headlamp configuration.

For both beginning and ending detection distances, the UV–A + HLB configurations and HLB (baseline) provided consistently longer detection distances, and no significant differences were found among them. The HLB VES appears to provide sufficient visibility without the addition of the UV–A. In contrast to the HID beam pattern, the HLB, HOH, and HHB VESs all had a straight-ahead beam pattern that did not contain a sharp cutoff, resulting in an increase in visibility down the road.[(23)]

The HID configurations generally had the shortest detection distances and were significantly shorter than the HLB configurations. As with the HLB configurations, the addition of UV–A did not significantly increase detection distance over the baseline HID VES.

When comparing the detection distances of all the configurations to the recommended pavement marking preview time of 3.65 s (i.e., at 40 km/h or 25 mi/h, about 41 meters or 134 ft) as suggested by Schnell and Zwahlen, all the VES designs, even the VES with the lowest detection distances (HLB–LP), provided adequate visibility for that benchmark.[(16)] A reduction in pavement marking visibility as speed is increased,[(7)] however, implies that the VES configurations with greater detection distances may be more beneficial at greater speeds.

The HLB–LP provided the lowest detection distances of all the VESs, perhaps resulting in part from the low profile of both the vehicle and its headlamp. When riding higher in a vehicle, a driver is more likely to obtain longer visibility distances because of the perspective rather than the specific headlamp configuration in use.

In summary, the overall best-performing VES is the HLB configuration. The addition of the UV–A headlamps to the HLB and HID headlamps did not significantly increase the detection distances obtained in the data. Within the confines of this research, it is not known how well other HLB headlamps would perform given the same evaluation technique but with a different beam pattern, with a different aiming strategy, or at higher speeds.

PAVEMENT MARKING MATERIALS

In addition to the VES configurations tested, a series of pavement marking materials were also evaluated, which included fluorescent paint, fluorescent thermoplastic, and a two-part liquid system. For the beginning detection distances, the fluorescent thermoplastic had the longest detection distances, followed by the liquid system. The detection distances for both the fluorescent thermoplastic and the liquid system were significantly longer than that of the fluorescent paint, but neither had statistically different detection distances when compared to each other. Similar findings occurred for the ending detection distances, with the liquid system having the farthest but not significantly longer detection distance than the thermoplastic. Again, both the thermoplastic and the liquid system had significantly longer detection distances than the fluorescent paint. The detection distance results are somewhat similar to other research (for example, Nitzburg et al., 1998) that found that thermoplastic outperformed other pavement marking materials.[(24)] However, the current research found no differences between the fluorescent thermoplastic and the nonfluorescent liquid system.

Both materials, the liquid system and the thermoplastic, outperformed the fluorescent paint, and hence they are recommended for increased night visibility. An interesting note is that all three materials exceeded the minimum visibility benchmark suggested by Zwahlen and Schnell.[(16)] These researchers suggested a minimum 3.65-s preview time to allow drivers to see pavement markings at a speed of 40 km/h (25 mi/h). The detection means for the three pavement marking materials for both the beginning and ending detection distances exceeded the approximately 41-m (134-ft) distance (i.e., 3.65-s visibility distance at 40 km/h or 25 mi/h). It is important to remember that these results are for a specific lower speed only; thus, all pavement marking materials tested in this research may be used effectively on lower-speed roadways. The visibility requirement on higher-speed roadways involves additional research that is beyond the scope of the current project.

The pavement markings used in the research were 2 months old when the data collection took place, and the florescent properties may have degraded in that time frame. This degradation may have affected the results for the UV–A configurations; however, the degradation of the material reflects normal weathering encountered on all roadways over time.

In summary, both the fluorescent thermoplastic and liquid system provided longer detection distances when directly compared to a fluorescent paint design. All three pavement marking materials provided the minimum visibility benchmark requirements for a specific low speed.[(16)]

INTERACTION OF PAVEMENT MARKING AND VES

Significant interactions were found between VES and the pavement marking materials for both the beginning and ending detection distances. When looking at the beginning mean detection distances for each headlamp and pavement marking, the fluorescent paint did not perform well for the HID configurations, HHB, and the HLB–LP. Because of the poor performance of the UV–A supplemental VES (discussed in more detail later), fluorescent paint is not recommended for implementation.

In fact, based on the results of the current research, recommending a specific pavement marking and VES combination is not advised. All three pavement marking materials provided beginning detection distances longer than 84 m (275 ft) when viewed with HLB configurations. Conversely, all three pavement markings had beginning detection distances close to or less than 76 m (250 ft) when viewed with the HID configurations. These results likely result from the interaction between the VES and pavement marking material used. For example, with the HID configurations, perhaps the physical property of the pavement marking (e.g., bead pattern) is less compatible with the increased blue light emitted by the HID headlamps. Another possibility is that the sharp cutoff of the HID headlamps send less light down the road, or that their higher foreground luminance makes it difficult to detect relatively low-luminance markings at greater distances.

The ending detection distances in combination with the various VESs were generally lower overall in comparison to the beginning distances. When reviewing the means for the HLB configurations, all pavement marking visibility distances were around 76 m (250 ft) or less. Visibility performance dropped to around 61 m (200 ft) or less for all three pavement marking materials for the HID configurations.

UV–A AND BASELINE HEADLAMP CONFIGURATIONS

The results of the post hoc tests for the VES main effects indicated no statistical difference between the HLB and the HLB with UV–A. There also was no statistical difference between the HID and the HID with UV–A. Table 7 shows the mean beginning detection distances for each of these VESs for each pavement marking. Table 8 shows the same information for ending detection distances. It is clear that there is little or no benefit from the supplementation of the HLB or the HID with UV–A. It should be noted that this lack of benefit from using UV–A on the fluorescent pavement marking materials may have been the result of the weathering of the material for 2 months; however, if only 2 months of weathering severely limited the benefit of the fluorescent material pavement marking, then such a system is not practical for implementation.

Table 7. Beginning detection distance means for VES baselines and supplemental UV–A.

VES	Beginning Distance Fluorescent Paint (ft)	Beginning Distance Fluorescent Thermoplastic (ft)	Beginning Distance Liquid System (ft)
HLB	272.9	314.6	305.3
Hybrid UV–A + HLB	297.8	316.6	307.9
Three UV–A + HLB	279.1	297.5	305.1
Five UV–A + HLB	280.3	294.7	307.9
HID	219.9	283.2	258.7
Hybrid UV–A + HID	229.3	296.5	263.2
Three UV–A + HID	212.9	274.2	266.8
Five UV–A + HID	216.9	284.2	273.1

1 ft = 0.305 m

Table 8. Ending detection distance means for VES baselines and supplemental UV–A.

VES	Ending Distance Fluorescent Paint (ft)	Ending Distance Fluorescent Thermoplastic (ft)	Ending Distance Liquid System (ft)
HLB	231.5	253.7	266.2
Hybrid UV–A + HLB	221.1	246.4	248.3
Three UV–A + HLB	227.9	0	255.6
Five UV–A + HLB	234.9	244.0	269.8
HID	190.8	211.3	193.8
Hybrid UV–A + HID	187.8	210.9	182.9
Three UV–A + HID	185.0	218.1	204.3
Five UV–A + HID	210.7	227.4	206.4

1 ft = 0.305 m

AGE

This research study focused on three age groups: 18 to 25 years, 40 to 50 years, and 60 years and older. A marginal age effect was found for the beginning detection distance, and a subsequent SNK revealed that younger drivers had longer detection distances than both the middle-aged and older age groups. Furthermore, a significant main effect was found for age with respect to ending detection distance. Again, younger drivers had longer detection distances than both the middle-aged and older drivers. It is likely that visual degradation influenced the detection distances of the older drivers when compared to the younger ones. Furthermore, researchers have also shown that older drivers have longer reaction times than younger drivers, resulting in shorter detection distances.[25]

RESEARCH LIMITATIONS

One limiting factor that was present in the current research was the pavement material on which the pavement markings were applied. Specifically, the fluorescent paint was applied only on concrete; the fluorescent thermoplastic and the liquid system were applied to asphalt. The different pavement materials provide different contrast levels in association with the pavement marking technology. More specifically, concrete generally provides the least contrast under all conditions. From the current data, it is difficult to determine how much the pavement material reduced the visibility of the fluorescent paint material, but the pavement type confound likely resulted in lower averages. The lack of improvement in detection distances when using supplemental UV–A, for both fluorescent materials, indicates that fluorescent paint likely would not be used as a pavement marking. Adding fluorescent material for no meaningful benefit would be cost prohibitive. Future research should take into consideration the type of pavement material onto which the pavement marking is applied. The type of pavement material may enhance or detract from the overall effect of the pavement marking visibility.

Another limiting factor that should be taken into consideration is that of participants' eye height between the vehicles used. Table 9 shows the vehicle, average participant eye height for that vehicle (measured from the pavement), and the VES configurations associated with each vehicle.

Table 9. Vehicle, average participant eye height, and headlamp configurations.

Vehicle	Average Participant Eye Height (in inches)	Headlamp Configurations
SUV	58.12	HLB Hybrid UV–A + HLB HID Hybrid UV–A + HID
SUV	58.69	Three UV–A + HLB Five UV–A + HLB Three UV–A + HID Five UV–A + HID
Pickup	61.56	HOH HHB
Sedan	47.87	HLB–LP

1 inch = 2.54 cm

Even between the taller vehicles there was still almost an 8-cm (3-inch) height difference between the SUV and the pickup truck. When comparing similar VES configurations (e.g., halogen) and detection distances for these vehicle types, the detection distance differences were not significant. It should be noted that the poorer detection distances recorded using the HLB–LP likely resulted at least in part from the lower visual perspective of the roadway from the vehicle.

The age of pavement markings also should be taken into consideration when discussing the research limitations. For example, when testing was conducted, the pavement markings were already 2 months old, which may have negatively affected the potential effect of the UV–A headlamps. If the pavement marking material had degraded substantially in that timeframe, perhaps its real-world use would not be cost effective or beneficial.

Finally, the last limitation in this research study concerns headlamp beam pattern and aiming strategy. The sharp cutoff pattern was represented only in the HID configurations; the straight-ahead beam pattern was found in all other visible light headlamps. As discussed previously, the HLB configurations and HOH VES likely had greater detection distances and the HHB likely had shorter detection distances than they would have had if they had been aligned more typically. The differences found between the VESs regarding the pavement marking material visibility may be attributable to differences in headlamp beam pattern and aiming. Caution should be taken when interpreting these results across headlamps with different beam patterns and aiming strategies.

CONCLUSIONS

The analysis of the data from this research study provides six conclusions:

- All of the VESs provided adequate minimal visibility distances for all of the pavement marking materials evaluated at the 40 km/h (25 mi/h) speed driven. It is likely that visibility would be adequate at much higher speeds, but additional research would be required to verify this.
- The supplemental UV–A did not improve detection distances for either the HID or the HLB headlamps.
- Both the liquid system and fluorescent thermoplastic outperformed the fluorescent paint; however, the fluorescent paint was on concrete while the other materials were on asphalt.
- Nothing in this study supported the additional cost of adding fluorescent material to pavement markings.
- Younger drivers attained the longest detection distances, which likely results in part from their faster reaction times and higher visual acuity levels.[25]
- Participants had longer detection distances when searching for the beginning of the pavement marking as compared to searching for the end of the pavement marking.

Finally, for this research, data were collected in clear weather conditions only. In an effort to more fully examine the effect of pavement markings on visibility, various weather conditions should be explored. For example, Schnell and Ohme commented on the degradation in pavement marking visibility in rain.[26] Researchers also have discussed how precipitation affects the transmissivity of the atmosphere, which in turn could affect the luminance of the pavement marking material.[1]

APPENDIX A—PARTICIPANT SCREENING QUESTIONNAIRE

Driver Screening and Demographic Questionnaire: ENV-Pavement Markings

Note to Screening Personnel:

Initial contact with the potential participants will take place over the phone. Read the following Introductory Statement, followed by the questionnaire (if they agree to participate). Regardless of how contact is made, this questionnaire must be administered before a decision is made regarding suitability for this study.

Introductory Statement (Use the following script as a guideline in the screening interview):

Good morning/afternoon! My name is _____ and I work at the Smart Road. I'm recruiting drivers for a study to evaluate new vehicle headlamps.

This study will involve you driving a car for two sessions on the Smart Road. The Smart Road is a test facility equipped with advanced data recording systems here in [contractor location]. *We will pay you $20 per hour. The total amount will be given to you at the end of the second session. Would you like to participate in this study?*

If they agree:

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

If they do not agree:

Thanks for your time.
****

Questions

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

Yes _____ No _____

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

3. How old are you? ______

4. Have you previously participated in any experiments at the [contractor facility]? If so, can you briefly describe the study?

Yes _____
Description:____
No _____

5. How long have you held your drivers' license? ____

6. What type of vehicle do you currently drive? ____

7. Are you able to drive an automatic transmission without assistive devices or special equipment?

Yes _____ No _____

8. Have you had any moving violations in the past 3 years? If so, please explain.

Yes _____ ____
No _____

9. Have you been involved in any accidents within the past 3 years? If so, please explain.

Yes _____ ____
No _____

10. Do you have a history of any of the following? If yes, please explain.

Heart condition	No____	Yes___________________________________
Heart attack	No____	Yes___________________________________
Stroke	No____	Yes___________________________________
Brain tumor	No____	Yes___________________________________
Head injury	No____	Yes___________________________________
Epileptic seizures	No____	Yes___________________________________
Respiratory disorders	No____	Yes___________________________________
Motion sickness	No____	Yes___________________________________
Inner ear problems	No____	Yes___________________________________
Dizziness, vertigo, or other balance problems	No____	Yes___________________________________
Diabetes	No____	Yes___________________________________
Migraine, tension headaches	No____	Yes___________________________________

11. Have you ever had radial keratotomy, corrective eye surgery, or other eye surgeries? If so, please specify.

Yes _____ ____
No _____

12. (Females only, of course) Are you currently pregnant?

Yes _____ No _____

13. Are you currently taking any medications on a regular basis? If yes, please list them.

Yes _____ ____
No _____

14. Do you have normal or corrected to normal hearing and vision? If no, please explain.
Yes _____
No _____ ____

I would like to confirm your full name, phone number (s) (home/work) where you can be reached, hours/days when it's best to reach you, and preferred days to participate.

Name ____ Male / Female

Phone Numbers (Home)________________________(Work)________________________

Best Time to Call ____

Best Days to Participate___________________

****

Criteria For Participation:

1. Must hold a valid driver's license.
2. Must be 18-25, 40-50, or 60+ years of age.
3. Must drive at least two times a week.
4. Must have normal (or corrected to normal) hearing and vision.
5. Must be able to drive an automatic transmission without special equipment.
6. Must not have more than two driving violations in the past three years.
7. Must not have caused an injurious accident in the past two years.
8. Cannot have a history of heart condition or prior heart attack, lingering effects of brain damage from stroke, tumor, head injury, or infection, epileptic seizures within 12 months, respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, chronic migraine or tension headaches.
9. Must not be pregnant.
10. Cannot currently be taking any substances that may interfere with driving ability (cause drowsiness or impair motor abilities).
11. No history of radial keratotomy, corrective eye surgery, or any other ophthalmic surgeries.

****

Accepted: ________ Days that will attend to Study:
(T):_________(N1):_________(N2):________

Rejected: ________ Reason:____

Screening Personnel (print name):_____________________ (Date):________

APPENDIX B—INFORMED CONSENT FORM

[Contractor Facility]
Informed Consent for Participants of Investigative Projects

Title of Project: Evaluation of the Degree of Enhanced Visibility of Pedestrians and Traffic Control Devices under Various Vision Enhancement Systems

Investigators: [List Name of Investigators Here]

THE PURPOSE OF THIS RESEARCH/PROJECT

THE PURPOSE OF THE PROJECT IS TO DETERMINE THE DEGREE OF ENHANCED VISIBILITY OF THE ROADWAY ENVIRONMENT WITH VARIOUS TYPES OF VISION ENHANCEMENT SYSTEMS WHILE DRIVING AT NIGHT.

I. PROCEDURES

Show a current valid driver's license.
Read and sign this Informed Consent Form (if you agree to participate).
Participate in three vision tests.
Perform one or more of the following portions of the study (you will be performing the studies that are marked with a check mark):

- ☐ Study 1: Drive a vehicle on the Smart Road at no more than 25-miles per hour and report when you see the first and the last pavement markings on a given portion of the road.

- ☐ Study 2: Drive a vehicle on the Smart Road at no more than 25-miles per hour and evaluate the level of discomfort caused by glare from headlamps of vehicles coming in the opposite direction.

- ☐ Study 3: Drive a vehicle along the Smart Road at no more than 25 miles per hour and respond when you see objects in and along the roadway.

II. RISKS

The primary risks that you may come into contact with are the obstacles on the road for Study 3. It is for this reason that you are to maintain a speed of not more than 25 miles per hour (this will be maintained for all three studies) and to maintain a 200-foot area between the vehicle and the obstacles (only applies to Study 3). For your safety, the following precautions are taken:

- The Smart Road is equipped with guardrails. Therefore, if you do lose control of the vehicle, the guardrails will prevent you from sliding off the road.

- You are required to wear a seat belt at all times in the vehicle, and the vehicle is equipped with anti-lock brakes.

- You do not have any medical condition that would put you at a greater risk, including but not restricted to heart conditions, head injuries, epilepsy, and balance disorders.

- In addition, you have not had radial keratotomy, [laser] eye surgery, or any other ophthalmic surgeries.

- The only other risk that you may be exposed to is fatigue after sitting in the driver's seat for a prolonged period of time. However, if you would like to take a break at any time, please inform the experimenter.

III. BENEFITS OF THIS PROJECT

While there are no direct benefits to you from this research (other than payment), you may find the experiment interesting. No promise or guarantee of benefits is made to encourage you to participate. Your participation will help to improve the body of knowledge regarding various vision enhancement systems.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The data gathered in this experiment will be treated with confidentiality. Shortly after you have participated, your name will be separated from your data. A coding scheme will be employed to identify the data by participant number only (e.g., Participant No. 3). After the experiment, the data will be kept in a locked safe.

V. COMPENSATION

You will be paid $20 per hour for participating in this study. You will be paid in cash at the end of your voluntary participation in this study.

VI. FREEDOM TO WITHDRAW

As a participant in this research, you are free to withdraw at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any question or respond to experimental situations without penalty.

VII. APPROVAL OF RESEARCH

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at [name of contractor review board]. You should know that this approval has been obtained.

VIII. SUBJECT'S RESPONSIBILITIES

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To follow the experimental procedures as well as you can, and

2. To inform the experimenter if you incur difficulties of any type.

3. Wear your seat belt.

4. Abide by the 25 mile-per-hour speed limit.

IX. SUBJECT'S PERMISSION

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Signature Date

Should I have any questions about this research or its conduct, I may contact: (List names and contact information for review board and investigators here).

APPENDIX C—PARTICIPANT VISION TEST FORM

PARTICIPANT NUMBER: __________

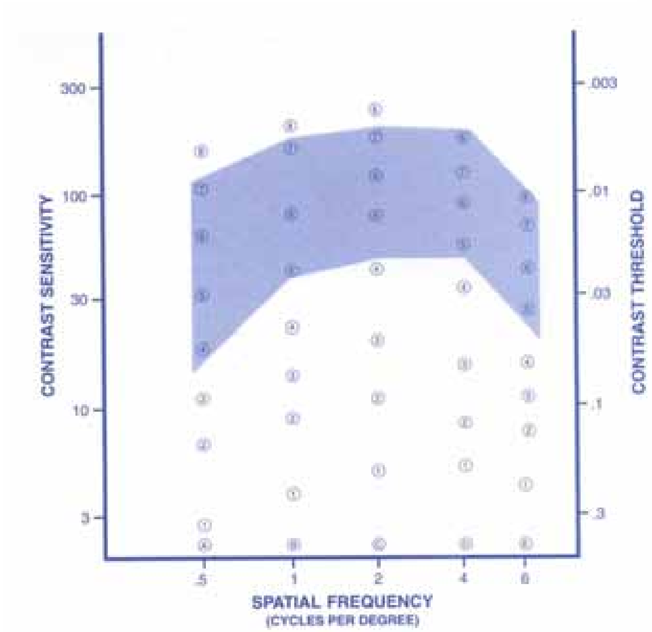
VISION TESTS

Acuity Test

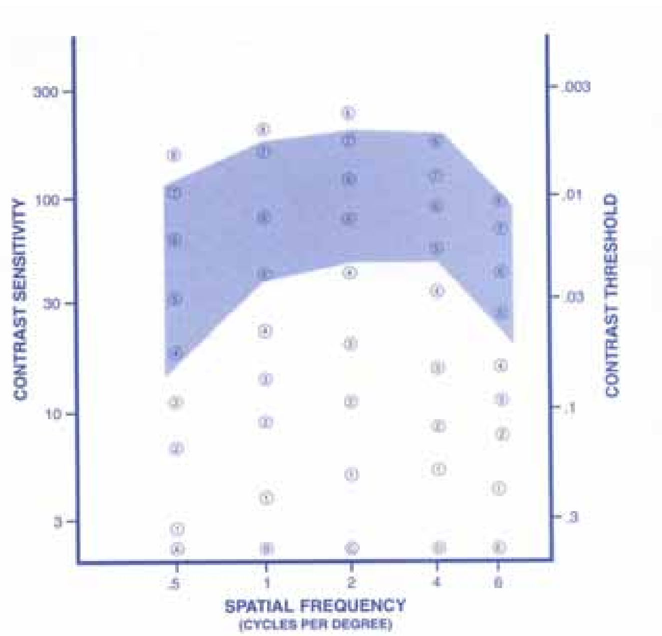
- Acuity Score:_________

Contrast Sensitivity Test

Left



Right



Ishihara Test for Color Blindness

1._____ 4._____ 7.____

2._____ 5._____

3._____ 6._____

APPENDIX D—IN-VEHICLE EXPERIMENTER PROTOCOL

<u>Protocol for Enhanced Night Visibility Pavement Markings- In-Vehicle Experimenters</u>

Session One

- Prior to the participant's arrival, make sure that all the needed forms are available and label them with the subject number.
- Greet Participant
- Record the time that the participant arrived on the debriefing form
- Show driver's license.

Before we begin, it is required for me to verify that you have a driver's license. Would you please show me your license?

Must be a valid Class A driver's license to proceed with the study. Out of state is fine.

Experimenter read text in italics out loud:

This research is sponsored by the Federal Highway Administration. The purpose is to gather information that will be available to the public, including car manufacturers. The goal is to determine the best vision enhancement systems to help drivers see pavement markings at night. The lights need to also be safe and not cause any discomfort for other drivers on the road.

The study will take place on the Smart Road testing facility. The road will be closed off to all traffic except for experimental vehicles. There will be at most four experimental vehicles on the road at one time including the vehicle you will be in.

During the experiment, I will be in the vehicle with you at all times. I will be responsible for asking you questions during the drive, recording some data, and monitoring the equipment. In addition, I will be able to answer any questions you have during the drive.

You will be exposed to eleven different vision enhancement systems. You will make one lap on the Smart Road for each vision enhancement system. You will be exposed to different pavement markings with each VES. Your job will be to tell the experimenter when you detect the first and the last pavement marking in each section .

Do you have any questions at this time? (Answer questions if needed).

Informed consent

Now I have some paperwork for you to fill out. This first form tells you about the study, what your job is, and any safety risks involved in the study. Please read through the document. If you have any questions, please feel free to ask. If not, please sign and date the paper on the last page.

- Give the participant the form
- Answer questions
- Have participant sign and date both forms
- Give the participant a copy of the informed consent

Tax forms.

To complete the W-9, the participant must fill out the following in the box:

- Name
- Address
- Tax ID number (social security number)
- Sign and date at the bottom

The other side of the form is a University Voucher stating they are not being "permanently" employed by our project. Have them print their name on the top of the form.

Vision tests.

Follow me and I will go through the vision tests with you.

The results for all three parts must be recorded on the Vision Test Form.
The first test is the Snellen eye chart test.

- Take the participant over to the eye chart test area.
- Line up their toes to the line on the floor (20 feet).
- Participants can leave on their glasses if they wear them for driving.

  Procedure*: Look at the wall and read aloud the smallest line you can comfortably read.*

  - If the participant gets every letter on the first line they try correct have them try the next smaller line. Continue until they miss a letter. At that time, record the one that they were able to read in full (line above).
  - If they get the first line they attempt incorrect, have them read the previous line. Repeat as needed until they get one line completely correct. Record this acuity.
  - Participant must have 20/40 or better vision using both eyes to participate in the study.

The next vision test is the Contrast Sensitivity test. Take the participant over to the eye chart test area.

- Line up their toes to the line on the floor (10 feet).
- Participants can leave on their glasses if they wear them for driving.

Procedure: *We are going to test how well you see bars at different levels of contrast. Your ability to see these bars relates to how well you see everyday objects. It is VERY IMPORTANT you do not squint or lean forward while you are taking the test.*

- Point out the sample patches at the bottom of the chart with the three possible responses (left, right, or straight).
- Cover one eye with an occluder. (DO NOT let the participant use his/her hand to cover the eye since pressure on the eye may cause erroneous contrast sensitivity test results).
- Instruct the participant to begin with Row A and look across from left to right. Ask the participant to identify the last patch in which lines can be seen and tell you which direction they tilt. If the response is incorrect, have the participant describe the preceding patch.
- Use the table in the ENV binder to determine if subjects' answers are correct.
- Each vertical column of numbers on the second part of the Vision Test form corresponds to a horizontal row on the chart. Record the last patch the participant correctly identifies in each row by marking the corresponding dot on the form.
- To form the participant's contrast sensitivity curve, connect the points marked.
- Cover the other eye and repeat all the steps above.

The last vision test is the Test for Color Blindness.

Procedure:

- Take the participant back to his/her desk.
- Place the book containing the plates on the testing apparatus

Please hold the red end of this handle to your nose and read the number on the following plates.

- Record the participants answers on the Vision Tests Form

Go to Turnaround 1 on the road

Take the participant to the rental vehicle and instruct them to drive to the road.
Radio the onroad experimenters that you are ready to begin.

We will ask you to drive four different vehicles. Once the vehicles arrive, you will meet the valet, who will escort you to your next vehicle. You will drive the vehicle down the road at a comfortable speed. Then you will drive up the road at 25 mph. You will need to indicate when you see the first and the last pavement markings in each section. By pavement markings I am referring to the lines down the middle of the road. We have three sections of pavement markings. Each section has a different type of paint, so some may or may not be more visible than other sections. You will press this button (show the button) when you see both the first and the last marking in each section. The sections are separated by segments of black tape. With the tape, the sections look like this.

Show the participant the drawing of the pavement markings. Point out the pavement tape.
Do you have any questions?

The on road experimenter will escort the participants to their first vehicle. In the mean time, you will get into the appropriate vehicle and set up the computer by entering in the participant information and current setup.

Wait while the on road experimenter performs the participant eye height measurement. This will occur once the participant has adjusted the seat to his/her satisfaction.
The measurements only occur when the participant is in a vehicle for the first time.
Once the on road experimenter is finished, make sure they check the vehicle lights for you. In addition, if you are in the Sedan you will need to adjust the fan down as soon as the vehicle is started. For the practice lap, you will scroll to "Practice" VES in the VES field. When the on road experimenter has completed the measurements, instruct the driver on the following:

Practice Lap
We will now have a practice lap to help you get used to driving the vehicle on the Smart Road and using the push buttons. I would like you to drive down the road at a comfortable speed.

Point out the location of the pavement dip cones.

<u>First vehicle at the bottom of the hill</u>
- Pull all the way to the first parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 2nd vehicle is parked

<u>Second vehicle at the bottom of the hill</u>
- Pull into the second parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 1st vehicle is up the hill
- Once stopped, explain the protocol again.

As I explained before, we have three sections of pavement markings. I need you to indicate when you see the first and the last middle line in each section. You will indicate when you see the markings by pressing this button (hand them the button*). When you press the button you will hear a beep. So, you will hit the button a total of six times, two times in each section. The first pavement marking section begins as soon as you pull onto the road so you will need to start looking right away. You will need to maintain a speed of 25 miles-per-hour. We are going to drive up the road and practice. Do you have any questions?*

- Answer questions.
- Start the computer as follows:

Command	Function
RUN/HOLD (DMI)	Starts the DMI counting
Shift S	Starts data collection

*Note that there is space at the bottom of the screen for error messages. Check to make sure that you are not receiving any error messages.

While going up the hill, you need to monitor the following on the computer:
- Screen will read "Looking for object"
- After they press button the first time, screen will say "Recognizing Object"

- After they press button the second time, screen will say “Done”

Press the computer space bar again when your body is in line with the last pavement marking. After space bar is pressed, screen will say “Set-up”

During the practice lap, you may need to assist the participant. For example, if they do not indicate the first pavement marking and the marking has passed, you need to say,
“Did you see the first marking back there? As soon as you see that, you need to hit the button. You will also be pressing it soon when you see the last one in this section.”

In addition, you will need to point out the pavement dip cones and explain:

See the white cones there. Those cones represent indentations in the pavement. We put those cones there so you do not mistake those areas for the end of the pavement markings. So, when you see the white cones, you know the end of the pavement markings are not there.

<u>First vehicle at the top of the hill</u>

- Pull up to white line just before the top of hill
- Wait for headlight glow from 2nd vehicle to appear
- Continue back down the road at comfortable speed

<u>Second vehicle at the top of the hill</u>

- Pull up to first cone on the right side of the road
- Put vehicle in park
- Turn off lights
- Turn lights back on and go down the hill when the first vehicle is out of sight

<u>First vehicle at the bottom of the hill</u>

- Pull all the way to the first parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 2nd vehicle is parked
- Change VES field to appropriate condition (Shift + H)

<u>Second vehicle at the bottom of the hill</u>

- Pull into the second parking space
- Put the vehicle in park
- Ask participants to close their eyes until the 1st vehicle is up the hill
- Change VES field to appropriate condition (Shift + H)

Data Collection

I would like you to do the same as before by indicating when you see the first and the last pavement marking in each section. You will push the button a total of six times. I need you to drive at 25 miles-per-hour again. Remember to begin looking as soon as you pull onto the road for the first section of markings. Any questions?

This will repeat for all five or six vision enhancement systems. When the valets move the participants between vehicles, you will need to:

- Quit the computer program, using SHIFT Q
- Start the computer program in the new vehicle
- Enter the participant and current set-up information

Also be alert to the fact that some of the vehicles have automatic locking doors that do not unlock until the vehicle is shut off. In that situation you need to unlock the doors to let the valet inside.

Post-Experiment

- Shutdown all computers
- Turn off DMI's
- Collect the "ENV Clear Participant Measurement Form" of your participant back and check that all the measurements needed are there. The form should be signed and dated by the participant's valet and his/her in-vehicle experimenter.
- Ask the participant what was his/her "strategy" to detect the beginning and end of the pavement markings and document it on your note sheet.
- Take the participant up to the building.
- Have them complete the payment voucher and pay them, if it is the 2nd evening.
- If it the first night, remind them of their next session.
- Thank him/her for the cooperation and have the participant sign the payment sheets.

APPENDIX E—ONROAD EXPERIMENTER PROTOCOL

Enhanced Night Visibility Pavement Marking - Onroad Experimenter Protocol

1. General Policies

The primary goal of this research effort is safety. For that reason, you need to be safe at all times.

- Drive in a safe manner at all times. This means observing the 25 mile-per-hour speed limit on the road.
- Use a spotter when moving vehicles in and out of the garage.
- Always step back from the road when participant vehicles begin to move.
- Wear closed-toe shoes at all times.
- Always wear your vest on the road.
- Do not travel with the tailgate open.
- Wear your safety glasses when checking ALL headlights.

Over the course of the study, it is likely that apparatus will be broken. If you notice something is broken or you are the one who broke it, tell someone immediately if it is crucial to the study or as soon as convenient if it is not crucial. At any rate, you must report such damage before you leave from your shift.

Each night, you will need to arrive to the building on time. The nightly meeting will cover topics such as protocol changes, problems from the previous night, and schedule concerns. Make sure you document any problems from the previous night and make a note of them on the whiteboard. Operation of the headlights are outlined with a diagram and description in each vehicle. Failure to follow the procedures will prevent the headlights from working, therefore leave gaps in the data. For this reason, you are to review the operations each night for your assigned vehicle.

While the study is being conducted, radio communications on Channel 3 need to be minimized (emergencies excluded). Note that the in-vehicle experimenters cannot always respond to questions if they are interacting with the participant at that time. For this reason, you will need to give the in-vehicle experimenters extra time.

2. Pre-Experiment

At the nightly meeting, you will find which vehicles you are responsible for that night. You will be solely responsible for all aspects of that vehicle.
Each experimenter will need to sign out two (SUV experimenters) or four (Sedan/Pickup experimenters) radios.

Each onroad experimenter will be responsible to prepare vehicles. Each night, you will be required to perform the following tasks on the vehicles:

- Review the headlamp operations procedure located between the seats of the vehicle.
- Clean the windshield inside and outside.
- Wipe off headlamps. You should not be using cleaning solutions but just a shop rag.

- Make sure all the headlights are working.
- Make sure the radio is off.
- Cover the side mirrors with the stuff sacks; cover the inside mirror with poster board.
- Set dashboard lights to the minimum setting (not off).
- Make sure the vehicle has the power inverter and the DMI cable.
- Place all equipment not used for the Night Visibility study into the trunk/back of the vehicle.
- Place one radio in each vehicle and turn it onto Channel 3 at a middle volume.
- Place a flashlight in each vehicle- the best place is on the passenger-side floor.
- Close sunroofs- glass and cover.
- Check tire pressure. Tire pressure should be as prescribed on the inside of the driver door. Load steps into one of the vehicles.

Onroad experimenters will need to move all of the vehicles out of the garage area. The onroad experimenters will then take all the experimental vehicles to the road. This includes the SUV's and Sedan/Pickup (which vehicle goes first depends on whether it is Session 1 or Session 2). The in-vehicle experimenters will take the compact cars to the front entrance of the building. Back the vehicles into the entrance area. Make sure the vehicles are staggered so the participant can easily get in and out.

The Sedan/Pickup will set up the parking space cones and set up the cone indicating the dip in the road. Cone location is indicated by spray paint marks on the side of the road. Place the cone in the middle of the road (i.e. on the yellow skip marks) perpendicular to the location. The dip cone is painted white.

SUV 1 driver will put the steps on the right-hand shoulder for the on road experimenters to use. The steps need to be far enough off the road so that the participants will not run the risk of running over them.

3. Data Collection

The onroad experimenters will serve as valets. As a valet, you will be responsible for one participant for the entire night. The experimenters whose vehicles are driven first will be the "personal" valets for that evening.

- Each person is responsible for driving their experimental vehicles down to the turnaround.
- Each valet needs to get their valet box filled with measurement stuff.
- Overall goal is to make subject feel as comfortable as possible in each car.
- Be sure to be wearing a vest at all times.
- Move the seat to the furthest position back before the participant gets in.
- Put the stepstools on the side of the road so you can get them if the participant needs them.
- Have a flashlight in hand.

- Meet participants at the first vehicle (the compact cars) and show them to their first vehicle as per the experimenter sheet.
- Introduce yourself to the participants before getting them out of the vehicle.
- Assist subject when he or she is getting out of the vehicle if necessary. Use the stepstools if necessary. Lead/Guide participant from one vehicle to the next by shining the flashlight on the road in front of them.
- Open the door for the participant and move the seat back before they get in.
- Orient person to each vehicle and turn on the lights. Be sure to turn on the lights yourselves- do not let the participant do it. If they reach for the light switch, tell them, “That’s OK, I’ll take care of this for you.”

Sedan

This one you need to have them start the vehicle before orienting them because the seat and wheel move when you start it. Be sure to warn the participants of that before you start the car.

- Button on left side of seat moves seat up and down, back and forth (show button).
- Button for the steering wheel moves the wheel up and down, in and out.
- There are many lights. The only ones they need to worry about are the speedometers, analog and digital (point each out). The subject is free to use whichever they feel most comfortable with.
- Hand the participant the keys and have them start the car.
- Turn on the headlights all the way (two clicks). Make sure they are on before you leave the vehicle.
- Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

SUV 1

- Button on left side of seat moves seat up and down, back and forth (show button).
- Button for the steering wheel moves the wheel up and down.
- Hand the participant the keys and have them start the car.
- Turn on the parking lights (one click only).
- Show the participant how to adjust the interior lights. Note that with this vehicle the lights do not dim unless the door is closed.

SUV 2

- Button on left side of seat moves seat up and down, back and forth (show button).
- Button for the steering wheel moves the wheel up and down.
- Hand the participant the keys and have them start the car.
- Turn on the parking lights (one click only).
- Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is comfortable.

Pickup

- Lever in front of seat moves seat up and down (show lever).
- Button for the steering wheel moves the wheel back and forth.
- Hand the participant the keys and have them start the car.
- Turn on the parking lights (one click only).
- Show the participant how to adjust the interior lights. If necessary, help them to adjust it by asking them to tell you when it is as bright as they would normally have it.
- Remind the participant to keep their seatbelt on at all times.
- Ask them if they have any questions.

Complete the measurements.

To do this, first explain to the participant that you are going to make a mark on the window as to where their eye level is located. Instruct them to adjust their seat to where they think they will be comfortable. Once they are situated, tell them to look ahead and relax. Close the door and take the measurements.

- Measure the horizontal height by taking the level and moving it up the window until it "intersects" with the eye level. Make a line at that point with your marker.
- Measure the vertical distance by taking the level and moving it across the window until it intersects with the eye level. Mark a vertical mark at the point.
- Use this point to measure the distances.
- Take vertical measurement with metal end of tape measure down where the glass intersects with the black plastic.
- Take horizontal measurement with metal end of tape measure to the right where glass intersects with black plastic.
- Before you return to a vehicle, walk in front of the experimental vehicle to ensure the headlights are on and working. The lights cannot be turned on until the vehicle is the furthest one forward so you may have to wait until the other vehicle leaves to check the lights. Be sure to step back from the vehicle as soon as you are done checking.

Sedan: Regular headlamps only.
SUV 1: If UV is required, make sure they are working. Otherwise, make sure the two standard ones are on.
SUV 2: The top three UV lights should be on at all times. In the five UV condition the bottom two should be on. Report if one is not working or extremely dull. The standard lights should be working at all times.
Pickup: The two external headlamps on the front of the vehicle should be on.
The first parking space on each side is termed a "vehicle drop off" and needs to be available at the end of every lap. The valets will move any vehicle that is left in those locations.

Otherwise, you can wait in the other vehicle while the participants are taking their pavement laps. When you see the vehicles approaching the turnaround, move to the left shoulder of the road. NOTE: For the first headlamp there will be a training lap. The experimental vehicle will not stop at the turnaround. You must stay in the parked vehicle for safety.

When the participant gets back up to the turnaround, meet them at the car as soon as it comes to a complete stop. Once the participant sees you, you may open the door.
Turn off the parking lights (see above).
Ask the participant to turn off the vehicle and to hand you keys.
Help the participant out of the vehicle. Use the step if necessary. NOTE: Never move the participant so that they are in direct view of the oncoming lights. Have the participant wait until the other vehicle has turned off their lights before you take them out of the vehicle.
Put the keys to each car in the door lock when it is not being used.
Escort the participant to the next vehicle:
Repeat the orientation if they have not been in the vehicle before.
If they have been in the vehicle before, ask them if they remember the controls.
Be sure to offer to answer questions.

Finally, never tell the participant how many more laps they have. This is because in the event of a computer failure, etc. they may repeat a lap at the end. If this is the case, the in-vehicle participant will tell you. We do not, however, want the participant to know that they are going to do an extra lap.

4. Interim

The interim would occur is there are two groups of participants that night. If there are not two groups, then skip to 6. Post-Experiment. If there are two groups, you will set up for glare (Section 3) when the in-vehicle experimenters contact you. The entire procedure will repeat for the second group.

5. Night Two

Procedures for the second night will be the same except that the Sedan/Pickup will be exchanged. The VES on the SUV's will be switched during the day therefore will be ready before 7:00. There will not be any practice laps the second night.

6. Post-Experiment

At the end of the last pavement markings, the participants and in-vehicle experimenters will return to the building in the compact cars. In addition, the SUV's need to uncover the road-closed signs at the end of the road and fold the tarps. SUV's also need to pick up the glare cones. The Sedan/pickup driver need to collect the cones from the first turnaround as well as the cones for the pavement dip on the road.

Once the cones are collected, the vehicles return to the [contractor]. The SUVs need to be parked in the Simulator Bay. The power inverters need to be unplugged and the DMIs need to be turned off. Do this by pressing the first button on the left.

Check the gas level in the vehicle. If it is below ¼ tank, put a note on the whiteboard.

Return all keys to the lock box and make sure the box is locked. The Sedan/Pickup driver will make sure the doors are closed completely and locked. At this time, you can note any vehicle problems on the vehicle preparation sheets.

Return the radios and vests to the Control Room. Be sure to sign in the radios in the second column of the log book. Also, make sure the power is “off” when you put the radios into the charger.

Return the paperwork to the appropriate folder. You will find a folder with the date on it- put them in there. Return the radios and vests to the Control Room. Note any vehicle problems on the white board. After you fill out your time sheet, you can leave for the night.

APPENDIX F—VES COUNTERBALANCE

Table 10. Group A VES counterbalancing.

1st	2nd	3rd	4th	5th
hybrid UV–A + HID	HLB–LP	HID	five UV–A + HLB	three UV–A + HLB
five UV–A + HLB	HID	hybrid UV–A + HID	HLB–LP	three UV–A + HLB
HLB–LP	three UV–A + HLB	hybrid UV–A + HID	five UV–A + HLB	HID
three UV–A + HLB	HID	HLB–LP	five UV–A + HLB	hybrid UV–A + HID
five UV–A + HLB	hybrid UV–A + HID	three UV–A + HLB	HLB–LP	HID
HID	five UV–A + HLB	three UV–A + HLB	hybrid UV–A + HID	HLB–LP
hybrid UV–A + HID	three UV–A + HLB	HID	five UV–A + HLB	HLB–LP
five UV–A + HLB	HID	three UV–A + HLB	HLB–LP	hybrid UV–A + HID
three UV–A + HLB	HID	hybrid UV–A + HID	HLB–LP	five UV–A + HLB
HID	HLB–LP	three UV–A + HLB	five UV–A + HLB	hybrid UV–A + HID
five UV–A + HLB	HLB–LP	hybrid UV–A + HID	HID	three UV–A + HLB
HLB–LP	hybrid UV–A + HID	five UV–A + HLB	three UV–A + HLB	HID
hybrid UV–A + HID	five UV–A + HLB	HLB–LP	HID	three UV–A + HLB
three UV–A + HLB	hybrid UV–A + HID	HID	five UV–A + HLB	HLB–LP
five UV–A + HLB	hybrid UV–A + HID	HID	three UV–A + HLB	HLB–LP
three UV–A + HLB	HLB–LP	five UV–A + HLB	hybrid UV–A + HID	HID
HID	HLB–LP	hybrid UV–A + HID	three UV–A + HLB	five UV–A + HLB
HLB–LP	HID	three UV–A + HLB	five UV–A + HLB	hybrid UV–A + HID
three UV–A + HLB	HLB–LP	five UV–A + HLB	HID	hybrid UV–A + HID
HLB–LP	HID	three UV–A + HLB	hybrid UV–A + HID	five UV–A + HLB
hybrid UV–A + HID	HLB–LP	five UV–A + HLB	three UV–A + HLB	HID
HID	five UV–A + HLB	hybrid UV–A + HID	three UV–A + HLB	HLB–LP
five UV–A + HLB	hybrid UV–A + HID	HID	HLB–LP	three UV–A + HLB
three UV–A + HLB	HID	HLB–LP	hybrid UV–A + HID	five UV–A + HLB
HID	three UV–A + HLB	five UV–A + HLB	HLB–LP	hybrid UV–A + HID
three UV–A + HLB	HID	hybrid UV–A + HID	HLB–LP	five UV–A + HLB
hybrid UV–A + HID	HLB–LP	three UV–A + HLB	five UV–A + HLB	HID
five UV–A + HLB	HLB–LP	hybrid UV–A + HID	HID	three UV–A + HLB
hybrid UV–A + HID	five UV–A + HLB	three UV–A + HLB	HID	HLB–LP
three UV–A + HLB	HID	five UV–A + HLB	HLB–LP	hybrid UV–A + HID
HLB–LP	HID	hybrid UV–A + HID	five UV–A + HLB	three UV–A + HLB
hybrid UV–A + HID	HLB–LP	HID	five UV–A + HLB	three UV–A + HLB
five UV–A + HLB	HLB–LP	three UV–A + HLB	hybrid UV–A + HID	HID
HID	hybrid UV–A + HID	three UV–A + HLB	HLB–LP	five UV–A + HLB
three UV–A + HLB	five UV–A + HLB	hybrid UV–A + HID	HID	HLB–LP
three UV–A + HLB	five UV–A + HLB	HID	HLB–LP	hybrid UV–A + HID

Table 10 represents the different counterbalanced orders for group A VESs for half of the participants, but they are not in the order in which they were presented. To run two participants at the same time, the orders above were paired so that the participants would not be in the same vehicles at the same time. In addition, this table represents the first night for half of the participants and the second night for the other half of the participants. Table 11shows the inverse for group B.

Table 11. Group B VES counterbalancing.

1st	2nd	3rd	4th	5th	6th
hybrid UV–A + HLB	HHB	HLB	five UV–A + HID	three UV–A + HID	HOH
five UV–A + HID	hybrid UV–A + HLB	HHB	three UV–A + HID	HOH	HLB
three UV–A + HID	HOH	five UV–A + HID	HLB	hybrid UV–A + HLB	HHB
HLB	three UV–A + HID	HOH	hybrid UV–A + HLB	HHB	five UV–A + HID
HOH	five UV–A + HID	hybrid UV–A + HLB	HHB	HLB	three UV–A + HID
HHB	HLB	three UV–A + HID	HOH	five UV–A + HID	hybrid UV–A + HLB
hybrid UV–A + HLB	HHB	three UV–A + HID	HLB	five UV–A + HID	HOH
HOH	HLB	five UV–A + HID	three UV–A + HID	hybrid UV–A + HLB	HHB
HLB	HOH	HHB	five UV–A + HID	three UV–A + HID	hybrid UV–A + HLB
three UV–A + HID	five UV–A + HID	HOH	hybrid UV–A + HLB	HHB	HLB
five UV–A + HID	hybrid UV–A + HLB	HLB	HHB	HOH	three UV–A + HID
HHB	three UV–A + HID	hybrid UV–A + HLB	HOH	HLB	five UV–A + HID
HLB	HOH	hybrid UV–A + HLB	HHB	five UV–A + HID	three UV–A + HID
hybrid UV–A + HLB	HLB	three UV–A + HID	HOH	HHB	five UV–A + HID
HOH	five UV–A + HID	HHB	HLB	hybrid UV–A + HLB	three UV–A + HID
five UV–A + HID	HHB	HOH	three UV–A + HID	hybrid UV–A + HLB	HLB
three UV–A + HID	hybrid UV–A + HLB	HLB	five UV–A + HID	HOH	HHB
HHB	three UV–A + HID	five UV–A + HID	hybrid UV–A + HLB	HLB	HOH
hybrid UV–A + HLB	three UV–A + HID	HLB	HHB	HOH	five UV–A + HID
three UV–A + HID	HLB	HOH	five UV–A + HID	HHB	hybrid UV–A + HLB
HOH	HHB	hybrid UV–A + HLB	three UV–A + HID	five UV–A + HID	HLB
five UV–A + HID	hybrid UV–A + HLB	three UV–A + HID	HOH	HLB	HHB
HLB	five UV–A + HID	HHB	hybrid UV–A + HLB	three UV–A + HID	HOH
HHB	HOH	five UV–A + HID	HLB	hybrid UV–A + HLB	three UV–A + HID
HLB	HOH	hybrid UV–A + HLB	five UV–A + HID	three UV–A + HID	HHB
HHB	five UV–A + HID	three UV–A + HID	HOH	hybrid UV–A + HLB	HLB
HOH	three UV–A + HID	HLB	HHB	five UV–A + HID	hybrid UV–A + HLB
hybrid UV–A + HLB	HLB	five UV–A + HID	three UV–A + HID	HHB	HOH
five UV–A + HID	HHB	HOH	hybrid UV–A + HLB	HLB	three UV–A + HID
three UV–A + HID	hybrid UV–A + HLB	HHB	HLB	HOH	five UV–A + HID
HOH	HHB	five UV–A + HID	three UV–A + HID	hybrid UV–A + HLB	HLB
Mid UV–A + HID	five UV–A + HID	hybrid UV–A + HLB	HOH	HLB	HHB
hybrid UV–A + HLB	HOH	three UV–A + HID	HLB	HHB	five UV–A + HID
five UV–A + HID	HLB	hybrid UV–A + HLB	HHB	three UV–A + HID	HOH
HLB	hybrid UV–A + HLB	HHB	HOH	five UV–A + HID	three UV–A + HID
three UV–A + HID	HHB	HLB	five UV–A + HID	hybrid UV–A + HLB	HOH

APPENDIX G—SMART ROAD

Figure 19. Photo. Aerial view of the Smart Road.

The Virginia Smart Road (figure 19) is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of Intelligent Transportation Systems (ITS) concepts, technologies, and products. It is the first facility of its kind to be built from the ground up with its research infrastructure incorporated into a section of public roadway. The Smart Road presently consists of 3.2 km (2 mi) of two lanes of roadway, originating in Blacksburg, VA, which are closed to public traffic and are designated a controlled test facility. When completed, the Smart Road will be a 9.6-km (6-mi) long, four-lane section of the U.S. Interstate system, connecting Blacksburg, VA with U.S. Interstate 81. This connection will serve an important role in the I–81/I–73 transportation corridor. After completion, provisions will be made to route traffic around controlled test zones on the Smart Road to allow for ongoing testing.

Construction of the Smart Road project was made possible through a cooperative effort of several Federal and State organizations, including Virginia's Center for Innovative Technology, the Virginia Department of Transportation (VDOT), the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), and Virginia Tech.

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

- All-weather testing facility.

- Variable lighting test bed.
- Ultraviolet (UV) pavement markings.
- Magnetic tape installed on roadway.
- Onsite data acquisition capabilities.
- In-house differential Global Positioning Systems (GPS).
- Surveillance camera systems.

APPENDIX H—SAMPLE PARTICIPANT ORDER FORM

Participant 1, Night 1

Pavement Markings

Order	VES	Vehicle
0	Practice	
1	hybrid UV–A + HID	Blk. SUV
2	HLB–LP	Sedan
3	HID	Blk. SUV
4	five UV–A + HLB	Wht. SUV
5	three UV–A + HLB	Wht. SUV

Pavement Marking Data Collection (In-Vehicle Experimenters)

VES System	Section No.	First Marking Detection Distance	Second Marking Detection Distance	Final Distance

Participant 1, Night 2

Pavement Markings

Order	VES	Vehicle
1	hybrid UV–A + HLB	Blk. SUV
2	HHB	Pickup
3	HLB	Blk. SUV
4	five UV–A + HID	Wht. SUV
5	three UV–A + HID	Wht. SUV
6	HOH	Pickup

Pavement Marking Data Collection (In-Vehicle Experimenters)

VES System	Section No.	First Marking Detection Distance	Second Marking Detection Distance	Final Distance

APPENDIX I—PAVEMENT MARKING MEAN DETECTION DISTANCES AND SNK GROUPINGS FOR THE VES MAIN EFFECT

Table 12. Mean beginning and ending detection distances and SNK groupings (means with the same letter are not significantly different) of pavement markings for the VES main effect.

VES	Beginning Detection Distance (ft)	Ending Detection Distance (ft)
HLB	Mean: 297.6 AB	Mean: 250.5 A
Hybrid UV–A + HLB	Mean: 307.5 A	Mean: 241.1 AB
Three UV–A + HLB	Mean: 294.1 AB	Mean: 243.1 AB
Five UV–A + HLB	Mean: 294.4 AB	Mean: 251.0 A
HID	Mean: 253.9 CD	Mean: 198.6 CDE
Hybrid UV–A + HID	Mean: 263.0 C	Mean: 195.7 DE
Three UV–A + HID	Mean: 251.1 CD	Mean: 206.8 CDE
Five UV–A + HID	Mean: 258.4 CD	Mean: 217.1 CD
HOH	Mean: 285.1 B	Mean: 245.7 A
HHB	Mean: 256.0 CD	Mean: 221.4 BC
HLB–LP	Mean: 241.2 D	Mean: 184.5 E

1 ft = 0.305 m

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