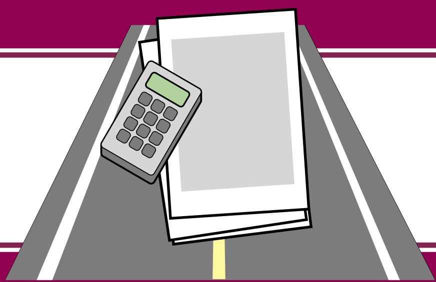

ENV

Volume XI

Enhanced Night Visibility Series: Phase II–Cost-Benefit Analysis

PUBLICATION NO. FHWA-HRT-04-142

DECEMBER 2005

U.S. Department of Transportation

Federal Highway Administration

Research, Development, and Technology
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McLean, VA 22101-2296

FOREWORD

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

The following document provides a cost-benefit analysis of the various technologies evaluated in the Enhanced Night Visibility (ENV) project. The ENV project provided a comprehensive evaluation of evolving and proposed headlamp technologies in various weather conditions. The individual studies within the overall project are documented in an 18-volume series of FHWA reports, of which this is Volume XI. 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 those involved in headlamp and roadway specifications.

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Director, Office of Safety
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-04-142	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Enhanced Night Visibility Series, Volume XI: Phase II—Cost-Benefit Analysis		5. Report Date December 2005 6. Performing Organization Code:
7. Author(s) James S. Gillespie		8. Performing Organization Report No.
9. Performing Organization Name and Address Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061		10. Work Unit No. 11. Contract or Grant No. DTFH61-98-C-00049
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code HRDS-05

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

16. Abstract
This volume of the Enhanced Night Visibility project is a cost-benefit analysis of the vision enhancement system (VES) and roadway marking technologies evaluated in the Phase II experiments of the Enhanced Night Visibility project. The cost-benefit analysis indicates that neither the ultraviolet-A (UV–A) headlamp nor the fluorescent pavement marking technologies are fully developed for implementation. Under the conditions simulated in the Virginia Smart Road tests, most of the combinations of experimental VESs and experimental marking materials show no net improvement in sight distance in comparison to the combination of halogen (i.e., tungsten-halogen) low-beam headlamps and a nonfluorescent pavement marking.

The best-performing VES configurations were the halogen low beam (HLB) and five UV–A + HLB. HLB serves as the benchmark, with both its estimated crash reduction benefit and its incremental cost defined to be zero. The slight overall benefit of five UV–A + HLB over HLB would lead to a positive crash savings, but its cost of implementation would result in a cost-benefit ratio of 0.001 and in negative net benefits of less than zero.

Among the pavement markings tested, the fluorescent paint generally performed worse than the fluorescent thermoplastic. Neither of the tested fluorescent pavement markings is forecast to generate positive benefits in comparison with the performance of the nonfluorescent pavement marking.

17. Key Words	18. Distribution Statement
Crash, Automobile, Benefit, Cost, Cost-Benefit Model, Detection, Fluorescent, Halogen, Headlamp, Night Vision, Nighttime, Road Marking, Ultraviolet, Visibility, Vision Enhancement System	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	52	

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

ENHANCED NIGHT VISIBILITY PROJECT REPORT SERIES

This volume is the 11th of 18 volumes in this research report series. Each volume is a different study or summary, and any reference to a report volume in this series will be referenced in the text as "ENV Volume I," "ENV Volume II," and so forth. A list of the report volumes follows:

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

General Terms

ENV ....Enhanced Night Visibility
FHWA................................Federal Highway Administration
GES ....General Estimates System
GDP...................................Gross Domestic Product
NASS ....National Automotive Sampling System
PDO...................................property damage only
VDOT ....Virginia Department of Transportation
VTRC................................Virginia Transportation Research Council
VES ....vision enhancement system

Vision Enhancement Systems

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...................................halogen (i.e., tungsten-halogen) low beam
Hybrid UV–A + HLB ....hybrid UV–A/visible output together with halogen low beam
IR–TIS...............................infrared thermal imaging system
UV–A................................ultraviolet A (wavelength 315 to 400 nanometers)

Cost and Benefit Computations

b...constant
CMF ....crash modification factor
CR ....crash rate
f ....coefficient of friction
G..grade
m..constant
S...stopping distance
t ....time between perception and reaction
u...velocity
x...year
y...forecast quantity

Measurements

ft ....feet
km ....kilometers
lf ....linear feet
lm ....linear meter
m ....meters
mi ....miles

CHAPTER 1—SUMMARY

This cost-benefit analysis suggests that neither the ultraviolet-A (UV–A) nor the fluorescent pavement marking technologies are fully developed for implementation. The equipment cost estimates and crash cost estimates made for this study indicate that the UV–A and pavement marking technologies tested would have to reduce night crash costs from 7 percent to more than 100 percent to cover their own costs. Under the conditions in the Virginia Smart Road tests, most of the experimental vision enhancement systems (VESs) alone or in combination with experimental marking materials show no net improvement in sight distance in comparison to the benchmark combination of halogen (i.e., tungsten-halogen) low-beam headlamps (HLB) and a nonfluorescent pavement marking. These findings make it appear unlikely that any of the experimental technologies would be break-even propositions.

The best-performing VESs are the five UV–A lamps plus halogen low beam lamps (five UV−A + HLB) and HLB alone. HLB serves as the benchmark, with both its sight distance benefit and its incremental cost defined to be zero. The crash savings forecast for five UV−A + HLB is positive because this system has a positive effect on sight distance.

Among the pavement markings tested, the fluorescent paint generally performs worse than the fluorescent thermoplastic. Because of their short service lives, neither of the tested fluorescent pavement markings can be expected to generate positive benefits in comparison with the performance of the nonfluorescent pavement marking.

CHAPTER 2—LITERATURE REVIEW AND METHODOLOGY

As a benchmark, the 1998 report *A Safety Evaluation of UVA Vehicle Headlights*, by Nitzburg, Seifert, Knoblauch, & Turner and published by the Federal Highway Administration, is useful for comparison with the findings of this study.(1) Nitzburg et al. used engineering estimates and a limited body of relevant literature to estimate the steady-state cost of maintaining a UV–A headlamp technology and a fluorescent pavement marking technology after implementation. Nitzburg et al. created a file that is a weighted combination of 1988–1991 Crashworthiness Data System (CDS) files and 1982–1986 National Accident Sampling System (NASS) files. Adding details from the CDS files to the personal injury statistics from the NASS files provided a more accurate injury cost estimate. Nitzburg et al. used the General Estimated System (GES) to estimate crash costs from this hybrid CDS/NASS file and tabulate the crash cost estimates in six categories defined by the crash geometry:

- Pedestrian crashes.
- Single-vehicle road departure.
- Opposite-direction crashes.
- On/off ramp.
- Work zone crashes.
- Sideswipe.
- All crashes, including the six categories above.

Nitzburg et al. then calculated what percentage of these estimated crash costs the UV–A headlights and fluorescent pavement markings would need to prevent to cover their estimated cost.(1) The report states that a 9.6 percent reduction in nighttime crashes involving pedestrians or a 3 percent reduction in all relevant nighttime crashes would make the UV–A and fluorescent technologies cost effective.

By ignoring the possible startup costs as well as the possible lag between the incurrence of costs and the realization of benefits during the period of implementation, the FHWA analysis subjected the UV–A and fluorescent technologies to a reasonable, but weak, assessment of cost-effectiveness. If this test had generated a cost-benefit ratio close to unity, then a less favorable dynamic analysis might be a matter of interest because it would have been possible that slow acceptance, in the presence of a nonlinear relationship between the percentage of implementation achieved and the percentage of potential benefits realized, might prove to be a barrier to an otherwise promising technology.

MODELING THE BENEFITS OF ENHANCED NIGHT VISIBILITY

The fundamental effect of an enhanced night visibility (ENV) system is to increase the driver's sight distance. The relationship between the sight distance to a point on the highway and the crash rate in the vicinity of that point is the hinge on which any crash reduction estimate hangs. Although some other quantities such as the horizontal curvature or the posted speed limit have been found to account for more of the statistical variance in total day and night crashes than sight distance, sight distance alone does have explanatory power.

Stopping Distance

The safe stopping sight distance depends on the condition of the pavement surface and the characteristics of the driver.[2,3] The equation in figure 1 is a typical model of stopping distance.[3]

$$S = 1.47ut - u^2/(30(f \pm G))$$

Figure 1. Equation. Stopping distance model.

In the equation, S equals the required distance in feet, u equals the velocity in miles per hour, t equals the time in seconds between perception and reaction, f equals the coefficient of friction between the tires and the road, and G equals the grade of the incline or decline, if any. A model such as this likely would be applicable in analyzing the effect of ENV on certain crash geometries.

Crash Rate to Sight Distance Relationship

Based on the findings of studies published between 1973 and 1980, a 1994 paper by Choueiri et al. contains a nomograph that quantifies the relationship between the crash rate in the neighborhood of an intersection and the sight distance for drivers approaching that intersection, holding other factors constant.[4] It should be noted that this relationship is between the average crash rate in all conditions of weather and lighting and the daytime sight distance that the geometrics of the highway permit. Table 1 shows five points on the nomograph by Choueiri et al. over the range of sight distances from 100 to 600 m (328 to 1,969 ft).

Table 1. The relationship between sight distance and crash rate.

Crash Rate per 100,000 Vehicle Kilometers Traveled	Sight Distance (m (ft))
3.20	106.68 (350)
2.60	213.36 (700)
2.40	290.47 (953)
2.25	396.24 (1,300)
2.10	609.60 (2,000)

The relationship between the sight distance and the crash rate is nonlinear; the elasticity of the crash rate with respect to sight distance ranges from –0.30 at the lower end of the sight distance range to –0.16 at the upper end.(4) This model, too, might be applicable in analyzing the effect of ENV on certain categories of crashes.

Crash Cause Interactions

Lum and Reagan(5) discuss a paper by Rumar(6) that classifies all causes of crashes as (1) driver characteristics, (2) roadway characteristics, or (3) vehicle characteristics. Rumar concludes that driver characteristics accounted for 57 percent of crashes, roadway characteristics for 3 percent, and vehicle characteristics for 2 percent. Rumar further concludes that the interaction of driver and roadway characteristics accounted for 27 percent of crashes and that the other possible two- and three-way interactions accounted collectively for 10 percent (1 percent was lost in rounding). Driver characteristics include variables such as age and blood alcohol level; roadway characteristics include curvature, pavement surface condition, and ambient light; and vehicle characteristics include vehicle type, tire type, and other equipment. With this classification of causes, installation of a new VES or pavement marking cannot be interpreted as a change in driver characteristics. This breakdown of crashes would imply that a new vision enhancement technology or a new pavement marking technology could affect at most 43 percent of potential crashes, while the other 57 percent would depend statistically on driver characteristics being unaffected. Under the assumptions (1) that changes in the fraction of crashes that depend statistically on roadway or vehicle characteristics would respond with an elasticity of exactly –1 to the changes in sight distance caused by the experimental technology, and (2) that this effect is restricted to the 43 percent of crashes that depend statistically on roadway or vehicle characteristics or both, the elasticity of the crash rate with respect to sight distance would equal −0.43. The applicability of this result is open to question; nonetheless, it is interesting to compare the elasticity derived from Lum and Reagan[5] with the elasticity derived above from Choueiri et al.[4]

Crash Modification Factors

The crash modification factor (CMF) is an established means of quantifying the effect of a safety improvement.[7,8] In principle, the crash rates implied by an equation or a nomograph, such as those noted above, make it possible to associate a specific CMF with any change from one system to another, provided the change in sight distance is known. The *proportion* between the predicted crash rate CR_1 for one sight distance and the predicted crash rate CR_2 for another, longer site distance is a forecast of the *proportion* by which the number of crashes would change if a night vision system were replaced with a night vision system that yields a longer sight distance. Figure 2 shows the equation for this CMF.

$$(1 - CR_2/CR_1)$$

Figure 2. Equation. Crash modification factor.

DISCUSSION

Although models that relate sight distance to crash rates exist and fit certain specific crash geometries, it is doubtful that any one model would provide valid results for all of the types of crashes in which VESs might have an effect. The approach of computing implementation costs, crash costs, and break-even crash reduction rates, while remaining agnostic about the precise relationship between sight distance and crash rates, has the virtue of allowing each reader to look at the measured effect of VESs on sight distance. This permits each reader to draw his or her own conclusions about the potential for crash reduction. For this study, the approach has the further advantage of permitting ready comparison between the new findings and the previous findings of Nitzburg et al., who used this approach.[1]

CHAPTER 3—COST ESTIMATION

One facet of the cost-benefit analysis encompasses the cost of the VESs and the fluorescent materials, as well as the cost of any changes to required miscellaneous equipment (e.g., headlamp ballast, paint trucks) that accompany these technologies.

TEST RESULTS PERTAINING TO COST

The pavement marking materials were monitored for changes over time in retroreflectivity, apparent color, and (in the case of the fluorescent materials) fluorescent efficiency. Table 2 lists the estimated service life of each experimental material and the historical average service life of the conventional materials used in Virginia.

Table 2. Estimated service lives of pavement marking materials and delineator posts.

	Name	Service Life (years)
Pavement Markings	Fluorescent Latex	0.5
	Fluorescent Thermoplastic	2.0
	Nonfluorescent Paint	0.5
Delineator Posts	Fluorescent	1.0
	Nonfluorescent	1.0

COST DATA FROM OTHER SOURCES

Headlamps

The service lives evaluated in the cost-benefit study are estimates supplied by the manufacturers. The contractor paid its supplier $1,300 each for the UV–A headlamps and ballasts that were installed on the experimental vehicles used for the Smart Road testing. The unit cost of the hybrid UV–A headlamps (provided by Visteon®) was not available. According to *Consumer Guide*®, the infrared (IR) night vision system in the 2002 Cadillac® DeVille® DHS had an invoice price of $1,913 and a suggested retail price of $2,250.[9] A Cadillac dealer in Charlottesville, VA, quoted a retail price of $2,895 for the infrared night vision system in the 2003 DeVille DHS.[10]

Pavement Markings

In fall 1999, three different types of pavement markings were installed on the Smart Road. Two of the three types of markings, a hydrocarbon-resin-based thermoplastic (Cleanosol®) and a latex-based paint (Mercalin®), had fluorescent properties. The third, a polyurea binder system (3M® Liquid System 1200™), served as a nonfluorescent control material. Pavement marking costs were from $0.0645 to $2.3476 per linear foot (lf) for the fluorescent paints and thermoplastics that were used in the field tests. A representative of the supplier provided an estimate of the cost of the polyurea binder system. Table 3 through table 11 itemize the cost per linear foot (lf) of each pavement marking material that was used in the Smart Road tests, plus the average cost per linear foot of the conventional thermoplastics and paints that the Virginia Department of Transportation (VDOT) uses in the field. Materials applied and tested on the Smart Road are marked with an asterisk. Cost figures used in the cost-benefit analysis are marked with two asterisks. Other materials and cost figures are unmarked. Delineator post unit costs are expressed in dollars per post. All other unit costs are expressed in dollars per linear foot; 1 lf = 0.305 linear meter (lm).

Table 3. Unit costs of fluorescent thermoplastic.

	White Fluorescent Thermoplastic*		**Yellow Fluorescent Thermoplastic**	
Add. Price Info	Project	Discounted	Project	Discounted
Material Cost	0.724	0.5570	0.8890	0.6838
Labor Cost	0.200	0.2000	0.2000	0.2000
Cost w/o Beads	0.924	0.7570	1.0890	0.8838
Cost w/Conv. Beads	0.949	0.7819	1.1139	0.9087
Cost w/Fluor. Beads	**1.9222	1.7552	2.5527	2.3475

*Materials applied and tested on the Virginia Smart Road testing facility.
**Costs used in the cost-benefit analysis.

Table 4. Unit costs of fluorescent paint.

	White Fluorescent Paint*		Yellow Fluorescent Paint	
Add. Price Info	Project	Discounted	Project	Discounted
Material Cost	0.1720	0.1203	0.1461	0.1023
Labor Cost	0.0635	0.0635	0.0635	0.0635
Cost w/o Beads	0.2355	0.1838	0.2096	0.1658
Cost w/Conv. Beads	0.2392	0.1875	0.2133	0.1695
Cost w/Fluor. Beads	**0.3847	0.3330	0.4284	0.3846

*Materials applied and tested on the Virginia Smart Road testing facility.
**Costs used in the cost-benefit analysis

Table 5. Unit costs of fluorescent glass beads.

	White Fluorescent Glass Beads		Yellow Fluorescent Glass Beads	
	In Paint	In Thermo.	In Paint	In Thermo.
Material Cost	0.1492	0.9982	0.2188	1.4637
Labor Cost				
Cost w/o Beads				
Cost w/Conv. Beads				
Cost w/Fluor. Beads				

Table 6. Unit costs of fluorescent delineator.

	Fluorescent Delineator	
	Without Sheeting	With Sheeting
Material Cost	10.68	12.18
Labor Cost		
Cost w/o Beads		
Cost w/Conv. Beads		
Cost w/Fluor. Beads		

Table 7. Unit costs of polyurea binder.

	White Polyurea Binder*	
	Y2000	Y2003
Material Cost		
Labor Cost		
Cost w/o Beads	0.75	**1.0000
Cost w/Conv. Beads		
Cost w/Fluor. Beads		

*Materials applied and tested on the Virginia Smart Road testing facility.
**Costs used in the cost-benefit analysis.

Table 8. Unit costs of conventional thermoplastic.

	White Conventional Thermoplastic		Yellow Conventional Thermoplastic	
	Low-end	High-end	Low-end	High-end
Material Cost	0.0960	0.1260	0.0960	0.1260
Labor Cost	0.2000	0.2000	0.2000	0.2000
Cost w/o Beads	0.2960	0.3260	0.2960	0.3260
Cost w/Conv. Beads	0.3209	0.3509	0.3209	0.3509
Cost w/Fluor. Beads	N/A	N/A	N/A	N/A

Table 9. Unit costs of conventional paint.

	White Conventional Paint		Yellow Conventional Paint	
	Low-end	High-end	Low-end	High-end
Material Cost	0.0097	0.0104	0.0122	0.0133
Labor Cost	0.0635	0.0635	0.0635	0.0635
Cost w/o Beads	0.0732	0.0739	0.0757	0.0768
Cost w/Conv. Beads	0.0769	0.0776	0.0794	0.0805
Cost w/Fluor. Beads	N/A	N/A	N/A	N/A

Table 10. Unit costs of conventional glass beads.

	Conventional Glass Beads	
	In Paint	In Thermo.
Material Cost	0.0037	0.0249
Labor Cost		
Cost w/o Beads		
Cost w/Conv. Beads		
Cost w/Fluor. Beads		

Table 11. Unit costs of standard delineator.

	Standard Delineator	
	Without Sheeting	With Sheeting
Material Cost	13.24	14.74
Labor Cost		
Cost w/o Beads		
Cost w/Conv. Beads		
Cost w/Fluor. Beads		

It was found that the labor and equipment cost per linear foot of installing a fluorescent marking material is identical to the cost of installing its nonfluorescent counterpart.

In addition to pavement markings—fluorescent and conventional nonfluorescent—delineator posts were installed along the side of the roadway. Their costs are tabulated in table 6 and table 11.[11] Because the delineator posts played no part in the visibility tests, their costs are excluded from the cost-benefit analysis.

COST METHODOLOGY

The Federal Highway Administration's (FHWA) annual *Highway Statistics* supplies historical tallies of motor vehicle registrations, centerline miles of road, and lane miles of road.[12,13] This information was retrieved from 1990–1998. These data help permit a forecast of the total cost of implementing any of the VESs or pavement markings.

Cost Principles—Automobile Equipment

The incremental cost of the UV–A technology takes into account the cost of the UV–A headlamps themselves, the cost of their installation, and the cost of modifications to the vehicle's body and electrical system to fit the headlamps and power them. The differential cost of producing new vehicles that are designed to operate UV–A headlamps would possibly be less than the cost of retrofitting existing vehicle models.

It is quite possible that the unit cost of UV–A headlamps in mass production will differ from the concessionary prices paid for the experimental equipment; however, spokespersons for the auto industry were hesitant to forecast the unit cost of the headlamps in mass production. The cost analysis computes the incremental cost of each headlamp technology on the assumption that the steady-state cost of equipping a new automobile with such headlamps would be equal to the prices the contractor has on record.

The average replacement age of the headlamps is assumed to be 8 years, matching the assumption made in the previous FHWA evaluation of UV–A headlamps.[(1)] The average replacement age of the thermal imaging system is assumed to be the same.

Cost Principles—Pavement Markings

A computation of the incremental cost of a fluorescent technology takes in the up-front cost of the fluorescent materials themselves, the differential cost of their installation, and the difference in the length of the replacement cycle (i.e., the service life). Each of the fluorescent materials tested was a fluorescent variant of a marking material already in use, namely thermoplastic or paint. The nonfluorescent control was a polyurea binder system. The standard nonfluorescent paint that VDOT uses is less expensive than any of the three alternatives that underwent sight-distance tests on the Smart Road. Because the technology for applying a given type of pavement marking is largely independent of the material's fluorescent properties, the cost-benefit analysis assumes no differential installation cost (i.e., that the installation cost of fluorescent paint is no different from the installation cost of conventional paint, and that the installation cost of fluorescent thermoplastic is no different from the installation cost of conventional thermoplastic).

As in the case of the headlamps, authoritative estimates of the unit cost of each fluorescent material in mass production were not available. The cost-benefit analysis computes the annualized costs of each pavement marking technology on the assumption that the steady-state cost of procuring fluorescent pavement markings would equal the prices that were actually paid. The average replacement age of the thermoplastic, either fluorescent or nonfluorescent, is taken to be 3 years. The average replacement age of the paint, either fluorescent or nonfluorescent, is taken to be 1 year. Both of these assumptions reflect VDOT experience with the conventional nonfluorescent products.

Cost Computations—Automobile Equipment

A simple log linear equation as shown in figure 3—where *y* is the forecast quantity, *x* is the year, and *m* and *b* are constants—was fitted to 9 years of annual FHWA statistics on the number of motor vehicle registrations in the United States 1990 through 1998.[12,13] The equation is used to create a 20-year forward forecast of motor vehicle registrations. Figure 4 compares the actual number of motor vehicle registrations in each year with the number implied by the fitted equation:

$$y = bm^x$$

Figure 3. Equation. Cost computation.

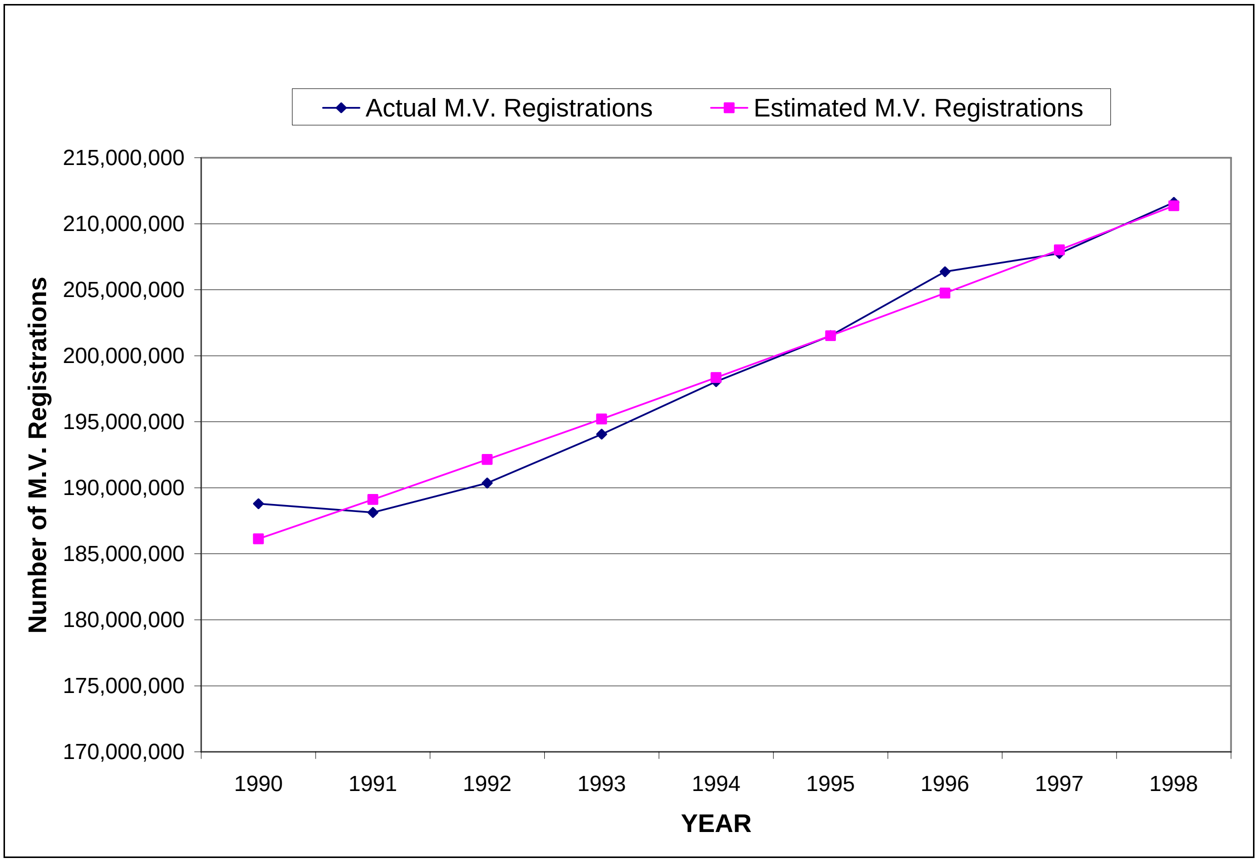


Figure 4. Line graph. Motor vehicle registrations 1990 through 1998.[12,13]

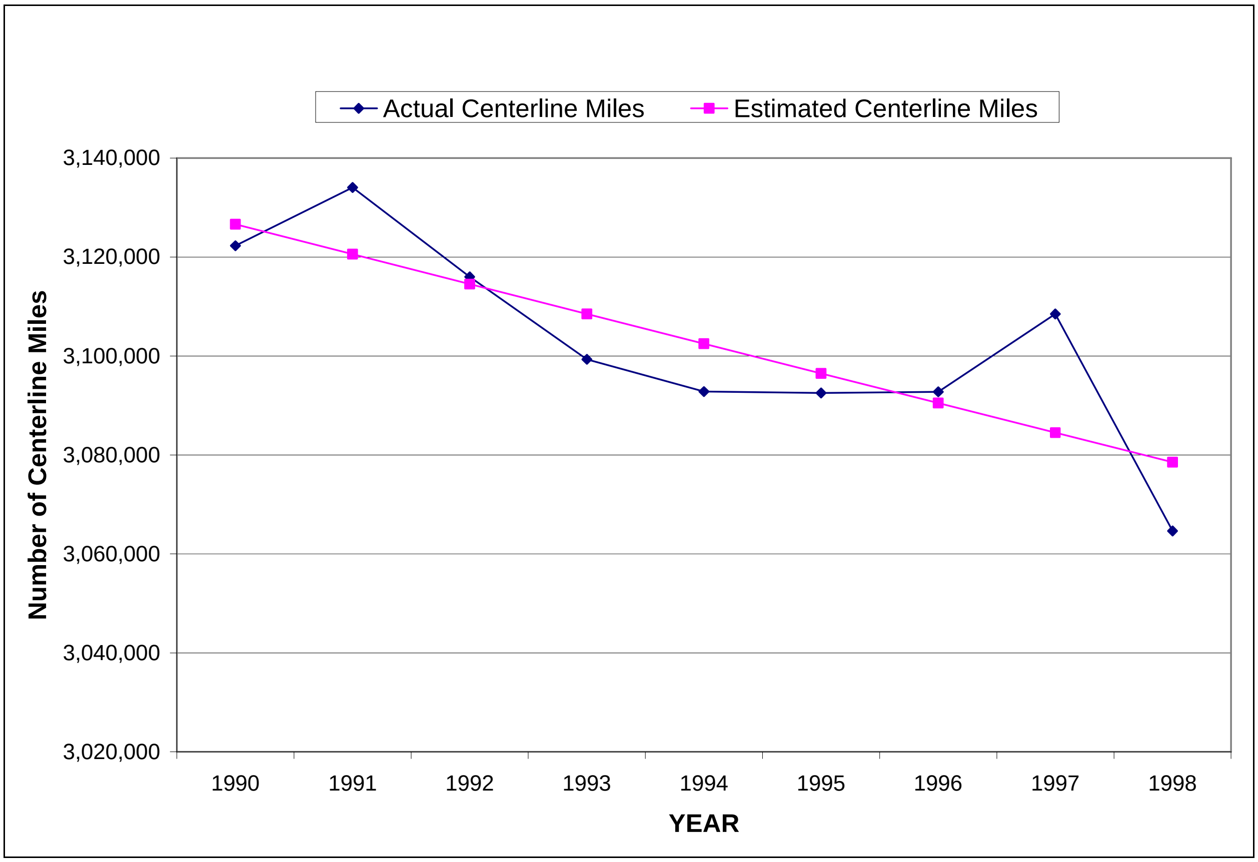
The forecast of registered motor vehicles measures the size of the market that a new VES would have to penetrate. The reported results are given on the assumption that this penetration would occur over a 20-year period in equal 5 percent increments from the first year until 100 percent implementation was achieved. The annualized cost of a given VES is applied to the number of equipped vehicles forecast in each future year to yield a total cost estimate for that year.

Cost Computations—Pavement Markings

The number of stripes needed to mark a given segment of highway is assumed to equal the number of lanes plus one. Under this assumption, the sum of the number of highway centerline miles plus the number of highway lane miles equals the number of miles of striping that would need to be placed on the Nation's roads.

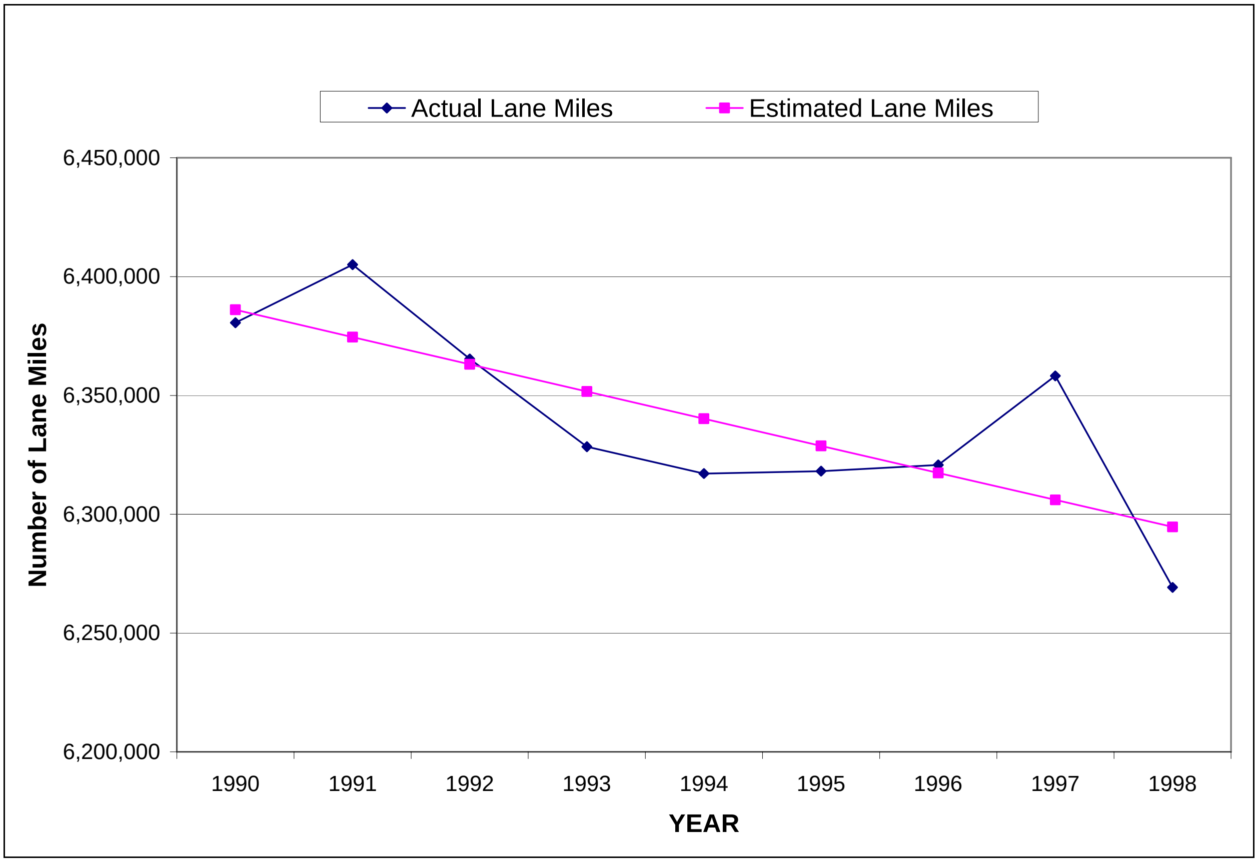
The simple log linear equation in figure 3 was fitted to 9 years of annual FHWA statistics on the number of highway (centerline) miles of road in the United States from 1990 through 1998.[12,13] The same equation was fitted to 9 years of data on the number of lane-miles of road.[12,13]

Figure 5 compares the actual number of centerline miles in each year with the number implied by the fitted equation. Figure 6 does the same for lane miles on rural roads. Each equation is used to create a 20-year forward forecast of the time series to which it was fitted. The forecast of each quantity is independent of the forecasts of the other.



1 mi = 1.6 km

Figure 5. Line graph. Centerline miles for highways from 1990 through 1998.[12,13]



1 mi = 1.6 km

Figure 6. Line graph. Lane miles of rural highway 1990 through 1998.[12,13]

It is assumed that implementation would occur only on unlighted highway segments. Because a tally of the number of unlighted highway miles was not readily available, the number of miles of rural highway is used as a proxy. It is assumed further that installation of a new marking system would occur over 20 years, in equal 5 percent increments from the first year until 100 percent implementation is achieved. The annualized cost of a given marking material is applied to the number of retrofitted miles of stripe forecast for a future year to yield a total cost for that year.

Additional Considerations

A case could be made that the graph of market penetration over time should be S-shaped, reflecting hesitant initial adoption, followed by a boom of installation that tails off as the number of unequipped vehicles and highway miles asymptotically approaches 0 percent. Given the results from the Smart Road field tests, it is not conceivable that such a modification would alter the cost-benefit findings.

A case could also be made that a cost computation based on installation cost rather than annualized cost would reflect better the time path of the costs, especially during the early years of implementation. Again, the cost-benefit findings are not sensitive to such a modification. The reported results are based on a present-value calculation using annualized costs.

CHAPTER 4—BENEFIT ESTIMATION

OVERVIEW OF THE FIELD TESTS USED FOR BENEFIT DATA

The field tests conducted on the Smart Road measured the effect of 12 different VESs on drivers' ability to detect pavement markings and drivers' ability to detect and recognize a given object. Four studies took place in four different meteorological conditions: clear, rain, snow, and fog. Thirty drivers, ten in each of three age groups—18 to 25 years, 40 to 50 years, and 65 years and over—participated in each field test (except for snow, where the oldest age group was omitted out of concern for the risk of slips while moving between vehicles). The tests included nine different objects, including pedestrians, bicycles, and tires.

In the case of the pavement markings, the study was conducted only in clear weather conditions. Thirty drivers, in the same three age groups, participated. Each of three different marking materials (i.e., one nonfluorescent and two fluorescent) was placed on the Smart Road as a yellow centerline and a white edgeline. The detection distances of the beginning and end of each marking type were recorded.

BENEFIT DATA FROM SECONDARY SOURCES

Number of Crashes, Number of Persons, and Vehicles Involved in Crashes

The National Highway Traffic Safety Administration's National Automotive Sampling System (NASS) and its General Estimates System (GES) supply historical estimates of the number of crashes each year.[14,15] The NASS database for a given year consists of a sample of all the crashes that were reported in the United States during that year.[14] The GES applies a multiplier weight to each crash in the sample to reconstruct an estimate of the total population of crashes.[15] The multiplier is based on the ratio between the total number of recorded crashes in the police jurisdiction where the crash occurred and the number of recorded crashes from that jurisdiction that are actually included in the NASS sample. The NASS database includes information such as the prevailing light and weather conditions, the severity of damage to each vehicle involved, the critical event that caused each vehicle's involvement, the age of each driver, and the severity of injury to each person involved for every crash in its sample.[14] GES can be queried to produce an estimate that breaks down the total number of crashes into very fine categories according to the conditions prevailing at the time of the crash, the proximate cause of the crash, and the age of the driver.[15] Likewise, GES can be queried to produce estimates of the number of personal injuries that occurred in each of these crash categories, and the number of vehicles that were damaged in each of these crash categories.

Unit Crash Costs

The NASS database classifies personal injuries according to the KABCO scale: "K" designates a fatal injury, "A" an incapacitating injury, "B" an evident injury, "C" a possible injury, and "O" no injury (property damage only).[14] FHWA Technical Advisory T7570.2 gives an estimate of the average cost of an injury of each degree of severity in the KABCO scale in 1994 dollars.[16] To project the average cost in any subsequent year, the advisory prescribes that the 1994 cost be divided by the Gross Domestic Product (GDP) implicit price deflator for 1994 and multiplied by the implicit price deflator for the subsequent year. This conversion, using the implicit price deflators for 1994 and 2003, is used to obtain an estimate of the average cost of each personal injury of each type in 2003 dollars.

The NASS database classifies vehicle damage into four categories: no damage, minor damage, functional/moderate damage, or disabling/severe damage.[14] The estimate of the average cost of a damaged vehicle in each category of severity is based on the average cost of a property-damage-only crash[16]—that is, category "O" in the NASS database.[14] Minor damage is assigned an average cost equal to one-half the average for all property damage only (PDO) crashes, moderate damage is assigned an average cost equal to the average for all PDO crashes, and severe damage is assigned an average cost equal to twice the average for all PDO crashes.[16]

Table 12 and table 13 reproduce the 1994 cost estimates from T7570.2,[16] the GDP implicit price deflators for October 1994 and June 2003, and the computed 2003 cost estimates.

Table 12. Crash casualty costs: injury.

Severity	Descriptor	Cost per person (in 1994 dollars; 10/31/94 GDP deflator = 96.284)[16]	Cost per person (in 2003 dollars; 6/30/03 GDP deflator = 111.93)
K	Fatal	2,600,000	3,022,496
A	Incapacitating	180,000	209,250
B	Evident	36,000	41,850
C	Possible	19,000	22,087
O	None (PDO)	2,000	2,325

Table 13. Crash casualty costs: damage.

Severity	Descriptor	Cost per vehicle (in 1994 dollars; 10/31/94 GDP deflator = 96.284)[16]	Cost per vehicle (in 2003 dollars; 6/30/03 GDP deflator = 111.93)
0	None	0	0
1	Minor	1,000	1,162
2	Functional/Moderate	2,000	2,325
3	Disabling/Severe	4,000	4,650
9	Unknown	500	581

BENEFIT METHODOLOGY

It is postulated that the motoring public would realize the benefits of enhanced night visibility in the form of reduced crash costs. To forecast the potential benefits of a VES in a given future year under this postulate, it is necessary to forecast the level of crash costs that would be incurred if the system were not adopted and the level of crash costs that would be incurred if the system were adopted. The crash data are grouped with the assumptions (1) that only a crash that occurs at night on an unlighted road might be averted by the ultraviolet or infrared VESs, and (2) that only a crash that begins with a roadway departure that occurs at night on an unlighted road might be averted by the fluorescent pavement marking technology. One might conjecture alternatively that a crash that occurs at night or at dusk or dawn may be affected. This alternative assumption expands the definition and the number of crashes that a night vision system may affect, and thus, magnifies the system's potential effect on crash costs.

The percentage of night crashes on unlighted roads that might be affected by a VES may be supposed to be equal to the percentage of vehicles in which the system is installed. The percentage of such crashes that may be affected by a fluorescent pavement marking system may likewise be supposed to be equal to the percentage of unlighted highway miles on which the system is installed. Because the number of unlighted highway miles was unavailable, the percentage of rural highway miles is tabulated as a proxy. If it has no other virtue, this proxy jibes conveniently with the computation of the cost of the pavement marking technology, which proceeds on the assumption that fluorescent markings would be installed only on rural roads.

Categorization of Vehicle Crashes

This benefit analysis sorts the recorded crashes into multiple categories according to the values in each of three fields from the NASS database: light conditions, weather conditions, and critical event (the critical event that initiated the crash—not necessarily identical to what the crash literature would call the "cause" of the crash).[14] Each of these categories matches one of the variables controlled in the Smart Road tests. Sorting on light conditions is obviously relevant because the VESs were tested only at night on an unlighted road, and they are not expected to help drivers avoid crashes that occur by day or on a lighted road. Sorting on weather conditions is relevant because of the different results that were obtained in clear weather and in simulated conditions of rain, snow, and fog. The critical event that precipitated a vehicle's involvement in a crash identifies the subsets of crashes where earlier detection of a pavement marking, pedestrian, cyclist, animal, or object might have enabled the driver to avoid the crash. This is of interest because of different results that were obtained when the volunteer drivers were asked to spot pavement markings, pedestrians, and so forth. It would also be possible to sort on driver age and gender to take account of the different results that were obtained from men and women in the three driver age groups.

Driver age and driver gender are also available in the set of data from the Smart Road tests and in the NASS database. Basic statistical tests holding age, light, and weather constant show no significant difference between the sight distances obtained from male and female drivers; therefore, the crash database is not sorted on driver gender. Drivers of different ages did exhibit different responses to the VESs (see ENV Volumes III through VI), but crash numbers and costs sorted by age of driver are not presented here.

Light and Weather Conditions

Incident-specific fields in the NASS Accident File identify the light and weather conditions at the time of each crash.(14) First, a crash is grouped with all other crashes that occurred under the same light and weather conditions. These two main categories create 15 groups.

The relevant sorting by light condition distinguishes three groups: crashes where the light condition field has the value "dark," crashes where the field has either of the values "dawn" or "dusk," and crashes where the field has any other value. This sorting is based on the assumption that night visibility enhancements can affect only the group of crashes that occur at night on unlighted roads, which is the light condition called "dark" in the GES database,(15) or the alternative assumption that the enhancements affect also the group of crashes for which the light field has the values "dawn" or "dusk."

The NASS database classifies the weather prevailing at the time of each crash in one of eight categories: "clear," "rain," "sleet," "snow," "fog," "rain with fog," "sleet with fog," and "other."(14) Because the Smart Road tests simulated only four weather conditions—clear, rain, snow, and fog—it is necessary to guess at the performance of each VES in the conditions "sleet," "rain with fog," "sleet with fog," and "other" from its performance in the simulated conditions. The sorting in the weather field supposes that a system's performance under conditions of sleet, rain with fog, and sleet with fog equals its performance in rain. The sorting further supposes that a system's performance under "other" conditions equals its performance in clear weather. Therefore, the sorting by weather condition distinguishes five groups: crashes where the weather field has either the value "clear" or "other," crashes where the weather field has either the value "rain" or "sleet," crashes where the weather field has the value "snow," crashes where the field has the value "fog," and crashes where the field has either the value "rain with fog" or "sleet with fog."

Figure 7 breaks down the estimated number of crashes in each year from 1992 to 2001 into three categories: those that occurred in daylight or on lighted roads, those that occurred in the dark, and those that occurred at dawn or dusk.[14] Some 12 percent of crashes occurred in dark conditions where enhanced night visibility would be expected to have an effect, while another 3 percent or so occurred in dawn or dusk conditions where it might be expected to have an effect.

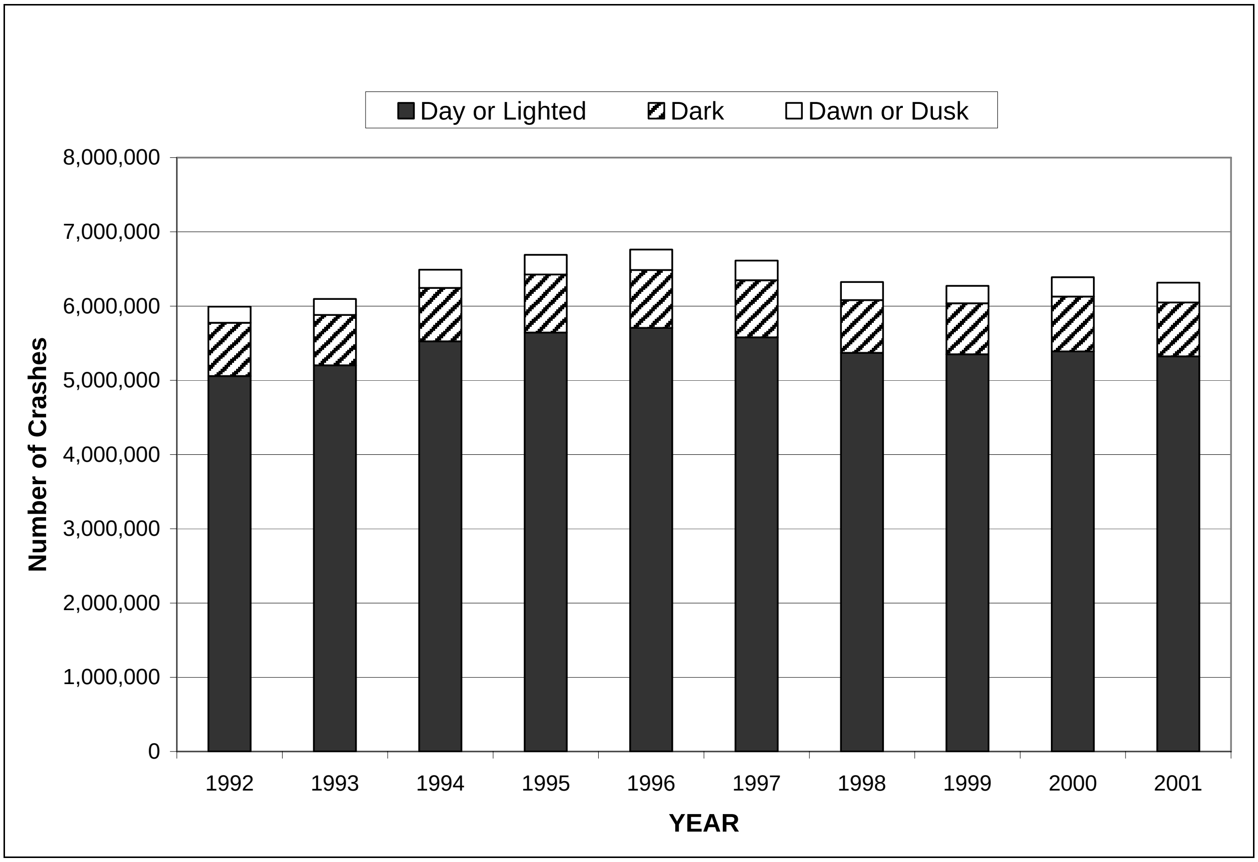


Figure 7. Bar graph. Number of crashes, 1992 through 2001, by light condition.[14]

Figure 8 breaks down the estimated number of crashes in each year from 1992 to 2001 into five categories: those that occurred in conditions identified as "clear" or "other," those that occurred in rain or sleet, those that occurred in snow, those that occurred in fog, and those that occurred in rain or sleet with fog.(14)

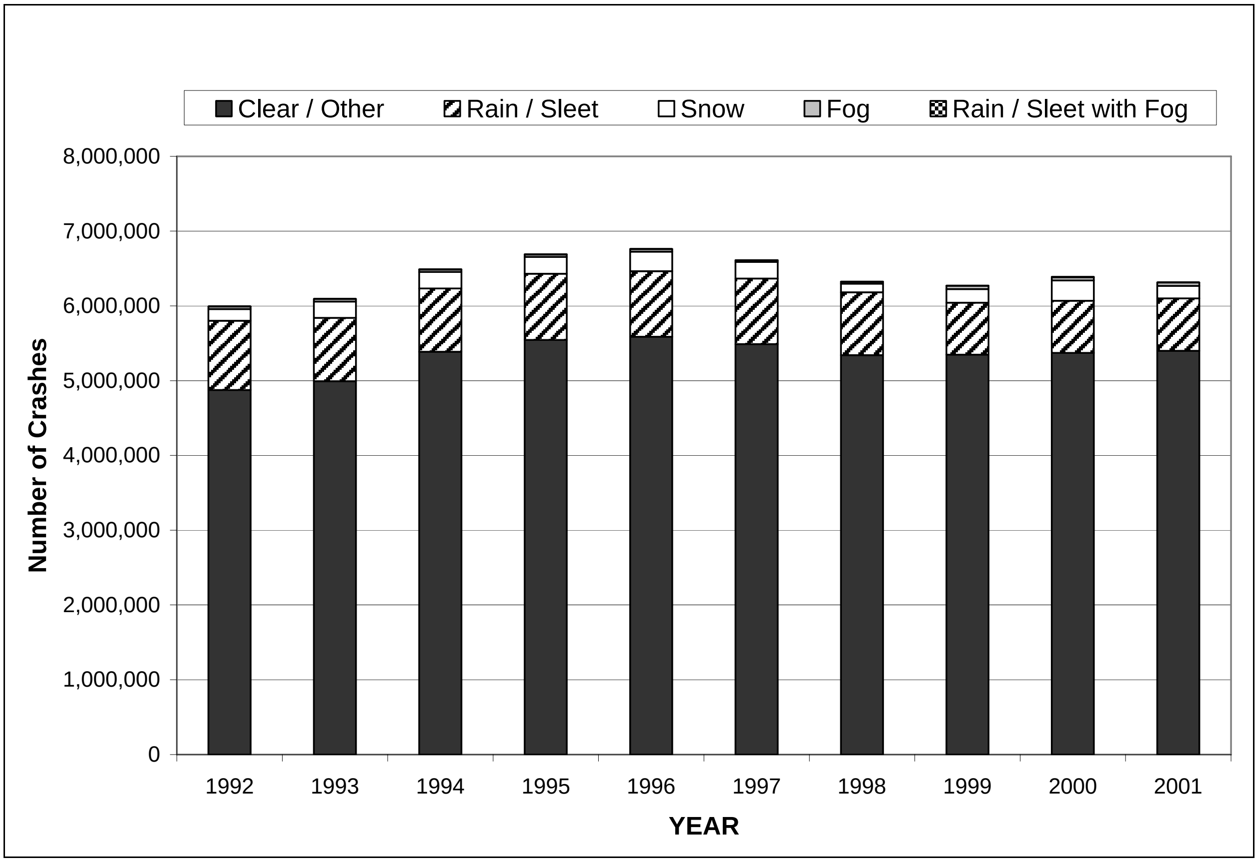


Figure 8. Bar graph. Number of crashes, 1992 through 2001, by weather condition.(14)

Critical Event

A vehicle-specific field called "Critical Event" in the NASS Vehicle File identifies the triggering event that involved each vehicle in each recorded crash.(14) The critical events on which enhanced night visibility would have an effect were identified. Enhanced visibility of pavement markings is postulated to have an effect on crashes triggered by a lane or roadway departure (field values 012–014); this excludes roadway departures that occur secondarily to some other precipitating event such as a blowout or the approach of another car. Enhanced visibility of pedestrians, cyclists, and inanimate objects are postulated to have an effect on crashes triggered by vehicle interaction with a pedestrian (field values 080–082), with a cyclist (values 083–085), and with an animal or an inanimate object (values 087–092).

Typically, if the Vehicle File records the involvement of more than one vehicle in a single crash, some primary cause (including those of interest to this study) is listed as the critical event for one of the vehicles, and some variety of secondary interaction between vehicles is listed as the critical event for each of the others.(14) A multicar crash, a critical event involving a lane departure, or an interaction with a nonmotorist (i.e., one of the critical events of interest) could very likely lead to a subsequent critical event of some other type (e.g., an interaction between two vehicles), but it is also possible that a critical event involving a lane departure or an interaction with a nonmotorist could be caused by a critical event of some other type. The sorting here postulates that if one of the critical event values that are relevant to this study is attributed to any vehicle in a multicar crash, then that critical event is the initial event of the multicar crash, and it is the criterion by which that crash will be categorized. Accordingly, it is possible to group the crashes by the presumed first critical event: any crash that includes a roadway departure is grouped with all other crashes that include a roadway departure; any crash that includes an interaction with a pedestrian is grouped with all other crashes that include an interaction with a pedestrian, and likewise for interactions with a cyclist, an animal, or an object.

The many other values of the critical event field represent critical events that are related in no obvious way to the sight-distance field tests(14)—that is, critical events on which enhanced night visibility would probably have no effect. A single large group of crashes remains in which none of the above critical events is listed. The largest group of critical event values within this category represents various interactions between two or more vehicles. Other critical events in this category include mechanical failure and loss of traction. The VESs studied in this project would seem unlikely to affect the night visibility of a car traveling with its headlights on, but the reader may make his or her own suppositions about the crashes in this category.

A negligible number of crashes, only a few dozen in tens of thousands of recorded crashes, involved more than one of the critical events of interest.(14) In these very few cases, the crash costs (explained below) are divided between two critical event categories.

Estimation of the Number of Casualties in Each Category of Crashes

GES estimates of the number of persons injured in each of the five degrees of severity (on the KABCO scale) and the number of vehicles damaged in each of the four degrees of severity. Using the NASS data of the years 1999, 2000, and 2001,[14] three separate estimates were generated.

GES estimates of the total number of crashes were generated for each of the 10 years 1992 to 2001. The simple log linear equation shown in figure 3 fitted to this 10-year series suggests how the number of crashes may be expected to grow over time in the absence of ENV technology.

Figure 9 compares the GES-estimated number of crashes in each year with the number implied by the fitted equation. The fitted equation provides a forecast of the number of crashes that would occur in any future year if no new VESs were introduced.

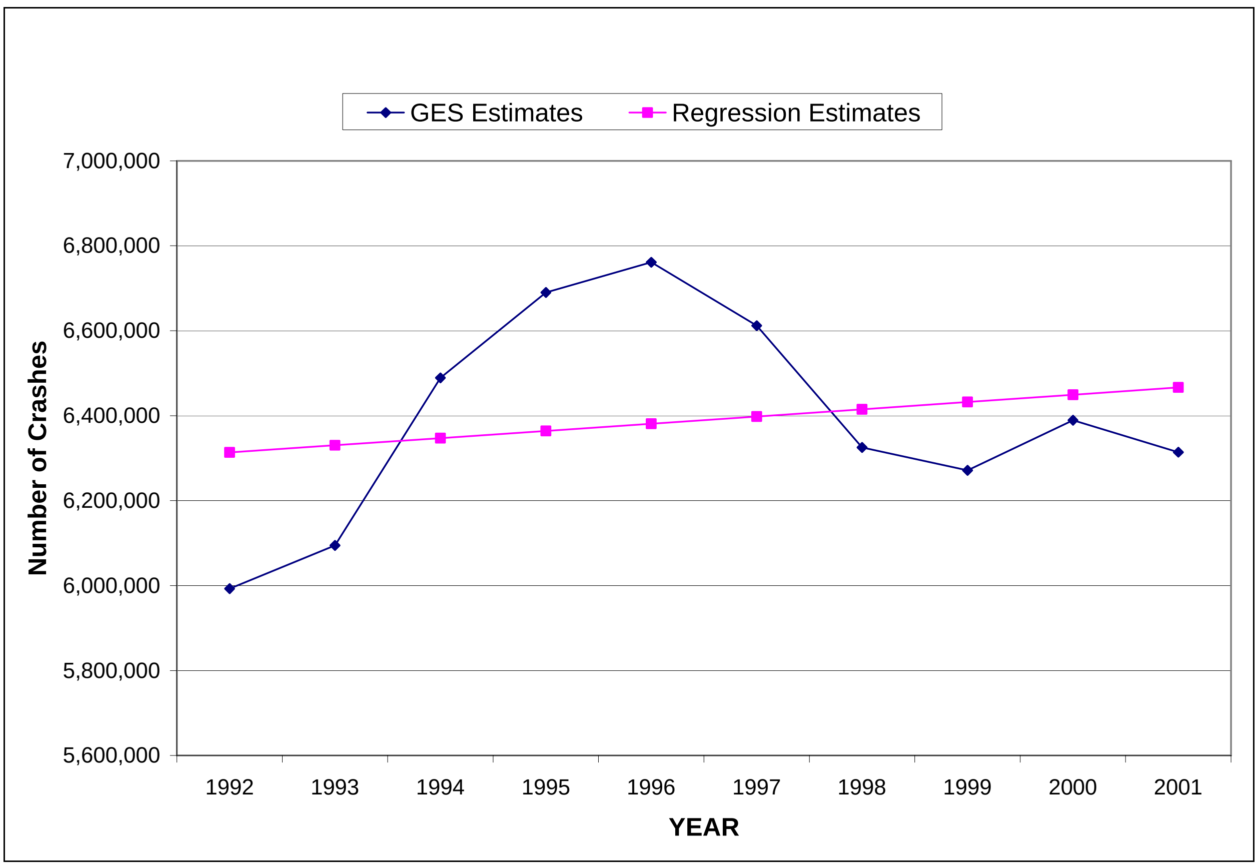


Figure 9. Line graph. GES estimates versus regression estimates of crashes, 1992 through 2001.

The ratio between the average number of personal injuries in each of the separate crash categories from the year 1999 through 2001 and the total number of crashes in the year 2000, multiplied by the total number of crashes forecast for any future year and described in the preceding paragraph, affords a forecast of the number of personal injuries in each crash category that would occur in that future year (if no new VESs were introduced).

The procedure for forecasting the number of vehicles damaged in any crash category for a given future year is completely analogous to the procedure for forecasting the number of personal injuries.

Figure 10 breaks down the number of persons involved in crashes from 1999 to 2001 into five categories, according to the critical event deemed to be the primary cause of the crash involved, and into seven crosscategories, according to the severity of their injuries (if any).

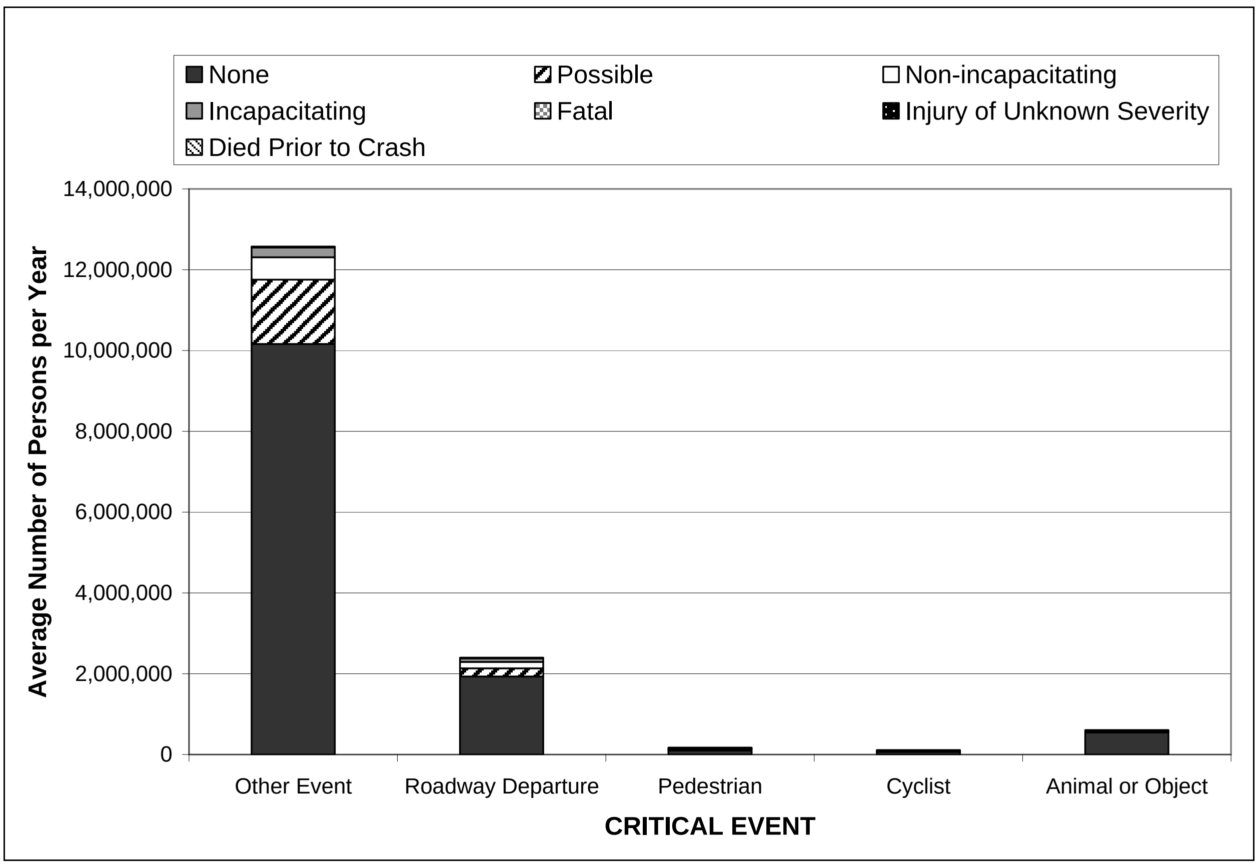


Figure 10. Bar graph. Estimated number of people involved in crashes, 1999 through 2001, by critical event and severity of injury.[13]

Figure 11 breaks down only the number of persons identified as injured in crashes from 1999 to 2001 into the same five cause categories and into five injury categories.

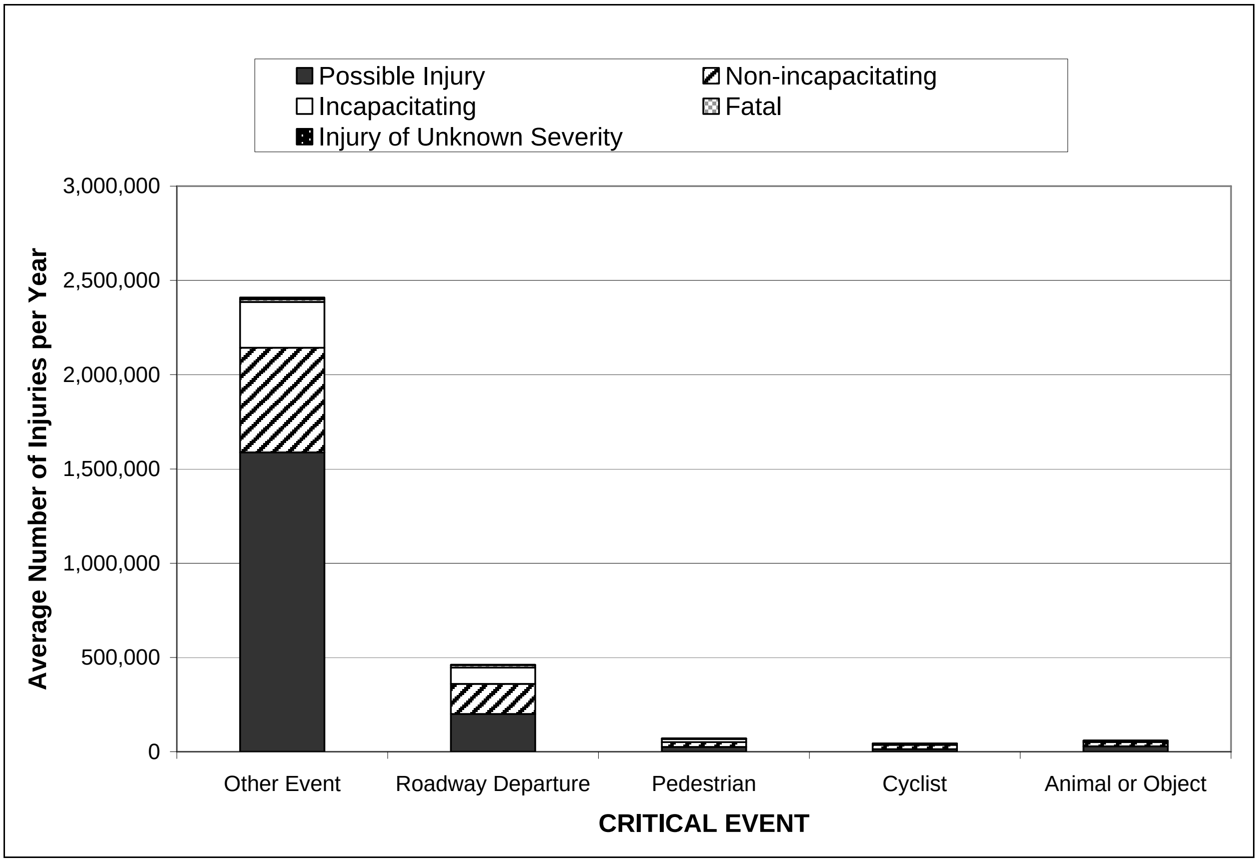


Figure 11. Bar graph. Estimated number of people injured in crashes, 1999 through 2001, by critical event and severity of injury.[(13)]

Figure 12 breaks down the number of vehicles involved in crashes from 1999 to 2001 into the same five cause categories and five cross categories according to the severity of the damage (if any) they sustained.

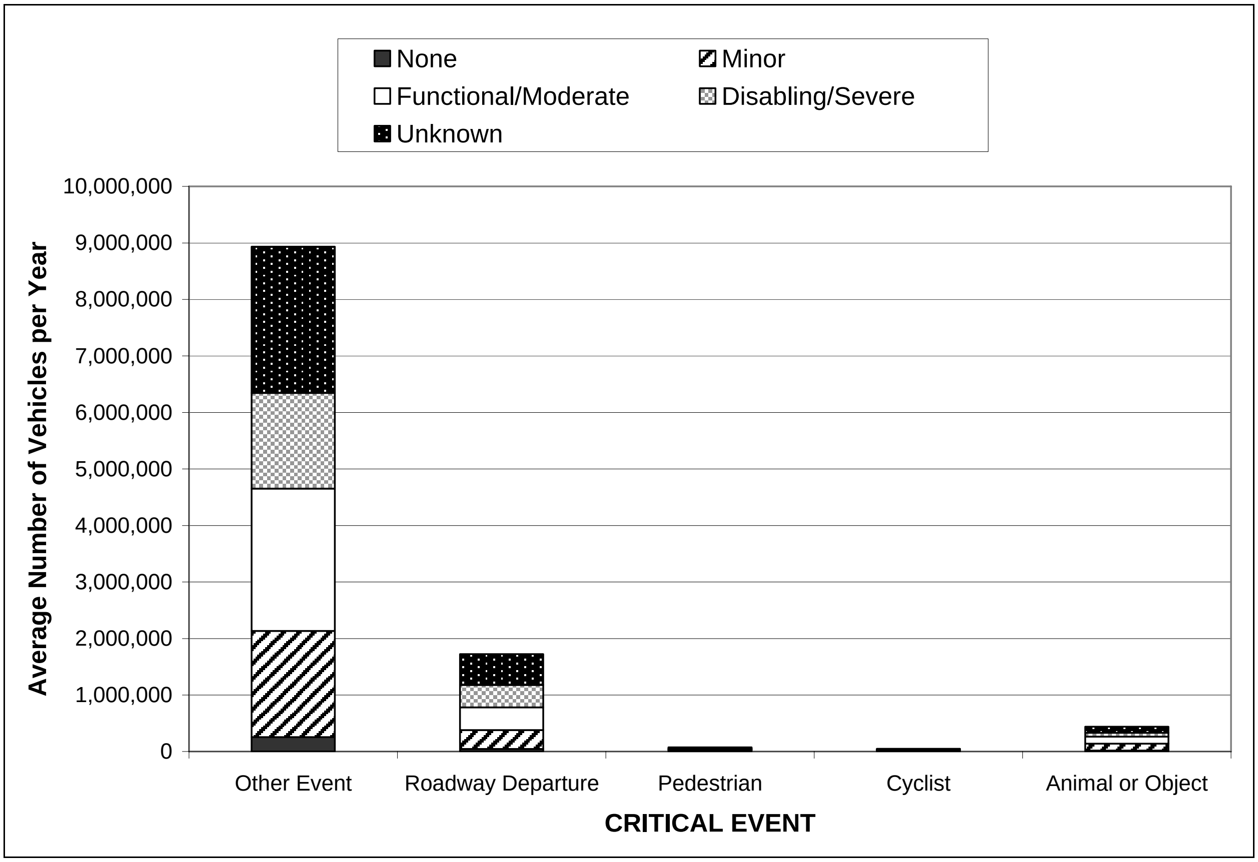


Figure 12. Bar graph. Estimated number of vehicles involved in crashes, 1999 through 2001, by critical event and severity of damage.[13]

Valuation of Crash Costs

Following the guidelines provided in the 1994 FHWA technical advisory mentioned above,[16] a dollar value is attributed to each personal injury and damaged vehicle in the GES estimates for 1999, 2000, and 2001.[13] For example, each personal injury of type "K" (fatal) is assigned the average value, in dollars, of such injuries expressed in year 2003. The result is a tally of crash costs that can be grouped according to the crash conditions identified with the variables in the Smart Road tests: light conditions (day or lighted; dark; or dusk/dawn), weather conditions (clear; rain/sleet; snow; or fog), and critical events (pedestrian interaction, cyclist interaction, animal or object interaction, roadway departure, or other) identified with the types of objects (pedestrian, cyclist, inanimate object, or pavement stripe) used in the tests.

Figure 13 breaks down the estimated cost of the crash casualties from 1999 to 2001 into five categories, according to the critical event in which each crash is recorded.

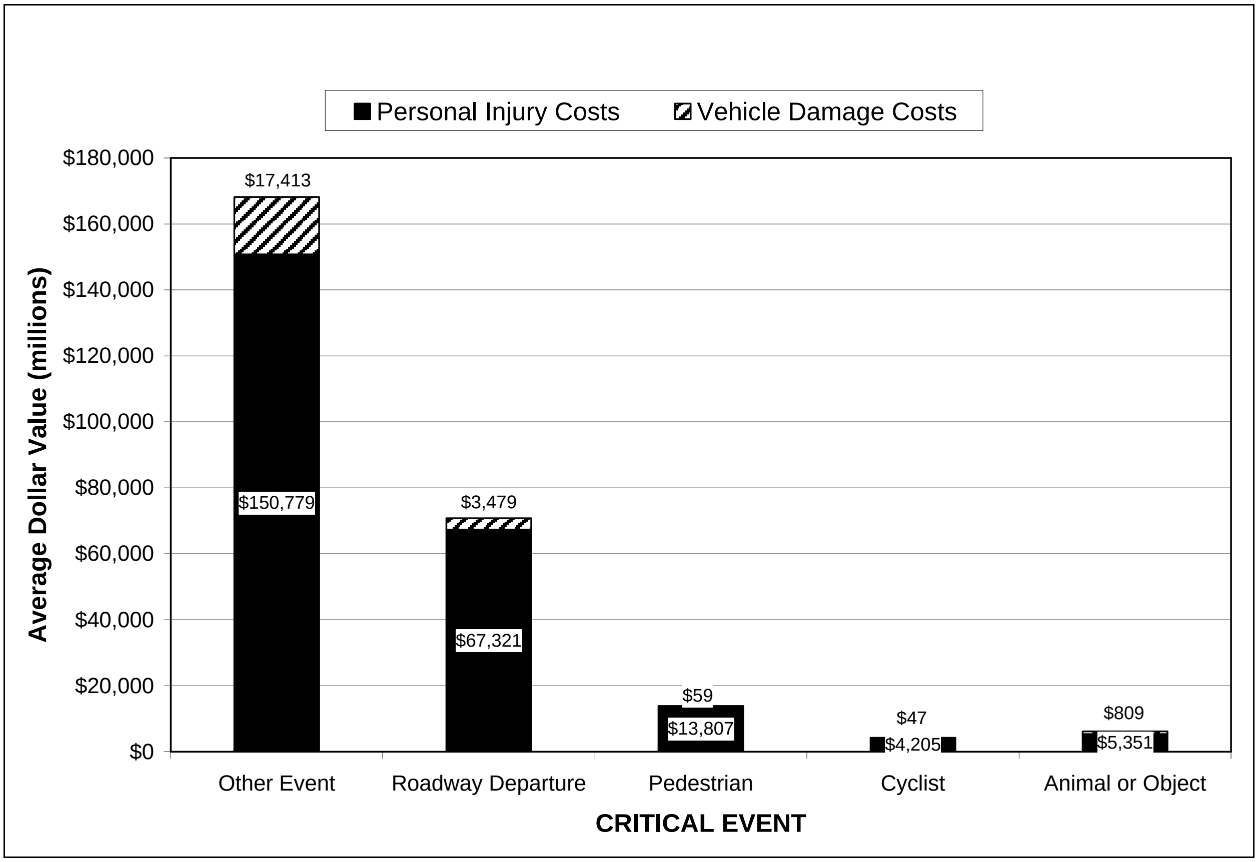


Figure 13. Bar graph. Estimated annual crash costs, 1999 through 2001, by critical event.(13)

Because the four critical event categories that represent interaction with creatures or objects that might or might not be seen at night account for 36 percent of the total costs, it is evident that a little over a third of crash costs arise from critical events in which enhanced visibility might be expected to have an effect.

CHAPTER 5—FINDINGS AND CONCLUSIONS

The procedures described above, applied to the data described above, generate an estimate of the cost of each VES and pavement marking system. They also generate an estimate of total annual crash costs and the percentage of crash costs most likely to benefit from enhanced night visibility.

STEADY-STATE COSTS AT 100 PERCENT IMPLEMENTATION

The cost of each innovative technology, and of the possible combinations of technology, is estimated in two different ways. The first set of results, displayed in table 14 through table 16, forecasts the incremental annual costs of each technology in the steady state when 100 percent implementation is reached; the forecasts are without regard to the costs that accrued in getting to that point. Here the incremental costs refer to the excess above and beyond the costs of the benchmark HLB technology with nonfluorescent pavement markings. The second set of results, displayed in table 20 through table 22, forecasts the costs, discounted to present value, over the course of an assumed 20-year implementation.

Steady-State Findings

Table 14 gives an estimation of the initial incremental cost of each VES per vehicle; table 15 does the same for each pavement marking system. The tables also show what the total annualized incremental cost of each system would be in the year 2020, if 100 percent implementation were achieved by that time. These costs are given in year 2003 U.S. dollars. They are incremental costs, that is, only those costs above and beyond the cost of HLB headlamps or nonfluorescent paint, which are used as benchmarks. For this reason the incremental cost of HLB, and of any system that costs as much as HLB does, is zero by definition; the same applies for nonfluorescent paint.

Table 14. Incremental cost of VESs using HLB benchmark.

VES	Initial Incremental Cost per Vehicle (in 2003 dollars)	Annualized Incremental Cost at 100% Implementation (in billions of 2003 dollars)
HLB	0	0.00
HID	100	4.28
Hybrid UV–A + HLB	2,600	111
Three UV–A + HLB	2,600	111
Five UV–A + HLB	2,600	111
Hybrid UV–A + HID	2,700	116
Three UV–A + HID	2,700	116
Five UV–A + HID	2,700	116
HOH	100	4.28
HHB	0	0.00
HLB–LP	0	0.00
IR–TIS	2,250	85.6

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

Table 15. Incremental cost of pavement marking systems with nonfluorescent paint baseline.

Pavement Marking System	Initial Incremental Cost per Mile (in 2003 dollars)	Annualized Incremental Cost at 100% Implementation (in billions of 2003 dollars)
Fluorescent Paint	1,263	15.9
Fluorescent Thermoplastic	5,010	16.4
Nonfluorescent Polyurea Binder	5,280	9.88
Nonfluorescent Paint	0	0.00

Table 16 shows the annual incremental cost of each combination of one VES with one pavement marking system. In other words, the dollar value entered in the "five UV–A + HLB" row and the "fluorescent thermoplastic" column is the sum of the total annualized incremental cost of the five UV–A + HLB system plus the total annualized incremental cost of the fluorescent thermoplastic system.

Table 16. Annualized incremental costs of each possible VES/pavement marking combination.

	Fluorescent Paint	Fluorescent Thermoplastic	Nonfluorescent Polyurea	Nonfluorescent Paint
HLB	15.9	16.4	9.88	0.00
HID	20.2	20.7	14.2	4.28
Hybrid UV–A + HLB	127	128	121	111
Three UV–A + HLB	127	128	121	111
Five UV–A + HLB	127	128	121	111
Hybrid UV–A + HID	132	132	125	116
Three UV–A + HID	132	132	125	116
Five UV–A + HID	132	132	125	116
HOH	20.2	20.7	14.2	4.28
HHB	15.9	16.4	9.88	0.00
HLB–LP	15.9	16.4	9.88	0.00
IR–TIS	102	102	95.5	85.6

Costs are at 100 percent implementation in the year 2020, stated in billions of dollars.

Break-Even Crash Reduction at 100 Percent Implementation

Table 17 shows the estimated annual cost of crashes in each of five critical event categories (compare figure 7 and figure 13). This presentation is intended to permit comparison with the similar tabulation used by Nitzburg et al.[1] The chief differences are that the table represents average crash costs in 1999–2001 rather than in the 1980s, and the crash costs are categorized by critical event and light condition rather than by crash geometry.

Table 17. Estimated average annual crash costs 1999 to 2001 by critical event and light condition.

		LIGHT CONDITION			TOTAL
		Day/Lighted	Dark	Dawn/Dusk	
CRITICAL EVENT	Other Event	165,914	26,802	8,043	200,760
	Roadway Departure	35,909	17,567	3,423	56,899
	Pedestrian	183	209	9	401
	Cyclist	130	6	4	140
	Animal or Object	2,384	2,230	456	5,070
TOTAL		204,520	46,814	11,936	263,270

Costs are in billions of dollars per year.

Table 18 shows what percentage reduction in the costs of total unlighted nighttime crashes each VES/pavement marking combination would need to achieve to create annual benefits (i.e., cost savings) that match its estimated annual incremental cost.

Table 18. Break-even reduction in unlighted night crash costs for VES/pavement marking combinations.

	Fluorescent Paint (%)	Fluorescent Thermoplastic (%)	Nonfluorescent Polyurea (%)	Nonfluorescent Paint (%)
HLB	34	35	21	0
HID	43	44	30	9
Hybrid UV–A + HLB	>100	>100	>100	>100
Three UV–A + HLB	>100	>100	>100	>100
Five UV–A + HLB	>100	>100	>100	>100
Hybrid UV–A + HID	>100	>100	>100	>100
Three UV–A + HID	>100	>100	>100	>100
Five UV–A + HID	>100	>100	>100	>100
HOH	43	44	30	9
HHB	34	35	21	0
HLB–LP	34	35	21	0
IR–TIS	>100	>100	>100	>100

Table 19 shows what percentage reduction in the costs of total unlighted nighttime, dawn, and dusk crashes each VES/pavement marking combination would need to create annual benefits (i.e., cost savings) that match its estimated annual incremental cost.

Table 19. Break-even percentage reduction in unlighted night, dawn, and dusk crash costs for VES/pavement marking combinations.

	Fluorescent Paint (%)	Fluorescent Thermoplastic (%)	Nonfluorescent Polyurea (%)	Nonfluorescent Paint (%)
HLB	27	28	17	0
HID	34	35	24	7
Hybrid UV–A + HLB	>100	>100	>100	>100
Three UV–A + HLB	>100	>100	>100	>100
Five UV–A + HLB	>100	>100	>100	>100
Hybrid UV–A + HID	>100	>100	>100	>100
Three UV–A + HID	>100	>100	>100	>100
Five UV–A + HID	>100	>100	>100	>100
HOH	34	35	24	7
HHB	27	28	17	0
HLB–LP	27	28	17	0
IR–TIS	>100	>100	>100	>100

Steady-State Interpretation

Because the only combination of pavement marking material and VES that shows systematic improvements in sight distance for drivers of different age groups (see ENV Volumes III through VI) is the five UV–A lamps with halogen low-beam lamps plus the nonfluorescent pavement markings, only these systems are likely to yield positive crash cost reduction. When the sight distance findings are broken down by the type of object to be detected and related to the corresponding critical event category, three systems may be expected to create pedestrian crash cost savings: three UV–A + HLB, five UV–A + HLB, and IR–TIS; these three systems may also be expected to create cyclist crash cost savings. Lane departure crash cost savings may be expected for the five UV–A + HLB, hybrid UV−A + HLB, three UV–A + HLB, and IR–TIS.

It should be evident that if the ENV technologies affect night, dusk, and dawn crashes rather than night crashes alone, then the potential crash cost savings of each combination would be about 25 percent larger (see figure 7 and compare table 18 and table 19). The relative rankings of the systems remain unchanged.

VALUE OF COSTS IN TRANSITION FROM 0 TO 100 PERCENT IMPLEMENTATION

Present Discounted Value Findings

The results in the tables that follow show costs discounted to the beginning of the first year of implementation at an interest rate of 4 percent per annum. Implementation is assumed to occur at the rate of 5 percent per year (i.e., an additional 5 percent of vehicles and 5 percent of highway miles are equipped each year) until full implementation is achieved at the end of 20 years.

Table 20 shows the incremental present discounted cost of each VES with conventional pavement markings. The table covers a 20-year period on unlighted highways when the system is introduced to the vehicle fleet, and then, in steps of 5 percent per year until 100 percent implementation is achieved; table 21 does the same for pavement marking systems. These costs are given in year 2003 U.S. dollars. They are incremental costs (i.e., only those costs above and beyond the cost of HLB headlamps or nonfluorescent paint) that are used as benchmarks. For this reason, the incremental cost of HLB (and any system that costs as much as HLB does) is zero by definition; the same goes for nonfluorescent paint.

Table 20. Incremental cost of VESs using HLB and conventional paint markings benchmark.

VES	Incremental Present Discounted Cost over 20-Year Horizon (in billions of 2003 dollars)
HLB	0.00
HID	23.9
Hybrid UV–A + HLB	622
Three UV–A + HLB	622
Five UV–A + HLB	622
Hybrid UV–A + HID	646
Three UV–A + HID	646
Five UV–A + HID	646
HOH	23.9
HHB	0.00
HLB–LP	0.00
IR–TIS	479

Table 21. Incremental cost of pavement marking systems using nonfluorescent paint benchmark.

Pavement Marking System	Incremental Present Discounted Cost over 20-Year Horizon (in billions of 2003 dollars)
Fluorescent Paint	101
Fluorescent Thermoplastic	104
Nonfluorescent Polyurea Binder	62.6
Nonfluorescent Paint	0.00

Table 22 shows the present discounted cost of each combination of one VES with one pavement marking system. In other words, the dollar value entered in the "five UV–A + HLB" row and the "Fluorescent Thermoplastic" column is the sum of the incremental present discounted cost of the five UV–A + HLB system plus the incremental present discounted cost of the fluorescent thermoplastic system. Again, the assumption that the systems would penetrate the vehicle fleet and the unlighted highways in steps of 5 percent per year underlies the computations.

Table 22. Incremental present discounted costs of possible VES/pavement marking combinations over 20-year implementation.

	Fluorescent Paint	Fluorescent Thermoplastic	Nonfluorescent Polyurea	Nonfluorescent Paint
HLB	101	104	62.6	0.00
HID	125	128	86.6	23.9
Hybrid UV–A + HLB	723	726	685	622
Three UV–A + HLB	723	726	685	622
Five UV–A + HLB	723	726	685	622
Hybrid UV–A + HID	747	750	709	646
Three UV–A + HID	747	750	709	646
Five UV–A + HID	747	750	709	646
HOH	125	128	86.6	23.9
HHB	101	104	62.6	0.00
HLB–LP	101	104	62.6	0.00
IR–TIS	580	583	541	479

Costs are in billions of 2003 dollars.

Present Discounted Value Interpretation

The percentage of effect on crash costs necessary to break even would tend to be slightly larger in the present discounted-value computation than in the steady-state computation for those technology combinations that include both UV–A headlamps and fluorescent pavement markings. (Put differently, any benefit-cost ratios that one might calculate would tend to be slightly smaller.) This slight difference results from the effect that the UV–A headlamps and the fluorescent pavement marking systems create when used in combination. At a constant implementation rate of 5 percent per year, the cost of these systems in combination grows at 5 percent per year also, while their positive effect on crashes (if any) grows very slowly at first.

COMPARISON WITH PREVIOUS RESEARCH FINDINGS

The cost-benefit analysis in this report, adhering closely to the cost-benefit framework in the FHWA report *A Safety Evaluation of UVA Vehicle Headlights*,[1] permits a relatively straightforward comparison of the cost and benefit estimates produced for this study with the earlier estimates that Nitzburg et al. produced in their steady-state analysis. The FHWA report, based on engineering estimates and a very limited body of relevant literature, unavoidably lacked precision, and it is instructive to see how far the Smart Road tests and the reported equipment costs corroborate its estimates.

The reports differ on a couple of methodological points. First, Nitzburg et al. used the GES to tabulate estimated crash costs from a hybrid CDS/NASS file that they created to correct some shortcomings in the personal injury data that NASS provided.[1] The current report uses GES to estimate crash costs from a set of NASS files. Second, Nitzburg et al. tabulated the crash cost estimates in six categories defined by crash geometry.[1] The current report tabulates the crash cost estimates in five categories defined by critical event. The category definitions may not be important, but they may lead to different judgments about which nighttime crashes appear to be relevant, that is, have a potential for reduction.

A glance at table 17 shows that the current study's estimate of total crash costs in unlighted conditions (dark, dawn, and dusk), $58.75 billion at 2003 prices, is reasonably close to the Nitzburg et al. estimate of $53.2 billion at 1995 prices.[1] Table 16, on the other hand, shows that the current study's estimate of the costs of the ultraviolet and fluorescent technologies, $111 to $116 billion for the UV–A headlights and some $16 billion for the fluorescent markings, is two orders of magnitude greater than the Nitzburg et al. estimate of $1.3 billion for the UV–A headlights and $0.23 billion for the fluorescent markings.(1) The ENV study's estimates of the cost of HID headlamps and IR imaging systems have no counterpart in Nitzburg's FHWA report.

DIRECTIONS FOR FUTURE RESEARCH

More Detailed Breakdown of Vehicle Miles Traveled

Traffic counts that indicate what fraction of vehicle miles traveled take place in clear, rainy, snowy, and foggy atmospheric conditions would permit a variant approach to the benefit calculation.

The analysis in this study postulates that the motoring public would realize the benefits of enhanced night visibility in the form of reduced crash costs. It is conceivable that some motorists would attempt to convert crash-cost savings into time-cost savings by driving faster. Any estimate of the cost savings based on constant traffic volume and speed must be considered a lower bound on the true benefits that might occur if motorists could capture additional net savings by trading safety for time.

Under the extreme assumption that motorists benefiting from one of the new night visibility technologies would choose to speed up so much that the risk of a crash remained exactly the same as before, the benefits of the new technology would accrue entirely in the form of travel-time savings. Estimating time savings would require an estimate of the vehicle miles traveled in each of the combinations of light conditions and weather (and, possibly, driver age and gender) by which the crash database can be categorized. Traffic counts that break down traffic volume on a road by the light conditions, weather, and driver age would minimize the number of assumptions and the margin of error in such a calculation.

More Detailed Inventory of Delineators

Some information about the cost of fluorescent delineator posts was collected while completing the cost-benefit analysis; however, the effect of fluorescent materials on the distance at which a delineator post might be detected by a driver was not measured. Therefore, the cost-benefit analysis does not include an assessment of the potential effect of fluorescent delineator posts on future crash costs.

In principle, if delineator post detection distances were obtained from a future study and if information on the distribution of delineator posts on the Nation's highways were collected, it would be possible to include the effect of fluorescent delineator posts in a study such as this one.

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