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REDUCED LIGHTING ON FREEWAYS DURING PERIODS OF LOW TRAFFIC DENSITY

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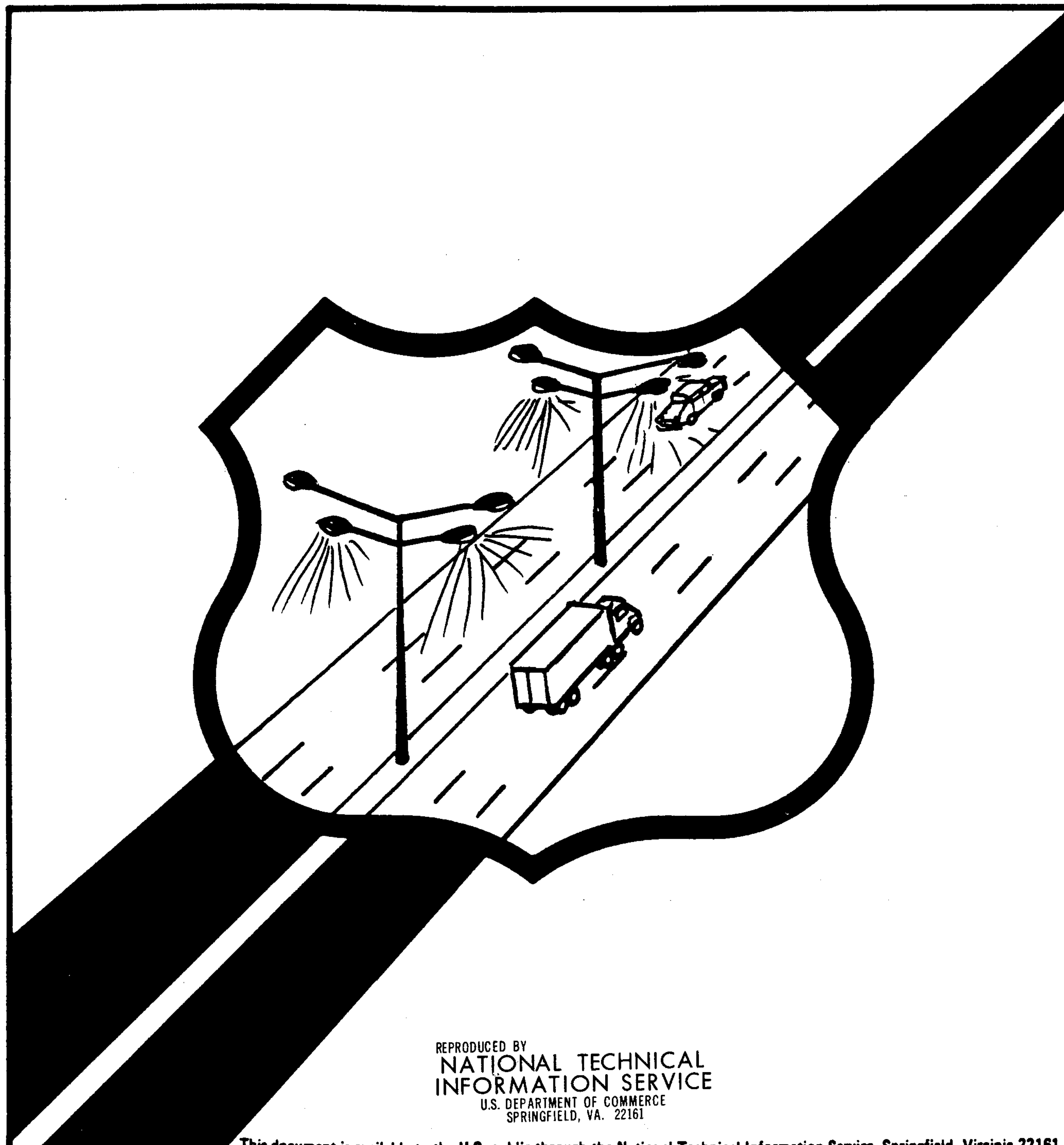

FOREWORD

This research report will be of interest to lighting and traffic engineers and researchers concerned with roadway safety, nighttime visibility, and energy conservation. It presents the costs of implementation and the savings possible when operating streetlighting installations at reduced levels during part of the night. The report also addresses the possible legal implications resulting from reduced roadway lighting.

The results and findings in this report provide a more thorough understanding of the effect of reduced lighting on the ability of motorists to detect targets at various distances. However, field application of the results of this study would conflict with other accepted guidelines and recommendations on lighting. To put the recommendations resulting from the research described in this report into proper context, the reader must be aware that while target detection may only deteriorate slightly under some of the reduced lighting schemes used in this study, the standards guiding practically all lighting designs of public roads in the U.S. reflect at least the minimum criteria set forth in the American National Standard Practice for Roadway Lighting (ANSI/IES RP-8, 1983). This document has been developed and is kept current by the members of the Roadway Lighting Committee of the Illuminating Engineering Society of North America and represents the national consensus of all groups having an essential interest in the provisions of this standard. Its recommendations are the result of continually ongoing work by representatives of the engineering community, various governmental bodies, academia, manufacturers, consultants, utilities, and user groups. It sets minimum lighting levels considered safe for nighttime visibility and traffic conditions. It is our strong opinion and recommendation that, regardless of the findings demonstrated for the particular research context addressed in this study, lighting shall not be reduced below ANSI minimum levels unless such ANSI standards may be changed.

Additional copies of the report are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161. An appendix titled, "A Relative Effectiveness Analysis of a Selected Fixed Lighting System Versus Vehicle Headlights," complementing this report, is available in a hot-copy version from this office on individual request.

Stanley R. Byington, Director
Office of Safety & Traffic Operations R&D

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1.0 INTRODUCTION

Over 50 percent of all motor-vehicle fatalities occur in darkness even though only 25 percent of all travel occurs at night[1]. This overrepresentation has been used as a justification for installing fixed roadway lighting on many highways. However, research that has attempted to determine the effect of such fixed lighting on the frequency and severity of night accidents appears to be mixed, such frequencies and severities being dependent on a host of geometric and traffic factors including the volume of traffic utilizing the road, how such volume is related to the road's capacity, and the complexity of the driver's visual search task.[2]

During the past decade, several highway agencies have switched off roadway lighting during periods of energy shortages to reduce maintenance and operating costs. However, quite often such lighting was restored when nighttime accidents increased.[3,4,5] One fundamental problem with these light reduction techniques was that lighting was reduced or eliminated during the entire nighttime period, rather than only when traffic volume was low.

By providing full lighting during periods when volumes are high and the roadway operates near capacity and providing reduced lighting as the traffic decreases, the potential exists for realizing considerable energy savings while still providing the benefits of full lighting at locations (e.g., interchanges) and at times (i.e., high volumes) where driver decision-making is the most critical and the greatest visibility is required.

1.1 Project Objectives

The overall goal of this study was to determine if freeway lighting can be reduced or eliminated during nighttime periods when traffic volume is much lower than design capacity without causing significant reductions in the ability of drivers to control their vehicles in a safe and effective manner.

Specific objectives of this study included:

- Developing alternative operating tactics for reducing or eliminating fixed roadway lighting on limited access highways during low-volume periods;
- Evaluating the relative effect of these tactics on driver performance for typical freeway situations;
- Performing an economic analysis that considers the costs, energy savings, and cost-benefits associated with such tactics;
- Determining the potential legal implications of the use of such tactics; and
- Preparing recommendations for the potential use of such tactics.

1.2 Summary of Research Results

The major findings of this study are:

- Tactics for reducing or eliminating freeway lighting during low traffic volume periods include (a) all off, (b) every other off, (c) one side off, (d) two lamps per pole--one off during low volumes, (e) fixed dimming (e.g., 50 percent), and (f) variable dimming (e.g., as a function of time, traffic volume or visibility). These are discussed in section 2.
- The tactics including all off, every other off, and one side off tend to be simpler and less expensive to implement, while the dual lamp and dimming circuit tactics are more complicated and more expensive to implement.

- Significant energy savings can be obtained from all tactics.

- There is a potential for serious legal problems associated with the use of such reduced lighting, especially when levels are reduced below ANSI recommendations. However, for lighting systems that exceed ANSI values, it appears that reductions down to ANSI-recommended values would have no adverse legal impact. The legal issues are described in section 2.

- A conceptual model that relates roadway lighting to driver visual needs has been developed and used as a basis for the experimental design that evaluated the effect of reduced lighting on driver performance. This model and an accompanying analysis of the relative effectiveness of fixed illumination versus vehicle headlights is presented in section 3.

- Driver performance under all reduced lighting conditions [all off; one side off; every other off; 75 percent power (50 percent light) and 50 percent power (30 percent light)] is decreased when compared to performance under full lighting that meets ANSI-recommended values. The reduction in performance is quite small (and not statistically-significant) for the dimmed tactics and is significantly larger for the one-sided and all off lighting tactics. The experimental methods and findings are discussed in sections 4 and 5, respectively.

- Benefit-cost ratios based on installation/operating costs and energy savings are quite high for the simpler tactics, reducing below 1.0 for the most expensive tactic (variable dimming). The economic analysis is discussed in section 6.

- Equipment is presently available to implement any of the six light-reducing tactics.

1.3 Recommendations

Major recommendations arising from this research include:

- Fixed, uniform dimming circuits provide a relatively effective means for providing energy savings of up to 25 percent in newly designed lighting systems while only resulting in a minimal adverse impact on safety. Benefit-to-cost ratios of about 1.0 can be expected.

- For either new or existing lighting systems, extinguishing every other luminaire provides a far less costly and more easily implementable option for conserving 25 percent of the energy with only a small-to-moderate impact on safety. For most freeway applications, however, established guidelines for lighting levels and uniformities may no longer be met. Agencies contemplating such a step should assure themselves that the reduced system conforms to AASHTO guidelines before implementing such a tactic and be fully aware of the possible legal problems they may encounter. Benefit-to-cost ratios in excess of 9.0 can be expected.

- Extinguishing the lighting on one side of a (divided) roadway is most strongly not recommended, as driver (simulated) hazard detection performance under this lighting condition falls below even that demonstrated under no lighting.

- Reducing or extinguishing the lighting on interchange ramps is not recommended at this time.

1.4 Report Organization

The remainder of this report is organized into the following sections:

2.0 SUMMARY OF LITERATURE, EXPERIENCES, AND LEGAL ASPECTS OF REDUCED LIGHTING

3.0 VISIBILITY NEEDS

4.0 EXPERIMENTAL TEST PLAN

5.0 RESULTS

6.0 ECONOMIC ANALYSIS

7.0 SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

8.0 GLOSSARY OF INCLUDED STATISTICAL TERMS

9.0 REFERENCES

2.0 SUMMARY OF LITERATURE, EXPERIENCES, AND LEGAL ASPECTS OF REDUCED LIGHTING

The first task in this project was a review and analysis of the literature and results of past experiences with reduced lighting. The objective of this task was to identify those reduced lighting tactics that have previously been employed; hypothesize additional ones that may reduce energy use without degrading safety; preliminarily evaluate these tactics by means of subjective ratings by lighting experts; determine the effect of such tactics on safety and traffic operation; estimate likely ranges of benefit-cost ratios that such tactics would provide; and determine the potential legal issues that might arise if reduced lighting were implemented. The following paragraphs in this section summarize the key results of this review.

(1) Reduced lighting tactics

The following previously-implemented tactics were identified as a result of the literature review:

- Extinguish all lighting after midnight.[1]
- Extinguish every other luminaire after midnight.[1]
- Extinguish one side (of two sides) after midnight.[1]
- Install two luminaires per pole and extinguish one after midnight.[1]
- Install special dimming circuit and dim all luminaires after midnight.[1]
- Install special dimming circuit plus automatic control of dimming as a function of volume, time, or visibility, to adjust the lighting levels in proportion to volume, time, or visibility.

Each of the above tactics can be applied to entire freeways or main-line sections only. In addition, for illuminated interchanges on non-illuminated roads these additional tactics were identified:

- Complete interchange lighting reduced to partial interchange lighting or no lighting, and partial lighting reduced to no lighting.

(2) Preliminary evaluation of reduced lighting tactics

A small group of lighting experts rated each of the preceeding tactics with respect to energy reduction, safety, practicality, costs, legal issues, and other effects (traffic operations, excluding safety).

In general, the simpler systems (all off, every other, one side) were rated higher (better) for energy savings, costs, and practicality, while the more complex systems were rated higher for safety, legal, and other effects.

(3) Preliminary cost-benefit analyses and effect on safety and performance, based on the results of past experiences

With reduced or eliminated lighting (all extinguished, one side extinguished and alternate lights extinguished) for entire nighttime periods, very low benefit-cost ratios were obtained, typically less than 1.0.[3,4,5,6] In addition, analysis of accident data from Milwaukee, Wisconsin[3], and Virginia[5], and driver performance data for Pennsylvania and Maryland for

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[1] or another designated time (e.g., 1:00 a.m.)

before-midnight and after-midnight periods[7,8] revealed mixed effects of reduced or eliminated lighting.

The Milwaukee data indicated that when the lighting was extinguished, the frequency of nighttime accidents, nighttime accident rates, and night-to-day accident ratios all increased, but more so after midnight, during the lowest traffic density.

The Virginia data seemed to indicate that when lighting was extinguished, safety was decreased most significantly during the evening rush hour during very high traffic density, and after midnight.

The driver performance data indicaated that partial interchange lighting provides some of the safety benefits of complete interchange lighting after midnight, but provides no benefits over no lighting before midnight.

(4) Legal analysis

Two approaches were employed to termine what legal problems might be incurred by a lighting agency that utilized reduced lighting tactics: (1) a review and critique of the legal literature and (2) a compilation and analysis of legal opinions of experts.

The review and critique revealed that under both the common law and State Tort Claims Acts, the specter of liability is present for a public entity which seeks to reduce or eliminate lighting on its highways during periods of low traffic density. Any agency which undertakes such a program will be well advised to do so only after extensive scientific research and study. Even then, of course, it may not avoid a lawsuit, but, at least, it could substantially lessen the probability of a plaintiff's recovery.

The literature and case histories indicate that a pattern is emerging; once the decision to reduce the lighting is made, that decision must be based upon sound, scientific information gleaned from careful previous investigation according to accepted scientific principles and procedures. Even if such an extensive prior project is undertaken, however, this will not preclude a court from determining, nonetheless, that the reduction in lighting ultimately created a hazardous condition on a particular stretch of road. That decision will not turn simply upon the one fact of reduced lighting, but upon the total facts existing at the time of the accident.

Sixteen opinions were obtained by personal telephone contacts and a personalized questionnaire. These 16 respondents include 9 from lighting engineers or consultants and 7 from attorneys, and include 10 municipal or State agencies and 6 individuals in private practice.

Since the responses varied so widely, a classification scheme was developed which placed each opinion into one of four categories, defined as follows:

Category 1: Wait for research.

> Research, to date, is inconclusive regarding safety of reducing or extinguishing lighting; until conclusive research establishes safety of decision, no reduction or extinguishing should take place.

Category 2: Definite problem.

Reduction or extinguishment of lighting definitely subjects municipal agency to liability.

Category 3: Good defenses exist.

(a) Prioritization; i.e., municipal decision based upon reasoned, rational prior study of options and/or alternative solutions.

(b) Decision whether or not to reduce or extinguish lighting is discretionary, not ministerial, giving rise to municipal tort immunity under State Tort Claims Act and common law.

(c) Past experience with reduced lighting indicated safe condition.

Category 4: Liability situation still unsettled.

Each case rises or falls on its particular facts.

The respondents provided 18 opinions (two respondents provided two opinions) which were classified as follows:

Opinion	Number of Responses	Percent of Responses
Wait for research	5	28
Definite problem	4	22
Defense exists	5	28
Liability unsettled	4	22

Effect of type of respondent (state/municipal versus private; attorney versus nonattorney) did not significantly affect the distribution of opinions.

The diversity of the responses summarized above reinforces the conclusion that tort liability will be an issue if lighting is reduced--especially below ANSI-recommended values.

3.0 VISIBILITY NEEDS

This section of the report briefly reviews a conceptual model of driver performance applicable to the present research context, and summarizes the results of an extensive set of calculations evaluating the relative effectiveness of fixed roadway illumination versus vehicle headlights (in the absence of overhead illumination). A substantial amount of additional material describing the logic and specific equations used in reaching the conclusions presented in this section may be found in a separate document prepared in association with this report.[1]

The objective in the development of a relevant conceptual model was to relate net operator-vehicle response effectiveness to the visual inputs provided by the existing source(s) of illumination in the roadway environment. In reviewing prior research in this area, the theoretical framework judged most appropriate to describe the overall hazard avoidance process was the decision sight distance (DSD) approach[(9)]. Accordingly, the environment-operator-vehicle model of visual information processing shown in figure 1 was adopted to help guide the subsequent analytical and experimental work in this project.

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1 L. Staplin and M. Janoff, "A Relative Effectiveness Analysis of a Selected Fixed Lighting System Versus Vehicle Headlights," prepared as a separate document for FHWA, reference the present research contract DTFH61-83-C-00056.

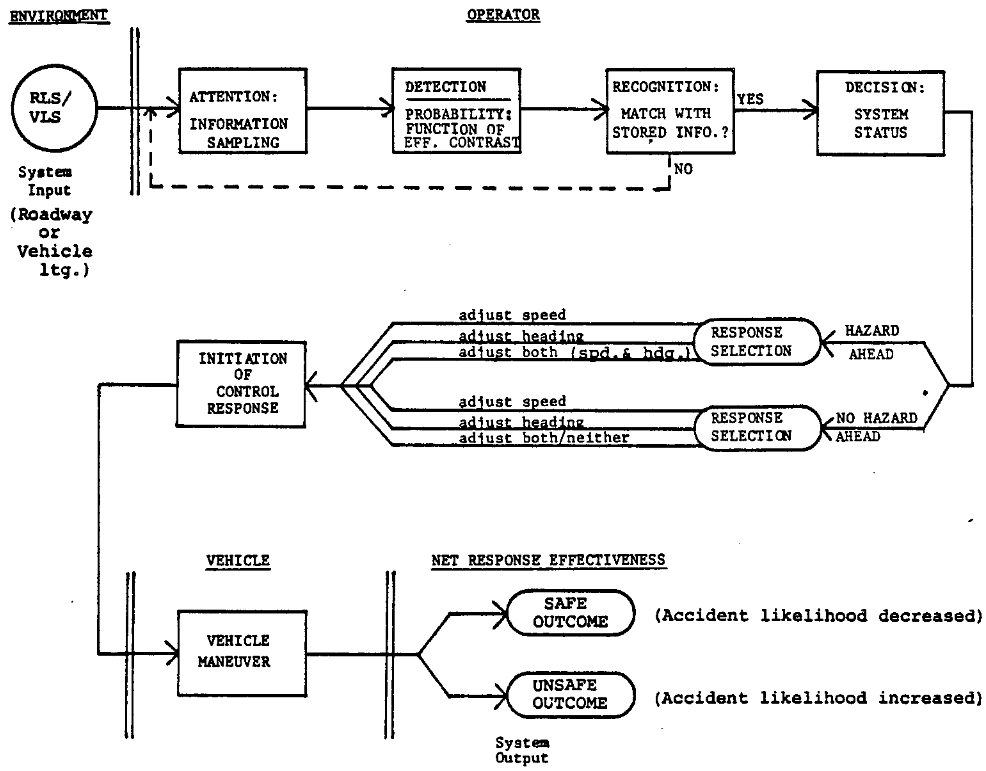

Figure 1. Flow chart of processing stages underlying driver (hazard avoidance) performance.

In analyzing the relative effectiveness of fixed roadway illumination versus vehicle headlights in providing drivers with the necessary visual inputs to detect and avoid a defined hazard in the roadway, the following key paramaters were initially identified:

- <u>Observer (driver)/target (hazard) separation distance</u>--650 ft (198 m).

- <u>Target (hazard) characteristics</u> -- 6-in (19.4 cm) height, gray color, 18 percent uniform reflectance level, three-dimensional (cylindrical) surface presented to driver, constituting a task detail size of 2.5 minutes.

- <u>Road surface reflectance properties</u> -- CIE R-1.

- <u>Fixed lighting system of interest</u> -- 200-watt high-pressure-sodium lamps, medium-cutoff type III distribution luminaires, 30 ft (9.15m) mounting height, 2 ft (.61 m) overhang, 68 ft (20.7 m) staggered spacing, 0.81 light depreciation factor.

- <u>Vehicle lighting system of interest</u> -- #4000, round, 5 3/4-inch (18.6 cm) type 2 sealed-beam incandescent headlamps, at 2 ft (.61 m) mounting height.

- <u>Roadway (lateral) dimensions</u> -- 104 ft (31.7 m) total width, including six 12-ft (3.66 m) wide lanes and a 12-ft (3.66 m) wide, flat medial strip.

- <u>Observer and target position in roadway</u> -- observer's vehicle travelling in center (northbound) lane of three lanes, with target located in straight-ahead orientation with respect to observer.

- <u>Observer (driver) characteristics</u> -- 57-in (1.45 m) eye height and 64 years of age.

It should be noted that the 650-ft (198 m) separation distance was defined in accordance with the "serial-contingent" model presented in figure 1, which postulates a sequential and dependent set of processing stages (i.e., one stage must be completed before the next is begun) that are additive in terms of predicting the total interval necessary to complete an effective vehicle maneuver. Estimates for the processing duration associated with each stage were derived from the DSD model referenced above, then were multiplied by an assumed vehicle velocity of 62 mph (99.75 km/h) and summed.(9) As described in a later section of this report, however, the results of both the pilot and controlled field studies provide a strong implication that additive calculations of this sort are not appropriate, and that in fact the stages of information processing involved in a hazard avoidance task most likely occur in a parallel rather than a serial (i.e., sequential) fashion. Consequently, the analyses performed in this part of the project were later expanded to further consider the case where the observer and the target are separated by only 250 ft (76.2 m).

Additional modifications of the initial parameters in the present effort included a consideration of a 30 percent-reflective target and a road surface with CIE R-3 reflectance properties, as indicated in the expanded analysis subtask headings listed below:

1) 18 percent-reflective target/650 ft (198 m) separation/R-1 road surface.
2) 18 percent-reflective target/650 ft (198 m) separation/R-3 road surface.
3) 30 percent-reflective target/250 ft (76.2 m) separation/R-1 road surface.

Substasks 1 and 2 thus provide some measure of the impact of road reflectance properties on the relative effectiveness of fixed illumination and vehicle headlights, while subtasks 1 and 3 together analyze boundary conditions judged to be most meaningful in terms of drivers' detection performance during the later field data collection efforts in this project. All other parameters identified earlier in this section remained constant throughout each subtask of the expanded analysis.

The results of the relative effectiveness analyses are expressed in table 1, based on calculated (pure) contrast values modified to include the influence of relative contrast sensitivity and a disability glare factor. Relevant equations include an expression of effective contrast (C_{eff}):

$$C_{eff} = C \times RCS \times DGF, \qquad [1]$$

where C ("pure" contrast), RCS(relative contrast sensitivity), and DGF (disability glare factor) are defined according to the American National Standard Practice for Roadway Lighting (ANSI/IES RP-8), published in 1983. Next, empirically-derived(10) equations for (forward) pavement reflectance[2] and pavement retroreflectance[3], respectively, were employed as follows:

$$R_p = .25\left[\frac{1}{i^{0.50} \times r^{0.76} \times h^{0.103}}\right] \qquad [2]$$

where i, r, and h refer to incident, reflected, and included angles; and,

Table 1. Results of relative effectiveness analyses for fixed versus vehicle lighting systems.

Analysis subtask	Lighting system	Target luminance, in fL**	Pavement luminance, in fL**	Relative contrast sensitivity	Disability glare factor	Calculated effective contrast
1) 18%-reflective target, 650 ft separation*, R-1 road surface	Fixed illumination (maximum contrast)	1.70×10^{-2}	1.036	2.91×10^{-1}	9.44×10^{-1}	2.7×10^{-1}
	Fixed illumination (minimum contrast)	1.77×10^{-1}	5.60×10^{-1}	2.06×10^{-1}	8.95×10^{-1}	1.3×10^{-1}
	Vehicle headlights only (no overhead lighting)	1.80×10^{-3}	1.14×10^{-3}	1.36×10^{-3}	N/A	7.9×10^{-4}
2) 18%-reflective target, 650 ft separation*, R-3 road surface	Fixed illumination (maximum contrast)	1.70×10^{-2}	7.25×10^{-1}	2.39×10^{-1}	9.49×10^{-1}	2.2×10^{-1}
	Fixed illumination (minimum contrast)	1.77×10^{-1}	3.92×10^{-1}	1.65×10^{-1}	9.08×10^{-1}	8.0×10^{-2}
	Vehicle headlights only (no overhead lighting)	1.80×10^{-3}	1.14×10^{-3}	1.36×10^{-3}	N/A	7.9×10^{-4}
3) 30%-reflective target, 250 ft separation*, R-1 road surface	Fixed illumination (maximum contrast)	2.80×10^{-2}	1.036	3.48×10^{-1}	9.44×10^{-1}	3.2×10^{-1}
	Fixed illumination (minimum contrast)	2.95×10^{-1}	5.60×10^{-1}	2.57×10^{-1}	8.95×10^{-1}	1.1×10^{-1}
	Vehicle headlights only (no overhead lighting)	2.05×10^{-2}	4.80×10^{-3}	7.92×10^{-3}	N/A	2.6×10^{-2}

*1 meter=3.28 ft
**1 cd/m2=0.2919 fL

$$R_p = 0.0331 + (7.578 \times 10^{-5} \times D), [3]$$

where D is separation distance (in ft). Also, an expression of veiling luminance was employed, as shown below:

$$L_v = 10\pi \sum_{i=1}^{2} \frac{E_i \cos \theta_i}{(\theta + 1.5)\theta_i}, \quad [4]$$

where E represents the illumination of a glare headlamp measured at an observer's eyes, and θ is the angle (in three dimensions) between an observer-target line-of-sight and an intensity vector (I) emanating from the glare headlamp(s) toward the observer.

Two fixed-illumination values are calculated for each of the three target reflectivity/separation distance/road reflectance combinations, corresponding to the situations where maximum versus minimum (pure) target contrast is obtained within a single luminaire cycle, given the lighting system parameters identified earlier.

From the results of the analyses summarized in table 1, it was concluded that overhead lighting reaches a level of effectiveness over 300 times greater --and is minimally at least 150 times more effective--than vehicle headlights alone, given an 18 percent-reflective target, 650 ft (198 m) separation distance, and an R-1 road surface. Given the same target and separation distance but an R-3 road surface, it was concluded that overhead lighting reaches a level of effectiveness over 250 times greater--and is minimally at least 100 times more effective--than vehicle headlights alone. However, given a 30 percent-reflective target and a 250 ft (76.2 m) separation (with R-1 surface), it was concluded that overhead lighting is at best only 12 times more effective--and may be as little as 4 times more effective--when compared to vehicle headlights alone.

Finally, the present analysis further elaborated on the results for the 18 percent-reflective target/650 ft (198 m)/R-1 surface combination to take into account the changes in pavement luminance and disability glare from an opposing vehicle positioned both upstream and downstream of the to-be-detected target. With the opposing vehicle downstream of the (simulated) hazard the overhead lighting system included in this analysis is at best roughly 14 times more effective than vehicle headlights alone, and under minimum contrast conditions falls to about 7 times the effectiveness of headlights alone. When the opposing vehicle is <u>up</u>stream of the target--i.e., located between the observer and the target--the relative effectiveness of overhead lighting is very close to that noted above for the situation without any opposing vehicle, i.e., roughly 150 to 300 times greater than that of vehicle headlights alone.

While these results were interesting in their own right, they also served to help guide the remaining (field data collection) efforts in this project. First, the consideration of different pavement reflectance properties (CIE R-1 versus R-3) indicated that this variable had a relatively smaller impact on effective contrast than target reflectance or (longitudal) separation distance; based upon this finding, it was judged acceptable to confine the subsequent field data collection to one pavement type (R-1). By comparison, the relatively large impact shown for target reflectance made it apparent that data gathered at one level of this factor could <u>not</u> be reliably generalized to targets viewed at other levels; this finding underscored the need to employ a uniform target reflectance value in the controlled and observational-validation experiments. Also, the strong impact of an opposing vehicle's headlights demonstrated in the relative effectiveness analysis made it clearly advisable to minimize the influence of this factor during field data collection; this finding reinforced a decision to maximize the lateral separation between drivers (in the test vehicle) and this glare source by placing the target in the shoulder (right-hand) lane, and contributed to the experimenter's judgment of when an adequate gap in (oncoming) traffic existed to initiate a test trial at non-illuminated sites.

4.0 EXPERIMENTAL TEST PLAN

This section presents material relating to the subjects, apparatus, and methodology associated with three separate field studies conducted during the performance of this research. In the subsequent discussion, these efforts will be referred to as the pilot study, the controlled field study, and the observational validation study, respectively.

The role of each study in meeting the project objectives may be briefly summarized as follows: The pilot study provided selective data regarding driver performance under meaningful operational boundary conditions, to help define the most appropriate test conditions for inclusion in the controlled field study; the controlled field study generated comprehensive behavioral and photometric measures to assess the relative effectiveness of a variety of alternative reduced lighting tactics for a designated roadway geometry and level of target reflectance; and the observational validation study demonstrated driver-vehicle system response patterns (for unalerted motorists under specific lighting conditions) which were consistent with the results of the controlled field study, thereby reinforcing the validity and generalizability of the present experimental approach. The purpose and procedures associated with each effort are covered in much greater detail in the remainder of this section.

4.1 Pilot Study

The pilot study in this project was designed to examine drivers' ability to detect a simulated roadway hazard under normal late night (i.e., low volume) freeway traffic conditions, for meaningful extremes of roadway geometry, fixed roadway illumination, and target (hazard) reflectance, incorporating both objective (distance-to-target) and subjective (visibility rating) measures of effectiveness. The test site characteristics, target characteristics, independent variables (lighting conditions), dependent variables (measures of effectiveness), experimental design, sample characteristics, data collection protocol, and data analysis techniques for this study are presented below.

Test site characteristics. Five test sites were selected for the pilot study along Interstate 95 in northeast Philadelphia as shown schematically in figure 2. Three of the sites (1, 2, and 4) were located in the right (shoulder) lane on tangent road sections, and two of the sites (3 and 5) were located on interchange ramps. In all cases, the pavement was composed of worn portland cement classified as a CIE R-1 reflective surface. Further, all fixed lighting installations (sites 1, 2, and 3) included 200-watt, high-pressure sodium (200 HPS) lamps in medium-cutoff, type-III distribution luminaires, with a 30 ft (9.1 m) mounting height and 2 ft (.61 m) overhang.

Additional information regarding site characteristics is presented in figure 3. First, the configuration of the two interchange ramp segments (sites 3 and 5) exhibited differences in radii of curvature of less than 2 degrees and the posted speed limit of 25 mph (40.2 km/h) was identical across locations, both important considerations when later analyzing and interpreting the data obtained at these

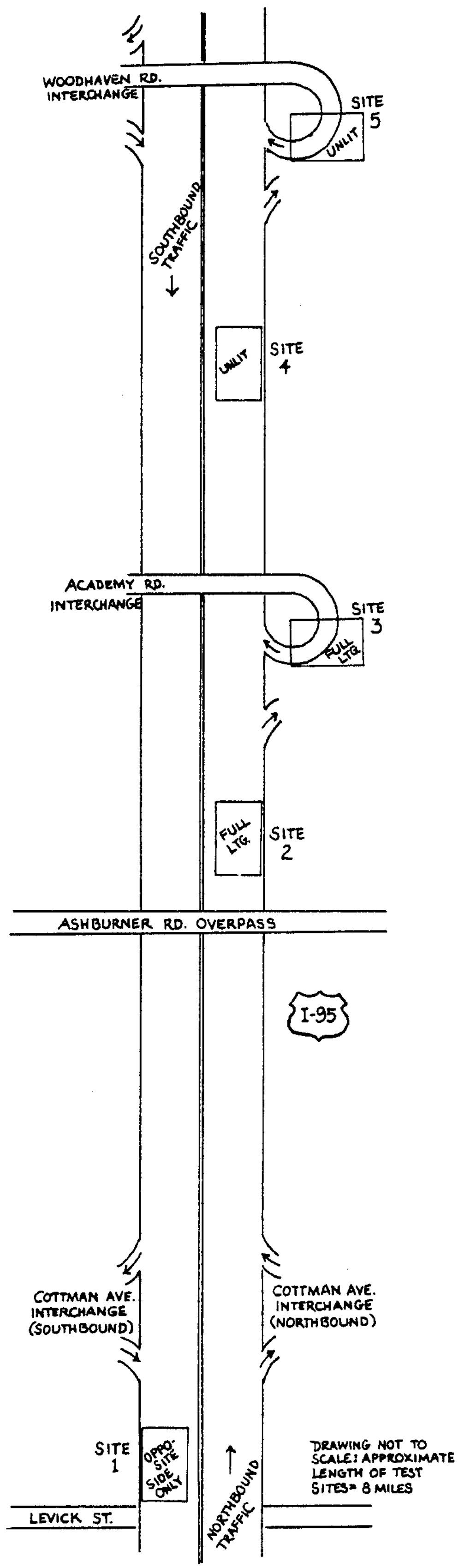

Figure 2. Five test sites along I-95 for pilot study.

respective test sites. Next, luminaire spacings at the three lit sites (1, 2, and 3) are indicated, demonstrating a 68 to 72 ft (20.7 to 22 m) staggered arrangement at site 1, an 84 to 88 ft (25.6 to 26.8 m) staggered arrangement at site 2,and a complete interchange lighting (CIL) arrangement as shown at site 3. All main-line/tangent sites had a posted speed limit of 55 mph (88.5 km/h).

At each fully lit site two target positions were defined, corresponding to the points of maximum and minimum (horizontal) illumination within a luminaire cycle. At the one-side-only site 1, illumination on the dark side was uniformly low, and only one target position was employed, as at the two unlit sites. For those sites with two target positions, half the data was collected with the target under maximum illumination and half was collected with the target under minimum illumination.

Target characteristics. The detection target used to simulate a roadway hazard in this study was an idealized three-dimensional form: a hemisphere atop a cylindrical base, both 6 inches (15.2 cm) in diameter. It was selected to be consistent with current AASHTO sight distance guidelines and with prior, related visibility research.[11,12]

Specifically--disregarding stimuli used primarily in laboratory studies of visual acuity/discrimination (e.g., Landolt rings)--three types of targets have been included in detection experiments under actual lighting conditions: 1) simulated pedestrians--either mannequins or visually equivalent objects[13]; 2) flat, two-dimensional disks or squares which "stand up"

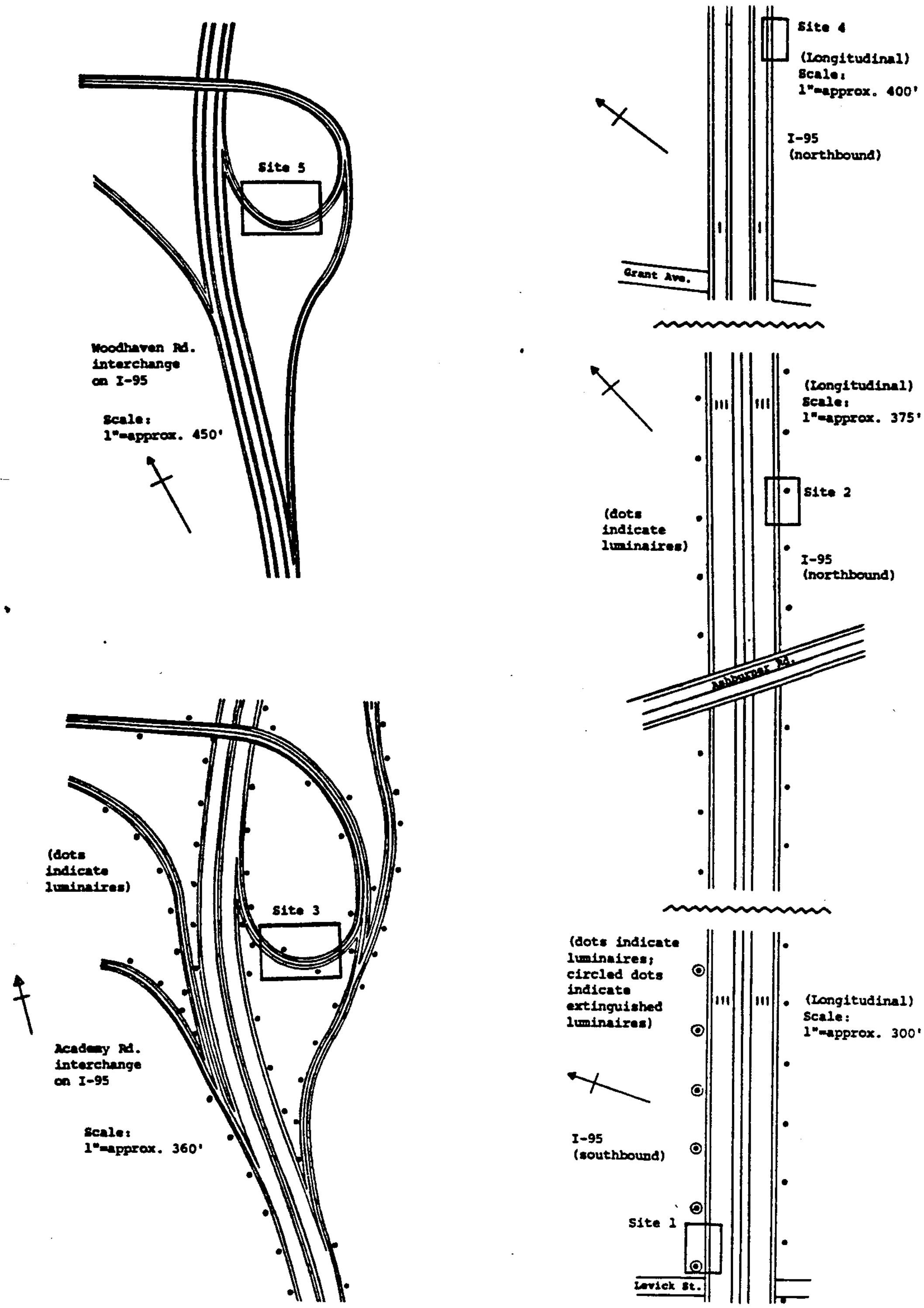

Figure 3. Site characteristics.

vertically in the roadway[14]; 3) three-dimensional objects, such as truncated cones.[15]

Pedestrians, first of all, are not common on freeways; further, by virtue of their size and highly familiar configuration, they cannot credibly be generalized--in terms of detection/recognition performance--to the types of roadway hazards of greatest interest in this investigation. Similarly, the degree of realism obtained by representing highway debris capable of resulting in damage or loss of control of a vehicle if hit at high speed (e.g., a detached muffler, construction materials, etc.) with two-dimensional, vertical targets leaves something to be desired. In this approach, the influence of horizontal illumination (E_H) -- i.e., the vertical component of the illumination vector--on target visibility is completely ignored. Thus it was the third category of (three-dimensional) targets that offered the greatest degree of realism, in terms of the present research objectives.

The target used in this study was made of foam rubber, coated with latex, and then painted a specially-mixed flat gray of either 18 percent or 30 percent uniform reflectance. Also, a piece of 1/16-inch-thick (1.6 mm) aluminum was cemented to the base of the target, to provide stability and durability during the test trials. This object is pictured in figure 4.

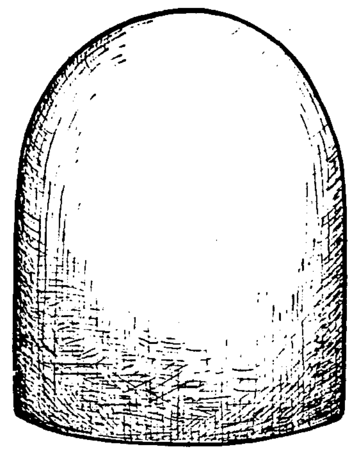

Figure 4. Target illustration.

Independent variables (lighting conditions). Only those conditions associated with extremes of freeway illumination and/or visibility were included as independent variables in the pilot study. Specifically, full (continuous) freeway lighting and no lighting conditions were implemented at main-line/tangent sites (2 and 4, respectively), and complete interchange lighting and no lighting were implemented at interchange sites (3 and 5, respectively). In addition, a main-line condition was implemented in which all luminaires were extinguished on one side of the freeway (site 1). In this situation, motorists (on the dark side of the roadway) were provided with illumination only marginally greater than that obtained under no lighting conditions, while still experiencing disability glare from the luminaires which remained lit on the opposite side of the highway.

Dependent variables (measures of effectiveness). The dependent measures obtained in the pilot study consisted of an objective, distance-to-target (DTT) measure, plus a rating scale response to subjectively assess (simulated) hazard visibility. The primary, DTT measure was designed to reveal--to the nearest foot--how far away an alerted driver was from a (downstream) target location when he could first detect the presence of the target in the (same lane of the) roadway ahead of his vehicle. Accordingly, a 1978 Ford Fairmont was instrumented with a device linked to the transmission capable of monitoring traversed distance, and a 4-inch-diameter (10.3 cm) response button mounted in the center of the steering wheel was wired into the distance recorder so that it was capable of switching the distance accumulation function off and on while the vehicle was in motion. The distance recording device was a Transwave, Inc. NK-1202, incorporating a microprocessor and digital readout, calibrated for use with the vehicle identified above.

The subjective measure of target visibility was generated through use of the rating scale shown below in figure 5. Immediately after the DTT measure was obtained on a given test trial, the subject was required to select a number on the scale to indicate his response.

Though not strictly defined as dependent variables, several additional measures were obtained in this study which played an important role in the subsequent analysis and interpretation of the DTT and rating scale data. First, the simple reaction time (RT) of each subject was measured prior to their participation in the field test, using a hood-mounted LED (light-emitting diode) triggered by the experimenter plus a response button (on the steering wheel) wired into a timing device located in the back seat of the vehicle. Next, two additional subjective measures were obtained through the administration of a brief post-experimental questionnaire. One measure involved a rating scale response in which subjects evaluated the realism of the detection target in relation to "small highway debris, including mufflers, construction materials, dead animals, and so forth." This scale is shown in figure 6. Further, if they gave the target a rating of 7 or lower, they were asked how it could be changed to make it more representative of these kinds of hazards.

Very poorly 1 2 3 4 5 6 7 8 9 10 Very well

"How well could you see the target?"

Figure 5. Rating scale for target visibility measurement.

Very poorly 1 2 3 4 5 6 7 8 9 10 Very well

"Overall, how well did the target simulate a hazard in the road?"

Figure 6. Rating scale to evaluate realism of target.

Finally, subjects were asked to give their opinion of the impact on safety of reducing lighting levels, using the rating scale shown in figure 7. Subjects made separate responses on the same scale for ramps versus main-line freeway sections.

Experimental design. The pilot study employed a repeated-measures design, in which all subjects generated data for all test conditions. Presentation order of the five test trials for a given subject was determined according to a Latin-square type of counterbalancing scheme, which assured that no site was presented to subjects a disproportionate number of times in any particular position within the sequence of test trials.

Roadway geometry served as a blocking variable, such that the subsequent analysis and interpretation of data from the three main-line sites was performed separately from that for the two ramp sites. The resulting experimental design for this study was therefore described as a one-way design, with two and three treatment levels (lighting conditions) associated with the ramp and main-line categories of the blocking variable (roadway geometry), respectively.

Sample characteristics. The test sample in the pilot study consisted of 14 male and 10 female licensed drivers whose (corrected) visual acuity was 20/40 or better. Subjects' ages ranged from 20 to 70, with an average of 42, distributed as follows across four brackets associated with significant age-related shifts in relative contrast sensitivity (RCS): 20 to 30 years, 6 subjects; 30 to 44 years, 7 subjects; 44 to 64 years, 9 subjects; and 64 to 80 years, 2 subjects.[16]

All test subjects in this study were recruited through advertisements placed in suburban Philadelphia newspapers and were paid $30 for their participation.

Data collection protocol. The initial step in the protocol for the study was the administration of a brief visual acuity screening under low light conditions--i.e., 0.4 fL (1.37 cd/m^2) target luminance--using a standard Snellen chart presented to seated subjects at a distance of 10 feet (3.0 m). This was performed at KETRON laboratory facilities prior to field data collection, to assure that all participants met the acuity criterion noted above.

At the outset of field testing, each subject was seated in the instrumented vehicle and all mirror and seat adjustments were made. In addition, the subject was made aware of the location and operation of all vehicle control systems. Next, the RT measure

Very unsafe 1 2 3 4 5 6 7 8 9 10 Very safe

"In general, how safe is it to reduce the level of lighting on freeways late at night when traffic volume is low?"

Figure 7. Rating scale for opinion of impact on safety of reducing lighting levels.

was obtained, using a hood-mounted LED; ten trials were performed, requiring a total of roughly 5 minutes. At this point, the experimenter--seated in the passenger position--explained the procedures for the study, and presented the subject with an example of the gray styrofoam target that was to be used as the detection target in the roadway. It was stressed that the subject should hit the response button (in the center of the steering wheel) as soon as one of the targets was seen in the road ahead, but to please be sure that it had been detected before response was made. When the subject indicated full understanding of the instructions and was comfortable driving the test vehicle, the experimenter directed the subject to enter the freeway at a designated location corresponding to the specific presentation order (i.e., site sequence) about to be administered.

Each of the five DTT measures was obtained by first requiring a test subject to pull off the freeway onto the shoulder and stop precisely at a "reference point" (usually a marked lamp pole) a predetermined distance upstream of a target location. The reference points were always located around a horizontal curve and at least a half-mile (0.8 km) away from a target location. At this time, the experimenter established radio contact with an assistant stationed off the shoulder and behind the guardrail at the target location downstream. The content of the radio contact was incidental; its purpose was merely to inform the assistant to be vigilant, as the test vehicle would soon be approaching his position.

When a gap in traffic occurred, the subject was directed to reenter the traffic stream and to drive in the right-hand (shoulder) lane at the posted limit of 55 mph (88.5 km/h). At the instant the vehicle began to move forward, the experimenter unobtrusively actuated the Transwave, Inc. NK-1202 to begin recording traversed distance, and triggered a flashing 100,000-candlepower directional xenon strobe mounted on the top of the test vehicle.

When the assistant spotted the flashing strobe approaching, he manipulated a pulley/sled arrangement to introduce the target into the center of the right-hand lane. The pulley/sled arrangement included a reel of clear test line epoxyed to the aluminum base of the target and anchored to a nail driven into the longitudinal expansion crack between the right-hand lane and the adjacent lane of the freeway. From its resting position on the shoulder, the target could be placed in the desired location in advance of the approaching test subject in approximately 3 seconds. In all cases, the target was properly positioned and stationary at a point in time well in advance of any driver's ability to detect its presence.

Upon detecting the target's presence ahead in the roadway, a subject hit the response button as instructed. In doing so, the subject also "froze" the display on the distance recording device, thereby revealing the number of feet the vehicle had travelled since stopping at the upstream reference point. This number was subsequently subtracted from the overall separation between reference point and target locations, to determine the resulting distance-to-target at which the detection response occurred.

Immediately after completing each DTT response, the subject chose a number on the 1-through-10 rating scale to evaluate target visibility, which was then recorded by the experimenter. After all five DTT responses had been completed, the post-experimental questionnaire was administered, containing the additional rating scales for subjective evaluations of target realism and the impact on safety of implementing reduced lighting tactics. Any questions concerning the purposes or procedures of the study were answered at this time, then the subject was paid $30 cash and excused.

Data analysis. The first component of data analysis was to correct the "raw" DTT data to take each subject's individual RT into account; in effect, the detection responses measured during the study were "contaminated" by individual differences in the interval it took to hit the response button once the target had been seen, and it was necessary to correct for this source of variance to obtain "pure" detection distances for each test condition.

The corrected DTT data was analyzed using a one-way repeated-measures analysis of variance (ANOVA) technique; as noted earlier, separate analyses were performed for the main-line and for the ramp sites. Also, ANOVAs were used to analyze subjective data regarding target visibility and to test for significant differences in the safety ratings related to implementing reduced lighting tactics on ramps versus main-line locations.

A linear, Pearson product-moment correlation was calculated to describe the relationship between the age of test subjects and (corrected) DTT.

Descriptive statistics were prepared for the mean, median, standard deviation, and 85th percentile DTT values in each test condition, and for the subjective ratings of target realism. Finally, t-tests were used to contrast the detection performance within a test condition associated with respective 12-response data sets for those sites which included two (maximum illumination/minimum illumination) target locations.

4.2 Controlled Field Study

The controlled field study in this project examined drivers' ability to detect a simulated roadway hazard under normal late night (i.e., low volume) freeway traffic conditions, at a single (main-line) roadway geometry and under a variety of reduced lighting tactics. Many of the measures and procedures associated with the pilot study were also incorporated into the controlled field study, augmented by the use of a novel visual screening technique and the collection of comprehensive photometric data for current test conditions. The following material describes aspects of the test plan as organized previously, in section 4.1.

Test site characteristics. Seven test sites were selected for the controlled field study, distributed along Interstate 95 in northeast Philadelphia as shown schematically in figure 8. All sites were located in the right (shoulder) lane of main-line/tangent sections of freeway, with pavement reflectance properties and basic lighting system parameters (for lit sites) identical to those described for the pilot study.

In addition, the common, group lighting control circuitry was modified at three sites (3, 4, and 5) to permit a uniform reduction in power for all (15 northbound-side and 14 southbound-side) luminaires in the circuit. This was accomplished through the installation of a Lutron, Inc., Paesar PRF Energy Control System at the Ashburner overpass location noted in figure 8.

Again, two target locations were employed at all lit test sites except where the one-side-only tactic was implemented (site 2), with one location corresponding to the point of maximum (horizontal) illumination and the other corresponding to the point of minimum illumination.

<u>Target characteristics</u>. The identical detection target used in the pilot study was also employed in the controlled field study, with a uniform reflectance level of 18 percent associated with the targets presented at test sites 1, 2, 3, 4, 5, and 7, and a target reflectance level of 30 percent employed only at site 6.

<u>Independent variables (lighting conditions)</u>. The independent variable manipulated in the controlled field study was the particular lighting tactic implemented and the resulting lighting condition obtained at a given test site. The various conditions examined ranged from full (continuous) lighting, through two levels of uniformly reduced lighting (i.e., for all luminaires in the circuit), to a strategy of extinguishing every other luminaire (on both sides of the freeway), to the tactic of extinguishing all luminaires on one side of the roadway (with the target location on the opposite/dark side), to no

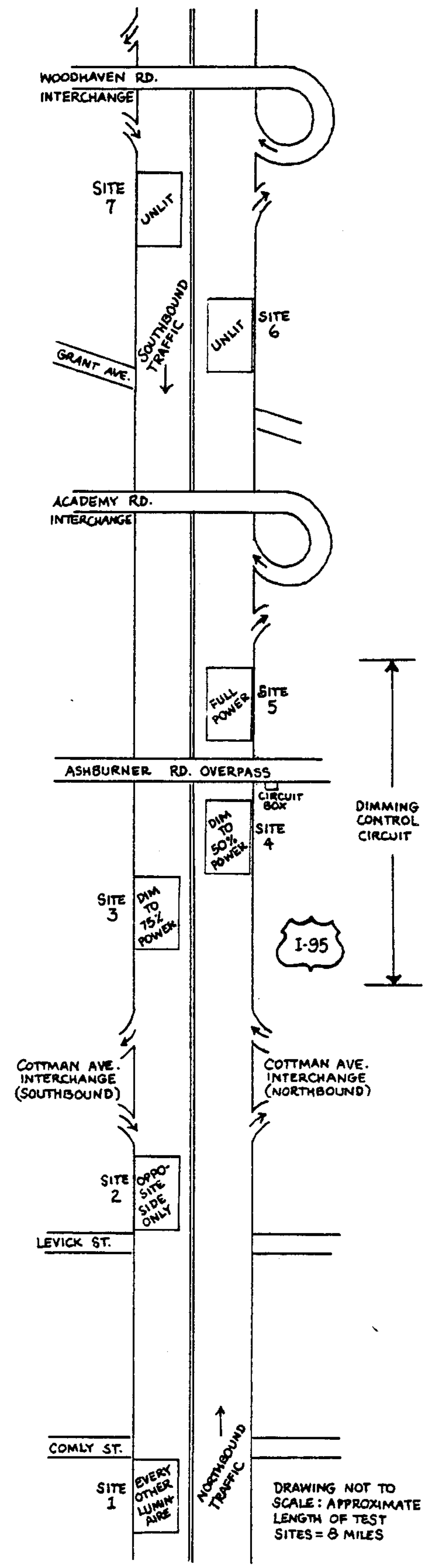

Figure 8. Seven sites along I-95 for controlled field study.

lighting. The distribution of lighting conditions across test sites, indicated in figure 8, is detailed further in table 2, which also presents the lighting control tactic associated with each condition.

It should be noted that sites 6 and 7 described in table 2 below differ only in the fact that an 18 percent-reflective target was presented at one location and a 30 percent-reflective target was presented at the other location. The purpose of this manipulation will be discussed in material relating to the experimental design of the study. It should be emphasized, however, that target reflectance was <u>not</u> identified as an independent variable in the controlled field study.

<u>Dependent variables (measures of effectiveness)</u>. Both dependent measures described for the pilot study were again collected for the controlled field study: The distance-to-target (DTT) detection measure, and the subjective rating of target visibility. The additional measures of reaction time, visual acuity, and the subjective ratings of target realism and the impact of lighting reductions on highway safety were also obtained.

Further, a novel technique for determining a person's visual contrast sensitivity was employed in this study. This measure was obtained under laboratory conditions at two ambient light (i.e., target luminance) levels--4.0 fL (13.7 cd/m^2) and 0.4 fL (1.37 cd/m^2). These luminance values were measured by holding a Spectra FC-200 probe to record the light reflected from the target at a distance of approximately 2 in (6.5 cm), at the

Table 2. Distribution of lighting conditions across test sites.

Test Site	Tactic	Lighting Condition
1	Pulled fuse	<u>Every other</u> luminaire extinguished on <u>both</u> sides of the freeway
2	Pulled fuse	<u>All</u> luminaires extinguished on <u>one side</u> of the freeway only, while other side remains fully lit
3	Dimming control set at 75% power	<u>All</u> luminaires in circuit dimmed to approximately 50% of their normal light output
4	Dimming control set at 50% power	<u>All</u> luminaires in circuit dimmed to approximately 30% of their normal light output
5	No reduction in lighting	Full (continuous) freeway lighting
6	(No fixed lighting installations)	Unlit
7	(No fixed lighting installations)	Unlit

eye-height of a seated observer. A specially-designed wall chart developed by Vistech, Inc.[1], was used in this effort.

Finally, complete photometric measures were obtained at each site with a Photo Research PR1980A Pritchard Photometer with CIE trapezoidal aperture and Fry lens attachment and a Tektronix J16 Digital Photometer with J6511 Illuminance Probe; these measures included horizontal illumination, pavement (background) luminance, target luminance, and veiling luminance.

Experimental design. The controlled field study employed a repeated-measures design, in which all subjects generated data for all test conditions. As in the pilot study, the presentation order of the test trials for a given subject was determined according to a Latin-square type of counterbalancing scheme.

One additional aspect of the design for this study deserving mention is the inclusion of two unlit test sites (6 and 7) that represented identical driving situations but differed in one respect: A target of 30 percent (uniform) reflectance was presented to subjects at site 6, while a target of 18 percent (uniform) reflectance was presented to subjects at site 7. As noted earlier, target reflectance was not identified as an independent variable in this study. Instead, site 4 from the pilot study was simply relabeled as site 6 for the controlled field study, and was included in the present effort to provide a basis of comparison between the test samples for the respective studies. Thus, drivers' detection performance at site 6 (i.e., with a 30 percent-reflective target) was not included in the subsequent analysis and interpretation of data from the remaining controlled field study sites, but was instead compared to the detection performance of drivers under the identical test condition in the pilot study. The resulting experimental design for this study was therefore described as a one-way design with six treatment levels (lighting conditions).

Sample characteristics. The test sample in this study consisted of 13 male and 11 female licensed drivers whose (corrected) visual acuity was 20/40 or better. Subjects' ages ranged from 20 to 67, with an average of 38, distributed as follows across four brackets associated with significant age-related shifts in relative contrast sensitivity (RCS): 20 to 30 years, 8 subjects; 30 to 44 years; 8 subjects; 44 to 64 years, 7 subjects; and 64 to 80 years, 1 subject.

All test subjects in the controlled field study were recruited through advertisements placed in suburban Philadelphia newspapers and were paid $30 for their participation.

Data collection protocol. The initial laboratory visual screening stage in the data collection protocol for this study included the collection of acuity measures with two target luminance levels--0.4 fL (1.37 cd/m^2) and 4.0 fL (13.7 cd/m^2)--using a standard Snellen wall chart presented to seated

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1 A more detailed description plus information concerning price and availability of this research instrument can be obtained from: Vistech, Inc.; 1372 N. Fairfield Rd.; Dayton, OH 45432.

subjects at a distance of 10 feet (3.04 m). Next, subjects' contrast sensitivity was measured under the same conditions, using the Vistech, Inc. chart.

The collection of field data began by seating the test subject in the instrumented vehicle and then performing all necessary adjustments, as described earlier for the pilot study. Similarly, the administration of the RT measure, the delivery of instructions to subjects, the completion of the DTT measures, and the presentation of the post-experimental questionnaire all were accomplished in exactly the same fashion as described in the previous section (4.1).

Data analysis. The RT-corrected distance-to-target (DTT) data were subjected to a one-way, repeated-measures analysis of variance (ANOVA) to test for significant differences in detection performance across the six treatment levels (lighting conditions). (See section 4.1.) Where main effects were demonstrated, additional post-hoc analyses were performed to isolate the source(s) of differences; these included the Scheffé test for all comparisons of interest among the various treatment conditions, as well as a linear trend analysis.

Pearson product-moment correlations were calculated to describe the degree of association between the visual acuity/contrast sensitivity indices and the primary behavioral (i.e., detection) data. The differences in subjects' responses on the rating of target visibility were evaluated with an additional ANOVA, and again, Scheffé post-hoc tests were used to localize the source(s) of main effects. The linear regression coefficients for the association between the detection performance data and lighting/visibility measures of interest (e.g., pavement luminance and illuminance, plus a calculated Visibility Index[1] value) were determined, and descriptive statistics for the responses to the post-experimental questionnaire were prepared.

Finally, t-tests were used to compare the detection performance of subjects in the controlled field study at site 6 to the performance of subjects in the pilot study at site 4, the identical (unlit) target location, and to contrast the performance within (lit) test conditions in this study for the maximum illumination versus the minimum illumination target locations.

4.3 Observational Validation Study

This section describes the final phase of research in this project, in which selected test conditions from the controlled field study were replicated using a trained observer and a limited tapeswitch system, to gather gross operator-vehicle system response data believed to indicate differences in target (hazard) visibility. The scope of this study was intentionally restricted to that of a validation effort, incorporating a design aimed at revealing the degree of generalizability between observed patterns in driver performance under specific lighting tactics for alerted versus unalerted motorists. The following material describes aspects of the test plan as organized previously, in sections 4.1 and 4.2.

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1 Visibility Index (V.I.)= Contrast (C) x Relative contrast sensitivity (RCS) x Disability glare factor (DGF).

Test site characteristics. A single test site was employed in the observational validation study. It was located on a main-line freeway section on Interstate 95 in northeast Philadelphia, immediately south of the Ashburner Rd. overpass. The location of the site is identical to that labeled site 3 in the controlled field study. At this location, 14 luminaires (i.e., in the southbound direction) were group-controlled by the special dimming circuit installed at the Ashburner overpass and described earlier in section 4.2. Figure 9 illustrates the test site.

Also indicated in figure 9 are the positions of four tapeswitches. Switches number 1 and 2 were positioned 10 ft (3.04 m) apart and approximately 700 ft (213.4 m) upstream of the target; switch 3 was positioned approximately 250 ft (76.2 m) upstream of the target; and switch 4 was positioned approximately 80 ft (24.4 m) upstream of the target. Switch 4 extended across the center lane of the roadway; all other switches were confined to the right (shoulder) lane.

As in the two prior studies, two target locations were employed for each lit test condition--one corresponding to the point of maximum horizontal illumination, and one (shown in figure 9) corresponding to the point of minimum illumination.

Target characteristics. The 18 percent reflective target used in the observational validation study was identical to that employed in the previous data collection effort. In this study, however, the pulley arrangement for positioning the target and then removing it from the roadway

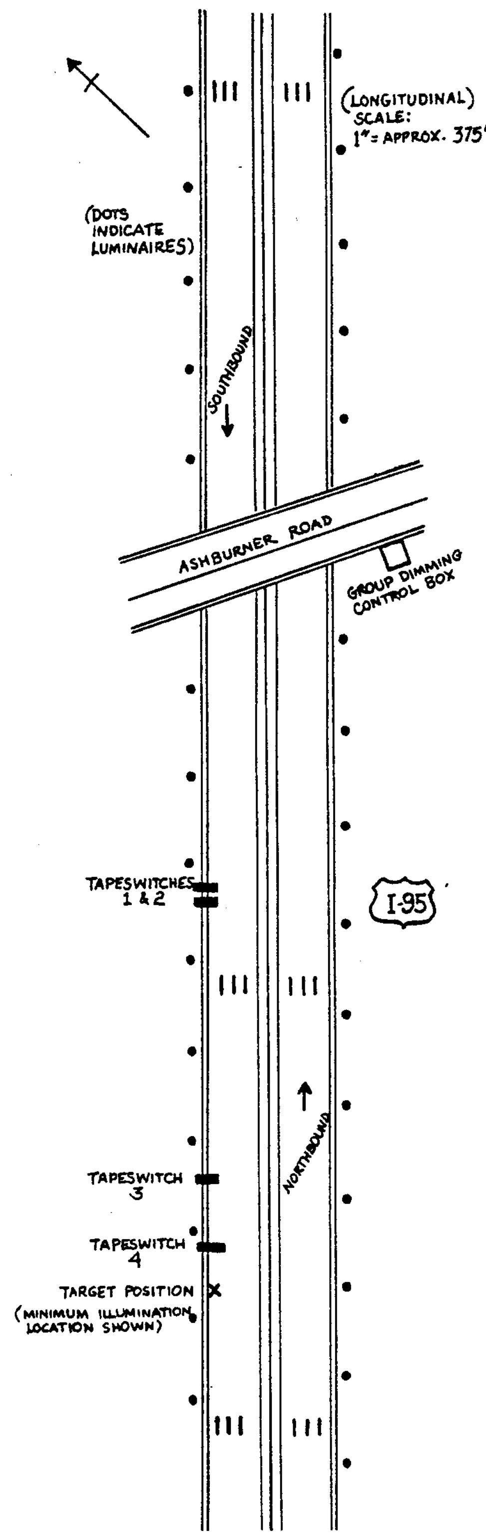

Figure 9. Test sites along I-95 for observational validation study.

was discarded in favor of a single line attached to the target's base.

Independent variables (lighting conditions). In this study, lighting level again served as the independent variable, and included the following three conditions: Full (continuous) lighting, no lighting (i.e., all luminaires extinguished), and uniformly dimmed lighting (50 percent power). As discussed in section 5.2 of this report, these particular lighting conditions were associated with the best detection performance, the worst detection performance, and a level of performance roughly halfway in between, respectively, in terms of the results of the controlled field study.

Dependent variables (measures of effectiveness). The dependent variable in the observational validation study consisted of the summed frequency count of three distinct events: Brake (light) actuation, high-beam use, and lateral shifts (swerves or abrupt lane changes). Together, these events were interpreted as indicators of a response to a perceived hazard in the road, when their incidence for a lead or isolated vehicle in the right (shoulder) lane occurred after that vehicle had passed the position of the initial pair of tapeswitches (numbers 1 and 2 in figure 9).

These events were monitored by a trained observer stationed on a highway overpass roughly 1000 ft (304.8 m) upstream of the target location (see figure 9), and were input to a multichannel recording device[1] where they were logged--simultaneously with the tapeswitch data--onto a continuous timed (to nearest millisecond) record of a vehicle's progress through the test site.

While not strictly defined as a dependent variable, vehicle velocity was also obtained, based on the input from tapeswitches 1 and 2. This measure was of interest in the later analysis and interpretation of the data in this study.

Experimental design. This study was conducted according to a single-factor design in which each unalerted "participant" generated data for one test (or control) condition only. Test trials were those in which a target was in place in the roadway, and control trials were those where motorists' behaviors were monitored without a target present in the roadway. This experimental approach was required to provide assurance that baseline levels of the occurrence of those events defining the dependent variable were equivalent among treatment (lighting) conditions evaluated in the study.

Sample characteristics. The test subjects included in the observational validation study consisted of a random sample of motorists driving southbound on I-95 between midnight and 4:30 a.m. on successive weekdays in September 1984. Specifically, every third lead or isolated vehicle was designated as a participant in a "target" trial, with the remaining (lead or isolated) vehicles serving as nontarget, or "control" participants. Only passenger vehicles using low beams and driving in the right (shoulder) lane were included in the study.

1 KETRON's VTMS, or Vehicle Trajectory Measurement System.

Data collection protocol. The collection of data in the observational validation study was coordinated by the trained observer stationed on the Ashburner Rd. overpass (see figure 9). With the ability to view (southbound I-95) traffic conditions nearly a mile upstream, the observer instructed an assistant (hidden off the freeway shoulder behind the guardrail at the target location) when to place a target in the center of the right lane. For both target and control trials, the observer enabled the VTMS (i.e., the multichannel recording device) to begin timing the progress of a vehicle through the test site as soon as it activated tapeswitch number 1. Whenever a brake (light) actuation, high-beam usage, and/or lateral shift occurred for the vehicle under scrutiny, this (these) event(s) was also routed to the VTMS, to be input to a continuous paper tape log of the test trial containing a timed (to nearest millisecond) sequence of tapeswitch closures and event markers.

In all cases, the target was removed from the roadway before a vehicle actually reached its position. This was accomplished by splitting the signal from Tapeswitch 4 to activate a battery-powered LED indicator light held by the downstream research assistant. As soon as the LED was activated, the assistant pulled sharply on the connecting line to quickly and immediately remove the styrofoam object from the vehicle's path. Tapeswitch 4 was positioned to provide the assistant with a 1-second interval in which to act, before the vehicle reached the target location.

Data analysis. The data from this study were first collapsed into a single summed frequency count for the events of interest (brake, high-beams, lateral shifts) for each treatment (lighting) condition. A chi-square contingency table was then constructed to evaluate the degree of dependence between 1) the occurrence (or nonoccurrence) of the measure of effectiveness during "target" trials and 2) the lighting condition under which motorists' behavior was monitored. In addition, summary descriptive statistics for target and control conditions were prepared, to compare the trend in this data to that associated with the same lighting conditions in the controlled field study.

5.0 RESULTS

This section reviews the research hypotheses and presents the findings of the pilot study, controlled field study, and observational validation study. However, all discussion regarding the implications of this research is deferred until section 7.0: Summary, Implications and Recommendations.

5.1 Pilot Study

The pilot study in this project tested the hypothesis that lighting tactics associated with extreme conditions of overhead illumination/roadway visibility would produce significant differences in the ability of alerted motorists to detect the presence of a (simulated) hazard on main-line freeway sections and ramps, under typical late-night (low volume) operating conditions. In addition, this study examined the effect of such tactics on subjective impressions of target (hazard) visibility, and obtained ratings of drivers' opinions regarding the impact on safety of implementing reduced lighting tactics. The results relating to these research issues plus other information gathered during the conduct of the pilot study are presented in the following pages.

One topic deserving brief mention at this time is the variable of target reflectivity. At the outset of data collection for this study, both 18 percent reflective and 30 percent reflective targets were prepared for use. During initial test trials with the 18 percent reflective target at the unlit ramp site, however, subjects actually ran over the styrofoam object before noting its presence, thus producing an effective DTT value of zero. This statistically-biasing "floor effect" ruled out the use of these targets at this site, and, given an approved experimental design that made it most desirable to hold other factors constant when evaluating the relative effectiveness of alternative lighting tactics, the use of 18 percent reflective targets was similarly eliminated for all test conditions in the pilot study. Consequently, only 30 percent reflective detection targets were employed in this effort.

Detection performance. The RT--corrected distance-to-target (DTT) values associated with the various test conditions are presented for main-line freeway sections and ramps, respectively, in tables 3 and 4.

A one-way analysis of variance (ANOVA) on the detection data shown below revealed no significant difference in driver performance at main-line sites ($F=0.94$; $df=2,23$; n.s.), but a substantial and highly-significant difference in performance on ramps ($F=45.3$; $df=1,23$; $p<.001$). Apparently, vehicle headlights provided visual inputs to drivers on main-line sites roughly equivalent to those provided by overhead lighting, with respect to the task of target (hazard) detection under the specific conditions described for this study. This was not the case on ramps, however, where the absence of fixed lighting led to a dramatic reduction in drivers' ability to detect the (simulated) hazard's presence in the roadway.

Subjective visibility ratings. Drivers' subjective impressions of the visibility of the detection target during test trials on main-line freeway sections and ramps are described by the

Table 3. Detection performance at main-line sites.

Lighting condition	Distance-to-target, ft			
	Mean	Median	Std. dev.	85th percentile
Full (continuous) lighting	206*	209	44.3	160
No lighting	209	203	52.2	156
One (opposite) side only lit	182	192	50.0	128

* $\bar{X}_{min. illum.}$ = 201 ft (61.26 m); $\bar{X}_{max. illum.}$ = 211 ft (64.31 m)

1 meter = 3.28 ft

Table 4. Detection performance at ramp sites.

Lighting condition	Distance-to-target, ft			
	Mean	Median	Std. dev.	85th percentile
Full (complete) lighting	113*	120	32.5	77
No lighting	63	64	19.6	39

* $\bar{X}_{min. illum.}$ = 110 ft (33.53 m); $\bar{X}_{max. illum.}$ = 115 ft (35 m)

1 meter = 3.28 ft

data shown in tables 5 and 6, respectively. For both sets of ratings, a 10-point scale was used where 1 was associated with the lowest visibility rating and 10 with the highest.

The one-way ANOVAs performed on this data indicated significant differences in the subjective visibility ratings for both main-line sites ($F=4.63$; $df=2,23$; $p<.025$) and ramps ($F=4.95$; $df=1,23$; $p<.05$). In both situations, drivers felt that they could see the target better given the visual inputs provided by (full) fixed lighting, even though the previous detection data did not always support this subjective impression. With respect to the main-line visibility ratings, the pattern of data in table 5 clearly indicates that drivers perceived visibility as being poorest when seeking to detect a (simulated) hazard on the dark side of the roadway under the one (opposite) side only lighting tactic.

Table 5. Target visibility ratings at main-line sites.

Lighting condition	Mean	Std. dev.
Full (continuous) lighting	7.6	1.5
No lighting	7.4	1.7
One (opposite) side only lit	6.6	1.9

Table 6. Target visibility ratings at ramp sites.

Lighting condition	Mean	Std. dev.
Full (complete) lighting	8.0	1.4
No lighting	7.2	1.7

Other pilot study findings. The remaining data collected during the pilot study is summarized below. The first measure to be described is that concerning drivers' subjective evaluations of the impact on safety of implementing reduced lighting tactics late at night on freeways when traffic volume is low. These results are presented below in table 7. Again, a 10-point rating scale was used to obtain this measure, where 1 was associated with the most negative safety rating and 10 with the most positive.

The one-way ANOVA performed on this data demonstrated a highly-significant difference in drivers' opinions concerning the impact of reduced lighting on safety as a function of roadway geometry ($F=16.2$; $df=1,23$; $p < .001$). The study participants evidenced only a lukewarm, middle-of-the-scale response on this issue with respect to straight (main-line) freeway driving situations, but were strongly opposed to any reduction in overhead lighting on ramps.

Next, the ratings of target realism are summarized. For this measure, subjects were presented with a 10-point scale where 1 was associated with the poorest rating of target realism and 10 was associated with the best. The group data on this measure demonstrated a mean

Table 7. Ratings of the effect of reduced lighting on safety.

Roadway geometry	Mean	Std. dev.
Main-line/tangent freeway sections	5.3	2.8
Freeway ramps	3.3	1.7

rating of 6.9, with a standard deviation of 2.3, indicating that in general test subjects considered the target used to represent small highway debris in this study to be an effective simulation. Specific criticisms of target characteristics were offered by 12 different subjects, relating principally to size and brightness. An approximately equal split was observed between those who felt the target should have been smaller and those who felt it should have been larger; whereas, three times as many drivers suggested using a darker object than suggested using a brighter target.

A linear regression between the age of test subjects and their performance on the primary, distance-to-target measure produced the set of correlation coefficients (i.e., r-values) and expressions of variance-accounted-for (r^2) presented below in table 8.

While all the correlations reported above are relatively low and thus account for nonsignificant amounts of the variance in driver detection performance, it is interesting to note that the strongest association between age and (simulated) hazard detection occurred with the one (opposite) side only lighting tactic. It was this test condition that simultaneously all-but-eliminated roadway illumination in the vicinity of the target yet preserved some amount of glare from the opposite-side luminaires which remained lit.

Finally, the results of the pilot study include a report of t-tests for significant differences between the maximum-illumination versus minimum-illumination mean response levels in the distance-to-target data presented earlier in tables 3 and 4. These tests revealed that performance at one target location (within a fully lit site) did not differ significantly from performance at the other location, for either main-line freeway sections (t=0.54, df=1, n.s.) or for ramps (t=0.39; df=1; n.s.).

5.2 Controlled Field Study

The controlled field study in this project provided a rigorous comparison among a variety of alternative lighting tactics, testing the hypothesis that subjects' ability to detect a (simulated) hazard of designated color, shape, and reflectivity while driving on main-line freeway sections under typical late night conditions would

Table 8. Correlation between age and detection performance.

Test condition (geometry/lighting tactic)	r	r^2
Main-line/full (continuous) lighting	-.28	.08
Main-line/no lighting	+.11	.01
Main-line/one (opposite) side only lit	+.43	.19
Ramp/full (complete) lighting	-.10	.01
Ramp/no lighting	+.29	.09

shift significantly as a function of the specific tactic implemented. As in the pilot study, the objective, distance-to-target data was considered the primary measure of effectiveness, supplemented by the subjective ratings of target visibility. Also, additional ratings of target realism and drivers' opinions regarding the impact of reduced lighting tactics on safety were again obtained.

The results reported in this section further include several novel sets of data. Complete photometric measures were obtained at all test sites and then correlated with the detection performance data, and exhaustive correlations between multiple vision screening measures and the DTT data were performed as well.

Again, the target reflectance level employed in this study deserves mention. First, it should be noted that data collection at interchange ramp sites was excluded from the controlled field study; the pilot study finding of such a large difference in detection performance between lit and unlit (ramp) sites led to a tentative conclusion that the likelihood of subsequently recommending lighting reductions at this geometry was relatively low. This being the case, the evaluation of alternative tactics on ramps was defined as a lower priority research need in this project, a conclusion that was reinforced by drivers' ratings which indicated a perceived impact of reduced lighting on safety that was significantly more negative for ramps than for main-line sites. Once the research focus was shifted to main-line sites, the lack of significant differences on the DTT measure in the pilot study for lit versus unlit (main-line) test conditions was examined more closely; specifically, the differential in relative effectiveness of vehicle headlights versus fixed illumination as a function of target reflectivity that was demonstrated in the prior analysis of visibility needs (table 1, section 3.0) became a crucial consideration. With the objective of providing a more rigorous test of alternative reduced lighting tactics, it was decided that the lower, 18 percent level of target reflectance was most appropriate for use in the controlled field study.[1]

<u>Detection performance</u>. The RT-corrected distance-to-target (DTT) values associated with the various test conditions in this study are presented in table 9.

A one-way analysis of variance (ANOVA) on the detection data shown in table 9 revealed highly significant differences in drivers' ability to detect the (18 percent reflective) target as a function of the alternative lighting tactics evaluated in this study ($F=6.58$; $df=5,115$; $p<.001$). Further, the apparent linear pattern in the mean DTT values was confirmed through a trend analysis, which identified a significant linear component ($F=10.1$; $df=1,23$; $p<.01$).

Next, the post-hoc Scheffé test conducted to localize the source(s) of

[1] NOTE: As described in section 4.2, the use of a 30 percent reflective target was retained at one site to provide a basis for comparison between the test samples in the pilot and controlled field studies.

Table 9. Detection performance under alternative lighting conditions.

Lighting condition	Distance-to-target, ft			
	Mean	Median	Std. dev.	85th percentile
Full (continuous) lighting	287.9	238	190.3	113
Uniformly dimmed: 75% power (50% light output)	232.6	209	124.8	112
Uniformly dimmed: 50% power (30% light output)	223.8	195	97.0	135
Ever other luminaire extinguished	204.8	180	92.5	125
One (opposite) side only lit	163.4	156	73.8	96
No lighting	163.2	156	44.1	132
No lighting (w/30%-reflective target)	238.8	236	79.0	186

1 meter = 3.28 ft

this treatment effect demonstrated significant differences at the .05 level, for those contrasts among test conditions involving the following specific comparisons of interest:

- The individual comparisons between full (continuous) lighting and each of the two conditions associated with the poorest detection performance (i.e., one side only and no lighting).

- The weighted, multiple comparison between full (continuous) lighting and the other five treatment conditions included in the present analysis.

Additional individual comparisons between full (continuous) lighting and the every other luminaire, uniform dimming/75 percent power, and uniform dimming/50 percent power conditions did not demonstrate significant ($p<.05$) differences, nor did a weighted multiple comparison between the two uniformly dimmed conditions versus the simpler, fuse-pulling tactics (i.e., every other luminaire and one side only).

Two additional findings of interest in the controlled field study DTT data may be demonstrated by a visual inspection of the standard deviation and 85th percentile values associated with the various test conditions. With increases in mean distance-to-target figures from one lighting condition to another, the variability in drivers' detection performance also increases substantially. The 85th percentile values remain much more tightly clustered, however, indicating that those motorists near the bottom of the distribution--in terms of the distance at which the present sample of drivers were able to detect the target under a given test condition--would be likely to have difficulty seeing hazards on the road no matter what level of fixed overhead illumination is provided.

Next, a t-test for significant differences between the DTT data obtained under no lighting with a 30 percent reflective target in the controlled field study (table 9) versus the same measure obtained at the same test site in the pilot study (table 3) was performed. While the mean, median, and 85th percentile values for the DTT data under this test condition were somewhat larger during the controlled field study, so too was the observed standard deviation in the data. In any event, the test statistic demonstrated that differences in performance between the two test samples participating in the respective studies were nonsignificant ($t=1.68$; $df=22$; n.s.) at the .05 level.

Finally, one further analysis of the detection performance data in this study was performed by expressing the mean uncorrected DTT values for each lighting condition (since RT for brake reaction, specifically, was not measured) as a percentage of several calculated braking distance requirements. Three criterion distances were considered:

- The existing minimum braking distance (MBD), using the AASHTO equation[1] for design recommendation assuming dry, level, worn Portland cement with a coefficient of friction of .60, average tires, and a 55 mph (88.5 km/h) vehicle velocity. The resulting figure for existing MBD is 168 ft (51.2 m).
- A worst-case minimum braking distance (MBD), again using the AASHTO equation but assuming wet conditions where the coefficient of friction is .30, worn tires, and a 55 mph (88.5 km/h) vehicle velocity. The resulting figure for worst-case MBD is 336 ft (102.4 m).
- A generalized minimum braking distance (MBD), which is simply the average of the worst-case MBD and existing MBD figures calculated above. The resulting value for generalized MBD is 252 ft (76.8 m).

Table 10 presents these expressions of drivers' detection performance in the controlled field study. Alternatively, it is interesting to note how many drivers (i.e., what percentage) met these braking distance criteria under each lighting condition; this information is also included (in parentheses) in table 10.

Subjective visibility ratings. Drivers' subjective impressions of the visibility of the detection target under the various lighting conditions are described by the data presented in table 11. A 10-point scale was used to obtain this measure, where 1 was associated with the lowest visibility rating and 10 with the highest.

The subjective ratings of target visibility resulted in the highest mean value under full (continuous) lighting, a cluster of moderate values associated with the uniformly dimmed, every other luminaire, and no lighting conditions,

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[1] Design braking distance = $\frac{V^2}{30f}$, where v = vehicle velocity in mph, and f = coefficient of friction.

Table 10. Uncorrected (mean) DTT values expressed in terms of braking distance requirements, and number of drivers who met criteria under each lighting condition.

Lighting condition	Uncorrected DTT (ft)	DTT as percentage of minimum braking distance (percentage of drivers meeting criterion shown in column heading)		
		Existing MBD	Worst-case MBD	Generalized MBD
Full (continuous) lighting	253.5	150.9% (58%)	75.0% (29%)	100.6% (42%)
Uniformly-dimmed: 75% power (50% light output)	198.2	118.0% (50%)	59.0% (21%)	78.7% (29%)
Uniformly-dimmed: 50% power (30% light output)	189.4	112.7% (46%)	56.0% (8%)	75.0% (21%)
Every other luminaire	164.6	98.0% (33%)	49.0% (8%)	65.3% (17%)
One (opposite) side only lit	125.2	74.5% (25%)	37.0% (0%)	49.7% (0%)
No lighting	132.6	79.0% (29%)	39.0% (0%)	52.6% (0%)
No lighting (w/30% reflective target)	204.0	121.0% (66%)	61.0% (4%)	81.0% (21%)

Table 11. Target visibility ratings under alternative lighting conditions.

Lighting condition	Mean	Std. dev.
Full (continuous) lighting	7.9	2.1
Uniform dimming: 75% power (50% light output)	7.1	2.1
Uniform dimming: 50% power (30% light output)	7.3	2.1
Every other luminaire extinguished	6.8	2.3
One (opposite) side only lit	6.3	2.7
No lighting	7.0	2.8
No lighting (w/30%-reflective target)	7.6	2.3

and a somewhat-isolated lower value for the one (opposite) side only lit condition. An ANOVA performed on this data demonstrated significant differences ($F=2.92$; $df=5,115$; $p<.05$), though not as strong as those observed for the DTT measure. A subsequent Scheffé test identified the source of this main effect to be the contrast between the full (continuous) lighting and the one (opposite) side only lit conditions, specifically; no other post-hoc comparisons among the subjective data showed significant differences at the .05 level.

Other subjective data. The results obtained for the additional sets of drivers' rating scale responses in the controlled field study paralleled those of the pilot study. First, subjects' evaluations of the degree of realism of the (18 percent reflective) detection target (i.e., as a simulated hazard) were favorable, as described by a mean rating of 7.4 (std. dev.=2.2) on a scale where 1 was associated with the poorest rating of target realism and 10 was associated with the best. Interestingly, the ratings on this measure for the 30 percent reflective target versus the 18 percent reflective target--though generated by separate test samples--showed that drivers on average felt the darker (less reflective) target to be more representative of roadway hazards and exhibited less variability in their opinions.

Next, subjects' ratings of the impact on safety of implementing reduced lighting tactics again demonstrated a significantly more positive response for straight (main-line) freeway sections (mean=4.8; std. dev.=3.2) than for interchange ramps (mean=3.3; std. dev.=2.4). On the scale used to obtain this measure, 1 was associated with the most negative opinion regarding safety impact and 10 was associated with the most positive.

Photometric measures. The data describing the horizontal illumination, average pavement luminance, target luminance and veiling luminance associated with the various lighting conditions in the controlled field study are presented in table 12, together with calculated illumination uniformity, (pure) contrast, and Visibility Index (V.I.) values.

Visual screening indices and detection performance. The results of a Pearson product-moment correlation between the visual acuity (Snellen) and visual contrast sensitivity indices obtained for each test subject, respectively, and subjects' DTT data are presented in table 13. Both indices reflect the ability of a stationary observer to accurately report information off a wall chart from a pre-measured distance under low light conditions; Snellen acuity requires the identification of progressively smaller strings of black alphabetic characters on a white background, while the contrast sensitivity measure requires discerning the orientation of a set of parallel gray bars within a white circular "diffraction grating" as the bars change both in their contrast with the background and in the sharpness of their edges (i.e., the amount of "high-frequency spatial information available to the observer). Thus with the Snellen approach target size is manipulated and character contrast and spatial frequency ("edge detail") remains constant, whereas the converse of this situation is described by the contrast sensitivity approach.

Table 12. Summary of photometric measurements.

Photometric measure	Lighting condition					
	Full	75% Power(1)	50% Power(2)	Every Other	One Side(3)	No Lighting
Horizontal Illumination-E_h(avg), in fc	1.15	0.58	0.35	0.58	0.04	0.01
Uniformity [E_h(avg)/E_h(min)]	4.50	4.14	4.19	14.50	-	-
Average Pavement Luminance-L_b, in fL*	0.58	0.29	0.15	0.27	0.049	0.016
Target Luminance L_t, in fL*, 18% reflectant gray	0.23	0.17	0.12	0.18	0.10	0.03
Veiling Luminance L_v, in fL*	0.39	0.19	0.07	0.25	0.14	0.01
Contrast $(L_t-L_b)/L_b$	-0.60	-0.41	-0.20	-0.33	1.04	0.88
Visibility Index V.I.=C x RCS_{L_b} x DGF**	8.78	4.43	1.66	2.93	2.82	1.57

(1) Approximately 50% light, relative to full condition.
(2) Approximately 30% light, relative to full condition.
(3) Values shown are for opposite (unlit) side; lit side measures same as Full (continuous) condition.
* 1 cd/m^2 = 0.2919 fL

$$** \ DGF = \frac{L_b \times RCS_{L_b'}}{L_b' \times RCS_{L_b}}, \quad \text{where } L_b' = \frac{L_b + L_v}{1.074}$$

A pattern of predominantly positive (i.e., direct) associations were demonstrated between the contrast sensitivity measure and detection performance, as contrasted with a predominantly negative (i.e., inverse) relationship between target detection and the standard (Snellen) acuity measure. In either case, however, the variance-accounted-for in detection performance by these screening indices is consistently quite modest.

Photometric/visibility indices and detection performance. An additional set of linear regressions was computed to describe the relationship between the DTT data and selected photometric measures obtained during the controlled field study. Specifically, the calculated coefficient describing the strength of relationship of detection performance with (horizontal) pavement illumination was r=.95, and with pavement luminance r=.94. These findings indicate that

Table 13. Correlations between detection performance and visual screening indices.

Lighting condition	Acuity (Snellen) Low luminance (0.4 fL)	Acuity (Snellen) High luminance (4.0 fL)	Contrast sensitivity, Low luminance (0.4 fL), Spatial frequency= 1.5 Hz	3 Hz	6 Hz	Contrast sensitivity, High luminance (4.0 fL), Spatial frequency= 1.5 Hz	3 Hz	6 Hz
Full (continuous) lighting	-.34	-.29	.37	.41	.37	.33	.34	.39
Uniformly dimmed: 75% power (50% light output)	-.26	-.18	.31	.54	.31	.43	.36	.27
Uniformly dimmed: 50% power (30% light output)	-.36	-.34	.34	.36	.42	.45	.24	.48
Every other luminaire	-.19	-.24	.36	.44	.36	.44	.17	.37
One (opposite) side only lit	-.03	-.02	-.20	-.23	-.07	-.33	-.46	-.18
No lighting	.29	.12	.13	.06	.26	.13	-.03	.14

either photometric measure, in isolation, can account for approximately 90 percent of the variability in target (hazard) detection performance. By comparison, the coefficient describing the relationship between the DTT data and the calculated Visibility Index (as defined in table 12) values for the various lighting conditions was *r*=.83, indicating that V.I. alone accounted for a somewhat smaller--though still considerable--amount of the variability in drivers' detection performance.

5.3 Observational Validation Study

The results of the observational validation study are initially described in terms of motorists' behavior on target versus nontarget (control) trials. An examination of the nontarget trials demonstrated that the full (continuous) lighting, uniformly-dimmed/50 percent power (30 percent light output), and no lighting conditions were associated with one, one, and zero operator/vehicle responses, respectively, that occurred independent of the introduction of the detection target into the roadway. This finding established a clear baseline equivalence, in terms of the designated measure of effectiveness in this study, between the three test conditions.

With the target in place, unalerted motorists responded as shown in table 14. As explained in section 4.3, brake (light) actuations and lateral shifts (swerves/lane changes) were included together in the response totals--no high beam activations occurred under any lighting condition in the observational field study.

The chi-square analysis of the data presented in table 14 did not yield a test statistic of sufficient magnitude

Table 14. Results of observational field study.

Lighting condition	Sample size	Total responses: Number (%)	Mean vehicle approach velocity, in mph*
Full (continuous) lighting	72	13 (18%)	58
Uniformly dimmed: 50% power (30% light output)	69	9 (13%)	59
No lighting	71	5 (7%)	56

*km/h = mph x 1.61

to exceed the critical value demonstrating significant (.05) differences; that is, the null hypothesis that the observed differences in number (percent) of responses between conditions was due to chance could not be rejected with a 95 percent level of confidence. Given the lack of experimental control in this data collection effort, however, findings that are of only marginal statistical significance but conform to the trend, or pattern exhibited in the more rigorous DTT data are encouraging, and may tentatively be cited as a validation of the prior research findings pending further work in this area.

It may also be noted that of those individuals who did demonstrate a response in the observational field study, the ordering of (mean) driver-target separation distances (measured from the point where the brake actuation or lateral shift occurred, as estimated from the continuous log of tapeswitch data) was the same as that described by the DTT measures for the identical lighting conditions in the controlled field study. That is, drivers who responded under the no lighting condition did so at an average separation distance of 232.6 ft (70.9 m); under 30 percent light output, drivers responded at an average separation distance of 254.7 ft (77.7 m); under full (continuous) lighting, drivers responded at an average separation distance of 265.6 ft (81.0 m). While small and uneven sample sizes plus the likelihood of significant variability in "driver factors" such as attention, fatigue, etc. make it impossible to attach any particular importance to the absolute magnitudes of these separation values, this trend--like that reported above--is encouraging as further validation of the controlled field study results.

6.0 ECONOMIC ANALYSIS

The objective of this task was to perform an economic analysis of the alternative reduced lighting tactics to compute the costs, energy savings, and benefit-cost ratios for each tactic. In addition, by combining effectiveness measures with the above costs and energy savings, a cost-effectiveness analysis was also performed for the six lighting tactics that were evaluated in the controlled field experiment.

Certain assumptions and simplifications were made for these analyses. These include:

- Employing only group controlled lighting circuits for all costs. (Individual control circuits are not as common on freeways; when costs are significantly different for individual control circuits they will be noted in the analyses.)
- Employing a cost per kilowatt hour of 6.4¢.[1]
- Employing only one lamp (200 HPS) for all systems except the twin luminaire where 2 x 100 HPS are used to equalize wattage.
- Employing a discount rate of 10 percent.
- Computing all costs and benefits on a per-mile basis, assuming an average spacing of 92.5 ft (28.2 m) for a two-sided system.[2] This yields approximately 57 poles per mile (34 per km).
- Costs of items such as luminaires, time clocks, photocells, cabinets, contactors, wiring and labor were based on 1984 Philadelphia costs; costs of specialized dimming circuitry was obtained from the manufacturers or users.

6.1 Required Equipment

Table 15 lists the components and labor required for each of the 6 light reduction techniques. For a number of techniques, two approaches are described in table 15 (e.g., photocell/timer or time clock).

6.2 Costs of Tactics

Based on the assumptions described previously and the equipment and labor described in table 15, the costs for each of the light reduction tactics were developed. They are summarized in table 16. The costs for the twin lamp system and for the volume dependent Canadian system were based on information supplied by A. Ketvirtis & V. McCullough--dimming costs are about 10 percent of total lighting system costs for new systems.

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1 The figure of 6.4¢ per kilowatt hour was derived from Edison Electric Institute data and is a nationwide average for street lighting electric costs. Although this average will be used in all energy cost calculations, the actual street lighting electric costs found in the United States range from about 1.5¢ to 12¢ per kilowatt hour.

The reader is urged to adjust the energy costs, and resulting benefit-cost ratios, to suit his own area's lighting costs.

2 Derived from a brief survey of typical freeway systems in the Delaware Valley.

Table 15. Equipment and labor requirements.

Tactic	Requirement		Comments
	Equipment	Labor	
All off after midnight	(a) Photocell/timer	Replace photocell with photocell/ timer	ARL watt-4 photocell Automatic reset after power failure
	(b) Time clock, cabinet and wiring	Install equipment (minimal)	Must be manually reset after power failure
Every other luminaire off after midnight	(a) Photocell/timer contactor, cabinet and wiring	Split circuit add photocell/timer, etc.	ARL watt-4 photocell Unequal burn time
	(b) Time clock, contactor cabinet and wiring	Split circuit, add time clock, etc.	Must be manually reset after power failure
One side off after midnight	(a) Photocell/timer, contactor, cabinet wiring	Split circuit add photocell/timer, etc.	ARL watt-4 Unequal burn time
	(b) Time clock, contactor, cabinet and wiring	Split circuit, add time clock, etc.	Must be manually reset after power failure
Dual luminaire--one off after midnight	Two headed luminaire, timer, circuitry (Oshawa, Ontario system)	Replace luminaires plus additional wiring	Circuits to alternate luminaires
Pre-set light reduction	Photocell/timer, control box (Lutron), cabinet and wiring	Replace photocell, add box, cabinet, and wiring	Time clock can also be used as alternative to photocell/timer
Volume/time dependent variable light reduction	Special ballasts, dimming circuits, computer control, wiring, etc. (A. Ketvirtis Ontario system)	Replace ballasts, add computer and volume sensing equipment	Wide-lite ballast

Table 16. Cost of tactics.

Tactic	Initial cost ($)				Annualized cost per mile* (10% discount)
	Equipment	Labor	Per Pole	Per Mile	
All off after midnight (a)(1)	62	38	2	114	11 (2)
(b)	450	450	18	1,026	103
Every other off after midnight (a)	300	300	12	684	68 (3)
(b)	450	450	36	1,026	103
One side off after midnight (a)	300	300	12	684	68 (3)
(b)	450	450	36	1,026	103
Dual luminaire-- one off after mid-night (new system)	--	--	--	7,650	765
Pre-set luminance reduction					
Lutron Regulator ballast	3,000/54 lamps	1,500/54 lamps	83	4,731	473
Reactor ballast	3,000/30 lamps	$4,000/30 lamps (disconnect capacitor from each lamp)	233	13,281	1,328
Volume/time dependent variable luminance based on:					
(1) new system in Canada	--	--	400	22,600	2,200
(2) Wide Lite (retro-fitted) System	about 500/ballast +2,150 control	13,575	815	46,455	4,646

(1) (a) refers to photocell/timer and (b) refers to time clock/contactor
(2) for individual control the costs are 570 and 296 respectively
(3) for individual control the costs are 285 and 182 respectively
* 1 mile = 1.6 km

The costs for the all off, one side, and every other luminaire systems apply to both new and retrofitted lighting systems--all three require installation of simple switching and timing equipment in the group control circuits.

The costs for the twin lamp, fixed dimming, and variable dimming systems apply to only new lighting systems. Costs for retrofitting would be significantly higher, probably on the order of 20% more for dimming (relatively easy to retrofit) but much higher for the twin lamp system which requires substantial lighting system modifications.

6.3 Potential Energy Savings of Reduced Lighting Tactics

Based on a full night burn time of 4200 hours (1/2 night = 2100 hours), and an energy cost of 6.4¢ per kilowatt hour, the potential energy savings for each of the six tactics were derived. This information is presented in table 17.

6.4 Benefit-Cost Ratios

Combining the data in table 16 with that in table 17, B/C ratios were derived for each of the six systems, as described in table 18. When alternative techniques are available (e.g., photocell or timer) the least expensive was employed. When two (or more) costs were derived for a given tactic (i.e., two different variable dimming methods) the average cost was employed. Ranges are also noted for the averaged cases.

It appears that the most complex dimming system (variable dimming) will not prove to be cost-effective, while the simpler systems will have very high B/C ratios.

Table 17. Energy savings of reduced lighting tactics.

Tactic	Energy savings per mile*
All off 1/2 night	$1,877
1/2 off 1/2 night (every other or one side)	938
Twin luminaires--one off 1/2 night	938
50% dimmed--fixed or variable	938

NOTES: All luminaires 200 HPS (except twin=2x100 HPS); Energy costs 6.4¢/kWh; Burn time (full night) = 4200 hrs; 57 luminaires per mile (34/km); and 45 watt ballast loss per lamp.

* 1 mile = 1.6 km

Table 18. Benefit-cost of reduced lighting tactics.

Tactic	Annual energy savings per mile*	Annual costs per mile*	B/C (average)	Range of B/C
All off	1877	11-103	100	18-171
1/2 off (every other or one side)	938	68-103	12	9-14
Twin luminaires	938	765	1.2	1.2
Fixed dimming (50% power)	938	473-1328	1.0	0.7-2.0
Variable dimming (50% power)	938	2260-4646	0.3	0.2-0.4

* 1 mile = 1.6 km

The former analysis does not include (possibly) increased maintenance costs or (negative) effects of reduced lighting on traffic operation and safety (to be discussed subsequently). In addition, two of the costs are based on new systems, which have lower costs than those of retrofitted systems. The B/C ratios in table 18 are thus probably optimistic.

Finally, if energy costs are inflated at four percent per year (based on Edison Electric Institute projections) then the anticipated benefits in table 17 would increase by 50 percent in 10 years, increasing all the benefit/cost ratios in table 18 to over 1.0, except for the variable dimming system.

6.5 Costs of Dimming Circuits Used in Field Experiments

The system designed by Lutron and installed by Carr & Duff on a 30-lamp circuit on I-95 had certain fixed costs. These included a price of approximately $3,000 for the dimming circuit and installation costs of about $6,000.[1] This would translate into a per-pole cost of $300, and a per-mile cost of $17,100 ($10,688 per km). Using a 10 percent discount rate the analyzed cost per mile would be $1,710 ($1,069 per km), or 29 percent higher than the costs found in table 16. Since this was an experimental installation, the 29 percent higher cost is not that unreasonable. If many miles of such a system were installed this difference would vanish, since both the cost per unit of dimming circuitry and the labor per installation would decrease.

1 The actual subcontract was for $7,400 which included removal of the dimming circuit, estimated at about 20 percent of total costs.

6.6 Cost/Effectiveness Analysis

The objective of this analysis was to combine the costs, energy savings, and effectiveness measures (mean reaction distances)[1] into a single analysis that provided an indication of the true cost per unit of effectiveness for each of the six lighting tactics evaluated in the field study.

The costs include those illustrated in table 16 (50 percent power and 75 percent power are the same). Energy savings are taken from table 17 (the savings for 75 percent power is one-half of the savings for 50 percent power), and effectiveness values are the mean detection distances for each light reduction technique (see table 9). Power is measured as input to the dimming circuit. This information is summarized in table 19.

True costs per mile (or km) are the sum of installation costs plus actual energy costs, where actual energy costs are equal to energy costs for all lights on for the entire night less the energy

Table 19. Survey of cost and effectivness data.

Tactic	Cost/mile/year (installation)	Energy savings/ mile/year	Effectiveness (5)
All on	0	0	287.9
75% power	473 (1)	469 (3)	232.6
50% power	473 (1)	938 (4)	223.8
Every other	68 (2)	938 (4)	204.8
One side	68 (2)	938 (4)	163.4
All off	11 (2)	1877 (4)	163.2

Notes: (1) Lutron, Regulator ballast
(2) One half of 50 percent power from table 17
(3) From table 17
(5) From table 9

[1] An alternative effectiveness measure would be the percentage of minimum braking distance (table 10). However, such a measure is merely the mean detection distance divided by the (AASHTO) minimum braking distance--a constant (for dry, wet, or average of dry and wet conditions)--and is thus statistically equivalent to mean detection distance.

savings for a given tactic; i.e., energy cost = $3,754[1] less the energy savings (from table 19).

Table 20 summarizes the cost-effectiveness ratios for the six tactics. Cost-effectiveness (C/E) is defined as:

$$C/E = \frac{IC + EC}{E}$$

where IC = Installation cost [per mile (km) per year]

EC = Total energy cost for all on (= $3,754) - energy savings [per mile (km) per year]

E = Mean detection distance

Table 20. C/E ratios.

Tactic	C/E
All on	13.0
75% power	14.1
50% power	14.7
Every other	14.1
One side	17.6
All off	11.6

The preceding analysis provides only a relative ranking of the six alternative tactics. Since we have no way of transforming a change in effectiveness (i.e., detection distance) into a change in accidents (i.e., increase/decrease in frequency or rate) the C/E ratios are not equivalent to benefit-cost ratios. All, some, or none of the six tactics could have benefit-cost ratios (considering installation costs, energy costs and accident cost) greater than 1, less than 1, or equal to 1. Only an evaluation of reduced lighting on accidents could provide such B/C ratios and this, of course, was not accomplished, for reasons discussed in the following section.

[1] $3,754 = 57 luminaires x 0.245 kW x $0.064/kWh x 4200 hours.

7.0 SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

7.1 Summary

A summary of the research findings is as follows:

- Techniques for reducing or eliminating fixed roadway lighting during periods of low traffic density that were investigated in this study include:
  - All off after a specific time.
  - Every other luminaire off after a specific time.
  - One side of roadway off after a specific time.
  - Twin luminaires, one extinguished after a specific time.
  - Dimming a fixed amount (e.g., 50%) after a specific time.
  - Dimming variable amounts, depending on time, traffic, visibility and weather.
- The technology and equipment is presently available for installation of all of the techniques listed above.
- Costs of the techniques range from as low as $11 per mile per year ($7/km/year) up to over $4,600 per mile per year ($2900/km/year). The simple extinguish-type systems have low costs and are simple to install while the dimming systems, especially variable dimming, have the highest costs.
- Energy savings for the techniques range from $940 to $1,880 per mile per year ($580 to 930 per km per year) when 200-watt HPS lamps are employed and energy costs are fixed at 6.4¢ per kWh.
- Based on the legal and transportation literature, there is a potential for serious legal problems associated with the use of such reduced lighting, especially when levels are reduced below ANSI recommended values. However, the opinions of both legal and lighting experts are quite mixed concerning such legal issues; many feel there will not be a problem while others feel that a definite legal problem exists.
- Analysis of the relative effectiveness of fixed roadway lighting and vehicle headlights, based on an additive model of driver visual information processing, indicate that drivers' detection and avoidance of AASHTO standard [i.e., 6-in (15 cm) height] hazards of relatively low reflectivity will be impaired substantially by the elimination of overhead lighting. No levels of roadway illumination associated with reduced (partial) lighting tactics were included in the analyses, however, and it was shown that the edge in effectiveness for fixed roadway lighting was diminished when higher levels of hazard reflectivity and/or detection distances shorter than those derived from additive processing models are considered.
- Three experiments were designed and conducted to determine the effect of alternative reduced lighting techniques on driver detection of a simulated roadway hazard. These experiments included: A pilot study to evaluate the extreme lighting tactics (all on, all off) on performance at extreme geometric (straight and level, interchange ramp) conditions; a controlled field study to evaluate the effect of a variety of alternative reduced lighting techniques on driver (simulated) hazard detection at a single (main-line) geometry; and an observational validation study to measure the reactions of naive, unalerted motorists to the simulated hazard under three selected reduced lighting conditions.

  The results of these three data collection efforts may be summarized as follows:

  The pilot study demonstrated that lighting should not be reduced on interchange ramps, but the potential exists for reducing lighting on main-line sections.

  In the controlled field study, driver performance under each of the tested reduced lighting conditions (all off; one [opposite] side only lit; every other luminaire turned off; 75 percent power [50 percent light] and 50 percent power [30 percent light]) showed a measured decrement when compared to performance under full lighting that meets ANSI recommended values. The reduction in performance was relatively small (and not statistically-significant) for the dimmed tactics, while larger and statistically-significant performance decrements were noted for the one-sided and no lighting tactics. For the various tactics examined, the actual (percent) decreases in detection performance in comparison to all on (full/continuous lighting) were: uniformly dimmed/75 percent power (19 percent), uniformly dimmed/50 percent power (22 percent), every other luminaire extinguished (29 percent), one (opposite) side only lit (43 percent), and no lighting (43 percent).

The results of the observational validation study indicated a pattern of decrements in performance for the uniformly dimmed/50 percent power and no lighting conditions that was similar to the pattern of detection decrements found in the controlled field study for the same lighting conditions.

- Benefit-cost ratios based on installation/operating costs and energy savings are quite high for the simpler extinguish-type tactics, being reduced to below 1.0 for the most expensive tactic (variable dimming).

- A cost-effectiveness analysis that included installation/operating costs, energy savings, and effect of lighting on driver detection provided a relative ranking--best to worst--as follows:

		C/E Ratio
All off	-	11.6
All on	-	13.0
75 percent power	-	14.1
Every other	-	14.1
50 percent power	-	14.7
One side only	-	17.6

7.2 Implications and Recommendations

The results of this research provide a number of implications and recommendations regarding potential uses of reduced lighting, further evaluation of the effect of reduced lighting, and related research issues.

7.2.1 Implications

From a practical standpoint--excluding safety effects which are discussed below--reduced lighting during periods of low traffic density is certainly feasible, both technically and economically. Further, all systems except those employing the variable dimming tactic should be cost-beneficial when installation/operating costs are compared to energy savings.

From a safety standpoint there is a definite reduction in (simulated) hazard detection performance, which theoretically implies some reduction in safety. This implied reduction in safety is statistically-significant for the all off and one side only lighting tactics, but not statistically-significant for the dimmed tactics and the every other off tactic. Unfortunately, it is not possible at this time to quantify the exact decrease in safety in terms of the frequency of nighttime accidents, the night accident rate, or the night-to-day accident ratio. Only an evaluation of long-term installations can address this issue (see following discussion of further research needs).

From a legal standpoint, potential problems exist. However, in 50 percent of the responses by lighting and legal experts, the issue was <u>not</u> considered to be a problem. Therefore, considerations of legal liability need not necessarily preclude the potential use of reduced lighting systems in many states.

7.2.2 Recommendations

Based on the results of this research, the following recommendations have been developed with regard to the proposed use of reduced freeway lighting during periods of low traffic density:

- Fixed, uniform dimming circuits provide a relatively effective means for reducing the energy required for freeway lighting while only resulting in a minimal, non-statistically-significant adverse effect on driver performance as measured in this research. Energy savings up to 25 percent[1] can be achieved, and at average nationwide energy costs of 6.4¢ per kWh the benefit-to-cost-ratio is about 1.0. For higher energy costs the benefit-to-cost ratio would be certain to exceed 1.0.

The initial installation costs for such systems are, however, relatively high--and more so for existing lighting systems than for new installations.

- An inexpensive method for conserving energy in urban and suburban centers where, due to the commercial nature of the area, lighting levels exceed ANSI/IES by a substantial margin, would be an every-other-luminaire-off configuration. Since most freeway lighting systems are of such design that turning off every other luminaire would result in uniformity ratios and lighting levels considerably below those suggested by AASHTO and endorsed by FHWA, however, it is impossible to issue an unqualified recommendation to implement this energy conservation tactic. Agencies contemplating such a step should first assure themselves that the lighting is still in conformance with established AASHTO guidelines. Benefit-to-cost ratios for such configurations range between 9 and 14 for average nationwide energy costs.

- Neither the variable dimming circuits nor the one-sided configurations are recommended; the former because of high costs, resulting in low benefit-to-cost-ratios and the latter because of its highly-significant, adverse impact on driver performance. In fact, an agency would be better off extinguishing <u>all</u> lights on a freeway rather than one side only, based upon the present research findings.

- Twin-lamp systems have a potential--in newly designed lighting systems--to save up to 25 percent of the energy, given that their effect on driver performance is minimal (i.e., the same as a dimmed circuit); however, this tactic would probably be too expensive to implement in existing lighting systems.

- Reduced freeway lighting tactics normally should not be implemented before about 11:00 PM in most urban areas, since traffic density typically remains relatively high until that time. Regularly scheduled sports events and other large traffic generators could change this time to a later hour, while cities with little or no evening activity might allow an earlier light reduction.

In application of the preceding recommendations, a prospective user must (1) be aware of the potential legal problems, especially if lighting is reduced below ANSI or AASHTO recommended levels and (2) modify the energy side of the benefit-to-cost ratio computation to reflect local energy costs.

7.2.3 Further Evaluation of the Effect of Reduced Lighting

At the present time there are two existing lighting systems in North America which provide reduced levels of lighting during periods of low traffic volume (Oshawa, Ontario and Highway 401, Ontario). The first is a twin luminaire system and the second a variable dimmed system, just being completed. It would be extremely useful to observe the changes in safety on these two roadways over an extended period of time to investigate whether the accident costs for such a system have any impact on the total cost-benefit analysis.

The legal issues will only be resolved after one or more reduced lighting installations are in place. Whether government agencies are liable if the lighting is reduced and accidents occur as an alleged result must be decided by the judicial system. The opinions received as part of this study do not clarify this matter.

Next, it should be emphasized that a comprehensive analysis of the effectiveness of fixed roadway lighting sys-

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[1] 50 percent for one-half of the night.

tems would include: (1) a quantification of the lighting (type, quality, quantity); 2) the total costs (or increased costs) of the lighting systems; (3) the effect of the changes in lighting on accidents; (4) monetary quantification of these effects to derive accident cost savings; and, (5) derivation of benefit-to-cost ratios that relate the accident cost savings to lighting costs in an <u>absolute</u> manner so that optimum choices of lighting can be made.

In actuality, items 1 and 2 are simple to obtain and if item 3 is available, the last two factors are easily computed. The basic problem in the preceding analysis is that the methodologies necessary for the computation of item 3 are wrought with problems. These include (1) the overpowering effect of geometric and traffic factors on accidents in comparison to the effect of lighting; (2) the extended period of time (typically years) necessary to obtain sufficient accident data for significant conclusions to be drawn; (3) control of the geometric, traffic, and environmental conditions during this extended time period; (4) the inherent problems in accident reporting, including nonreporting, poor quality reporting, delayed reporting, subjective bias in after-the-fact reporting, and the extensive cost of providing on-scene investigators to counteract such reporting problems; (5) the cost to install and maintain different types (levels) of lighting on sufficiently extended portions of roadway, all sections of which must be similar in geometric and traffic factors; and (6) problems such as legal issues, roadway maintenance effects, and others.

In reviewing the extensive literature that has attempted to isolate the effect of fixed roadway lighting on accidents, very mixed results are encountered. It is generally believed that good lighting has a beneficial effect on safety, especially compared to no lighting. However, there are conflicting conclusions in the literature on this issue and few studies have found highly (statistically) significant results.[2]

For these reasons, most studies--including the present research project--that attempt to analyze the effect of fixed lighting on safety do so by relating alternative lighting conditions to surrogate measures of safety (i.e., measures of driver performance, such as detection, that are logically related to safety--e.g., braking, erratic maneuvers, speed changes, etc.). While experts generally would agree that minimizing the frequency of such surrogate measures contributes to highway safety, the exact relationship between a change in such measures and a change in safety is not known. Clearly, a roadway situation where 50 percent of the drivers actuate their brakes in a given situation is more dangerous than the same situation where only 5 percent actuate their brakes, but one could not generalize this finding to state that an equivalent (or any other specific) decrease in accidents will occur.

Such a finding allows one to perform only a cost-effectiveness analysis which yields a <u>relative</u> ranking of alternatives (including costs and effectiveness). For a true cost-benefit analysis--desired as the optimum--it would be necessary to translate the change in surrogate measures into a safety change, which is not possible at this time.

As noted at the outset of this discussion, reduced lighting tactics have already been implemented in Ontario; if other States or cities similarly elect to implement reduced lighting tactics, analyses to further quantify costs, energy savings, and, especially, changes in safety are most strongly recommended.

7.2.4 Related Research Issues

One clear implication of the present research concerns the need to develop more realistic models of driver visual information processing. Such models have the potential to be valuable design aids, but their utility is called into question when the predictions they generate about driver behavior are shown to be substantially in error when tested under real-world traffic conditions. In the controlled field study, the mean detection distance for the test condition with the highest visibility was determined to be under 300 ft (91.5 m), as compared to estimates ranging from 450 ft (137 m) to over 800 ft (244 m) that were based on existing decision sight distance formulations in the technical literature.[9]

The principal shortcoming of the model employed in this project appeared to be the assumption of additivity, i.e., that the processing task associated with a given stage, such as "recognition," necessarily must be completed before the driver proceeds to initiate the next processing function. In fact, the experience of most drivers in freeway situations will confirm that some type of response, or movement-to-control, typically occurs as soon as an object is detected in the road ahead, as much as several seconds (and hundreds of feet of traversed distance) before that object can be reliably identified. A provision for the accomplishment of multiple processing tasks in a parallel, rather than a serial and contingent, fashion thus seems indispensable to the development of new models with greater predictive validity; the challenge lies in quantifying the extent to which the various (recognition, decision-making, response selection) tasks may be shared in defined driving situations.

A further implication of this research pertains to the strong influence of target characteristics on the outcome of experiments measuring driver detection/recognition of simulated hazards in the roadway. This influence was demonstrated by objective (distance-to-target), subjective (rating scale), and analytical data alike in the controlled field study, pilot study, and visibility needs assessment segments of this project, and has the unfortunate effect of sharply limiting the generalizability of the present findings with respect to (simulated) hazards differing substantially in size or reflectivity from the 6 in (15 cm) high, 18 percent reflective gray target object. The development of a standardized target that best serves to define driver visibility needs in actual traffic conditions thus remains a high priority, to maximize the interpretability and design/applications value of continuing research efforts in this area.

8.0 GLOSSARY OF INCLUDED STATISTICAL TERMS

The following glossary has been prepared to provide brief definitions of statistical terms included in this report. While it is in no sense intended as a "primer" or exhaustive listing of relevant material in this area, it may serve as a useful reference for readers whose areas of specialization do not involve the frequent or common usage of such terms.

- Analysis of variance (ANOVA)--A computational technique for testing the null hypothesis in an experiment that involves the construction of an F-ratio:

$$\frac{(\text{treatment effects})+(\text{experimental error})}{\text{experimental error}}$$

  Essentially, this ratio measures the extent to which (response) differences between groups exceed differences within groups; with no treatment effects, the ratio (i.e., the F value) will approximate 1.0. As the magnitude of the ratio increases, however, a progressively stronger treatment effect is demonstrated, expressed as relatively greater levels of statistical significance.

- Blocking variable--A classification factor to identify important sources of differences among subjects or stimuli that are well-known prior to the conduct of an experiment; when included in an experimental design (e.g., the "randomized block design") a blocking variable can restrict the obvious and unwanted influence of such a known source of differences by dividing an experiment into separate and independent "blocks", with test subjects then randomly assigned to treatment conditions within each block. The primary criterion for the selection of a blocking variable is a substantial correlation with the response measure (i.e., the dependent measure) in an experiment. Since it is known that roadway geometry, for example, exerts a powerful influence on many aspects of driver performance, it may be useful to designate this factor as a blocking variable in experimental designs where the influence of some other factor (e.g., lighting level) on performance is to be measured, and to assign subjects to treatment groups accordingly.

- Correlation (Pearson product-moment, or linear)--The strength of association between two variables, measured in terms of a correlation coefficient (r) whose value may range from -1.0 (extreme inverse association, or negative correlation, where one variable increases as the other decreases) through 0.0 (no association between variables) to +1.0 (extreme direct association, or positive correlation, where one variable increases as the other increases). Even extreme values of r do not constitute sufficient evidence to conclude that a cause-effect relationship exists, however; for example, while driver age may be highly correlated with involvement in certain types of accidents, it is in fact differences in exposure, knowledge/experience, risk-taking behavior, etc., that account for the "effect" on accidents.

- Dependent variable--A factor (such as driver response/performance) for which some type of change typically is hypothesized as the consequence of a "treatment effect", or a change in another (independent) variable; the variable that is associated with "effect" in a cause-effect relationship.

- Independent variable--A factor, or "treatment" (such as lighting level) which is purposefully manipulated during an experiment to measure its effect on some behavior, performance, or other outcome; the variable that is associated with "cause" in a cause-effect relationship.

- Latin-square designs--A type of "counterbalanced" experimental design in which one subject or group is tested in one sequence of treatment conditions while another subject or group is tested in a different sequence. This is done simply to guarantee that any significant treatment effects demonstrated during an experiment are not in part due to the order in which treatments (e.g., varying levels of roadway illumination) are presented to subjects. Specifically, the present Latin-square design contained an ordering scheme where an initial sequence of n treatments was described by the expression 1, n, 2, n-1,..., and each additional sequence was generated by adding one to each term in the expression (i.e., 2, 1, 3, n,...; then, 3, 2, 4, 1,..., etc.).

- Mean--The arithmetic average of a set of data (values, scores, etc.).

- Median--The data point (value) which falls exactly in the middle of the range of a set of data, when all values are arranged in order of magnitude.

- Null hypothesis--The hypothesis that observed (response) differences between treatment groups in an experiment are due to chance, or experimental error.

- Post-hoc analysis--Comparisons within a group of treatment means (or sums) that are unplanned at the start of the experiment, but are instead performed after an analysis of variance has demonstrated a significant overall treatment effect, in order to determine which particular treatment level(s) was (were) responsible for that effect. A variety of different post-hoc tests exist, each tailored to a specific application and each including a slightly different expression for calculating "experimental error".

- Repeated-measures design--An experimental design in which all test subjects participate in all treatment conditions in an experiment.

- Scheffé test--A type of post-hoc analysis that is appropriate when conducting all possible comparisons among different treatment levels in an experiment; the Scheffé test is relatively the most conservative of post-hoc analyses in that it provides the greatest control over "experimental error", thus providing the greatest assurance that no Type I error (see explanation under Statistical significance level) has occurred when significant differences are detected.

- Standard deviation--A measure of the degree of dispersion, or distribution, in a set of data, equal to the positive square root of the variance.

- Statistical significance (level)--An indirect measure of the degree of confidence with which the null hypothesis in an experiment can be rejected, expressed as a probability p that an alpha--or Type I--error has occurred (i.e., that the null hypothesis has been incorrectly rejected) during data analysis. Thus smaller values of p denote higher levels of statistical significance, with $p < .05$ (i.e., a 5% chance of Type I error) serving as a widely-accepted cut-off point for any claims of statistically-significant treatment effects.

- Trend analysis--A type of post-hoc analysis that seeks to determine the simplest mathematical function that can adequately describe the results, or pattern of data, in an experiment.

- t-test (also known as Student's t)--A computational technique for testing the null hypothesis that may be regarded as a special case of the more general analysis of variance technique, to be employed when there are only two treatment groups in an experiment.

- Variance (data)--The average of the square of the deviations of individual data points, or measurements, about their mean.

9.0 REFERENCES

1. National Safety Council, Accident Facts, 1982 Edition.

2. CIE, "Road Lighting as an Accident Countermeasure," Technical Report #8/2, 4th Draft, November 1982.

3. S.H. Young, "Turn On the Lights!", Lighting Design and Application, June 1982, pp. 28-32.

4. S.H. Richards, "Effects of Turning Off Selected Roadway Lighting as an Energy Conservation Measure," Transportation Research Record No. 811, 1981.

5. M.H. Hilton, "Continuous Freeway Illumination and Accidents on a Section of I-95," Virginia Highway and Transportation Research Council, August 1978.

6. P.C. Box, "Effect of Lighting Reduction on an Urban Major Route," TE, Vol. 46, #10, October 1975.

7. M.S. Janoff et al., "Partial Lighting of Interchanges," NCHRP 5-9, Final Report, January 1983.

8. M.S. Janoff, Quarterly Report for NCHRP Projects 5-9, December 31, 1981.

9. H. McGee, "Decision Sight Distance for Highway Design and Traffic Control Requirements," Transportation Research Record No. 736, 1979.

10. V. Bhise, E. Farber et al., "Modeling Vision with Headlights in a Systems Context," Paper presented to Society of Automotive Engineers, February 28 - March 4, 1977, Detroit, MI.

11. AASHTO, "A Policy on Geometric Design of Highways and Streets," 1984.

12. M.S. Janoff et al., "Effectiveness of Highway Arterial Lighting," Report No. FHWA-RD-77-37, Federal Highway Administration, July 1977.

13. V.D. Bhise, "Quantifying the Driver's Night Visual Scene," Proceedings of 15th Annual Workshop on Human Factors in Transportation, Transportation Research Board, 1982.

14. O.M. Blackwell and H.R. Blackwell, "Individual Responses to Lighting Parameters for a Population of 235 Observers of Varying Ages," Journal of the Illuminating Engineering Society, July 1980.

15. V.P. Gallagher and P.G. Meguire, "Contrast Requirements of Urban Driving," In: Driver Visual Needs in Night Driving, TRB Special Report No. 156, 1975.

16. CIE, "An Analytic Model for Describing the Influence of Lighting Parameters Upon Visual Performance," Report #19/2, 1981.

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.