NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **256**

PARTIAL LIGHTING OF INTERCHANGES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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PARTIAL LIGHTING OF INTERCHANGES

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AREAS OF INTEREST:

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HUMAN FACTORS
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(HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.

DECEMBER 1982

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation
Research Board

This report will be of special interest to highway lighting and design engineers who are involved in the specification of lighting systems for freeway interchanges. Information is provided on the relative effectiveness of no lighting, partial lighting, and complete lighting in regard to influencing traffic operations and safety. The research included a literature review, a survey of current lighting practices in the United States and Canada, and field studies at two freeway interchanges.

Partial lighting of freeway interchanges is often used at locations where complete lighting is not considered to be justified. Installation and maintenance costs are lower when lighting is provided only at critical points within the interchange (i.e., partial lighting), and operations and safety are generally considered to be better than under a no-lighting condition. However, limited data are available regarding the actual effectiveness of partial lighting in comparison to complete lighting.

The objective of this research was to determine the extent to which partial lighting provides benefits similar to complete lighting. Traffic operations and driver performance were investigated at interchanges on the Pennsylvania Turnpike and Baltimore Beltway. Although only two sites were included, the lighting was varied at each site to simulate as many partial-lighting configurations as possible within the funding limitations. Also, sufficient accident data were not available to generalize the effectiveness of each type of lighting. Instead, various traffic characteristics were used as surrogate measures to provide an indication of relative effectiveness. Cost data were not obtained because these are readily available from other sources.

Although the research findings provide valuable insights regarding the benefits of partial vs. complete lighting, development of specific warrants was not possible within the constraints of the project. Until such warrants can be specified through additional research, the decision to install partial or complete lighting at an interchange will continue to be based on information from various sources.

A comprehensive survey of freeway interchange lighting practices in most states and several Canadian provinces is summarized in the Appendix. An excellent response was received to the survey questionnaire, and the information summary regarding current practices should be of interest to individual agencies.

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The research reported herein was performed under NCHRP Project 5-9 by the Transportation Programs Group of Ketron, Inc.

Michael S. Janoff, Manager of the Transportation Programs Group, was the Principal Investigator. Mark Freedman, Senior Transportation Engineer, directed the field experiments and performed the analysis of the field data. Larry E. Decina, Research Psychologist, had major responsibilities for the literature review, survey of nationwide practices, and field experiments.

Contributing staff included Messrs. Paul Davit, Dave Shender, Peter Stampfl, Paul Kovnat, and Miss Monique Gray. Mr. Vincent P. Gallagher, Consultant, contributed toward the experiment design.

PARTIAL LIGHTING OF INTERCHANGES

SUMMARY

As a means of facilitating the driving task and reducing the potential for accidents, partial lighting of interchanges has been used for areas where complete or continuous lighting was not deemed to be justified. Use of partial lighting is based on the premise that it will provide, at lower costs, many of the benefits attributable to complete interchange lighting. This premise is for the most part unsubstantiated and is subject to doubts concerning the effectiveness of partial lighting. Prior to this research, information was urgently needed to provide guidance concerning the effectiveness and conditions favoring the use of partial lighting of interchanges.

The objective of this research was to determine the effectiveness of partial lighting of interchanges and to develop recommendations for its use. Partial lighting is defined as lighting that consists of a few luminaires located in the general areas where entrance and exit ramps connect with the through traffic lanes of the freeway. This research concentrated on the benefits of lighting rather than on the costs, and crossroad lighting at the ramp terminals was not included.

The study began with a literature review that identified the types of interchanges and some indication of their frequencies and operational differences (e.g., accident rate by interchange type); general information on lighting warrants, recommendations, practices, and effectiveness; the most important and most usable measures of effectiveness; and the most applicable experimental methods.

In order to obtain an accurate picture of the range of practices of interchange lighting in North America, a mailback questionnaire was designed and sent to 63 agencies. This survey solicited information on interchange design and practices, lighting design and practices, and safety and operational data. Approximately 78 percent of the agencies responded to the survey, supplying information on over 14,000 interchanges and over 7,500 interchange lighting systems.

The major results of this survey are that 55 percent of all interchanges are diamond, followed by partial cloverleaf (18 percent), half diamond (8 percent), three-leg (7 percent), and full cloverleaf (5 percent). Of the 52 percent of all interchanges that are illuminated, 49 percent are in urban areas, 25 percent are in rural areas, and 26 percent are in suburban areas. Thirty-seven percent of the interchange lighting is complete interchange lighting (CIL), and 63 percent is partial interchange lighting (PIL).

Mercury lamps are used in 57 percent of the installations, high-pressure sodium in 38 percent, and low-pressure sodium, metal halide, and fluorescent in 5 percent. Conventional mounting heights are used in 82 percent of the installations and high mast in 18 percent. CIL systems are part of a continuous lighting system in 74 percent of the installations and isolated in 26 percent of the installations. PIL consists of one to two luminaires in 57 percent of the systems, three to five luminaires in 34 percent of the systems, and more than five or high mast in 9 percent of the systems. The most frequent locations of the PIL luminaires are directly upstream of the gore and in the gore (exit) and directly downstream of the gore (entrance).

The survey data were further stratified by region (9 FHWA regions, Canada, turnpike authorities) to disclose regional differences (e.g., greater use of PIL in

western states). Additional analyses were accomplished to isolate reasons for selecting or rejecting specific types of lighting and specific interchange designs; the variation in lighting warrants (83 percent follow AASHTO or equivalent, 17 percent have different warrants—typically stricter); and the availability of accident and traffic operational data and the results of any studies conducted to analyze the effectiveness of interchange lighting and the effects of changes in interchange lighting on safety and traffic operations.

An experimental design was developed which considered the independent variables, dependent measures of driver behavior and traffic operations, and the recommended experimental test conditions. The independent variables chosen for study included the lighting (various levels of PIL, CIL, no lighting, and daylight), the geometry of the interchanges (straight versus curved ramps); and presence of weaving area versus no weaving area. The dependent measures included speed and acceleration of individual vehicles traversing the interchanges, merge and diverge points of individual vehicles entering the main road or leaving it, and erratic maneuvers such as brake activations, use of high beams, and gore or shoulder encroachments. The test conditions were defined to include the various combinations of ramp type, merge area, and lighting condition.

Officials in all 50 states were contacted to identify interchanges that satisfied the geometric test conditions and had complete lighting systems that could be physically modified to produce the desired lighting test condition. Two sites were selected for the experiment: a three-leg interchange in suburban Philadelphia for a pilot study and a full cloverleaf in suburban Baltimore. The State of Pennsylvania, the Pennsylvania Turnpike Commission, and the State of Maryland provided both cooperation and permission to temporarily change the lighting from CIL to PIL and no lighting.

Concurrent with the experimental design, a data collection system was designed and fabricated to allow Ketron to unobtrusively collect the required traffic operational data. The system consists of a series of pressure-sensitive electronic switches placed at specific locations on the roadway, an electronic circuit to control the data collection, a printer to provide coded data output, and necessary power supplies, cabling, and peripheral devices. This system, called the Vehicle Trajectory Measurement System (VTMS), can measure the time/position history (i.e., the trajectory) of individual vehicles traversing the interchange. When data collected under one specific test condition (i.e., fixed lighting and geometry) are grouped and compared to a different set of grouped data collected under another specific test condition (e.g., only a change in the lighting), the effect of the change in the lighting variable alone on the dependent measures can be assessed. Photometric measurements were also planned.

Data reduction and analysis techniques were developed to isolate the effect of the different lighting levels and the different geometric conditions (the independent variables) on the dependent measures in order to assess the relative effectiveness of PIL, CIL, and no lighting on traffic operations.

The design of the field experiments made it possible to strictly control—actually to fix—all variables other than lighting, so that the results of this research are directly related to the lighting conditions. Only traffic volume could not be controlled, and the effects of this variable were minimized by collecting data under a wide range of traffic volumes for all lighting conditions.

The major results of the two observational experiments are summarized as follows:

MEASURE	RESULT	IMPLICATIONS
Brake activations	Frequencies higher under PIL than under CIL	CIL performs better than PIL
Mean braking distance	Improved under CIL for cloverleaf interchange	CIL performs better than PIL
High beam use	Frequencies higher under PIL than under CIL	CIL performs better than PIL
Diverge/merge patterns	Improved under CIL	CIL performs better than PIL
Gore and shoulder encroachments	Frequencies higher under PIL than under CIL for three-leg interchange	CIL performs better than PIL
Velocity and acceleration	Not affected by lighting	None

Except for velocity and acceleration, which were unaffected by lighting, each of the dependent measures was adversely affected when CIL was reduced to either one of the PIL systems or to no lighting.

On the basis of the effect of the various lighting conditions on the dependent measures of driver behavior and traffic operations, the major conclusions of the research are as follows:

1. CIL performs better than PIL consisting of one, two, or four luminaires.
2. Either CIL or PIL normally performs better than no lighting.
3. PIL systems with fewer luminaires (one or two) frequently perform better than PIL systems with a greater number of luminaires (four).
4. There is a trade-off between cost and traffic operations and safety factors in the design of freeway interchange lighting systems.
5. Existing CIL systems should not be reduced to PIL systems if traffic operations and safety (defined in terms of the driver behavior measures) are important considerations.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

As a means of facilitating the driving task and reducing the potential for accidents, partial lighting of freeway interchanges has been used for areas where complete or continuous lighting was not deemed to be justified. Use of partial interchange lighting (PIL) is based on the premise that it will provide, at lower costs, many of the benefits attributable to complete interchange lighting (CIL). This premise is for the most part unsubstantiated and is subject to doubts concerning the effectiveness of partial lighting. Information is urgently needed to provide guidance concerning the effectiveness and conditions favoring the use of partial lighting of interchanges.

RESEARCH OBJECTIVES

The overall objective of this research was to determine the effectiveness of partial lighting of freeway interchanges and to develop recommendations for its use. For purposes of this research, PIL is defined as lighting that consists of a few luminaires located in the general areas where entrance and exit ramps connect with the through traffic lanes of the freeway. This research has concentrated on the benefits of lighting rather than on the costs. Specifically, the cost of installing and maintaining lighting and the amount of energy used were excluded. Also, crossroad lighting at the ramp terminals was not included.

The specific objectives of the research were as follows:

1. Determine the range of practice in those states where PIL is used, including both high-mast and conventional mounting heights, and review the literature and past experiences to determine the effectiveness of PIL.

2. Develop a methodology (including an experimental plan) for evaluating the effectiveness of PIL relative to no lighting and to CIL. The methodology was to be based on measures of visibility and effectiveness (e.g., accident data, traffic characteristics, or some surrogates) that resulted in the precise definition of the boundary conditions for roadway and traffic characteristics.

3. Conduct field evaluations based on the experimental plan.

4. Analyze the data to determine the effectiveness of PIL as compared to no lighting and CIL for typical interchanges.

5. Prepare a final report including recommendations regarding the effectiveness of PIL.

RESEARCH APPROACH

To meet the preceding objectives a research plan was adopted which consisted of seven tasks.

The first task was to conduct a literature review. This review was a comprehensive compilation and critical review of interchange design, practices, operations, and safety; lighting system warrants, recommendations, practices, and effectiveness; measures of effectiveness of lighting systems; and experimental methods for evaluating the effectiveness of lighting systems (App. A).

The second task was to design and conduct a mailback survey (App. B). The survey was sent to 63 lighting and highway agencies to obtain an accurate picture of the range of practices of interchange lighting in North America. Information was solicited on interchange design and practices, lighting design and practices, safety and operational data, and past experiences evaluating the effectiveness of PIL.

The third task was to design the experiment for evaluating the effectiveness of PIL. The experimental design included specification of independent variables, dependent measures, and test conditions; selection of specific test sites that met the prescribed test conditions; and obtaining permission from the lighting agencies to perform the necessary studies. In addition, a data collection system was designed to allow the researchers to unobtrusively collect the required traffic operational data. The design of the field experiments made it possible to strictly control—actually to fix—all variables other than lighting, so that the results of this research are directly related to the lighting conditions.

Site selection involved classification of all interchanges by ramp geometry and exit/entrance geometry, definition of an "ideal" site, and identification of potential sites based on the information provided in the mailback survey. A Maryland interchange (I-695/MD 147) was selected as the main test site, and a site for a pilot study was selected in Pennsylvania (I-276/PA 9).

The study considered geometry and lighting, both of which could be controlled by design, and traffic volume, which could not be controlled, as the independent variables. There were three types of dependent measures: locational (merge/diverge points), time/position history (spot and average velocities and accelerations), and erratic maneuver (brake activations, high-beam use, gore and shoulder encroachments).

The data collection equipment, called the Vehicle Trajectory Measurement System (VTMS), is a simplified version of the FHWA Traffic Evaluation System (TES). The VTMS made it possible to automatically record the effects of lighting changes on the performance of unimpeded, naive (i.e., unknowing) drivers.

The fourth task was to conduct a pilot study to fully evaluate the data collection system, field procedures, and analysis methods developed in Task 3. Two partial lighting conditions, in addition to no lighting, complete lighting, and daylight, were evaluated in this pilot study.

The fifth task was to repeat the experiment designed in Task 3 at a more complex interchange.

Appendix D provides the details of the design and conduct of the field experiments.

The sixth task was to analyze the traffic operational and photometric data collected in Tasks 4 and 5 to determine the effectiveness of PIL in comparison to no lighting and CIL.

The final task included the development of recommendations for use of PIL based on its effectiveness relative to CIL and no lighting, as defined by the results of Task 6, and the preparation of the final report summarizing the work performed in this study.

ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADT	average daily traffic
cd	candela(s)
CFL	continuous freeway lighting
CIE	Commission Internationale de l'Eclairage
CIL	complete interchange lighting
Eh	horizontal illumination
fc	footcandle(s)
FHWA	Federal Highway Administration
fL	footlambert(s)
ft	foot (feet)
h	hour(s)
ISAR	Interstate accident records
Lav	average pavement luminance
Lb	pavement luminance
Lt	target luminance
Lv	glare
mph	miles per hour
MUTCD	Manual of Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
PIL	partial interchange lighting
s	second(s)
TES	Traffic Evaluation System
VI	visibility
VTMS	Vehicle Trajectory Measurement System
W	watt(s)
WASHTO	Western Association of State Highway and Transportation Officials

CHAPTER TWO

FINDINGS

LITERATURE REVIEW

A search of the TRIS data base disclosed 32 references that were related in some way to the objectives of the study. These items were obtained, reviewed, and classified into four major categories of information: (1) interchange design, practices, operations, and safety; (2) lighting system warrants, recommendations, practices, and effectiveness; (3) measures of effectiveness of lighting systems; and (4) experimental methods for evaluating the effectiveness of lighting systems. The major results of this review will be presented as four groups of findings, summarized in this chapter and discussed in detail in Appendix A.

Interchanges

The three principal types of interchanges are cloverleaf, diamond, and directional (*1*). The most frequent type is the diamond (48 percent), followed by the partial cloverleaf (14 percent) and full cloverleaf (13 percent) (*2*).

Accident rates at cloverleaf interchanges appear to be higher than at diamond interchanges (*2, 3*), and the rates at exit ramps are higher than the rates at entrance ramps (*3*). For lower volumes (under 10,000 ADT), the diamond had lower accident rates than the partial cloverleaf, but the opposite was true at ADT greater than 10,000 (*2*).

Lighting Systems

No references were found that pertain directly to the subject of interchange lighting. However, the literature on roadway lighting is immense, covering the topics of warrants, recommendations, practices, and effectiveness.

Warrants for roadway lighting have been published by FHWA (*4*), AASHTO (*5*), and NCHRP (*6*); most states adhere to the AASHTO warrants. None of the present warrants are based on any proven empirical measures of effectiveness or need (e.g., behavioral measures, accident reduction, or improved traffic operations); rather, they are based on engineering judgment or analytic theory. Recommendations for roadway lighting (quantity and quality) suffer from the same problem.

Nationwide practices are generally based on the warrants and recommendations mentioned above, but the actual application of these warrants and recommendations allows a wide latitude in choice of systems. The variations in source type, mounting height, spacing, placement, and lamp size and distribution are not described in any data base covering interchange lighting practices. A small survey was conducted by AASHTO (*7*) to determine freeway lighting practices in the western states, but only CIL was described.

The effectiveness of roadway lighting has been studied since the advent of lighting on roadways. The list of references in this area alone would run to hundreds of entries. Although past research has shown that lighting appears effective as a countermeasure in reducing nighttime accidents, only generalized results are available. Only one study attempted to evaluate the effectiveness of freeway interchange lighting on a national scale, and this study found inconclusive results (*8*). More recently, Young (*9*) in Wisconsin found a 35 percent increase in nighttime interchange ramp accidents when the lighting was reduced from complete to partial for seven major interchanges and from complete to none for the rest (not statistically significant because of small samples).

The problem in most past research has been the underlying independent variable, illumination, which is not directly related to how drivers see. If luminance (or visibility) is used instead, proven empirical relationships exist between the independent lighting variable and measures of driver performance (*10, 11, 12*).

Measures of Effectiveness

The most frequently employed measures of effectiveness for roadway lighting have been accident reduction, improved traffic operations (other than safety), improved driver (and pedestrian) performance, increased comfort and convenience, and nonroadway-related improvements (e.g., crime), as well as measures of the quality of the lighting itself (e.g., improved visibility, luminance, contrast, and glare). Almost nothing is known that relates directly to the evaluation of freeway interchange lighting, although there is a wide range of literature relating all of the preceding measures to the broad topic of roadway lighting.

Experimental Methods

There are four major experimental methods that are used for evaluating the effectiveness of roadway lighting. These include accident analyses, lighting measures, analytic methods (e.g., modeling), and behavioral and traffic operational measurements. Other techniques combine two or more of the four major methods. Table A-8 summarizes each of the methods and its application to lighting research, advantages, disadvantages, cost, and validity.

MAILBACK SURVEY

This section summarizes the results of a mailback survey on interchange lighting practices in the United States and Canada. The questionnaires were sent to lighting engineers, highway engineers, and other representatives of state (U.S.) and provincial (Canadian) transportation/highway departments, and to selected turnpike authorities. The findings are presented in three parts: completion rate (responders versus nonresponders), interchange design practices, and interchange lighting practices. Appendix C presents tabular summaries of the responses to the key questions.

Completion Rate

Sixty-three questionnaires were sent to all 50 states, 10 Canadian provinces (Ontario, Quebec, Manitoba, Saskatchewan, Alberta, Newfoundland, Nova Scotia, New Brunswick, British Columbia, and Prince Edward Island), and the turnpike agencies of New Jersey, New York, and Pennsylvania. Fifty completed questionnaires (79 percent of total sample) were returned. Of the 48 questionnaires mailed to the state highway agencies in the continental United States, 40 were returned (83 percent).

Interchange Design Practices

The most frequently employed interchange designs in North America are the full diamond (55 percent), the partial cloverleaf (18 percent), and the half diamond (8 percent). The partial cloverleaf and three-leg are employed more frequently in the eastern regions (FHWA Regions 1, 3, 4, 5, 6) than in the western regions (FHWA Regions 7, 8, 9, 10). (The FHWA Regions are as follows: Region 1 (ME, CT, MA, NH, NJ, NY, RI, and VT), Region 3 (DE, MD, PA, VA, and WV), Region 4 (AL, FL, GA, MS, NC, SC, KY, and TN), Region 5 (IL, IN, MI, MN, OH, and WI), Region 6 (AR, LA, NM, OK, and TX), Region 7 (IA, KS, MO, and NE), Region 8 (CO, MT, ND, SD, UT, and WY), Region 9 (AZ, CA, HI, and NV), and Region 10 (ID, OR, WA, AK).) The full diamond is used more frequently in the western regions than in the eastern regions. Canada's most frequently employed design is the partial cloverleaf. The New Jersey and New York turnpike authorities employ three-leg and full cloverleaf interchanges to a large extent.

The most frequently cited factors involved in selection of an interchange design type are traffic operations, cost, and crossroad classification. Specifically, the most frequent reason cited for selecting a full diamond or half diamond interchange design is low cost. The most frequent reason cited for choosing a cloverleaf (partial or full), three-leg, or directional interchange design is good traffic operations. The most frequent reason cited for rejecting a three-leg or directional interchange design is high cost, and the most frequent reason cited for rejecting a cloverleaf (partial or full) or a diamond (half or full) is poor traffic operations.

The only direct comparison of data between that found in the literature and that disclosed by the survey was the frequency of types of interchanges found nationwide. This is illustrated in Table 1.

Table 1. Comparison of survey data with Interstate accident study data.

Type of Interchange	Survey Response (%)	IAS Response (%)*
Diamond	55	55
Partial Cloverleaf	18	14
Half Diamond	8	7
Full Cloverleaf	5	13
Three-Leg	7	11
Other	7	0

*Source: Reference 2.

Interchange Lighting Practices

Warrants

Fifty-four percent of the state agencies follow the AASHTO warrants (*5*) and 46 percent follow modified AASHTO warrants. The turnpike agencies follow AASHTO warrants. The Canadian provinces have their own warrants, which are comparable to those of AASHTO.

Unlit Versus Illuminated Interchanges

Figure 1 summarizes (by frequency and percent) the total sample of interchanges by the key variables (illuminated versus unlit, CIL versus PIL, mounting height, presence of continuous freeway lighting (CFL) for CIL and number of luminaires for PIL).

Fifty-two percent of the total number of interchanges reported in North American are illuminated. This ranges from a high of about 90 percent in the western United States (FHWA Regions 9 and 10) to a low of 17 percent in the southeastern United States (FHWA Region 4). This is shown in Figure 2.

Illuminated Interchanges by Type of Lighting and Area Type

Of the illuminated interchanges, 37 percent have CIL systems and 63 percent have PIL systems. CIL is more common in the East, South, and Midwest than in the West, as illustrated in Figure 3. When California data are excluded from the total the use of CIL increases to 55 percent and the use of PIL decreases to 45 percent. (California data will frequently be excluded in these analyses since this one State has over 57 percent of all reported PIL systems and clearly biases the figures reported by the other agencies.)

Most of the CIL systems are in urban areas, while PIL systems are almost equally represented in urban, suburban, and rural areas. Excluding California, most of the CIL systems are in suburban and urban areas and most of the PIL systems are in suburban and rural areas. Figure 4 illustrates the use of CIL and PIL systems in urban/suburban/rural areas.

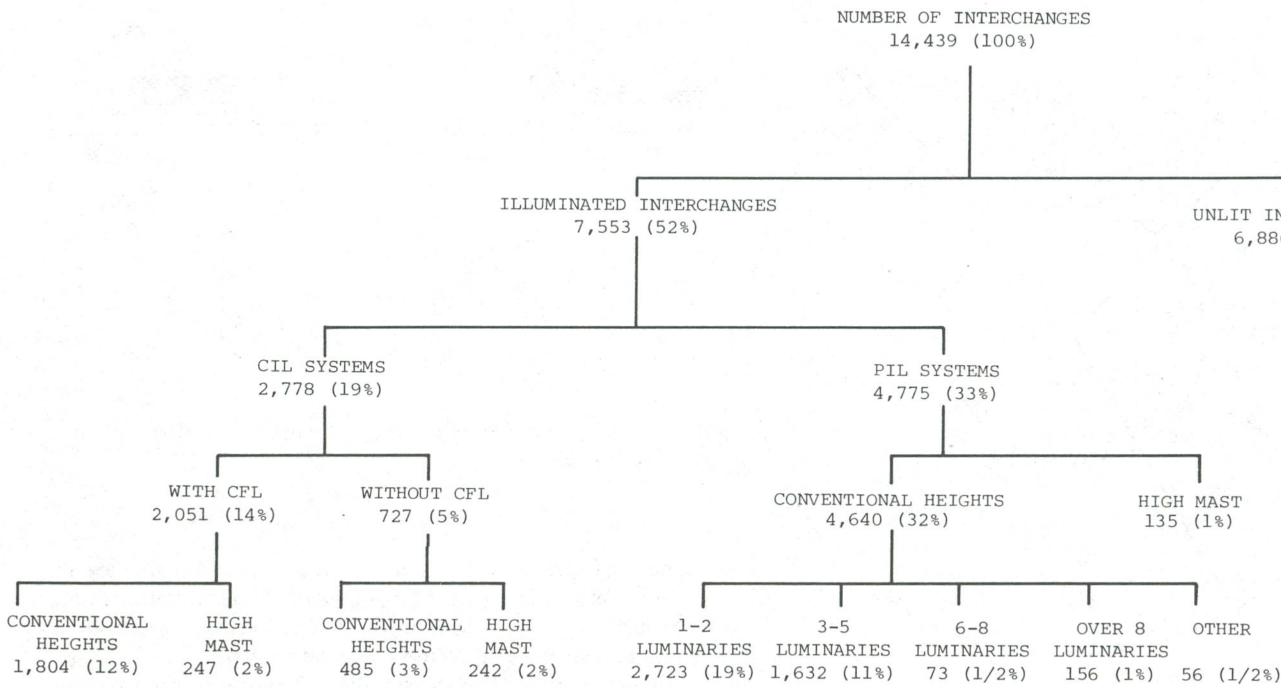

Figure 1. Distribution of illuminated interchanges.

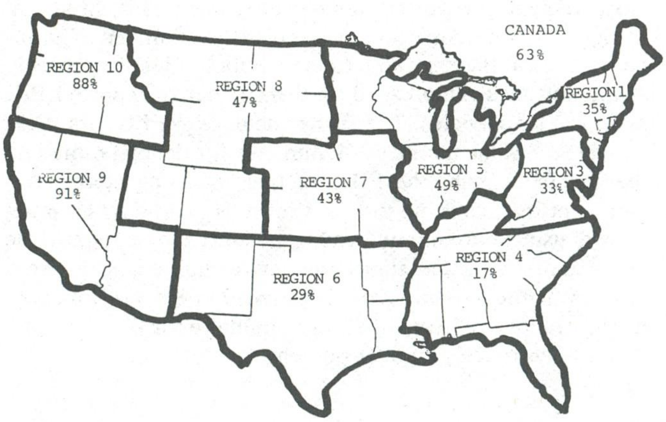

Figure 2. Percent illuminated interchanges by FHWA region.

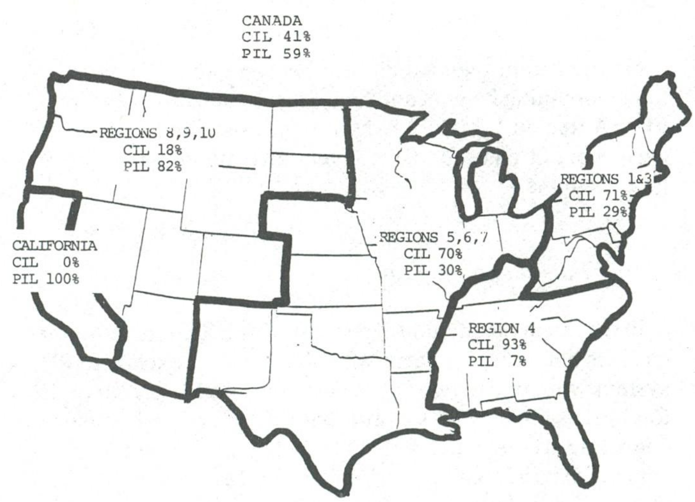

Figure 3. Percent CIL versus PIL by area and FHWA region.

Interchange Lighting by Source Type

Mercury lamps are used more frequently (57 percent) than any other source type for interchange lighting, followed by high-pressure sodium (38 percent), but the trend is toward high-pressure sodium for modern installations. The only regions that presently use more high-pressure sodium for interchange lighting than mercury are FHWA Regions 4 and 5. Metal halide is minimally used in all of the regions. Low-pressure sodium is minimally used in the Canadian provinces.

Complete Interchange Lighting

CIL systems make up 37 percent of the illuminated interchanges but only 55 percent when California is excluded. Seventy-four percent of the CIL systems are part of a CFL system; 26 percent serve to light only the interchange area.

Conventional mounting heights are used in 82 percent of the CIL installations, and high-mast lighting is used in only 18 percent. The ratio of conventional mounting height use to high-mast use is about 7:1 in the presence of CFL and about 2:1 in the absence of CFL.

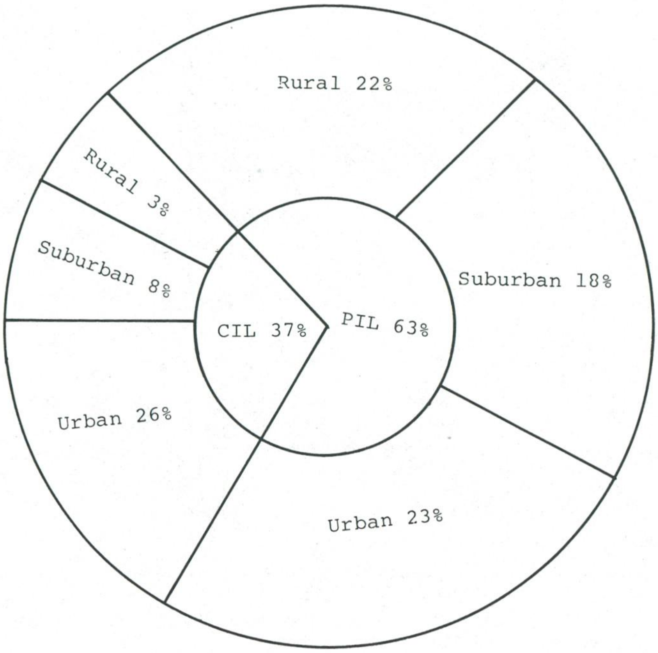

Figure 4. Comparison of CIL versus PIL by urban/suburban/rural area.

No significant regional differences were noted for conventional mounting heights and high-mast applications except in FHWA Region 1 (ME, MA, NH, VT), where high-mast lighting is more often used than conventional mounting heights in CFL systems.

Partial Interchange Lighting

PIL systems made up 63 percent of the illuminated interchanges but only 45 percent when California is excluded. PIL systems with one to two luminaires make up 57 percent of the total PIL sample. PIL systems with three to five luminaires constitute 34 percent of the PIL total. If California is excluded from the total, the most frequent PIL system includes three to five luminaries (50 percent), in agreement with AASHTO warrants. High-mast lighting accounts for only 3 percent of the PIL total. The western FHWA regions, especially California which has 2,500 PIL systems, use more PIL systems than the eastern FHWA regions.

The statistical data concerning the PIL systems summarized in the remainder of this section represent percentages based on the number of reported practices, not number of agencies or number of interchanges. An agency may employ more than one lighting practice.

Of the 39 PIL system practices reported (conventional mounting heights only), 74 percent place luminaries at both the exit ramp and entrance ramp areas. Twenty-three percent of the lighting practices place luminaires at exit ramp areas only. The practice of placing luminaries in just the entrance ramp area was reported only once (2 percent).

Figure 5 shows (by percentage of the number of reported PIL system practices) the frequency of locations for luminaire placement on exit and entrance ramps. The two most

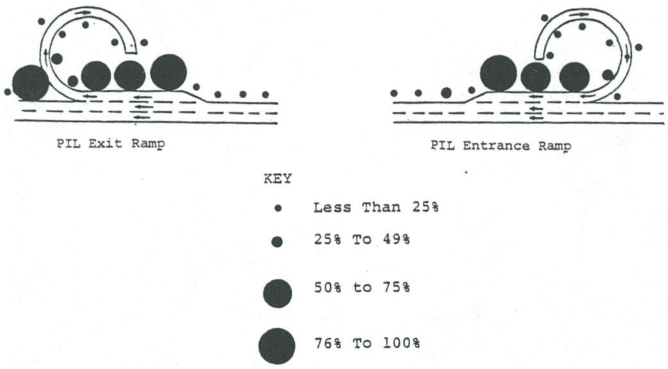

Figure 5. Frequency of luminaire locations for PIL systems (25 state practices).

common locations for a luminaire at an exit ramp area are in the gore area and near the beginning of the deceleration lane. The most common location for a luminaire at an entrance ramp is near the end of the acceleration lane.

Figure 6 shows (by the number of practices reported by agencies) the number of luminaires at the exit and entrance ramps. The most frequently reported number of luminaires at an exit ramp is four. The second most frequently reported number of luminaires is three. For an entrance ramp, the most frequently reported number of luminaires is three.

Figure 7 provides a comparison of the number of luminaires used at the exit ramp to the number of luminaires used at the entrance ramp based on the number of reported PIL practices by agencies. The figure includes the PIL practices of using the same number of luminaires for the exit ramp and the entrance ramp, the PIL practices of using more luminaires for the exit ramp than the entrance, and the PIL practices of using more luminaires for the entrance ramp than the exit ramp. Using the same number of luminaires for both ramps was the most frequent practice (23 percent), followed by the practice of using one more luminaire for the exit ramp than the entrance ramp (21 percent).

Miscellaneous Lighting Information

The most important reasons for selecting CIL are greater safety and geometric/physical characteristics of the highway. The most important reason for selecting PIL was economics (lower cost than CIL). For PIL systems with three to five luminaires, the most important reason for selection was warrants. The most important reasons for rejecting a CIL system were high cost and warrants. The most important reasons for rejecting a PIL system were high cost, warrants, and geometric/physical characteristics of the highway.

Thirty-five percent of the states have modified, to some extent, interchange lighting systems. (Only a limited number of responses were received on this question.) Maine and Wisconsin have modified CIL systems to no lighting, California modified PIL systems to no lighting, and Wisconsin reported a change from CIL to PIL. A number of other states reported that they modified lighting systems but did not provide any information about the type of modification. Only the

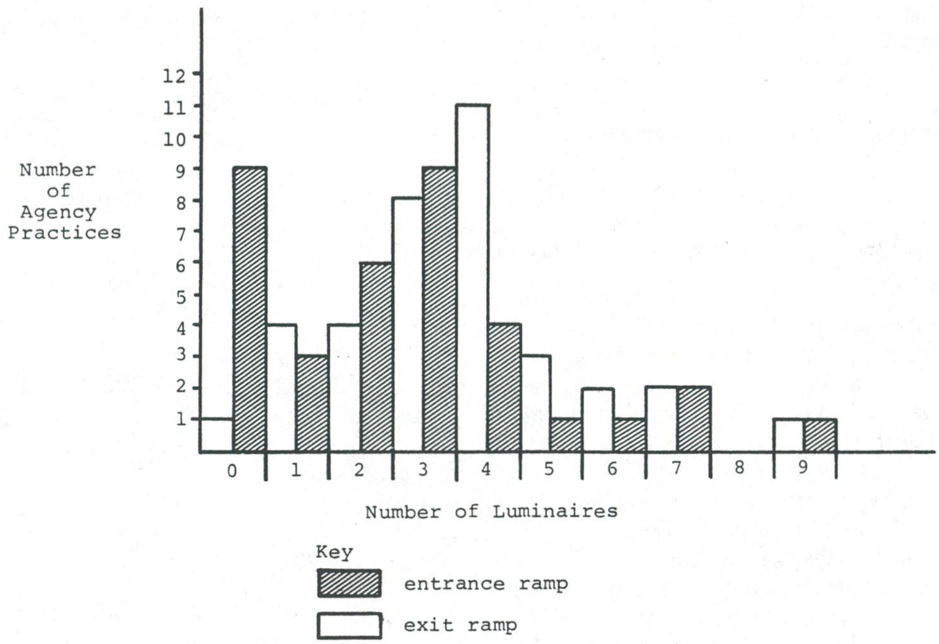

Figure 6. Number of luminaires per exit ramp and entrance ramp by number of agency practices (note: the 0 number of luminaires column represents the practice of placing luminaires either on exit ramp or entrance ramp but not both; hence the ramp without any luminaires would have 0 number of luminaires).

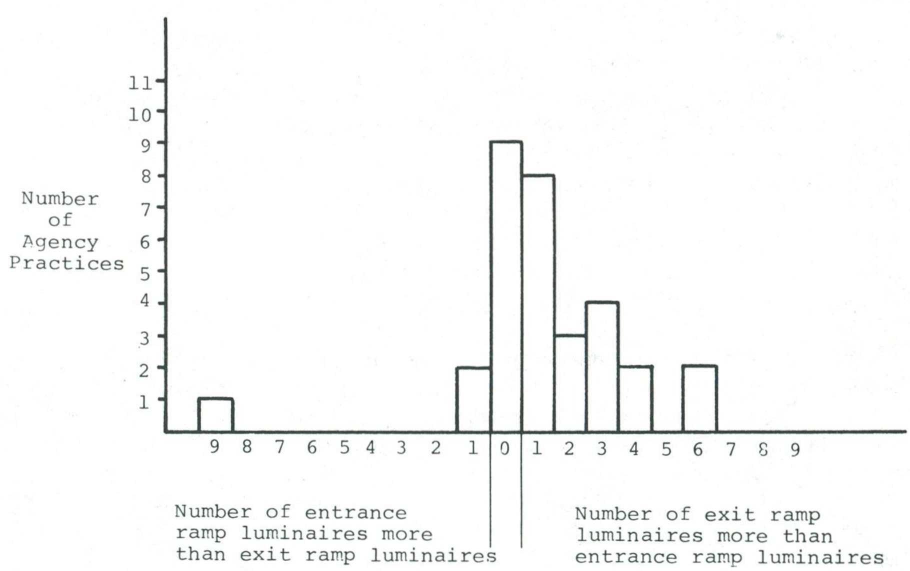

Figure 7. Comparison of exit ramp luminaires to entrance ramp luminaires by number of agency practices (note: there are 9 agency practices using the same number of luminaires for exit and entrance ramps).

Wisconsin changes have been evaluated, and these are reported in Appendix A.

Implications for Field Experiments

The results of the mailback survey provided guidance in developing the experimental plan for the proposed field studies. The most important results of the mailback survey were as follows:

1. Location—Outside of California, both CIL and PIL are most frequently used in suburban areas.
2. Source type—Fifty-seven percent of the installations use mercury and 38 percent use high-pressure sodium, but the trend is toward the latter.
3. Mounting heights—Conventional mounting heights are used in 83 percent of the CIL installations and in 97 percent of the PIL installations.
4. Number of luminaires (PIL)—Fifty-seven percent of the installations used one to two luminaries and 34 percent used three to five luminaires.
5. Location of luminaires (PIL)—Seventy-four percent of the reported PIL practices recommended lighting at both the exit and entrance ramp, with an equal number of luminaires at both the exit and entrance being the most frequent practice. PIL luminaires are most frequently placed between the gore and the beginning of the deceleration ramp (for the exit) and between the gore and the end of the acceleration ramp (for the entrance).

The implications of these main results were that the field experiment should evaluate interchanges in suburban areas where both PIL and CIL are commonly used, high-pressure sodium luminaires, only conventional mounting heights (PIL), PIL lighting systems using one to five luminaires, and PIL lighting systems with luminaires located between the gore and the end (beginning) of the acceleration (deceleration) ramp.

FIELD EXPERIMENTS AND DATA ANALYSIS

The objective of the field experiments (described in detail in App. D) was to determine the effect of PIL—in comparison to CIL and no lighting—on traffic operations at one or more freeway interchanges. To meet this objective an experimental design was developed that fixed all variables except lighting (e.g., environmental, geometric) and then varied the lighting to disclose its effect on specific key aspects of traffic operations.

Table 2 summarizes the number of observations for each of the 22 test conditions.

Data analysis was conducted separately for the pilot site and for the main site. Both analyses included VTMS data and photometric data.

Pilot Site

The analysis was divided into three parts: (1) a manual analysis of high-beam use and brakelight occurrences; (2) a computerized analysis of gore and shoulder encroachments, velocity, acceleration (and acceleration noise), and the distribution of diverging patterns (for the exit) and merging patterns (for the entrance); and (3) the combination of the above two data types with the photometric data.

Table 2. Total observations.

Site	Ramp	Lighting Condition	Number of Observations*
Pilot	Exit	Daylight	204
		No Lighting	189
		PIL-2	269
		PIL-4	153
		CIL	147
Pilot	Entrance	Daylight	176
		No Lighting	176
		PIL-2	197
		PIL-4	193
		CIL	152
Main	Exit	Daylight	135
		No Lighting	142
		PIL-1	143
		PIL-2	136
		CIL	141
		PIL-1R**	145
Main	Entrance	Daylight	123
		No Lighting	127
		PIL-1	146
		PIL-2	140
		CIL	149
		PIL-1R	134

*Good observations: 10%-20% of the data was discarded because of system malfunctions, temporarily bad switches, and other anomalies.

**40-ft mounting heights.

Manual Analyses

Table 3 presents the frequency of high-beam use by study condition for the exit and the entrance. As expected, the frequencies increased as the illumination decreased from daylight to CIL to PIL to no lighting.

The data on brakers was derived in two ways. For the exit, only VTMS-recorded lead cars were classified as either brakers or nonbrakers. For the entrance (because of initial observer placement problems), all lead cars were classified as either brakers or nonbrakers (on nights other than those when the VTMS was used). The type of data collected at the exit is a subset of the type collected at the entrance (it consisted of 75 percent of the early-night volume and up to 95 percent to 100 percent of the late-night volume).

Table 4 presents the braker data for the entrance and the exit. Again, as the lighting decreased, the percentage of occurrence of brake activations increased.

Table 3. High-beam use—pilot site.

Study Condition	Frequency of Use (%)	
	Exit	Entrance
Daylight	0	0
CIL	0	1.8
PIL-4	2.4	8.9
PIL-2	4.2	5.4
No lighting	5.8	12.6

The braker data were further classified by time period: early (8 to 11 p.m.) and late (1 to 5 a.m.) corresponding to higher and lower than average (for 8 p.m. to 5 a.m. period) volumes. It was found that the frequency of brakers normally increased during higher volumes and decreased during lower volumes (for the four night conditions), indicating that the effect of increased traffic volume is an increase in the frequency of brakers.

Attempts to observe and record gore and shoulder encroachments manually were unsuccessful under the PIL and no-lighting conditions because the gore markings could not be seen by the observers under these conditions. These data were instead analyzed from the VTMS data.

Computer Analyses

The vehicle trajectory data (time in milliseconds at which the front wheels of each vehicle encountered each switch) were manually transcribed onto coded data reduction forms, then keyed to a disk file. Preliminary data screening was accomplished during the transcription process to remove those data records with gross errors.

A computer program was developed to perform four different operations: error checks; individual record calculations (for each vehicle); pooled data calculations (for each location for each study condition); and summary statistics (for each study condition). These operations are described below.

1. Error Checks/Reconstruction

- Data screening for miscodings or logical errors and reasonableness tests to identify times that are excessively out of range (e.g., a time of 5 s between two switches when the average time between preceding switches is only 1 s).
- Reconstruction of time profiles when one or more switches were temporarily out of operation.

2. Individual Record Calculations

- Compute spot speed across each pair of switches and averge speed between consecutive individual switches or pairs for each record.
- Compute spot acceleration from consecutive spot speed and average accelerations from consecutive average speeds for each record.
- Compute average acceleration noise from consecutive average accelerations.
- Compute individual diverge or merge points for each vehicle traversing the exit or entrance ramp and identify unusual or dangerous exit points from the system—both exit and entrance (i.e., a record in which the first switch hit was located downstream of the beginning of the gore on the exit ramp, or before the point of the gore or entrance ramp; these are equivalent to gore and shoulder encroachments).

3. Pooled Data Calculations

- Compute means of spot speeds and frequencies of switch hits across each pair of switches and compute means of average speeds and frequencies between consecutive switches or pairs for each study condition.

Table 4. Brakelight data—pilot site.

Study Condition	Frequency of Use (%)	
	Exit	Entrance
Daylight	40.1	74.0
CIL	45.0	73.2
PIL-4	49.1	85.9
PIL-2	48.5	84.8
No lighting	52.2	86.8

- Compute means of spot accelerations and frequencies between consecutive pairs of switches and compute means of average accelerations across three consecutive pairs of individual switches for each study condition.
- Compute means of average acceleration noises across four consecutive switches or pairs for each study condition.
- Compute mean diverge (merge) speeds and frequencies at each diverge (merge) point for all study conditions for exit (entrance) ramp.
- Compute frequencies and locations of unusual exit points for all study conditions.

4. Summary Statistics

- Number of records, accepted records, and errors (rejected data).
- Number of cars and trucks.

Eight sets of data were output by the computer program for each study condition:

1. Average velocity by location by study condition.
2. Average acceleration by location by study condition.
3. Average acceleration noise by location by study condition.
4. Spot velocity by location by study condition.
5. Spot acceleration by location by study condition.
6. Average diverge velocity (exit) and merge velocity (entrance) by location by study condition.
7. Distribution of diverging patterns (for exit) and merging patterns (for entrance).
8. Frequencies of unusual (dangerous) existing vehicles from the VTMS system (equivalent to gore and shoulder encroachments).

It was hypothesized that as the lighting conditions changed, a systematic, measurable change in velocity, acceleration, and acceleration noise would be noticed. This proved to be false. All three of these variables, whether computed as average values between switch locations or as spot values at switch pairs, proved to be insensitive to the changes in the independent variable. Although certain differences were found (e.g., day velocities higher than night velocities and night no-lighting velocities greater than all of the night lighting velocities), these differences were quite small (e.g., 1 to 3 ft/s) and did not distinguish between CIL and PIL lighting conditions. (Although the increase in brake use as lighting was reduced from CIL to PIL to no lighting should reduce velocities (and result in more deceleration), this was not shown to be true. This partial inconsistency in the data is explainable. The great majority of the braking was observed to occur upstream of the first tapeswitch. Thus the measurement of velocity occurred after the observation of brakelights. Without knowing the velocities of the vehicles before brakelight activations it is impossible to determine the effect of the braking on the velocities. The 1 to 3-ft/s difference may result only from normal velocity variations between different data collection nights.)

Table 5 summarizes the diverging/merging patterns for the exit and entrance. It is evident from the data that at the exit drivers diverge later (i.e., farther downstream past the first switch) under PIL conditions than under the CIL condition, and at the entrance they merge earlier (further upstream before the last switch) under the PIL conditions than under the CIL condition.

Unusual exiters, defined as drivers who left the VTMS system after the gore (for the exit) or before the gore (for the entrance), either crossed the gore into the main stream of traffic or encroached on the left shoulder. Either condition would be indicated by a VTMS output which stopped after the last contacted switch.

Table 6 summarizes the frequencies of these unusual exiters for both the exit and entrance ramps. Again, the frequencies under the PIL conditions are higher than under the CIL condition.

Table 7 summarizes the results for the four maneuvers (high beams, brakers, unusual exiters, and diverge/merge patterns). For each of the four variables, CIL is better than PIL for both the exit ramp and the entrance ramp. In four of the eight study conditions (three of four for entrance; one of four for exit) PIL-2 is better than PIL-4. The reverse is true in the other four conditions.

CIL performs better than no lighting in seven of the eight comparisons (not merge, which is very dependent on traffic volumes). PIL performs better than no lighting in only five of the eight comparisons (brakers, exit and entrance; high beams, exit and entrance; and diverging patterns). This is summarized in Table 8.

Table 5. Diverging/merging patterns—pilot site.

Study Condition	Frequency (%)	
	Exit (diverging late)	Entrance (merging early)
Daylight	51.0	37.5
CIL	20.0	36.2
PIL-4	25.5	47.7
PIL-2	26.1	47.2
No lighting	26.9	26.1

Table 6. Unusual exiters—pilot site.

Study Condition	Frequency (%)	
	Exit	Entrance
Daylight	3.9	1.7
CIL	4.8	1.3
PIL-4	8.5	10.4
PIL-2	6.0	9.6
No lighting	4.3	2.8

Table 7. Summary of pilot study results—CIL versus PIL.

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	Increases with each decrease in lighting (CIL-PIL-4-PIL-2-0). (0.01)**	Increases as lighting decreases (CIL-PIL-0; reversal in PIL cases)*** (0.01)
Frequency of brakers	Increases as lighting decreases (Day-CIL-PIL-0; PIL cases the same) (NS)	Increases as lighting decreases (Day-CIL-PIL-0; reversal in PIL cases)*** (0.05)
Frequency of unusual exiters (gore and shoulder encroachments)	Increases as lighting decreases (Day-CIL-PIL-0; reversal in PIL cases)*** (0.01)	Increases as lighting decreases (CIL-PIL-0; reversal in PIL cases)*** (0.01)
Diverge/merge patterns	Drivers diverge later under PIL than under CIL (0.01)	Drivers merge earlier under PIL than under CIL (0.01)

*Quantitative comparisons for the four measures are indicated by combining the data in Tables 3, 4, 5 and 6, respectively, with the data in Table 2.

**Level of statistical significance for t-test of percent under CIL versus percent under PIL (2 and 4 combined).

***PIL-2 better than PIL-4.

Additional comparisons revealed significantly better performance during daylight than at night (five of six comparisons) and better performance under lighting (CIL plus PIL) than no lighting in only five of eight comparisons.

Based on the analyses performed on the four types of data, it appears that driver performance under CIL is significantly better than under either of the PIL conditions. The frequency of the erratic behavior measures all increase under PIL in comparison to CIL and frequently decrease again under the no-lighting condition. In addition, driver performance under PIL-2 is often superior to that under PIL-4 (see, for example, Table 7 entries with symbol ***).

It was suspected that drivers experience transitional visibility problems under the PIL lighting conditions when they are forced to drive from dark to light to dark areas and at the same time perform a relatively complex maneuver: diverge/merge plus track a 90° curve. The problem is more difficult under the PIL-4 condition, when the lighted area is about 550 ft long (8 s at 70 ft/s) than under PIL-2, when the lighted area is only 180 ft long (2.5 s). Photometric measurements were made to try to explain these suspected conclusions.

Photometric Analyses

Photometric measurements were made at the exit ramp of the PA Turnpike site under two lighting conditions—PIL-2 and CIL—to investigate differences in illumination and luminance that may help to explain some of the operational measures (e.g., early exit/entrance, gore/shoulder encroachments, brake activations).

Illumination was measured with a spectra illuminance meter every 20 ft in the center of both the right lane and exit ramp over three cycles for CIL or from ambient (i.e., Eh = 0) to ambient through the illuminated section.

Luminances, consisting of target, pavement (two measures), and glare, were measured with a 1980 Pritchard Telephotometer following CIE recommended procedures. The effect of vehicle headlights on either illuminance or luminance was excluded.

Four measurement positions were selected:

A. Motorist view of the beginning of the deceleration ramp.
B. Upstream of the gore, in the deceleration ramp.
C. At the gore.
D. In the curved ramp.

These positions corresponded to the four tasks:

A. Locating the beginning of the deceleration ramp.
B. Traversing (i.e., negotiating) the deceleration ramp.
C. Locating the gore.
D. Traversing the curved ramp.

The average illuminance over three cycles of fully illuminated roadway (i.e., CIL) was relatively constant, ranging from 0.62 to 1.01 fc. The average over the three cycles was 0.82 fc. Additional measurements are given in Table 9. For PIL the illuminance ranged from 0 (where there were no lights operating) up to 0.8 fc in the illuminated area, with an average of 0.21 fc (average illuminance at the four target positions).

Table 8. Summary of pilot study results—lighting versus no lighting.

CIL versus no lighting

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	Lower under CIL (0.01)**	Lower under CIL (0.01)
Frequency of brakers	Lower under CIL (NS)	Lower under CIL (0.05)
Frequency of unusual exiters	Higher under CIL (NS)	Lower under CIL (0.01)
Diverge/merge patterns	Better under CIL (0.01)	Better under no lighting (0.01)

PIL versus no lighting

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	Lower under PIL (NS)	Lower under PIL (NS)
Frequency of brakers	Lower under PIL (NS)	Lower under PIL (NS)
Frequency of unusual exiters	Higher under PIL (0.01)	Higher under PIL (0.01)
Diverge/merge patterns	Better under PIL (NS)	Better under no lighting (0.01)

*See footnote * of Table 7.
**See footnote ** of Table 7.

Table 9. Illumination measurements—pilot site exit ramp.

Variable	Lighting Condition					
	CIL		PIL-4		PIL-2	
	Ramp	Rt. Lane	Ramp	Rt. Lane	Ramp	Rt. Lane
Average Illumination (PIL-2 cycle) (A)	0.73	1.03	0.77	1.10	0.80	1.08
Maximum Illumination (M)	1.90	2.10	2.05	2.35	2.17	2.35
Minimum Illumination (m)	0.12	0.61	0.11	0.61	0.12	0.58
M/A	2.60	2.04	2.66	2.14	2.71	2.17
A/m	6.08	1.84	7.00	1.80	6.67	1.86
M/m	15.83	3.75	18.64	3.85	18.08	4.05
Average Illumination (four target positions)	0.80	*	*	*	0.21	*

*Not measured

Table 10 summarizes the luminance measurements at the four target positions for both of the lighting conditions. The average pavement luminance (Lav) for the CIL condition was relatively constant from the beginning of the deceleration ramp through the gore, dropping slightly in the ramp itself, as expected. (The luminaires in the ramp are 150 W versus 250 W on the main road.) For the PIL case, average luminance was nearly 0 (≤ 0.03 fL) except in the lit area where it was the same as under the CIL condition, as expected. Target luminance, glare, and pavement luminance (Lb) all varied considerably for PIL (Lt and Lb varied by over 100:1, Lv by 15:1) but less so for CIL (2:1 for Lt and Lb, 5:1 for Lv) again as expected.

Figures 8 through 11 graph Lb, Lav, Lv, and VI, respectively, for the two lighting conditions. For all four measures, all the luminances (and visibility) under CIL are greater than those under PIL. Also, Lb and Lav follow very similar patterns for both CIL and PIL. Both of these results were expected.

The average (over the four measurement points) of each of the four variables in Figures 8 through 11 for the CIL conditions is greater than the average for the PIL conditions. The ratios of CIL to PIL range from a low of 2.8:1 for visibility to a high of 6:1 for glare.

To check on the precision of the photometric measurements, the ratios of CIL to PIL were compared for the three measurements Lb, La, and Eh. Since the only difference between Lb and Lav is the area measured by the photometer and both differ from Eh predominantly by a (constant) scale factor (pavement reflectance), all three ratios should be similar. This was found to be true, as indicated by the data in Table 11.

From the previous data the following can be observed:

- Average pavement luminance is approximately 4 times higher under CIL than under PIL (using either Lb or Lav).
- Average glare is 6 times higher under CIL than under PIL.
- Average visibility is approximately 3 times higher under CIL than under PIL.
- At the beginning of the deceleration ramp, pavement luminance under CIL is 12 (Lav)-20 (Lb) times higher than under PIL, while visibility is almost 11 times higher under CIL.
- In the center of the deceleration ramp, pavement luminance under CIL is 6 times higher than under PIL (either Lb or Lav), while visibility is about 3 times higher.
- At the gore, pavement luminances and visibility are the same under CIL as under PIL. (This is, of course, expected because this is the only area of roadway illuminated by the PIL system.)
- On the ramp itself, pavement luminances are about 165 times higher under CIL than under PIL, while visibility is 8 times higher under CIL.

Table 10. Luminance measurements—pilot site exit ramp.

Location	Luminance Measurements				
(PIL-2)	Lt	Lb	Lv	VI	Lav
A	0.0170	0.0110	0.0500	0.53	0.0220
B	0.0189	0.0287	0.0560	0.76	0.0304
C	0.1690	0.1220	0.0840	2.64	0.2000
D	0.0010	0.0008	0.0015	0.11	0.0009
(CIL)					
A	0.1050	0.2260	0.0910	5.58	0.2700
B	0.1190	0.1743	0.4610	1.78	0.2150
C	0.2410	0.1475	0.4750	3.06	0.2030
D	0.1530	0.1345	0.1640	0.86	0.1488

Except for the area of roadway directly around the gore (where the PIL luminaires are located), the CIL system provides much better photometric properties (except for glare). Even with the high-glare luminances, the visibility under CIL at all three of these locations is clearly superior to that provided by the PIL lighting system. In the local area around the gore, the performance of both systems is quite similar (defined in terms of Eh, Lb, Lav, and VI).

Of the five dependent traffic operational measures—late divergence, gore encroachments, shoulder encroachments, brake activations, and high-beam use—three can be related to the visibility at one unique target position. The cues for divergence occur upstream of the deceleration ramp, at about target position A. Gore encroachments occur because of inadequate visibility at position C, and shoulder encroachments occur because of poor visibility at position D. The last two measures—brake activations and high-beam use—occur throughout the exit area and were not isolated by location in the pilot study.

Late divergence was 30 percent higher for PIL than for CIL (26 percent versus 20 percent of traffic). The visibility at target positions A is 11 times higher under CIL.

Gore encroachments occur at position C where the visibility under PIL and CIL is approximately the same. The frequencies of gore encroachments (1.0 percent for PIL and 0 percent for CIL) were too small to be statistically compared.

The visibility at location D was 8 times higher under CIL than under PIL, but both had visibility under 1.0. The measurements were made on a curved section of roadway (the ramp) and may not be as precise as those measurements made at the other points. The frequency of shoulder encroachments for CIL and PIL were 4.0 percent and 4.1 percent, respectively.

Although the visibility (and pavement luminances) provided by the CIL system was superior to those provided by the PIL system, the relationships between these measurements and the traffic operational measures provide little if any additional indication as to why CIL is superior other than there is more light (illuminance or luminance). This was known before the photometric measurements were taken. No systematic relationship was found (e.g., VI, Lb, or Lav increases by X percent, yielding an increase in traffic operational measure performance of Y percent).

Simple illuminance measurements will probably provide sufficient data to determine the average ratio of flux between any two lighting conditions (and hence the average ratio between pavement luminances is known).

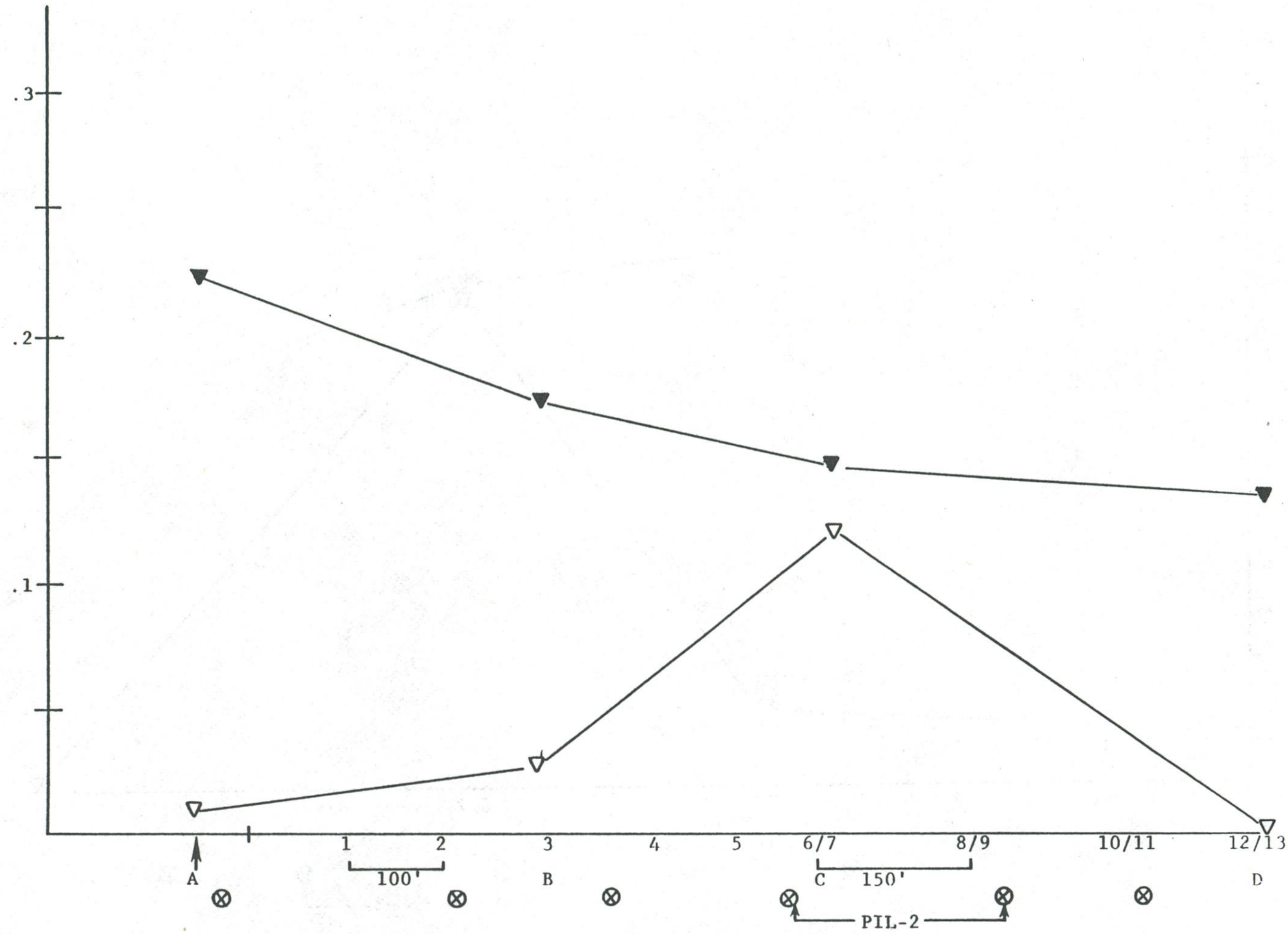

Figure 8. Pavement luminance (Lb)—pilot site.

Table 11. Comparative measurements for Lav, Lb, and Eh—pilot site.

	PIL	CIL	CIL/PIL
$\overline{Lav}$*	0.06	0.21	3.5
$\overline{Lb}$*	0.04	0.17	4.3
Eh	0.212**	0.82***	3.9

*Average of four target positions.

**Average illuminance measured from ambient (i.e., 0) to ambient through illuminated area. At four target positions average illuminance is 0, 0.05, 0.80, and 0.

***Average of three cycles (1.01, 0.62, 0.83).

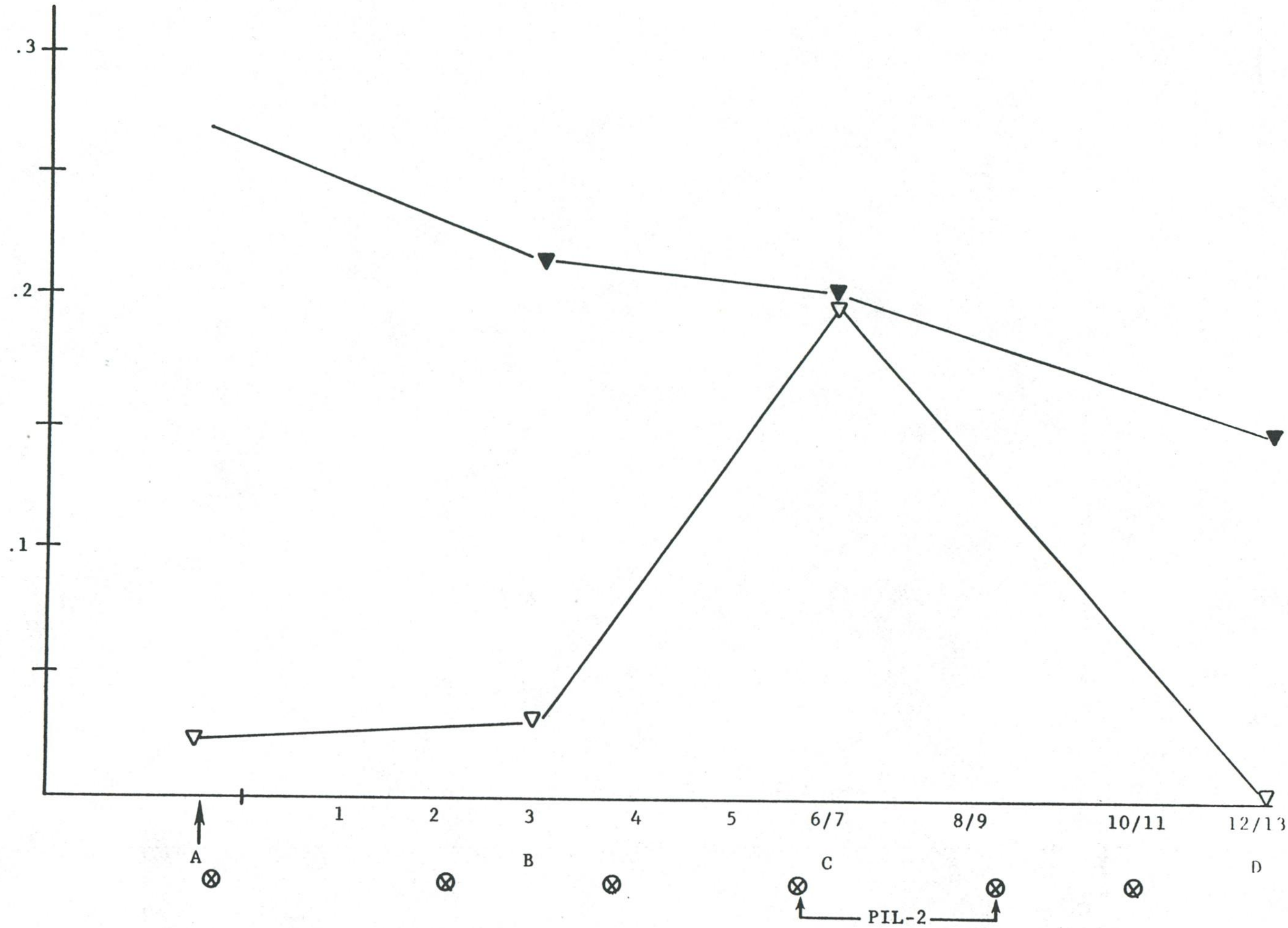

Figure 9. Pavement luminance (Lav)—pilot site.

Main Site

The data analysis for the main site followed the same outline as for the pilot site except that all analyses, except of course the photometrics, were accomplished using the computer program of the pilot study, modified to expand its versatility. The computer analyses included frequency and location of high-beam use, frequency and location of braking, frequency of gore encroachments, frequency and location of shoulder encroachments, merging and diverging behavior, velocity profiles, acceleration profiles, and merging and diverging velocities.

High Beams

There was infrequent use of high beams at the main site. At the entrance ramp the frequencies were higher under the three PIL conditions and under the no-lighting condition than under CIL. At the exit ramp the frequencies were 0 at three of the night conditions, so no trends were identified. The data are summarized in Table 12.

Table 12. High-beam use—main site.

Study Condition	Frequency of Use (%)	
	Exit	Entrance
Daylight	0	0
CIL	0	0.6
PIL-2	0.7	3.6
PIL-1	0	4.1
PIL-1R	0	2.9
No lighting	4.2	2.3

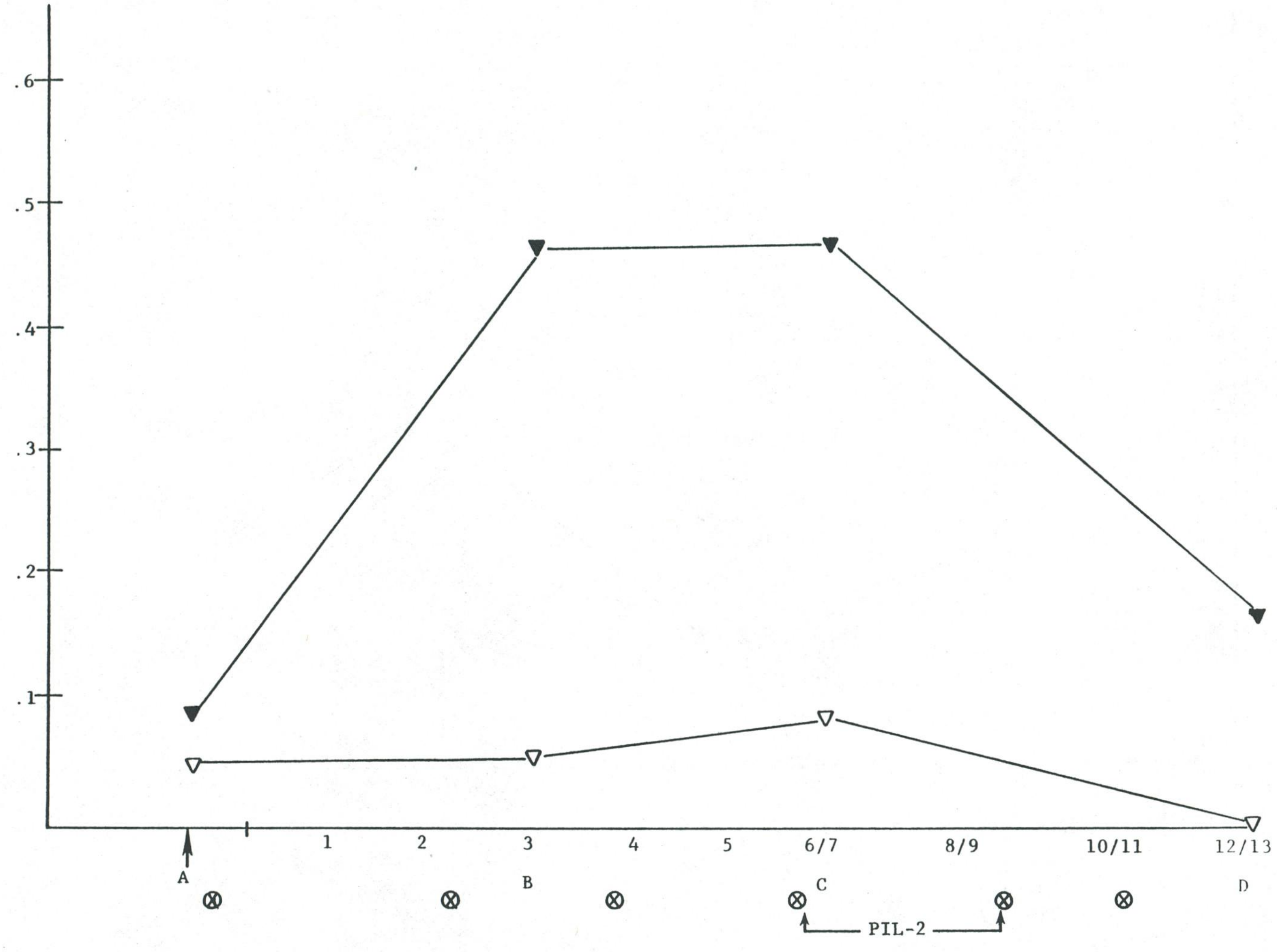

Figure 10. Glare (Lv)—pilot site.

Because of the relatively low frequencies of high-beam use, no analysis of frequency by location was made.

Brakelights

The frequencies of brakelight activations were quite high, ranging up to 99 percent for the exit and up to 52 percent for the entrance. For the exit there was a definite increase in the frequency of brakelight activations as the lighting was reduced from CIL to PIL-2 to PIL-1 (either condition) to no lighting. For the entrance the frequencies were 2 to 2.5 times higher under PIL and no lighting than under CIL. The data are summarized in Table 13.

The brakelight data were further analyzed by location to derive mean braking distance from the first switch. The data for the exit revealed a general increase in this distance as the lighting decreased from CIL to PIL-2 to PIL-1 to no lighting.

For the entrance the mean braking distance under CIL was downstream of the first switch. For all three PIL conditions and the no-lighting condition, the mean distance was at or upstream of the first switch. The data are summarized in Table 14.

Table 13. Brakelight data—main site.

Study Condition	Frequency of Use	
	Exit	Entrance
Daylight	97.0	28.5
CIL	88.7	20.1
PIL-2	89.7	48.6
PIL-1	95.1	41.8
PIL-1R	96.6	50.0
No lighting	99.3	52.0

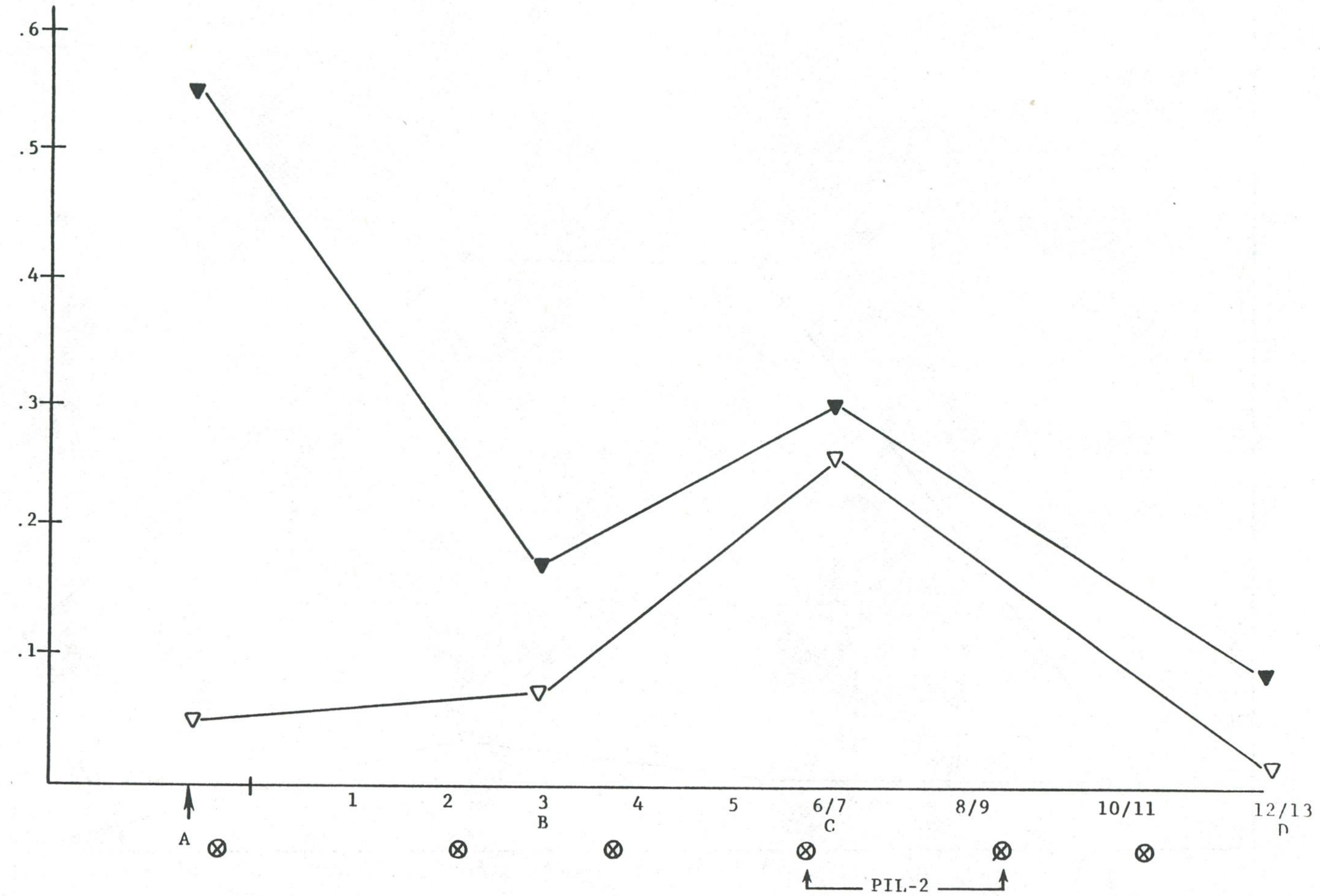

Figure 11. Visibility (VI)—Pilot site.

Table 14. Mean braking distance—main site.

Study Condition	Mean Braking Distance (ft)*	
	Exit	Entrance
Daylight	186.1	110.6
CIL	152.9	65.4
PIL-2	169.3	-23.5
PIL-1	239.4	-9.8
PIL-1R	173.8	0.4
No lighting	247.9	-3.4

*From first Tapeswitch.

Graphs of the frequencies of brakelight occurrences by location on the ramp were developed from the raw data and indicated generally normal-shaped curves with little difference for the exits (similar peaks and shapes). For the entrance, the PIL and no-lighting conditions had distinctly different peaks (modes) from the CIL and daylight curves, the former with modes nearly 100 ft upstream of the first switch, the latter with modes about 50 ft downstream of the first switch. This agrees with the analyses of mean braking distances given in Table 14.

Gore Encroachments

Two types of gore encroachments were considered: those resulting from a conflict with another vehicle (i.e., the driver was impeded by a vehicle in an adjacent lane) and nonconflicting gore encroachments. The first type was related to traffic volume rather than lighting and was not analyzed. The second type did not occur (i.e., frequencies were always 0).

Shoulder Encroachments

The frequencies of shoulder encroachment did not follow a consistent pattern, as indicated in Table 15. There was some indication of a greater number of such encroachments during higher visibility conditions (e.g., day or CIL) than under lower visibility conditions (no lighting or PIL), primarily for the exit ramp, but the sample sizes were too small to be meaningfully analyzed.

Merge/Diverge Points

At night, the mean point of divergence from the main line of traffic to the exit (and the mean point of merging from the entrance to the main line) appeared to increase as the lighting decreased. The data are summarized in Table 16. For the exit, the distance downstream of the gore at which diverging occurred under CIL was about 20 percent less (28 ft) than under no lighting and 10 percent less (16 ft) than under PIL (average of three conditions). For the entrance, the merging point under CIL was 11 percent less (32 ft) than under no lighting and 10 percent less (29 ft) than under PIL. These distances are equivalent to about 0.5 s at highway speeds.

Unlike the pilot site, where merging was relatively unconstrained (i.e., the entrance ramp/acceleration ramp continued for a few thousand feet and drivers could merge almost at their leisure), the main site required merging within about 500 ft (the length of the acceleration/weave lane). Thus a decrease in merge distance was considered better from a traffic operational standpoint for the main site.

Average Velocity

Although average velocity was not found to discriminate between study conditions in the pilot study, it was analyzed for the main site because of its theoretical importance. For the exit ramp, all six study conditions had average velocity profiles (i.e., average velocity across the entire ramp) that were almost identical. Differences between study conditions were never more than a few feet per second, and these were not consistent (i.e., the plots crossed rather than remaining distinctly apart).

For the entrance ramp, the velocity profiles were identical through the first 400 ft of the ramp (± 1 ft/s) and then began to differ slightly at the merge point, with the velocities for the three PIL conditions somewhat higher than the CIL, no-lighting, and daylight conditions.

Average Acceleration

For the exit, the plots of average acceleration profiles were almost identical except that the CIL and daylight conditions had slightly higher peaks (maximum decelerations), and all of the PIL conditions and the no-lighting conditions were tightly grouped (i.e., very similar).

For the entrance, distributions were similar but not identical (i.e., the graphs crossed). They differed, with no fixed pattern, as drivers began to merge into the main traffic lanes. Maximum acceleration did not differ by more than 0.5 ft/sec^2.

Table 15. Shoulder encroachments—main site.

Study Condition	Frequency (%)	
	Exit	Entrance
Daylight	14.8	5.7
CIL	9.2	4.9
PIL-2	5.6	5.7
PIL-1	5.6	4.8
PIL-1R	2.7	2.9
No lighting	6.3	2.3

Table 16. Diverging/merging patterns—main site.

Study Condition	Mean Distance From Gore (ft)	
	Exit	Entrance
Daylight	135.2	258.1
CIL	144.1	249.0
PIL-2	136.7	228.5
PIL-1	156.7	254.5
PIL-1R	169.7	273.2
No lighting	172.0	281.0

Summary

Table 17 summarizes the results of the previous analyses. Of the seven comparisons, four indicate that CIL is better than PIL, two reveal nothing, and one seems to indicate that PIL was better than CIL at the exit, although there were small sample sizes.

CIL performs better than no lighting in 8 of 10 comparisons, and PIL performs better than no lighting in 7 of 10 comparisons. This is summarized in Table 18.

The traffic operations at both the pilot and main site responsed similarly to the changes in lighting from CIL to PIL. Of the five common measures (brakers, high beams, encroachments, merge/diverge, and velocity/acceleration), three revealed that CIL performed better than PIL at both interchanges, one was unaffected by lighting, and one revealed that CIL performed better than PIL at only the pilot site. These comparative data are given in Table 19.

Table 17. Summary of main study results.

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	No effect (NS)	Frequency greater under PIL than under CIL (NS)
Frequency of brakers	Increases with each decrease in lighting (0.05)**	Frequency greater under PIL than under CIL (0.01)
Mean braking distance	Increases as lighting decreases	Greater under CIL than under PIL
Gore/shoulder encroachments	Shoulder encroachments somewhat higher under CIL (small samples) (NS)	No effect (NS)
Diverge/merge patterns	Diverge later under PIL	Merge later under PIL
Average velocity	No effect	No effect
Average acceleration	No effect	No effect

*Quantitative comparisons for the first five measures are indicated by combining the data in Tables 12, 13, 14, 15, and 16, respectively, with the data in Table 2.

**Level of statistical significance for t-test of percent under CIL versus percent under PIL (all PIL conditions combined).

Table 18. Summary of main study results—lighting versus no lighting.

CIL versus no lighting

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	Lower under CIL** (.01)***	Lower under CIL** (NS)
Frequency of brakers	Lower under CIL (0.01)	Lower under CIL (0.01)
Mean braking distance	Lower under CIL	Lower under CIL
Shoulder encroachments	Higher under CIL** (NS)	Higher under CIL** (NS)
Diverge/merge patterns	Better under CIL	Better under CIL

PIL versus no lighting

Measure	Result*	
	Exit	Entrance
Frequency of high-beam use	Lower under PIL** (.01)***	Higher under PIL** (NS)
Frequency of brakers	Lower under PIL (0.01)	Lower under PIL (NS)
Mean braking distance	Lower under PIL	Lower under PIL
Shoulder encroachments	Lower under PIL** (NS)	Higher under PIL** (NS)
Diverge/merge patterns	Better under PIL	Better under PIL

*Same as Table 17.
**Small sample.
***Level of significance.

Table 19. Comparison of pilot and main study results.

Measure	Result		Comment
	Pilot	Main	
Brakers	CIL better than PIL	CIL better than PIL	Similar results at both interchanges
High beams	CIL better than PIL	CIL better than PIL	Similar results at both interchanges
Gore/shoulder encroachments	CIL better than PIL	PIL marginally better than CIL (but not significant)	Differences may be attributed to higher volumes and more complex geometry
Merge/diverge	CIL better than PIL	CIL better than PIL	Similar results at both interchanges
Velocity/acceleration	No effect	No effect	Similar results at both interchanges

Photometric Analyses

Since the photometric measurements at the pilot site revealed no systematic relationships between these measures and driver performance (other than CIL being superior to PIL), photometry at the main site was restricted to measuring illuminance under all four lighted conditions and measuring pavement luminance and glare under the three PIL conditions. The intent of the measurements was primarily to document the differences in lighting quality resulting from the differences in mounting height.

Illuminance was measured every 20 ft in the center of the instrumented lane (see Fig. D-3) for all four lighted conditions. The data are given in Table 20. In the center cycle (around the PIL-1 luminaire), average illuminance was a relatively constant 2.0 fc for all three 30-ft mounting height systems, falling to 1.0 fc when the poles were raised to 40 ft. Average illuminance in the entire instrumented area was highest under CIL, falling, as expected, with each decrease in number of luminaires.

Luminances, both pavement and glare, were measured at three positions for each of the three PIL systems:

A. Motorist view of the deceleration/acceleration ramp (weave lane).

B. Motorist view of the diverge point.
C. Motorist view of the merge point.

The exact locations and procedures are described in Appendix D. Table 21 summarizes the luminance measurements.

As expected, pavement luminances (over three locations) dropped 45 percent when mounting height was increased (under PIL-1) and glare dropped by 37 percent. In comparison, the change from PIL-2 to PIL-1 caused a drop in average pavement luminance of only 17 percent and a drop in glare of only 17 percent.

The accuracy of the measurements was checked by comparing measured values with predicted ones. A change in mounting height from 30 ft to 40 ft should decrease the light flux at the surface by a factor of 9/16 since it is inversely proportional to the square of the distance (i.e., flux at 40 ft = 9/16 × flux at 30 ft). Table 22 compares the predicted with the actual measurements for illuminance and luminance. Excluding glare, the errors are less than 14 percent, which is reasonable for photometry on operating roadways.

Table 21. Luminance measurements—main site.

Location	Luminance Measurements	
	Lav	Lv
PIL-2		
A	0.9450	0.1528
B	1.2440	0.3780
C	0.8910	0.1103
PIL-1		
A	0.5130	0.1349
B	1.2140	0.3030
C	0.8480	0.0894
PIL-1R		
A	0.3640	0.0876
B	0.4490	0.2140
C	0.4880	0.0463

Table 20. Illumination measurements—main site entrance ramp.

Variable	Lighting Condition			
	CIL	PIL-2	PIL-1	PIL-1R
Average illumination (PIL-1 cycle) (A)	2.02	2.01	1.96	0.95
Maximum illumination (M)	5.60	6.00	5.60	2.04
Minimum illumination (m)	0.15	0.10	0.05	0.10
M/A	2.77	2.99	2.86	2.15
A/m	13.47	20.10	39.20	9.50
M/m	37.33	60.00	112.00	20.4
Average illumination (instrumented area)--exit and entrance ramps	1.76	1.23	0.69	0.35

Table 22. Comparison of measured and predicted illumination and luminance.

	Measured (PIL-1R)	Predicted (PIL-1 x 9/16)	Error (%)
Average illumination over PIL-1 cycle	0.95	1.10	0.15 fc (14)
Average illumination over instrumented section	0.35	0.39	0.04 fc (10)
Average pavement luminance over three positions	0.43	0.48	0.05 fL (10)
Average glare luminance over three positions	0.12	0.10	0.02 fL (20)

CHAPTER THREE

INTERPRETATION AND APPLICATION

In this chapter the results of the two field experiments are synthesized and interpreted to define the relative effectiveness of complete lighting, partial lighting, and no lighting for freeway interchanges.

COMPLETE VERSUS PARTIAL LIGHTING

Traffic Operational Measures

Both field experiments indicated that CIL provides a better traffic operating environment than does PIL. This improvement in traffic operations is defined in terms of frequency of brake activations, location of braking, frequency of use of high beams, frequency of gore and shoulder encroachments, and diverging and merging patterns.

The key dependent measure was the frequency of brake activations. This measure, which is dependent on the visual quality in the interchange area and is directly related to both the safety and the smoothness of traffic flow in the interchange area, showed a significant increase as the lighting was reduced from CIL to PIL. In addition, the location of the brake activations was negatively shifted when the lighting was reduced from CIL to PIL.

The use of high beams, indicative of driver uncertainty caused by inadequate visibility, increased as the lighting was reduced from CIL to PIL on three of the four ramps.

The merging and diverging patterns, which directly relate to the smoothness of traffic flow, also worsened as the lighting was reduced from CIL to PIL. The later divergence at the exit and earlier merging at the entrance under PIL conditions are probably indicative of uncertainty concerning the location of the ramps. The changes in distance at which diverging and merging occurred are probably indicative of better visibility under CIL, which allowed drivers to see the exit ramp or main lanes more easily and thus diverge or merge sooner.

The frequencies of gore and shoulder encroachments, which are indicative of erratic behavior, increased slightly on the simpler interchange as the lighting was reduced from CIL to PIL. A mixed effect was found on the cloverleaf interchange.

Average velocities and accelerations, which are directly related to the smoothness of traffic flow in the interchange, were not affected by the changes in visual quality from CIL to PIL.

Table 23 summarizes the implications of the above interpretations and their limitations.

Photometric Measurements

Illuminance, target luminance, and pavement luminance were all higher under CIL than under PIL. Glare was higher under CIL than under PIL, but visibility, which combines pavement luminance, target luminance, and glare, was higher under CIL than under PIL.

As expected, illuminance, pavement luminance, and visibility all increased as the number of luminaires per ramp increased. No systematic relationships were found between any of the photometric variables and any of the traffic operational measures other than gross descriptive ones that define the number of luminaires per ramp.

LIGHTING VERSUS NO LIGHTING

Both field experiments indicated that any interchange lighting normally performs better than no lighting, although the differences are not always as great as between CIL and PIL. These improvements in traffic operations are defined in terms of frequency and location of brake applications, frequency of use of high beams, frequency of gore and shoulder encroachments, and diverging and merging patterns.

The results, and their implications, are similar to those described in the preceding section. They are summarized in Table 24.

APPLICATION OF RESULTS

The results of both experiments indicate that CIL performs better than either no lighting or partial lighting consisting of one, two, or four luminaires per ramp. In addition, lighting, whether complete or partial, normally performs better than no lighting.

Before applying the results of this study to the selection or modification of freeway interchange lighting systems, the following limitations of this study must be considered:

1. Only two interchanges were studied, one with a weaving lane and one without.
2. Only four ramps of two different types were studied—two exit and two entrance.
3. Four different PIL systems were evaluated: two with one luminaire, one with two luminaires, and one with four luminaires.
4. It was impossible to accurately determine the effect of traffic volume, other than high versus low (i.e., early night versus late night).
5. No high-quality accident data were available for comparative analyses (e.g., between PIL and CIL systems).
6. The effect of lighting on traffic operations is small in comparison to other factors such as interchange geometry. An improvement in the latter would have a much more positive effect on traffic operations than any lighting improvement.

If a choice must be made to install new lighting, and economics are not the overriding issue, then a CIL system is preferred. If cost is an important factor, a PIL system with one or two luminaires per ramp will normally perform better than no lighting (but not nearly as well as CIL) at far lower cost than a CIL system.

There are insufficient data to recommend a change in existing lighting warrants. Although our results demonstrate the superiority of CIL over PIL, safety, economics, energy use and availability, local policies, and other factors will influence the selection of the type of interchange lighting system.

The results do indicate that existing CIL systems should not be reduced to PIL systems if traffic flow and safety, defined in terms of the dependent surrogate measures evaluated in this study, are important issues.

Although a major objective of this research was to develop specific (i.e., quantitative) recommendations regarding the effectiveness of CIL and PIL, such recommendations are difficult to make without adequate accident data related to CIL and PIL. In the absence of such accident data, only a summary of the changes in the surrogate measures can be provided. Therefore, Table 25 was developed by reanalyzing the data in Tables 3–6 and Tables 12–16 to show the changes in all four surrogate measures resulting from changing no lighting to PIL, no lighting to CIL, and PIL to CIL. Data are provided for both sites and for both exit and entrance ramps. In addition, the average changes (over the four measures) are presented for both the pilot and main sites.

The last two rows of Table 25 were derived by averaging each of the six columns of data for pilot and main site data conbined and combining the exit and entrance ramps together to derive three averages. Recognizing that averages are not necessarily ideal (some surrogate measures may be more important in representing safer and smoother traffic operations than others), averages are nonetheless shown in the table for general comparisons. The average effect of a change from no lighting to CIL is the greatest (5.8 percent), followed by a change from PIL to CIL (5.4 percent), and a change from no lighting to PIL (0.3 percent).

For the exit ramp the effect of a change from no lighting to PIL is one-half (2.3 percent) the effect of a change from no lighting to CIL (4.6 percent), but on the entrance the CIL far outperforms PIL (the latter being negative).

Table 23. CIL versus PIL—traffic operational implications.

Measure	Result	Implication	Limitation
Brake activations	Frequencies higher under PIL than under CIL	CIL performs better than PIL	None
Mean braking distance	Improved under CIL	CIL performs better than PIL	Only evaluated at the clover-leaf interchange
High-beam use	Frequencies higher under PIL than under CIL	CIL performs better than PIL	Except on the exit ramp of the clover-leaf interchange
Diverge/merge patterns	Improved under CIL	CIL performs better than PIL	None
Gore and shoulder encroachments	Frequencies higher under PIL than under CIL for three-leg interchange	CIL performs better than PIL	Only at three-leg interchange; not shown at cloverleaf
Velocity and acceleration	Not affected by lighting	None	None

Table 24. Lighting versus no lighting—traffic operational implications.

Measure	Result	Implication	Limitation
Brake activations	Frequencies higher under no lighting than either PIL or CIL	Lighting performs better than no lighting	None
Mean braking distance	Improved by lighting	Lighting performs better than no lighting	Only evaluated at cloverleaf interchange
High-beam use	Frequencies higher under no lighting than under CIL and higher under no lighting than PIL at three-leg interchange	Lighting performs better than no lighting	Except in comparison to PIL on clover-leaf inter-change
Diverge/merge patterns	Improved by lighting on three of four ramps	Lighting performs better than no lighting	Except at entrance ramp on three-leg interchange
Gore and shoulder encroachments	Mixed results	Unknown	Unknown
Velocity and acceleration	Not affected by lighting	None	None

Table 25. Quantitative effects of lighting on surrogate measures effect (change in percent).*

	From No Lighting To PIL		From No Lighting To CIL		From PIL to CIL	
Pilot Site	Exit	Entrance	Exit	Entrance	Exit	Entrance
High beams	2.5	5.4	5.8	10.8	3.3	5.4
Braking	3.4	1.4	2.2	13.6	3.8	12.2
Diverge/merge	1.1	-21.4	6.9	-10.1	5.8	11.3
Encroachments	-3.0	-7.2	-0.5	1.5	2.5	8.7
Average (four measures)	1.0	-5.5	4.9	4.0	4.0	9.4
Main Site						
High beams	4.0	-1.2	4.2	1.7	0.2	2.9
Braking	5.5	5.2	10.6	31.9	5.1	26.7
Diverge/merge**	3.5	5.9	5.6	6.4	2.1	0.5
Encroachments	1.7	-2.2	-2.9	-2.6	-4.6	-0.4
Average (four measures	3.6	1.9	4.4	10.0	0.7	7.4
Average of two sites	2.3	-1.8	4.6	7.0	2.4	8.4
Average (combination of exit and entrance	0.3		5.8		5.4	

*The entries in this table (except the diverge/merge values--see footnote **) were derived by subtracting the percentages found in Tables 3-6 and 12-16. For example, the entry in Row 1, Column 1 (pilot site, high beams, exit) was obtained by subtracting the high-beam percentage under PIL in Table 3 (exit) from the high-beam percentage under no lighting (5.8% - 3.3% = 2.5%). The PIL percentage is the average of the two PIL lighting conditions.

**These percentages were derived from Table 16 by dividing each entry by 500 ft (the length of the weaving lane) to yield percentage of weaving lane required to diverge or merge. These percentages were then analyzed (i.e., subtracted) to yield the entry in this table.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Based on the effect of the various lighting conditions on the dependent measures of traffic operations and driver behavior, the most important result of this study is that CIL provides a better traffic operating environment (i.e., performs better) than PIL or no lighting.

The design of the field experiments made it possible to strictly control—actually to fix—all variables other than lighting, so that the conclusions of this research are directly related to the lighting conditions. Only traffic volume could not be controlled, and the effects of this variable were minimized by collecting data under a wide range of traffic volumes for all study (i.e., lighting) conditions. Observational measurements were made from early evening, when traffic volumes were high, through early morning when traffic volumes were extremely low.

Since the geometry and environment of the two interchanges remained fixed, the effect on dependent measures of only the change in lighting was measured. The specific conclusions of this study are the following:

1. CIL systems perform better than PIL systems consisting of one, two, or four luminaires.
2. Either CIL or PIL normally performs better than no lighting.
3. PIL systems with fewer luminaires (one or two) frequently perform better than PIL systems with a greater number of luminaires (four).
4. There is a trade-off between cost and traffic operations and safety factors in the design of freeway interchange lighting systems.
5. Existing CIL systems should not be reduced to PIL systems if safety and traffic flow, defined in terms of the dependent measures, are important considerations.

RECOMMENDATIONS FOR FURTHER RESEARCH

A number of questions were unanswered in this research and should be addressed in further studies.

1. The economics of CIL versus PIL systems were not analyzed. A cost-effectiveness analysis which combines the effectiveness data from the present study with costs of CIL and PIL systems might provide valuable information to help the decision-maker determine better and more cost-effective lighting systems for freeway interchanges.
2. High-quality accident data related to type, quantity, and quality of freeway lighting systems were unavailable for analysis. Such data are collected by all states but are not coded properly for analyses that would reveal the effect of freeway interchange lighting on accident histories. Such data could be collected and, if combined with the first recommendation, would provide valuable information for both effectiveness and cost-effectiveness analyses of freeway interchange lighting.
3. The effectiveness and cost-effectivness of part-night lighting (e.g., CIL during high-volume periods, PIL during low-volume periods) should be investigated, especially as an economic and energy-saving technique.
4. It would be most desirous to reevaluate an interchange under CIL and PIL using the FHWA Traffic Evaluation System (which was unavailable for the present study) so that the effects of the lighting on traffic operations on the ramps, in the weave areas, and upstream and downstream of the interchange, could be studied. It is unknown whether the effect of interchange lighting extends out of the immediate interchange areas (where traffic operations were studied) and if so, how far and what the effects are. Similarly, all through traffic lanes should be instrumented and traffic operations measured on all through lanes.

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APPENDIX A

LITERATURE REVIEW

This appendix presents the results of a literature review covering the following subjects and their relationships to the objectives of this study: interchanges, lighting systems, measures of effectiveness, and experimental methods. The goal of this review was to attempt to reduce the number of variables to a more manageable quantity and to form a basis for the conduct of the remaining research.

INTERCHANGES

Design Types and Frequencies

The AASHTO Policy on Geometric Design of Highways (1) describes the various types of interchanges and their variations. However, they point out that there are only three principal types: cloverleaf, diamond, and directional.

In a California study (2) of 722 interchanges, the most frequent types were

Diamond	174 (24%)
Cloverleaf ramps (without col/dist*)	153 (21%)
(All cloverleaf ramps)	194 (26%)
Buttonhook ramps	129 (18%)
Loops (without col/dist)	116 (16%)

No other type comprised more than 6 percent of the total number of interchanges.

In the Interstate Accident Study (3), the most frequent types of interchanges were

*Collector/distributor

Full Diamond	681 (48%)
Partial Cloverleaf	191 (14%)
Full Cloverleaf	186 (13%)
Three-Leg/Trumpet	160 (11%)
Full Slip Ramp Diamond	96 (7%)
Half Diamond	94 (7%)

Similar results were found in a recent study by FHWA (4), but the data base used for this study was actually part of the Interstate Accident Records (ISAR) data base. All of these results emphasize the belief that diamond and cloverleaf are the most frequent types of interchanges.

Foody and Wray (5), in a study of the traffic operations and safety of cloverleaf interchanges, conducted a survey of 10 states to determine the number of cloverleaf interchanges. The data, however, provide no comparative information for other interchange types.

Although no additional nationwide surveys of total interchange designs were found in the literature, Loutzenheiser (6) conducted a nationwide survey of state practices in ramp design. The objective of this survey was to document the state of the art of ramp design in terms of the design variables of width, use of shoulders, throat, use of speed change lanes, surface type, etc. His findings illustrated averages and variations in these individual design parameters (e.g., lane widths 16 to 25 ft) but did not include the frequencies of such designs. Therefore, no real measure of "typicalness" is apparent, other than existing ranges on the variables.

Frequency is only one measure of importance. Others may include complexity (geometric and traffic) and accident experience.

Geometric and Traffic Complexity

Martin and Newman (7), in a California study, classified freeway interchange ramps by complexity of geometric characteristics (standard vs. multiple on/off-ramps; freeway merge; collector-distributor; parallel auxiliary lanes) and traffic characteristics (medium volume/high volume). Their general finding was that freeway ramp designs that offer the greatest flexibility (freedom of choice to driver) will result in smoother and more efficient operation.

The relatively less obvious implication of this study is that problems will occur under more complex situations, and that in these cases remedial treatments (such as lighting) are probably most beneficial.

Accident Experience

Lundy (2) analyzed the accident rates for 10 types of interchanges as illustrated in Table A-1. In general, his study showed that accident rates at on-ramps were consistently lower than those at off-ramps and that diamond and cloverleaf ramps (with col and/or dist) were the safest (lowest accident rate) and left side ramps and scissors the least safe. Cloverleafs without col/dist fell nearly in the center of the range. The findings of this study indicate that for a range of complexity, the diamond and cloverleaf types (both with and without col/dist) should be considered.

Table A-1. Accident rates in California.

Ramp Type	On	Off	On + Off
1. Diamond ramps	0.40	0.67	0.53
2. Trumpet ramps	0.84	0.85	0.85
3. Cloverleaf ramps without col/dist roads	0.72	0.95	0.84
4. Cloverleaf ramps with col/dist roads*	0.45	0.62	0.61
5. Loops without col/dist roads	0.78	0.88	0.83
6. Cloverleaf loops with col/dist roads*	0.38	0.40	0.69
7. Left side ramps	0.93	2.19	1.91
8. Direct connections	0.50	0.91	0.67
9. Buttonhook ramps	0.64	0.96	0.80
10. Scissors ramps	0.88	1.48	1.28
Average	0.59	0.95	0.79

*Only the On + Off rate includes the accidents occurring on the col/dist roads.

Source: Ref. 2.

In the Interstate Accident Study (3) a range of accident rates for interchanges from 0.25 to 1.69 accidents per million vehicle-miles was found as illustrated in Table A-2. These statistics are similar to the preceding ones reported for California. However, when accident experience for a 1-mile area of Interstate containing an interchange was studied, the full cloverleaf was found to be the safest of the full interchange designs and the half diamond the safest of the partial designs (and all designs). Also, for volumes less than 10,000 ADT the full diamond appeared safer than the partial cloverleaf (similar types of traffic movement), but the opposite was true at volumes greater than 10,000 ADT.

LIGHTING SYSTEMS

Warrants

The general purpose of lighting is to provide improved visibility for the various users of the roadway and associated facilities. For interchanges, the users are almost exclusively drivers. Warrants or justifications for lighting to meet this purpose have been published by FHWA (8), AASHTO (9), and NCHRP (10), among others.

The AASHTO warrants (9) are based on experience, and the objective is to identify those roadways which should be considered in the process of setting priorities for the allocation of available resources to roadway lighting. The primary emphasis is on Interstate-type freeways.

Table A-2. Accident rates.

Type	Accident Rate (per million vehicle miles)
Full Cloverleaf	1.69
Partial Cloverleaf	0.94
Three-leg	0.80
Diamond	1.02
Half Diamond	0.25
Full Slip Ramp Diamond	1.23

Source: Ref. 3.

The FHWA Informational Guide to Roadway Lighting (8) contains design criteria based on the AASHTO warrants which must be followed for federal-aid projects. For freeways they cover continuous freeway lighting, complete interchange lighting, partial interchange lighting, and special conditions (a realm of options). The principal considerations are traffic volume, interchange spacing, area development, area lighting conditions, and night-to-day accident ratios. The severity of visual information problems created as a result of specific geometric and operational conditions of the traffic facility are reflected in these principal considerations.

An analytic approach to roadway lighting warrants has been published by NCHRP (10). In this study, the justification of roadway lighting has been related to driver visual information needs. These needs are summarized in Table A-3. Characteristics of the traffic facility that contribute to each of the informational needs (Table A-4) were identified, and a quantitative measure (Table A-5 for interchange lighting) was developed by means of a numerical rating of each characteristic based on the extent to which the characteristic influences driver informational needs (e.g., wide lanes rate low (less critical] and narrow lanes rate high [more critical)). The characteristics themselves are also weighted (by magnitude of effect) as illustrated in Table A-4. Finally, the total number of points from Table A-5 indicates whether lighting (partial or complete) is warranted.

Table A-3. Visual information needs to be satisfied by fixed roadway lighting.

Noncontrolled Access Facilities	Controlled Access Facilities
Roadway geometry	Roadway geometry
Roadway surface	Roadway surface
Roadway objects	Roadway objects
Roadway edge	Roadway edge
Roadway markings	Roadway markings
Signs	Signs
Signals	Signals on crossroads
Delineation	Delineation
Intersection location	Intersection location
Channelization outline	Channelization outline
Access driveways	Curb locations
Shoulders	Shoulders
Roadside objects	Roadside objects
Curb locations	Vehicles on facility
Vehicles on facility	Vehicles on interchanging facilities
Exit, entrance, and crossing vehicles	Pedestrians
Pedestrians	Ramp entrances
Pedestrian crosswalks	Ramp exits
Sidewalks	Merge points
	On-ramp geometry
	Off-ramp geometry

Source: Ref. 10.

Table A-4. Traffic facility characteristics producing or contributing to visual information needs.

	Characteristics		
Type of Facility	Geometric	Operational	Environmental
Streets and Highways	Number of lanes Lane width Median openings Curb cuts Curves Grades Sight distance Parking lanes	Signals Left-turn signals and lanes Median width Operating speed Pedestrian traffic	Development Type of development Development setback Adjacent lighting Raised curb medians
Intersections	Number of legs Approach lane width Channelization Approach sight distance Grades on approach Curvature on approach Parking lanes	Operating speed on approach Type of control Channelization Level of service Pedestrian traffic	Development Type of development Adjacent lighting
Freeways and Expressways	Number of lanes Lane width Median width Shoulders Curves Slopes Grades Interchanges	Level of service	Development Development setback
Interchanges	Ramp types Channelization Frontage roads Lane width Median width Number of freeway lanes Main lane curves Grades Sight distance	Level of service	Development Development setback Crossroad lighting Freeway lighting

Source: Ref. 10.

Table A-5. Evaluation form for interchange lighting.

Classification Factor	Rating 1	2	3	4	5	Unlit Weight (A)	Lighted Weight (B)	Diff. (A-B)	Score [Rating X(A-B)]
Geometric Factors									
Ramp Types	Direct	Diamond	Button Hooks Cloverleafs	Trumpet	Scissors and Left-side	2.0	1.0	1.0	
Cross-Road Channelization	none		continuous		at interchange intersections	2.0	1.0	1.0	
Frontage Roads	none		one-way		two-way	1.5	1.0	0.5	
Freeway Lane Widths	> 12'	12'	11'	10'	< 10'	3.0	2.5	0.5	
Freeway Median Widths	> 40'	34-40'	12-24'	4-12'	< 4'	1.0	0.5	0.5	
No. Freeway Lanes	4 or less		6		8 or more	1.0	0.8	0.2	
Main Lane Curves	< 1/2'	1-2'	2-3'	3-4'	> 4'	13.0	5.0	8.0	
Grades	3%	3-3.9%	4-4.9%	5-6.9%	7% or more	3.2	2.8	0.4	
Sight Distance Cross Road Intersection	> 1000'	700-1000'	500-700'	400-500'	< 400'	2.0	1.8	0.2	
							Geometric Factors		
Operational Factors									
Level of Service (any dark hour)	A	B	C	D	E	6.0	1.0	5.0	
							Operational Factors		
Environmental Factors									
% Development	none	1 quad	2 quad	3 quad	4 quad	2.0	0.5	1.5	
Set-Back Distance	> 200'	150-200'	100-150'	50-100'	< 50'	0.5	0.3	0.2	
Cross-Road Approach Lighting	none		partial		complete	3.0	2.0	1.0	
Freeway Lighting	none		interchange only		continuous*	5.0	3.0	2.0	
							Environmental Factors		
Accidents									
Rate of Night-to-Day Accident Rates	< 1.0	1.0-1.2	1.2-1.5	1.5-2.0	> 2.0*	10.0	2.0	3.0	
							Accident Factors		

*Complete lighting warranted.

GEOMETRIC TOTAL = ______
OPERATIONAL TOTAL = ______
ENVIRONMENTAL TOTAL = ______
ACCIDENT TOTAL = ______
SUM = ______ POINTS

COMPLETE LIGHTING WARRANTING CONDITION = 90 points

PARTIAL LIGHTING WARRANTING CONDITION = 60 points

Source: Ref. 10.

A more complex lighting warrant based on an analytic model of driver informational needs has been developed by Walton and Messer (11). It can be summarized as

$$I = \frac{D \text{ (information demand)}}{C \text{ (information supply)}}$$

Roadway lighting is warranted if I>1.

All of the preceding warrants fail on one important point. They are not based on any proven empirical measure of effectiveness or need (e.g., behavioral measures, accident reduction, improved traffic operations). This will be further discussed subsequently.

Recommendations

Recommendations for roadway lighting (quantity and quality) are also available for the highway or lighting engineer (e.g., see Refs. 9 and 12). Unlike warrants, they provide design levels (normally in illuminance and uniformity) for different roadway situations. Tables A-6 and A-7 provide examples. The same problem exists as for warrants: no proven empirical relationship between recommended levels and measures of effectiveness or need. (The next version of the IES roadway lighting recommendations will be based, in part, on pavement luminance, with reference to visibility as an alternate standard. This is based largely on the work of Blackwell, Gallagher, and Janoff as well as Canadian and European standards. Some of this work will be discussed subsequently.) These lighting recommendations were established based on

Table A-6. Recommendations for roadway average maintained horizontal illumination.

Vehicular Roadway Classification	Commercial		Urban Intermediate		Residential	
	(fc)	(lux)	(fc)	(lux)	(fc)	(lux)
Freeway*	0.6	6	0.6	6	0.6	6
Expressway*	1.4	15	1.2	13	1.0	11
Major	2.0	22	1.4	15	1.0	11
Collector	1.2	13	0.9	10	0.6	6
Local	0.9	10	0.6	6	0.4	4
Alleys	0.6	6	0.4	4	0.4	4

Source: Ref. 12.

Note: The recommended illumination values shown are meaningful only when designed in conjunction with other elements. The most critical elements as described in this practice are illumination depreciation, quality, uniformity, luminaire mounting heights, spacing, transverse location of luminaires, luminaire selection, traffic conflict areas, border areas, transition lighting, alleys, and roadway lighting layouts.

*Both mainline and ramps.

Table A-7. Recommended roadway average-to-minimum uniformity ratios.

Type of Area	Recommended Ratios	
	IES/ANSI (2)	FHWA/AASHTO (3)
Commercial	3:1	4:1
Intermediate	3:1	4:1
Residential	6:1	6:1

Source: Ref. 12.

experience, severity of information problems (analytic research), and subjective and engineering judgments.

Effectiveness

The relationship between roadway lighting and effectiveness measures such as accident experience, traffic operations, crime, driver comfort, driver and pedestrian performance, and a host of other measures has been studied since the advent of lighting on roadways. The list of references in the area of roadway lighting and traffic accident experience alone would run to hundreds of entries. Researchers have attempted to display the benefits of roadway lighting with statistical methods ranging from simple before-after frequencies to sophisticated multiple regression techniques with dozens of factors.

Comprehensive literature reviews relating the quality and quantity of roadway lighting to traffic safety, traffic operations, crime, and other measures have been published by Janoff (13), Courage and Wolfe (14), Fisher (15), and others (16). The consensus of such reviews has been that although lighting appears effective as a countermeasure in reducing nighttime accidents, only generalized results are available. Fisher (15) quotes a figure of 30 percent reduction for urban accidents and states that 40 percent or more reduction is possible on rural roads or freeways. However, in the same paper he presents results that show the direct opposite.

It has been generally agreed that fixed roadway lighting is most beneficial in reducing pedestrian accidents, but even there the literature is not completely without disagreement.

The study most related to the objectives of the proposed work was recently completed by FHWA (4). This research attempted to determine the effect of illumination level and number of lights (indirectly a measure of partial versus complete versus no lighting) on nighttime accident experience. Extensive data were collected on accident histories, lighting (number and average illuminance), traffic volumes, geometries, etc., and multiple regression techniques were applied to determine the significance of the independent variables in affecting nighttime accidents at freeway interchanges.

The major conclusions were two-fold: illumination level did not significantly affect total accident rates or numbers, and number of lights did not significantly affect total accident rates or numbers. Factors other than lighting were found to be more significant than lighting in their influence on accidents, e.g., traffic volume, type of interchange, and area type (rural, urban, suburban). In combination with these variables, illumination showed a significant influence on total accident rates. For two of nine types of accidents, illumination and number of lights alone did show a significant effect on accident rates. These accidents accounted for 61 percent of the total.

A recent study by Young (17) reports on the effect of turning off all Milwaukee (WI) freeway lighting for 20 days. The effect on all nighttime accidents was an increase of 14 percent compared to a decrease of 16 percent for daytime accidents. The

night-to-day accident ratio increased by 21 percent, and the night accident rate increased by 8 percent. (Because of small sample sizes, all changes may not be significant.) For interchange ramp accidents, when the lighting was reduced from complete to partial for seven major interchanges and from complete to none for the rest, the nighttime number increased by 35 percent.

The results relating safety to roadway lighting (illuminance based) are at best inconclusive and at worst conflicting. This is not meant to be a condemnation of past work, only to say that very few studies have approached the problem on a firm theoretical basis and found statistically significant results. The problem in past research has been the underlying independent variable. Illumination level and uniformity have been the basis of roadway lighting design for many years. Historically, the reasons were that it was easy to describe, measure, and calculate and, hence, straightforward to design roadway lighting systems with illumination as the basis of design. Recommendations for roadway lighting in the United States are still couched in terms of illumination and uniformity.

Research by Blackwell (18), Gallagher (19), Janoff (20), and others has shown that lighting effectiveness must be measured in terms of a luminance-based visibility concept. Drivers see by the light that enters their eyes (i.e., luminance), not by the light that falls on the roadway (i.e., illuminance). Relationships between driver performance and lighting quality (e.g., luminance or visibility) have been demonstrated by Blackwell in the laboratory and Gallagher in the field--both for performance measures--and finally by Janoff, also in the field, but for accident histories. In addition, a recent study by Hargroves (21) showed that the dark/day accident ratio for two-lane, 30-mph roads in Great Britain under dry conditions was directly related to average road luminance. Roads having a luminance between 1.2 and 2.0 cd/m showed ratios 20 percent to 30 percent less than roads with luminance between 0.3 and 1.2 cd/m. The consistency of findings alone provides a substantial basis for proposed lighting evaluation/design based on these concepts. A discussion of these luminance/visibility concepts can be found in Ref. 22.

Although the research has been oriented toward the nighttime urban arterial lighting problem, the relationships between lighting quality and driver performance (and hence accident experience) are fundamental, with application to any nighttime visual driving situation. That is, although the absolute values of luminance or visibility found to be optimal by Hargroves, Gallagher, and Janoff pertain to specific road types, the notion that higher values of luminance or visibility produce safer traffic environments is applicable to other driving situations. More simply put, higher visibility implies safer roadways.

For freeway interchanges the same fundamental principles can be applied. By relating visibility to effectiveness in terms of lighting quality, driver performance, or accident experience, the basis for rational, objective lighting design can be made.

There are, of course, disadvantages to luminance-based concepts, primarily related to their difficulty in application by the practicing highway or lighting engineer. However, for research studies relating lighting design to visual quality they are the preferred methods for development of relationships between lighting and effectiveness. After the basic relationships have been developed, practical applications can be determined by development of simplified techniques to relate specific situations (interchange/lighting) to visibility and, hence, to effectiveness.

Practices

Lighting practices nationwide are generally based on the previously described warrants and recommendations as well as additional state or local warrants and recommendations. However, the application of these warrants and recommendations allows a wide latitude in choice of systems.

The selection of type of lighting system is influenced by past experience, local political and economic conditions, availability of supplies and energy, and a host of other factors. What results is a wide variation in actual designs which include high mast and standard heights, multiple luminaire sources and distributions, many different lighting geometries, and many different road surfaces (affecting luminance but not illuminance). No nationwide survey of interchange lighting practices has been identified to even provide a basis for estimates of the magnitude of the variations.

For the general topic of Interstate highway lighting, the same problem exists. There is no individual source or data base that reflects present lighting conditions on the Interstate Highway System. (The ISAR data base is old and incomplete in terms of lighting factors.) In individual state highway departments there are records of interchange design and lighting design for every segment of Interstate roadway; however, the data are available only as individual state sources. They are primarily in manual form (i.e., hard copy). The variations in the lighting of interchanges run from none to complete, with many variations in types of complete lighting and types of partial lighting. Personal contacts with a number of federal and state lighting experts have revealed that the variations in partial interchange lighting are from one or two lights per ramp (e.g., CA and MN) up to six or eight lights per ramp (e.g., TX and FL). AASHTO recommends about four lamps per ramp (9).

A survey of 14 states was conducted by WASHTO (23) to determine freeway lighting and lighting energy conservation practices in the western states. Information on use of partial and complete lighting (and recent changes) was solicited, but empirical data were presented which only describe the use of complete interchange lighting (i.e., number of CIL interchanges) and continuous mainline illumination.

Surveys have been undertaken for other areas of roadway lighting. Janoff (20) contacted nine utilities and nine state/city highway lighting engineers to determine the range of practices of modern arterial lighting systems (as well as many other variables such as costs) for urban streets. Cassel and Medville (24) did a survey of state lighting engineers, utilities, manufacturers, etc., with a primary objective of reviewing types and costs of roadway lighting systems. FHWA did a small survey of Interstate lighting, but was primarily interested in energy use. (C. Craig, FHWA, personal communication. 1981.)

MEASURES OF EFFECTIVENESS

In addition to the fundamental measures of the quality of the lighting itself (e.g., improved visibility, luminance, illuminance, contrast, and glare), measures of effectiveness of lighting systems can be classified into the following categories: accident reduction, improved traffic operations (other than safety), improved driver (and pedestrian) performance, increased comfort and convenience, and nonroadway-related improvements such as reduced crime, increased business or industry, and improved aesthetics.

Accidents

Accident reduction and its relationship to roadway lighting were discussed in the previous section, but to summarize the important results:

- The relationship between illumination level (and uniformity) and accident frequencies is at best uncertain. The fundamental belief is still that "good" lighting provides a safer environment than no lighting or "poor" lighting.
- Improved visibility (luminance-based) provides a safer roadway environment.

Traffic Operations

Traffic operations, other than accidents, can be described in terms of a wide number of measures, including vehicle placement, vehicle headways, vehicle velocities, densities and volumes, and speed-density relationships. Little research has been conducted that relates any of these traffic operational measures to roadway lighting. In addition, of the few existing studies, the lighting basis has been illumination, not luminance or visibility.

Tarigin and Rudy (25) found no consistent changes in traffic operations at on-ramps on the Connecticut Turnpike related to changes in illumination. Huber and Tracy (26), in a study for NCHRP, confirmed the conclusions of Tarigin and Rudy.

For special cases of illumination vs. traffic operations, a number of positive findings have been noted. Janoff (27) found an improvement in traffic operations, as measured by vehicle velocity maintenance and deceleration characteristics,

when the lighting was improved in the portal of a tunnel on I-76. Freedman (28) found improved traffic and pedestrian operations at urban intersections after installation of specialized crosswalk illumination.

Behavior Measures

The effect of illumination on driver and pedestrian behavior measures has been studied in analytic, laboratory, and field experimental situations. An excellent (although now somewhat out-of-date) discussion of behavioral measures and their relationship to lighting is presented by Farber (29) in which target detection, seeing distance, psychophysical judgments, gap acceptance behavior, and driver control are fully discussed.

More recently, Gallagher developed a fundamental relationship between visibility and driver performance defined in terms of driver responses to a roadway obstacle (19). In this study the basic concept of visibility for roadway lighting was quantified and related to driver performance measures. The full experimental situation is discussed in detail in Ref. 19, but the findings are summarized here.

Visibility, defined by

$$VI = C \times RCS_{LB} \times DGF$$

where $C = \dfrac{Lt}{Lt - Lb}$ (physical contrast),

RCS_{LB} = relative contrast sensitivity of observers adapted to a luminance condition = Lb, and

DGF = disability glare factor,

is directly related to driver performance, defined by

$$TTT = \text{Time-to-target} = \frac{\text{Distance-to-target-at-reaction}}{\text{Velocity of vehicle}}$$

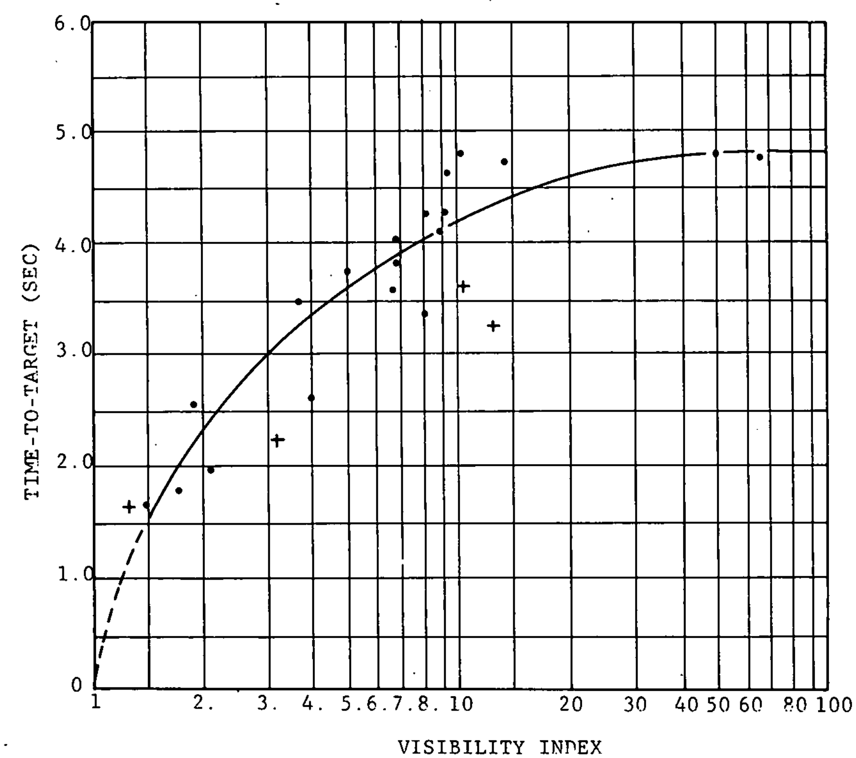
by means of Figure A-1. That is, as the visibility is increased, the performance of naive (i.e., unknowing) motorists improves. The measure of improvement is the increase in time available before interception of (striking) the target had the motorist continued at the same speed. These findings were the result of over 1,300 observations on the performance of unalerted motorists, and directly related a driving task closely associated with safety to a measure of lighting quality.

No experimental work of this type has been accomplished for interchange lighting. For general freeway lighting NCHRP Report 60 (26) reports inconclusive relationships between lighting (defined in terms of illumination) and driver performance (defined in terms of steering and accelerator activity and individual velocities). The researchers found that road geometry affected driver performance more than lighting.

Carter (30) studied the effect of environmental conditions on driver on-ramp merging behavior and found mean gap acceptance behavior at night (dry pavement) to be more conservative (larger gaps) than during the day. However, during wet night conditions, the gap acceptance behavior was more like the daytime (less conservative).

Other Measures

Very little is known concerning the relationships between roadway lighting and comfort and convenience, crime, increased



Source: Ref. 9.

Figure A-1. Regression line for mean driver responses (raw data) and visibility index.

business, etc. There was an extensive review of the relationships between roadway lighting and crime done by Janoff (13), but the findings were inconclusive.

Another part of the NCHRP study (26) that attempted to relate driver comfort in terms of apprehension and dissatisfaction to roadway lighting levels (illumination) showed no significant effect of higher illumination levels. Surprisingly, the results indicated greater comfort at lower illumination levels.

The quantification of these variables (e.g., comfort) is rather difficult, the variables being very subjective in nature.

EXPERIMENTAL METHODS

There are many experimental methods that are applicable to the evaluation of the effectiveness of lighting systems. These methods can be broadly grouped into four categories: accident analyses, lighting measurements, analytic methods (e.g., modeling), and behavioral and traffic operational measurements. Other techniques or methods combine two or more of these categories. The following discussion provides some background pertaining to the use of such methods, their advantages, problems, and validity, and Table A-8 summarizes this information.

Accident Analyses

Accident analysis is probably the most common and ideally the best method for analyzing the effectiveness of lighting

systems, since it directly addresses the fundamental issue of safety. In a typical application, before-after studies (preferably with controls) are accomplished to ascertain the effect of lighting on accident experience. As noted previously, the literature contains hundreds of such studies, but results are very mixed. Typically this method is applied in conjunction with a statistical technique to assess significance. Reference 4 provides a complex application of this technique.

The advantages of this approach are in its basis (accident reduction is a powerful, realistic benefit) and low cost (typically only existing data files are employed). The disadvantages of such an approach lie primarily in the quality of the accident and lighting data, which are normally very general, have many missing factors, and are of uncertain accuracy (e.g., police reports are largely subjective, after-the-fact interpretations). Also, lighting data are typically found only in illumination terms, rather than luminance.

Lighting Measurements

Based on assumptions stated by Fisher (15), one can measure illumination levels and assess the quality (effectiveness) by means of a "more is better" analysis. The advantage of such an approach lies in its simplicity of field measurements (or analytic calculations). The problems are that only generalities relating lighting quantity to safety exist (and none with respect to other traffic operations), and these are conflicting at best.

Table A-8. Summary of experimental methods.

Method	Description	Application to Lighting Research	Advantages	Disadvantages	Costs	Validity
Accident Analysis	Use accident data bases and statistical analyses.	Compare to lighting data bases using statistical techniques.	Simplicity. Firm basis.	Data are of poor quality for illuminance, and relationships only general. No luminance data available.	Low	Low (unless good data is available).
Physical Lighting Measurement	Measure illuminance, luminance, VI, glare etc. at actual road sites.	Basic assumption is "more-is-better" true for VI; unknown for illuminance.	Analytic for illuminance. Good relationships between VI & accidents/behavior.	Ill: no good relationship to accidents or behavior. Lum: field experiments can be complex.	Ill: low Lum: med	Ill: low Lum: high
Analytic (Models)	Model of lighting and road geometry vs. illuminance, luminance, VI, etc.	Basic assumption is "more-is-better" true for VI; unknown for illuminance.	Simplicity (i.e., computer program) Lum: good relationships to accidents and behavior.	Ill: no good relationships to accidents and behavior. Lum: calculations difficult and very site-specific.	Ill: low Lum: low-med depending on # of sites and quality of data and model.	Ill: low Lum: med-high depending on quality of input data and model modifications.
Behavioral and Traffic						
(a) Controlled	Test subjects in lab or field and statistical analyses.	Vary lighting and record changes in behavior and traffic.	Explicit control	Lack of realism and use of surrogate measures.	Med-high	Med
(b) Observational	Observe (and record) behavior/operations and statistical analyses.	Vary lighting and record changes in behavior and traffic.	Realism	Extensive set-up and use of surrogate measures.	High	High

If luminance-based measurements are made using photometers and recording circuitry, preferably housed in a mobile facility such as a van, the field measurements become extensive. The advantages are that proven relationships exist relating such luminance-based measurements to both behavior and safety. The disadvantage is in the complexity (i.e., cost) of collecting data.

Analytic Methods

Analytic methods consist of statistical techniques applied typically in conjunction with accident analyses or behavioral/-traffic operational measures, or models (computerized or manual) which analytically relate lighting and roadway design parameters to lighting quality in terms of illumination, luminance, visibility, etc. The calculation of illuminance is straightforward, but as noted previously, is of only a generalized (at best) use, with much uncertainty.

The calculation of luminance and visibility is not simple. It relies on lighting parameters, road geometry, pavement surface characteristics, the choice of object (reflective characteristics), and other factors. The manual computation of visibility defined in terms of VI (19) is extremely difficult and for any practical application must rely on computerized methods. A computerized model exists for such calculations (31) and is available from FHWA.

The advantage of using such a technique is that it provides a rapid method of calculating VI (as well as pavement luminance,

glare, and other measures of lighting quality). This is especially important when numerous situations must be analyzed. Reference 31 presents an application of this technique.

The disadvantages of such an approach lie primarily in the area of validity. The original model was developed for arterial roads. A generalization to freeways is probably straightforward, but for specific interchanges with horizontal and vertical curvature the model would have to be modified.

The actual use of the model is straightforward given that the user understands some computer programming (or is assisted by a programmer) and is able to develop the basic input data describing the lighting system, the roadway, and the road surface.

Behavioral and Traffic Operational Measurements

Behavioral and traffic operational measurements are obtained in two distinct ways: by controlled experiments using test subjects and by observational experiments involving naive (unknowing) subjects.

Experimental techniques of the first type consist primarily of detection- or recognition-type experiments in which the test subjects are informed of tasks they must complete and then tested under different conditions of the independent variable. With respect to lighting this type of experiment may consist of classical detection threshold under different lighting conditions (e.g., Ref. 32) driver eye marker research, or vehicle control. The advantages of such a technique relate to the explicit control of variables that can be attained. Disadvantages include lack of realism (i.e., a "test" situation), slow data collection rates, and the use of a surrogate measure (e.g., detection distance) rather than a direct measure of either traffic safety or traffic operations. The measure must be carefully selected and related to traffic safety or traffic operations for the results to be valid.

The observational type of experiment, in which naive test subjects are exposed to different levels of the independent variables (controlled or not), has been used successfully by Gallagher (19) and others to measure the performance of drivers in a detection-type experiment (actually the "reaction" was measured) in which the independent variable was lighting quality defined in terms of visibility (VI). The advantage of such a method is its realism (unknowing drivers are remotely monitored). Disadvantages include the use of surrogate measures and expensive set-up costs. As in the controlled experiment, care must be exercised in selecting the measures.

For other traffic operational measures such as headways, gap acceptance, and speed-density relationships, the FHWA Traffic Evaluator System provides a powerful tool for collecting such data. However, the set-up expense can be prohibitive for limited data collection purposes at many sites.

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APPENDIX B

MAILBACK SURVEY

NCHRP PROJECT 5-9

"PARTIAL LIGHTING of INTERCHANGES"

SURVEY OF STATE PRACTICES

PART I INTERCHANGE DESIGN

STATE:

RESPONDENT

JOB TITLE:

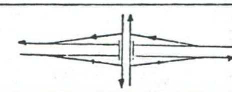
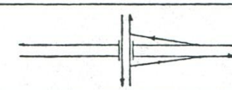
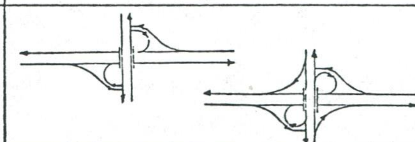
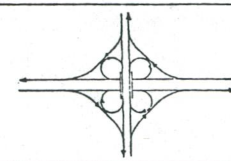
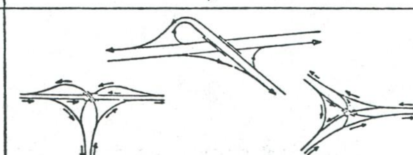
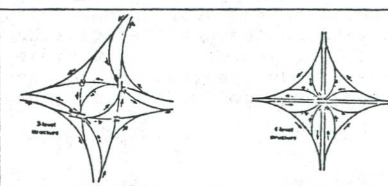
BRIEF JOB DESCRIPTION:

The objective of this section of the survey is to identify specific freeway interchange design characteristics in your state. We are interested in the following information:

- Estimate of Total Number of Interchanges
- Estimate of Number or Percentage of the Types of Interchanges
- Results of Studies Evaluating Interchange Types
- Reasons for Selecting Particular Interchange Types

1. Please provide us with an estimate of the total number of freeway interchanges that are in your state. ____________

2. Estimate the number or percentage of interchanges by design type in your state. (Answer in the table provided.)

INTERCHANGE DESIGN TYPE	DESCRIPTION	NUMBER OR PERCENTAGE (indicate which)
(a) Full Diamond		
(b) Half Diamond		
(c) Partial Cloverleaf		
(d) Full Cloverleaf		
(e) Three-Leg (Direct Connection)		
(f) Directional (Direct Connection)		
(g) Other ____________ ____________		

3. Has your state conducted any studies to measure or evaluate the effects of specific interchange designs on safety or traffic operations? (Check the appropriate reply for the studies listed below.)

(a) SAFETY STUDIES	YES ______	NO ______
(b) TRAFFIC OPERATIONS	YES ______	NO ______
(c) OTHER (briefly explain)	______	______

If you have answered "yes", to any of the categories above, please send us a copy of any related reports. If this is not feasible, briefly explain the nature of the studies in the space below and provide us with sample data, or give us the name and phone number of the person in your organization who might be able to provide this additional information.

4a. (OPTIONAL, complete if time and effort permit.)

Please specify the positive reasons for selection of a particular interchange design type (i.e., the reasons for using the specific type of interchange) in the table on the next page. Include brief reasons for selection in comments section.

For each design type, choose the three most positive reasons and identify them in the table by the numbers 1 (most important); 2 (second most important); 3 (third most important) in the proper spaces. See example below.

INTERCHANGE DESIGN TYPE	REASONS FOR SELECTION (POSITIVE)							
	Crossroad Classification (e.g., class of intersecting highways)	Environmental Factors (e.g., land-use constraints community effects, topography)	Traffic Operations (e.g., vehicle speeds/ volumes)	State/ Local Policies (e.g., uniformity)	Economics (e.g., initial/ operating/ maintenance costs)	Safety (e.g., accident experience)	Aesthetics	Other ____
(X) Example 1				3	1	2		

COMMENTS: For Example 1, 1: Low cost; 2: More safe operations; 3: Similar to other designs on roadway

INTERCHANGE DESIGN TYPE	REASONS FOR SELECTION (POSITIVE)								
(a) Full Diamond	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(b) Half Diamond	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(c) Partial Cloverleaf	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(d) Full Cloverleaf	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(e) Three Leg (Direct Connection)	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(f) Directional (Direct Connection)	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______
(g) Other	______ Crossroad Classification	______ Environmental Factors	______ Traffic Operations	______ State/ Local Policies	______ Economics	______ Safety	______ Aesthetics	______ Other	______

COMMENTS *(Place additional comments on the back of this page):

4b. (OPTIONAL, complete if time and effort permit.)

Please specify the negative reasons for rejection of a particular interchange design type (i.e., the reasons for refusing to use the specific type of interchange) in the table on the next page. Include brief reasons for rejection in comments section.

For each design type, choose the three most negative reasons and identify them in the table by inserting the numbers 1 (most important); 2 (second most important); 3 (third most important) in the proper spaces. See example below:

INTERCHANGE DESIGN TYPE	REASONS FOR REJECTION (NEGATIVE)							
(X) Example 1	3		2		1			
	Crossroad Classification (e.g., class of intersecting highways)	Environmental Factors (e.g., land-use constraints community effects, topography)	Traffic Operations (e.g., vehicle speeds/ volumes)	State/ Local Policies (e.g., uniformity)	Economics (e.g., initial/ operating/ maintenance costs)	Safety (e.g., accident experience)	Aesthetics	Other ____

COMMENTS: For Example 1, 1: High cost; 2: Complex traffic operations; 3: Intersecting highway too complex

INTERCHANGE DESIGN TYPE	REASONS FOR REJECTION (NEGATIVE)							
	Crossroad Classification	Environmental Factors	Traffic Operations	State/Local Policies	Economics	Safety	Aesthetics	Other
(a) Full Diamond	____	____	____	____	____	____	____	____ Other ____
(b) Half Diamond	____	____	____	____	____	____	____	____ Other ____
(c) Partial Cloverleaf	____	____	____	____	____	____	____	____ Other ____
(d) Full Cloverleaf	____	____	____	____	____	____	____	____ Other ____
(e) Three Leg (Direct Connection)	____	____	____	____	____	____	____	____ Other ____
(f) Directional (Direct Connection)	____	____	____	____	____	____	____	____ Other ____
(g) Other	____	____	____	____	____	____	____	____ Other ____

COMMENTS (Place additional comments on the back of this page):

NCHRP PROJECT 5-9

"PARTIAL LIGHTING of INTERCHANGES"

SURVEY OF STATE PRACTICES

PART II INTERCHANGE LIGHTING

STATE:

RESPONDENT:

JOB TITLE:

WORK ADDRESS/PHONE:

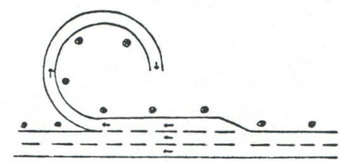
BRIEF JOB DESCRIPTION:

The objective of this section of the survey is to identify specific interchange lighting practicies in your state. We are interested in the following information:

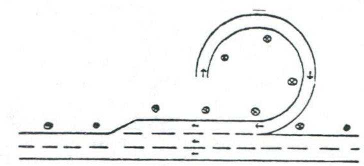
- Warrants Used for Determining Interchange Lighting Needs
- Estimates of the Number of Interchanges, Lighted Interchanges, and Types of Lighted Interchanges
- Results of Studies Evaluating Interchange Lighting Systems
- Rationale for Selecting Specific Interchange Lighting Systems
- Rationale for Selecting Specific Types of Lighting for Specific Interchange Design Types

DEFINITIONS:

A complete interchange lighting system (referred to as a CIL) includes lighting on both the deceleration/acceleration area plus the ramps through to the terminus; it may be of conventional height or high mast. An example is illustrated below.

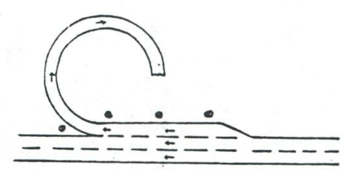


CIL Exit Ramp

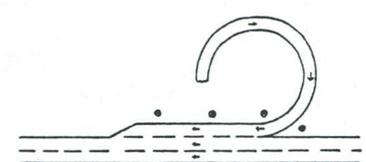


CIL Entrance Ramp

A partial interchange lighting system (referred to as a PIL) generally includes lighting only in or near the acceleration/deceleration area; it may be of conventional height or high mast. An example is illustrated below.



PIL Exit Ramp

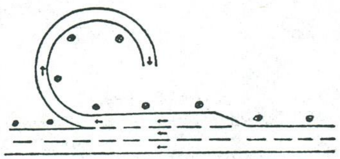


PIL Entrance Ramp

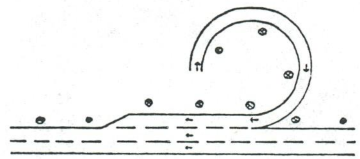
⊗ Represents a typical luminaire

DEFINITIONS:

A complete interchange lighting system (referred to as a CIL) includes lighting on both the deceleration/acceleration area plus the ramps through to the terminus; it may be of conventional height or high mast. An example is illustrated below.

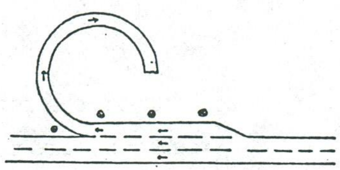


CIL Exit Ramp

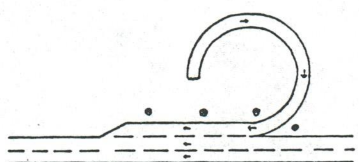


CIL Entrance Ramp

A partial interchange lighting system (referred to as a PIL) generally includes lighting only in or near the acceleration/deceleration area; it may be of conventional height or high mast. An example is illustrated below.



PIL Exit Ramp



PIL Entrance Ramp

⊗ Represents a typical luminaire

1. What warrants does your state employ in determining interchange lighting needs? (Check appropriate response.)

AASHTO* YES _______ NO _______

Other___________________________ YES _______ NO _______

Briefly explain any warrants other than AASHTO (i.e., the difference between your warrants and AASHTO's in the space provided below or include a copy of your warrants).

2. Estimate the number of interchanges in your state.

____

3. Estimate the number of interchanges in your state that are lighted.

____

4. Estimate the number of complete (CIL) and partial (PIL) interchange lighting systems in your state.

CIL _______________ PIL _______________

(Note: The sum of the entries in 4 should equal the entry in question 3. If they differ, please explain.)

* AASHTO, "An Informational Guide for Roadway Lighting", March 1976.

5. Of the complete lighting systems, what percentage or number are:

(a) In Urban Areas ______________

(b) In Surburban Areas ______________

(c) In Rural Areas ______________

Of the partial lighting systems, what percentage or number are:

(a) In Urban Areas ______________

(b) In Surburban Areas ______________

(c) In Rural Areas ______________

6. Of the lighted interchanges in your state, what percentage or number are:

(a) Mercury ______________

(b) HPS ______________

(c) Other ______________ (Please describe) ______________

____

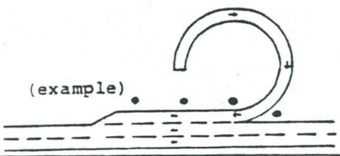
7. Estimate the number of interchanges or percentage of interchanges, by type, that have complete interchange lighting systems in your state. (Use the space provided in the table below.)

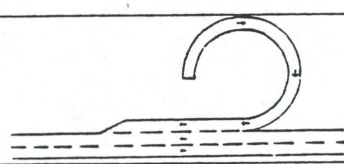
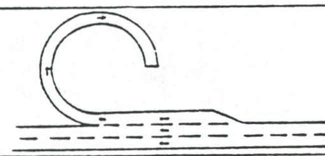
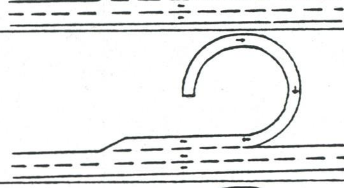
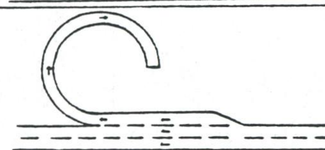
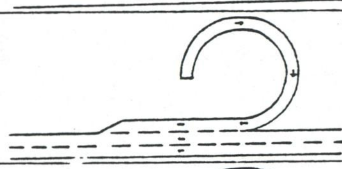
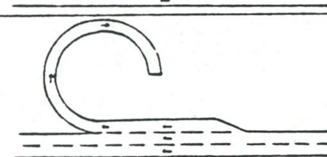
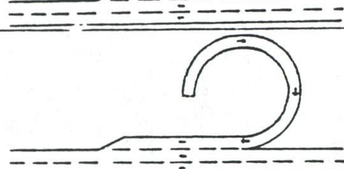
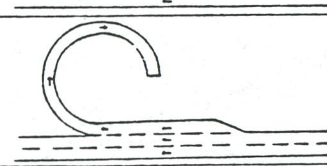
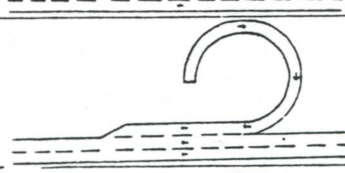
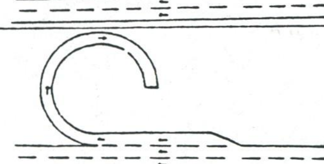
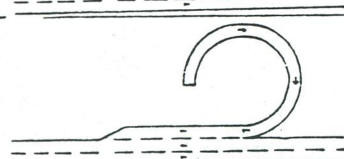
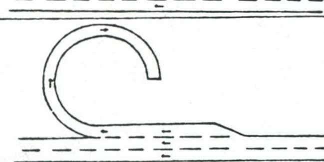
COMPLETE INTERCHANGE LIGHTING SYSTEM TYPE	NUMBER or PERCENTAGE (indicate which)
Conventional Heights (a) With Continuous Freeway Lighting (b) Without Continuous Freeway Lighting	 ______________ ______________
High Mast (a) With Continuous Freeway Lighting (b) Without Continuous Freeway Lighting	 ______________ ______________
Other (briefly describe) ______________ ______________________________	______________

8. Estimate the number of interchanges or percentages of interchanges, by type, that have partial interchange lighting in your state. (Use the space provided in the table below.)

Also, describe the luminaire arrangements of a typical partial interchange lighting system for each type by drawing an x at the approximate location of each luminaire on the ramp exit (on-ramp) and ramp entry (off-ramp). An example is included below.

(example)



PARTIAL INTERCHANGE LIGHTING TYPE	NUMBER OR PERCENTAGE (indicate which)	RAMP EXIT (ON-RAMP) DESCRIPTION	RAMP ENTRANCE (OFF RAMP) DESCRIPTION
1-2 Luminaires			
3-5 Luminaires			
6-8 Luminaries			
Over 8 Luminaires			
High Mast			
Other			

9. Has your state conducted any studies to measure the photometrics of interchange lighting or evaluated the effects of interchange lighting systems on safety or traffic operations? (Check the appropriate reply for the studies listed below.)

(a) Safety Studies Yes ______ No ________

(b) Traffic Operations Yes ______ No ________

(c) Photometrics Yes ______ No ________

(d) Other (briefly explain) ______________________

If you have answered "yes", to any of the categories above, please send us a copy of any related reports. If this is not feasible, briefly explain the nature of the studies in the space below and provide us with sample data, or give us the name and phone number of the person in your organization who might be able to provide additional information.

10. Has your state recently modified any interchange lighting systems? (e.g., changed selected systems from PIL to CIL; from CIL to PIL; turned off selected systems, etc.) (Check the appropriate reply).

Yes ________ No __________

11. Have you evaluated such changes? (Check the appropriate reply).

Yes ________ No __________

If you have answered "yes", please send us a copy of any related reports. If this is not feasible, briefly explain the nature of the studies in the space below and provide us with sample data, or give us the name and phone number of the person in your organization who might be able to provide additional information.

12. Do you plan to install a new complete interchange lighting system on an unlit freeway within the next four months?

Yes ________ No __________

If "yes", please describe the installation.

13a. Please specify the positive reasons for selection of a specific type of interchange lighting system (i.e., the reasons for using the specific type of lighting design) in the table on the next page.

For each type of interchange lighting, choose the four most positive reasons and identify them in the following table by inserting the numbers 1 (most important); 2 (second most important); 3 (third most important); 4 (fourth most important) in the proper spaces. For each reason selected, please clarify as illustrated in the example below.

Note: Your answer to this question should reflect your practices for unlit freeways only (i.e., without continuous lighting; the only illumination is at or near the interchange) not for the continuously illuminated sections of freeways.

TYPE OF INTERCHANGE LIGHTING SYSTEM	REASONS FOR SELECTION (POSITIVE)									
	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(X) Example 1					4	1	3	2		
	(e.g., land-use constraints, community effect, topography	(e.g., of interchange or intersecting highway)		(e.g. vehicle speeds or volumes)	(e.g. uniformity)	(availability)	(e.g., initial/ operating/ maintenance costs)	(e.g., accident rates)		

COMMENTS: For example 1, 1: Low energy use; 2: Safer traffic operations; 3: Low initial cost; 4: Similarity to other systems

TYPE OF INTERCHANGE LIGHTING SYSTEM	REASONS FOR SELECTION (POSITIVE)									
	COMPLETE INTERCHANGE LIGHTING									
(a) Conventional Heights	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(b) High Mast	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(c) Other ______	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
	PARTIAL INTERCHANGE LIGHTING									
(a) 1-2 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(b) 3-5 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(c) 6-8 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(d) Over 8 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(e) High Mast	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____
(f) Other ______ ______	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other ____

COMMENTS (Place additional comments on the back of this page):

13b. Please specify the negative reasons for rejection of a specific type of interchange lighting system (i.e., the reasons for refusing to use the specific type of lighting design) in the table on the next page.

For each type of interchange lighting, choose the four most negative reasons and identify them in the following table by inserting the numbers 1 (most important); 2 (second most important); 3 (third most important); 4 (fourth most important) in the proper spaces. For each reason selected, please clarify as illustrated in the example below.

Note: Your answer to this question should reflect your practices for unlit freeways only (i.e., without continuous lighting; the only illumination is at or near the interchange) not for the continuously illuminated sections of freeways.

TYPE OF INTERCHANGE LIGHTING SYSTEM	REASONS FOR REJECTION (NEGATIVE)									
	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(X) Example 1				1		3	4		2	
	(e.g., land-use constraints, community effect, topography	(e.g., of interchange or intersecting highway)		(e.g. vehicle speeds or volumes)	(e.g. uniformity)	(availability)	(e.g., initial/ oper/ ating/ maintenance costs)	(e.g., accident rates)/		

COMMENTS: For example 1, 1: Complex traffic operations; 2: Does not aesthetically blend with environment; 3: High energy use; 4: High operating costs

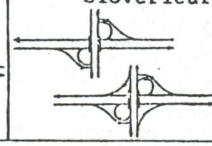
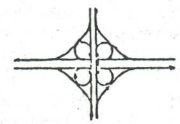
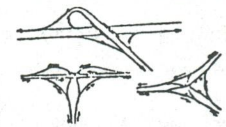
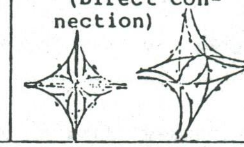
TYPE OF INTERCHANGE LIGHTING SYSTEM	REASONS FOR REJECTION (NEGATIVE)									
	COMPLETE INTERCHANGE LIGHTING									
(a) Conventional Heights	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(b) High Mast	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(c) Other ________	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
	PARTIAL INTERCHANGE LIGHTING									
(a) 1-2 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(b) 3-5 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(c) 6-8 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(d) Over 8 Luminaires	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(e) High Mast	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other
(f) Other ______ ________	Environmental Factors	Geometric/ Physical	Warrants	Traffic Operations	State/Local Policies	Energy	Economics	Safety	Aesthetics	Other

COMMENTS (Place additional comments on the back of this page):

14. Certain combinations of interchange lighting systems and interchange design configurations may always be used. Other combinations may never be used. Please identify in the matrix below, those combinations which, according to current practices in your state, are <u>always used</u>, <u>sometimes used</u>, or <u>never used</u>. (Use an "A" for always used, "S" for sometimes used, and an "N" for never used).

Note: Your answers to these questions should reflect your practices for unlit freeways only (i.e., without continuous lighting; the only illumination is at or near the interchange) not for continuously illuminated sections of freeways.

INTERCHANGE DESIGN

INTERCHANGE LIGHTING SYSTEM	(a) Full Diamond 	(b) Half Diamond 	(c) Partial Cloverleaf 	(d) Full Cloverleaf 	(e) Three Leg (Direct Connection) 	(f) Directional (Direct Connection) 	(g) Other
COMPLETE INTERCHANGE LIGHTING							
Conventional Heights							
High Mast							
Other ________ ____________							
PARTIAL INTERCHANGE LIGHTING							
1-2 Luminaires							
3-5 Luminaires							
6-8 Luminaires							
Over 8 Luminaires							
High Mast							
Other ________ ____________							
NO INTERCHANGE LIGHTING							

NCHRP PROJECT 5-9

"PARTIAL LIGHTING of INTERCHANGES"

SURVEY OF STATE PRACTICES

PART III ACCIDENT and TRAFFIC OPERATION DATA

STATE:

RESPONDENT:

JOB TITLE:

BRIEF JOB DESCRIPTION:

The objective of this section of the survey is to assess the quality and form of the accident and traffic operational data collected by your state. We are interested in the following information:

- Availability of Accident Data
- Form of Accident Data
- Availability of Traffic Volume Data
- Form of Traffic Volume Data
- State Cooperation in Accessing Data

For the questions below, place a check next to the appropriate answer to each question

1. Is accident data compiled (recorded) in your state? Yes ______ No ______

2. If you answered "yes" in what form is the data? (multiple answers)

   Hard Copy (e.g., Police Reports) ______

   Automated Database File ______

   Summary Statistics ______

   Other ______________ ______

3. From the information available in your accident data base, can accidents be classified according to:

   (a) Date Yes ____ No ____
   (b) Lighting condition (i.e., day, night with lighting, night without lighting, dawn/dusk) Yes ____ No ____
   (c) Location (interchange versus non-interchange)* Yes ____ No ____
   (d) Type of Accident Yes ____ No ____
   (e) Severity (e.g., fatal, injury, property damage) Yes ____ No ____
   Reporting Level $________

Please enclose a sample of your accident data or send us a sample of the form indicating the elements which are available.

* What is your definition of an interchange accident? Please be specific about the limits of the area designated as the interchange, e.g. some states may call any accident that occurs within 1/4 mile of any part of an interchange (ramp entrance, ramp, over-crossing etc.) an interchange accident. Others would call it as such only if it occurred on a ramp but not on the main stream.
Please Describe ______________________________

____

4. Is traffic volume data for interchanges compiled (recorded) in your state? Yes ____ No ____

5. If you answered "yes", how is the data summarized?

   (a) AADT by Route Segment Yes ______ No ______

   (b) AADT by Interchange Leg (Directional Movements) Yes ______ No ______

   (c) Day vs. Night (or hourly) Yes ______ No ______

   (d) Other (briefly describe) ______ ______ Yes ______ No ______

6. Do you have any other traffic operational data available (e.g., vehicle speeds, level of service)? Yes ____ No ______

   Please enclose a sample of any available traffic operational data for an interchange (volume or other).

7. Would your state be willing to assist us by providing either raw or summarized accident, volume, or other traffic operational data for interchanges which may have undergone lighting changes?

   Yes ______ No ______

8. What lead time would be required in providing us with this data?

   ________ days

   Whom should we contact for further information?

   Name ______________________________

   Telephone Number ______________________________

APPENDIX C

TABULAR DATA FROM MAILBACK SURVEY

Table C-1. Survey completion rate.

Region	Status of Survey		
	Total	Received	Completion Rate (%)
1	8	5*	63
3	5	4	80
4	8	7	88
5	6	6	100
6	5	3	60
7	4	4	100
8	6	6	100
9	4	3	75
10	4	3	75
Canada	10	7	70
Turnpike Authorities	3	2	67
TOTAL	63	50	79

*Rhode Island data are incomplete and are not included in the remaining tables.

Table C-2. Frequency of interchange design by region.

Region	Number of Inter-changes	Type of Interchange Design (%)						
		Full Diamond	Half Diamond	Partial Clover-leaf	Full Clover-leaf	Three-leg	Direc-tional	Other
1	563	21	12	44	10	10	0.5	2.5
3	1,150*	35	10	25	12	15	2.7	0.3
4	2,374	57	6	21	5	9	2	0
5	2,990**	38	12	19	7	9	6	9
6	711	56	1	16	1	9	1	16
7	1,228	68	12	11	4	3	1	1
8	1,099	80	8	4	2	5	0.8	0.2
9	3,064	71	7	11	3	3	2	3
10	514	54	9	12	2	7	1	15
Canada	588***	18	3	53	8	7	4	7
Turnpike Authori-ties	145	7	8	6	19	46	4	10
TOTAL	14,439	55	8	18	5	7	3	4

* Pennsylvania data (450 interchanges) are not included in the percentages.
** Ohio data (620 interchanges) are not included in the percentages.
***Manitoba data (13 interchanges) are not included in the percentages.

Table C-3. Frequency of unlit versus illuminated interchanges and percentage of illuminating interchanges by interchange lighting type (CIL and PIL).

Region	Total Number of Interchanges	Total Number of Unlit Interchanges	Total Number of Illuminated Interchanges	Type of Illuminated Changes (% of Illuminated Interchange)	
				CIL	PIL
1	563	359	204 (36%)	42	58
3	1,150	771	379 (33%)	87	13
4	2,374	1,806	568 (24%)	90	10
5	2,990	1,526	1,464 (49%)	70	30
6	711	508	203 (29%)	76	24
7	1,228	696	532 (43%)	43	57
8	1,099	582	517 (47%)	16	84
9	3,064*	281	2,783 (91%)	2	98
10	527	64	463 (88%)	20	80
Canada	588	216	372 (63%)	42	58
Turnpike Authori-ties	145	77	68 (47%)	100	0
TOTAL	14,439	6,886	7,553 (52%)	37	63

*California has 2,600 interchanges, of which 2,500 are illuminated and use PIL. Excluding California's data from the total, the percentage for CIL is 55 and the percentage for PIL is 45.

Table C-4. Frequency of illuminated interchanges and percentage of illuminated interchanges by location, region, and lighting type.

Region	Total Number of Illuminated Interchanges	Type of Illuminated Interchange (%)					
		CIL			PIL		
		URB	SUB	RUR	URB	SUB	RUR
1	204	35	6	1	23	14	21
3	379	48	32	7	2	8	3
4	568	50	22	18	0	2	8
5	1,464	52	17	1	3	8	19
6	203	59	15	2	1	20	3
7	532	35	6	2	31	8	18
8	517	11	4	1	19	16	49
9	2,783*	1.6	0.3	0.1	46	28	24
10	450	16	3	1	5	39	36
Canada	372	31	3	8	13	22	23
Turnpike Authorities	68	85	7.5	7.5	0	0	0
TOTAL	7,553	26	8	3	23	18	22

*Of the 2,500 illuminated interchanges in California, 1,250 are urban, 750 are suburban, and 500 are rural. Excluding California's data from the total, CIL urban is 39%, CIL suburban is 12%, CIL rural is 4%, PIL urban is 10%, PIL suburban is 12%, and PIL rural is 23%.

Table C-5. Percentage of luminaire source type by region.

Region	Total Number of Illuminated Interchanges	Luminaire Source Type (%)			
		Mercury	High-Pressure Sodium	Metal Halide	Other
1	204	51	44	5	0
3	379	64	33	1	2
4	568	33	60	2	5*
5	1,464	18	77	5	0
6	203	78	18	4	0
7	532	71	16	13	0
8	517	68	28	4	0
9	2,783	73	26.9	0.1	0
10	463	81	15	4	0
Canada	372	59	21	0.2	19.8**
Turnpike Authorities	68	54	46	0	0
Total	7,553	57	38	3	2

*Combination mercury and metal halide.
**Low-pressure sodium or fluorescent.

Table C-6. Frequency of CIL systems classified by mounting height, presence/absence of continuous freeway lighting (CFL), and region.

Region	Total Number of CIL Illuminated Interchanges	CIL SYSTEMS (%)			
		Without CFL		With CFL	
		Conventional	High Mast	Conventional	High Mast
1	87	16	1	32	51
3	329	45	11	40	4
4	509	7	14	76	3
5	1,019	16	6	69	9
6	155	7	7	76	10
7	231	11	16	60	13
8	81	30	7	57	6
9	56	18	0	75	7
10	91	17	6	73	4
Canada	22	12	.2	69	12
Turnpike Authorities	68	29	7	63	0
TOTAL	2,778	17	9	65	9

Table C-7. Frequency of PIL systems classified by number of luminaires and region.

Region	Total Number of PIL Systems	PIL SYSTEMS (%)					
		1-2 Luminaires	3-5 Luminaires	6-8 Luminaires	More than 8 Luminaires	High Mast	Other
1	117	2	77	14	0	7	0
3	50	10	90	0	0	0	0
4	59*	0	4	0	0	29	67
5	445**	0	64	7	10	18	1
6	48	4	85	0	4	7	0
7	301	3	85	0.5	0.5	11	0
8	436	45	27	2.8	24	0.2	0
9	2,727***	77	23	0	0	0	0
10	372	88	12	0	0	0	0
Canada	220	34	61	3	1	1	0
Turnpike Authorities	0	0	0	0	0	0	0
TOTAL	4,775	57	34	2	3	3	1

*PIL data from Mississippi (17 systems) are not included in the percentages.
**PIL data from Michigan (5 systems) are not included in the percentages.
***Excluding California's data on PIL interchanges (2,500), the total for each PIL luminaire type would be as follows: 1-2 luminaires (31%), 3-5 luminaires (50%), 6-8 luminaires (4%), more than 8 luminaires (6%), high mast (6%), and other systems (3%).

APPENDIX D

FIELD EXPERIMENTS

This appendix describes the design and conduct of the field experiments. The discussion covers the following areas: site selection, independent variables, dependent measures, test conditions, lighting control, data collection equipment and procedures, and photometric measurements.

SITE SELECTION

Site selection was probably the most important, most controversial, and most time-consuming part of the study. It began during the first month of the study and was not completed until an entire year had elapsed.

It began by classifying all interchanges by two distinct types of operational variables: ramp geometry and exit/entrance geometry. Ramp geometry consists of three levels: no or minimum curvature on the ramp between the main road and the crossroad (e.g., diamond or half-diamond); 90° curvature (nominal--may range from 60° to 120°) between the main road and the crossroad (e.g., outer ramps of cloverleaf, direct connection); and 270° of curvature (nominal--may range from 200° to 300°) between the main road and the crossroad (e.g., left turn maneuver of cloverleaf). Exit/entrance geometry can be of two types: with (classic) weaving area (i.e., entrance upstream of exit as in a full cloverleaf) or without weaving area (i.e., entrance downstream of exit as in a diamond).

Table D-1 illustrates the most frequent types of interchanges classified by the two variables, ramp geometry, and exit/entrance geometry. The simplest types are the diamond and half diamond, which have no ramp curvature and no weave area. The most complex is the full cloverleaf, which has mixed ramp curvature and weave areas. The three-leg and partial cloverleaf fall in between these extremes.

Based on this classification scheme three potential site types were selected: a full diamond, a partial cloverleaf or three-leg, and a full cloverleaf, spanning the full range of interchange operating conditions. For each site type, a number of specific interchanges were located.

The major problem with this first part of the site selection process was that all of the interchanges that were selected had inadequacies. These inadequacies included rural locations, low mounting heights, relatively low traffic volumes, and relatively old lighting designs (10 to 20 years). To overcome this problem an "ideal" site was defined and the NCHRP panel and a few states were solicited to help locate such "ideal" site.

The specifications for the ideal site were as follows:

Area Type: Located in a suburban area including some background complexity (e.g., light industry or strip development).

Geometric: A full cloverleaf design with straight and level alignment, good surfaces, 2-3 through lanes, and 1 lane per ramp.

Table D-1. Interchange types classified by ramp geometry and entrance/exit geometry.

Type of Interchange	Ramp Geometry	Entrance/Exit Geometry
Diamond	No curvature	No weave
Half Diamond	No curvature	No weave
Directional	90°	No weave
Three-leg	90° and 270°	No weave
Partial Cloverleaf	90° and 270°	May have weave
Full Cloverleaf	90° and 270°	Weave

Traffic: Good markings and signing (meets MUTCD) and ramp volumes of at least 1,000 per day.

Lighting: None on the main road, CIL on the interchange consisting of high-pressure sodium, 35+ ft mounting heights, and controllable lighting circuits.

Other: State cooperation (permission to temporarily change lighting to PIL and no-lighting and assistance with traffic control).

A small mailback survey was designed and sent to the NCHRP panel (OR, MI, VA, MA, IL, NM, CA, WI) and a group of cooperative states (PA, NJ, DE, MD, FL, NY) to identify one or more sites with these ideal characteristics. Five interchanges were identified (three in Maryland, two in Illinois) that had many of the characteristics, and two (I-695/MD 147 and I-57/IL 13) were determined to have all except two of the characteristics. The Maryland site had 30-ft mounting heights and mercury luminaires. The Illinois site had somewhat low traffic volumes and some surface problems (e.g., red colored ramps).

The Maryland Department of Transportation stated that the mercury lamps would be upgraded to high-pressure sodium before experiments were begun and the mounting height on one PIL configuration would be temporarily raised (to 40 ft) so that mounting height could be evaluated as a separate variable. Since it was not possible to increase the volumes at the Illinois site and the red colored ramps could not be easily changed (and their effect on traffic operations was unknown), the Maryland site was selected as the main test site. Its specifications are illustrated in Table D-2.

Table D-2. Maryland test site.

Variable	Test Site Description
ENVIRONMENTAL	
Area Type	Suburban
Development	Residential/Light Commercial/Strip
Topography	Relatively Flat
GEOMETRIC	
Type of Interchange	Full Cloverleaf
Number of Through Lanes	3
Number of Lanes Per Ramp	1
Alignment	Straight and Level
Surface Type	Portland Cement
Surface Quality	Good
TRAFFIC	
Markings	Good
(Meet MUTCD)	Yes
Signing	Good
(Meet MUTCD)	Yes
Volumes (Main)	80,000 ADT
(Ramps)	2,000-4,000 ADT
LIGHTING	
Main Road	None
Interchange	CIL
Type (Main)	250 High-Pressure Sodium
(Ramps)	150 High-Pressure Sodium
Mounting Height	30 ft (40 ft also for PIL)
Number of Luminaires	97
Spacing (Main)	180 ft
(Ramps)	120-200 ft
Distribution	Mixed (II and III)
Setback	2 ft
Mast Arm (Main)	12 ft
(Ramps)	4 ft and 6 ft
Controls	Photocells, Fuses, Control Panel

The original plan was to evaluate the effect of the different lighting conditions on traffic operations at both the outer and inner ramps of the cloverleaf (two exit ramps, two entrance ramps). However, since the site selection process took so long it was decided to begin the field evaluations on the outer ramps of a less than ideal site in proximity to Ketron's Wayne office. A three-leg interchange, with 90° ramps similar to the outer ramps of a cloverleaf, was selected, and a pilot study was conducted in the Fall of 1981. Table D-3 describes the pilot site. The inner ramps of the cloverleaf interchange (including the effects of the weaving area) were to be evaluated in the spring of 1982, once the ideal site was located.

The reason for performing this pilot study was the opportunity it would provide to evaluate the data collection equipment, the field procedures, and the dependent measures. The proximity to Ketron's offices was felt to be essential in case problems occurred with the newly designed instrumentation.

The pilot site (I-276/PA 9) on the Pennsylvania Turnpike met all of the ideal specifications (for outer ramps) except for the 31-ft mounting height and the fact that although in a suburban area, the environment was visually more like a rural area.

INDEPENDENT VARIABLES

There were two major types of independent variables that were controlled by design--geometry and lighting--and

Table D-3. Pilot site.

Variable	Test Site Description
ENVIRONMENTAL	
Area Type	Suburban/Rural
Development	Residential/Light Industry
Topography	Relatively Flat
GEOMETRIC	
Type of Interchange	Three-Leg
Number of Through Lanes	2
Number of Lanes Per Ramp	1
Alignment	Straight and Level
Surface Type (Main)	Bituminous (overlay)
(Ramp)	Portland Cement
Surface Quality (Main and Ramp)	Excellent
TRAFFIC	
Markings	Good
(Meet MUTCD)	Yes
Signing	Good
(Meet MUTCD)	Yes
Volumes (Main)	44,000 (E-W)/16,500 (N-S)
(Ramps)	2,600-5,600
LIGHTING	
Main Road	None
Interchange	CIL
Type - Main	250 High-Pressure Sodium
Ramps	150 High-Pressure Sodium
Mounting Height	31 ft
Number of Luminaires	54
Spacing (Main)	175-185 ft
(Ramps)	175-185 ft (130 ft on 270° ramp)
Distribution	II (some III on 270° ramp)
Setback	2 ft
Mast Arm	15 ft
Controls	Photocell, Fuses, Control Panel

one independent variable that was uncontrolled--traffic volume. No environmental variables such as rain were considered; all experiments were performed during dry conditions.

Geometry was defined in terms of type of ramp. Each of the four ramps--outer (90°) exit, outer entrance, inner (270°) exit, and inner entrance--was evaluated separately.

The primary lighting variable was lighting condition--CIL versus PIL versus no lighting--and PIL was further stratified by number of lights at each ramp--1 (inner ramps), 2 (inner and outer ramps), and 4 (outer ramps). The lighting conditions were further quantified by measured illuminance and uniformity, average pavement luminance, average glare luminance, and average visibility, which combines object luminance, pavement luminance, and glare (see App. A for a complete definition), for the pilot study.

The reason for making photometric measurements was to investigate whether there were any relationships between the photometric measurements of the lighting systems' quality (e.g., pavement luminance) and the traffic operational measures that could not be explained purely in terms of the number of luminaires or simple PIL versus CIL versus no-lighting classifications.

At the pilot site illuminance was measured under all six nighttime lights-on conditions (CIL, PIL-4, PIL-2--exit and entrance). Luminances, however, were measured only at the exit and only under two lighting conditions: CIL and PIL-2. This was done to determine if the luminance measurements could provide any additional explanation of systematic relationships (other than simple ones such as number of luminaires). If such systematic relationships had been disclosed, they could have been investigated further at the main site in greater detail. Since it was found that no systematic relationship existed, the photometry at the main site was reduced to checking the effect of mounting height on pavement luminance and glare, and measuring illumination.

An attempt was made to measure one other traffic operational variable: traffic volume. At the pilot site, tube counters were used to record ramp and main-line volumes (by lane), but the counters consistently broke down. Thus, few usable volume data were collected. At the main site, ramp volumes were obtained during all data collection periods. (Ideally the FHWA Traffic Evaluation System (TES) could have been used to record all lane volumes and many other traffic operational parameters, but it was unavailable during this study.)

DEPENDENT MEASURES

Three types of dependent measures were selected:

- Locational measures describing where drivers diverged from the main stream of traffic into the deceleration ramp or merged from the acceleration ramp into the main stream of traffic.

- Time/position history measures describing average velocities and accelerations both in the deceleration/acceleration areas and in the ramps (and spot velocities and accelerations for the pilot study).

- Erratic maneuver measures such as braking, use of high beams, gore encroachments or shoulder encroachments. For the pilot study these maneuvers were only counted; for the main study the exact locations of these maneuvers were recorded.

The "erratic maneuver" measures were used as surrogates for direct measures such as accident frequencies or rates because the latter is either unavailable or, when available, of low quality. In addition, the average number of accidents per ramp per year for most freeway interchanges is less than one, prohibiting any meaningful statistical analysis.

The locational measures and time/position history measures were used as descriptors of the traffic flow or traffic operations in the interchange area. They are summarized in Table D-4.

The objective of these field studies was to determine whether interchange lighting facilitates traffic flow and if it does, whether it is possible to differentiate the effects on the basis of the independent geometry and lighting variables. Two basic issues were addressed:

- The beacon function of roadway lighting which primarily alerts the motorist to the presence of a special roadway feature, such as an interchange (or a gore area), and secondarily provides optical guidance by delineating the road markings and road edge.

Table D-4. Dependent measures.

RAMP	MEASURE	DESCRIPTION
Exit	Diverge Point	Distance upstream from gore
"	Diverge Velocity	Velocity between first two switches
Exit/ Entrance	Average Velocity	Velocity between any two switches or pairs
"	Spot Velocity*	Velocity across pair of switches
"	Average Acceleration	Acceleration between any three switches or pairs
"	Spot Acceleration*	Acceleration across two consecutive pairs
"	Brake Activations	Frequencies (and locations for main site)
"	High-Beam Use	Frequencies (and locations for main site)
"	Gore Encroachments	Frequencies (and locations for main site)
"	Shoulder Encroachments	Frequencies (and locations for main site)
Entrance	Merge Point	Distance downstream from gore
"	Merge Velocity	Velocity between last two switches

*For pilot site only.

- The driver control function of lighting which provides optical guidance that allows the motorist to track the curved ramps and merge/diverge smoothly and safely.

The beacon function was primarily addressed by determining the location of diverge points from the main stream into the deceleration ramp (for the exit ramp) and the frequency of erratic maneuvers upstream of the deceleration ramp (e.g., brake use and high-beam use). Secondary measures include diverge velocity and acceleration. For the entrance ramp the beacon function was determined downstream of the gore.

The driver control function was addressed by investigating velocities and accelerations after diverging (or before merging) as well as erratic maneuvers in these areas (gore and shoulder encroachments, high-beam and brake use).

TEST CONDITIONS

The test conditions that were evaluated in the field experiment are illustrated in Table D-5. There were 22 test conditions: 10 for the pilot site and 12 for the main site. All but two conditions at the main site were evaluated at 30-ft mounting heights, as indicated in this table. All mounting heights at the pilot site were 31 ft.

The locations of the luminaires used for all PIL configurations were determined from the results of the mailback survey. They are illustrated in Figures D-1 and D-2 for the pilot site and in Figure D-3 for the main site.

Table D-5. Test conditions.

Site	Ramp	Lighting Condition
Three-leg	Exit (90°)	Daylight No lighting PIL-2 PIL-4 CIL
Three-leg	Entrance (90°)	Daylight No lighting PIL-2 PIL-4 CIL
Cloverleaf	Exit (270°)	Daylight No lighting PIL-1 PIL-1R (40 ft) PIL-2 CIL
Cloverleaf	Entrance (270°)	Daylight No lighting PIL-1 PIL-1R (40 ft) PIL-2 CIL

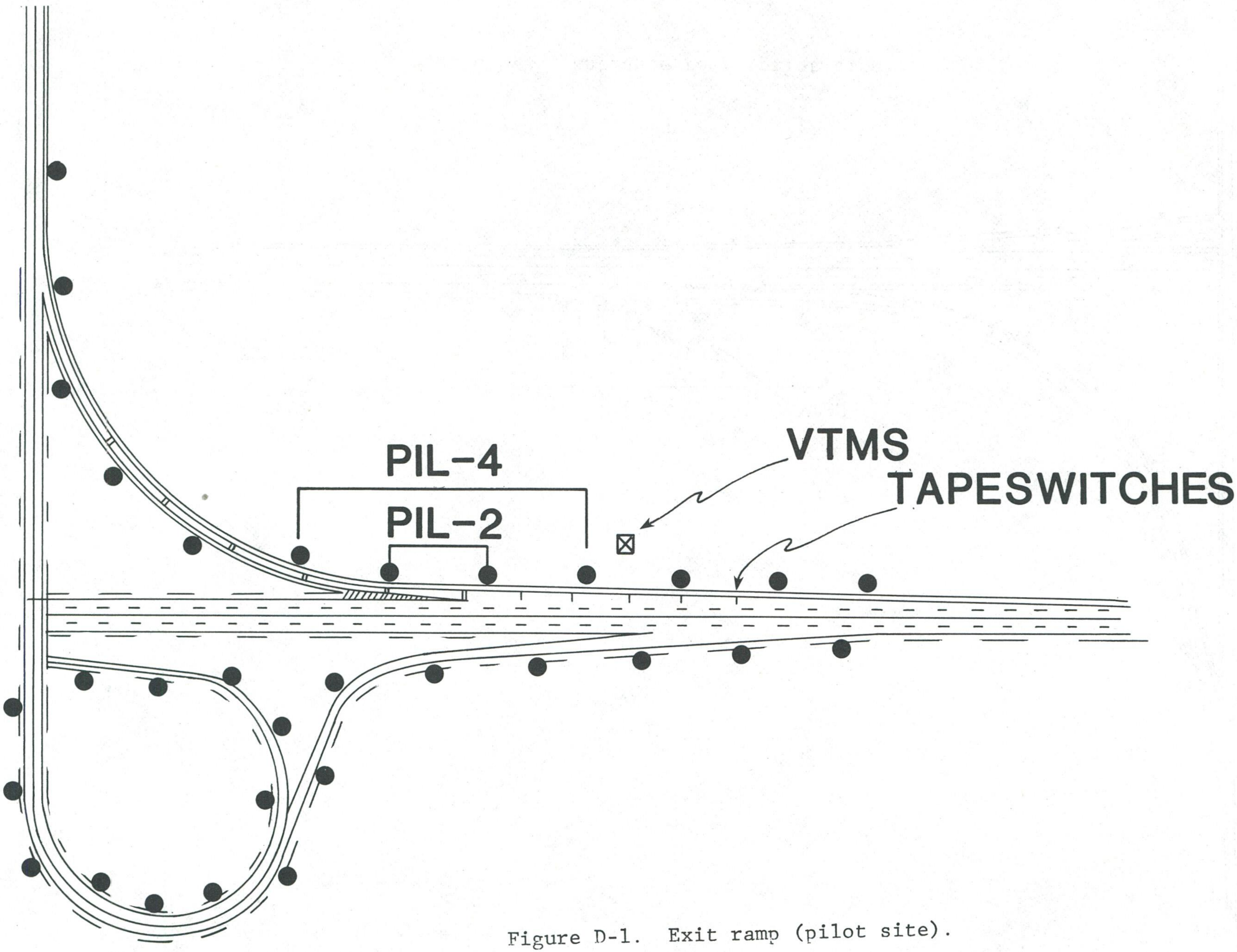


Figure D-1. Exit ramp (pilot site).

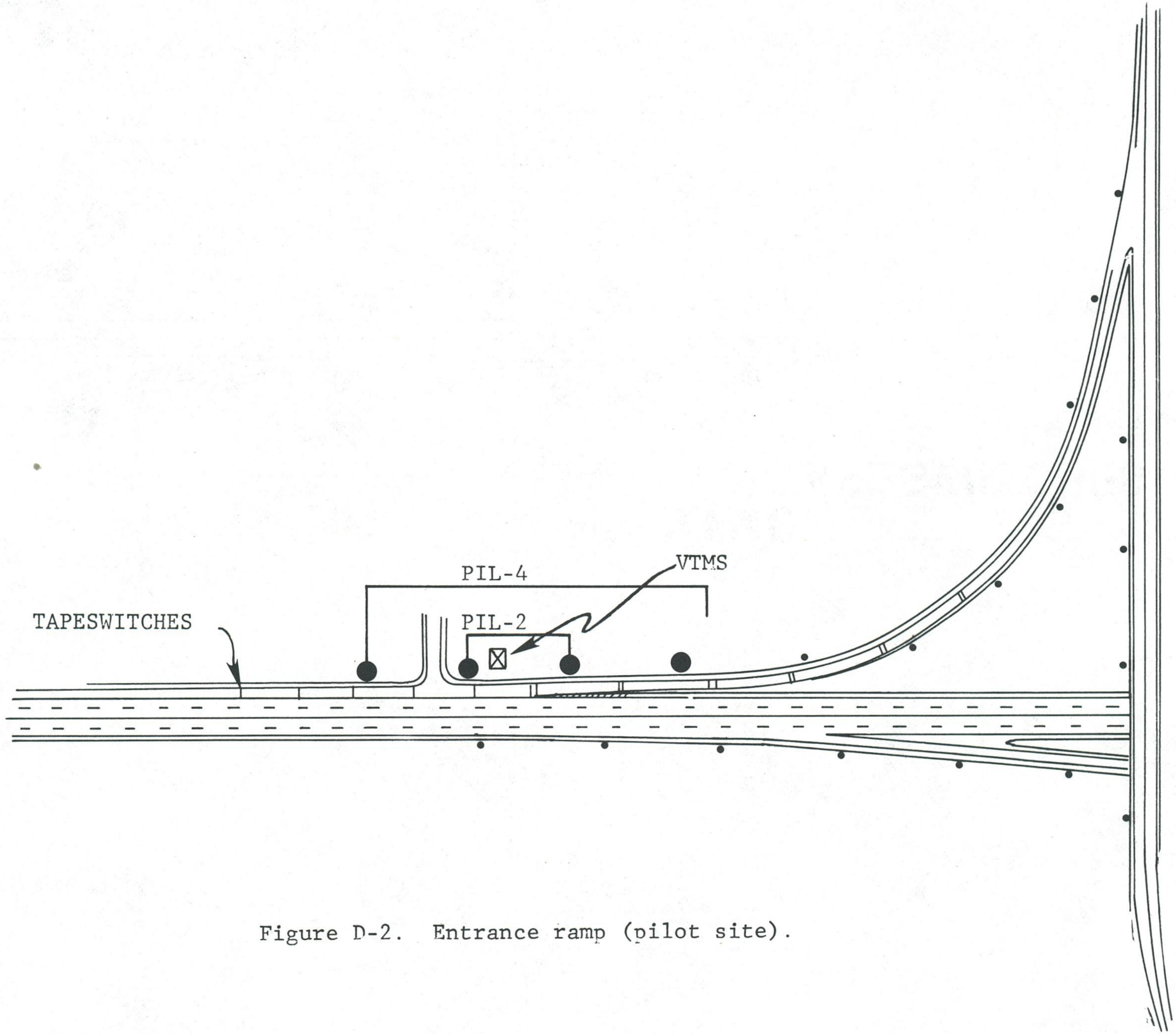


Figure D-2. Entrance ramp (pilot site).

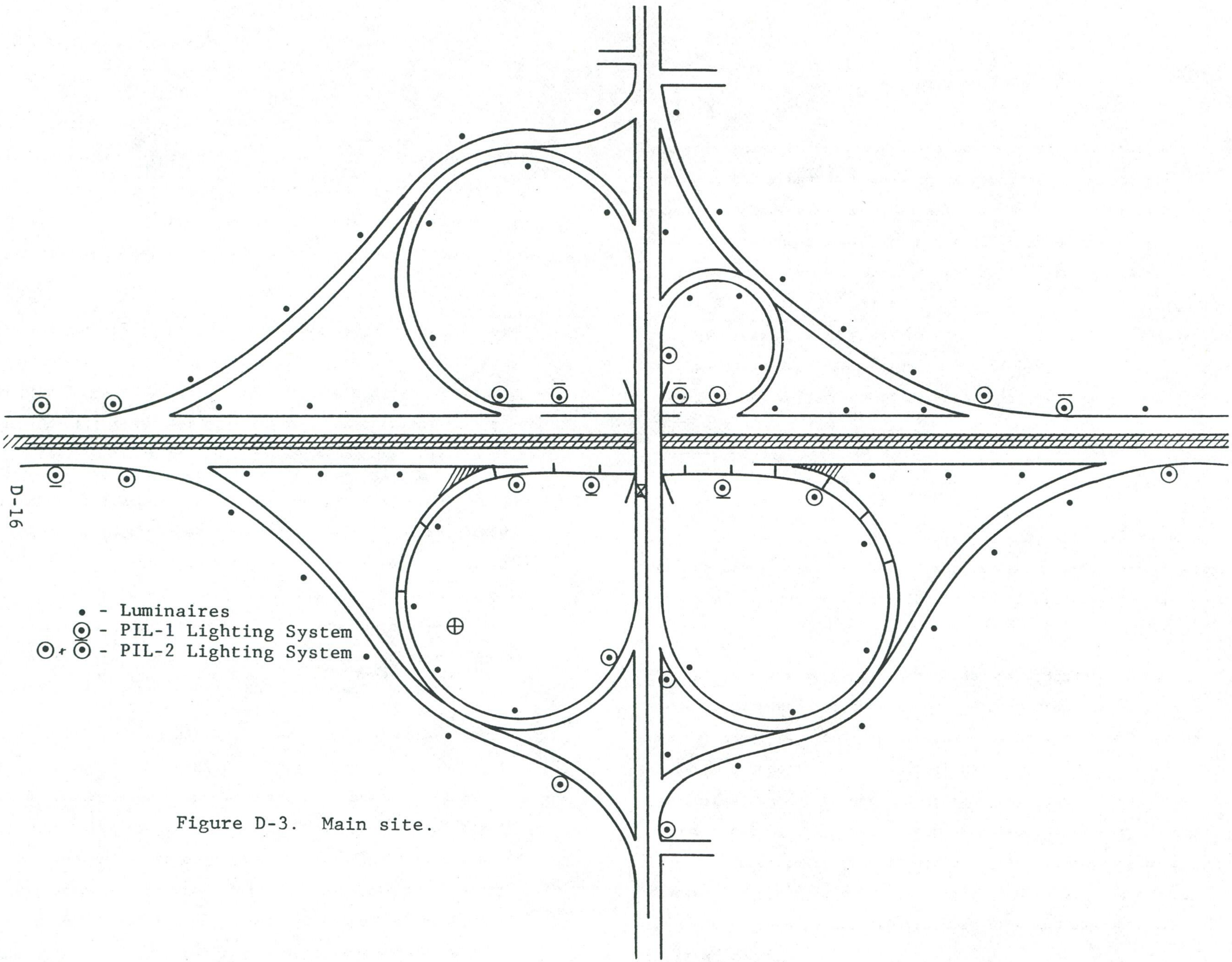


Figure D-3. Main site.

The PIL-1 configuration at the main site and the PIL-2 configuration at the pilot site correspond to the California practice (one or two lights per ramp); the PIL-4 configuration at the pilot site corresponds to the AASHTO practice (three to five lights per ramp); and the PIL-2 configuration at the main site approximates both the California practice (two lights per ramp) and the AASHTO practice (there are actually four lights in the weaving lane between the two gore areas).

Had a PIL-4 lighting configuration been used at the main site, the relatively short distance between gore areas (about 500 ft) would result in almost a CIL system on the main road. The PIl-1/PIL-2 configurations were selected instead. (The initial results of the pilot study also indicated that PIL-4 was inferior to PIL-2, yielding another reason to evaluate a PIL system with fewer luminaires (e.g., PIL-1).)

The testing order at the pilot site was exit (daylight, no lighting, PIL-2, PIL-4, CIL) followed by entrance (daylight, no lighting, PIL-2, PIL-4, CIL). A 2-week acclimation period was provided when the lights were first changed from CIL to no lighting for the exit, and 4 days acclimation was provided for the entrance.

The testing order at the main site was daylight (entrance-exit), no lighting (entrance-exit), PIL-1 (entrance-exit), PIL-2 (entrance-exit), CIL (entrance-exit), PIL-1R (entrance-exit). A 1-week acclimation period was provided before the no-lighting test condition.

LIGHTING CONTROL

A key issue in the experimental plan was the ability to control the CIL lighting system (i.e., to be able to reduce the CIL system to various levels of PIL). In this respect both systems were similar. Both employed individually fused luminaires powered through multiple electric circuits. The fuses were located at the base of each pole, and the electrical control panel was located in close proximity to the interchange (in a maintenance building about 1/4 mile from the pilot site and in a small steel shed located on the right-of-way of the main site.)

The no-lighting condition was set by deenergizing the main control panel. The PIL configurations were set by disconnecting fuses from the base of the poles and energizing only selected circuits.

DATA COLLECTION

Equipment

The data collection equipment, called the Vehicle Trajectory Measurement System (VTMS), is a simplified version of the FHWA TES. The VTMS has the capability of recording the time-position history (i.e., the trajectory) of an individual vehicle traversing a section of roadway--in this case an exit or entrance ramp--which has been instrumented with tapeswitch sensors. These sensors are merely electronic switches which can be purchased or fabricated in various lengths and which are applied to the road at predetermined locations (e.g., every 100 ft). As a vehicle passes over the switch, a signal is sent to the VTMS and the time and unique switch identification code is output on a printer. A single vehicle may then be tracked through the instrumented area of road by its time-position history (i.e., the times and codes of each switch). (There is no measurable effect of the data collection equipment on traffic operations (1).)

The equipment used for the data collection effort consisted of a series of tapeswitches, electronic circuitry, connecting cables, and output device (printer), as well as a power supply for operating the equipment in the field. The basic specifications are as follows:

INPUTS

1. Fifteen pairs of tapeswitches (30 switches).
2. Time marks (2)--manually input by separate clocks and switches.
3. Event recorders (3)--input by separate tapeswitches.

OUTPUTS

1. Identifier/time for each tapeswitch.
2. Identifier/time for each mark.
3. Totals in event recorders (output at fixed units of time, e.g., every minute and manually).

CONTROLS

1. On-off (system).
2. Reset--for switches (system). (There is no measurable effect of the data collection equipment on traffic operations (1).)
3. Reset--for event recorders (individual).

4. Start mode (i.e., switches 1-N, N≤30 open, all others closed).
5. Individual controls (on-off) for each tapeswitch (to delete individual switches and preserve logic).
6. Pilot light for each switch to show status (i.e., functioning normally, permanently shorted closed, permanently open). The light should flash as a vehicle passes over a switch; stay on if shorted (closed) and stay off if permanently open.
7. Time marks (2-push buttons). (Also on remote control box.)

POWER SUPPLY

12 VDC

RECORDING (OUTPUT) DEVICE

Printer

CABLES

Lengths	# of Each	Type
300 ft	6	7 conductor (6 switches and 1 ground)
100 ft	12	4 conductor
5 ft	6	4 conductor
100 ft	6	2 conductor

CONNECTORS (four types)

(5) between control panel and 7-conductor cables

(15) between 4-conductor and 7-conductor cables

(30) from tapeswitches to 4-conductor cables

(6) from event recorders to cables and to control panel

LOGIC

Step/Mode

1. Switches 1 through N open ($N \leq 30$) and switches (N + 1) through 30 closed. N variable.

2. Vehicle enters system and passes over switch N ($M \leq N$). Switches 1 through M closed; switches (M + 2) through 30 closed. Only switch (M + 1) open.

3. Vehicle passes over switch (M + 1). Switches 1 through (M + 1) closed; switches (M + 3) through 30 closed. Only switch (M + 2) open.

   (Continue logic incrementally)

4. After vehicle passes over switch 30, system resets into mode 1.

5. Alternatively you may choose to use only P switches ($P \leq 30$) and the logic of 2, 3, and 4 should repeat up to P, then reset.

VTMS can manually shift into mode 1 at any time, place two different time/identifier marks on the output tape at any time, record the totals in the event recorders at any time (and automatically every 1 min), delete any number of switches in the range 1 through P and still operate under the same logic, and start the clock without resetting the system into mode 1 (via time mark 2).

The tapeswitch layouts for the pilot and main sites are illustrated in Figures D-1 through D-3.

For the pilot site 17 switches were employed at both the exit and entrance ramps--five single switches at 100-ft spacings in the acceleration/deceleration lanes and six pairs at 150-ft spacings in the ramps, beginning at the tip of the gore. The

total length of instrumented area was 1,250 ft. The single switches were placed to record merge/diverge locations of individual vehicles and average speeds and accelerations in the acceleration/deceleration lanes. The six pairs were placed to record average speeds, spot speeds (at pairs), average accelerations (from average speeds), and spot accelerations (from spot speeds).

For the main study 12 single switches were employed covering a section of road 1,100 ft long: 500 in the weave area and 300 in each ramp. Pairs were not used since the analysis of the pilot study data revealed no advantages of pairs over single switches.

Procedures

Before data collection began, site visits were made to measure and mark the exact locations of the tapeswitches and to determine the best location for the VTMS (see Figures D-1 through D-3). These measurements were made during the daytime, and temporary marks were placed on the road indicating the exact position of each tapeswitch.

During one or more nights before data collection began, each site was visited and traffic observed to identify observational locations for the field crew. Since the brakelight activations and high-beam use were manually recorded (actually manually input into the VTMS, which then printed this information in a time code), it was necessary to place the field crew in a position where they could observe such events (gore and shoulder encroachments were automatically recorded). The locations are illustrated in Figures D-1 through D-3. Another reason for visiting the sites was to finalize the decision concerning sample size, i.e., how many nights were required to collect an adequate number of observations for each test condition.

For the velocity measures, it was necessary to collect 107 observations to ensure that a true 1-mph difference could be detected with 95 percent confidence 90 percent of the time (based on a standard deviation of 5 mph) (2). It was planned that 150 to 160 observations per study condition would be collected to allow for unanticipated data losses.

At the pilot site the proportion of observed brakers (on the nights before data collection) was found to be extremely high (up to 75 percent under no lighting) and the proportion of high beams was also relatively high (up to 13 percent under no lighting). Gore and shoulder encroachments could not be observed except under daylight and CIL.

Based on the actual night volumes on the ramps at the pilot site (observed at 50/h up to 11 p.m. and falling to 5/h before sunrise), it was planned that 2 nights would be allowed for each study condition. At the main site the ramp volumes often exceeded 60/h through midnight, falling only to 20/h by sunrise. Only one night per condition was thus planned.

On the night before data collection began, the research team met with a traffic control crew of the cooperating agency (either the Pennsylvania Turnpike Commission or the Maryland Department of Transportation). With the assistance of these agencies the tapeswitches were laid (affixed with double-sided tape and covered by wide duct tape), cabling was attached, the VTMS was checked out, and the entire system was tested. The entire procedure required about 4 hours.

Data collection began on the following day and continued every night except when there was rain. One VTMS malfunction, caused by nearby lightning, necessitated a 2-week delay to obtain VTMS parts (at the pilot site).

At the pilot site each test condition required 1 or 2 nights. At the Maryland site each test condition required only 1 night (the night volumes at the Maryland site were 2 to 3 times higher).

The field crew reported to the site about 1 hour before sunset (8:30 p.m.) to connect and test the VTMS (only the cabling and switches were left in place between study conditions). The lighting condition was always set at the conclusion of the previous night's testing.

At approximately 9:30 p.m. data collection began and continued until about 1 hour before sunrise at the pilot site or until about 2:00 to 3:00 a.m. at the main site.

Individual lead cars (entering or exiting) were identified by the upstream observer, the system was reset (by the observer at the VTMS), and the vehicle was automatically tracked through the interchange. Brake activations and high-beam occurrences of tracked vehicles at the pilot site were manually input by the VTMS operator after identification by either the VTMS operator or the upstream observer. (The field crew conversed via C-B radios.) At the main site the VTMS was modified to allow both members of the field crew to manually input brake activations or high-beam occurrences, so that locations (times) as well as frequencies of such events were recorded.

VTMS data were collected at the pilot site between September 23 and October 28, 1981, and at the main site between June 30 and July 16, 1982. Illuminance measurements were made at the pilot site the last week of October 1981, and luminance measurements were made in April 1982. Illuminance and luminance measurements were made at the main site during the second and third weeks of data collection, normally after 2:00 a.m.

PHOTOMETRIC MEASUREMENTS

Pilot Site

Photometric measurements were made at the exit ramp under CIL and PIL-2 conditions. Illumination was measured using a spectra illuminance meter every 20 ft in the center of the deceleration lane of the exit ramp and in the center of the right lane.

Luminance measurements consisting of target, pavement (two measures), and glare were measured with a 1980 Pritchard Telephotometer, employing a target developed by the research team in previous research (3). Target luminance, Lt, was measured using a 6-ft aperture centered on the target; glare, Lv, was measured using a 1° aperture with a Fry lens; pavement luminance, Lb, was measured using the split-slit aperture (3); and average pavement luminance, Lav, was measured using the CIE trapezoid aperture (3).

Figure D-4 illustrates the four points at which these luminances was measured. The four positions simulated

1. A motorist view of the beginning of the deceleration ramp (with the associated task of locating the beginning of the deceleration ramp).
2. Upstream of the gore in the deceleration ramp (equivalent to negotiating the deceleration ramp).
3. At the gore (i.e., locating the gore).
4. In the ramp (tracking the curved ramp).

The target was always placed in the center of the lane, and the photometer was located 272.5 ft upstream at a height of 4.76 ft.

Main Site

At the main site illuminance was measured in the entire instrumented area (i.e., between the first switch in the entrance through the last switch in the exit ramp) every 20 ft in the center of the lane for all four lighting conditions.

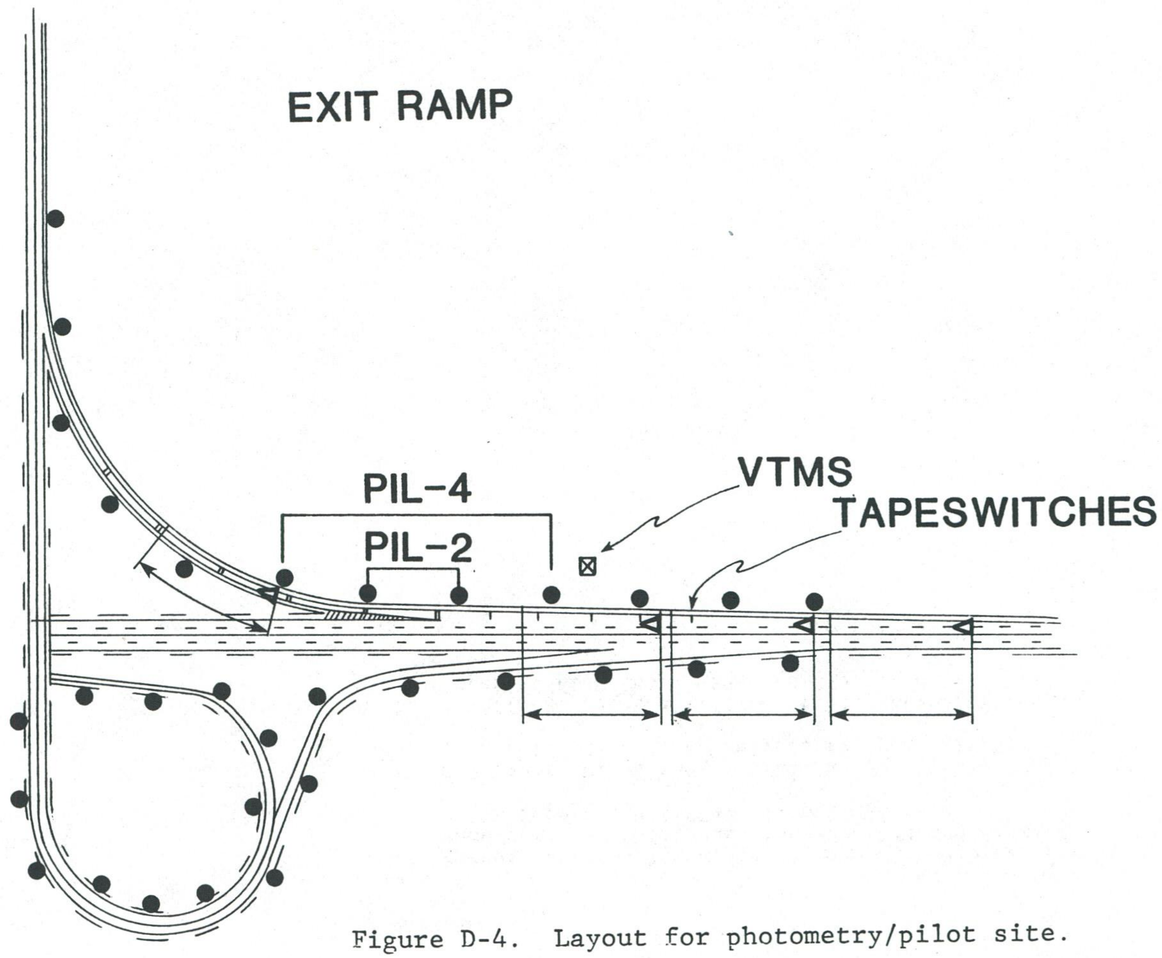


Figure D-4. Layout for photometry/pilot site.

Average pavement luminance (Lav) and glare (Lv) were measured following the same procedures as in the pilot study, under the three partial lighting conditions, at the three locations illustrated in Figure D-5. These three locations correspond to:

1. Entering view of merge point.
2. Exiting driver's view of diverge point.
3. Driver's view of center of weave area from downstream edge of weave area (view common to both exiting and entering drivers).

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2. Sneadecor, G. W. and Cochran, W. G., Statistical Methods (6th ed). Iowa State University Press (1967).

3. Janoff, M. S. et al., "The Effectiveness of Highway Arterial Lighting." FHWA PB-273527 (July 1977).

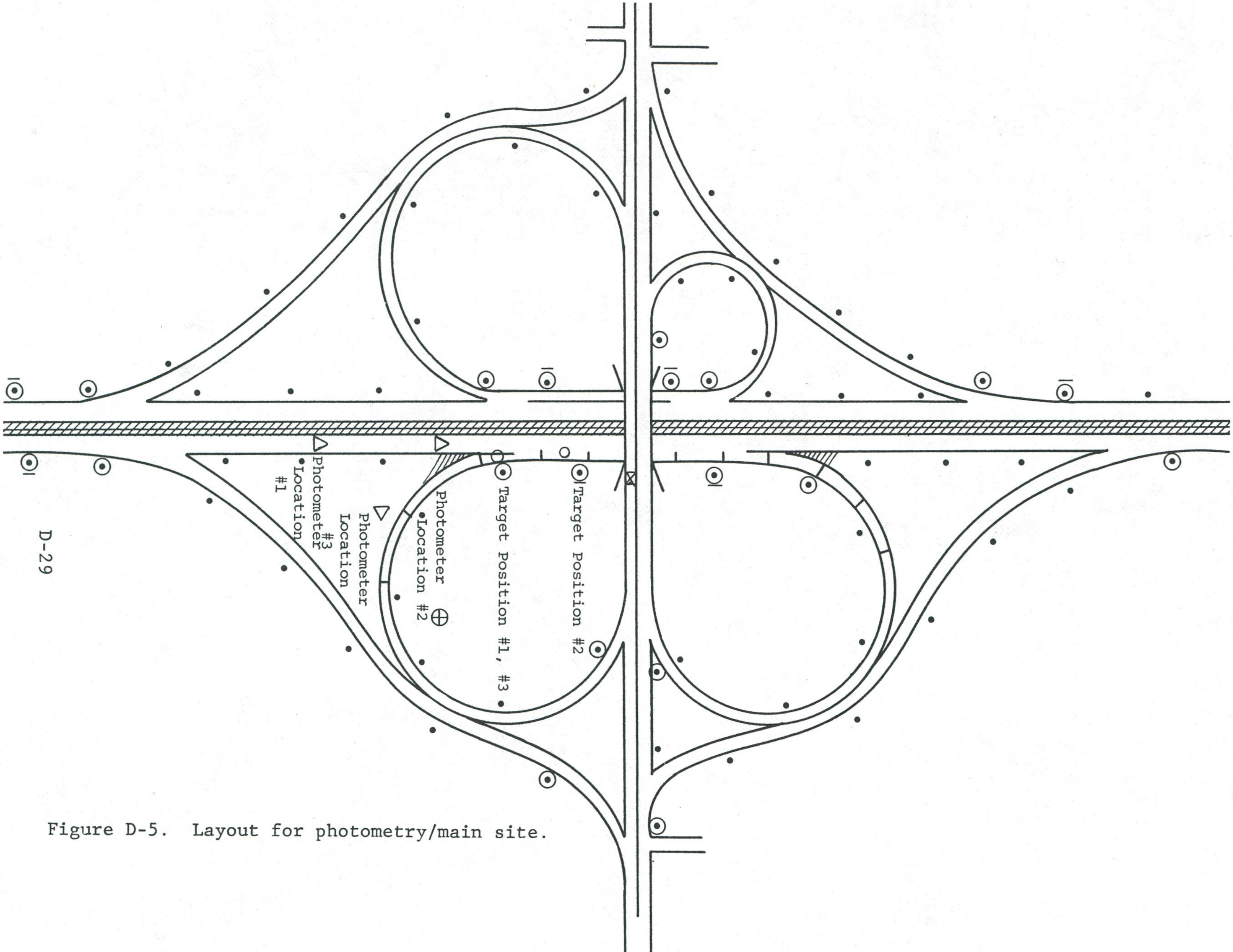

Figure D-5. Layout for photometry/main site.

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