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ROADWAY ILLUMINATION SYSTEMS
FINAL REPORT

by

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Research Report 137-2(F)
Roadway Illumination Systems
Research Study Number 2-8-69-137

Sponsored by the
Texas Highway Department

In Cooperation with the

Department of Transportation
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May, 1972

Texas Transportation Institute
Texas A&M University
College Station, Texas

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

Roadway Illumination Systems, Research Study 2-8-69-137, has been a cooperative research effort between Texas Transportation Institute and the Texas Highway Department, in cooperation with the Federal Highway Administration. The study was originally developed as a five-year effort at a funding level of $300,000, but was reduced to three years and approximately $130,000. As a result, the project objectives were terminated short of completion. This report presents the progress of the research through the three-year effort.

ABSTRACT

Discussions on test and evaluation of new lighting equipment and systems, high-mast lighting, transitional lighting, safety lighting, driver visual behavior, and lighting cost-effectiveness are given. Photometric data are given for newer light sources, as well as comparisons made with mercury vapor. A technique for extrapolation of photometric data is given which indicates close correlation with field measured data. High-mast lighting data and a design procedure is reported.

A relative hazard index was developed for use of luminaire supports in medians. The effect of glare upon driver behavior is also included. The eye-mark camera was used to determine driver visual behavior. A cost-effectiveness technique is reported that can serve as a tool for the decision-making process.

Key words--roadway lighting, light sources, luminaire supports, vision, cost-effectiveness, photometric data.

SUMMARY

Research was conducted under the Texas Highway Department Research Study 2-8-69-137, Roadway Illumination Systems. Investigations were made in the areas of tests and evaluations, high-mast lighting, transitional lighting, safety lighting, driver visual behavior, and lighting cost-effectiveness.

Tests and evaluation of high-intensity discharge lamps revealed a high degree of effectiveness for the high-pressure sodium. Public opinion surveys also indicated good acceptance by the public.

Based on the crash tests and analysis conducted in this research, it appears that breakaway luminaire supports may be used safely in medians 32 feet or wider without guardrail or barrier protection.

A model for extrapolating illumination data was developed. Comparison of model results with field measured data indicated virtually an absolute correspondence.

A design process, readily adaptable to computer application was developed. The process uses candela curves and point-by-point calculations.

Investigations of transitional lighting and glare indicated that these factors affect steering wheel reversal rates and speed. Brake pedal movements, gas pedal movements, and vehicle side force were not affected.

Diagnostic studies of safety lighting at two interchange locations resulted in 11 guides to be considered in safety lighting.

The eye-mark camera system was used to study driver visual behavior. Limited analysis of data indicated that road geometry is a key visual input to drivers.

A cost-effectiveness technique was developed to serve as a tool for the decision-making process. Guides were developed to assist in making selections from alternative designs.

IMPLEMENTATION STATEMENT

Although the research reported herein was terminated before completion of the project objectives, several findings are deserving of implementation.

Tests and evaluation of high intensity discharge lamps, notably high-pressure sodium, indicate immediate application. The high pressure sodium lamps can be used effectively and economically for continuous lighting applications. Photometric data for the lamps are available from the Department.

The tests and evaluation of IES Type V and Type III (asymmetric) light units also indicate immediate application to high-mast lighting. These units can be used to provide very effective lighting in interchange areas.

The design process reported herein can be used for high-mast interchange area lighting design. The process is readily adaptable to computer application, reducing the need for time-consuming hand calculations.

Safety lighting design may benefit from considering the eleven primary guides established through the field studies. The limited results of the eye-mark camera studies may also be used to assist in determining lighting needs at interchange areas.

The cost-effectiveness technique should provide the designer and administrator a tool for the decision-making process. Alternate designs may be evaluated to insure optimum results.

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INTRODUCTION

The Problem

The cooperative research project, "Supplementary Studies in Roadway Illumination," contributed greatly to the technology of roadway illumination of freeway type facilities. This project, approached in truly a cooperative manner, yielded results that were directly applicable. The basic framework for the establishment of design specifications for roadway lighting by the Texas Highway Department and other states resulted from the research. However, the research was conducted in such a manner as to provide the greatest expediency in designing more functional roadway lighting systems. Specifically, the greatest emphasis was placed on subjective development of roadway lighting systems which provide a better driving environment for the modern high-speed freeway driver.

In projects conducted in this manner it is difficult to extrapolate the results to systems with different characteristics and to establish design criteria on job specifications. Many questions that underlie the basic highway lighting problem remain to be answered. The subject research of this report was addressed to some of these questions.

Objectives

The overall scope of this research was to improve the safety and efficiency of operations in the night driving environment through optimization of roadway illumination systems. Seven objectives were established in response to this scope:

1. Test and evaluation of new lighting equipment and systems.
2. Test and evaluation of high-mast lighting as related to the driving environment so as to assure that appropriate environments are being created for the driver.
3. Development of performance criteria for luminaire and floodlight designs to effectively create a satisfactory driving environment.
4. Development of performance criteria for transitional lighting that will assure compatible changes in the driving environment.
5. Development of performance criteria for safety lighting of rural interchanges that will provide for safety and efficiency of operation.
6. Development, test and evaluation of equipment and measures of driver visibility and comfort under night driving environments to use as "figure of merit" for functional lighting.
7. Determination of roadway illumination benefits through economic and safety analysis in an effort to determine the effectiveness of illumination.

Each of the seven objectives is amplified in the following paragraphs.

Test and Evaluation

Due to the rapid advancement in technology of lighting, there is a need to continuously examine roadway lighting practices to assure that optimum results are being obtained. This objective was established to provide flexibility throughout the project duration in the testing and evaluation of new concepts, equipment or schemes that indicated possible practical application to roadway lighting. These concepts, equipment and schemes could originate from the research agency, industry, or the sponsor.

High-Mast Lighting

High-mast lighting has shown tremendous potential in illuminating interchanges, and other large areas, safely and efficiently. However, the concept is yet young and yet to be proven in all respects. This objective was established to answer some of the more pressing questions involving application of the technique.

Criteria for Luminaire and Floodlight Design

Current roadway lighting practices are based on application of presently available equipment, much of which is outdated with regard to technology. The need exists to develop criteria for luminaires that will produce desired results, rather than developing performance criteria on the basis of what existing equipment will do.

Criteria for Transitional Lighting

Only vague attempts have been made to specify the applications of transitional lighting. In this area of study, there is a need to realistically define transitional lighting and its applications.

Criteria for Safety Lighting

A pressing problem for the Texas Highway Department has been the application of "safety lighting" to the hundreds of rural interchanges on the Interstate Highway System. The "how, when, and where of safety lighting" have been the frequent questions that demand attention.

Driver Visibility and Comfort

This area of study was intended to be a support service for testing and evaluation of the other areas of study. Major emphasis was to be placed on the physiological and psychological behavior of the driver and on measurable variables of the night-driving environment.

Economic and Safety Analysis

As with the expenditure of any funds, lighting costs are seriously examined by highway administrators. This area of study is addressed to cost-effectiveness and safety analysis of lighting system design as a tool for the decision-making process.

TESTS AND EVALUATIONS

High Efficiency Discharge Lamps

The mercury vapor discharge lamp has been the work-horse of roadway lighting for many years. Its desirable attributes of acceptable color rendition and long life have proven very attractive to the lighting designer. However, its efficacy (output of light in the visible spectrum as related to power input) of approximately 55 lumens per watt has left much to be desired. Recent developments in higher efficacy lamps, notably metal halides and high-pressure sodium, indicate major breakthroughs for application. Both metal halide and high-pressure sodium lamps were examined during the course of this research.

Metal Halides

Metal halide lamps involve the combination of various metallic vapors in the arc tube as compared to primarily mercury vapors in the mercury vapor lamp. Metal halide lamps provide 85-90 lumens per watt and are available in sizes of 175-1000 watts for highway lighting application. The present rated life (20 percent lumen depreciation) is 12,000 hours, roughly one-half that of mercury vapor. Manufacturers of the lamps express confidence that this rating will be increased in the near future.

To determine the feasibility of using metal halide lamps in conventional lighting design, photometric data were collected for comparison to mercury vapor by the Texas Highway Department. Test procedures for collecting the data have been reported previously[1].

The test photometric data were reduced to iso-footcandle diagrams and submitted to the sponsor. These diagrams are available from the sponsor on request. The test data revealed that if a luminaire mounting and spacing were optimal for a mercury vapor source, replacement with the equivalent wattage metal halide lamp and ballast did not effect an overall improvement. The general result was a "hot-spot" (in excess of 5 footcandles for the 1000-watt unit at 50-foot mounting height) directly below the lamp, and otherwise similar distribution. Uniformity was changed from approximately 3:1 to nearly 10:1. The conclusion was that overall system compatibility must be designed for, including the luminaire itself. A short discussion of an evaluation of the multi-vapor lamps is included in the appendix.

Use of metal halide lamps for high-mast lighting has proven much more effective and is reported in later sections of this report.

High-pressure Sodium

One of the newest editions to the discharge lamp family is the high-pressure sodium vapor lamp. This lamp, with an efficacy of 120 lumens per watt and rated life of 20,000 hours, is proving to be very popular with lighting designers. Its high output and relatively long, and increasing, life offer substantial savings in costs of maintenance and operation.

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[1]Refers to corresponding references in the List of References.

Photometric data were collected for the high-pressure sodium lamps and reduced to iso-footcandle diagrams (available from the sponsor). In general, the 400-watt high-pressure sodium lamp produces comparable results to the 1000-watt mercury vapor in single, dual and continuous installations. Additional benefits may be realized in the future from the high-pressure sodium due to its small size and expected increases in efficacy and life.

<u>Light Source Color</u>

There have been, in the past, several negative comments from lighting designers regarding the color of certain lamps. Mercury vapor received these comments for years and the color-corrected lamps resulted. In the meanwhile, the public and the designer began to accept the blue light of the mercury. Metal halides, utilizing the various metal additions, have missed most of the negative comments because of its superior color rendering properties. High-pressure sodium, however, has not been so fortunate. In fact, negative comments from designers on the source, have exceeded those originally bestowed upon the mercury vapor.

Public opinion surveys were conducted in this research to test the acceptance of high-pressure sodium by the motorist. These surveys were conducted for two high-pressure installations in College Station and Dallas. The results strongly indicated that the high-pressure sodium is acceptable and in fact preferred by the motorist over mercury vapor lighting. Similar responses to installations in other states have been received.[2] The designs, surveys and their results are presented in the appendix of this report. The reader is referred to this appendix for details.

Pavement Texture and Color

It has long been apparent that both pavement texture and color affect the end result of roadway lighting. It appears that those attributes producing good pavement texture for anti-skid properties are detrimental from the lighting standpoint.

In this research effort, it was originally planned that detailed literature reviews and field studies be conducted to identify the interaction between pavement texture and color and reflectance. This phase of research was not completed, however, due to project termination, and the progress to date includes only the literature review. A summary of this review is included in the appendix.

Crash Testing

The Texas Highway Department has been a forerunner in the use of median-mounted luminaires. Quality of light and economy have been strongly in their favor. Objection has been voiced, however, to the use of median mountings unless the median equals or exceeds the mounting height of the light source. This objection has been based on the thought that secondary collisions may occur with a downed pole occupying a traffic lane. To resolve this problem, it was requested that crash tests be conducted to determine the severity of this problem.

Three full-scale crash tests were conducted using 50-foot luminaire supports. The results indicate, based on relative hazard, 50-foot supports may be used in medians of approximately 32 feet or wider. Details of these tests are being published in a report on Research Study 2-8-68-146. A technical memorandum on development of a relative hazard index for luminaire supports is contained in the appendix of this report. This memorandum resulted from the crash tests. For further details the reader is referred to the 2-8-68-146 report.

Extrapolation of Illumination Data

In the design of lighting systems it is often necessary to determine the illumination distribution pattern for many different types of luminaires at several mounting heights. Field measurement of illumination distribution patterns is possible, but is a tedious and costly procedure. Moreover, the precision of field measurement depends on a combination of several elements; perhaps the most important is properly trained personnel. Other important factors are control of electric power, adequate measuring instruments, and meticulous care to avoid sources of error which frequently arise from insecure luminaire mounting, stray light and infrequent inspection of electrical equipment.

In the solution of engineering problems it is always convenient to create hypothetical models of experiments to facilitate computation of the theoretical data. This reduces the engineer's difficulty by minimizing the need to collect and analyze field data.

In this research effort a mathematical model, based on Lambert's Cosine Law of Incidence, was used to estimate the horizontal illumination at any point on a horizontal plane for different mounting heights. Field collected data were used to check the accuracy of the extrapolation. Statistical results indicated virtually an absolute correspondence in the measured and extrapolated data.

A full report on this research effort is included in the appendix.

Modification of Old Systems

The state of Texas has some installations of roadway lighting that are considered to be sub-standard. It was desired in this research effort to make a study of the methods and feasibility of modifying these systems to meet current standards.

The research agency and Texas Highway Department worked cooperatively in the initial formulation of a plan of research for this effort. The plan involved basic investigations of existing foundation and circuit capacity and methods of increasing the effective mounting height of light sources.

The Texas Highway Department was to be responsible for the analysis of foundation and circuit capacity whereas the research agency was to be responsible for methods of increasing effective mounting height. This research effort was terminated in favor of other areas. The department also felt that there existed sufficient information to permit engineering analysis of the feasibility of modifying any particular sub-standard system.

Tests for Texas Highway Department

In addition to the specific items discussed previously, the Tests and Evaluations effort provided a testing service to the Texas Highway Department. Several luminaires, including low-pressure sodium from Europe, were tested. The primary purpose of the tests was to indicate possible application to Texas lighting. Test data for the several luminaires were submitted to the Department.

HIGH-MAST LIGHTING

Higher Heights

Previous studies in high-mast lighting under Research Study 2-8-64-75 (3) indicated that heights greater than 100-150 feet may be desirable for complex multi-level interchanges. It was requested by the Texas Highway Department that heights of 150-250 feet be investigated in this research project.

Initial plans required the purchase and installation of a 250-foot self supporting tower for the higher-height studies. This plan was approved and preliminary foundation and support investigations were conducted by the research agency. However, decisions were reached which terminated this plan in favor of limited studies by the Texas Highway Department at the University of Texas Balcones Research Institute, and extrapolation studies by TTI. The results of the extrapolation studies are reported in the appendix. Results of the limited studies at Balcones by the Texas Highway Department are available from the Department.

New Luminaire Units

In addition to the study on higher heights, the research agency investigated the use of new IES Type V and IES Type III (asymmetric) light units. These investigations involved various light sources and light center placement within the units. Results of these tests were submitted to the sponsor in grid data and isofootcandle form. The grid data are included in the appendix.

Design Process

Research Report 75-12, "High-Mast Lighting" (3) reported a preliminary design procedure for high-mast lighting based on use of isofootcandle curves. A procedure, readily adaptable to computer application, has been developed during the course of this study, and is reported in the appendix.

TRANSITIONAL LIGHTING

Two efforts have been involved in this area of study. The first effort was a support service to the Texas Highway Department in providing trial installations of transitional lighting at the Texas A&M Research Annex. The second effort involves detailed study of transitional lighting effects on driver performance and behavior.

Support Service

Trial transitional lighting systems were installed on the portable lighting towers at the Research Annex. These systems were installed upon request of the Texas Highway Department. Engineers from the Department made subjective evaluations of the systems for possible field applications.

The systems evaluated by the Department consisted of gradual increases and decreases in lighting intensity into and out of higher intensity areas.

Transitional Lighting and Driver Performance

This research was undertaken to examine the relationship between glare factors in a transitional highway lighting system and driver behavior. The hypothesis was tested that the level of glare in a transitional lighting system has no measurable effect upon driver performance.

In this study, five measures of driver behavior were objectively examined under four different lighting conditions. The five measures were vehicle speed, steering wheel reversals, gas pedal movements, brake pedal movements, and side force. The four lighting conditions consisted of 3 experimental transitional lighting conditions and one control condition. The fixed lighting in the 3 experimental conditions was provided by 9 luminaires mounted at 50 feet on portable towers and spaced 240 feet apart. In the control condition illumination was provided by the vehicle headlight system. In Experimental Lighting Condition 1(E1), illumination was provided by nine 1000-watt luminaires. In Experimental Lighting Condition 2(E2), illumination was provided by graduating the wattage of the nine luminaires from 175 watts to 1000 watts and back to 175 watts. In Experimental Lighting Condition 3(E3), illumination was provided by graduating the wattage of the nine luminaires from 175 watts to 700 watts and back to 175 watts. (See Table 1, page 135)

A total of 24 volunteer male subjects, six for each lighting condition, drove an instrumented vehicle through a test course. Data were continuously recorded on magnetic tape during the time the instrumented vehicle was in the test area portion of the test course.

A completely randomized analysis of variance design was used to determine if there were any significant differences between test groups. The significance level chosen for the analysis was the 0.05 level.

Results of the study did not support the hypothesis that the level of glare in a transitional lighting system has no measurable effect upon driver behavior. Two measures, speed and steering wheel reversals, were found to be significantly affected by glare. The other measures, gas pedal movements, brake pedal movements, and side force were not significantly affected:

The conclusions drawn were:

1. Glare in a transitional situation does have an effect upon two measures of driver behavior: speed and steering wheel traversals.
2. Brake pedal movements, gas pedal movements, and side force are not affected significantly by glare.

Details of the study are reported in the appendix.

SAFETY LIGHTING

An objective was established with the overall research project to develop criteria for safety lighting of rural interchanges. A pressing problem for the Texas Highway Department has been the application of safety lighting to the hundreds of rural interchanges on the Interstate Highway System. The "how, when, and where" of safety lighting have been the frequent questions that demand attention.

To arrive at a solution to the objective, subjective criteria from the literature were established. Diagnostic field studies were then planned to evaluate the criteria. Two interchanges in the Paris District were selected for study. It was anticipated that the interchanges would be used for "before" and "after" studies and supplemented by additional studies in Eastland County. "Before" studies were conducted at the Paris locations. However, since the project was terminated, follow-up studies at Paris, and the supplemental studies in Eastland County were not conducted. Therefore, the guidelines established must be considered as tentative and not final.

The diagnostic studies were conducted by a team of eight members. Questionnaires, interviews and review sessions were used for data collection. Techniques for the studies have been widely used in past research (4), (5), and (6).

Because of the premature termination of the research effort, the "after" studies for safety lighting could not be conducted. In order to present useful results from the studies conducted, it was necessary to draw heavily on prior experience and professional judgment of the researchers to supplement the results of the "before" studies. On this basis, the following eleven "guidelines" for the design of safety lighting are offered:

1. The location of the entrance point to a frontage road or an on-ramp from the major arterial is difficult to identify at night. Delineation and signing are the basic informational sources. Illumination is needed in complex situations to complete the total information for the driver. Channelization adds to the complexity of maneuver points and most generally requires illumination for full understanding for what is required of the driver.

2. The definition of entrance ramps from frontage roads, particularly two-way frontage roads, are difficult to identify at night. Signing and delineation are of utmost importance. Illumination can be helpful, particularly from the standpoint of geographic orientation at this point in the interchange.

3. At the merge point of the ramp with the main lanes, it is first necessary that the driver be able to identify the section of roadway at which the merge is to take place. Delineation is a great asset, but, due to the limited distance over which headlights are effective, it is frequently advantageous to provide illumination to fully identify the complete merge section.

4. At the merge point it is necessary that the driver be able to positively identify the main lanes of the facility with which he is merging prior to the merge point. Also, he must be able to judge the position, speed, distance, and closing rate of traffic

in the main lanes prior to the merge point. Detection of the vehicles is not a difficult task under unlighted conditions, but the remaining informational needs are virtually impossible to obtain unless the main lanes are illuminated prior to the merge point. Critical geometrics, such as horizontal or vertical curves, in the merge area and on the main lanes prior to the merge area tend to compound the problem severely because the driver seldom has the cue or cues in which to correct his expectancies to fit the geometric requirements.

5. In the exit ramp situation, it is first necessary that the driver identify not only the ramp nose, but also the beginning of the point of divergence as well. Signing and delineation are the two most common methods of identifying these points, but the task becomes considerably more complex when the pavement markings are weak and there is little or no natural delineation of the pavement surfaces. Also, there is the matter of extraneous lighting at many of the interchanges, and this tends to reduce the driver's visibility through a veiling brightness effect.

6. Once the driver has negotiated the exit maneuver, ramp geometry becomes a serious informational need. Critical vertical alignment, such as existed in the diamond interchange, results in a loss of visual contact with the roadway surface, even within the range of the vehicle headlights; however, this is not a problem that can be effectively solved with illumination. Horizontal alignment, particularly on ramps connecting to two-way frontage roads, are

common examples of critical horizontal alignment. These can be remedied considerably with illumination, provided there is sufficient coverage to properly define the geometry.

7. The connection of the ramp to the frontage road poses informational problems in some instances. In rural areas where there is no extraneous lighting, it is not too difficult for the driver to satisfy his informational needs regarding the geometry of the roadway and other traffic; however, the addition of extraneous lighting from adjacent development frequently compounds the problem beyond that which can be remedied through the normal processes of markings and pavement delineation.

8. Once the driver has negotiated the maneuver onto the frontage road and has been made aware that it is, in fact, a two-way frontage road if such condition exists, the next major informational need occurs at the intersection of the frontage road with the interchanging traffic facility. Assuming that there is the minimum level of control, a stop condition at the intersection, the driver's informational needs can be described mainly as geometric and operational. He must first ascertain the geometric configuration of the intersection, particularly if the arterial is divided and there are other channelization features. In this particular study there was a strong tendency for drivers to turn on the wrong side of a divisional island simply because they could not see the roadway surface beyond the divisional island under normal headlight conditions. When the driver must concentrate so

intently on the vehicle path, he has a tendency to overlook the presence of oncoming vehicles on the arterial. Further, without lighting on the arterial it is somewhat difficult to detect the speed, distance, position, and rate of closure of traffic on the arterial. In summary, as the width of the interchanging arterial increases, and as channelization features are introduced, the complexity of the driving situation increases, and the need for illumination to supplement the vehicle headlights increases.

9. As a general indication from the team study, certain points can be made concerning the need for illumination of a diamond-type interchange. The character of the diamond interchange is such that interchanging maneuvers are much more identifiable because of the obvious differentiation between the main lanes of the freeway and the ramps. Thus, the principal function in providing sufficient information to the driver is to use the various techniques or devices that help him to identify the various elements of the roadway. When this is accomplished, it is not difficult for the driver to determine the proper maneuvers. On the other hand, a directional interchange poses a completely different situation. Most frequently, directional interchanges are composed of a series of turning roadways that are designed for the same, or similar operational requirements. Thus, the maneuvers required of the driver are those of direction-finding, rather than the responding to rapidly-changing roadway conditions. This suggests that the informational require-

ments for negotiating a directional interchange are more strongly related to continuity of the communications system more than interpretation of roadway geometry. However, there is the consideration that the driver must maintain a reasonable level of orientation throughout the directional interchange which frequently calls for additional sources of information to be made available at the terminal points or connections of the turning roadways.

10. In the team study of the directional interchange in Paris, there were a number of geometric deficiencies that created problems from the standpoint of the driver not having sufficient information to perform safely and efficiently. The first of these was an at-grade intersection. The team members indicated that the large expanse of pavement, in conjunction with confusing signs, simply could not be interpreted under nighttime conditions. Since these confusing factors were not a problem during daylight hours, apparently lighting, or illumination, would alleviate the problem.

11. Where loop-type ramps are incorporated in a directional interchange, it is of utmost importance that the driver be able to identify the point of exit and entry and also be able to see the surface of the ramp and judge its safe operating speed well in advance in order to make the necessary adjustments. In this particular study, it was found that this information was not available

during daylight hours and was even more critical at night. This substantiates the fact that lighting frequently can help the driver to identify geometric deficiencies, but cannot by any means provide a total solution.

DRIVER VISIBILITY

One apparent problem involving roadway lighting is the determination of those elements of the visual environment that serve as input for proper vehicle control and operation. A number of attempts have been made to characterize driving performance in terms of the ways and means in which drivers extract information from the environment and translate this information into vehicular control action. Some of the more significant efforts have been those of Gordon (7), Senders (8), Rockwell, Ernst, and Rulon (9), and Woods, Rowan, and Johnson (6).

The current research being reported investigated the use of the eye-mark camera as a means of determining driver visual behavior. The assumption was made that night visual behavior will approximate that of day when given the opportunity. The immediate objective was to determine distinct daytime driver visual behavior and to extrapolate to nighttime conditions. It was concluded from the limited analysis that:

1. Both sides of the traveled way should be visible to the driver.
2. The far side of geometrics involving lane changes, ramps, etc., should either be visible, or some vertical cue provided.
3. The need for information provided by road geometry takes precedence over information provided by other visual cues.

4. The traveled way should be delineated, especially when there is a change in alignment. In cases where the traveled way was not delineated, the subjects used other features of the roadway as substitute.
5. Critical and complex geometric features should be clearly visible and, where possible, unrestricted sight distance should be provided. This is predicated on the fact that a disproportionate amount of the driver's viewing time was spent on complex geometric features and areas with limited sight distance.
6. Key geometric features should be visible from 600 to 1200 feet ahead, depending upon speeds and other conditions.
7. Those areas involving the most view time (critical maneuvers, geometry, limited sight distance, etc.) probably warrant lighting.

Details of the eye-mark studies are reported in the appendix.

COST-EFFECTIVENESS

Cost-effectiveness is the only method of economic analysis amenable to roadway lighting. All other methods use monetary evaluations of effectiveness, and not all lighting effectiveness can be measured in dollar terms.

A cost-effectiveness technique was developed within the scope of this research to serve as a tool for the decision-making process. This research was reported as Research Report 137-1. A summary of this report is given in the appendix.

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COMPARISON OF MERCURY VAPOR, MULTI-VAPOR, AND METAL ARC LAMPS FOR USE IN ROADWAY ILLUMINATION SYSTEMS

COMPARISON OF MERCURY VAPOR, MULTI-VAPOR AND METAL ARC LAMPS FOR USE IN ROADWAY ILLUMINATION SYSTEMS

The data for this comparison was obtained at TTI using Metal Arc and Multi-Vapor lamps in a luminaire that was designed for mercury vapor lamps. Data for mercury vapor lamps in this luminaire were on record from previous studies.

Horizontal footcandles were measured over an area consisting of 20x25 foot intervals. Three sets of measurements were made for each type of lamp at two different mounting heights, 50 feet and 60 feet, so that an average of three measurements was obtained at each point for each lamp at a particular height.

To show the intensity variations due to different lamps at a particular height a statistical parameter, σ^2, known as the variance,* was calculated for each of the three points corresponding to a particular set of data for Metal Arc and Multi-Vapor lamps. These values are arranged similar to raw data for one quadrant with the luminaire positioned in the top left hand corner, denoted "pole." This shows that replacing a lamp with another of the same type will probably cause a considerable change in intensity near the pole but

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*The variance is defined as $\sigma^2 = \frac{\sum_{i=1}^{N}(E_i-\overline{E})^2}{N}$

where E_i is the intensity at a particular point, $\overline{E}$ is the average of all measurements at that point and N is the number of measurements.

the change becomes negligible seventy-five to one hundred feet from the pole. (Due to the wide use of mercury vapor lamps, variance analysis of these would not be pertinent to this report.)

In comparing photometric data from this study with that from a similar study on mercury vapor lamps, the following is to be noted:

1. The area covered for a given intensity is about equal, ±10%.
2. Visibility and glare are not noticeably affected.
3. Colors are least distinguishable under mercury vapor lighting.
4. Metal Arc lamps showed the widest variation in output.

To conclude this report, the study indicates that to obtain full benefit from the higher output Multi-Vapor or Metal Arc lamps, luminaires designed for these lamps would have to be employed rather than the existing luminaires for mercury vapor lamps.

Variance of Intensity for Three Multi -Vapor Lamps at 50' Mounting Height

Distance - feet

Pole X (Distance - feet)	20	40	60	80	100	120	140
25	3.74	.506	.028	.006	.005	-	-
50	1.20	.428	.033	.012	-	-	-
75	.29	.154	.019	.003	-	-	-
100	.05	.070	.013	.012	-	-	-
125	.06	.010	.008	-	-	-	-
150	-	.003	.002	-	-	-	-
175	-	-	-	-	-	-	-

Variance of Intensity for Three Multi-vapor
Lamps at 60' Mounting Height

Distance - feet

Distance - feet: Pole X	20	40	60	80	100	120	140
25	2.470	.430	.084	.007	.002	-	-
50	1.200	.690	.073	.016	.004	-	-
75	.310	.070	.016	.003	.001	-	-
100	.150	.085	.010	.052	-	-	-
125	.022	.020	.004	.033	-	-	-
150	.020	.040	.007	-	-	-	-
175	.030	.020	.007	-	-	-	-

Variance of Intensity for Three Metal
Arc Lamps at 50' Mounting Height

Distance - feet

Distance - feet / Pole X	20	40	60	80	100	120	140
25	5.620	1.480	.074	.048	.034	.017	.007
50	6.110	2.290	.394	.031	.060	.030	.006
75	2.340	.316	.004	.048	.007	.017	.011
100	.512	.163	.020	.026	-	-	-
125	.348	.169	.007	.007	-	-	-
150	.076	.042	.003	-	-	-	-
175	-	-	-	-	-	-	-

Variance of Intensity for Three Metal Arc Lamps at 60' Mounting Height

Distance - feet

Distance - feet: Pole X	20	40	60	80	100	120	140
25	2.330	2.600	.089	.002	.001	.003	.003
50	1.000	.623	.400	.115	.200	.005	.002
75	1.120	.335	.019	.044	.026	.009	.002
100	.720	.015	.002	.002	.002	.001	.001
125	.224	.028	.006	-	-	-	-
150	.888	.005	.001	-	-	-	-
175	-	-	-	-	-	-	-

PUBLIC OPINION STUDY OF HIGH-PRESSURE SODIUM LUMINAIRES

PUBLIC OPINION STUDY OF HIGH-PRESSURE SODIUM LUMINAIRES

Objective

One of the adverse characteristics of high-pressure sodium lighting is its seemingly offensive source color. However, the advantages of this type of light source over other methods of lighting warrants its consideration as a means of lighting our highways. The objective of this research was to ascertain what effect, if any, this source color has on the driving public's opinion of high-pressure sodium as a method of roadway illumination.

Research Approach

The basic research approach was a measurement of the drivers' attitudes, using questionnaire techniques. The design of this questionnaire was based upon the following criteria:

1. It must be of adequate length to provide for sensitive and reliable measurement of the driver's attitudes towards high-pressure sodium lighting.
2. The specified design must allow for the comparison of most types of road users' attitudes about this type of light.
3. The expressed attitudes of the drivers must indicate some degree of like or dislike rather than a yes or no type response.

Selection of Study Site

The selection of study sites depended upon how well it met the following criteria:

1. Pollers must have easy access to potential respondents without unnecessarily impeding the flow of traffic or taking too much of the respondents' time.
2. The traffic facility must have a large enough night traffic load to permit the selection of an adequate number of drivers, as well as an adequate range of road users.
3. The facility must also have a large enough system of high-pressure sodium to give respondents adequate exposure to this type of light source.
4. The actual polling site must not create a traffic hazard in itself, i.e., the study site should have some area where the drivers selected can be physically removed from the traffic stream.

Two sites were selected for the study. They were:

1. Section of Wellborn Road, FM 2154,
   College Station, Texas

Physical characteristics:

A. Four lane, undivided highway--
no median barrier

B. Length--1/2 mile

C. System design--one-sided, single
mast, high-pressure sodium at
40 ft. with 400 watt units

2. North Dallas Toll Road, Dallas, Texas

Physical characteristics:

A. Multilane divided highway

B. Length--approximately 3 miles

C. System design--opposed single mast
high-pressure sodium, at 30 ft.
with 400 watt units

Results

Results for the two studies are given in the following tables. These results strongly indicate that the high-pressure sodium is acceptable and in fact preferred by the motorists over mercury vapor lighting.

SUMMARY OF OPINION SURVEY RESULTS
HIGH-PRESSURE SODIUM LIGHTING
WELLBORN ROAD (FM 2154)
COLLEGE STATION, TEXAS

PERCENT OF SUBJECTS RESPONDING IN EACH CATEGORY

	Strongly Agree	Agree	Undecided	Dis-Agree	Strongly Disagree
1. I do not object to the yellow color of the lighting on Wellborn Road.	37%	53%	3%	2%	5%
2. There is a reduced amount of harshness and glare due to the color of the light.	34%	33%	24%	9%	0%
3. I feel that I can see better at night on Wellborn Road as compared to other lighted roads in the Bryan area.	28%	30%	33%	5%	4%
4. I prefer the color effect of other lighting in the Bryan area over the color effect of the lighting on Wellborn Road.	13%	13%	29%	35%	10%
5. If the type of lighting used on Wellborn Road cost 25% more, I would still prefer it to other types of lighting.	11%	15%	37%	24%	13%
6. If the type of lighting used on Wellborn Road cost 25% less, I would consider it acceptable.	55%	30%	10%	3%	2%

SUMMARY OF OPINION SURVEY RESULTS
HIGH-PRESSURE SODIUM LIGHTING
NORTH DALLAS TOLLWAY
DALLAS, TEXAS

PERCENT OF SUBJECTS RESPONDING IN EACH CATEGORY

	Strongly Agree	Agree	Undecided	Dis-Agree	Strongly Disagree
1. I do not object to the yellow color of the lighting on the North Dallas Tollway	28%	67%	4%	1%	0%
2. There is a reduced amount of harshness and glare due to the color of the lights.	31%	54%	15%	0%	0%
3. I feel that I can see better at night on the North Dallas Tollway as compared to the LBJ Freeway and/or other locations in Dallas.	44%	37%	19%	0%	0%
4. I prefer the color effect of other lighting in the Dallas area, particularly I635, over the color effect of the lighting on the North Dallas Tollway.	12%	23%	12%	38%	15%
5. If the type of lighting used on the North Dallas Tollway cost 25% more, I would still prefer it to other types of lighting.	12%	46%	27%	15%	0%
6. If the type of lighting used on the North Dallas Tollway cost 25% less, I would consider it acceptable.	46%	44%	10%	0%	0%

SUMMARY REVIEW OF PAVEMENT TEXTURE, COLOR, AND REFLECTANCE

SUMMARY REVIEW OF PAVEMENT TEXTURE, COLOR AND REFLECTANCE

Introduction

Purpose of the Review

The purpose of this review is to provide background information for a research plan in roadway lighting. This research plan is to satisfy the objective of developing roadway lighting design techniques that consider driver informational needs. Thus, the review is primarily concerned with those aspects of roadway pavement characteristics that interact with roadway lighting and the resulting informational environment.

Specific characteristics of pavements that are reviewed in this report are:

1. Pavement texture
2. Pavement color
3. Pavement reflectance

Problem Statement

In the design of any ideal system, each and every sub-system must be carefully analyzed and manipulated to produce a final system approaching optimality. Various restraints, however, normally require sub-system manipulations that are below optimum and thus result in a sub-optimum system. The highway is one such system. An analysis of the highway system would indicate that some of the sub-systems are near optimal with respect to one variable and perhaps very sub-optimal with respect to another variable. The sub-system that is addressed in this report, the pavement, is a prime example of this thought.

Highway pavement surfaces must have properties to provide sufficient friction forces during all operating modes of vehicle tires. These same surfaces must also have properties to provide sufficient visual information to drivers of vehicles, especially at night. Pavement surfaces are currently receiving prime attention to optimize friction forces for vehicle operation. At the same time, pavement surfaces are receiving increasing attention to optimize their visual producing characteristics. The relationships that exist between these two concerns are not apparent.

There is a need to review efforts of the past and present to uncover relationships that may exist. Background information can be developed from the review that will provide guidance to a research plan aimed at optimizing visual producing characteristics while maintaining optimum skid resistance.

LITERATURE REVIEW METHOD

Sources of Information

The exhaustive listing of Highway Research Information Services (HRIS) abstract selections has served as the basic source of information for this review. In addition, the holdings of Texas A&M University Library, Texas Transportation Institute Library and personal libraries have been searched. It is thought that these sources provide a substantial majority of the information necessary to complete the review.

Information Analysis

A subjective analysis of the HRIS abstracts was made to select the publishings pertinent to this effort. The selected publishings were obtained, when available and reviewed. Personal contacts were also made with interested researchers to obtain documents they felt were pertinent to the task.

Limitations of the Review

This review has been limited to those documents readily available in the sources mentioned previously. In addition, only those documents considered applicable by the authors have been reviewed. The authors, therefore, accept full responsibility of subjective analysis of the material and the inclusion or deletion herein of any particular work.

PAVEMENT TEXTURE CHARACTERISTICS

There are three major components of the driving environment. These are:

1. The roadway - includes geometric design, structural design, roadway signing and other appurtenances, and other elements that make up the roadway environment;
2. The vehicle - includes vehicle characteristics and operations, considered both independently and as a part of a traffic system; and

3. The driver - includes human factors in driving and driver interaction with the other components.

Safe operation on today's traffic facilities requires that the three components be compatible.

The information characteristics of the environment must be such that the driver can interpret, and judge accordingly, his control over the vehicle. The vehicle, in turn, must be matched to the environment, especially the roadway surface, so that appropriate and often inappropriate actions on the part of the driver result in safe operation.

One aspect of the driver-vehicle-roadway interaction is that of friction between the vehicle tires and the roadway. Friction is defined as "the act of rubbing one body against another," or "resistance to the relative motion of one body sliding, rolling, or flowing over another with which it is in contact." Friction in a highway sense has been defined by Gallaway (1) to describe a sliding system in which energy is dissipated by an irreversible process, regardless of the nature of the process. Skid resistance is often used to describe a desirable surface characteristic for a pavement and/or a desirable interaction between a vehicle tire and the road surface. Thus, when discussing vehicle tire-road surface friction, skid resistance is usually the figure of merit discussed.

Definition of Texture

The literature has indicated that skid resistance is the result of numerous interacting factors involving the vehicle, the roadway and the driver. The discussion in this report is limited primarily, however, to surface texture of the road surfacing.

The texture of a pavement surface has been defined by Gallaway, Epps and Tomita (2) as the character of the surface profile consisting of a series of rather abrupt changes in elevation. Variations in textures can result from the different sizes of aggregate on the surface and from various pavement finishing operations. The texture resulting from construction can be altered by the effects of traffic wear and environment. In general, the textures can be categorized into three groups (2):

1. Large-scale macroscopic texture,
2. Small-scale macroscopic texture, and
3. Microscopic texture

The large-scale macroscopic texture describes the average spacing of the peaks or the average peak-to-valley depth of the larger changes in elevation and determines in large measure, the water drainage properties of the pavement surface. The small-scale macroscopic texture is the "grittiness" of the surface caused by cemented sand-sized particles or by sharp projections on the larger aggregates. This macroscopic texture is a major input to the friction properties at any given speed (3). The microscopic texture, also influencing the friction properties, is the minute surface characteristics of aggregates in the micro-inch range.

Methods of Measurement

The belief that surface texture is somehow related to the degree of skid resistance provided by a pavement has led to the development and application of methods for measuring surface texture. These methods, with references are listed below:

1. Sand Patch Method - Reference 4
2. Modified Sand Patch Method - Reference 5
3. NASA Grease Method - Reference 6
4. Profilograph - Reference 2
5. THD Profilograph - Reference 2
6. Surfindicator - Reference 2
7. Texturemeter - Reference 7
8. Putty Impression Method - Reference 2
9. Drainage Meter - Reference 8
10. Foil Piercing Method - Reference 9
11. Linear Traverse Method - Reference 2
12. Stereophotographic Method - References 10, 11
13. Casting or Molding Method - Reference 12
14. CKE Method - Reference 13
15. Wear and Roughness Meter Method - Reference 14
16. Mineralogical Studies and Profilograph Method - Reference 2
17. Photo Interpretation Method - Reference 15
18. Subjective Method - Reference 16
19. Dial Guages - Reference 2
20. Light - References 2, 30

Texture-Skid Relationships

The forces that are required in driving, steering, and braking an automobile are provided by the frictional resistance developed between the tires and the pavement surface. For any given tire and pavement combination there is a maximum friction potential; if it proves to be inadequate for the intended maneuver, the wheels begin to slide, the driver's control over the vehicle is drastically reduced, and the vehicle is said to be "skidding." The frictional resistance offered by the pavement surface to the sliding tires is called "skid resistance."

The most common example of vehicle skidding occurs during a panic stop, when all the wheels are locked and cease to rotate but the vehicle continues to slide. The implications of adequate skid resistance with respect to traffic safety are fairly obvious.

Skid resistance is usually considered to be a frictional force consisting of two components - the adhesion term and the deformation term. The adhesion term is the result of molecular forces, and its magnitude is determined by the nature of the two materials in contact, in this case the tire and the pavement surface, and by the normal force between them. Adhesion is usually the dominating factor on dry pavements; its effect diminishes with lubrication and becomes negligible on wet pavements. On wet pavements the deformation term is far more important. It is the result of the deformation of the tire rubber by the surface asperities and the ensuing energy dissipation in the rubber.

Under any given set of conditions the effective skid resistance (F) is the sum of the adhesion (F_a) and deformation (F_d) components; dividing it by the vertical load (L), it can be expressed in terms of an effective coefficient of friction (f): $f = F/L = (F_a + F_d)/L$. Since the adhesion term is greatly reduced by lubrication, the skid resistance of a pavement is always lower in the wet state than in the dry state. Typically, the difference may be of the order of 50 percent, depending on surface texture and testing speed. The great majority of wet-road skid resistance measurements are in the 0.30 to 0.70 range (17).

Surface Macro-Texture. To be able to puncture thin "squeeze-film" between the tire and the pavement, and to cause appreciable grooving of the tire rubber, the aggregates in a paving mix should be angular, hard, and polish-resistant under wear. Opinions differ on particle size and gradation characteristics.

Numerous experiments have proved the importance of particle shape. Using the same aggregate type, skid resistance is normally higher of bituminous mixes with angular aggregates than on mixes with rounded aggregates (17).

It is not sufficient for the aggregates to be sharp and angular initially; they should also retain these characteristics in service. Experience shows that considerable reductions in skid resistance may be caused by traffic wear - as much as 50 percent of the initial skid resistance is lost on some pavements during the first two years of service. Much of this is caused by the polishing of the individual aggregate particles in the mix. The rate of deterioration is considerably slower in the later stages of service, and polishing practically levels out once the "ultimate state of polish" is reached. Heavy and fast vehicles cause more rapid reduction of skid resistance than light and slow ones; under heavy traffic the ultimate state of polish may be reached as early as two years after construction. Polishing always requires the presence of some abrasive material, such as the clay, silt, and sand-sized dirt and dust usually covering road surfaces.

In order to resist polishing, the individual aggregate particles should be hard. Calcite, with a Mohs hardness of 3, is susceptible to polishing by just about any ingredient of the road scum; quartz has a Mohs hardness of 7, and the only mineral abundantly present in the road scum that would be hard enough to cause it to polish is quartz itself.

It is, therefore, not surprising that limestones are often a major cause of slipperiness on both flexible and rigid pavements. Sandstones and slags are usually regarded as good anti-skid aggregates. Sandstones give a good example of wear by particle attrition, which is a desirable kind of wear. Due to the difference in hardness between the hard crystals and the friable matrix, traffic wear actually contributes to a rough, uneven surface texture on sandstone aggregates (17).

Surface Micro-Texture. A sharp, gritty, surface texture, with adequate channels and escape paths among the asperities, facilitates the escape of the lubricating water from the contact patch, and is therefore an important factor in providing good skid resistance.

The large-scale texture (roughness) of a pavement surface may be important in breaking up the contact patch into smaller areas that drain faster. This effect is definitely significant for smooth tires; with patterned tires, however, the roughness of the surface may become a secondary factor since the tire pattern itself can adequately subdivide the contact area (17). Also important is the small scale texture of the surface, i.e., the sharpness of the very small-scale projections and ridges and the surface characteristics of aggregates. This micro-texture provides rubber-to-aggregate contact, and piercing of waterfilm.

Anti-Skid Roads

The ultimate objective of past and current research and practice in skid resistance is to develop ways and means of avoiding skidding accidents. The major aspect has been to make the roads safe by constructing surfaces which offer high frictional resistance throughout their service life.

In general terms, the requirements of adequate skid resistance call for angular and non-polishing aggregates, a harsh surface texture permitting fast drainage, and proper mix design and construction methods (17).

Slippery stretches of road are normally resurfaced using some non-skid mix. Special techniques include the application of resinous surface treatments (17), the removal of excess asphalt by burning, the dissolution of excess cement by acid treatment, and the mechanical roughening of portland cement concrete pavements (17).

In 1967 Gallaway published an article (18), outlining solutions to providing non-skid pavements. Further discussions were made in 1970 by Gallaway (1). Some of the more important methods follow.

Surface Renewal by Attrition. Surface renewal by attrition involves the use of a mixture of two aggregates which wear at two distinctly different rates. The theory is that even for aggregates that polish in time under heavy traffic, a high coefficient will be maintained if the surfaced aggregate is dislodged before it has polished appreciably. In this approach, it is advisable to limit the top size of the aggregate used since this minimizes most of the undesirable side effects of a raveling surface.

Surface Renewal by Granulation. A granulating material as the coarse aggregate in a pavement surface offers a satisfactory approach to prolonged skid resistant surfaces. Sandstone, the individual crystals of which are cemented only to the extent that they are dislodged by traffic before the stone is polished, make excellent non-skid pavements. Unfortunately, the proper type of sandstone is not widely available for such use without excessive haul costs. In bituminous paving mixtures, many sandstones are water susceptible and unless treated or used with a treated bituminous binder, will create a stripping problem.

Surface Renewal by Dispersion of Hard Particles in a Soft Matrix. Certain types of limestone used as surface aggregate have been found to polish rapidly under heavy traffic; whereas limestones from other sources are known to produce pavements with prolonged high skid resistance (1).

The latter results from discrete impurities in the form of hard particles dispersed throughout the softer limestone matrix.

James (19) suggests that an aggregate such as that described above might be manufactured specifically for use in non-skid pavements and at a reasonable cost.

Surface Renewal by Wear of Vesicular Aggregate. In the mid 1950's, some researchers in the United States were experimenting with the use of "manufactured aggregates" in paving mixtures. The aggregates were produced by heating raw materials such as clays, shales, or slates in a rotary kiln to about 2000°F (1090°c). Such aggregates are referred to as lightweight or synthetic aggregates. Some of these aggregates have proven to have exceptional non-skid properties, independent of the volume of traffic on the facility (1).

Current Status of Technology

The phenomena of tire-pavement friction are apparent. In general terms the requirements of adequate skid resistance call for angular and non-polishing aggregates, a harsh surface texture permitting fast drainage, and proper mix design and construction methods. The best experiences in non-skid road construction have been obtained with silica-sand mixes, rock asphalt, slag mixes and synthetic mixes on the bituminous side, and with similar non-polishing aggregates and broom or burlap finish on the portland cement concrete side.

The other main aspect of providing adequate skid resistance on the roads is to increase the anti-skid characteristics of the vehicle itself.

The two main possibilities are: (a) improving the frictional properties of the tires and (b) controlling the braking action (17).

Tire friction can be improved by synthetic rubber tread compounds exhibiting high hysteresis losses and by bold tread patterns. Studded tires or tire chains may be needed on icy surfaces.

In order to utilize the maximum frictional resistance of pavements, devices are being developed which prevent wheel-locking during braking (20, 21). Experimental versions of such devices have led to skid resistance improvements on the order of 10 to 30 percent (17).

Also, the driver himself must be alerted to the dangers of skidding. He, too, can take anti-skid measures by adjusting his speed to road and weather conditions, and by using the "pumping" braking technique on wet or icy pavements.

There is a definite need for continued research in many aspects of tire-pavement friction. Uniform standards on measuring friction need to be established to serve as the common base or denominator.

Interest should be continued with regard to new techniques of measuring the frictional resistance of pavements, such as the light reflectivity technique. This may serve a secondary function of providing a measure of pavement reflectance characteristics for roadway lighting purposes.

There is still a need for determining quantitative characteristics of aggregates and of surface texture to correlate with frictional resistance. In addition the effect of temperature, climatic conditions, and traffic wear should be evaluated in terms of pavement type.

There is a pressing need for the establishment of realistic minimum acceptable values of frictional resistance in terms of pavement type, layout features, and traffic conditions. Such a specification can then be used to judge the adequacy, with respect to frictional resistance, of individual road sections.

PAVEMENT COLOR CHARACTERISTICS

The color of roadway pavements influence the amount of light reflected from any given source. Thus, from an informational standpoint, pavement color and color characteristics are important considerations for roadway lighting design. The paragraphs that follow summarize some of the more important data on color.

Definition of Color

Color is usually defined or described in terms of three appearance dimensions or attributes. These attributes have been formalized into the Munsell System (23) of color.

Hue. Hue indicates whether a color is red, yellow, green, blue, or purple, or some color intermediate or exclusive to these. There are ten hue steps or colors, with each hue representing the center of a hue family.

Value. Value indicates the degree of lightness or darkness of a color, in relation to a scale of neutral values arranged in a vertical column with the darkest color (black) at the bottom, extending to the lightest color (white) at the top. In the Munsell System of color there are eight value steps.

Chroma. Chroma indicates strength or saturation, the degree of departure of a particular hue from a neutral gray of the same value.

Color Reflectance

Every color reflects some portion of the light it receives. This portion, expressed in percentage, is called the reflectance. In general the lighter the color, the higher the reflectance, with white having the highest reflectance and black the lowest reflectance.

Measurement of Color

Color can be measured in one of two ways: subjectively and photometrically. Both appear to have application in pavement color determination.

Subjective Measurement. Subjective measurement or determination of color is probably the method most used today. It consists of qualified observers comparing a color with the Munsell System attributes. It does, however, have limitations.

The ability of observers to discriminate between small color differences is by no means equal, even when persons of deficient color vision are excluded. Visual judgments, combined with instrument data can be very useful if the limitations of both are well understood. The problem of perception, in which sources of different spectral composition may appear to have the same color, makes it quite possible for visual and instrument results to disagree.

Photometric Measurement. Photometric measurement of color is achieved through the use of various colorimeters. Colorimeters produce electrical responses to light of various wavelengths that are intended to be proportional to color temperatures. Color temperature is the relation of a color to the color of a completely radiating blackbody source and of light sources which color match such a source (23).

The limitations of colorimeters can be understood from filters used to approximate response functions of the human eye. Thus a firm knowledge of eye response and spectroradiometric characteristics of color is necessary. Otherwise, colors that measure alike may differ in perceived color.

Pavement Colors

Normal pavements (portland cement concrete and asphaltic) are usually cool in hue, low in value, and weak in chroma. Whites, browns and blacks are the usual. Subjective measurement of color has been shown to better estimate the light reflecting properties of pavement. These subjective measurements usually consist of estimates of value (light to dark) only (24).

Walker and Christie (22) have demonstrated that the lighter colors, estimated through subjective measurement, reflect higher percentages of light for comparable textures.

Desirable Colors of Pavement

From a light-reflecting standpoint, pavements should be light in color (high value) to better utilize both vehicle and overhead lighting. There are also indications that colors of strong hue and chroma can serve informational purposes especially from a guidance standpoint (25).

Methods of Achieving Light Colored Pavements

From a practical standpoint, portland cement concrete has been the best method of producing pavements light in color. Recent efforts, however, have indicated that various synthetic materials can be used to effectively produce light colored pavements. Surface treatments using lightweight synthetic aggregates is one promising application.

Synopal, a synthetic white mineral aggregate, is another material of current use in producing light pavements. Synopal is produced by melting sand and lime fluxes in a kiln, then reheating to cause crystallization. In this process, the material acquires a high strength and a white color. A variety of studies involving Synopal have demonstrated its applications (26).

PAVEMENT REFLECTANCE CHARACTERISTICS

Under fixed lighting, drivers see objects primarily as dark silhouettes against a bright background formed by the roadway and its surroundings, and only occasionally is this silhouette reversed (23). Therefore, the most important use of fixed lighting is to brighten not the objects, but the roadway surface, and in producing this brightness, the reflection of light from the surface is equally important as the surface illumination.

Efficient fixed lighting systems should provide suitable light distribution in which the bright patches of light cover the roadway from any direction of viewing, with the surface being as brightly and uniformly illuminated as possible yet avoiding excessive glare. However, luminaires do not usually produce a uniform intensity distribution. Instead, more light is directed up and down the roadway to lengthen the patch and so reduce the number of luminaires required.

The way in which a roadway is brightened by street lighting depends on the exposed face or surface. The reflection characteristics of a surface depend on a number of properties of the surface: its surface texture, the material of which it is composed, its color and lightness, discussed previously, the extent to which it has been polished by traffic, and whether it is wet or dry (24).

Bloch (24) considered the luminance of the road surface produced by fixed lighting to be due largely to specular reflection at small facets in the surface. He hypothesized that the luminance factor depended on the number and areas of the facets which are correctly oriented to reflect in the appropriate direction; on the specular reflection factor of the facets; and on the amount of shading of one facet by another which prevents some from being illuminated and some from being visible.

Christie (22) concluded that the reflecting facets of Bloch were to be found mainly on portions of the surface which become polished by traffic. Although only a portion of the exposed surface of many roads comes into contact with the vehicle tires (only the "peaks" of protruding aggregate particles), reflection from the "valleys" is unimportant because the driver cannot see the "valleys" due to the very oblique viewing angle. Also, much of the surface is illuminated only by obliquely incident light which cannot penetrate to the bottom of the "valleys."

Christie defined surface form to be either "peaky" or "even;" the former referring to surfaces having wide "valleys" and peaky projections, the latter having flat-topped projections and "valleys" occupying only a small fraction of the surface area. Similarly the scale of the surface texture was classified as either "fine" or "coarse."

Figures 1 and 2 show that the luminance of the roadway may be different for different surface types. In Figure 1, the patches obtained on two bituminous surfaces are compared. The rolled asphalt with precoated chippings had a fairly even surface texture and a pinkish color. The non-skid rock asphalt had a coarse peaky surface texture and was medium grey in color. Figure 2 shows a comparison of luminance on two concrete surfaces. One was a concrete specially polished to make it smooth and slippery for use in experimental skid tests. The other was a machine-finished concrete with a more peaky surface texture. In both cases, the bright patches were obtained under standard conditions

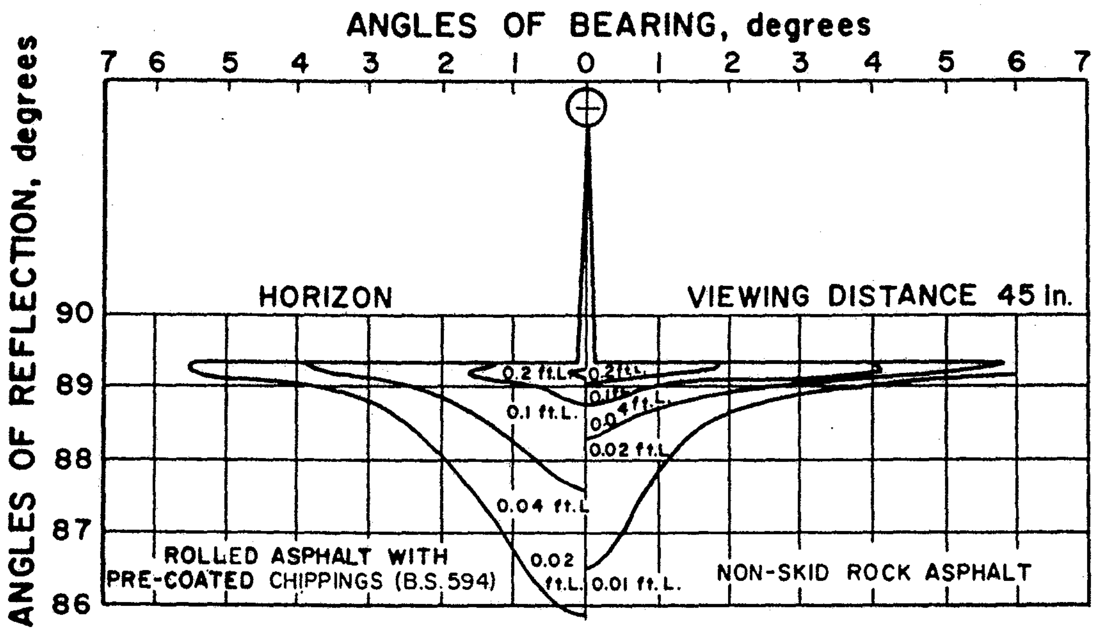

Figure 1

Isoluminance contours in perspective for rolled asphalt with pre-coated chippings and non-skid rock asphalt (Ref. 32)

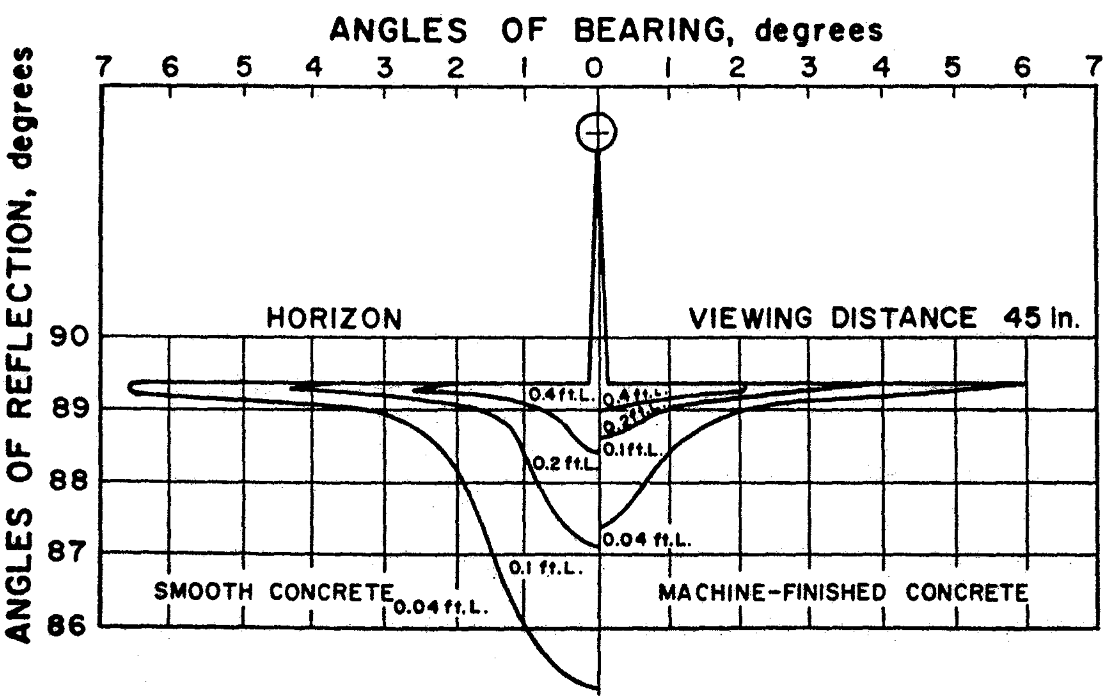

Figure 2

Isoluminance contours in perspective for smooth concrete and machine-finished concrete (Ref. 32) on dry surfaces. The light source emitted an intensity of 1000 candelas in all directions, and was mounted at a height of 25 feet. The observer was 400 feet from the light standard, his eye being 5 feet above the road surface.

Luminance Measurements

According to deBoer (24), objects on the road can be seen if the three following conditions are fulfilled:

1. The luminance of the object differs sufficiently from the background luminance, the latter being normally that of the road surface;
2. The object is large enough; and
3. The time available for perception is sufficient.

Visibility is, therefore, determined by contrast sensitivity, visual acuity, and reaction time, all factors being strongly dependent on the luminance of the road surface. The comfort of seeing depends to a high degree on the luminance qualities of the road also, being affected primarily by the presence of glare.

Luminance does not bear any simple relationship to the illumination of the road. All road surfaces exhibit characteristics of a mat mirror on which light from lamps in the direction opposed to that of traffic contributes to the road luminance to a much greater degree than light radiated in the direction of traffic. Therefore, the reflection properties are a function of two parameters - the direction of illumination and observation. It is also clear that the distribution of the illumination does not constitute a measure for the quality of a street lighting installation (24).

Several methods and instruments have been developed to measure road luminance. A luminance meter is used to collect data on the distribution of the luminance in the normal visual field of the driver, primarily the perspective image of the roadway. The most important part of this image is the road surface against which objects will be seen. On high speed facilities, a driver must be able to detect objects 300 to 600 feet ahead. Consequently, the luminance distribution in this region is vitally important. On urban facilities and in winding roads, shorter distances are available. DeBoer (24) illustrated that to a driver whose eye is 1.50 meters above the road looking 200 meters ahead, a 10-meter stretch of road subtends an angle of 1.3 minutes with a vertical angle; α, of 89° 34'. A variation of one minute in α results in a shift of 8 meters in the stretch of roadway observed. He also pointed out that a box 0.20 meters high on the road 50 meters ahead of a driver would be silhouetted against a 7-meter length of road. At distances of 100 meters and 200 meters, the box would apparently cover 15 and 30 meters, respectively. Therefore, a luminance meter should be able to measure average luminance values of fractions of the perspective image not greater than these lengths. To measure the luminance of a "point" of the road surface, 200 meters ahead, the vertical dimension of the field of the luminance meter must be very small. Further, the direction of observation must be fixed with the utmost accuracy.

Figure 3 illustrates the portion of the road covered by a luminance measurement at a point 150 meters ahead of the observer using various instruments. If this figure is viewed at 0.60 meters, the impression on the eye is that as seen by a driver traveling in the center of the right lane. The road width is 10 meters. Most normal photometers have a circular field of comparison subtending an angle of more than 1 degree. The large circle in Figure 3 shows the part of the road covered by a circular field of 1 degree, which is a stretch between 80 and 1200 meters in front of the observer. The oval-shaped field of comparison of a luminance meter manufactured by Salford Electrical Instruments, Ltd., England for measurements in interiors and for photographic purposes, covers a range from 110 to 225 meters. The luminance meter for road lighting purposes manufactured by the General Electric Company has a circular comparison field which covers a stretch of the road from 130 to 180 meters. DeBoer considers even this to be too large for obtaining an accurate impression of the luminance distribution in the lengthwise direction of the road. The field of comparison of the luminance meter developed by DeBoer, Onate, and Oostrijck (31) as shown in Figure 3 measures a portion of the road ranging from 147 to 153 meters.

Asmussen and DeBoer, in a later publication (27), stated that a luminance meter for street lighting should satisfy the following conditions:

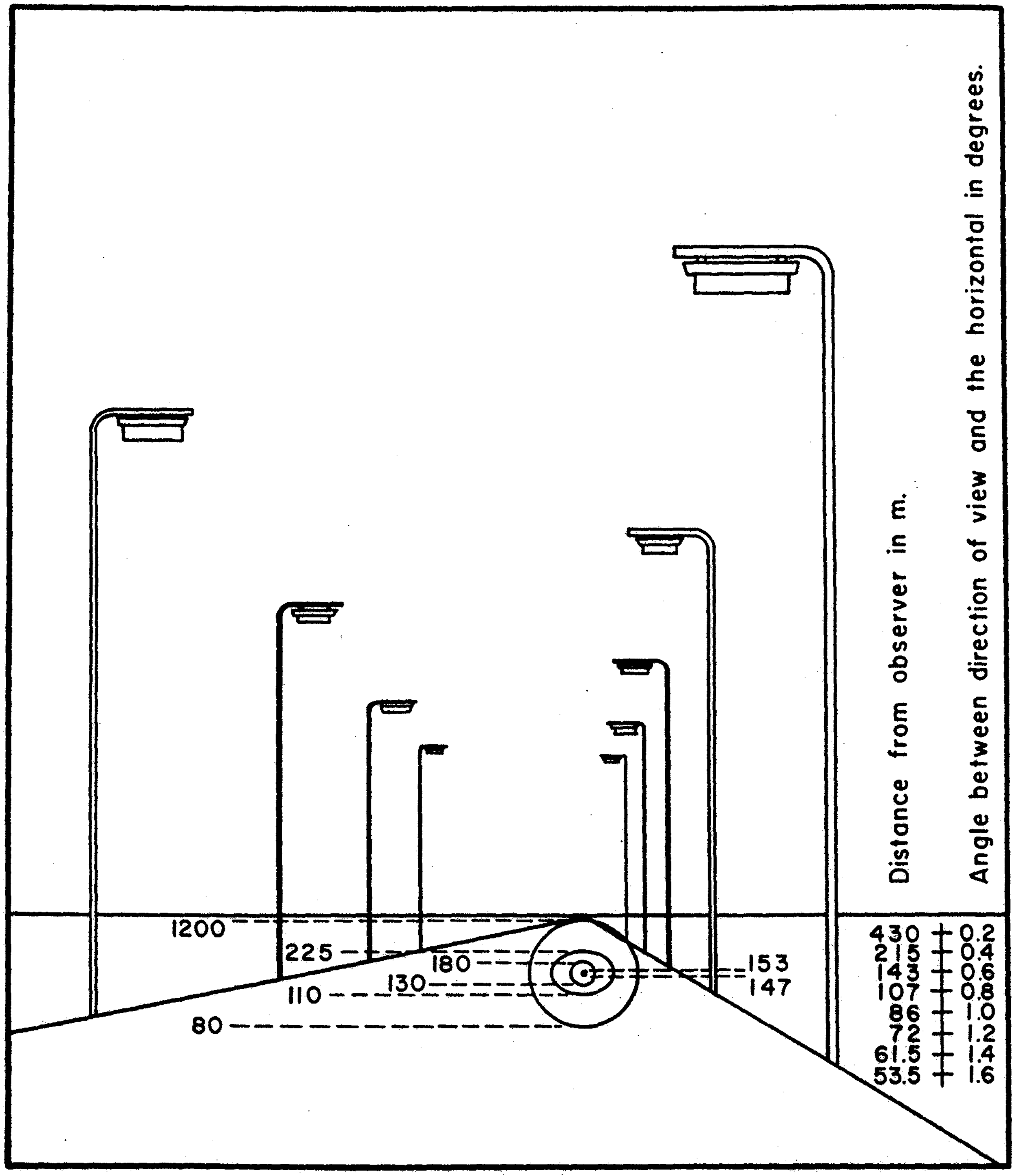

Figure 3

The part of the road encompassed by a luminance measurement at a point 150 m (492 ft) in front of the observer when using various instruments (Ref. 31)

1. Local luminance measurements should be carried out at short distances so that

(a) it is no longer necessary to adjust the instrument with such extreme accuracy;

(b) the measurements can be carried out by one person;

(c) the investigator can inspect the state of the road surface under measurement from close-quarters.

2. The mean luminance of a part of the road between about 150 feet, and 600 feet from the driver (on a straight road) must be directly measurable.

3. It should be possible for personnel who have had no photometric experience to use the luminance meter. This is connected with the need for a generally applicable instrument, which would help in the introduction of the luminance concept into public lighting on a large scale. As a consequence, only photo-electric models come into consideration, as visual photometry can only give reliable results after careful training when the luminance is low and the field of vision restricted as is often the case.

Further demands of a general nature are:

4. The sensitivity of the instrument should correspond to the spectral sensitivity of the eye as laid down by the C.I.E., or it should be easy to apply corrections for the difference in sensitivity corresponding to the various light sources normally used in public lighting, and

5. The measuring range should be variable from about 0.5 to 30 cd/m^2 full-scale deflection, and it should be possible to extend this range upwards by several powers of ten if necessary (e.g., for determining the luminance of light sources of lanterns).

Finally, many years of experience with several sorts of luminance meters (which may all be regarded as more or less precursors of the one described here) in many lighting installations have led to the following practical demands:

6. It must be possible to calibrate the instrument on the spot. This is not only because photo-electric cells (which must be used according to Para. 3 above) are temperature-sensitive and sometimes also moisture-sensitive, but also because the deposition of moisture and sometimes even dirt on the optical system is not always avoidable. The calibration must thus be carried out so that allowance is made for all the possible ways in which the sensitivity can be affected, in particular the last-mentioned one.

7. The instrument must be provided with a built-in source of energy, in order to avoid the tedious business of laying out a supply cable in busy traffic.

8. Since the instrument should be operable by one person, its weight and size should be limited.

Several instruments meeting some or most of these requirements are available (24).

COORDINATION OF TEXTURE-COLOR-REFLECTANCE CHARACTERISTICS

From the foregoing discussion it is apparent that pavement materials are important from two standpoints; skid characteristics and light reflectance characteristics. It is not difficult to conceive that both characteristics can and should be considered in the planning and design stages of pavements.

The technology is available to provide for adequate skid qualities in most pavements. The technology is also available to produce pavements light in color with proper texture for reflecting capabilities. One of the difficult problems is coordination between the pavement designer and lighting designer at the planning and design stages of the pavement. In many cases just knowing the type of pavement to be constructed and scheduled overlays, will help in determining the type and/or amount of fixed roadway lighting necessary.

There is every indication that lighter pavements of portland cement concrete, synthetic aggregates, and certain surface treatments, can be used where it is apparent that roadway lighting is justified for safety reasons. Walker and Christie (22), for example, have indicated that the total reduction in accidents alone in using light chippings might be sufficient to pay for the excess cost. Other benefits, such as improved comfort or lack of apprehension are obvious.

Regardless of the paving material used, there are aspects of pavement texture and color that can be taken into consideration in the design of a lighting system. This would be unique to lighting practice in the United States since at present no consideration is given to texture or color. All lighting design is based on incident light rather than reflected light and resulting brightness or luminance.

DeBoer (24) has developed reflectance factors for a wide range of pavement types. These factors range from .19 for dark and course pavement surfaces to .34 for light and smooth pavement surfaces. These reflectance factors can be used with adequate accuracy in predicting the resulting luminance levels of pavements when illuminated. King (28) and King and Finch(29), have developed similar factors as well as measuring techniques for highway pavements common to the United States.

It appears desirable, therefore, that pavement designers and lighting designers work jointly in selecting paving materials for roads warranting lighting. When desirable lightness of pavements cannot be achieved due to technical or economic feasibility, the lighting designer should at least consider the pavement characteristics and adjust his lighting design accordingly.

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DEVELOPMENT OF A RELATIVE HAZARD INDEX FOR LUMINAIRE SUPPORTS

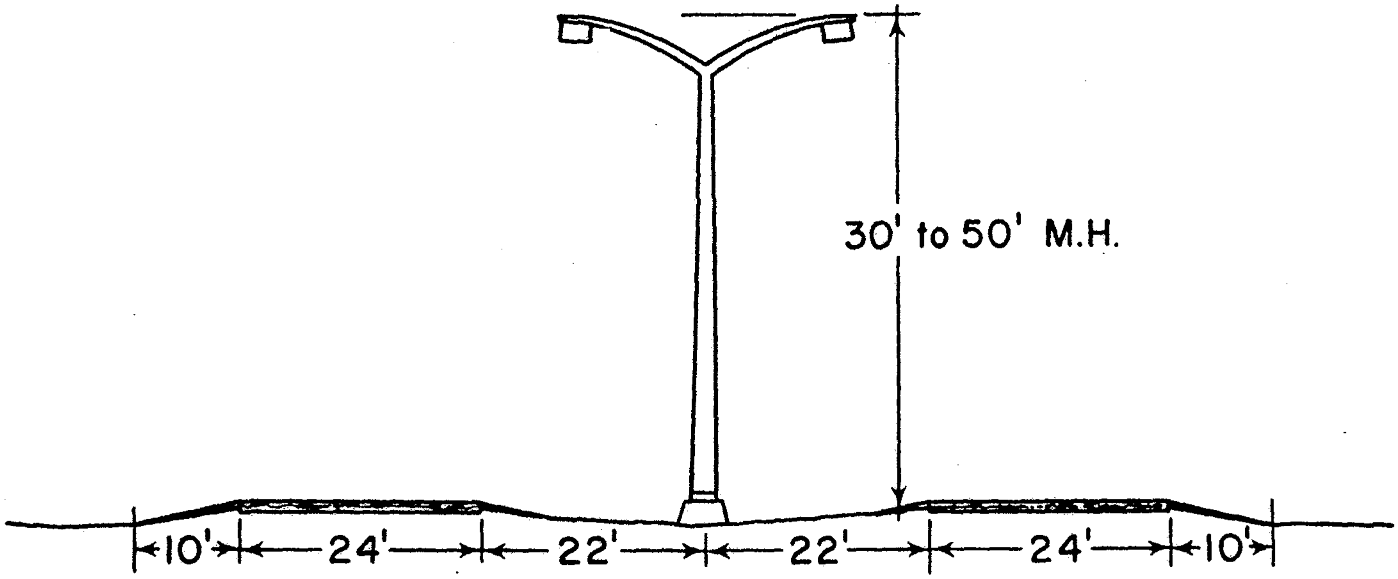
DEVELOPMENT OF A RELATIVE HAZARD INDEX FOR LUMINAIRE SUPPORTS

The purpose of this report is to formulate the procedure for determining a "Relative Hazard Index" for alternative lighting systems on a typical freeway-type traffic facility. Specifically, the "Relative Hazard Index" describes the relative hazard created by the proximity and frequency of luminaire supports.

The alternative lighting systems presented in this comparison are basically "median-mounted" and "house-side" lighting systems at mounting heights of 30, 40, 45, and 50 feet at a 5:1 spacing-to-mounting height ratio. Each of the systems is illustrated in Figure 1 and described briefly in Table 1.

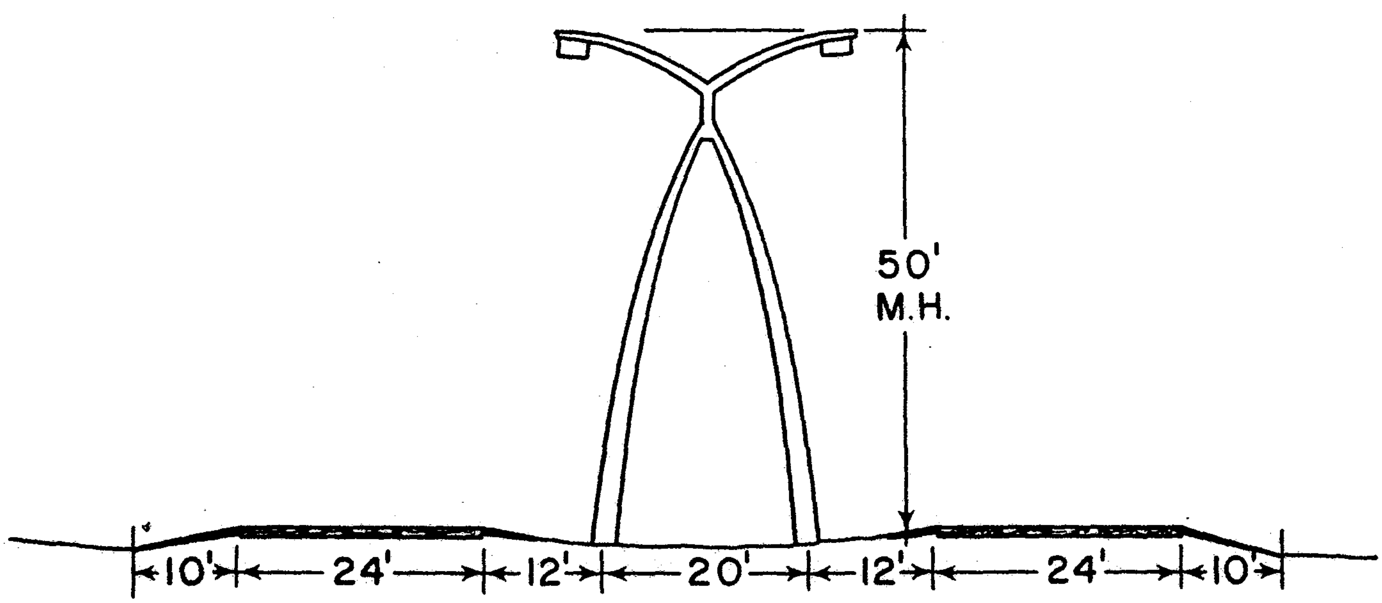
Table 1 summarizes the data for each of the alternative lighting systems and presents the Relative Hazard Index for a 44-foot median, a design of special current interest to the Texas Highway Department. A similar comparison can be made for any median width. This Relative Hazard Index is computed as the product of:

1. The relative probability of a vehicle impacting a luminaire support based on lateral distance from the traveled way;
2. The relative number of hazards per unit length of roadway; and



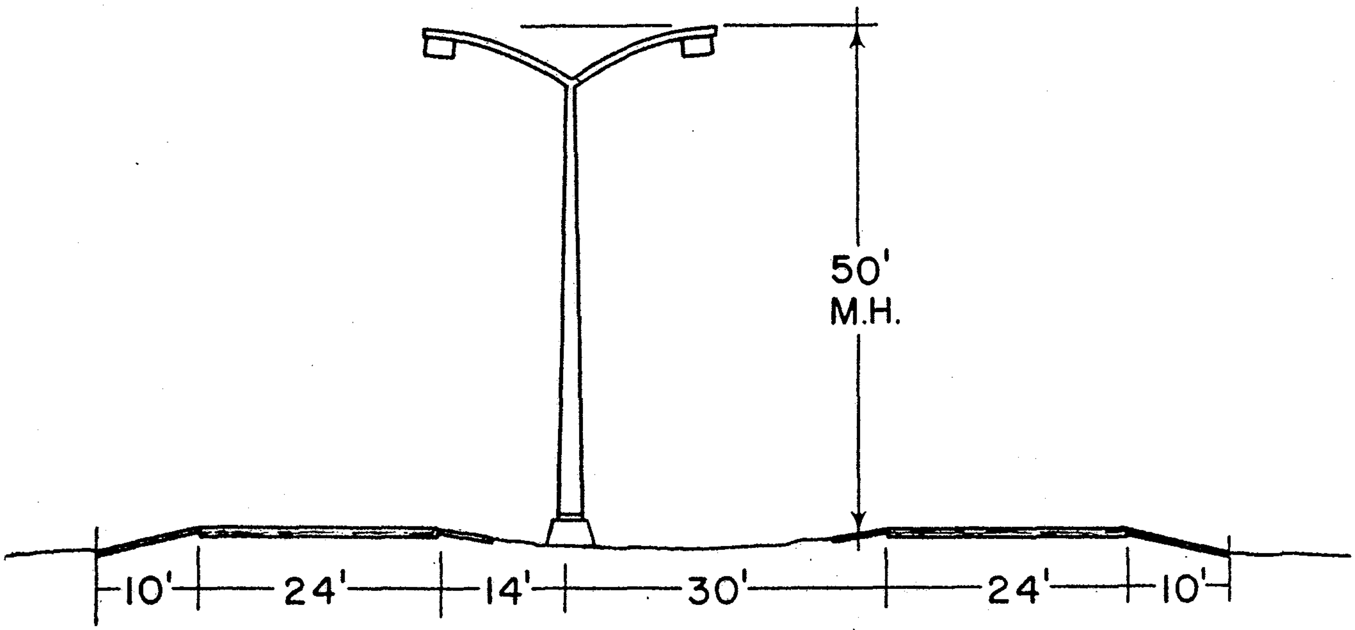
1(a)

Typical median installation with cast aluminum T-Bases 30, 40, 45, & 50' MH. Alternate Designs 1-4.



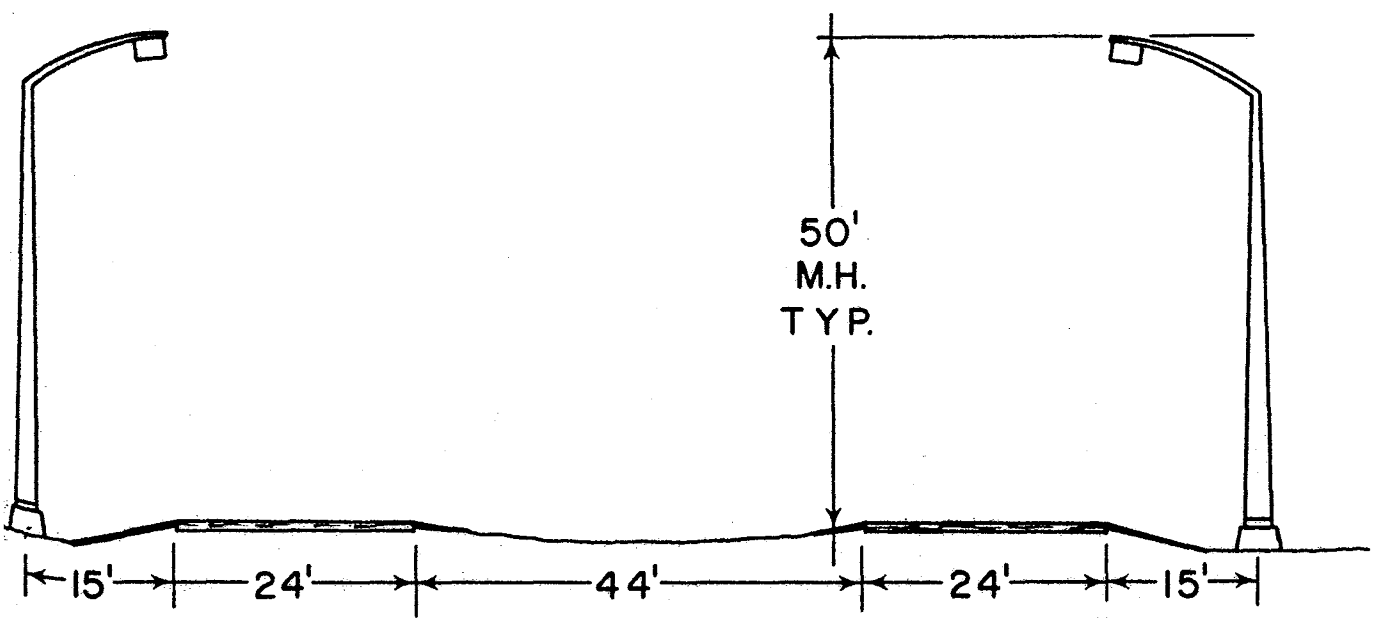
1(b)

A new concept in median-mounted systems. This concept is intended to provide a dual support with either support having the strength to support the lighting units independently should one of the supports be struck by a vehicle. Alternate Design 5.



1(c)

Median-mounted system offset 30 feet from one direction of traffic. The concept is intended to reduce to a minimum the probability of an impact that would cause the support to enter the opposing traffic. Alternate Design 6.



1(d)

Typical House-side installation with cast aluminum T-base. Alternate Designs 7-10.

Table 1
RELATIVE HAZARD INDEX COMPARISON

FOR A 4-LANE

FREEWAY WITH 44-FOOT MEDIAN

(1) Description of Alternative Lighting Design				(2) Percent Probability of Vehicles Traveling Indicated Distance From Edge of Roadway			(3)	(4)	(5)	(6)	(7)
(a)	(b)	(c)	(d)	(a)	(b)	(c)					
Alternative Design No.	Mounting Height of Luminaires (ft)	Longitudinal Spacing of Luminaire Support (5:1 S/MH)	Location of Luminaire Support	Distance from Roadway to Luminaire Support (ft)	Percent Probability (GM Curve)	Percent Probability of Impact Angle > 20°	Relative Probability of Vehicle Collision with Luminaire Support	Relative No. of Luminaire Supports Per 250'	No. of Traffic Streams Exposed to Luminaire Supports	Total Probability or Relative Hazard Index	Relative Hazard Index
1	30'	150'	Median	22'	30%		.30	1.66	2.00	.995	1.42
2	40'	200'	Median	22'	30%		.30	1.25	2.00	.750	1.07
3	45'	225'	Median	22'	30%	5%	.35	1.11	2.00	.777	1.11
4	50'	250'	Median	22'	30%	5%	.35	1.00	2.00	.700	1.00
5	50'	250'	Median	12' 32'	55% 22%		.38	2.00	2.00	1.520	2.17
6	50'	250'	Median	30' 14'	22% 41%	10%*	.36	1.00	2.00	.720	1.03
7	50'	250'	House-side	15'	45%		.45	2.00	1.00	.900	1.29
8	45'	225'	House-side	15'	45%		.45	2.22	1.00	1.000	1.43
9	40'	200'	House-side	15'	45%		.45	2.50	1.00	1.124	1.61
10	30'	150'	House-side	15'	45%		.45	3.32	1.00	1.492	2.13

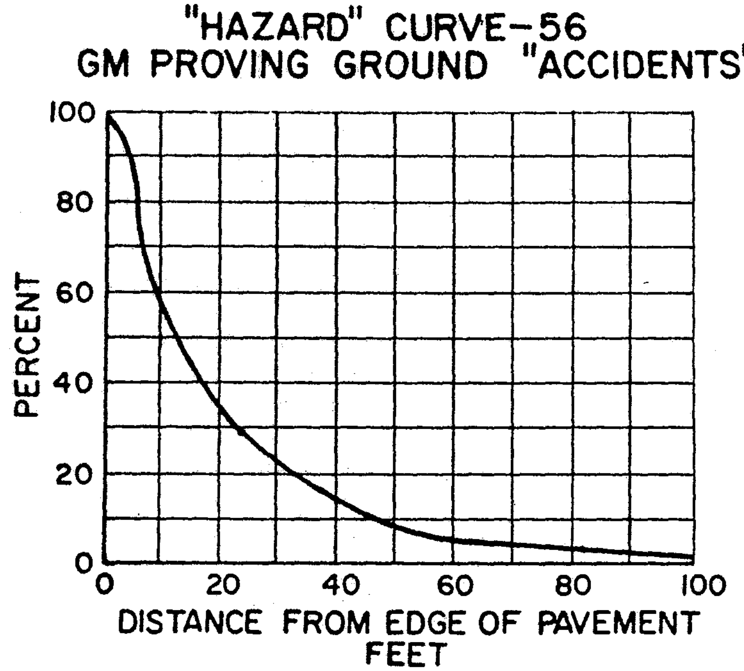
*Assumes support may fall across two lanes

3. The relative number of traffic streams (directions) to which the luminaire supports are exposed.

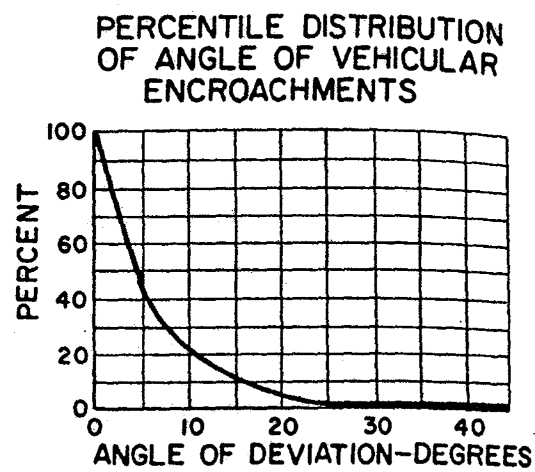
To explain the source of each of these factors, reference is made again to Table 1. Column 2(a) gives the lateral distance of the support from the edge of the traveled way for each of the alternative designs. The two distances given for Alternative Design Numbers 5 and 6 represent two supports in Alternative Design Number 5 and an offset situation in Alternative Design Number 6. Column 2(b) of Table 1 gives the percent probability that an errant vehicle will travel a sufficient lateral distance from the traveled way to become involved in a collision with a support. These values are based on frequently referenced data reproduced in Figure 2(a) from the General Motors Proving Ground.

Column 2(c) of Table 1 gives the percent probability of a secondary collision caused by the luminaire support falling in an opposing traffic lane and being struck by an oncoming vehicle. The percent probability is determined on the basis that only supports struck at angles greater than 20 degrees will fall in the opposing traffic lanes. Further, this effect is considered only for 45-and 50-foot supports. Shorter support lengths are assumed to always fall within the median. The percent probabilities were obtained from Figure 2(b), data from the General Motors Proving Ground.

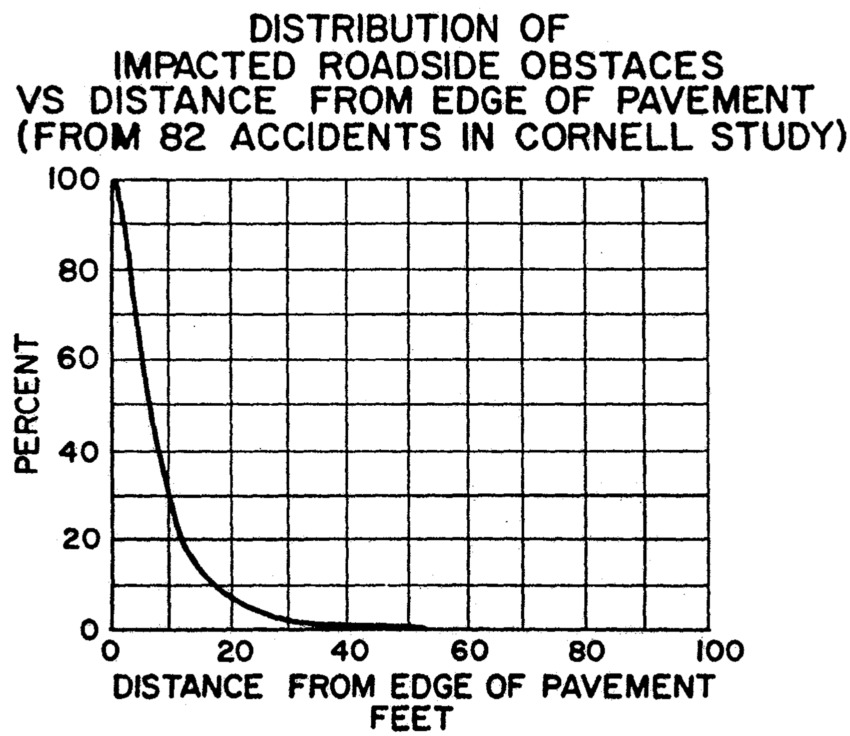
In another recent test involving a vehicle running over a downed 50-foot steel luminaire support (Research Study 146), there was strong



2(a)



2(b)



2(c)

From Stonex, K. A. Relation of Cross-section Design and Highway Safety.

evidence that the secondary collision was of no greater severity than the initial impact with the upright support. Therefore, the probability of collision in this instance is equal to the sum of the probabilities of the initial and secondary collisions. The relative probability of a collision with a luminaire support is computed by averaging the percent probabilities and converting to probability rather than percent.

In Column 4, the relative frequency of exposure of a vehicle to luminaire supports is computed using the 250-foot spacing of the 50-foot median-mounted system as unity.

Column 5 lists the exposure indices based on the exposure of the traffic streams to luminaire supports. The median-mounted systems can be struck from either direction, whereas the house-side systems can only be struck from one direction.

Column 6 represents the combined probability of a vehicular collision with a luminaire support based on lateral distance from the roadway to the luminaire support, the relative number of hazards per mile, and the exposure to traffic flows. It is obtained by computing the product of Columns 3, 4, and 5.

For ease of interpretation, the total probability values of Column 6 are converted to a base of unity by dividing all values by the smallest value in the column. These values, called the "Relative Hazard Index," are presented in Column 7.

TABLE 2

MEDIAN WIDTH VS RELATIVE PROBABILITY INDEX

50' MEDIAN AND HOUSE-SIDE LUMINAIRE SUPPORTS

250' SPACING

Location	Median Width (ft)	Percent Probability of Vehicles Traveling Indicated Distance From Edge of Roadway			Relative Probability of Vehicle Collision with Luminaire Support	No. of Traffic Streams Exposed to Luminaire Supports	Relative No. of Supports Per 250'	Total Relative Probability of Being Hit	Relative Hazard Index
		Distance from Roadway to Luminaire Support	Percent Probability (GM Curve)	Percent Probability of Impact Angle > 20°					
Median	60'	30 '	22%	--	.22	2.00	1.00	.44	1.00
Median	55'	27.5'	25%	--	.25	2.00	1.00	.50	1.14
Median	48'	24.0'	28%	5%	.33	2.00	1.00	.66	1.50
Median	46'	23.0'	29%	5%	.34	2.00	1.00	.68	1.55
Median	44'	22.0'	30%	5%	.35	2.00	1.00	.70	1.59
Median	42'	21.0'	32%	5%	.37	2.00	1.00	.74	1.68
Median	40'	20.0'	35%	5%	.40	2.00	1.00	.80	1.82
Median	35'	17.5'	38%	5%	.43	2.00	1.00	.86	1.95
Median	30'	15.0'	45%	10%	.55	2.00	1.00	1.10	2.50
Median	25'	12.5'	52%	10%	.62	2.00	1.00	1.24	2.82
Median	20'	10.0'	59%	10%	.69	2.00	1.00	1.38	3.14
Median	15'	7.5'	76%	10%	.86	2.00	1.00	1.72	3.91
Median	10'	5.0'	85%	10%	.95	2.00	1.00	1.90	4.32
House-side		15 '	45%	--	.45	1.00	2.22*	1.00	2.27

*Recommended Spacing of 225 feet for House-side Installations

RELATIVE HAZARD INDEX VS. MEDIAN WIDTH

To compare the relative hazard for various median widths, a similar analysis was made of a 50-foot, median-mounted system in median widths ranging from 10 to 60 feet. The details of the analysis are shown in Table 2.

It should be noted that Column 3(c) of Table 2 contains the relative probability of a secondary collision occurring due to opposing traffic striking the downed support in the opposing traffic lane. This information is based on a crash test of a 4000-pound vehicle striking a 50-foot support at 25 degrees and 60 mph, in which the lateral translation of the base of the pole was 31 feet. Assuming that an encroachment of more than four feet into a traffic lane may result in a collision, the percent probability values were determined from Figure 2(b).

Figure 3 shows a plot of the values for Relative Hazard Index vs. Median Width for a median-mounted system and for a 50-foot house-side system with supports located 15 feet from the edge of the roadway on both sides. This comparison indicates that median-mounted lighting systems produce less hazard than house-side systems for median widths 35 feet or greater.

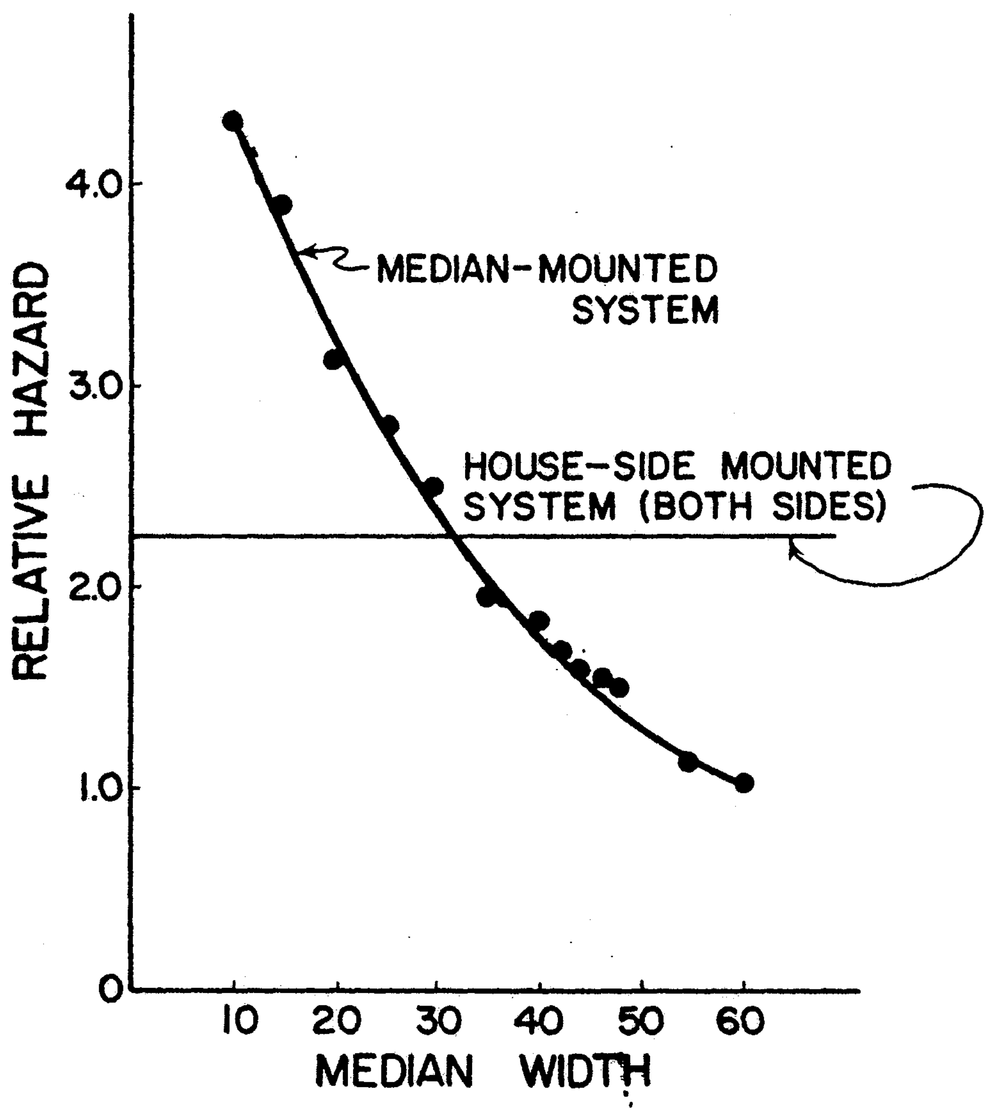


Figure 3

Relationship of Relative Hazard Index to Median Width for Median-Mounted and House-Side Mounted 50' Luminaire Supports.

EXTRAPOLATION OF ILLUMINATION DATA

EXTRAPOLATION OF ILLUMINATION DATA

Introduction

In the design of lighting systems it is often necessary to determine the illumination distribution pattern for many different types of luminaires at several mounting heights. Field measurement of illumination distribution patterns is possible, but is a tedious and costly procedure. Moreover, the precision of field measurement depends on a combination of several elements; perhaps the most important is properly trained personnel. Other important factors are control of electric power, adequate measuring instruments, and meticulous care to avoid sources of error which frequently arise from insecure luminaire mounting, stray light, and infrequent inspection of electric equipment.

In the solution of engineering problems it is always convenient to create hypothetical models of experiments to facilitate computation of the theoretical data. This reduces the engineer's difficulty by minimizing the need to collect and analyze field data.

Economics dictates that models be set up in laboratories in the same way; the acquisition of photometric data from a laboratory model is cheaper and easier than conducting a field study.

This paper deals with the possibility of using mathematical models to estimate the horizontal illumination (E_H) at any point on a horizontal plane for different luminaire mounting heights.

Computational Procedure

Original Data. Photometric data were obtained for the following:

(i) 400-watt high-pressure sodium lamps in Type III luminaires for mounting heights of 30 feet, 50 feet, and 60 feet.

(ii) 1000-watt clear mercury vapor lamps in Type III luminaires for mounting heights of 50 feet and 60 feet.

(iii) Ten 1000-watt clear mercury vapor lamps in floodlights aimed at 45 degrees for mounting heights of 100 feet, 120 feet, 140 feet and 150 feet.

The illumination distribution patterns for the 400-watt and 1000-watt luminaires were determined by measurement at each point of a grid system laid out with 10-foot longitudinal grid line intervals and 12.5-foot transverse grid line intervals.

In the case of the high-mast studies, photometric data were taken on a line bisecting each of the floodlights (on the ray) and on a line midway between two floodlights. Readings were recorded at an interval of 20 feet.

The procedure for collecting photometric data has been described in detail by Rowan and Walton (1). The reader is referred to this source for details of the data collection and data preparation procedures.

Mathematical Model. Lambert's Cosine Law of Incidence states that:

$$E_H = \frac{I_\theta \ COS\theta}{R^2} \qquad (1)$$

Where E_H = Horizontal illumination (footcandles)

R = Direct distance (line of sight) from source to the point of measurement

θ = Angle formed between a normal to the surface and a line from the luminaire to the point of measurement

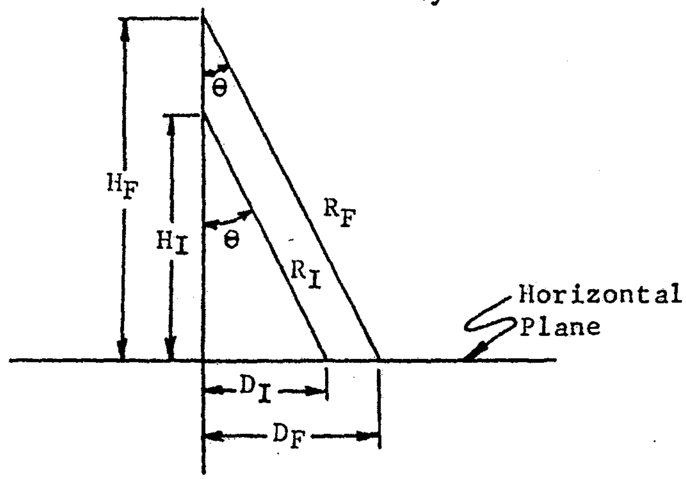
I_θ = Intensity of the source at any angle θ from the normal

As previously stated, the purpose of this study is to test the hypothesis that when photometric data from one mounting height of a luminaire are measured in the field, the illumination for other mounting heights can be computed, with an acceptable degree of accuracy, using a mathematical model. This can be accomplished by comparing the results obtained from Equation 1 (expected value) with the measured value obtained from field observations. If the resulting differences are negligible, it can be concluded that the hypothesis is true.

The value of I_θ can be calculated from the measured or observed value of E_H for the base condition as follows:

$$I_\theta = \frac{E_H^{OBS} R^2}{COS\theta}$$

Sketch of Luminaire Geometry



The values of I_θ were obtained for all grid points. When the mounting height is changed from H_I to H_F, I_θ remains constant, but the values of D_I and R_I change to D_F and R_F, respectively.

Since the values of I_θ and R_F are known for all grid points, $E_{H_1 F}$ can be computed as follows:

$$E_{H_1 F} = \frac{I_\theta \cos\theta}{R_F^2} = \frac{E_{H_1 OBS} R_I^2}{\cos\theta} \; \frac{\cos\theta}{R_F^{\,2}} = \frac{E_{H_1 OBS} R_I^2}{R_F^2}$$

Interpolation of Photometric Data. When the mounting height of the luminaire is changed, the values of D_F and R_F change, creating a new grid that does not necessarily correspond to the basic grid used in collecting the original photometric data.

The new grid was superimposed on the original grid and since photometric data were available for all points of the basic grid, the values of horizontal illumination for each new grid point were calculated by interpolation. These values are considered as field observations for the purpose of this paper.

Analysis Procedures

Two methods have been utilized to evaluate the degree of acceptability of the extrapolated photometric data. These are: 1) statistical analysis of the difference between the measured and extrapolated photometric data and 2) graphical comparison of the resulting isofootcandle contours for the measured and extrapolated data.

Statistical Analysis Procedure. The statistical procedure described above results in two measures of the same parameter for each grid point. The original hypothesis of this study stated that the extrapolated value of horizontal illumination would reproduce, with a high degree of accuracy, the measured values (i.e., the expected difference is zero). This suggests the use of the students' "t" test for paired data to determine if a significant difference exists between the measured and extrapolated values. The "t" statistic can be written as follows:

$$t = \frac{\bar{D}-\mu_D}{S_D}$$

Hypothesis: $\mu_D = 0$

Alternate Hypothesis: $\mu_D \neq 0$

where t = the "t" statistic

$\bar{D}$ = mean difference

μ_D = expected mean difference (zero in this case)

S_D = standard deviation of differences

The "t" statistic is compared to the tabulated value for the desired confidence level and appropriate degrees of freedom. If the computed value is less than the tabulated value, the hypothesis is accepted (i.e., no statistically significant difference exists). A confidence level of 0.1 percent (i.e., $\alpha = 0.001$) has been selected for use in this comparison.

The "t" test can establish statistical significance but does not describe the degree to which the extrapolated values fit the measured values. To evaluate the goodness-of-fit, the correlation coefficient (r) was selected. The value of r can be computed as follows:

$$r = \frac{(E_{EXT})\ (E_{OBS})}{\sqrt{(\Sigma\ E^2_{EXT})(\Sigma E^2_{OBS})}}$$

where r = correlation coefficient

E_{EXT} = extrapolation

E_{OBS} = measured value of horizontal illumination

If the correlation is good, r should have a value near 1.0 and, if no correlation exists, the value would be near zero.

Graphical Analysis. Isofootcandle contour plots have been prepared for several situations to graphically illustrate the comparison of the extrapolated and measured values. The two contour plots were developed separately and then superimposed for direct comparison.

Comparison of Results

Each of the situations compared was handled in a manner similar to that illustrated in Table 1. Table 1 contains data for one ray of a high-mast lighting system and is used here for illustrative purposes only.

TABLE 1

HORIZONTAL ILLUMINATION DATA FOR TEN 1000-WATT FLOODLIGHTS FOR A MOUNTING HEIGHT OF 100 FEET

Location	Observed Value of E_H (Ft-Cd)	Extrapolated Value of E_H (Ft-Cd)	Difference D	Deviation d $(D - \overline{D})$
1	1.44	1.85	-0.41	-0.37
2	2.01	2.14	-0.13	-0.09
3	1.95	2.10	-0.15	-0.11
4	1.69	1.68	+0.01	+0.05
5	1.58	1.64	-0.06	-0.02
6	1.67	1.72	-0.05	-0.01
7	1.53	1.58	-0.05	-0.01
8	1.20	1.20	0	+0.04
9	0.91	0.84	+0.07	+0.11
10	0.69	0.73	-0.04	0
11	0.49	0.46	+0.03	+0.07
12	0.36	0.31	+0.05	+0.09
13	0.18	0.18	0	+0.04
14	0.14	0.15	-0.01	+0.03
15	0.10	0.13	-0.03	+0.01
16	0.09	0.10	-0.01	+0.03
17	0.08	0.08	0	+0.04
18	0.07	0.07	0	+0.04
19	0.05	0.05	0	+0.04
20	0.05	0.04	+0.01	+0.05

$\Sigma D = -0.77$

$$D = \frac{-0.77}{20} = -0.04$$

$$\Sigma d^2 = (D-\overline{D})^2 = .1977$$

$$S_d^2 = \frac{.1977}{20} = 0.0098$$

$$S_d = 0.0990$$

$$t = \frac{D - \mu_D}{S_d} = \frac{-0.04-0.00}{0.0990} = 0.404$$

Hypothesis: The mean value of the difference ($\overline{D}$) is zero

Alternate Hypothesis: The mean value of difference ($\overline{D}$) is other than zero

$\alpha = 0.001$

degrees of freedom = 20-1 = 19

$t_{0.001,19} = 3.883$

Since the computed value of "t" is less than the tabulated value, there is no statistically significant difference in the extrapolated and measured data. Similarly, we can compute the correlation coefficient as follows:

$$r = \frac{\Sigma(E_{OBS})(E_{EXT})}{\sqrt{(\Sigma E_{OBS})^2(\Sigma E^2_{EXT})}} = \frac{24.9169}{\sqrt{(23.5988)(26.4623)}}$$

$$= \frac{620.8519}{624.4785} = 0.994$$

This indicates that there is virtually an absolute correspondence in the measured and extrapolated data.

A summary of the statistical analysis of all situations compared is presented in Table 2. Isofootcandle contour plots for four randomly selected situations are presented in Figures 1 through 4. A review of these figures indicates that the differences between the measured and extrapolated horizontal illumination distribution patterns are indeed minor.

TABLE 2

SUMMARY OF STATISTICAL ANALYSIS

Illumination Unit	Base Data Mounting Height (feet)	Mounting Height Used in Extrapolation (feet)	Degrees of Freedom (d·f)	Computed "t" Value	$t_{0.001,\ d \cdot f}$	Correlation Coefficient r
Single, 1000-Watt Type III, Mercury Vapor Luminaire	50	60	90	0.318	3.40	0.999
Single, 400-Watt Lucalux Luminaire	30	50	58	0.476	3.460	0.997
Single, 400-Watt Lucalux Luminaire	30	60	42	0.160	3.540	0.993
Ten, 1000-Watt Floodlamps	120	100 (on ray)	19	0.404	3.883	0.997
Ten, 1000-Watt Floodlamps	120	140 (on ray)	19	1.08	3.883	0.996
Ten, 1000-Watt Floodlamps	120	150 (on ray)	19	1.14	3.883	0.992

NOTE: No statistically significant differences exist.

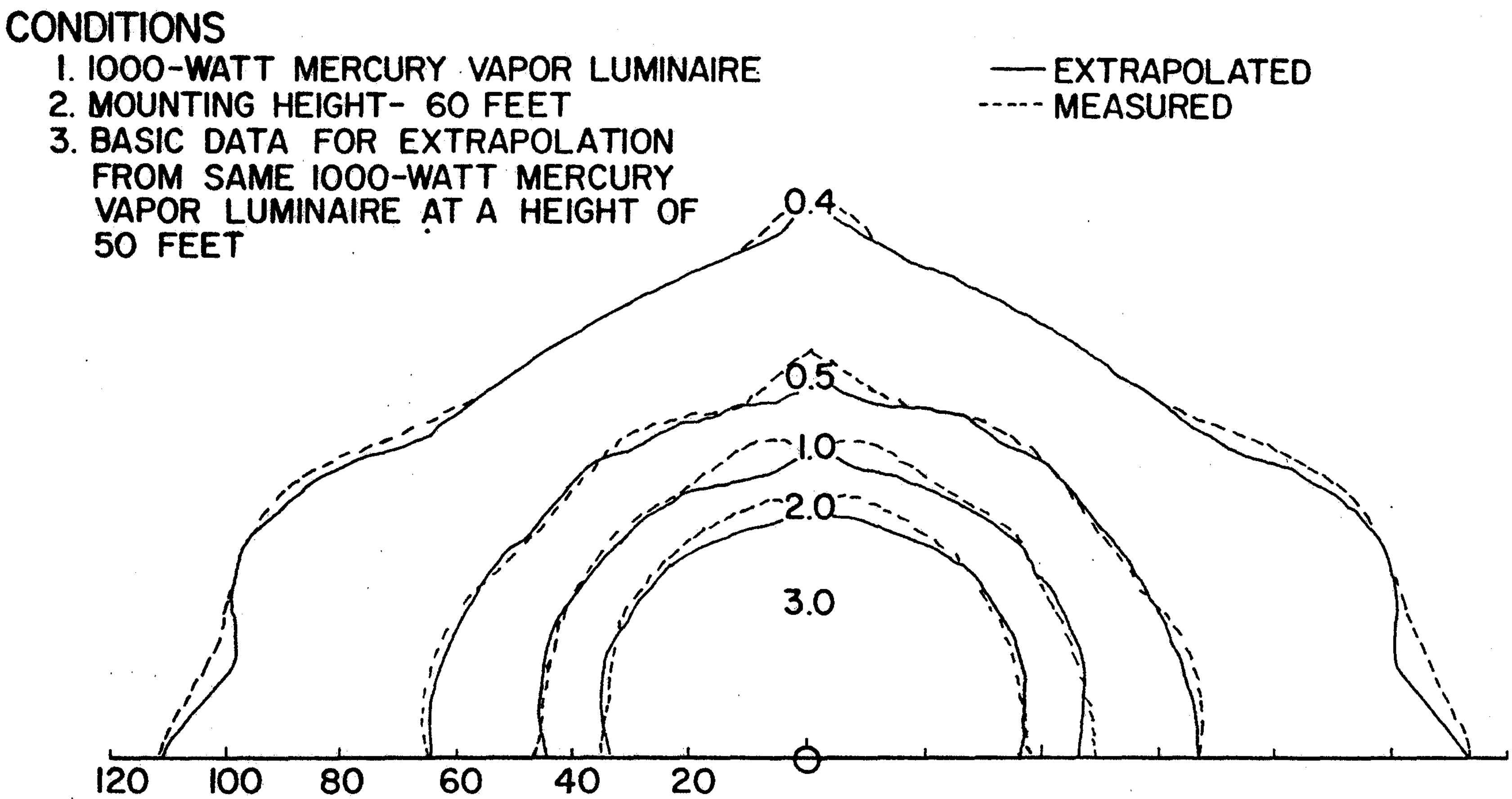


Figure 1

Comparison of Measured and Extrapolated Iso-Foot Candle Curves

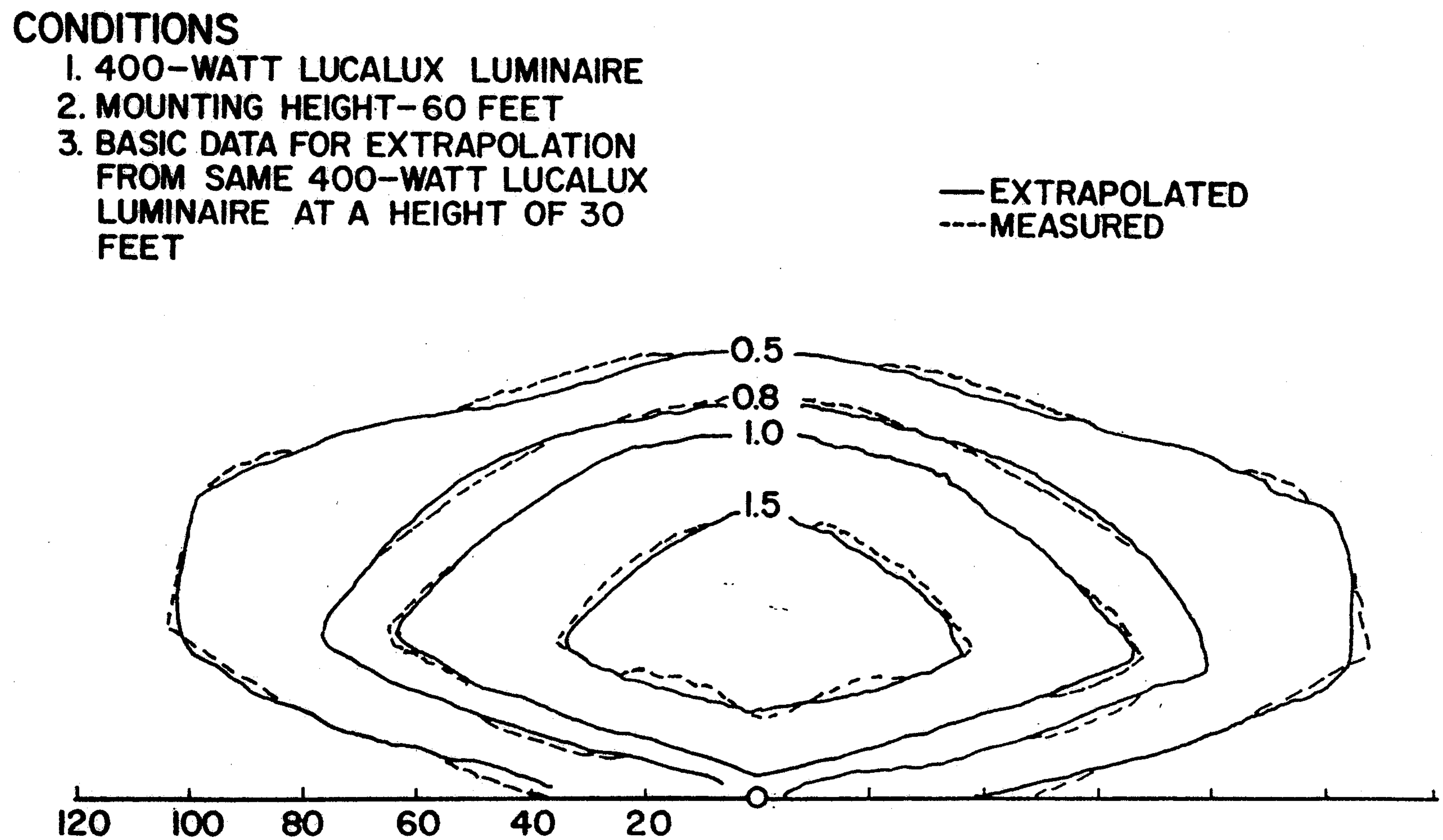


Figure 2

Comparison of Measured and Extrapolated Iso-Foot Candle Curves

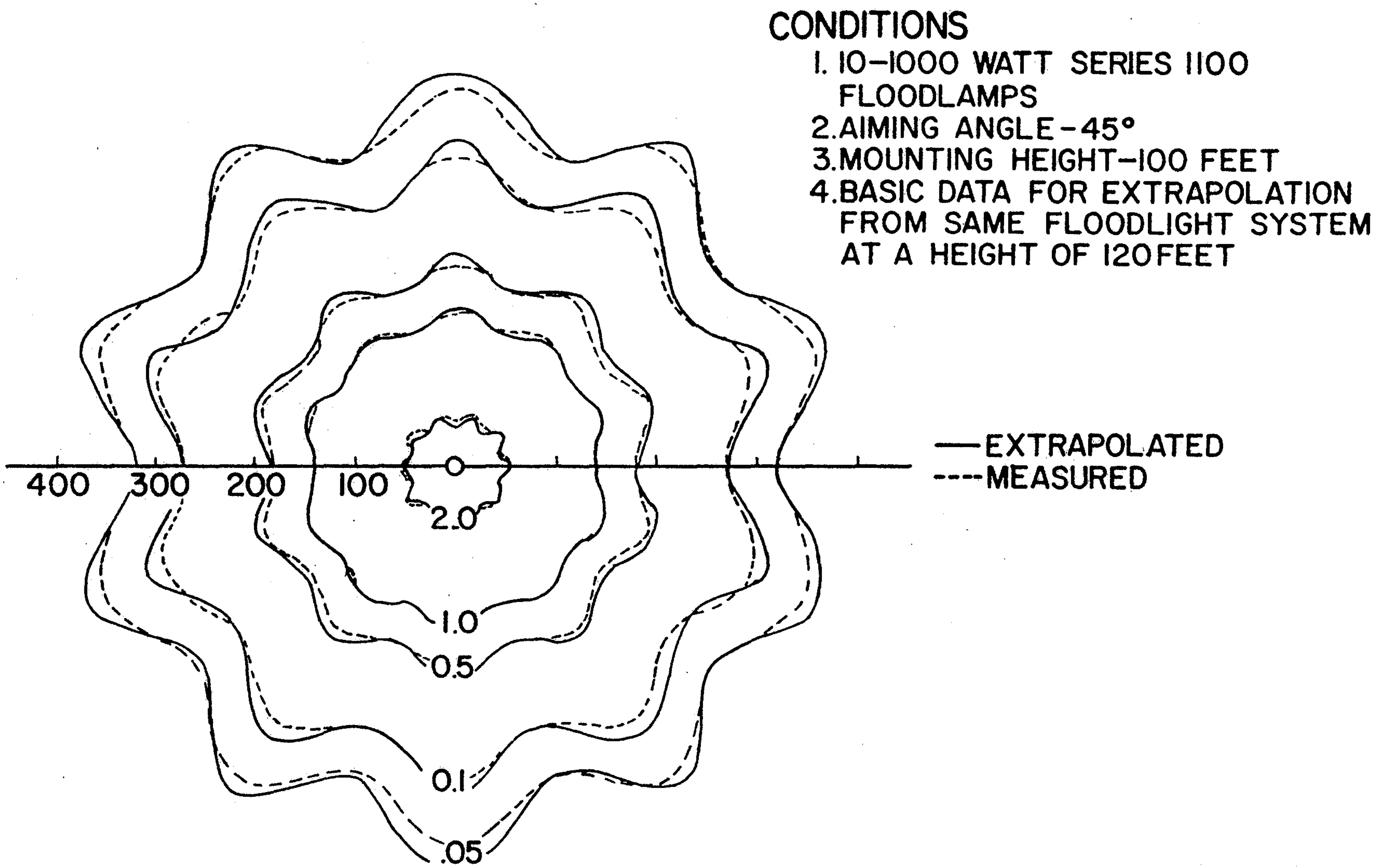


Figure 3

Comparison of Measured and Extrapolated
Iso-Foot Candle Curves

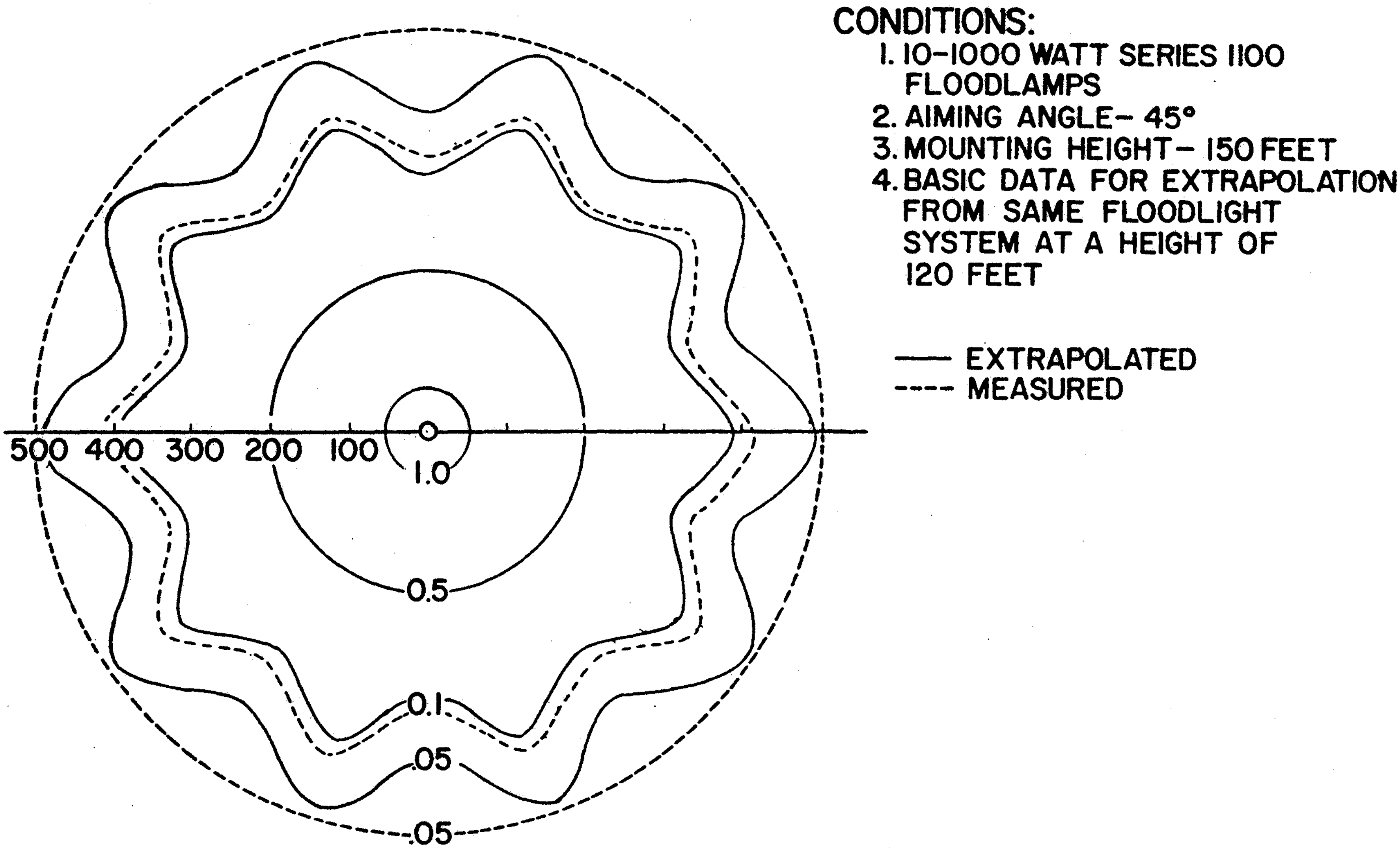


Figure 4

Comparison of Measured and Extrapolated Iso-Foot Candle Curves

Concluding Remarks

The use of Equation 1 to extrapolate observed photometric data from one mounting height to another has been shown to yield results which are very similar to the values actually measured for the same luminaire at that mounting height. This suggests that expensive test installations to evaluate the illumination distribution patterns for a variety of luminaire types at each of several mounting heights is unnecessary. The basic data can be obtained for the luminaire mounted on an existing support and extrapolated to any desired mounting height.

Further, the extrapolation procedure used here could be utilized to evaluate the variation in horizontal illumination patterns associated with differences in pavement elevation within the illumination patterns.

The procedure has been validated for both single sources and groups of sources. This fact suggests that questions regarding the illumination patterns for high-mast lighting at 200 to 250 feet can be determined from data currently available in the literature. In short, it permits the designer to inexpensively test his own ideas as to the best combination of source intensity, mounting height, and source location to produce the desired illumination distribution pattern.

References

1. Rowan, Neilon J. and Walton, Ned E. Optimization of Roadway Lighting Systems. HRB Bulletin No. 216, pp. 34-47, 1968.

2. Walton, Ned E. and Rowan, Neilon J. Photometric Studies of Austin Moonlight Tower Lighting Systems. Texas Transportation Institute Research Report No. 75-4, October 1967.

3. IES Lighting Handbook. Illumination Engineering Society. New York, 1968.

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5. Snedecor, George W. Statistical Methods. Iowa State College Press, Ames, Iowa, 1956.

EXTRAPOLATION OF HIGH-MAST ILLUMINATION DATA

EXTRAPOLATION OF HIGH-MAST ILLUMINATION DATA

Objectives

The objectives of this area of study were:

1. To develop design data for high-mast lighting using ten IES Type V luminaires at 150 feet
2. To measure the light distribution of 15 Revere 1100 floodlights at 150' with mercury vapor and metal halide lamps
3. To extrapolate illumination data between 100 and 200 feet for various numbers of luminaires

Design Data

Photometric data were measured for a system of ten units from the following manufacturer designations:

1. G. E. HM 1000 luminaires
2. Holophane 1100 luminaires

The data were measured using previously reported techniques (1) and included the use of clear mercury, metal halide, and high-pressure sodium lamps in the G. E. HM 1000 luminaires and clear mercury and metal halide lamps in the Holophane 1100 luminaires. In addition, the photometric data were measured for three light center positions within the luminaires.

The photometric data were tabulated in two forms:

1. Average distance at which a given illumination level occurs along a ray extending from the center of the high-mast support
2. Average intensity along a ray extending from the center of the high-mast support for a given distance from the center of the support

These data are presented in Tables 1-5. Through the use of these tables, circular isofootcandle diagrams may be constructed. These diagrams would be very representative of actual constructed isofootcandle curves as the IES Type V units studied produce near circular distributions.

The data may also be used to construct overall high-mast lighting layouts. The intensities from different systems may be summed to determine the total intensity at a given distance from the supports.

Light Distribution of 15 Floodlights

Photometric data were collected for a high-mast system consisting of 15 Revere 1100 floodlights mounted at 150 feet and aimed at 45 degrees with the vertical. Data were measured on and between major rays and averaged as reported previously (1). This data is presented in Figure 1 for clear mercury vapor and metal halide lamps.

TABLE 1

PROJECT 137

HIGH-MAST LIGHTING DATA

10 GE HM 1000 LUMINAIRES

MOUNTING HEIGHT 150 FEET

Illumination (Horiz. Ft-Cd)	Average Distance Along Ray (Measured from Center of Pole Along 12 Rays)					
	7" Light Center Position (Position #1)		8" Light Center Position (Position #2)		9" Light Center Position (Position #3)	
	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)
3.0						
2.5						
2.0		123				
1.5	137	191		176		75
1.0	178	230	178	234	115	177
0.50	235	277	237	300	221	278
0.20	308	345	321	280	320	383
0.10	365	400	375	475	400	463
0.05	450	450	437	525	475	550

TABLE 2

PROJECT 137

HIGH-MAST LIGHTING DATA

10 GE HM 1000 LUMINAIRES

MOUNTING HEIGHT 150 FEET

Distance Along Ray From Center of Pole	Average Intensity Along Ray (Measured in 12 Rays) Horizontal Footcandles					
	7" Light Center Position (Position #1)		8" Light Center Position (Position #2)		9" Light Center Position (Position #3)	
	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)
25	1.56	1.84	1.37	1.91	1.23	1.42
50	1.48	1.80	1.36	1.95	1.25	1.56
75	1.46	1.76	1.29	1.84	1.14	1.50
100	1.68	1.84	1.24	1.68	1.05	1.36
125	1.65	2.01	1.21	1.58	.91	1.18
150	1.32	2.03	1.19	1.56	.79	1.02
175	1.03	1.73	1.03	1.52	.68	.86
200	.79	1.46	.81	1.35	.60	.78
225	.56	1.05	.63	1.08	.48	.71
250	.41	.73	.47	.81	.39	.63
275	.29	.51	.35	.60	.31	.51
300	.22	.36	.26	.50	.24	.41
325	.16	.26	.19	.34	.19	.33
350	.12	.19	.14	.26	.15	.26
375	.09	.13	.10	.21	.12	.21
400	.07	.10	.08	.16	.10	.17
425	.06	.07	.06	.14	.08	.14
450	.05	.05	.04	.12	.06	.11
475	.04	.04	.03	.10	.05	.09
500				.07	.04	.07
525						.06
550						.05

TABLE 3

PROJECT 137

HIGH-MAST LIGHTING DATA

10 HOLOPHANE 1100 LUMINAIRES

MOUNTING HEIGHT 150 FEET

Illumination (Horiz. Ft-Cd)	Average Distance Along Ray (Measured from Center of Pole Along 12 Rays)					
	7" Light Center Position (Position #1)		8" Light Center Position (Position #2)		9" Light Center Position (Position #3)	
	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)
5.0		61				
4.0	65	95		69		
3.0	92	134	78	96		88
2.0	123	191	110	120	95	118
1.0	185	246	182	252	148	200
0.50	247	297	250	314	255	320
0.20	320	338	305	390	330	420
0.10	385	385	350	440	400	500
0.05	450	425	390	479	475	

TABLE 4

PROJECT 137

HIGH-MAST LIGHTING DATA

10 HOLOPHANE 1100 LUMINAIRES

MOUNTING HEIGHT 150 FEET

Distance Along Ray from Center of Pole	Average Intensity Along Ray (Measured on 12 Rays) Horizontal Footcandles					
	7" Light Center Position (Position #1)		8" Light Center Position (Position #2)		9" Light Center Position (Position #3)	
	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)	Clear Mercury Lamps (1000w)	Metal Halide Lamps (1000w)
25					2.60	3.14
50	4.36	5.11			2.59	3.47
75	3.76	4.86	2.85	3.80	2.50	3.25
100	2.67	3.67	2.25	2.80	1.96	2.67
125	1.93	3.09	1.75	2.00	1.34	1.65
150	1.55	2.83	1.45	1.70	1.01	1.14
175	1.13	2.29	1.05	1.50	.83	1.04
200	.91	1.82	.85	1.30	.71	1.00
225	.67	1.31	.63	1.15	.61	.98
250	.48	.94	.46	1.00	.49	.90
275	.35	.64	.34	.80	.38	.76
300	.25	.43	.24	.60	.29	.61
325	.19	.27	.17	.45	.22	.47
350	.14	.17	.12	.35	.17	.37
375	.11	.11	.08	.25	.13	.30
400	.08	.08	.05	.15	.10	.24
425	.06	.05	.03	.10	.09	.19
450	.05	.04	.02	.08	.06	.16
475	.04		.01	.05	.05	.13
500				.03	.04	.10
525						
550						

TABLE 5

PROJECT 137

HIGH-MAST LIGHTING DATA

10 GE HM 1000 LUMINAIRES*

MOUNTING HEIGHT 150 FEET

	Average Distance Along Ray (Measured from Center of Pole Along 12 Rays)		
	7" Light Center Position (Position #1)	8" Light Center Position (Position #2)	9" Light Center Position (Position #3)
Illumination (Horiz. Ft-Cd)	HIGH PRESSURE SODIUM LAMPS	HIGH PRESSURE SODIUM LAMPS	HIGH PRESSURE SODIUM LAMPS
4.0	91		
3.5	104		
3.0	113	116	
2.5	122	132	
2.0	133	144	
1.5	145	158	160
1.0	162	174	194
0.50	190	208	237
0.20	227	235	292
0.10	250	273	325
0.05	283	300	363

*Equipped with 400-watt HPS lamps.

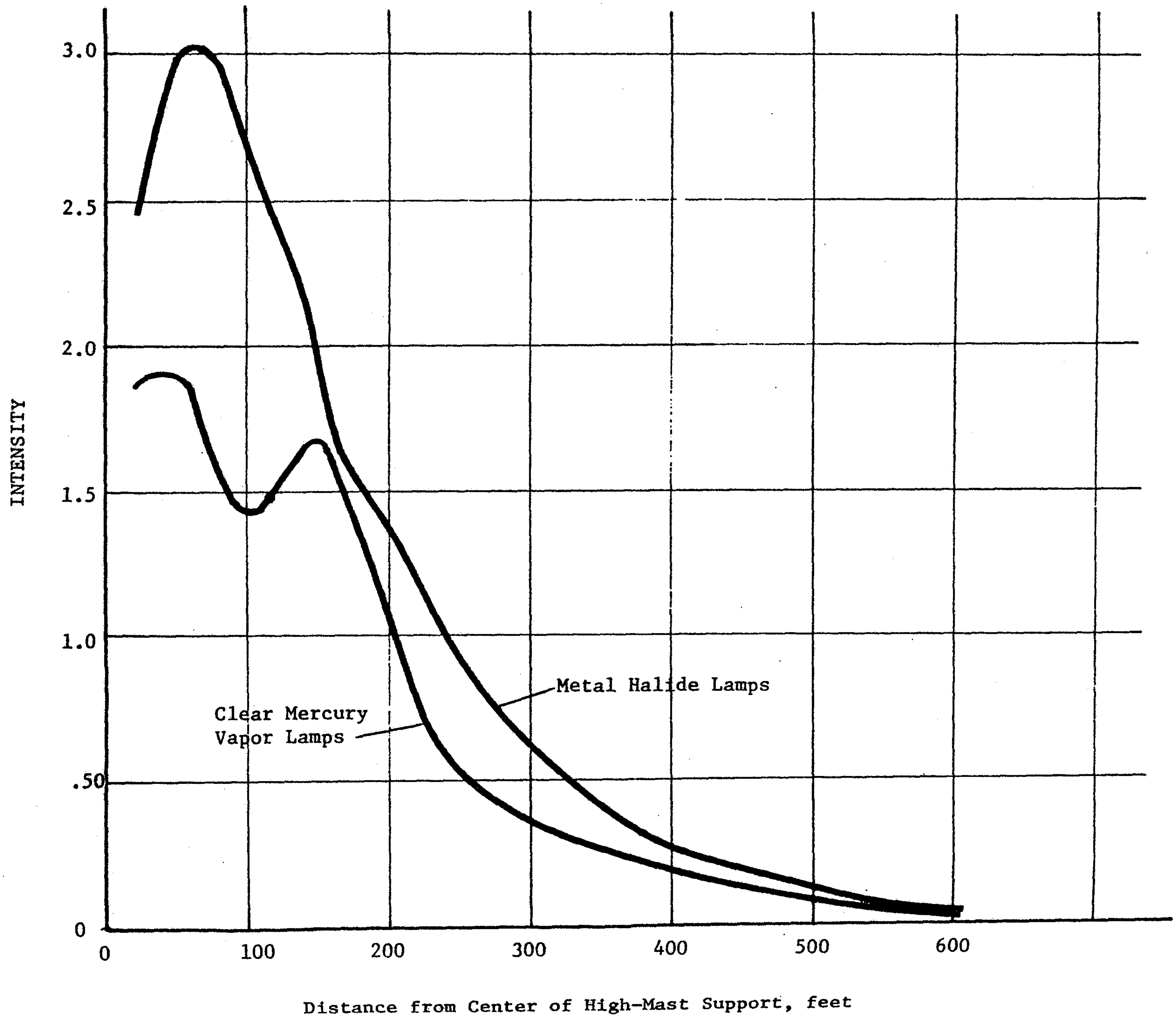

INTENSITY
3.0
2.5
2.0
1.5
1.0
.50
0
0
100
200
300
400
500
600
Metal Halide Lamps
Clear Mercury
Vapor Lamps
Distance from Center of High-Mast Support, feet

Figure 1

Extrapolation of High Mast Data

This area of research has been devoted to the development of design data for various mounting height-spacing ratios and for various numbers of luminaires per assembly. Photometric data were collected for various members of units at 150-foot mounting heights. These data were extrapolated to heights ranging from 100 to 200 feet using the basic extrapolation scheme discussed in preceding sections of this appendix.

Hypothetical square grids were established for the extrapolations in terms of mounting height to spacing ratios. For example, on the 100-foot mounting height extrapolations at a mounting height to spacing ratio of 5 to 1, illumination assemblies were placed on a square grid every 500 feet. For 200-foot mounting heights and 5 to 1 ratios, illumination assemblies were placed on the square grid every 1000 feet. Illumination intensities from all assemblies were summed at each point on a 25' x 25' grid. From these values the following parameters were determined:

1. Maximum intensity within the system
2. Minimum intensity within the system
3. Average intensity within the system
4. Maximum to minimum ratios of intensity
5. Average to minimum ratios of intensity

Tables 6-15 summarize the results. Included are values for clear mercury vapor and metal halide lamps and 8-inch and 9-inch light center spacings within each luminaire. For a given mounting height and for given design criteria (average, avg/min, etc.) these tables can be read to establish spacing for illumination assemblies in a total area

REFERENCES

1. Walton, N. E., and Rowan, N. J. High-Mast Lighting, Research Report 75-12, Texas Transportation Institute, College Station, Texas.

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
100-FOOT MOUNTING HEIGHT
CLEAR MERCURY VAPOR LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT CLEAR MERCURY VAPOR LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	3	1.99	.51	.99	3.90	1.93	1.93	.65	.99	2.97	1.53
4:1	3	1.93	.12	.53	16.08	4.42	1.75	.24	.54	7.29	2.26
5:1	3	1.93	.01	.34	193.00	33.59	1.75	.07	.34	25.00	4.89
3:1	4	2.66	.65	1.30	4.09	2.00	2.59	.86	1.32	3.01	1.53
4:1	4	2.58	.15	.70	17.20	4.67	2.35	.32	.72	7.34	2.25
5:1	4	2.58	.01	.44	258.00	44.43	2.35	.08	.45	29.38	5.67
3:1	5	3.30	.82	1.62	4.02	1.98	3.21	1.08	1.64	2.97	1.52
4:1	5	3.20	.19	.87	16.84	4.59	2.91	.40	.90	7.27	2.24
5:1	5	3.20	.01	.55	320.00	55.37	2.91	.09	.56	32.33	6.27
3:1	6	3.97	.99	1.96	4.01	1.98	3.86	1.29	1.97	2.99	1.53
4:1	6	3.85	.23	1.05	16.74	4.57	3.50	.48	1.08	7.29	2.24
5:1	6	3.85	.01	.67	385.00	66.68	3.50	.12	.68	29.17	5.66

*Holophone, IES Type V Luminaires

TABLE 7

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
100-FOOT MOUNTING HEIGHT
METAL HALIDE LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT METAL HALIDE LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	3	2.81	1.32	1.70	2.13	1.29	2.71	1.36	1.67	1.99	1.23
4:1	3	2.57	.38	.92	6.76	2.42	2.33	.59	.93	3.95	1.57
5:1	3	2.57	.05	.57	51.40	11.40	2.25	.20	.58	11.25	2.88
3:1	4	3.74	1.77	2.27	2.11	1.28	3.62	1.79	2.21	2.02	1.24
4:1	4	3.44	.49	1.22	7.02	2.50	3.12	.76	1.23	4.11	1.61
5:1	4	3.44	.06	.76	57.33	12.63	3.02	.27	.76	11.19	2.83
3:1	5	4.64	2.19	2.82	2.12	1.29	4.48	2.22	2.74	2.02	1.24
4:1	5	4.26	.61	1.52	6.98	2.49	3.86	.95	1.52	4.06	1.60
5:1	5	4.26	.09	.94	47.33	10.47	3.74	.33	.95	11.33	2.87
3:1	6	5.59	2.64	3.39	2.12	1.29	5.41	2.68	3.31	2.02	1.23
4:1	6	5.13	.74	1.83	6.93	2.47	4.65	1.15	1.83	4.04	1.59
5:1	6	5.13	.10	1.13	51.30	11.34	4.51	.40	1.14	11.27	2.85

*Holophone, IES Type V Luminaires

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
125-FOOT MOUNTING HEIGHT
CLEAR MERCURY VAPOR LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT CLEAR MERCURY VAPOR LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	3	1.27	.24	.56	5.29	2.33	1.21	.34	.56	3.56	1.65
4:1	3	1.23	.08	.35	15.37	4.33	1.13	.14	.35	8.07	2.48
5:1	3	1.23	.01	.24	123.00	23.95	1.13	.01	.24	113.00	23.91
3:1	4	1.69	.32	.73	5.28	2.30	1.63	.46	.75	3.54	1.63
4:1	4	1.65	.08	.45	20.62	5.67	1.51	.18	.46	8.39	2.58
5:1	4	1.65	.01	.31	165.00	31.37	1.51	.01	.32	151.00	31.95
3:1	5	2.08	.40	.90	5.20	2.26	1.99	.56	.93	3.55	1.66
4:1	5	2.04	.08	.56	25.50	6.96	1.87	.22	.58	8.50	2.62
5:1	5	2.04	.01	.39	204.00	38.51	1.87	.01	.40	187.00	39.69
3:1	6	2.51	.48	1.09	5.23	2.28	2.41	.68	1.12	3.54	1.65
4:1	6	2.46	.12	.68	20.50	5.63	2.25	.28	.69	8.04	2.48
5:1	6	2.46	.01	.47	246.00	46.69	2.25	.01	.48	225.00	47.77

*Holophone, IES Type V Luminaires

TABLE 9

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
125-FOOT MOUNTING HEIGHT
METAL HALIDE LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT METAL HALIDE LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	3	1.76	.70	1.05	2.51	1.50	1.67	.70	.93	2.39	1.33
4:1	3	1.64	.24	.65	6.83	2.70	1.46	.30	.58	4.87	1.92
5:1	3	1.64	.01	.44	164.00	44.24	1.46	.01	.39	146.00	39.05
3:1	4	2.33	.92	1.39	2.53	1.51	2.22	.94	1.23	2.36	1.31
4:1	4	2.20	.28	.85	7.86	3.05	1.96	.40	.76	4.90	1.91
5:1	4	2.20	.01	.58	220.00	58.30	1.96	.01	.52	196.00	51.82
3:1	5	2.89	1.14	1.72	2.54	1.51	2.75	1.16	1.53	2.37	1.32
4:1	5	2.72	.36	1.06	7.56	2.95	2.42	.50	.95	4.84	1.89
5:1	5	2.72	.01	.72	272.00	72.43	2.42	.01	.64	242.00	64.22
3:1	6	3.49	1.38	2.08	2.53	1.51	3.32	1.40	1.85	2.37	1.32
4:1	6	3.28	.44	1.28	7.45	2.91	2.92	.60	1.14	4.87	1.90
5:1	6	3.28	.01	.87	328.00	87.31	2.92	.01	.77	292.00	77.47

*Holophone HM 1000, IES Type V Luminaires

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
150-FOOT MOUNTING HEIGHT
CLEAR MERCURY VAPOR LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT CLEAR MERCURY VAPOR LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	4	1.18	.28	.60	4.21	2.15	1.16	.36	.60	3.22	1.66
4:1	4	1.14	.04	.33	28.50	8.30	1.04	.12	.33	8.67	2.74
5:1	4	1.14	.01	.21	114.00	20.66	1.04	.01	.21	104.00	20.59
3:1	6	1.79	.32	.90	5.59	2.80	1.72	.52	.89	3.31	1.72
4:1	6	1.71	.08	.49	21.38	6.14	1.56	.20	.49	7.80	2.44
5:1	6	1.71	.01	.31	171.00	30.95	1.56	.01	.31	156.00	30.72
3:1	8	2.37	.56	1.21	4.23	2.15	2.32	.72	1.19	3.22	1.66
4:1	8	2.28	.08	.67	28.50	8.32	2.08	.24	.66	8.67	2.74
5:1	8	2.28	.01	.41	228.00	41.47	2.08	.01	.41	208.00	41.19
3:1	10	2.97	.68	1.51	4.37	2.22	2.88	.88	1.49	3.27	1.69
4:1	10	2.85	.12	.83	23.75	6.90	2.60	.32	.82	8.13	2.55
5:1	10	2.85	.01	.52	285.00	51.83	2.60	.01	.51	260.00	51.31

*Holophone, IES Type V Luminaires

TABLE 11

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
150-FOOT MOUNTING HEIGHT
METAL HALIDE LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT METAL HALIDE LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	4	1.68	.72	1.03	2.33	1.43	1.55	.76	.96	2.04	1.27
4:1	4	1.52	.16	.55	9.50	3.46	1.37	.32	.53	4.34	1.67
5:1	4	1.52	.01	.35	152.00	34.52	1.30	.01	.33	130.00	32.94
3:1	6	2.52	1.08	1.54	2.33	1.43	2.32	1.12	1.44	2.07	1.29
4:1	6	2.28	.24	.83	9.50	3.47	2.08	.44	.80	4.73	1.81
5:1	6	2.28	.01	.52	228.00	51.89	1.95	.01	.49	195.00	49.22
3:1	8	3.36	1.44	2.06	2.33	1.43	3.10	1.52	1.93	2.04	1.27
4:1	8	3.04	.32	1.11	9.50	3.47	2.78	.64	1.07	4.34	1.67
5:1	8	3.04	.01	.69	304.00	69.19	2.60	.01	.66	260.00	65.87
3:1	10	4.20	1.80	2.57	2.33	1.43	3.87	1.88	2.41	2.06	1.28
4:1	10	3.80	.40	1.39	9.50	3.47	3.47	.76	1.33	4.57	1.75
5:1	10	3.80	.01	.86	380.00	86.41	3.25	.01	.82	325.00	82.16

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
175-FOOT MOUNTING HEIGHT
CLEAR MERCURY VAPOR LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT CLEAR MERCURY VAPOR LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	10	2.21	.68	1.22	3.25	1.80	2.15	.80	1.19	2.69	1.49
4:1	10	2.09	.08	.61	26.13	7.58	1.91	.24	.59	7.96	2.47
5:1	10	2.09	.01	.39	209.00	38.90	1.91	.01	.38	191.00	37.51
3:1	12	2.65	.82	1.46	3.23	1.79	2.57	.96	1.43	2.68	1.49
4:1	12	2.51	.08	.73	31.38	9.07	2.29	.28	.71	8.18	2.54
5:1	12	2.51	.01	.47	251.00	46.51	2.29	.01	.45	229.00	45.10
3:1	15	3.33	1.02	1.84	3.26	1.81	3.23	1.22	1.79	2.65	1.47
4:1	15	3.13	.12	.91	26.08	7.61	2.87	.36	.89	7.97	2.48
5:1	15	3.13	.01	.59	313.00	58.57	2.87	.01	.57	287.00	56.61

*Holophone, IES Type V Luminaires

TABLE 13

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
175-FOOT MOUNTING HEIGHT
METAL HALIDE LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT METAL HALIDE LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	10	3.15	1.66	2.05	1.90	1.24	3.06	1.56	1.93	1.96	1.24
4:1	10	2.79	.28	1.01	9.96	3.61	2.46	.55	.97	4.47	1.76
5:1	10	2.79	.01	.64	279.00	63.68	2.46	.01	.60	246.00	60.41
3:1	12	3.79	1.98	2.46	1.91	1.24	3.67	1.87	2.32	1.96	1.24
4:1	12	3.35	.32	1.21	10.47	3.79	2.95	.66	1.16	4.47	1.76
5:1	12	3.35	.01	.76	335.00	76.41	2.95	.01	.73	295.00	72.60
3:1	15	5.57	2.50	3.22	2.23	1.29	4.59	2.34	2.90	1.96	1.24
4:1	15	5.03	.44	1.60	11.43	3.63	3.69	.83	1.45	4.45	1.75
5:1	15	5.03	.01	1.01	503.00	100.66	3.69	.01	.91	369.00	90.80

*Holophone, IES Type V Luminaires

TABULATION OF DATA FROM
HYPOTHETICAL GRIPS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
200-FOOT MOUNTING HEIGHT
CLEAR MERCURY VAPOR LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT CLEAR MERCURY VAPOR LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	10	1.71	.40	.89	4.27	2.22	1.59	.58	.84	2.74	1.44
4:1	10	1.67	.08	.49	20.88	6.11	1.47	.16	.46	9.19	2.89
5:1	10	1.67	.01	.31	167.00	31.26	1.47	.01	.29	147.00	29.21
3:1	12	2.10	.48	1.07	4.37	2.24	1.94	.68	1.01	2.85	1.49
4:1	12	2.02	.08	.59	25.25	7.41	1.78	.20	.56	8.90	2.79
5:1	12	2.02	.01	.38	202.00	37.87	1.78	.01	.35	178.00	35.36
3:1	15	2.61	.60	1.34	4.35	2.23	2.42	.86	1.27	2.81	1.47
4:1	15	2.53	.12	.74	21.08	6.16	2.22	.24	.70	9.25	2.91
5:1	15	2.53	.01	.47	253.00	47.19	2.22	.01	.44	222.00	44.25
3:1	20	3.46	.80	1.77	4.32	2.21	3.22	1.16	1.68	2.78	1.45
4:1	20	3.34	.16	.98	20.88	6.10	2.94	.32	.93	9.19	2.91
5:1	20	3.34	.01	.62	334.00	62.35	2.94	.01	.59	294.00	58.79

*Holophone, IES Type V Luminaires

TABLE 15

TABULATION OF DATA FROM
HYPOTHETICAL GRIDS OF EXTRAPOLATED
HIGH-MAST LIGHTING*
200-FOOT MOUNTING HEIGHT
METAL HALIDE LAMPS

Mounting Height to Spacing Ratio	No. of Units Per Pole	1000-WATT METAL HALIDE LAMPS									
		8" Light Center					9" Light Center				
		Max	Min	Avg	Max/Min	Avg/Min	Max	Min	Avg	Max/Min	Avg/Min
3:1	10	2.44	1.08	1.43	2.26	1.33	2.31	1.11	1.37	2.08	1.23
4:1	10	2.24	.20	.79	11.20	3.93	1.93	.44	.76	4.39	1.72
5:1	10	2.24	.02	.49	112.00	24.65	1.93	.10	.48	19.30	47.70
3:1	12	2.95	1.32	1.75	2.23	1.32	2.78	1.35	1.65	2.06	1.23
4:1	12	2.71	.24	.96	11.29	3.98	2.34	.52	.92	4.50	1.76
5:1	12	2.71	.04	.60	67.75	15.00	2.34	.12	.58	19.50	4.80
3:1	15	3.67	1.64	2.18	2.24	1.33	3.49	1.68	2.07	2.08	1.23
4:1	15	3.39	.32	1.19	10.59	3.73	2.93	.64	1.15	4.58	1.79
5:1	15	3.39	.04	.75	84.75	18.71	2.93	.16	.72	18.31	4.50
3:1	20	4.84	2.16	2.87	2.24	1.33	4.60	2.22	2.75	2.07	1.24
4:1	20	4.48	.44	1.57	10.18	3.56	3.86	.88	1.51	4.39	1.73
5:1	20	4.48	.04	.98	112.00	24.59	3.86	.22	.96	17.55	4.35

*Holophone, IES Type V Luminaires

DESIGN OF HIGH-MAST LIGHTING

DESIGN OF HIGH-MAST LIGHTING

Neither the Standard Practice or the AASHO Guide provide any detail in the guidelines for the design of high-mast lighting. A design procedure is presented in Research Report 75-12, High-Mast Lighting by Rowan and Walton. This procedure, however, is based largely on the use of iso-footcandle curves produced from field laboratory tests and judgment or experience. Considerably more rationale is contained in the procedure described in this report.

Illumination Levels

The Standard Practice and AASHO Guide do not specify illumination levels for interchanges other than for the freeway in general, except in the Standard Practice it is stated,

> Intersecting, converging, or diverging roadway areas require higher illumination. The illumination within these areas should at least be equal to the sum of the values recommended for each roadway which forms the intersection.

This guide does not take into consideration the design and operational conditions and, therefore, it is considered more appropriate that the illumination level for interchanges be determined on the same basis as that for continuous sections of freeways.

Achieving a specified illumination level is a function of mounting height, type of light source, type of luminaire or floodlight, and number of luminaires or floodlights in a system (system refers to the assembly on a single mast). It is possible to estimate a trial number of units in a system by a computational process involving total lamp lumens, a coefficient of luminaire efficiency and the area to be covered, but experience is extremely valuable in this process. In any case, the designer will likely determine the number of units required to provide a given illumination level by trial and error.

Location and Spacing of Masts

Preliminary spacing of masts in the interchange area should be made on a maximum spacing-to-mounting height ratio of 5:1 if the objective is to achieve the same cut-off characteristics that are achieved using Medium Distribution luminaires in continuous lighting. Adjustments to spacing should be made on the basis of location criteria and computational procedures of illumination by the point-by-point method discussed later.

There are certain considerations to be made in the location of masts in order to achieve the greatest effectiveness from the lighting system. These are as follows:

1. Masts should be located such that the driver's line of sight is not directly toward the light source in the range of 1500 feet to two mounting heights from the source. Preferably, the line of sight would not be above the lower third point of the mast while the line of sight is within 10° either side of the mast.

2. Masts should be located in such a manner that the light source will not at any time be in the direct line of sight with signs, especially overhead signs, and other visual communication media.
3. Masts should not be placed at the end of long tangents or other vulnerable locations where there is an appreciable probability of collision. If such a location is necessary, adequate impact attenuation should be provided.
4. Masts are desirably located such that the highest localized levels of illumination fall in the traffic conflict areas, such as ramp terminals. Otherwise, masts should be located a sufficient distance from the roadway to position the greatest uniformity of illumination on the pavement surface. This is done using plastic overlays of iso-footcandle curves of the light units to be used. This will normally result in the masts being placed a sufficient distance from the roadway to virtually eliminate the probability of collision.

Illumination Computational Procedures

Following the preliminary location and spacing of masts and the initial selection of the number of units on each mast, it is necessary to check the distribution of illumination against the established criteria. The most rational approach to this check process is by computation of illumination using a point-by-point procedure. To facilitate computations, the entire interchange area is superimposed with grid lines at 25' to 50' intervals. Intervals of 25' are desirable if a computer is used, whereas 50' intervals are more appropriate for hand calculations.

The point-by-point computational process utilizes a candlepower distribution curve as illustrated in Figure 1. Candlepower distribution curves are normally developed for single-unit Type V luminaires, in which case they must be multiplied by the number of luminaires in the system. Such a curve can be developed for all symmetrical high-mast systems, whether they are made up of Type V units or individual floodlights arranged in a symmetrical pattern.

The illumination in horizontal footcandles at a grid point resulting from one high-mast assembly can be computed using the formula:

$$E_H = \frac{CP \text{ Cos } \theta}{d^2}$$

Where:

E_H = Illumination at the point in horizontal footcandles

CP = Candlepower at angle θ, lumens

θ = The angle from the vertical axis through the system to the point in question (Figure 1), and

d = The distance from the light source to the point in question (Figure 2)

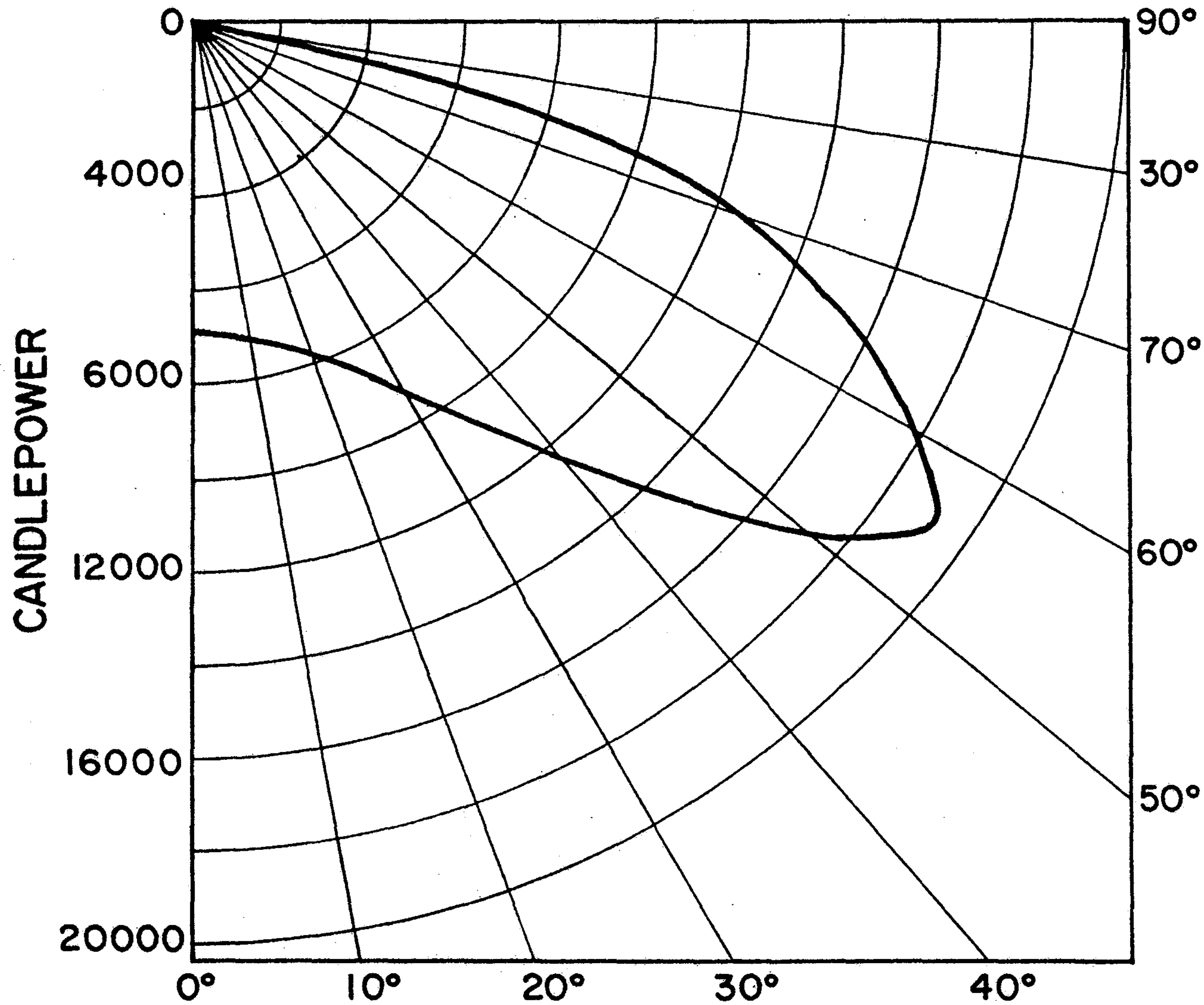
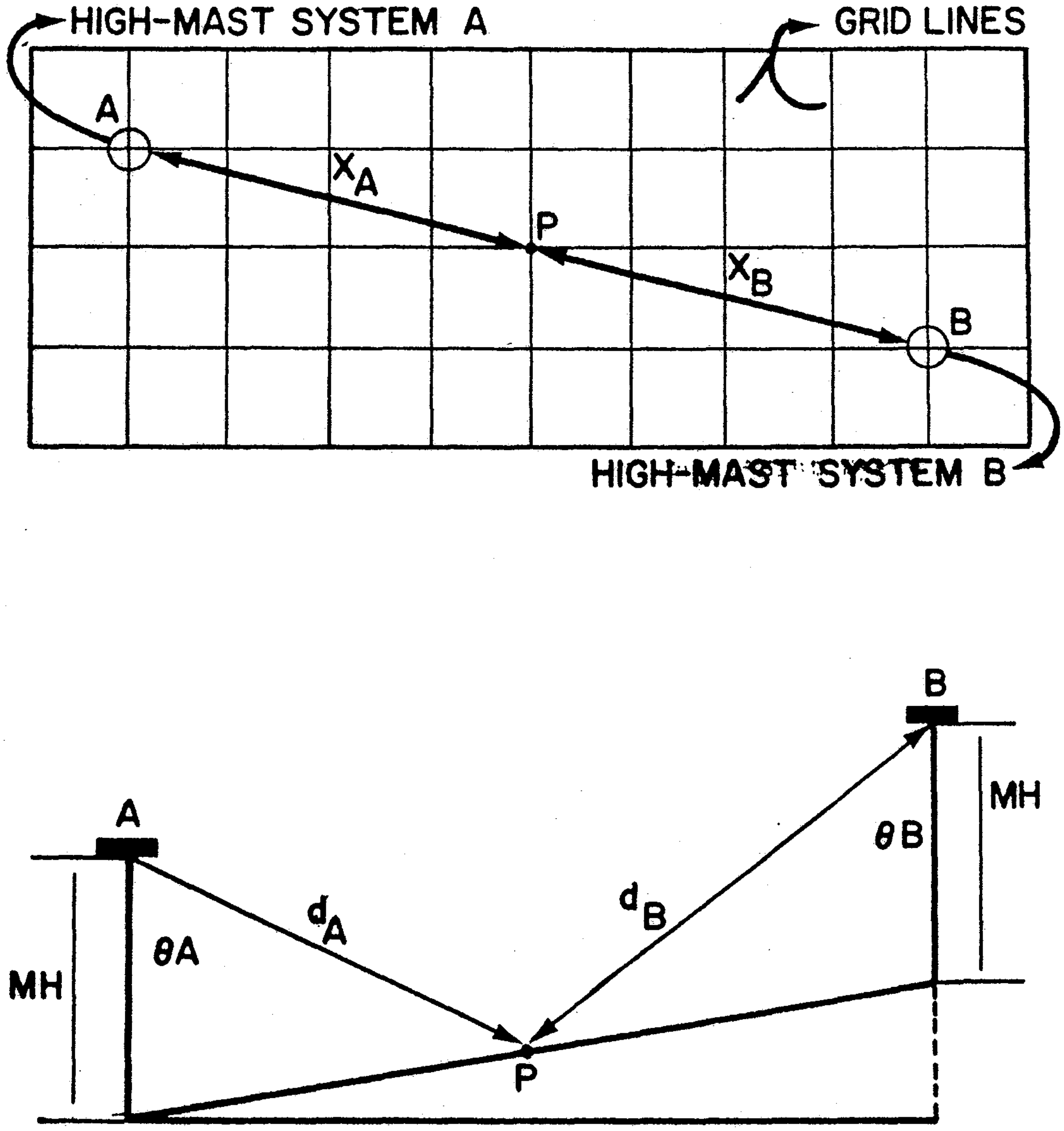


Figure 1

Typical Candlepower Distribution Curve



$$d_A = \sqrt{\bar{X}_A^{\,2} + (\text{Elev. A} - \text{Elev. P})^2} \quad \text{and}$$

$$d_B = \sqrt{\bar{X}_B^{\,2} + (\text{Elev. B} - \text{Elev. P})^2}$$

$$\text{Then } EH_P = \frac{CP_{\theta A} \ \text{Cos } \theta_A}{\bar{X}_A^{\,2} + (\text{Elev. A} - \text{Elev. P})^2} + \frac{CP_{\theta B} \ \text{Cos } \theta_B}{\bar{X}_B^{\,2} + (\text{Elev. B} - \text{Elev. P})^2}$$

Figure 2

Illustration of Point-by-Point Process of Illumination Computations

Then, the total illumination at each of the grid points is the sum of the contributions of illumination from the high-mast assemblies within an effective range of the point in question. This process is illustrated in Figure 2.

Once the amount of illumination is computed for all of the grid points, an iso-footcandle diagram may be drawn for the entire interchange area. This will facilitate an overall appraisal of the illumination design.

For a more specific appraisal the designer should plot an illumination profile for each section of roadway in the interchange. For wider roadways, it may be necessary to plot two or more profiles to fully represent the traveled way. These profiles are plotted using the contour values and contour spacings along the roadway, or by using interpolation of the grid matrix of illumination values at the grid points. If computer techniques are used, the latter is the more adaptable process. From the illumination profile, the average illumination values and uniformity ratios are computed. By comparing the average illumination and uniformity ratios with the previously established criteria, the spacing of masts and/or number of units on each mast may be adjusted accordingly, and the computational process repeated until the desired criteria are achieved.

The major weakness in the point-by-point design process is the reliability of the input photometric data, as in the case of computational procedures for continuous lighting. The candlepower distribution curve is developed under controlled laboratory conditions.

There is some preliminary indication from unpublished research that the loss from laboratory to field installation is on the order of 25 percent. Therefore, it seems justified that the designer consider reducing the candlepower values by 25 percent unless there is evidence that he can be assured of achieving the light output indicated by the candlepower distribution curve.

THE EFFECT OF GLARE UPON DRIVER BEHAVIOR
IN A TRANSITIONAL LIGHTING SITUATION

TABLE 1

Wattages for the Experimental Lighting Conditions

	Luminaire Position 1	2	3	4	5	6	7	8	9
Lighting Condition 1	1000	1000	1000	1000	1000	1000	1000	1000	1000
Lighting Condition 2	175	250	400	700	1000	700	400	250	175
Lighting Condition 3	175	175	250	400	700	400	250	175	175

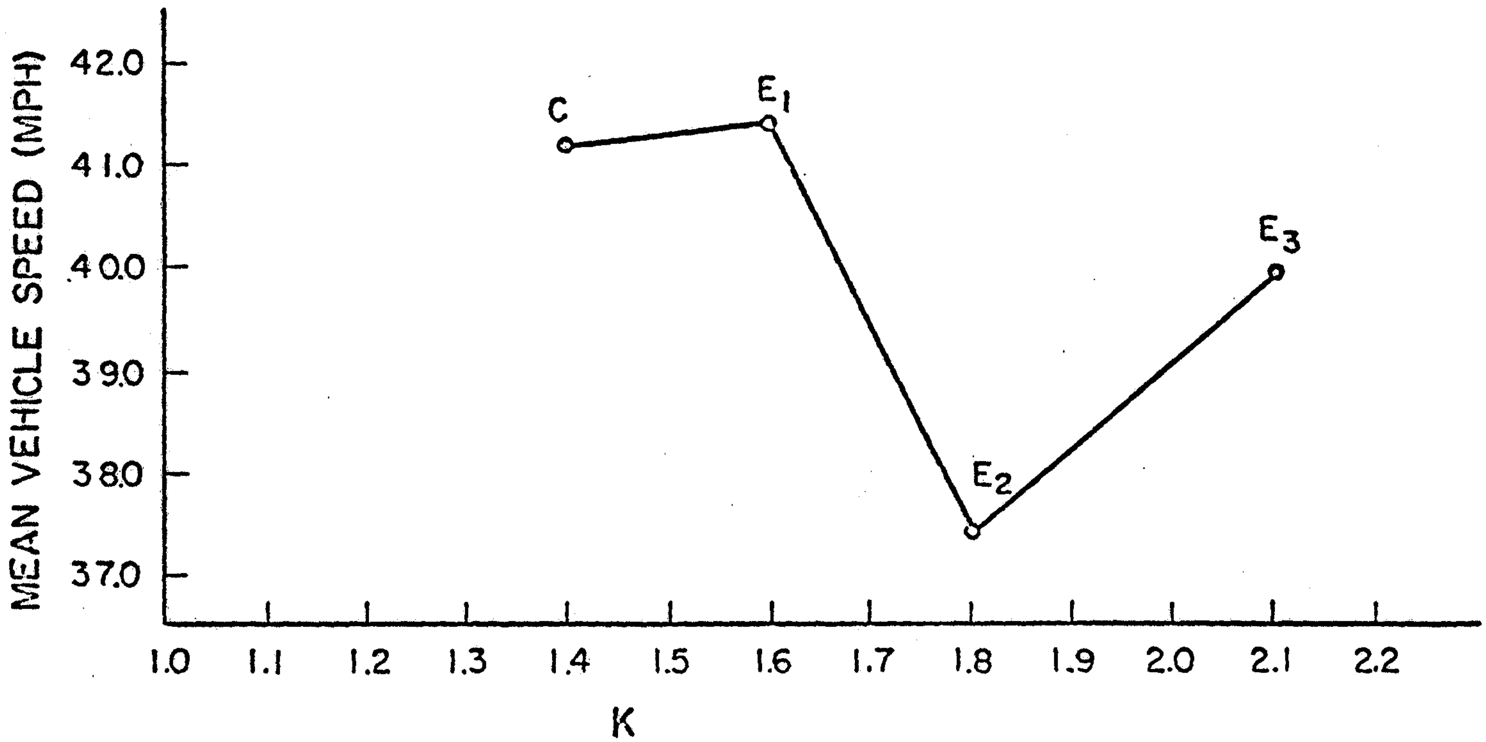


Fig. 1. The Effect of Glare Upon Vehicle Speed

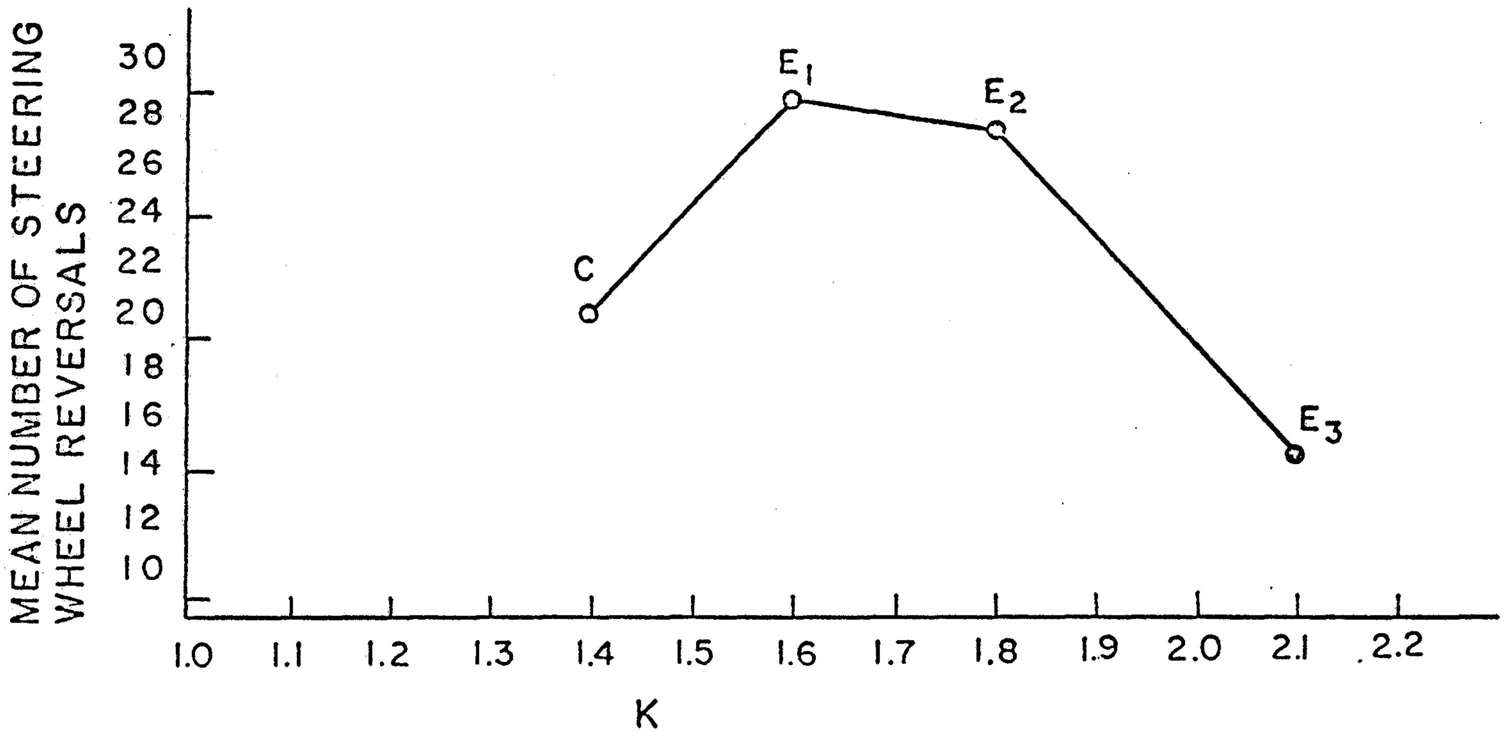


Fig. 2. The Effect of Glare Upon Steering Wheel Reversals

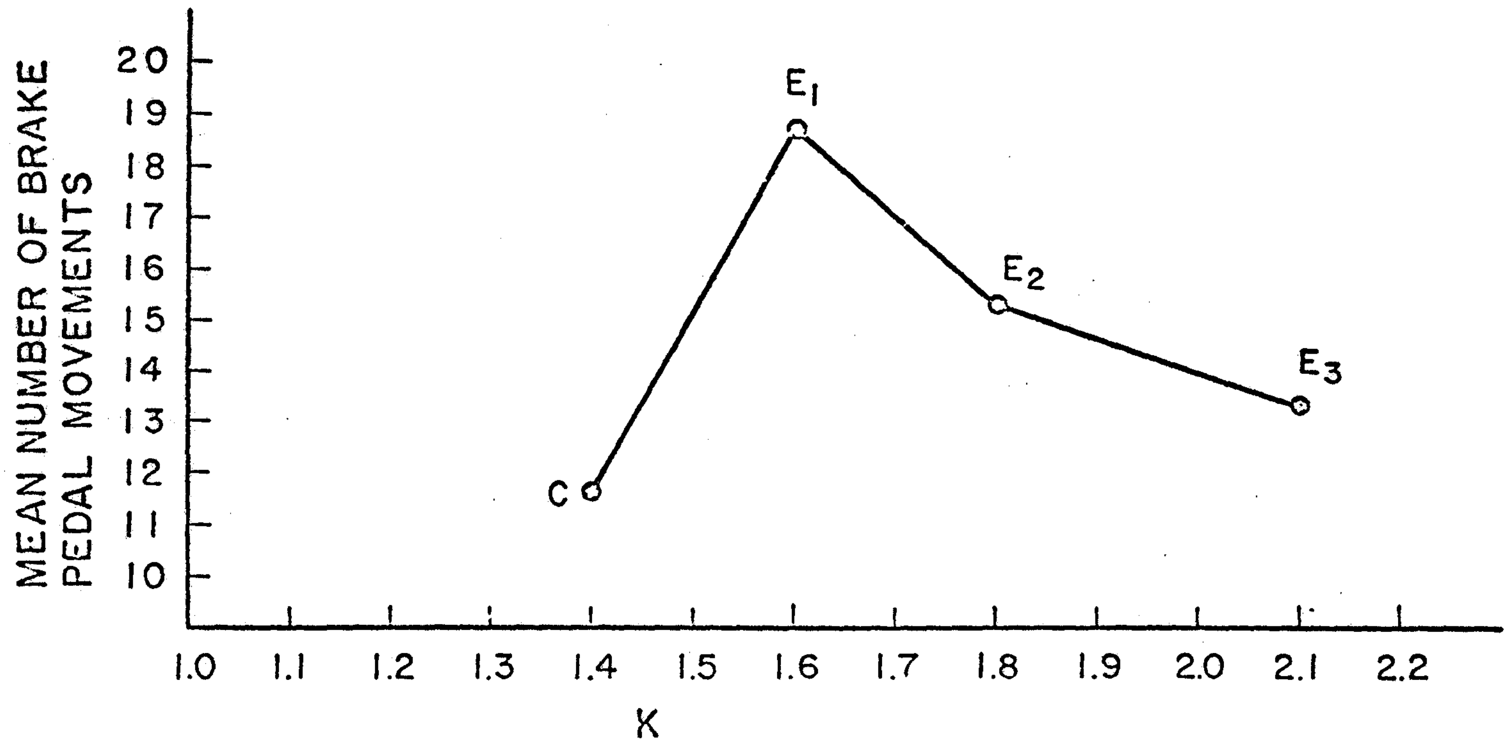


Fig. 3. The Effect of Glare Upon Brake Pedal Movement

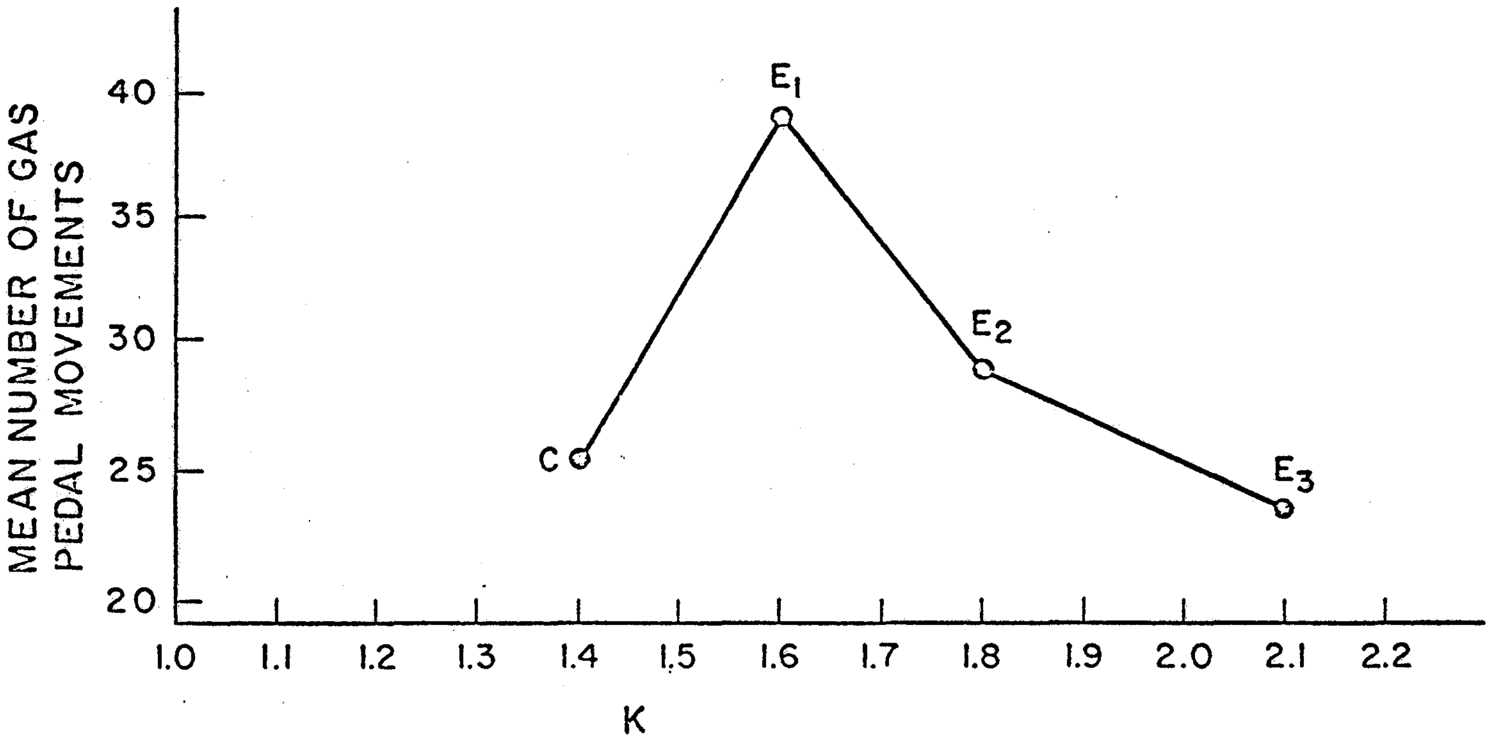


Fig. 4. The Effect of Glare Upon Gas Pedal Movement

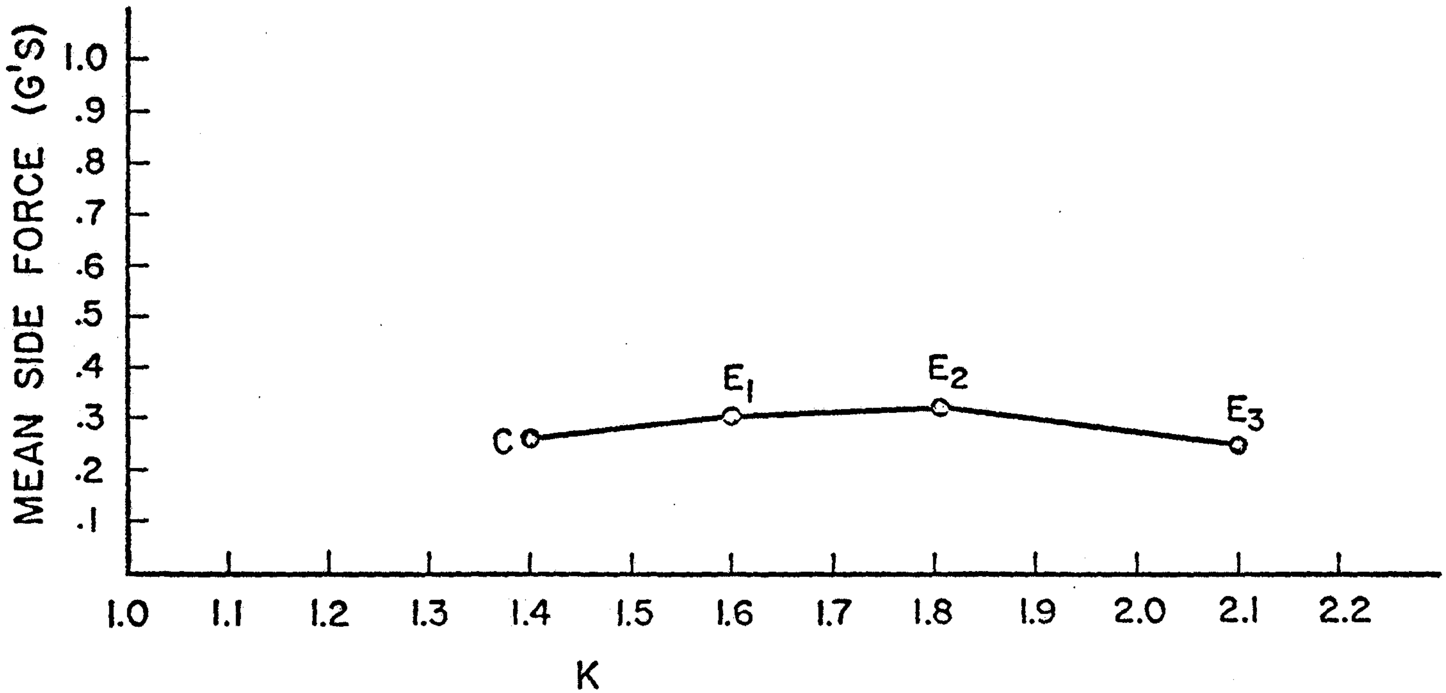


Fig. 5. The Effect of Glare Upon Side Force

TABLE 2

ANALYSIS OF VARIANCE - SPEED DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Treatments	3	7139.05	2379.68	88.46*
Error	36	968.48	26.90	
Total	40	8107.51		

Note. - Since entry speed into the lighted section of roadway was not controlled, the significant differences in speed could also be a function of normal driving habits.
*$p < .05$

TABLE 3

ANALYSIS OF VARIANCE - STEERING WHEEL REVERSAL DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Treatments	3	787.13	262.37	15.14*
Error	20	346.50	17.32	
Total	23	1133.63		

*p < .05

TABLE 4

ANALYSIS OF VARIANCE - BRAKE PEDAL DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Treatments	3	2.82	.94	.85
Error	36	38.54	1.11	
Total	39	41.33		

TABLE 5

ANALYSIS OF VARIANCE - GAS PEDAL DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Treatments	3	216.17	72.05	.97
Error	20	1475.67	73.78	
Total	23	1691.84		

TABLE 6

ANALYSIS OF VARIANCE - SIDE FORCE DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Treatments	3	.21	.07	.01
Error	45	213.35	4.74	
Total	48	213.56		

TABLE 7

TESTS OF ALL COMPARISONS AMONG MEAN SPEEDS

Experimental Condition	Mean	-37.47	-39.94	-41.43
C	41.76	4.29*	1.82	.33
E_1	41.43	3.96*	1.49	
E_3	39.94	2.47		
E_2	37.47			

*$p < .05$

TABLE 8

TESTS OF ALL COMPARISONS AMONG MEAN STEERING WHEEL REVERSALS

Experimental Condition	Mean	-14.50	-20.00	-27.50
E_1	28.50	14.00*	8.50*	1.00
E_2	27.50	13.00*	7.50*	
C	20.00	5.50		
E_3	14.50			

*p < .05

USE OF THE EYE-MARK CAMERA IN THE ANALYSIS OF DRIVER VISUAL BEHAVIOR

USE OF THE EYE-MARK CAMERA IN THE ANALYSIS OF DRIVER VISUAL BEHAVIOR

Introduction

The eye-mark camera is a photographic instrument which photographs the scene viewed by an observer and simultaneously records where the observer looks by superimposing a spot of light on the scene which corresponds to the position of the observer's fovea (the one degree area of sharp vision). This report summarizes the use of the eye-mark camera in exploratory study of driver visual behavior in interchange driving.

Procedure

This study was conducted at an interchange (US271-US82) in the Paris District of the Texas Highway Department. Three subjects, all undergraduate engineering students at Texas A&M University and unfamiliar with the study site were used.

The eye-mark camera used was a modified version of Model V-0165-1L4, supplied by Polymetric Products of Itek Corporation. The modification consisted of a stabilizing head-piece for better calibration accuracy. High-speed daylight color film was used. The equipment, fitted to one of the test subjects is shown in Figure 1.

Each subject was directed to take a specific route through the study site. At the beginning of the data run, the directions were read from notes. No further instructions were given. At the end of each data run, the calibration of the system was checked and recorded.

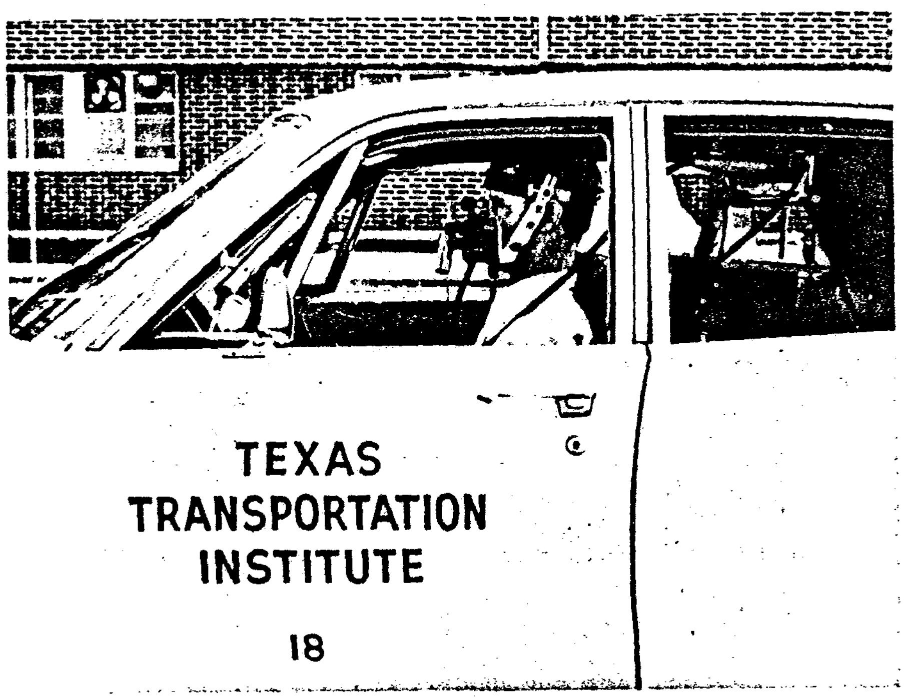


Figure 1

EYE-MARK CAMERA

FITTED TO TEST SUBJECT

Data Reduction

The film data was reduced frame by frame on a Gerber Motion Analyzer. Time of fixation was determined by counting frames. Since the frame rate was 16 frames per second, each frame represented approximately .06 seconds. At the same time, the position of the fixation along the traveled way was noted. Transverse distances were computed as cross sections of the traveled way. The data was normalized by dividing total time by the time spent looking at a particular category (geometry, signs, other) in each 50-foot interval.

Results

The results from the data runs are illustrated in Figures 2-22. Figure 2 is a schematic of the interchange study site.

The interchange was broken into four sections for data analysis and presentation. Figure 3 is a schematic of Section 1. Figures 4 and 5 illustrate the relative total fixation time spent in looking at the three categories. Road geometry accounted for 76.5% of the fixation time in Section 1. It is noted that unclassified fixations (those fixations not involved with road geometry, signs, or other features of the roadway) accounted for 60% of all fixation time. This time was primarily devoted to sky-watching. This visual behavior consisted of the drivers looking at the sky with long fixations which irregularly oscillate about the direction of travel.

It is believed that this behavior occurs when the driver is relatively unstressed and the need for detailed or anticipatory information is satisfied.

Section 2 of the interchange is shown in Figure 6. Figures 7 and 8 illustrate the fixation times. In this section, only 37% of the total time was unclassified.

Section 3 of the study site is represented by Figure 9. Fixation times are illustrated in Figures 10-13.

The final section of the interchange area is shown in Figure 14, with fixation times represented by Figure 15.

The data for Section 1 was also used to analyze in detail, by sequence, the visual behavior of one subject for a 500-foot section (Figure 16). Photographs of the section are shown in Figures 17 and 18. Figures 19-22 reconstruct the sequence of eye fixations for the 500-foot section.

A final result of the data was a tabulation of distances at which drivers being to search for geometry inputs. This tabulation is given in Table 1.

Discussion

The most salient feature of the data is that there are portions of the scene which are never looked at directly and other portions which receive a great deal of attention. These portions of the road, which receive a great deal of foveal fixation, imply that details of geometry are very important.

Although the reduction of the data was limited by termination of the project, it does indicate that the eye-mark camera can be a useful instrument for the analysis of driver visual behavior. From the limited analysis several general findings are suggested:

1. Both sides of the traveled way should be visible to the driver.
2. The far side of geometrics involving lane changes, ramps, etc., should either be visible, or some vertical cue provided.
3. The need for information provided by road geometry takes precedence over information provided by other visual cues.
4. The traveled way should be delineated, especially when there is a change in alignment. In cases where the traveled way was not delineated, the subjects used other features of the roadway as substitutes.
5. Critical and complex geometric features should be clearly visible and, where possible, unrestricted sight distance should be provided. This is predicated on the fact that a disproportionate amount of the driver's viewing time was spent on complex geometric features and areas with limited sight distance.

6. Key geometric features should be visible from 600 to 1200 feet ahead, depending upon speeds and other conditions.

7. Those areas involving the most viewing time (critical maneuvers, geometry, sight distance, etc.) probably warrant lighting.

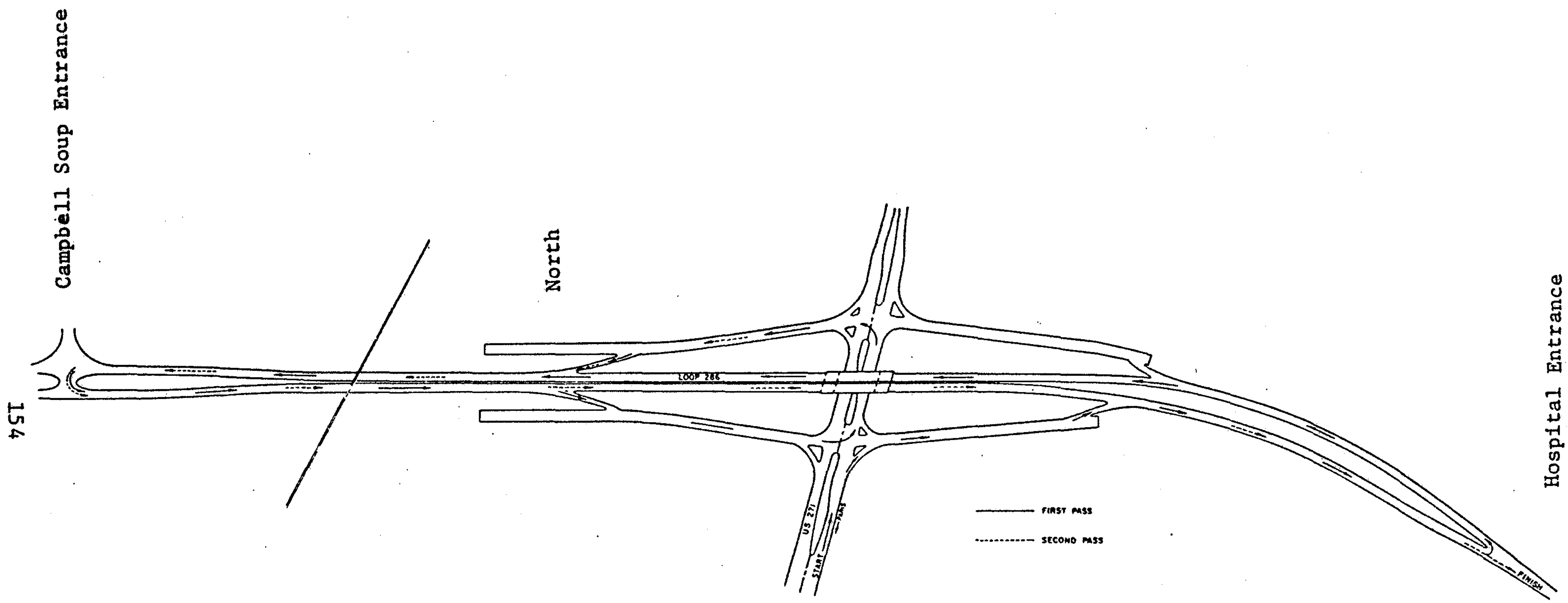


Figure 2 This drawing shows the interchange as a whole. The arrows indicate the routes followed in consecutive order.

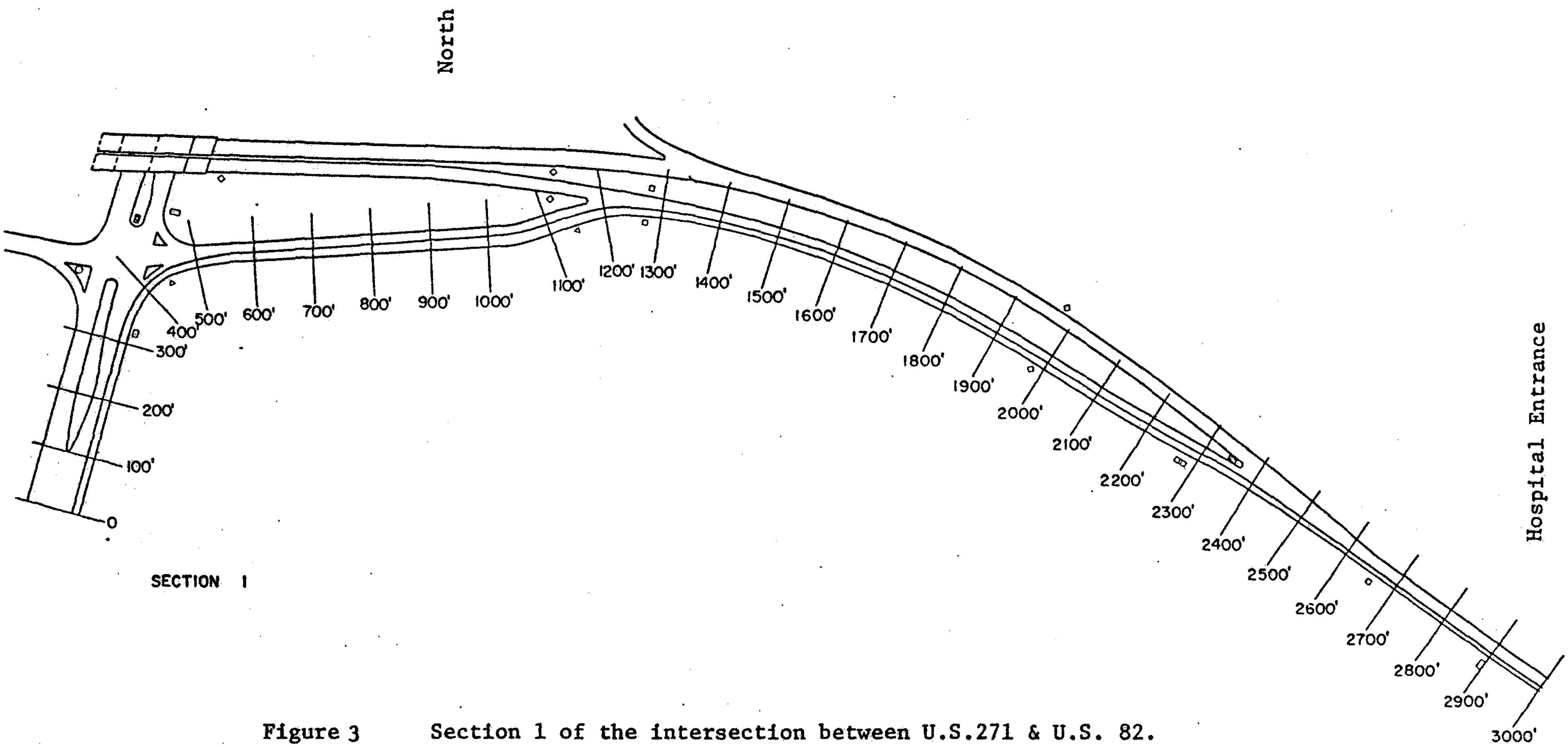


Figure 3 Section 1 of the intersection between U.S.271 & U.S. 82.

On this figure and those following the numbers and the lines perpendicular to the traveled way indicate station numbers measured from the beginning of a run.

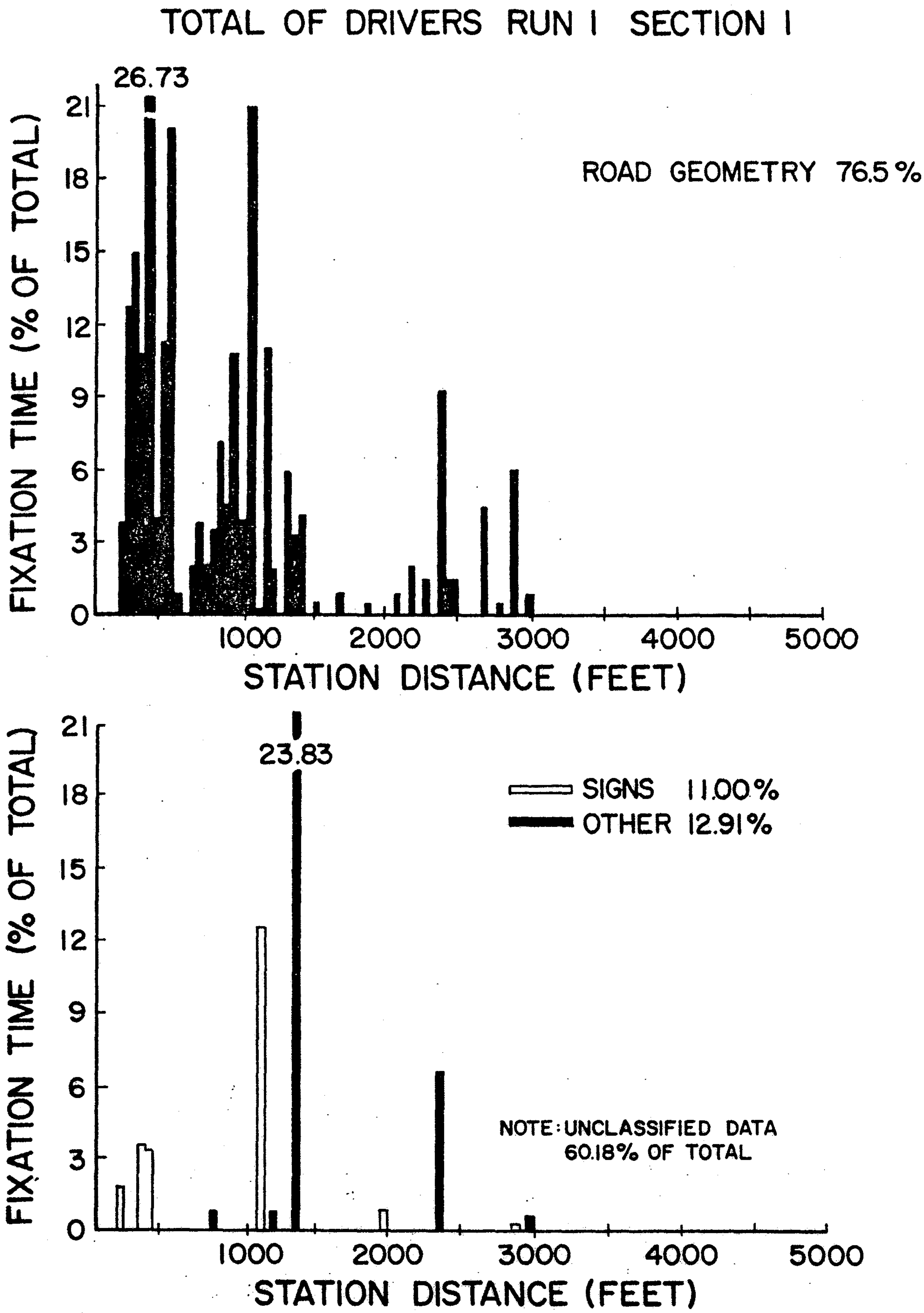


Figure 4

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

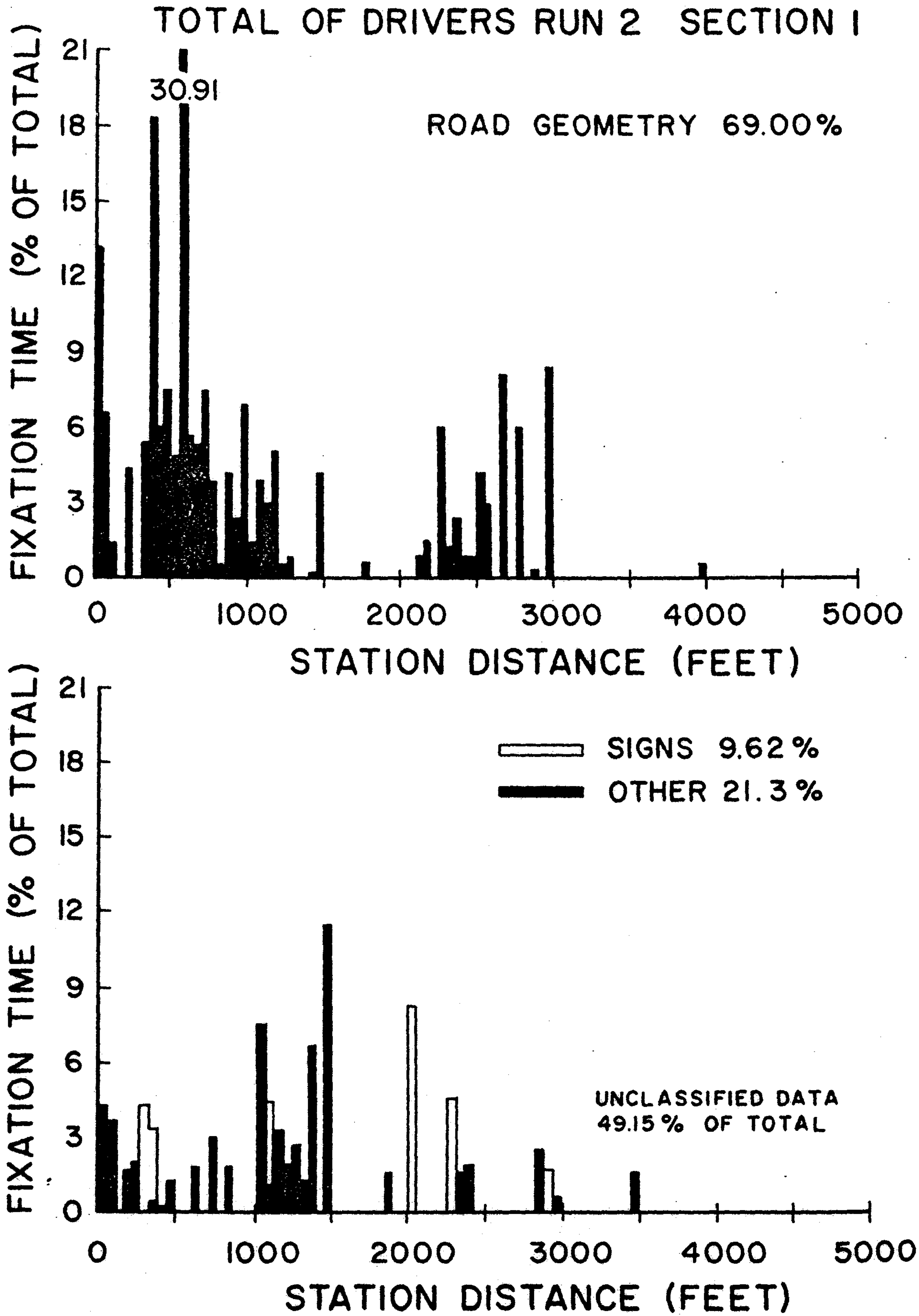


Figure 5

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

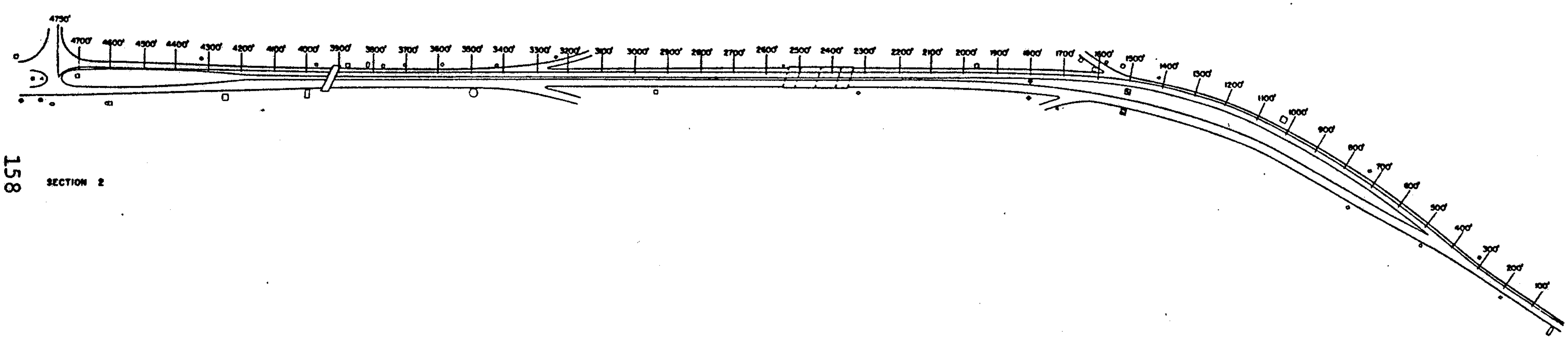


Figure 6   Section 2 of the Intersection Between U.S. 271 and U.S. 82.

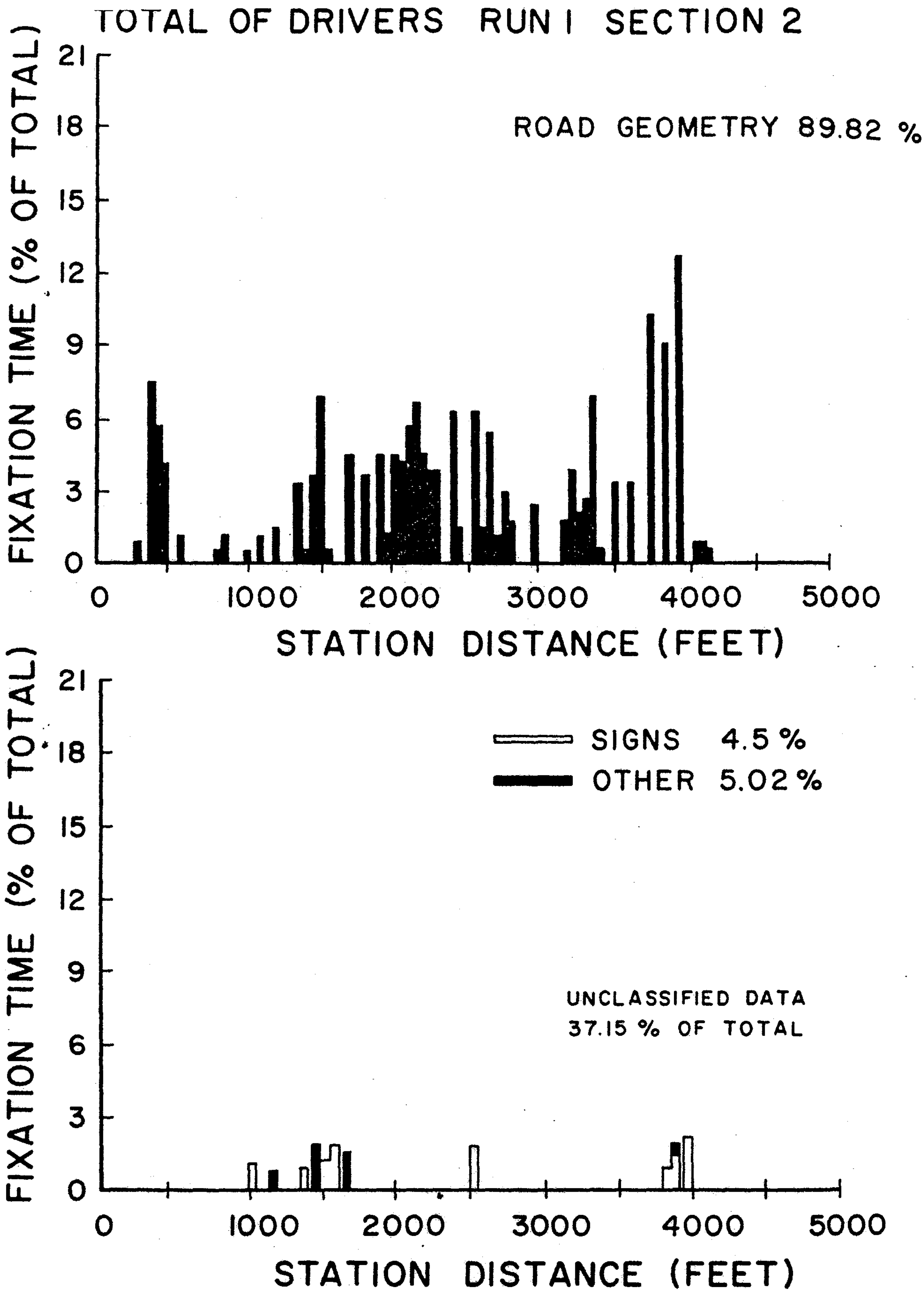


Figure 7

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

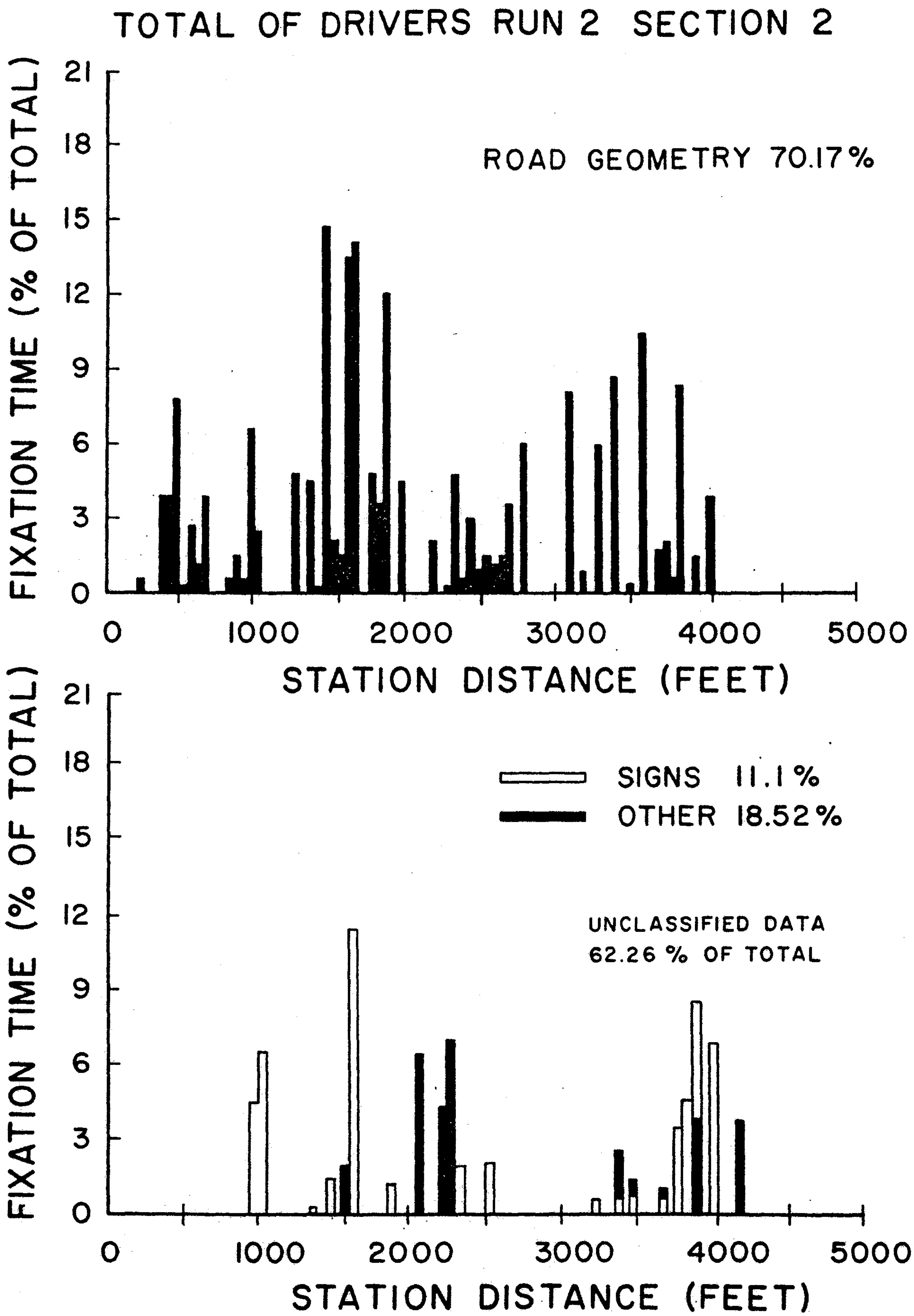
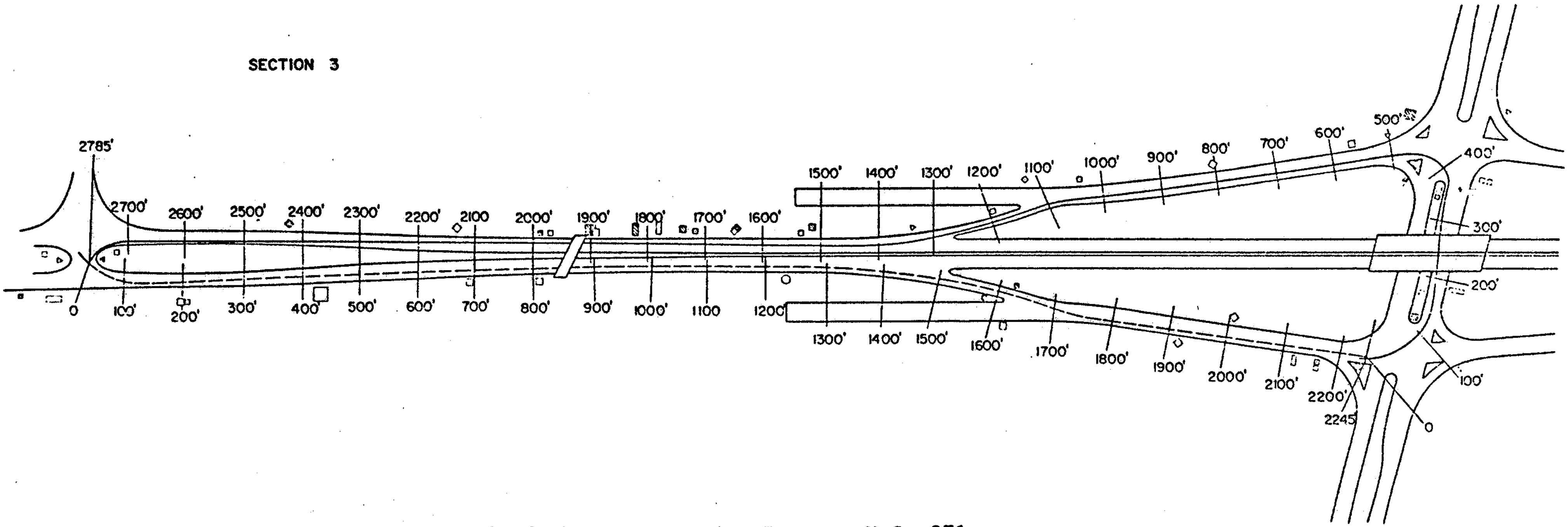


Figure 8

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

SECTION 3



Section 3 of the Intersection Between U.S. 271
and U.S. 82.

Figure 9

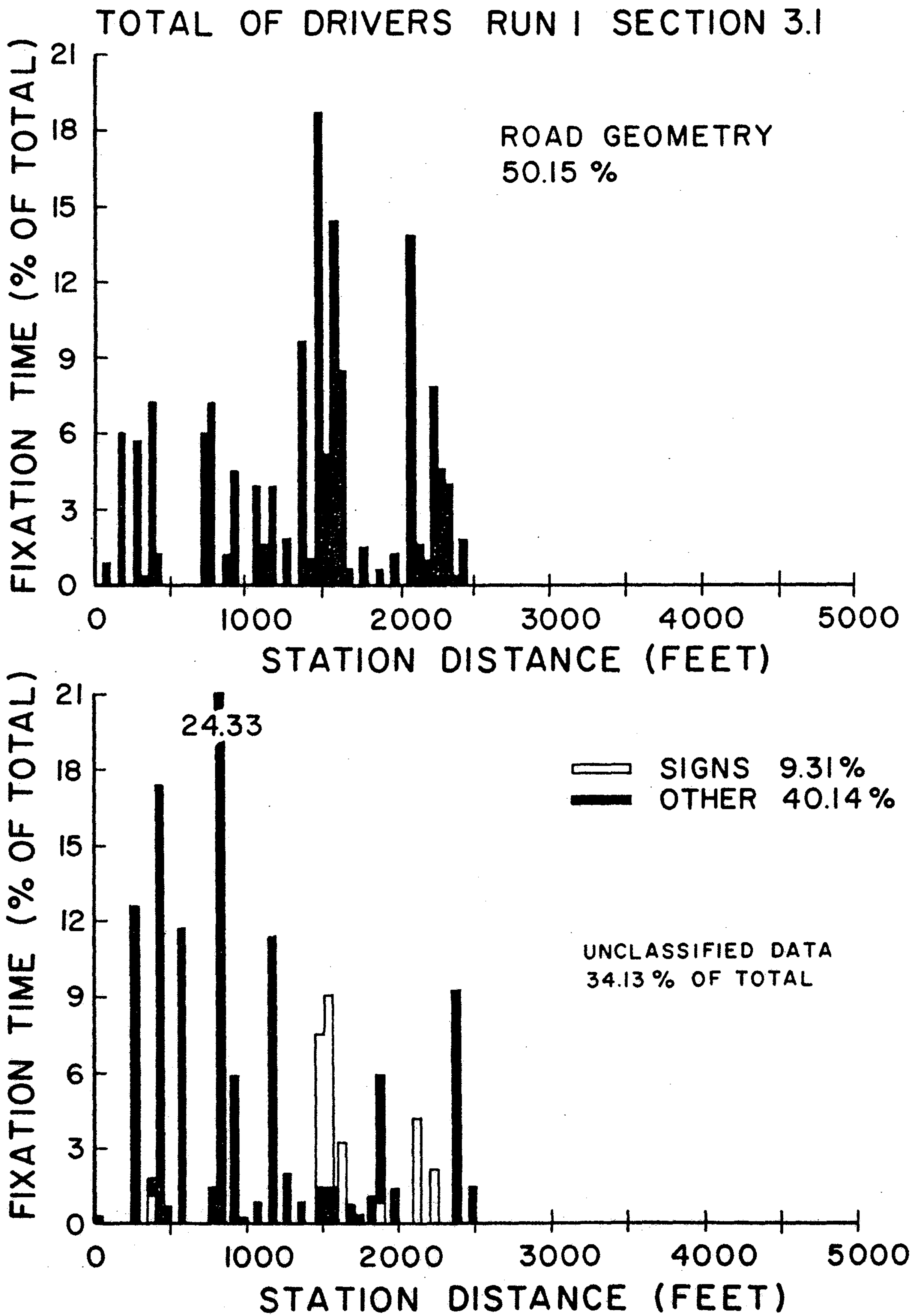


Figure 10

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

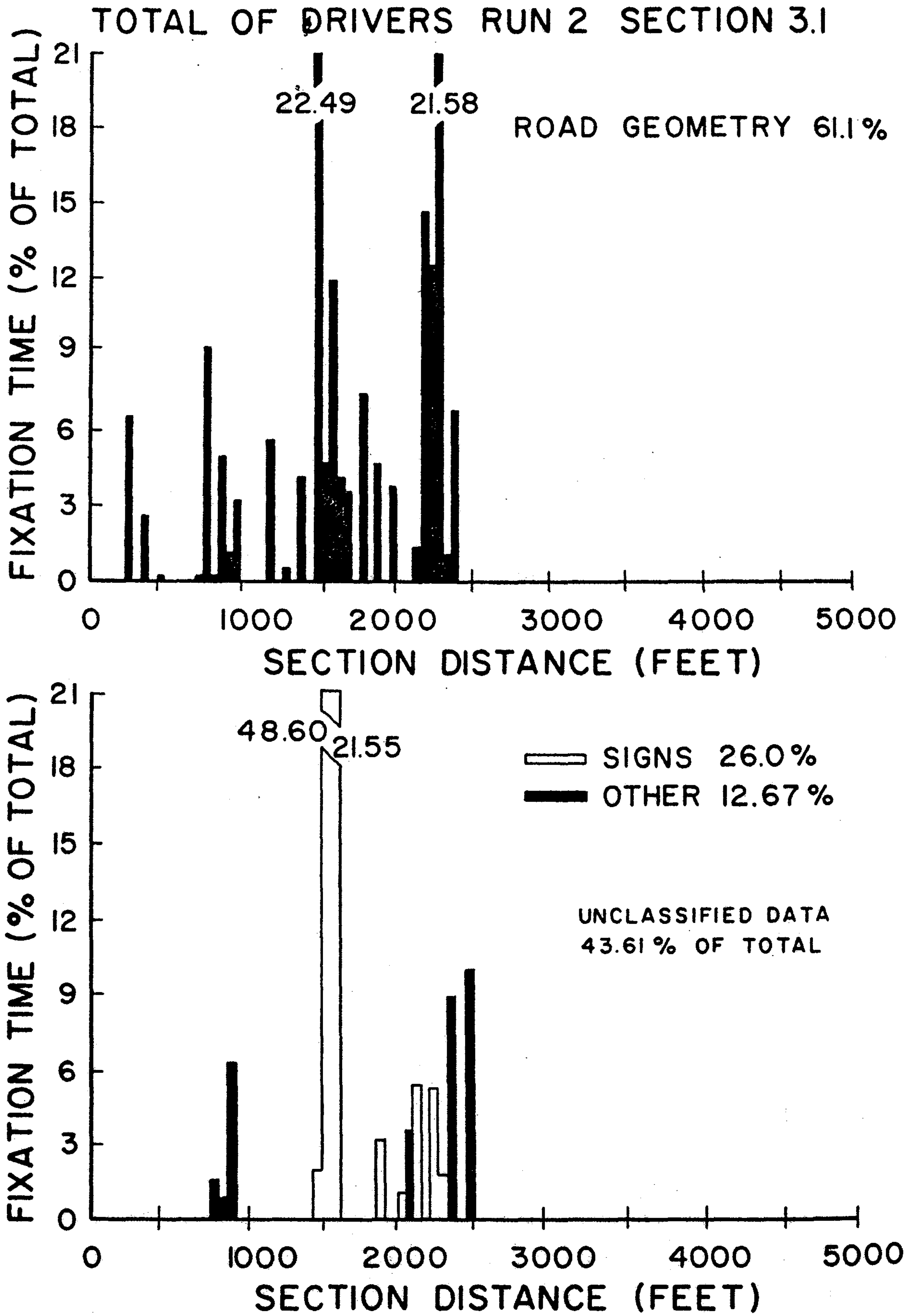
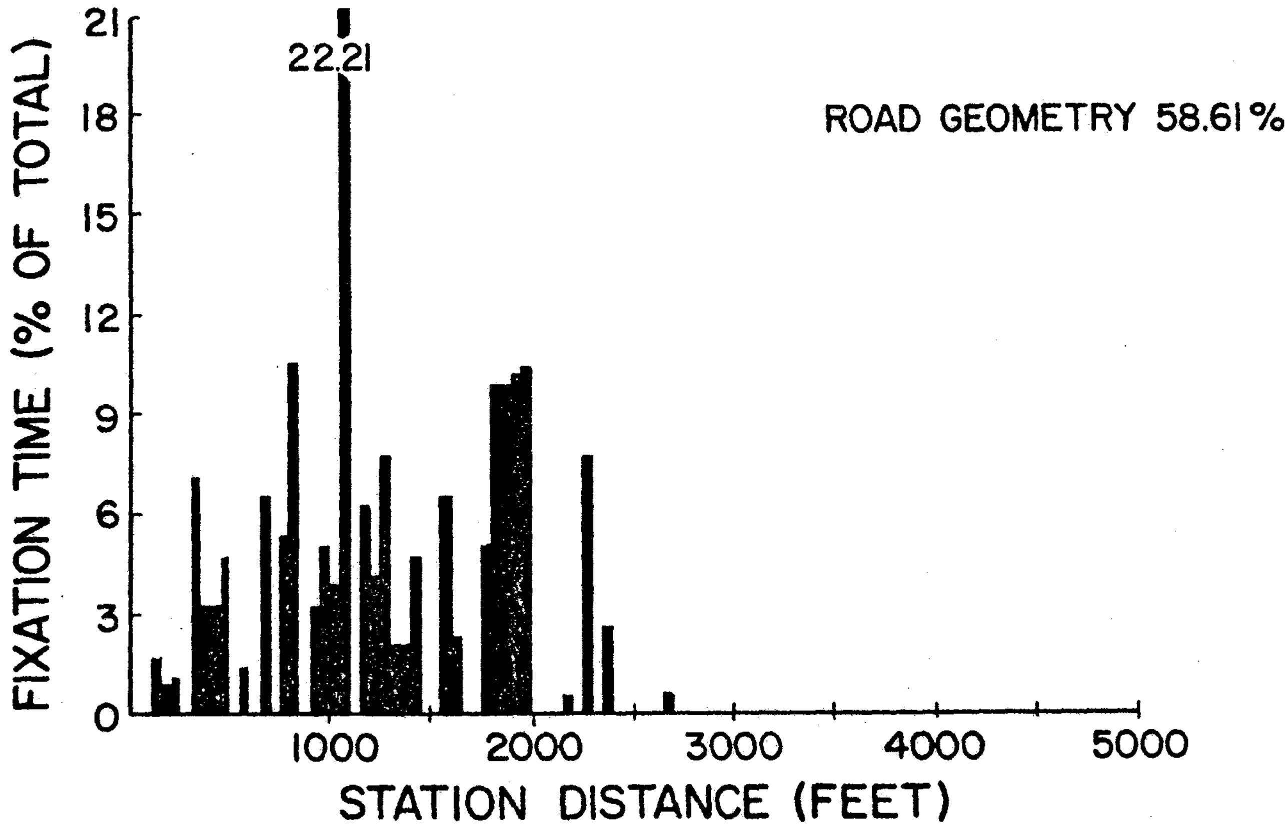


Figure 11

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

TOTAL OF DRIVERS RUN I SECTION 3.2



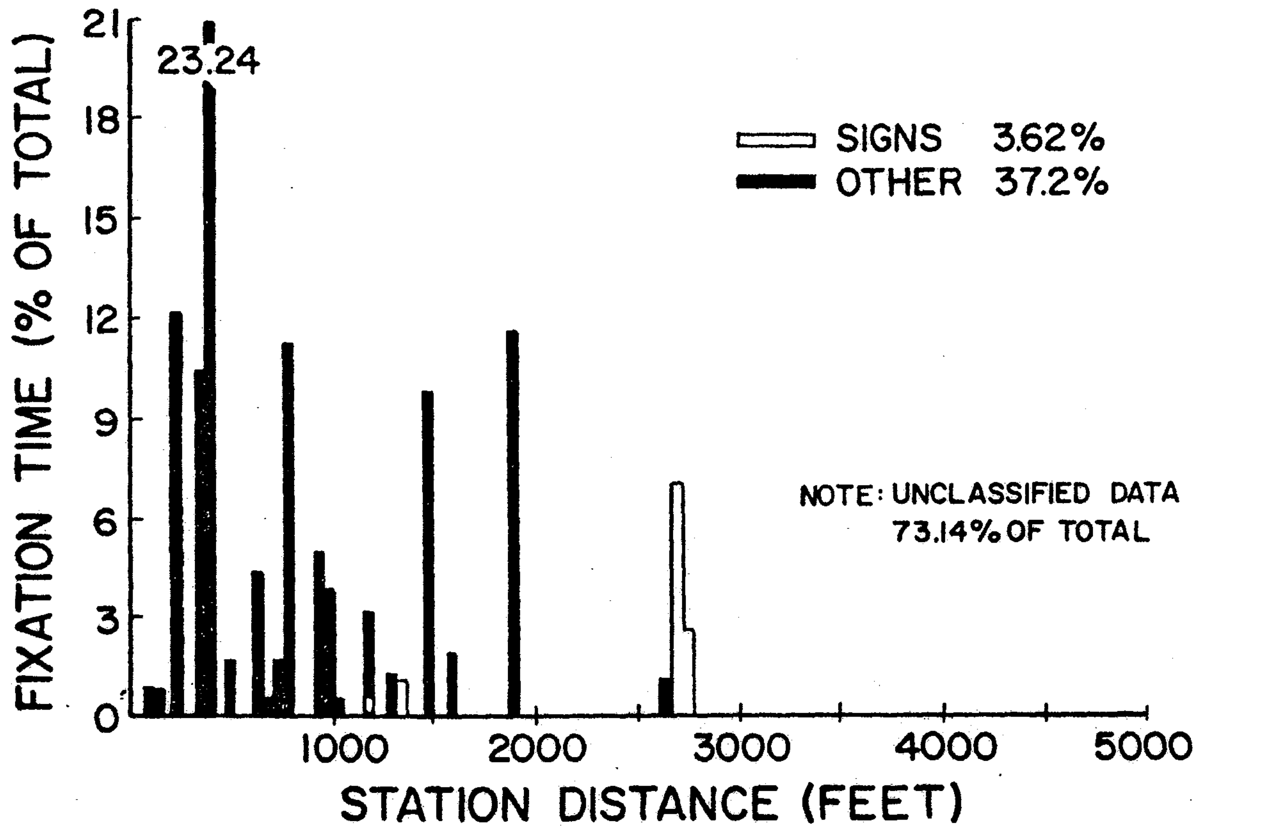


Figure 12

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

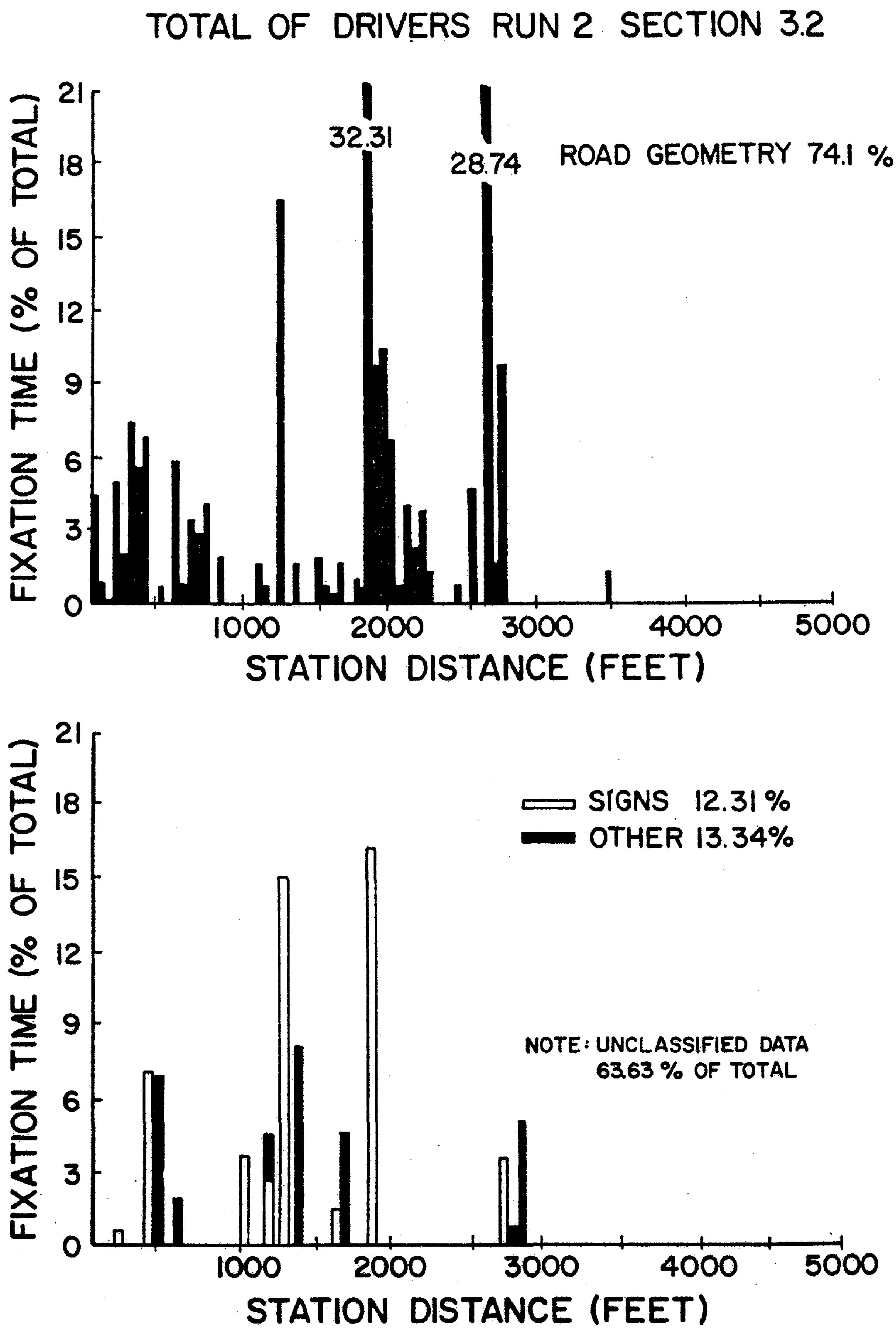


Figure 13

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

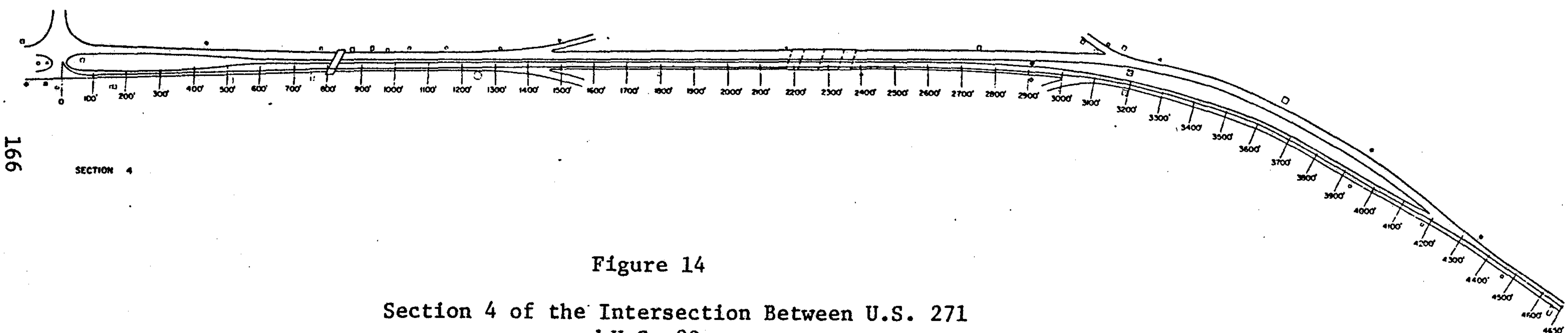


Figure 14

Section 4 of the Intersection Between U.S. 271 and U.S. 82.

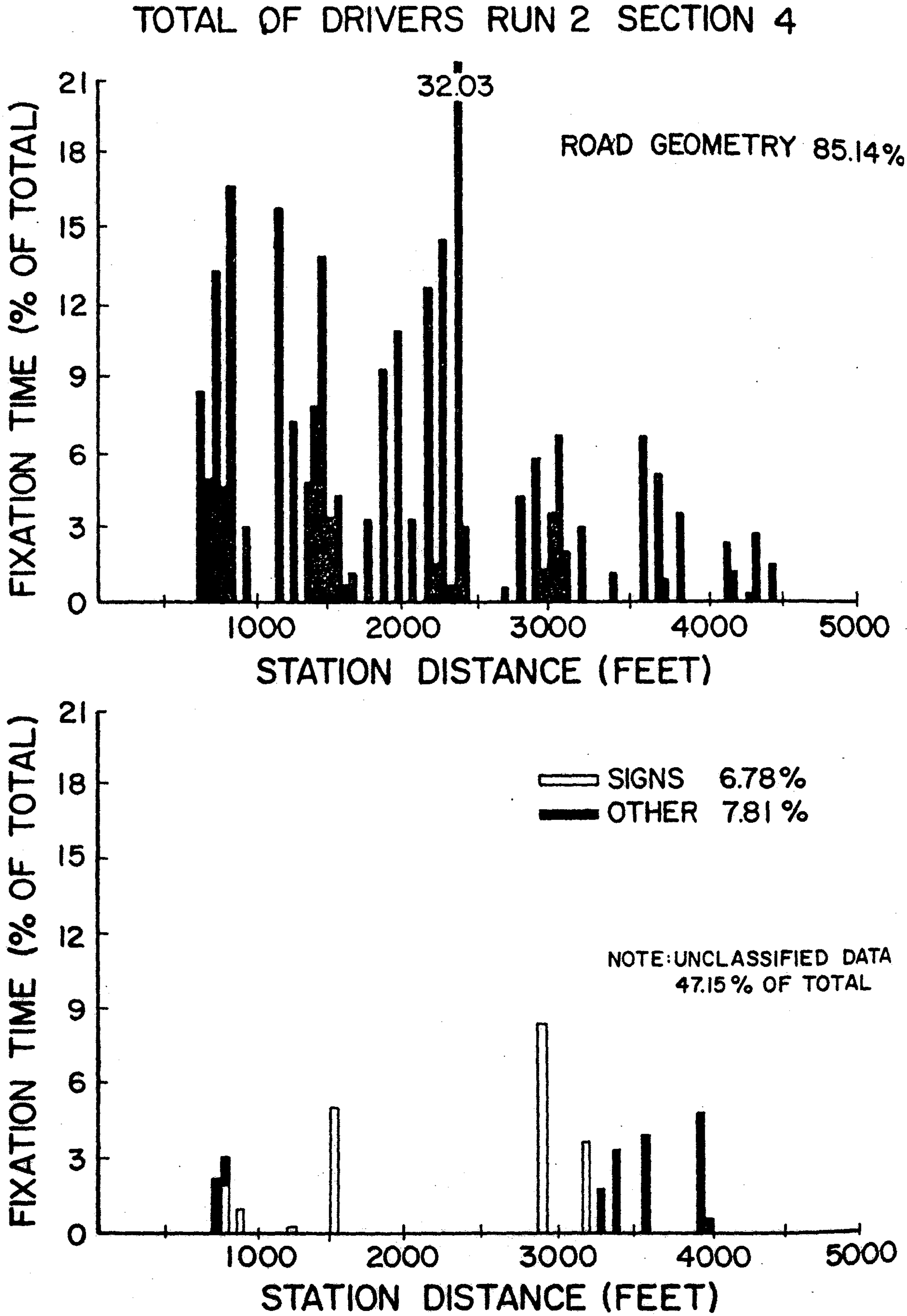


Figure 15

The average relative fixation time on the traveled way by stations at 50 ft. intervals.

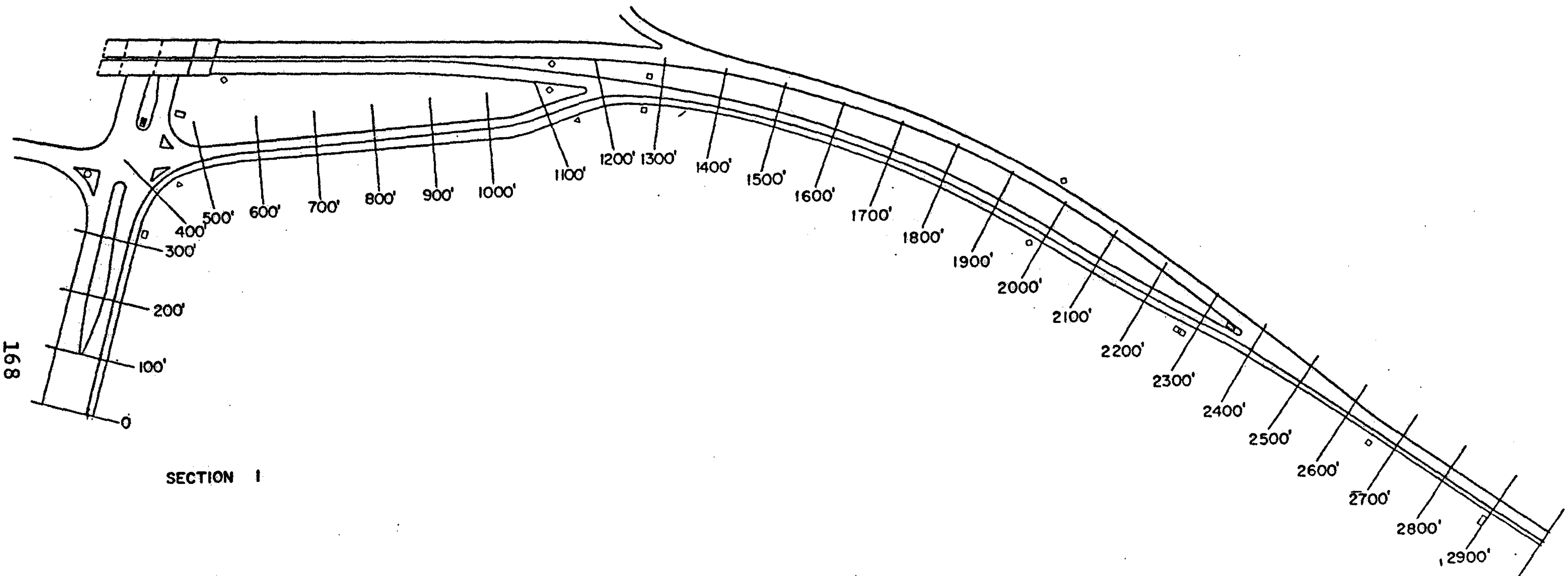


Figure 16. The part of section 1 that was analyzed in detail by sequence was between station 0 and 500.

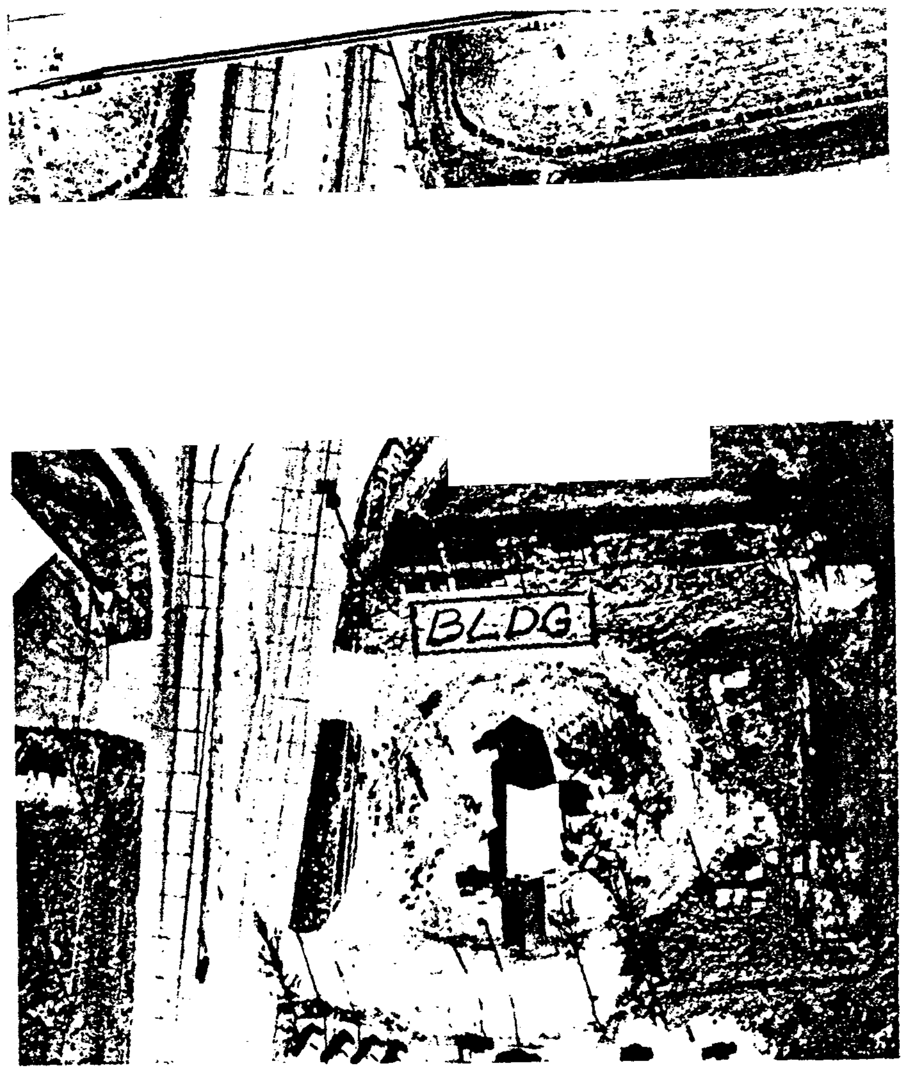


Figure 17. An Aerial Photograph of the First Turn of Sect. 1, Between Stations 0 to 500. Note: This photograph was taken in 1965. The building indicated on the photograph was completed since that time.

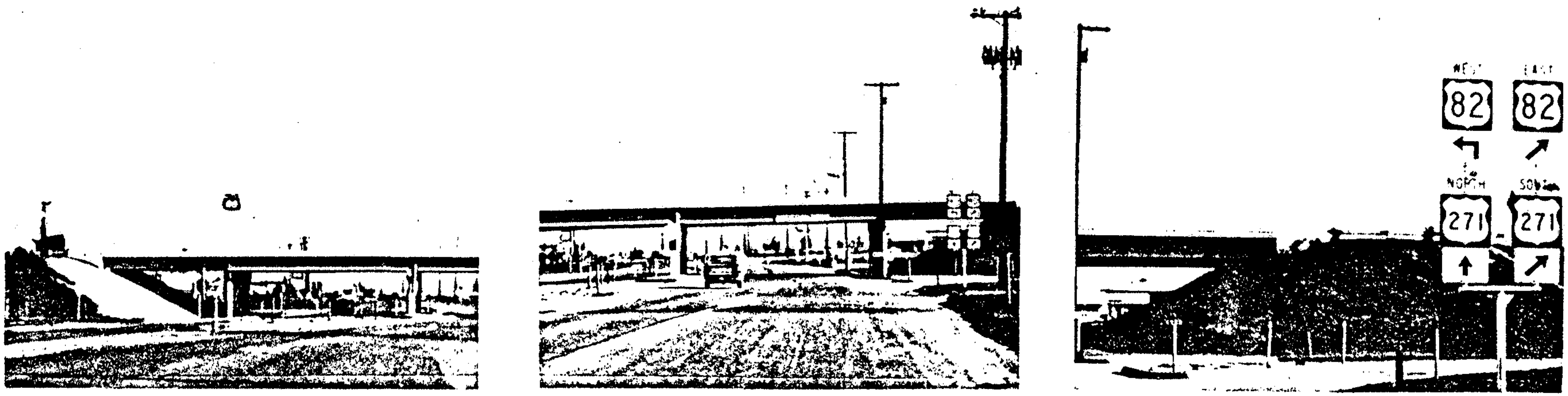
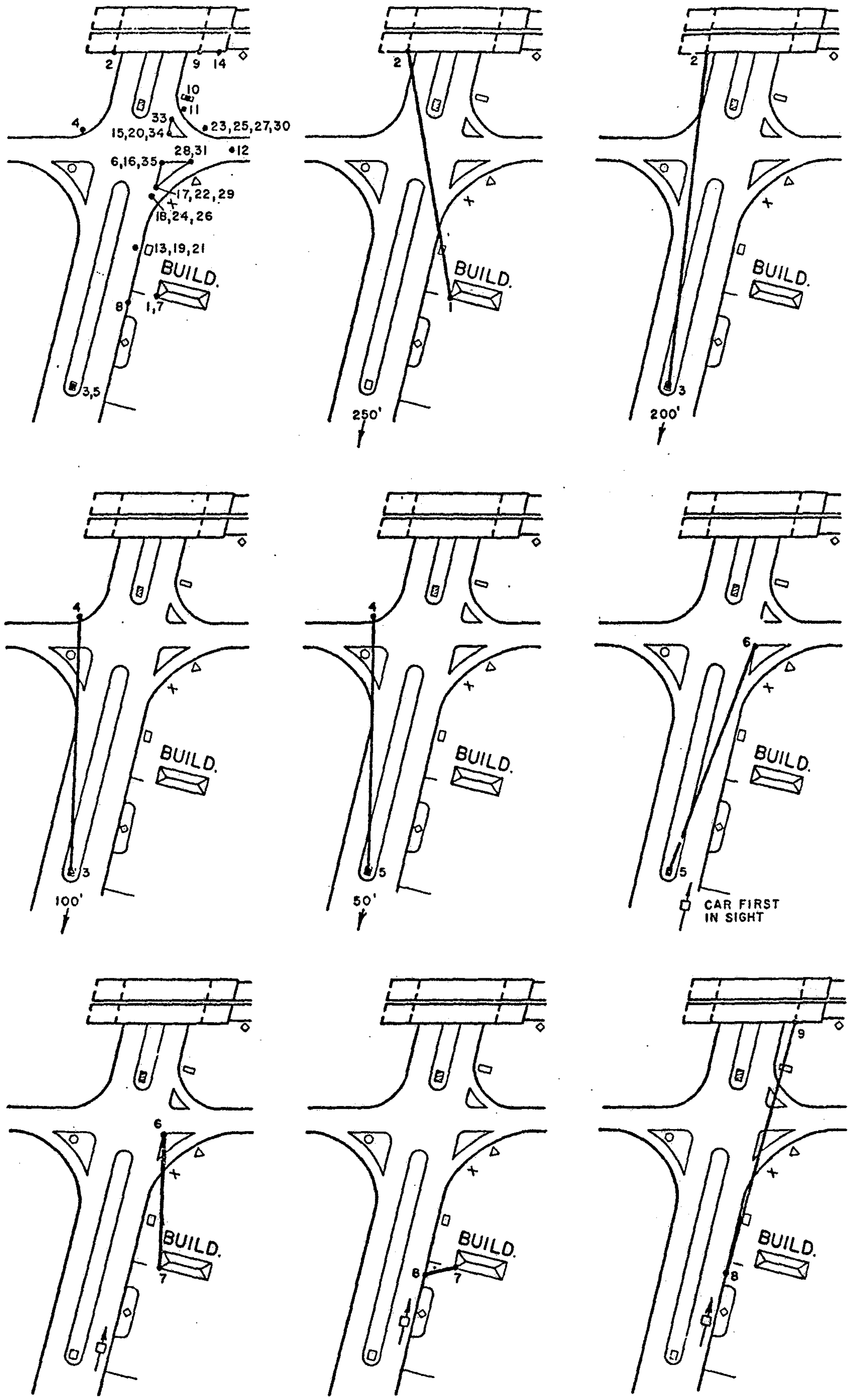


Figure 18. A Panoramic View of the Facility Which Shows Most of the Details Fixated by Subject as He Negotiated the First Turn.



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CAR FIRST
IN SIGHT
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Figure 19

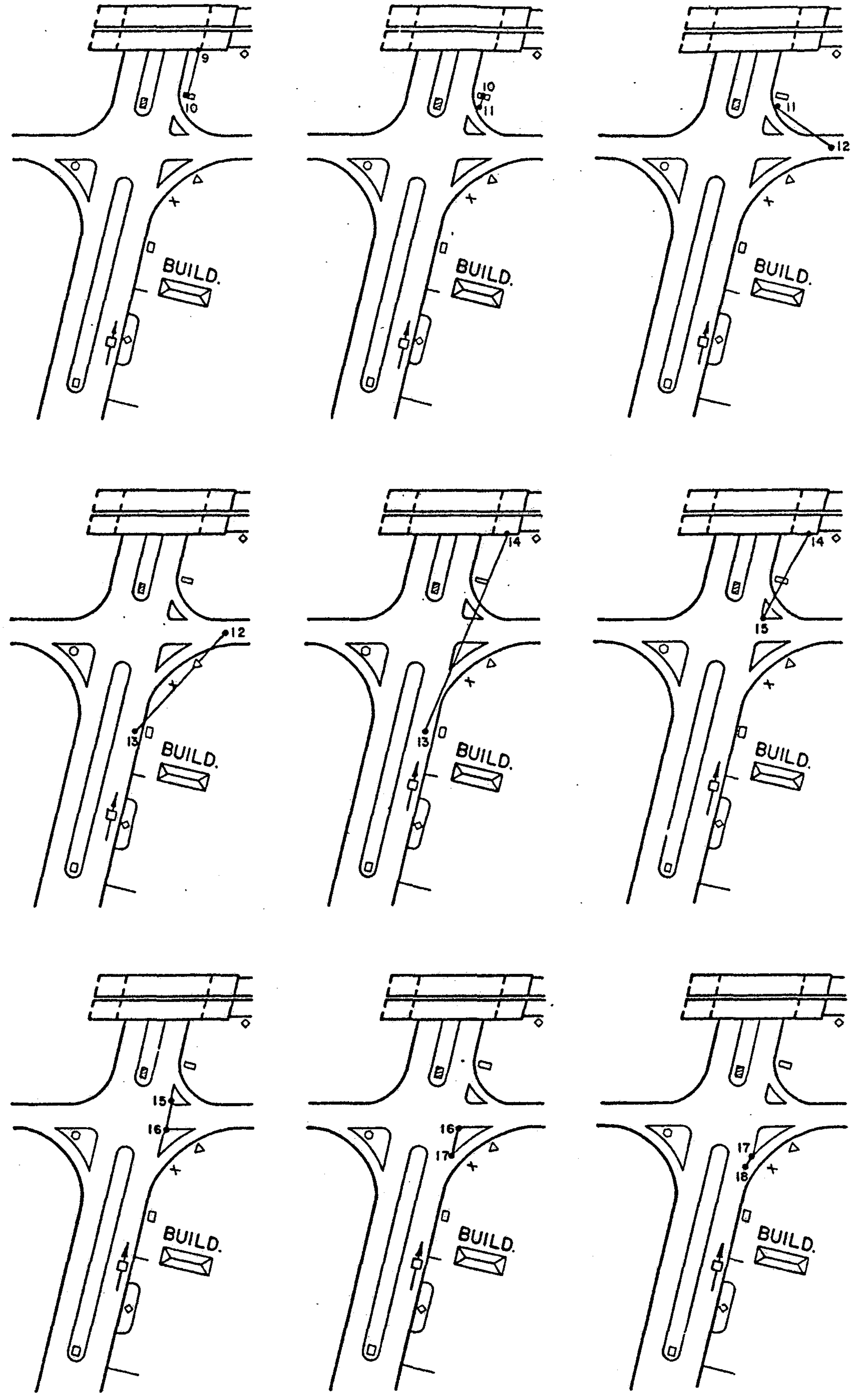
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Figure 20

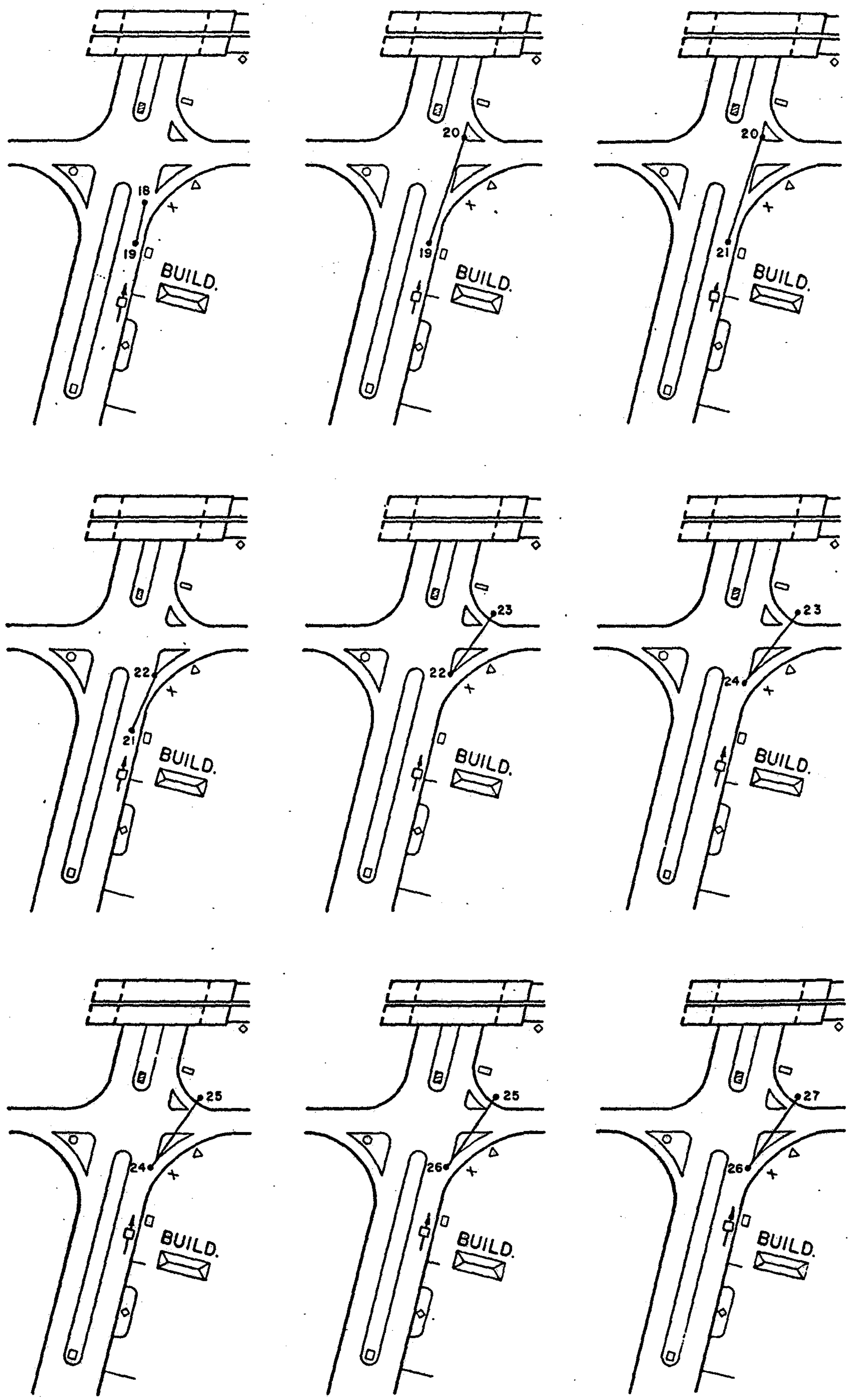

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Figure 21

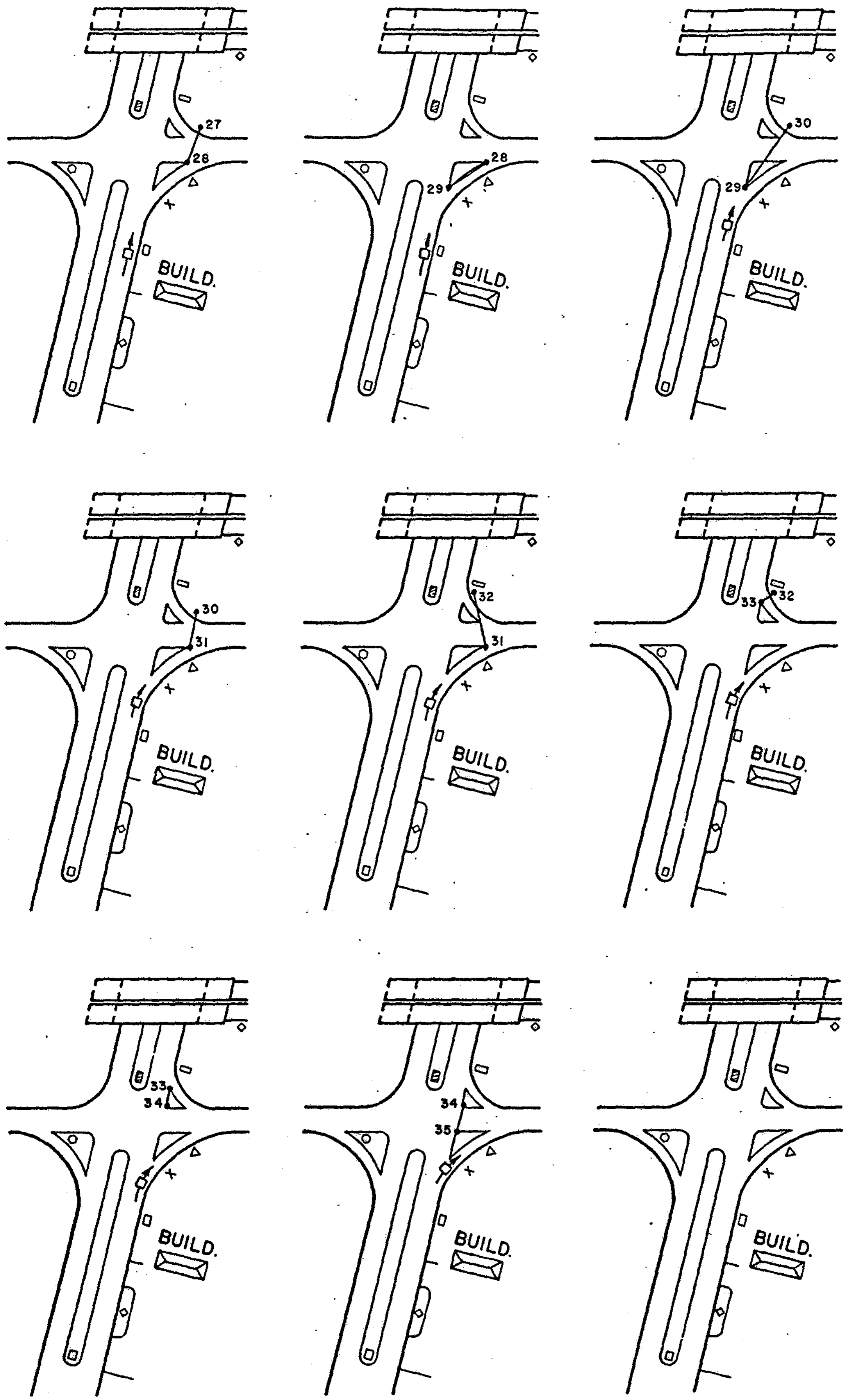
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Figure 22

Table 1

Summary of Distance at which the Driver Searches
for Information on Geometry

Section	Geometry Being Searched for by Driver To Complete Instructed Route	Sight Distance Between Driver & Geom					
		Run 1			Run 2		
		Driver			Driver		
		1	2	3	1	2	
1	Exit to Hwy 82 East	250'	400'	150'	400'	500'	2
1	Entrance to On Merge Lane to Hwy 82	300'	550'	400'	400'	550'	5
1	Entrance to Hospital	200'	200'	200'	300'	550'	4
2	Island Between Exit Ramp and Overpass	500'	900'	600'	500'	600'	8
2	Entrance to Campbell's Soup	----	800'	650'	800'	850'	3
3.1	Exit Ramp to Get Back on 82 West	350'	950'	300'	950'	950'	9
3.1	Intersection to Turn Left to 82 West	400'	650'	500'	550'	650'	7
3.2	Entrance Ramp to 82 West	350'	600'	450'	650'	600'	6
3.2	Turn Around at Campbell's Soup	800'	900'	900'	1150'	1100'	11
4	Clarksville Sign	----	----	----	200'	400'	4

---- Data not available.

COST-EFFECTIVENESS ANALYSIS OF ROADWAY
LIGHTING SYSTEMS, SUMMARY REPORT

COST-EFFECTIVENESS ANALYSIS OF ROADWAY LIGHTING SYSTEMS SUMMARY REPORT

The objective of this study was to investigate and report cost-effectiveness relationships for various roadway lighting design criteria and roadway geometry. The research objective was applied to the following considerations:

A. Design Criteria

1. Average illumination
2. Average to minimum ratios of illumination
3. Maximum to minimum ratios of illumination

B. Roadway geometry configurations

1. Four traffic lanes (total)
2. Six traffic lanes (total)
3. Eight traffic lanes (total)
4. Ten traffic lanes (total)

Alternatives for use in roadway lighting systems were selected for study according to three effectiveness measures:

1. A uniformity ratio of average to minimum illumination of not greater than 3 to 1.

2. A uniformity ratio of maximum to minimum illumination of not greater than 6 to 1.

3. Three levels of average illumination

   Level III - 1.25 foot-candles
   Level II - 1.00 foot-candles
   Level I - 0.75 foot-candles

The five lighting systems chosen, designated as A, B, C, D, and E, are described in the following table:

TABLE 1

DESCRIPTION OF ILLUMINATION ALTERNATIVES

Letter Used To Designate Alternative*	Unit Placement	Luminaire Wattage	Mounting Height (feet)	Unit Spacing (feet)
A(M-40-200)	Median	400	40	200
B(O-50-300)	One-Side	1000	50	300
C(M-50-300)	Median	1000	50	300
D(S-50-260)	Staggered	1000	50	260
E(S-50-300)	Staggered	1000	50	300

NOTE: Alternatives A and C with median placement have double arms and two luminaires. The other alternatives have single arms and one luminaire.

*The letters and numbers in parentheses refer to (Placement-Mounting Height in feet-spacing of units in feet); M refers to units placed in the median: O refers to units placed on one side of the roadway; S refers to units which are staggered, alternating on opposite sides of the roadway.

Each of the illumination alternatives provides stipulated levels of effectiveness for roadways with different lane configurations. In addition, for a given number of lanes, some alternatives may satisfy more than one design criteria.

Accident predictions and statistics are a major factor in cost-effectiveness analyses for roadway lighting systems. Consequently, one aspect of this study dealt with a method of predicting the number of vehicles which could be expected to collide with illumination units per year. These predictions were based upon the five alternative study designs, with different traffic volumes and with placement of the luminaire units making up the system at varying lateral distances from the edge of the roadway. Before such predictions can be made, however, the following facts must be known:

1. The number of vehicles that run off the road each year.
2. The paths vehicles follow after leaving the roadway.
3. The location of light supports with respect to the prescribed travel lanes.

Information about behicle median encroachment rates from research by Hutchinson and Kennedy was used in making accident rate predictions. "Encroachment", as defined by Hutchinson and Kennedy,[1] is "the travel of vehicle outside the designated lane(s) of travel and onto the median". From their study it was found that approximately one median encroachment per mile occurs each year for every 2,000 vehicles of two-way average daily traffic. This was determined by investigating rural divided highways without roadway lighting. Since the encroachment rates of Hutchinson and Kennedy were considered by Texas Transportation Institute investigators to be excessively high for this application, the following assumptions were made to apply throughout the present study:

1. There is only one median encroachment per mile per year for each 5,000 vehicles of two-way average daily traffic.
2. There is one non-median (off the right side of the road) encroachment per mile per year for each 5,000 vehicles of two-way average daily traffic -- half of them in each direction.

For purposes of this study, therefore, it was stipulated that there is only one encroachment per mile per year for each 10,000 vehicles of two-way average daily traffic. The rates presented in the report are considered by the investigators to be meaningful estimates, rather than absolute values, since encroachment rates vary according to the conditions which exist on each particular facility.

Hutchinson and Kennedy found that the average angle at which encroaching vehicles leave the roadway is 11 degrees. The distribution of the maximum lateral distances that these vehicles travel from the edge of the pavement follows a normal distribution pattern, with a mean of 23 feet and a standard deviation of 11 feet, for maximum lateral distances of less than 40 feet. Information based on this calculation is presented in Table 2.

Placement of the lighting poles and the path which the encroaching vehicle follows influence the proportion of vehicles that actually hit illumination units. It is estimated, on the basis of Hutchinson and Kennedy data, that the probability of a vehicle hitting an illumination unit, given that its lateral distance of encroachment is not less

TABLE 2

APPROXIMATE PROBABILITY THAT ENCROACHING VEHICLE WILL EQUAL OR EXCEED CERTAIN LATERAL DISTANCES

Maximum Lateral Movement (feet)	Approximate Probability That Encroaching Vehicle Will Equal or Exceed Given Lateral Movement
10	.90
20	.65
25	.45
30	.25

than the distance that such units are from the pavement, is equal to 131.3 feet divided by the spacing, in feet, between illumination units. There is less probability of collision with longer spacings between illumination units.

TABLE 3

CONDITIONAL PROBABILITY THAT VEHICLE ENCROACHING SUFFICIENT DISTANCE WILL HIT ILLUMINATION UNIT, BY SPACING

Illumination Unit Spacing (feet)	Conditional Probability That Vehicle Which Encroaches By Sufficient Lateral Distance Will Hit Illumination Unit*
200	.66
260	.50
300	.44

*This probability represents the proportion of vehicles that will hit illumination units <u>given</u> that their maximum lateral encroachment distance equals or exceeds the lateral distance that illumination units are from the near edge of the traffic lane. It is assumed that the point of departure from the roadway is random, i.e., is not related to the location of lighting units.

Table 4 illustrates the probabilities for collision, as related to both the spacing of illumination units and the lateral distance that such units are from the edge of the traffic lane.

Table 4 can also be interpreted as the average number of lighting units placed in the median, with a two-way average daily traffic of 5,000 vehicles. For units placed on only one side of the roadway ("house side") the values in Table 4 apply to a roadway with a two-way average daily traffic volume of 10,000 vehicles. Accident rates are assumed to change in direct proportion to changes in traffic; therefore, accident rates can be calculated for any average daily traffic volume.

TABLE 4

PROBABILITY THAT AN ENCROACHING VEHICLE WILL HIT AN ILLUMINATION UNIT, BY LATERAL DISTANCE AND SPACING OF ILLUMINATION UNITS

Unit Spacing (feet)	Distance of Units From Edge of Traffic Lane (feet)			
	10	20	25	30
200	.594	.429	.297	.165
260	.450	.325	.225	.125
300	.396	.286	.198	.110

Initial and maintenance costs must be considered when installing a roadway lighting system, as well as accident costs for motor vehicles hitting the installation. Table 5 presents initial costs for 400-watt, 40-foot, and 1000-watt, 50-foot units. A distinction is also made between 12-foot and 15-foot mast arm lengths.

TABLE 5

COST PER ILLUMINATION UNIT BY POLE HEIGHT NUMBER OF ARMS, AND ARM LENGTH

Number of Arms and Arm Length	Initial Cost Per Unit by Mounting Height and Wattage	
	40-foot 400-watt	50-foot 100-watt
Single Arm:		
12-foot	$500	$625
15-foot	525	650
Double Arm:		
12-foot	575	725
15-foot	625	775

NOTE: Cost includes foundation and installation cost but does not include cost of duct cable, conduit, or service poles. Costs are for galvanized steel poles on steel transformer bases or aluminum transformer bases.

Tables 6, 7, and 8 are based on information from collisions with lighting installations in six areas of Texas. Accident costs are shown for the different types of bases and poles.

The five luminaire designs previously presented were compared on a cost basis. Analysis periods of twenty and forty years were calculated, using an interest rate of .05 per year. "Low" and "high" maintenance costs were used to establish values -- $25 and $40 for 400-watt luminaires and $50 and $70 for 1000-watt units, respectively. In determining accident costs, two sets of average daily traffic volumes

TABLE 6

AVERAGE ACCIDENT COSTS BY TYPE OF COST
FOR DIFFERENT BASE AND POLE TYPES

Type of Pole	Type of Base	Average Injury Cost	Average Vehicle Damage Cost	Average Lighting Installation Damage Cost	Average Total Accident Cost
Aluminum	Aluminum Transformer	$174 (58)	$381 (48)	$221 (47)	$776
Steel	Aluminum Transformer	272 (19)	400 (15)	313 (13)	985
Steel	Steel Transformer	603 (37)	501 (31)	231 (25)	1335
Steel	Steel Shoe	823 (35)	541 (35)	103 (35)	1467

NOTE: Numbers in parentheses are the numbers of accidents used in that particular average.

TABLE 7

NUMBER OF ACCIDENTS AND NUMBER OF INJURIES BY TYPE OF INJURY, FOR FOUR POLE-BASE COMBINATIONS

Type of Pole	Type of Pole	Number of Accidents	Number of Injuries of this type		
			A	B	C
Aluminum	Aluminum Transformer	58	2	4	7
Steel	Aluminum Transformer	19	3	0	2
Steel	Steel Transformer	37	12	3	5
Steel	Steel Shoe	35	14	9	0

TABLE 8

ESTIMATED AVERAGE INJURY COSTS FOR TEXAS FOR THE YEAR 1967

Type of Injury	Cost
A	$1,415
B	1,000
C	465

were used -- 10,000 and 30,000 vehicles.

Table 9 includes initial costs per mile of roadway for the five designs, with both 12-foot and 15-foot mast arms. It is apparent that design B is least expensive, followed by designs C, E, A, and D.

TABLE 9

INITIAL COST, BY TYPE OF ILLUMINATION DESIGNS, PER MILE OF ROADWAY, WITH 12-FOOT AND 15-FOOT ARMS

Illumination Design	Arm Length (feet)	Number of Illumination Units Per Mile	Initial Costs Per Mile		
			Illumination Units	Other*	Total
A(M-40-200)	12	26.4	$15,180	$3,400	$18,580
A(M-40-200)	15	26.4	16,500	3,400	19,900
B(O-50-300)	12	17.6	11,000	3,400	14,400
B(O-50-300)	15	17.6	11,440	3,400	14,840
C(M-50-300)	12	17.6	12,760	3,400	16,160
C(M-50-300)	15	17.6	13,640	3,400	17,040
D(S-50-260)	12	20.31	12,694	6,500	19,194
D(S-50-260)	15	20.31	13,201	6,500	19,702
E(S-50-300)	12	17.6	11,000	6,500	17,500
E(S-50-300)	15	17.6	11,440	6,500	17,940

*Includes costs of duct cable, conduit, and service pole.

Tables 10 and 11 present "low" and "high" maintenance costs per mile for twenty and forty-year periods. From this table, it can be seen that the maintenance costs for designs B and E are the same for all considerations, and, in addition, are the least expensive of the alternatives.

TABLE 10

LOW MAINTENANCE COSTS FOR DIFFERENT ILLUMINATION DESIGNS FOR TWENTY-YEAR AND FORTY-YEAR ANALYSIS PERIODS

Illumination Design	Number of Luminaires Per Mile	Maintenance Cost Per Mile Per Year	Present Value of Maintenance Cost Per Mile by Length of Analysis Period	
			20 Years	40 Years
A(M-40-200)	52.80	$1,320.00	$16,450	$22,650
B(0-50-300)	17.60	880.00	10,967	15,100
C(M-50-300)	35.20	1,760.00	21,933	30,200
D(S-50-260)	20.31	1,015.50	12,655	17,425
E(S-50-300)	17.60	880.00	10,967	15,100

In Table 12, accident costs are given for the various luminaire designs over a twenty-year period. The costs per mile are based upon the accident rate information from Table 4. The costs per accident are derived from the $985 value for steel poles with aluminum transformer bases shown in Table 6. The accident costs are for different daily traffic volumes and different distances from the edge of the travel lane to the illumination units. For a specified average daily traffic volume and distance from the pavement edge, the lowest accident costs are for designs B and E.

TABLE 11

HIGH MAINTENANCE COSTS FOR DIFFERENT ILLUMINATION DESIGNS, FOR TWENTY-YEAR AND FORTY-YEAR ANALYSIS PERIODS

Illumination Design	Number of Luminaires Per Mile	Maintenance Cost Per Mile Per Year	Present Value of Maintenance Cost Per Mile by Length of Analysis Period	
			20 Years	40 Years
A(M-40-200)	52.80	$2,112.00	$26,320	$36,240
B(0-50-300)	17.60	1,323.00	15,353	21,140
C(M-50-300)	35.20	2,464.00	30,706	42,280
D(S-50-260)	20.31	1,491.70	18,590	25,596
E(S-50-300)	17.60	1,232.00	15,353	21,140

TABLE 12

PRESENT VALUE OF ACCIDENT COSTS PER MILE FOR DIFFERENT ILLUMINATION DESIGNS BY AVERAGE DAILY TRAFFIC AND DISTANCE OF ILLUMINATION UNITS FROM TRAFFIC LANE, FOR AN ANALYSIS PERIOD OF TWENTY YEARS

Illumination Design	Accident Cost by ADT and Distance of Units from Traffic Lane							
	ADT = 10,000				ADT = 30,000			
	10'	20'	25'	30'	10'	20'	25'	30'
A(M-40-200)	$14,485	$10,532	$7,291	$4,051	$43,454	$31,596	$21,874	$12,152
B(0-50-300)	4,861	3,511	2,430	1,346	14,583	10,532	7,290	4,050
C(M-50-300)	9,722	7,021	4,861	2,701	29,166	21,064	14,583	8,102
D(S-50-260)	5,524	3,989	2,767	1,533	16,571	11,968	8,300	4,598
E(S-50-300)	4,861	3,511	2,430	1,346	14,583	10,532	7,290	4,050

The following tables, 13, 14, 15, and 16, show the present value of the sum of initial and maintenance costs for the different illumination designs. Tables 14, 15, and 16 also include accident costs for units placed different distances from the pavement edge. It can be seen that accident costs are lower, the farther the lighting units are located off the roadway.

TABLE 13

PRESENT VALUE OF INITIAL AND MAINTENANCE COSTS, PER MILE OF ROADWAY FOR DIFFERENT ILLUMINATION DESIGNS, BY LENGTH OF ARMS, LEVEL OF MAINTENANCE COSTS, AND LENGTH OF THE ANALYSIS PERIOD

Illumination Design	12-ft. Arm(s)				15-ft. Arm(s)			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	$35,030	$41,230	$44,900	$54,820	$36,350	$42,550	$46,220	$56,14
B(0-50-300)	25,367	29,500	29,753	35,540	25,807	29,940	30,193	35,98
C(M-50-300)	38,093	46,360	46,866	58,440	38,973	47,240	47,746	59,32
D(S-50-260)	31,849	36,619	37,784	44,790	32,357	37,127	38,292	45,29
E(S-50-300)	28,467	32,600	32,853	38,640	28,907	33,040	33,293	39,08

NOTE: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of .05 per year is used.

To conclude this study, comparisons were made on a cost basis for those designs which give a particular level of effectiveness for a specific roadway, based on the effectiveness levels established at the beginning the the report. For lighting four-lane facilities, design B satisfies criteria III, and both designs A and B meet criteria II and I.

TABLE 14

PRESENT VALUE OF INITIAL, MAINTENANCE, AND ACCIDENT COSTS, PER MILE OF ROADWAY, FOR DIFFERENT ILLUMINATION DESIGNS, BY AMOUNT OF AVERAGE DAILY TRAFFIC, LEVEL OF MAINTENANCE COST, AND LENGTH OF ANALYSIS PERIOD FOR UNITS WITH 12-FOOT ARMS, PLACED TEN FEET FROM THE TRAFFIC LANE

Illumination Design	ADT = 10,000				ADT = 30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	$49,515	$61,169	$59,385	$74,759	$78,484	$101,063	$88,354	$114,653
B(O-50-300)	30,228	36,192	34,614	42,232	39,950	49,576	44,336	55,616
C(M-50-300)	47,815	59,744	56,588	71,824	67,259	86,512	76,032	98,592
D(S-50-260)	37,373	44,220	43,308	52,391	48,420	59,440	54,355	67,611
E(S-50-300)	33,328	39,292	37,714	45,332	43,050	52,676	47,436	58,716

NOTE: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of .05 per year is used.

TABLE 15

PRESENT VALUE OF INITIAL, MAINTENANCE, AND ACCIDENT COSTS, PER MILE OF ROADWAY, FOR DIFFERENT ILLUMINATION DESIGNS, BY AMOUNT OF AVERAGE DAILY TRAFFIC, LEVEL OF MAINTENANCE COST, AND LENGTH OF ANALYSIS PERIOD FOR UNITS WITH 15-FOOT ARMS, PLACED TWENTY FEET FROM THE TRAFFIC LANE

Illumination Design	ADT = 10,000				ADT = 30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=40
A(M-40-200)	$46,882	$57,049	$56,752	$70,639	$67,946	$86,048	$77,816	$99,638
B(O-50-300)	29,318	34,779	33,704	40,819	36,339	44,439	40,725	50,479
C(M-50-300)	45,994	56,901	54,767	68,981	60,037	76,239	68,810	88,319
D(S-50-260)	36,346	42,618	42,281	50,789	44,325	53,600	50,260	61,771
E(S-50-300)	32,418	37,879	36,804	43,919	39,439	47,539	43,825	53,579

NOTE: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of .05 per year is used.

TABLE 16

PRESENT VALUE OF INITIAL, MAINTENANCE, AND ACCIDENT COSTS, PER MILE OF ROADWAY, FOR DIFFERENT ILLUMINATION DESIGNS, BY AMOUNT OF AVERAGE DAILY TRAFFIC, LEVEL OF MAINTENANCE COST, AND LENGTH OF ANALYSIS PERIOD FOR UNITS WITH 15-FOOT ARMS, PLACED THIRTY FEET FROM THE TRAFFIC LANE

Illumination Design	ADT = 10,000				ADT = 30,000			
	Low MC		High MC		Low MC		High MC	
	M=20	M=40	M=20	M=40	M=20	M=40	M=20	M=4
A(M-40-200)	$40,401	$48,127	$50,271	$61,717	$48,502	$59,280	$58,372	$72,8
B(0-50-300)	27,153	31,793	31,539	37,833	29,857	35,517	34,243	41,5
C(M-50-300)	41,674	50,964	50,447	63,044	47,075	58,393	55,848	70,4
D(S-50-260)	33,890	39,238	39,825	47,409	36,955	43,459	42,890	51,6
E(S-50-300)	30,253	34,893	34,639	40,933	32,957	38,617	37,343	44,6

NOTE: MC signifies maintenance cost; M is the length, in years, of the analysis period. In calculating present values, an interest rate of .05 per year is used.

It is apparent that design B is generally less expensive than design A. One exception, however, is the case involving a long analysis period and/or high traffic volume, when the design A lighting units are located in a rigid median barrier and the units for design B are exposed on the side of the roadway. Design A is preferable in this situation.

For six-lane roadways, designs C and D meet Level III criteria. Design D is less expensive than design C, unless design C units are located with a rigid median barrier and relatively high average daily traffic counts are expected. For the lower effectiveness criteria at Levels II and I, designs A, B, and E are also feasible, and design B is the least costly of the alternatives.

For eight-lane facilities, only design C meets the effectiveness criteria for Level III. Design D meets the criteria for Levels II and I and is less expensive than design C. If, however, design C units are located with a rigid median barrier, accident costs for design C are zero. Design C is the only acceptable alternative for use on ten-lane roadways.

In designing roadway lighting systems, the future addition of traffic lanes to meet increasing demands should be taken into consideration. Flexibility of the various designs must be a factor when comparison is made, as changing the design of a roadway may alter the type of lighting system which would be most effective on the improved facility.

The comparisons made among the various designs in this study are based on the assumption that illumination units consisting of steel poles on aluminum transformer bases are about $350 per accident less expensive than steel poles and steel transformer bases and about $482 per accident less expensive than steel poles with steel shoe bases. The aluminum and steel transformer bases have approximately the same initial costs; therefore, the aluminum base is advantageous for exposed units. It also appears that aluminum poles on aluminum transformer bases provide lower costs per accident. For exposed illumination units, the extra cost of aluminum poles may be justified by accident cost savings. Because of the vibration characteristic of the aluminum poles, however, this type of lighting unit has not proven entirely satisfactory at the higher mounting heights. Even at low mounting heights, if the illumination units are to be located in a rigid median barrier or behind a bridge guardrail, thereby decreasing the chance of accident, steel poles are more economical.

REFERENCE

1. Hutchison, John W., and Kennedy, Thomas W., "Median of Divided Highways: Frequency and Nature of Vehicle Encroachments," University of Illinois, Engineering Experiment Station Bulletin 487, Urbana, Illinois, 1966.