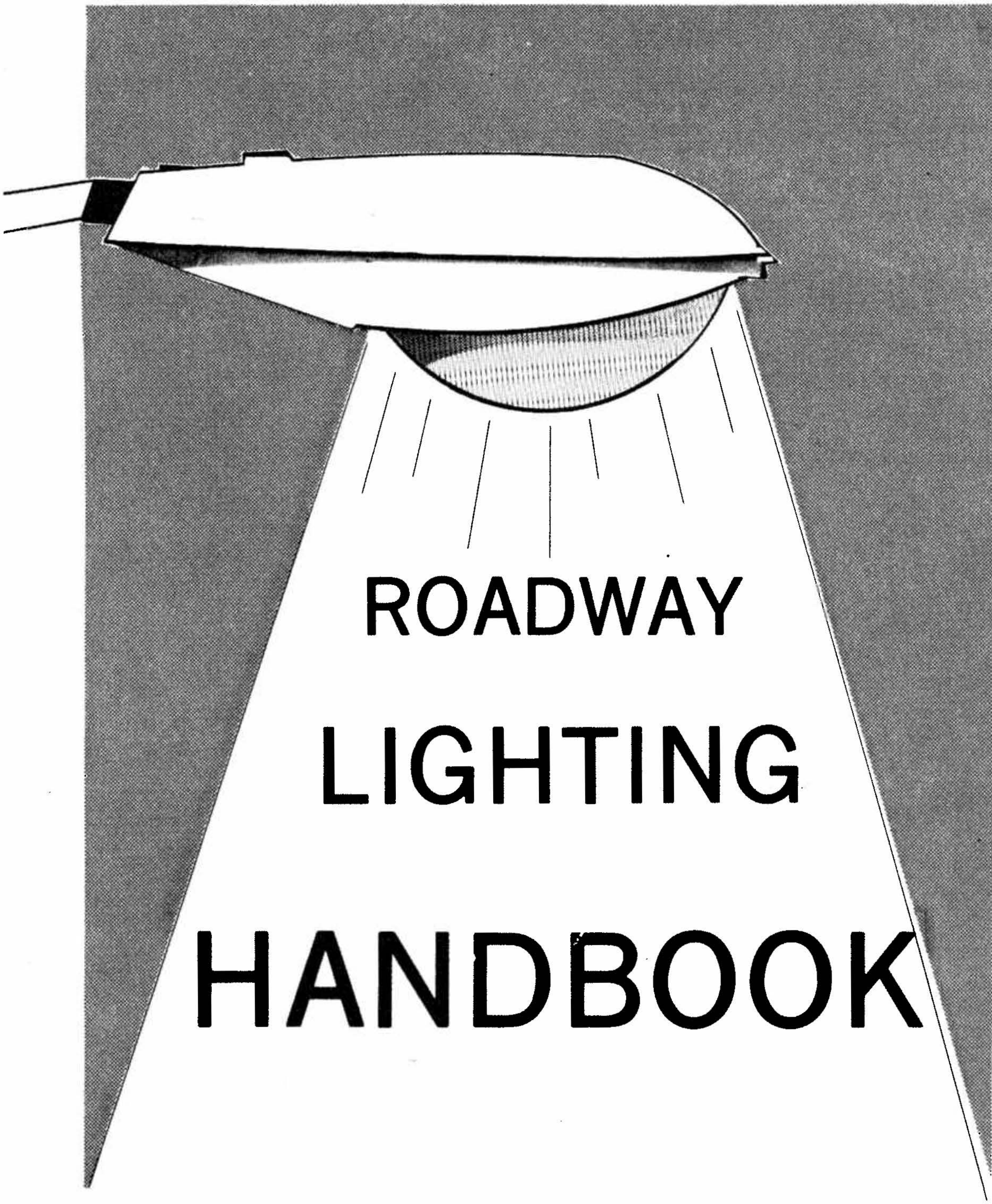

ROADWAY LIGHTING HANDBOOK

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

Implementation Package 78-15

ROADWAY LIGHTING HANDBOOK

December 1978

U. S. DEPARTMENT of TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
OFFICES OF RESEARCH AND DEVELOPMENT
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FOREWORD

One of the most important characteristics of the 20th century society is the extent to which mobility has been achieved through the use of our transportation facilities. The consequential effect on society created by this mass mobility has yet to be fully understood. One effect, however, is apparent: engineers and administrators are faced with the challenge of providing a safe and efficient system of streets and highways.

Nighttime conditions on our streets and highways present a special challenge to the engineering community. How can the mass mobility be maintained in the hours of darkness with reasonable degrees of comfort and safety?

Under present technological and economic conditions, fixed roadway lighting probably offers the most comprehensive means of providing good environments at night. Lighting practices over the years have indicated that roadway lighting, when properly applied, can provide quick, accurate, and comfortable seeing conditions for the driver, bicyclist, and pedestrian, and can result in improved accident and crime histories. In addition, civic betterment often results from the increased patronage of newly lighted areas of towns.

As the United States enters a period of energy constraints, it is important that we make careful judgments in the application of lighting to our transportation facilities. Efficient systems, considering first costs and energy costs, must be employed.

This ROADWAY LIGHTING HANDBOOK has been prepared to assist the engineering community in responding to lighting needs. The handbook presents the basic principles for the design, installation, operation, and maintenance of lighting systems for streets and highways. Widespread use of the contents of this document should significantly improve night roadway environments.

It is envisioned that this handbook will be used in combination with accepted standards of lighting practices. Together, they will go a long way toward providing safe, comfortable, and efficient transportation facilities.

TECHNICAL NOTE

The Roadway Lighting Handbook is an excellent manual to use in the design of roadway lighting systems. In order to make the book complete, we have included the most up-to-date warrants available for roadway lighting. These include warrants for continuous freeway lighting; however, in these days of rising energy costs, it should be noted that the Federal Highway Administration does not encourage the use of continuous freeway lighting except for those cases where no other practical alternative is feasible. It is felt that in many cases modern delineation systems may be used in lieu of continuous freeway lighting.

There are no research results currently available which will enable us to objectively define those situations when the use of delineation is optimal versus those situations where continuous freeway lighting may be necessary.

Users of the handbook should note that the Federal Highway Administration's position is that an engineering analysis should be made to evaluate the feasibility of using modern delineation techniques at the same time that continuous freeway lighting is considered. The most effective method of providing adequate guidance and safety to the driver should be selected.

ACKNOWLEDGEMENTS

This Handbook is the result of the work of numerous individuals and organizations. It is appropriate, therefore, to recognize their efforts.

Texas Transportation Institute - Texas A&M University

Ned E. Walton of the Texas Transportation Institute, Texas A&M University, was the principal author and editor of the Handbook prepared under contract to the Federal Highway Administration. Contributing authors from the Texas Transportation Institute were Neilon J. Rowan, John M. Mounce, Donald A. Andersen, and Anton Huber. Mrs. Linda Hatcher was the typist for the final manuscript and also prepared the layout and artwork.

Federal Highway Administration

The Office of Development, Implementation Division, conceived this work and contracted with Texas Transportation Institute for its preparation. Mr. William L. Williams represented FHWA in the preparation of the Handbook and provided the guidelines for development, preparation, and publication of the final text.

The Office of Traffic Operations, Street and Highway Lighting Branch, provided the detailed guidance and review for the Handbook. This office was represented by Mr. Charles Craig and Mr. John Arens. Mr. Arens served as the Contract Technical Manager and provided the detailed review and critique of the manuscript. In addition, he authored portions of Chapters 4 and 6.

The Office of Research provided valuable research input into the review of the Handbook. This office was represented by Mr. Richard N. Schwab.

Others

It is impossible to recognize all individuals and organizations who had an interest and input into this Handbook. The authors are appreciative, therefore, for all review comments, data and personal correspondence that contributed in many invaluable ways.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1

INTRODUCTION

INTRODUCTION

PURPOSE OF HANDBOOK

This handbook has been written to satisfy the need for an all-inclusive and up-to-date manual covering most aspects of public roadway lighting. Information is intended to be widely applicable and, whenever adaptable, international source material has been incorporated.

The handbook is intended for use as a guide in planning, design, operation, and maintenance of roadway lighting systems. The material is presented in a way that the handbook may be used as a reference document by engineers and other public officials. Also, it is intended that this handbook serve the academic needs as a textbook for formal education and training in roadway lighting. It is envisioned that this document will bridge the gap between practical and theoretical concepts in the field of roadway lighting.

While this document provides the basic tools to the practicing engineer in the design of a functional and cost-effective lighting system, it does not set Federal Highway Administration policies. Its purpose is one of a "when," "where," and "how" to do handbook. It contains the experiences gained by many lighting experts and provides a basis to solve lighting problems of public roadways in a practical manner. Policies and directives issued by FHWA, as applicable to all Federal Aid Highway and Federal Aid Road Projects, must be adhered to. Wherever applicable, this handbook should be used in conjunction with the latest edition of "An Informational Guide for Roadway Lighting," published by the American Association of State Highway and Transportation Officials (1), and the latest edition of the "American National Standard Practice for Roadway Lighting," published by the Illuminating Engineering Society of North America (2).

PURPOSE OF ROADWAY LIGHTING

The general purpose of roadway lighting is to provide improved visibility for the various users of the roadways and associated facilities. To be more specific, one must define users, roadways, and associated facilities. The term "users" may include vehicle operators (autos, trucks, buses, motorcycles, bicycles), pedestrians, and other citizens of the community. "Roadways" are defined as freeways, highways, and city streets of various types. "Associated facilities" include appurtenances of a traffic and non-traffic nature: traffic appurtenances include the physical features along the roadway such as traffic barriers, bridge piers, roadside ditches, curbs, channelization, etc. To illustrate the specific purposes served by roadway lighting, consider the freeway and the local street. On the freeway, roadway lighting serves the principal function of improving driver visibility by supplementing vehicle headlight illumination so that drivers can view satisfactorily the roadway, its appurtenances, and other traffic. In contrast, roadway lighting on local streets is multi-purposed; that is, it provides driver visibility and pedestrian visibility, serves as a deterrant to crime, promotes commercial interests, and enhances community pride. Thus, the specific purpose of lighting is dependent upon the nature of the facility which it serves, and the development surrounding the facility. For example, crime is associated with the surrounding development to a greater extent than to the roadway. Yet, roadway lighting serves a very significant purpose of crime prevention.

It is not so important at this point to outline the various purposes of lighting relative to specific facilities, but to emphasize that lighting is a tool that aids traffic facilities in satisfying their intended purpose at night in much the same way as these traffic facilities perform during hours of daylight. Lighting, in general, can be expected to reduce night accidents by about 30 percent. Lighting should not be expected to produce daytime equivalent accident rates as fatigue, intoxication, and other modifying factors often play a prominent role in nighttime accident rates.

It is encumbent upon the designer to study all of the functions of a facility that is being considered for lighting, and design a lighting system that compliments the functions.

DEFINING DRIVER INFORMATION NEEDS

To this point, we have identified improvement of driver visibility as one of the primary purposes of roadway lighting. If we are to identify the roadways which need to be lighted and design lighting systems to improve driver visibility, then we must have some understanding of what the drivers need to see. To drive safely and efficiently, drivers need a constant flow of information relative to the roadway, traffic, and environmental conditions. In engineering terms, this information is described as geometric, operational, and environmental related information.

The geometric category includes the physical characteristics of the roadway such as curves, grades, curbs, medians, number of lanes, lane drops, and other physical features that influence driver decisions. The operational category includes two major information sources: other traffic operation on the roadway, including pedestrians, and the regulatory and warning devices intended to control the operation of traffic. It is important that drivers be able to judge the speed, distance, and location of other vehicles, particularly when other vehicles are present in great numbers. Also, the driver must be able to see the various signs, signals, markings, and channelization devices. The environmental category of driver information includes the characteristics of roadside development that influence driver decisions and, as a result, influence driver safety and efficiency. Such characteristics include type and extent of property development, the clearance or setback distance to the development, access and traffic generation potential, and the type and amount of extraneous light.

It is well documented that the driver continually analyzes the information available and makes speed, distance, and maneuver decisions accordingly. Accidents, or at least poor driver decisions, result when 1) the driver has failed to analyze the information correctly, or 2) the driver has failed to receive sufficient information. Failure to receive sufficient information indicates lack of visibility which, in turn, may indicate the need for roadway lighting. Thus, a rational approach to justifying or warranting the installation of roadway lighting is through an evaluation of whether driver information needs are satisfied. This will be covered in greater depth in a subsequent chapter on analyzing lighting needs.

OBJECTIVES OF FIXED ROADWAY LIGHTING

It should be emphasized at this point that illumination of the roadway and the adjacent areas is the basic medium for transmitting nighttime driver information. Indeed, virtually all of the rural highway mileage and a substantial amount of suburban and urban street mileage depends on illumination by vehicle headlights. On many of these facilities, illumination by vehicle headlights is entirely adequate. On other sections of roadways, particularly the more complex and more heavily traveled urban streets and highways, additional information is needed. The objectives in providing this additional roadway lighting can be summarized as follows:

- To supplement vehicle headlights, extending the visibility range beyond their limits both laterally and longitudinally.

- To improve the visibility of roadway features and objects on or near the roadway.
- To delineate the roadway ahead.
- To provide visibility of the environment.
- To reduce the apprehension of those using the roadway.

The achievement of these objectives is expected to yield benefits that are very succinctly outlined in the "Street Lighting Manual" by Edison Electric Institute (3):

> "The basic motivation of people responsible for the lighting of streets and highways remains unchanged, except for emphasis in 400 years of recorded history. Listed approximately in its order of chronological development, the objectives (benefits) of street lighting might be classified as follows:
>
> 1. Crime Reduction
> 2. Civic Betterment
> 3. Traffic Safety."

ORGANIZATION OF THE HANDBOOK

This handbook is designed to serve as a guide in virtually all aspects of planning, designing, and operating roadway lighting systems. The overall process of designing and operating a roadway lighting system consists of several well-defined steps. These steps are identified as follows:

- Understanding Visibility Requirements
- Analyzing Lighting Needs
- Selecting Lighting Equipment
- Selecting the Lighting System Configuration
- Designing the Lighting System
- Designing the Lighting Hardware
- Operating and Maintaining the Lighting System
- Analyzing the Economics of the Lighting System

Beginning with Chapter 2, these steps represent the chapter-by-chapter organization of the handbook.

DEFINITIONS

Definitions of terms used throughout this text may be found in the Glossary.

REFERENCES

1. "An Informational Guide for Roadway Lighting," American Association of State Highway and Transportation Officials, Washington, D.C., 1976.
2. "American National Standard Practice for Roadway Lighting," RP-8-1977, Illuminating Engineering Society-American National Standards Institute, New York, N.Y., 1977.
3. "Street Lighting Manual," Edison Electric Institute, New York, N.Y., 1972.

2

UNDERSTANDING VISIBILITY REQUIREMENTS

UNDERSTANDING VISIBILITY REQUIREMENTS

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
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It is evident that the lighting engineer has a great responsibility to:

- provide adequate visibility so that driving tasks can be performed with required standards of speed and accuracy, and
- provide lighting conditions that will result in maximum safety and absence of visual disability and visual discomfort.

This chapter discusses basic concepts which will allow the lighting designer to understand the relationships between light, vision, and visibility, and thus fulfill his responsibilities. Detailed discussions of the concepts may be found in the IES Lighting Handbook (1).

LIGHT

The Illuminating Engineering Society has defined light as *visually evaluated radiant energy.* From a physical standpoint, light is that portion of the electromagnetic spectrum which lies between the wavelength limits of 380 nanometers and 780 nanometers. Radiant energy of the proper wavelength makes visible anything from which it is emitted or reflected in sufficient quantity to activate the receptors in the eye.

ILLUMINATION

The time rate of flow of light is defined as luminous flux. The density of luminous flux incident on a surface is illumination. The term illumination also is commonly used in a qualitative or general sense to designate the act of illuminating or the state of being illuminated. Usually the context will indicate which meaning is intended, but occasionally it is desirable to use the expression level of illumination to indicate that the quantitative meaning is intended. Lighting design standards in the United States specify illumination as the basic design criteria in terms of horizontal footcandles or lux (see Glossary).

LUMINANCE

Luminance (photometric brightness) is the luminous intensity of any surface in a given direction per unit of projected area of the surface as viewed from that direction. In common usage, the term brightness usually refers to the intensity of sensation resulting from viewing surfaces or spaces from which light comes to the eye. This sensation is determined in part by the definitely measurable luminance defined above and in part by conditions of observation such as the state of adaptation of the eye. In much of the literature the term brightness, used alone, refers to both luminance and sensation. The context usually indicates which meaning is intended.

Most European lighting standards specify luminance as the basid design criteria in terms of footlamberts or candela/m^2 (see Glossary).

VISION

The eyes are our primary sources of information. Without light we have no vision, and thus little information. With inadequate light or the wrong kind of lighting, vision may be inefficient, uncomfortable, or hazardous. It is important, therefore, that the lighting designer understand the basic functions of the eye.

The human eye is diagrammed in Figure 1. It is maintained in a spherical shape by the sclera--a tough outer coat that also protects the eye, and the cornea--the clear front covering of the eye. The iris, lens, and associated muscles divide the eye into two chambers, each filled with a transparent fluid.

The optical system of the eye consists of three major components:

- the cornea, which supplies about 75 percent of the eye's light refracting power,
- the pupil, which controls the amount of light entering the eye, and
- the lens, which focuses images on the light sensitive surface of the retina.

The cornea is largely responsible for refracting and focalizing light as it enters the eye. The pupil, in turn, confines the light entering the eye to a limited central area of the lens. This minimizes the aberrations of the eye by eliminating light on the outer edges of the cornea and lens. The size of the pupil is affected by a number of factors. Stimulating the retina with light produces a constriction of the pupil. Conversely, when the eye is in the dark, the pupil dialates. The pupil diameter may range from 8 mm to as small as 2 mm, depending upon the luminance or brightness to which the eye is exposed.

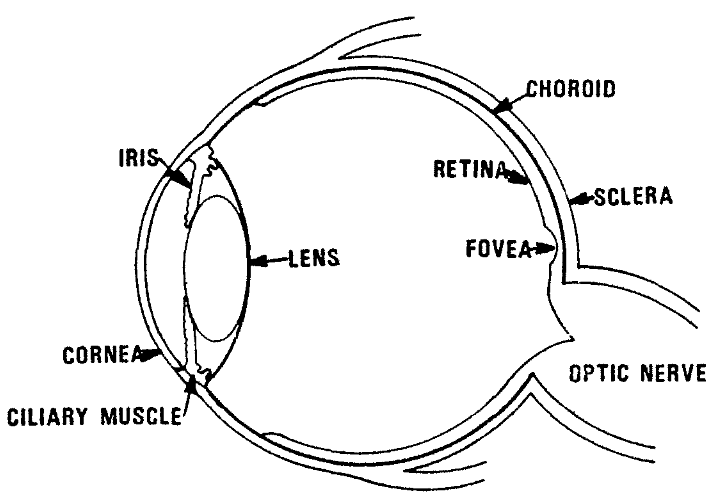

Figure 1. A horizontal cross-section of the human eye. Approximate length from cornea to fovea of retina is 24 mm. Thickness of choroid is about 0.05 mm, and the sclera 1.0 mm.

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The lens permits the eye to focus on an object at a given distance (accommodation). The lens is an elastic structure, its form and position being determined by the tension of the suspensary ligaments. During accommodation, the ciliary muscle contracts and relaxes the suspensary ligaments; this permits the lens to assume a more spherical shape, thereby increasing its power in order to focus on near objects. When viewing distant objects, the ciliary muscle relaxes and tension is exerted on the lens which becomes flattened out and has less power.

The retina of the eye consists of a delicate layer of nerve tissue in which there are two types of photo receptors called cones and rods. The concentration of cones and rods varies over the retinal area. A small depression in the center of the retina, having a diameter of about 0.55 mm, contains only cones (fovea). Outside this rod-free area, the rods and cones are mixed with the proportion of cones decreasing towards the periphery of the retina. The functions of cones and rods are as follows:

- Central or foveal vision. The cones in the fovea produce a very sharp image showing the greatest detail of which the eye is capable. The eye attempts to fixate images upon the fovea.

- Peripheral vision. The periphery of the retina, which is composed chiefly of rods, does not produce sharp vision, and objects seen by this area appear as fuzzy silhouettes. The periphery is, however, highly sensitive to movement and flicker.

- Scotopic vision. Vision by the normal human eye when it is adapted to levels of luminance below about 0.05 cd/m^2 (.015 fL) is termed scotopic or night vision. In scotopic vision, the rods are considered to be the principal active elements, and here peripheral detection is superior to foveal detection. There is no sensation of color in scotopic vision.

- Photopic vision. When the eye is adapted to levels of luminance above 3 cd/m^2 (.9 fL), vision is said to be photopic. At these levels, the cones are considered to be the principal active elements, central vision is good, and normal color vision is possible.

- Mesopic vision. Vision at luminance levels intermediate to the scotopic and photopic levels is referred to as mesopic vision. The ability to distinguish color diminishes with decreasing lighting level and, due to a shift in relative spectral sensitivity, the eye becomes more sensitive to color at the red end of the spectrum.

Most night-driving situations occur under conditions of mesopic vision, although a well-designed roadway lighting system can approach the photopic vision range in luminance.

VISIBILITY

Visibility is the quality or state of being perceivable by the eye. In many applications, visibility is defined in terms of the distance at which an object can be just perceived by the eye. In other situations, visibility is defined in terms of the contrast or size of a standard test object, observed under standardized viewing conditions, having the same threshold as the given object.

VISUAL ACUITY

The visual size of any detail that needs to be seen is a function of its physical size and its distance from the point of observation. By combining these two dimensions, one can express the size as a visual angle which usually is measured in minutes of arc. Thus, the farther a given object is from the eyes, the smaller its visual size becomes. Various types of test objects, three of which are shown in Figure 2, have been used for evaluating the size discriminatory ability of the eye. In each case, the critical detail which must be discriminated is indicated by the dimension d; for a constant viewing

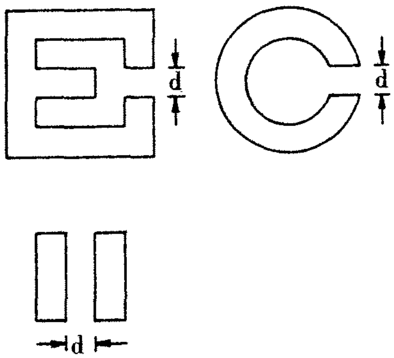

Figure 2. Commonly used test objects for determining size discrimination and visual acuity.

distance, the visual angle subtended at the eye by d is the same for the three objects, even though the maximum dimensions are different. Another often used way of expressing the size threshold of the eye is in terms of visual acuity. Quantitatively, this is the reciprocal of the visual angle. It quite often is defined as the ability of the eyes to resolve small detail. In driving, two types of visual acuity are of concern--static and dynamic visual acuity.

Static visual acuity occurs when both the driver and the object being viewed are stationary and is a function of background, brightness, contrast, and time. With increasing illumination, visual acuity increases up to a background brightness of about 10 millilamberts, and then remains constant despite further increases in illumination. Static visual acuity also increases with increasing contrast of the object. Optimal exposure time for a static visual acuity task is 0.5 to 1.0 sec when other visual factors are held constant at some acceptable level.

When there is relative motion between the driver and an object, such as occurs in driving, the resolving ability of the eye is termed dynamic visual acuity. Dynamic visual acuity is more difficult than static visual acuity because eye movements are not generally capable of holding a steady image of the target on the retina. The image is blurred and therefore its contrast decreases. The conditions favorable for dynamic visual acuity are slow movement, long tracking time, and good illumination. These are rarely found in the nighttime driving environment, but are very important for sign reading, distance judgment, object discrimination, and other dynamic visual acuity tasks.

CONTRAST

Contrast is probably more important than visual acuity in nighttime visual performance during driving. Contrast (C) is defined as:

$$C = \frac{L_b - L_o}{L_b}$$

where L_b and L_o are the luminances (photometric brightness) of two contrasting areas--the background and the object, respectively. The recognition of objects is most often based upon a discrimination of the background and object luminance differences. For nighttime conditions, an obstacle may appear as a dark area against a bright background (discernment by silhouette), or it may appear as a bright area against a dark background (discernment by reverse silhouette). To enhance discernment by silhouette, brightness of the pavement and uniformity of brightness along and transverse to the roadway are essential. Discernment by reverse silhouette usually applies to the visibility of objects on areas adjacent to the roadway, projections above the pavement surface, and the upper portions of pedestrians and vehicles.

PAVEMENT BRIGHTNESS

Under fixed lighting conditions, drivers usually see objects within the roadway as dark silhouettes against a bright background formed by the roadway and its surroundings. Therefore, one of the most important uses of fixed lighting is to brighten the roadway surface. In producing this brightness, the reflection of light from the surface and the surface illumination are equally important.

Efficient lighting systems should provide suitable light distribution in which the bright patches of light cover the roadway from any direction of viewing, and the surface is as brightly and uniformly illuminated as possible without excessive glare. Luminaires are designed to direct light up and down the roadway to achieve the brightness uniformity. A lighting designer should determine the type of pavement to be illuminated, its reflectance properties, and select lighting equipment and designs that will achieve the appropriate brightness conditions.

GLARE

Two types of glare have a critical influence on driver visual performance:

- Discomfort glare (psychological glare) - Ocular discomfort from a bright light source.
- Disability glare (physiological glare) - Stray light which reduces contrast sensitivity, and thus produces a loss of visual efficiency.

Glare is an especially disturbing influence when viewing a difficult task under low brightness conditions (such as night).

LIGHTING CRITERIA

In the United States, the principal criteria in the design of lighting systems are average illumination level and uniformity of illumination. Average level of illumination, expressed in horizontal footcandles (lux), is a measure of the total illumination on the roadway surface. Uniformity, expressed in terms of average-to-minimum or maximum-to-minimum ratios, describes how the total illumination is distributed on the roadway surface. Adequate brightness levels can be achieved through specification of average illumination level and uniformity. However, careful consideration must be given to the pavement surface characteristics and adjust levels and uniformity if necessary based on experience. There is considerable concern among lighting designers that average levels of illumination and uniformity do not adequately reflect visual qualities provided. Many feel that the United States should adopt a design system based on luminance and visibility measures. It should be pointed out, however, that the same end results can be produced using illumination rather than luminance if adequate attention is given to distribution geometry. The lighting designer has little control over luminance values except the maintained light output of the source itself and distribution geometry. Pavement reflectance characteristics cannot be measured or controlled to the extent necessary to predict luminance effectiveness over a period of time. It is estimated that the reflective properties of Portland Cement Concrete pavement may deteriorate by as much as 50 percent over its life, whereas an asphaltic surface may actually improve in reflective qualities over time (2). It seems prudent, therefore, to use long-standing experience to specify illumination (that light striking the pavement and over which the designer has almost total control) rather than luminance (that light reaching the driver's eye and over which the designer has almost no control). Very acceptable visibility conditions can be provided, although there is no direct measure of visibility in the design criteria. Means of achieving such conditions will be discussed in later chapters.

REFERENCES

1. IES Lighting Handbook, Fifth Edition, Illuminating Engineering Society, New York, N.Y., 1972.

2. Ketvirtis, Antanas, Highway Lighting Engineering, Foundation of Canada Engineering Corporation Limited, Toronto, Canada, 1967.

3

ANALYZING LIGHTING NEEDS

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The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for .the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

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- *Analyzing the Economics of the Lighting System*

INTRODUCTION

The roadway lighting engineer generally must address his efforts to three basic questions relative to lighting practice.

- Which roadways should be lighted? What are the determining factors and the methodology by which one identifies those roads on which vehicle headlighting is adequate and those which must have supplemental illumination?
- Which roadways should be lighted first, etc? It is eternally obvious that we have neither time nor money to implement every needed improvement. Therefore, one must ask what are the determining factors and the rational methodology by which one may establish priorities in the selection of roadway facilities for the implementation of supplemental lighting.
- How does one effectively provide and maintain adequate illumination on the roadway? What are the determining factors and the methodology by which one determines the required level of illumination, designs the system to provide the required level, and maintains the system so as to assure that the required illumination level is provided continuously?

There are some who claim that all roadways should be illuminated with fixed source lighting systems while others claim that vehicle lighting is adequate on virtually every roadway. Somewhere in between these two extremes is a rational approach to the application of roadway lighting.

The justification of roadway lighting is not completely rational in the sense that it is measured or calculated on an analytical basis. Rather, it is rational from the standpoint that engineering judgment, coupled with analytical/scientific methods, is used to reach a decision, considering the prevailing user needs and the user benefits that may be realized as a result of roadway lighting.

This chapter will address the various methods of determining where lighting is warranted and the establishment of priorities for lighting. Two approaches to identifying or determining warranting conditions for lighting are presented. First is the experience approach developed by AASHTO and published in "An Informational Guide for Roadway Lighting," AASHTO, March 1976 (1). Its primary application is to Interstate Class roadways. The second method is an approach based on an analytical evaluation of driver information needs. It is published in NCHRP Report No. 152, "Warrants for Highway Lighting" (2). This has application to urban streets as well as freeway-type facilities. Although not completely proven, it does offer a means of setting priorities as well as warrants.

WARRANTS FOR ROADWAY LIGHTING

A warrant is defined as factual evidence justifying or standing as assurance that there is substantial reason for undertaking a proposed project. Warrants are used by administrators and designers in reaching decisions relative to the planning and design of current and future lighting projects. The meeting of warrants does not obligate a public agency to provide lighting. In every facet of public service, warranting conditions indicate a greater need for improvements than there are resources to provide the improvement. There are varying degrees of need, and therefore it is the responsibility of the administrator to allocate resources to the projects of greatest need: thus, the necessity for a method of establishing priorities. Where needs are intense, administrators must acquire or allocate additional resources. These are judgmental decisions of administration and do not relate to the technical aspects of warrants.

Lighting warrants should be based on conditions relating to the need for roadway lighting and the benefits that may be derived from lighting. Factors such as traffic volume, speed, road use during the night, night accident rate, road geometrics, and general night visibility are important in determining the minimum conditions to justify lighting. Justification for lighting should also be based on the economic returns of lighting as compared to the costs of not lighting. Economic returns for lighting are measured in terms of reductions in personal injuries, fatalities, property damage, and other societal costs. More effective usage of the road and the possible increase in its capacity should also be considered.

Illumination Warrants Based on Experience (AASHTO)

The American Association of State Highway and Transportation Officials (AASHTO) has developed criteria on warranting conditions based on present experience (1). These warrants were prepared by the Joint Task Force for Highway Lighting of the AASHTO Operating Subcommittees on Design and Traffic Engineering. The approach in establishing these warrants has been a compilation and description of current practice with associated warranting criteria. These warrants set forth a description of operational, geometric, and development conditions that must be matched or exceeded in order to justify the installation of roadway lighting. It should be pointed out, however, that meeting these warrants does not obligate an agency to provide lighting. The objective is to identify those roadways which should be considered in the process of setting priorities for the allocation of available resources to roadway lighting.

AASHTO warrants are developed for five principal areas of roadway lighting:

- Freeways
- Interchanges
- Tunnels and Underpasses
- Roadway Safety Rest Areas
- Roadway Sign Lighting

In reviewing the publication, it is immediately obvious that primary emphasis on warrants is in the area of Interstate-type freeways. Thus, the reader may find greater applicability of other warranting procedures for lighting on urban streets.

The publication, "An Informational Guide for Roadway Lighting," (1) is an essential publication for the lighting designer, particularly where the designer is involved in federal-aid projects. The document has been adopted by FHWA as the official guide to warrants and design criteria for federal-aid projects. Because of its importance, the sections pertaining to warrants are quoted directly from the 1976 edition for those who do not have ready access to the Guide.

Warrants for Lighting Freeways. Quotations taken directly from the Guide mentioned previously are presented below. It should be noted that the warranting statements are given separately for continuous freeway lighting, complete interchange lighting, and partial interchange lighting. It will be noted further that the principal considerations are traffic volume, interchange spacing (relative frequency of traffic maneuvers), development and lighting conditions in the area surrounding the freeway, and the night-to-day accident ratio. The severity of visual information problems created as a result of specific geometric and operational conditions of the traffic facility are reflected in these principal considerations. The effect of all these factors must be considered in applying the warrants.

Continuous Freeway Lighting

Case CFL-1. Continuous freeway lighting is considered to be warranted on those sections in and near cities where the current ADT is 30,000 or more.

Case CFL-2. Continuous freeway lighting is considered to be warranted on those sections where three or more successive interchanges are located with an average spacing of 1½ miles or less, and adjacent areas outside the right-of-way are substantially urban in character.

Case CFL-3. Continuous freeway lighting is considered to be warranted where for a length of two or more miles the freeway passes through a substantially developed suburban or urban area in which one or more of the following conditions exist: (a) local traffic operates on a complete street grid having some form of street lighting, parts of which are visible from the freeway; (b) the freeway passes through a series of developments such as residential, commercial, industrial and civic areas, colleges, parks, terminals, etc., which include roads, streets and parking areas, yards, etc., that are lighted; (c) separate cross streets, both with and without connecting ramps, occur with an average spacing of ½ mile or less, some of which are lighted as part of the local street system; and (d) the freeway cross section elements, such as median and borders, are substantially reduced in width below desirable sections used in relatively open country because of the high costs of right-of-way due to proximity of existing land developments.

Case CFL-4. Continuous freeway lighting is considered to be warranted on those sections where the ratio of night to day accident rate is at least 2.0 or higher than the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night accident rate.

Complete Interchange Lighting

Case CIL-1. Complete interchange lighting is considered to be warranted where the total current ADT ramp traffic entering and leaving the freeway within the interchange areas exceeds 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.

Case CIL-2. Complete interchange lighting is considered to be warranted where the current ADT on the crossroad exceeds 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.

Case CIL-3. Complete interchange lighting on unlighted freeways is considered to be warranted at locations where existing substantial commercial or industrial development, which is lighted during hours of darkness, is located in the immediate vicinity of the interchange, or where the crossroad approach legs are lighted for ½ mile or more on each side of the interchange.

Case CIL-4. Complete interchange lighting is considered to be warranted where the ratio of night-to-day accident rate within the interchange area is at least 1.5 or higher than the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night accident rate.

Partial Interchange Lighting

Case PIL-1. Partial interchange lighting is considered to be warranted where the total current ADT ramp traffic entering and leaving the freeway within the interchange area exceeds 5,000 for urban conditions, 3,000 for suburban conditions, or 1,000 for rural conditions.

Case PIL-2. Partial interchange lighting is considered to be warranted where the current ADT on the freeway through traffic lanes exceeds 25,000 for urban conditions, 20,000 for suburban conditions, or 10,000 for rural conditions.

Case PIL-3. Partial interchange lighting is considered to be warranted where the ratio of night to day accident rate within the interchange area is at least 1.25 or higher than the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night accident rate.

Special Considerations

Continuous, complete, or partial interchange lighting is considered to be justified where the local governmental agency finds sufficient benefit in the forms of convenience, safety, policing, community promotion, public relations, etc., to pay an appreciable percentage of the cost of or wholly finance the installations, maintenance, and operation of the lighting facilities.

Where there is continuous lighting, there should be complete interchange lighting. When continuous freeway lighting is warranted, but not initially installed, partial interchange lighting is considered to be justified under the continuous freeway lighting warrants CFL-1 or CFL-2. This would preclude the requirements of satisfying the partial interchange lighting warrants PIL-1 or PIL-2.

Where complete interchange lighting is warranted, but not initially fully installed, a partial lighting system which exceeds the normal partial installation in number of lighting units is considered to be justified.

Lighting of crossroad ramp terminals is warranted regardless of traffic volumes, where the design requires the use of raised channelizing or divisional islands, and/or where there is poor sight distance.

Where applicable, the National Cooperative Highway Research Program Report No. 152, "Warrants for Highway Lighting," may be considered for determining the priority of lighting projects.

One major point that should be viewed with a great deal of caution is the first provision under "Special Considerations" where, in essence, lighting is warranted if the local agency agrees to pay for operation and maintenance. If a freeway passes through the principal developed area of a community and serves that community to a great extent, then perhaps the local community may realize a reasonable return for its investment. If, however, the freeway is not an integral part of the local street network, but serves principally an intercity function (such as a bypass route), then the local operations and maintenance may not be justified. Every case is different; precise rules cannot be established. The local agency should make a realistic evaluation of the costs and benefits involved.

It should be noted that priorities are not addressed specifically other than to point out the availability of a procedure in NCHRP Report No. 152. That procedure will be presented in a subsequent section of this chapter.

Warranting Conditions for Streets and Highways, Walkways, and Bikeways. As pointed out previously, and as stated in the quote below, the joint task force which prepared "An Informational Guide for Roadway Lighting" did not choose to be specific in establishing warrants for lighting urban streets. The wide diversity of prevailing and/or anticipated conditions preclude specific warrants at the present time.

Warranting Conditions

> It is not practical at this time to establish specific warrants for the installation of roadway lighting to satisfy all prevailing or anticipated conditions. In general, lighting may be considered for those locations where the respective governmental agencies concur that lighting will contribute substantially to the efficiency and safety and comfort of vehicular or pedestrian traffic. Lighting may be provided for all major arterials in urbanized areas and for locations or sections of streets and highways where the ratio of night to day accident rates is high (say, higher than the statewide average for all similar locations) and a study indicates that lighting may be expected to significantly reduce the night accident rate. Where such determinations to install lighting have been made on the basis of experience and accident data under certain existing conditions, application should be made of these conclusions to other similar highway sections. The latter should include similar geometric layouts on which experience or accident data is not available and also highway sections where anticipated increase in vehicular and pedestrian traffic (either normal growth or sudden changes) will present problems within a few years. Lighting may be considered at locations where severe or unusual weather or atmospheric conditions exist. In other situations, lighting may be considered where the local governmental agency finds sufficient benefit in the form of convenience, safety, policing, community promotion, or public relations to pay an appreciable percentage of the cost of, or wholly finance, the installation, maintenance and operation of the lighting facilities.

It is obvious that these warrants provide very little technical direction to the consideration of lighting in the urban area. In order to supplement these generalized warranting statements with more technical information, the urban lighting designer may refer to several publications including the Transportation and Traffic Engineering Handbook (3) and NCHRP Report No. 152 (2).

Warrants for Tunnel Lighting. A tunnel is defined as a structure of any type surrounding a vehicular roadway which requires the use of artificial illumination or equivalent means to provide adequate roadway visibility necessary for safe and efficient daytime traffic operation. AASHTO warrants for the lighting of tunnels are quoted as follows:

Warrants for Tunnel Lighting

> The installation of artificial daytime lighting is warranted when tunnel user visibility requirements are not satisfied without the use of an illumination system supplement to natural sunlight. Overall tunnel visibility varies considerably with such items as the geometry of the tunnel and its approaches, the traffic characteristics, the treatment of roadway and environmental reflective surfaces, the climate and orientation of the tunnel, and with visibility objectives determined to be essential for safe, efficient tunnel operation.

Additional references on tunnel lighting are given in the AASHTO publication and may be helpful in applying these warrants.

Analytical Approach to Illumination Warrants (NCHRP Report No. 152)

An analytical approach to roadway lighting warrants is embodied in four comprehensive evaluation forms (1, 2, 3, and 4) which apply to non-controlled access facilities, intersections, freeways, and interchanges, respectively. A brief description of the forms, how they were developed, and how to use them is presented herein.

Through a research effort, the justification of roadway lighting has been related to driver visual information needs. The first step was to identify

FORM 1

EVALUATION FORM FOR NON-CONTROLLED ACCESS FACILITY LIGHTING

CLASSIFICATION FACTOR	RATING 1	2	3	4	5	UNLIT WEIGHT (A)	LIGHTED WEIGHT (B)	DIFF. (A - B)	SCORE [RATING X (A - B)]
Geometric Factors									
No. of lanes	4 or less	--	6	--	8 or more	1.0	0.8	0.2	______
Lane Width	> 12'	12'	11'	10'	< 10'	3.0	2.5	0.5	______
Median Openings Per Mile	< 4.0 or one-way operation	4.0 - 8.0	8.1 - 12.0	12.0 - 15.0	> 15.0 or no access control	5.0	3.0	2.0	______
Curb Cuts	< 10%	10-20%	20-30%	30-40%	> 40%	5.0	3.0	2.0	______
Curves	< 3.0°	3.1 - 6.0°	6.1 - 8.0°	8.1 - 10.0°	> 10°	13.0	5.0	8.0	______
Grades	< 3%	3.0 - 3.9%	4.0 - 4.9%	5.0 - 6.9%	7% or more	3.2	2.8	0.4	______
Sight Distance	> 700'	500 - 700'	300 - 500'	200 - 300'	< 200'	2.0	1.8	0.2	______
Parking	prohibited both sides	loading zones only	off-peak only	permitted one side	permitted both sides	0.2	0.1	0.1	______
							Geometric Total		______
Operational Factors									
Signals	all major intersections signalized	substantial majority of intersections signalized	most major intersections signalized	about half the intersections signalized	frequent non-signalized intersections	3.0	2.8	0.2	______
Left Turn Lane	all major intersections or one-way operation	substantial majority of intersections	most major intersections	about half the major intersections	infrequent turn bays or undivided streets	5.0	4.0	1.0	______
Median Width	30'	20 - 30'	10 - 20'	4 - 10'	0 - 4'	1.0	0.5	0.5	______
Operating Speed	25 or less	30	35	40	45 or greater	1.0	0.2	0.8	______
Pedestrian Traffic at Night (peds/mi)	very few or none	0 - 50	50 - 100	100 - 200	> 200	1.5	0.5	1.0	______
							Operational Total		______
Environmental Factors									
% Development	0	0 - 30%	30 - 60%	60 - 90%	100%	0.5	0.3	0.2	______
Predominant Type Development	undeveloped or back-up design	residential	half residential &/or commercial	industrial or commercial	strip industrial or commercial	0.5	0.3	0.2	______
Setback Distance	> 200'	150 - 200'	100 - 150'	50 - 100'	< 50	0.5	0.3	0.2	______
Advertising or Area Lighting	none	0 - 40%	40 - 60%	60 - 80%	essentially continuous	3.0	1.0	2.0	______
Raised Curb Median	none	continuous	at all intersections	at signalized intersections	a few locations	1.0	0.5	0.5	______
Crime Rate	extremely low	lower than city average	city average	higher than city average	extremely high	1.0	0.5	0.5	______
							Environmental Total		______
Accidents									
Ratio of Night-to-Day Accident Rates	< 1.0	1.0 - 1.2	1.2 - 1.5	1.5 - 2.0	2.0*	10.0	2.0	8.0	______
*Continuous lighting warranted.							*Accident Total*		______

GEOMETRIC TOTAL = ______

OPERATIONAL TOTAL = ______

ENVIRONMENTAL TOTAL = ______

ACCIDENT TOTAL = ______

SUM = ______ POINTS

WARRANTING CONDITION = 85 points

FORM 2

EVALUATION FORM FOR INTERSECTION LIGHTING

CLASSIFICATION FACTOR	RATING					UNLIT WEIGHT (A)	LIGHTED WEIGHT (B)	DIFF. (A - B)	SCORE [RATING X (A - B)]
	1	2	3	4	5				
Geometric Factors									
Number of Legs		3	4	5	6 or more (including traffic circles)	3.0	2.5	0.5	______
Approach Lane Width	> 12'	12'	11'	10'	< 10'	3.0	2.5	0.5	______
Channelization	no turn lanes	left turn lanes on major legs	left turn lanes on all legs, right turn lanes on major legs	left and right turn lanes on major legs	left and right turn lanes on all legs	2.0	1.0	1.0	______
Approach Sight Distance	> 700'	500-700'	300-500'	200-300'	< 200'	2.0	1.8	0.2	______
Grades on Approach Streets	< 3%	3.0 - 3.9%	4.0 - 4.9%	5.0 - 6.9%	7% or more	3.2	2.8	0.4	______
Curvature on Approach Legs	< 3.0°	3.0 - 6.0°	6.1 - 8.0°	8.1 - 10.0°	> 10°	13.0	5.0	8.0	______
Parking in Vicinity	prohibited both sides	loading zones only	off-peak only	permitted one side only	permitted both sides	0.2	0.1	0.1	______
							Geometric Total		______
Operational Factors									
Operating Speed on Approach Legs	25 mph or less	30 mph	35 mph	40 mph	45 mph or greater	1.0	0.2	0.8	______
Type of Control	all phases signalized (incl. turn lane)	left turn lane signal control	through traffic signal control only	4-way stop control	stop control to minor legs or no control	3.0	2.7	0.3	______
Channelization	left and right signal control	left and right turn lane signal control on major legs	left turn lane signal control on all legs	left turn lane signal control on major legs	no turn lane control	3.0	2.0	1.0	______
Level of Service (Load Factor)	A 0.0	B 0-0.1	C 0.1 - 0.3	D 0.3 - 0.7	E 0.7 - 1.0	1.0	0.2	0.8	______
Pedestrian Volume (peds/hr crossing)	very few or none	0-50	50-100	100-200	> 200	1.5	0.5	1.0	______
							Operational Total		______
Environmental Factors									
Percent Adjacent Development	0	0-30%	30-60%	60-90%	100%	0.5	0.3	0.2	______
Predominant Development near Intersection	undeveloped	residential	50% residential 50% industrial or commercial	industrial or commercial	strip industrial or commercial (no circuity)	0.5	0.3	0.2	______
Lighting in Immediate Vicinity	none	0-40%	40-60%	60-80%	essentially continuous	3.0	1.5	1.5	______
Crime Rate	extremely low	lower than city average	city average	higher than city average	extremely high	1.0	0.5	0.5	______
							Environmental Total		______
Accidents									
Ratio of night-to-day Accident Rates	1.0	1.0-1.2	1.2-1.5	1.5-2.0	2.0*	10.0	2.0	8.0	______
							Accident Total		______

*Intersection lighting warranted.

GEOMETRIC TOTAL = ______
OPERATIONAL TOTAL = ______
ENVIRONMENTAL TOTAL = ______
ACCIDENT TOTAL = ______
SUM = ______ POINTS
WARRANTING CONDITION = 75 points

FORM 3

EVALUATION FORM FOR CONTROLLED ACCESS FACILITY
(FREEWAY) LIGHTING

CLASSIFICATION FACTOR	RATING					UNLIT WEIGHT (A)	LIGHTED WEIGHT (B)	DIFF. (A - B)	SCORE [RATING X (A - B)]
	1	2	3	4	5				
Geometric Factors									
Number of Lanes	4		6		≥ 8	1.0	0.8	0.2	______
Lane Width	> 12'	12'	11'	10'	≤ 9'	3.0	2.5	0.5	______
Median Width	> 40'	24-39'	12-23'	4-11'	0-3'	1.0	0.5	0.5	______
Shoulders	10'	8'	6'	4'	0'	1.0	0.5	0.5	______
Slopes	≥ 8:1	6:1	4:1	3:1	2:1	1.0	0.5	0.5	______
Curves	0-1/2°	1/2-1°	1-2°	2-3°	3-4°	13.0	5.0	8.0	______
Grades	< 3%	3 - 3.9%	4 - 4.9%	5 -6.9%	> 7%	3.2	2.8	0.4	______
Interchange Frequency	4 miles	3 miles	2 miles	1 mile	< 1 mile	4.0	1.0	3.0	______
							Geometric Total		______
Operational Factors									
Level of Service (any dark hour)	A	B	C	D	E	6.0	1.0	5.0	______
							Operational Total		______
Environmental Factors									
% Development	0%	25%	50%	75%	100%	3.5	0.5	3.0	______
Offset to Development	200'	150'	100'	50'	< 50'	3.5	0.5	3.0	______
							Environmental Total		______
Accidents									
Ratio of Night-to-Day Accident Rates	1.0	1-1.2	1.2 - 1.5	1.5 - 2.0	2.0*	10.0	2.0	8.0	______
*Continuous lighting warranted.							*Accident Total*		______

GEOMETRIC TOTAL = ______
OPERATIONAL TOTAL = ______
ENVIRONMENTAL TOTAL = ______
ACCIDENT TOTAL = ______
SUM = ______ POINTS
WARRANTING CONDITION = 95 points

FORM 4

EVALUATION FORM FOR INTERCHANGE LIGHTING

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

*Complete lighting warranted.

GEOMETRIC TOTAL = ______
OPERATIONAL TOTAL = ______
ENVIRONMENTAL TOTAL = ______
ACCIDENT TOTAL = ______

SUM = ______ POINTS

COMPLETE LIGHTING WARRANTING CONDITION = 90 points

PARTIAL LIGHTING WARRANTING CONDITION = 60 points the various driver visual information needs that can be satisfied with roadway lighting. These needs are summarized in Table 1. Second, there are one or more identifiable characteristics of the traffic facility that contribute to each of the informational needs listed in Table 1. These characteristics are listed in Table 2.

To achieve an analytical approach to warrants, a quantitative measure of the characteristics listed in Table 2 must be hypothesized. This quantitative measure was formulated as illustrated in Forms 1-4. Note that a rating system of 1 to 5 has been established for each of the characteristics. This permits a numerical rating of each characteristic based on the extent to which the characteristic influences driver informational needs. For example, wide lanes rate low while narrow lanes rate high. Thus, the more critical the characteristic, the higher the rating.

Some of the characteristics have a greater effect on driver information needs than do others. This is taken care of by weighing each of the characteristics for lighted and unlighted conditions. For example, compare "Number of Lanes" and

TABLE 1

VISUAL INFORMATION NEEDS TO BE SATISFIED BY FIXED ROADWAY LIGHTING

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

TABLE 2

TRAFFIC FACILITY CHARACTERISTICS PRODUCING OR CONTRIBUTING TO VISUAL INFORMATION NEEDS

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

"Curves" under GEOMETRIC FACTORS. "No. of Lanes" has a Lighted Weight of 0.8 and an Unlighted Weight of 1.0, giving a difference of 0.2. On the other hand, "Curves" have 5.0 and 13.0, respectively, giving a difference of 8.0. This means that information relative to curves is far more important than information relative to the number of lanes. Now, if we multiply the rating of a characteristic times the difference in its lighted and unlighted weight, we have a quantitative measure of the effect of that characteristic on driver visual information needs. Similarly, if we rate all characteristics listed in Form 1 under GEOMETRIC, OPERATIONAL, ENVIRONMENTAL FACTORS, and ACCIDENTS, and multiply these ratings times the corresponding differences in Lighted and Unlighted Weights, then the sum of all of these products would be the quantitative measure of driver visual information needs for the roadway under question.

To have a warranting procedure, there must be a method of identifying the numerical level of the quantitative measure where lighting would be justified. It will be noted in each of Forms 1, 2, 3, and 4 there is an established minimum WARRANTING CONDITION of a given number of points. The exact number of points for each of the four types of facilities was determined by assuming a rating of 3 for each of the characteristics and calculating a total number of points. It was felt that the rating of 3 represented average conditions. It should be emphasized that the Minimum Warranting Condition as established herein is not firm, but simply a starting point. One major advantage of this system is that it is flexible and it does permit modifications to fit local needs and requirements. Any agency can be more liberal by lowering the number of points, or it can be more conservative by raising the number of points required.

Taking information for a typical facility (Table 3) and using the appropriate evaluation form, as shown in Form 1 (example), which typifies the roadway facility, choose the correct response for each factor as shown. For each factor, take the rating number (x) at the top of the column and multiply it by the difference between unlit weight (A) and lighted weight (B) giving Score Rating x(A-B). Write this in the blank provided. This rating number scales the various geometric, operational, and environmental factors, along with accidents, from 1-5. One (1) represents least severe conditions while five (5) represents greatest severity. Sum all of the geometric factors, operational factors, environmental factors, and accidents. If this number is larger than the warranting condition, continuous lighting is warranted. Caution must be taken in choosing the proper evaluation form, depending on roadway classification (i.e., non-controlled access, intersection, controlled access, interchange, etc.). The weighted factors may also require adjustment to suitably fit each engineer's needs.

Informational Needs Approach to Warrants

Walton and Messer developed an analytical model for evaluating fixed roadway lighting needs. A complete treatment of this proposed approach to warrants is published in Transportation Research Record No. 502 (4). The approach used to warrant fixed roadway lighting is based on the driver's information needs to perform his or her driving task on the facility in question within the driving environment present. From this viewpoint, fixed lighting is warranted along a section of roadway or at interchanges or intersections when the information demand exceeds the information supply without fixed roadway lighting.

The information demand is the time required to fulfill the sequence of positional, situational, navigational, and redundant positional information searches. Demand is given as the equation:

$$D = \Sigma(P_i + S_i + N_i + P_{i+1})$$

285-027 O - 79 - 3

EXAMPLE FORM 1

EVALUATION FORM FOR NON-CONTROLLED ACCESS FACILITY LIGHTING

CLASSIFICATION FACTOR	RATING 1	2	3	4	5	UNLIT WEIGHT (A)	LIGHTED WEIGHT (B)	DIFF. (A - B)	SCORE [RATING X (A - B)]
Geometric Factors									
No. of lanes	4 or less	--	6	--	8 or more	1.0	0.8	0.2	0.2
Lane Width	> 12'	12'	11'	10'	< 10'	3.0	2.5	0.5	1.0
Median Openings Per Mile	< 4.0 or one-way operation	4.0 - 8.0	8.1 - 12.0	12.0 - 15.0	> 15.0 or no access control	5.0	3.0	2.0	8.0
Curb Cuts	< 10%	10-20%	20-30%	30-40%	> 40%	5.0	3.0	2.0	10.0
Curves	< 3.0°	3.1 - 6.0°	6.1 - 8.0°	8.1 - 10.0°	> 10°	13.0	5.0	8.0	8.0
Grades	< 3%	3.0 - 3.9%	4.0 - 4.9%	5.0 - 6.9%	7% or more	3.2	2.8	0.4	0.4
Sight Distance	> 700'	500 - 700'	300 - 500'	200 - 300'	< 200'	2.0	1.8	0.2	0.2
Parking	prohibited both sides	loading zones only	off-peak only	permitted one side	permitted both sides	0.2	0.1	0.1	0.1
							Geometric Total		27.9
Operational Factors									
Signals	all major intersections signalized	substantial majority of intersections signalized	most major intersections signalized	about half the intersections signalized	frequent non-signalized intersections	3.0	2.8	0.2	0.8
Left Turn Lane	all major intersections or one-way operation	substantial majority of intersections	most major intersections	about half the major intersections	infrequent turn bays or undivided streets	5.0	4.0	1.0	4.0
Median Width	30'	20 - 30'	10 - 20'	4 - 10'	0 - 4'	1.0	0.5	0.5	1.0
Operating Speed	25 or less	30	35	40	45 or greater	1.0	0.2	0.8	4.0
Pedestrian Traffic at Night (peds/mi)	very few or none	0 - 50	50 - 100	100 - 200	> 200	1.5	0.5	1.0	3.0
							Operational Total		12.8
Environmental Factors									
% Development	0	0 - 30%	30 - 60%	60 - 90%	100%	0.5	0.3	0.2	1.0
Predominant Type Development	undeveloped or back-up design	residential	half residential &/or commercial	industrial or commercial	strip industrial or commercial	0.5	0.3	0.2	1.0
Setback Distance	> 200'	150 - 200'	100 - 150'	50 - 100'	< 50	0.5	0.3	0.2	0.6
Advertising or Area Lighting	none	0 - 40%	40 - 60%	60 - 80%	essentially continuous	3.0	1.0	2.0	10.0
Raised Curb Median	none	continuous	at all intersections	at signalized intersections	a few locations	1.0	0.5	0.5	1.0
Crime Rate	extremely low	lower than city average	city average	higher than city average	extremely high	1.0	0.5	0.5	1.0
							Environmental Total		14.6
Accidents									
Ratio of Night-to-Day Accident Rates	< 1.0	1.0 - 1.2	1.2 - 1.5	1.5 - 2.0	2.0*	10.0	2.0	8.0	32.0
*Continuous lighting warranted.							Accident Total		32.0

GEOMETRIC TOTAL = ________

OPERATIONAL TOTAL = ________

ENVIRONMENTAL TOTAL = ________

ACCIDENT TOTAL = ________

SUM = ________ POINTS

WARRANTING CONDITION = 85 points

TABLE 3
EXAMPLE
INFORMATION FOR EVALUATION FORM

(1)	Facility location: Dallas, Harry Hines Blvd.
(2)	Facility type: Divided arterial
(3)	Road length: 1 mile
(4)	Road width(s): 72'
(5)	Number of lanes (n): 4 - 12'
(6)	Affected lane-miles (L): 4
(7)	Design average daily traffic: 32,000
(8)	Design night average daily traffic (ADT_n): 8,000
(9)	Median openings per mile: 14.0
(10)	Curb cuts: 74%
(11)	Grades: 23%
(12)	Sight distance: 700'
(13)	No parking
(14)	One-half of intersections signalized
(15)	One-half of intersections have left turn bays with a volume of 6400 vph
(16)	Speed: 45 mph
(17)	Pedestrians per mile: 75
(18)	100% developed commercial - 150' setback
(19)	Continuous advertising lighting
(20)	Continuous raised curb median
(21)	Average degree of horizontal curves: 2.75
(22)	Low crime rate
(23)	1.5 accidents (night/day)

where:

- D = information demand in seconds on a section of roadway,
- P_i = time required to obtain positional information on cycle i,
- S_i = time required to obtain situational information on cycle i,
- N_i = time required to obtain navigational information on cycle i,
- P_{i+1} = next required positional information search update on cycle i+1, which must be achieved within the section of roadway visible during P_i.

The positional information supply, C, depends on the suitability of the night driving environment without fixed roadway lighting. This factor is computed considering visibility distance, headlight condition (low, high), glare sources, degree of curvature, oncoming vehicle spacing, and traffic volume. To check a section of roadway to determine if fixed roadway lighting is warranted, the information index, I, is given by the following relationship:

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

Fixed roadway lighting is warranted if the information index, I, is greater than 1. The reader is referred to the TRB report for application of the method. It is probably the most objective method available for establishing warrants.

Warrants for Rural Intersection Lighting

Wortman and others at the University of Illinois (5) conducted a research project in cooperation with the Illinois Department of Transportation to develop factual warrants for rural intersection lighting. Based on the research, Wortman, et al., suggested several new warranting statements.

Rural intersections should be considered for lighting if the average number of night-time accidents (N) per year exceeds the average number of day (D) accidents per year divided by three. All the accident data available since the date of the last modification to the intersection should be used when calculating these averages. If N is greater than D/3, the likely average benefit should be taken as N - D/3 accidents/year.

The likely benefits of lighting new or modified intersections should be estimated from previous experience. It is recommended that illumination should be provided whenever an intersection is channelized.

The estimated cost of lighting the intersections, which shows a benefit using the above criteria, should be computed. The lighting program should then be based on the resulting list of intersections ranked in priority order by means of the benefit/cost ratio (expressed as annual reduction in accidents/annual cost).

The lighting program should be reviewed at intervals as additional accident data becomes available.

The recommended warrant was designed to give the decision-makers the most information possible based on current knowledge. It has been implicitly assumed that the highway improvement budget will be limited and thus interest will be focused on maximizing the benefits of a limited budget. For this reason, reductions in number of accidents rather than accident rates have been used. One important implication of this approach is that the distribution of funds for lighting improvement will tend to be directed into the areas of high traffic volumes. Thus, if intersections are ranked on a statewide listing, the distribution of the budget will not be the same as one distributed by listing intersections on a district basis. The latter would spread improvements more uniformly throughout the state, but at a lower overall benefit/cost ratio.

As more data becomes available, it is likely that the predictor used in the warrant can be refined.

It is anticipated that the overall warrant philosophy will continue to be useful in the decision-making process, particularly as the benefits of lighting become more accurately measurable and hence the predictor is improved.

Warrants for Application of Specialized Crosswalk Illumination

M. Freedman and others, in performing a research study for the Federal Highway Administration, developed a comprehensive set of warrants for the application of specialized crosswalk illumination at high problem areas (6). The warrants were established in accordance with the concept that the distinctive color of illumination of the specially designed system will serve as a visual clue to drivers and pedestrians that a hazardous area is ahead. The warrants should not be confused with the general IES or AASHTO warrants for typical sidewalks. Freedman, et al., took into consideration vehicle and pedestrian volumes, accidents, adverse geometry and environmental conditions, photometric conditions, and pedestrian behavior in establishing the special warrants. Warranting statements are extracted from the referenced research report in the paragraphs that follow.

Volume Warrant

Special crosswalk illumination shall be warranted if the following minimum average of at least three nights of traffic counts of pedestrians and vehicular volumes are present during the nighttime period of 10-hour duration from the beginning of darkness until dawn, on nights representative of normal traffic patterns, according to the area-roadway classifications in Table 4.

The pedestrian and vehicular traffic volumes shown in Table 4 for each roadway-area classification were derived through experience in data collection (traffic counts and pedestrian observations), pedestrian accident reports, and benefit-cost analysis. The actual volumes shown in the table are the minimum average volumes, rounded to the nearest 100 vehicles and nearest 50 pedestrians, of the accident sites that were both evaluated in a study of pedestrian accidents in Philadelphia, and visited during the observational experiments. Theoretically, the minimum warranting volumes should be those that result in a benefit-cost ratio of exactly 1.0, assuming that accident production is related to volume and environment in a predictable way. In actuality, the lowest benefit-cost ratio calculated for the observed sites, based upon a 33% accident reduction potential, was 2.32/1. However, in the interest of conservatism in predicting accident reduction potential, and to prevent the initiative to install special crosswalk illumination solely on the basis of traffic volumes, the tabular values are suggested for the minimum warranting volume conditions. This warrant applies when it is determined that conventional illumination systems designed to provide the crosswalk illumination levels recommended by IES will not reduce pedestrian accident potential. This determination should be made by comparing environmental and traffic conditions at other sites which have been improved to the illumination levels recommended by IES, to the site under consideration for special crosswalk illumination, and relating this comparison to the accident reduction experienced at those other sites. A measure that is useful for comparison is the difference between the ratio of night-to-day accidents both before and after the improvement to IES recommendations at those other sites. However, engineering judgment must be used to relate the differences between improved sites and the site under consideration to the accident reduction potential, because neither IES nor other sources have reported the effect of the recommended conventional lighting improvement on pedestrian safety.

TABLE 4

WARRANTING CONDITIONS ACCORDING TO VOLUME

AREA		ROADWAY CLASSIFICATION		
		MAJOR ARTERIAL	COLLECTOR DISTRIBUTOR	LOCAL
	CBD (COMMERCIAL)	*	500 veh/night 100 ped/night	200 veh/night 50 ped/night
	FRINGE (INTERMEDIATE)	1000 veh/night 100 ped/night	500 veh/night 100 ped/night	200 veh/night 50 ped/night
	OBD (INTERMED-COMM)	1000 veh/night 100 ped/night	500 veh/night 100 ped/night	200 veh/night 50 ped/night
	RESIDENTIAL	1000 veh/night 50 ped/night	500 veh/night 50 ped/night	200 veh/night 50 ped/night

Pedestrian volume is defined as the total volume of pedestrians crossing the roadway in the subject crosswalk during the ten (10) hour period for all area classifications except residential. For residential areas, the pedestrian volume may be taken as the total number of pedestrians crossing in all crosswalks which traverse the roadway in the direction of the subject crosswalk. Vehicular volume during the time period is the total number of vehicles which pass across the subject crosswalk, by either through or turning movements. Measurement of the subject pedestrian and vehicular volumes should be avoided during periods of atypical activity, such as Christmas shopping season in the CBD.

Special attention is recommended for locations at which pedestrian traffic is not uniform throughout the evening. Where this traffic is frequently heavy (at least 10 times each night for short periods of time in which arriving pedestrians are platooned), at such locations as major transit stops, schools, hospitals, and large industrial operations, crosswalk illumination shall be warranted if the sum of the volumes recorded for the peak five minutes of five separate platooned arrivals is equal to the warranting volumes shown in Table 4.

For locations at which heavy pedestrian activity exists for a single period of short duration each night (e.g., early evening in summer) or is highly seasonal, permanently installed special crosswalk illumination is not warranted.

Accident Warrant

Special crosswalk illumination shall be warranted provided a study of four consecutive years of nighttime accidents indicates a minimum of three (3) pedestrian accidents in the subject crosswalk which may be partially or wholly attributed to poor visibility of the pedestrian and which condition can be remedied by illumination.

To determine whether or not pedestrian accidents may be attributed to visibility factors that may be remedied by crosswalk illumination, the engineer should make a complete investigation of several sources of information. They are:

A. Accident Records and/or Interviews with Victims
   - Did accidents occur at night?
   - Were drivers able to see the pedestrians?
   - Were drivers aware of the presence of the crosswalks?
   - Was glare produced by other vehicles a factor?
   - Would the provision of increased reaction time have prevented the accidents?
   - Was driver fatigue a factor?
   - Was the pedestrian distracted by environmental stimuli?
   - Was the pedestrian attentive to vehicular traffic and signal indications?

B. Accident Site Visit
   - Do physical obstructions exist which block the view of drivers?
   - Do background glare sources exist which may affect the driver?

C. Observations of Random Pedestrian Crossings (Minimum of 100 per accident crosswalk over a period of at least 3 nights)
   - Record total volume of vehicles traversing the crosswalk
   - Record total volume of pedestrians using the crosswalk(s)
   - Record the frequency of pedestrians exhibiting behavioral characteristics discussed under Pedestrian Behavior Warrant. If the frequency of occurrence of any one of these characteristics is found to be 5% of the total, then a visibility-behavior deficiency will be established.

Although the benefit-cost ratio of reduction in annual accident costs to illumination cost is greater than 1 for a reduction of 33% at an intersection with only one accident in four years, it is reasonable to require a four-year history of at least three accidents to ensure that the pattern of accidents suggests inadequate visibility due to poor lighting. However, if it is obvious after only one accident (or none) that a lighting-visibility problem exists, and would continue to exist at illumination levels recommended by IES for crosswalks, crosswalk illumination shall be warranted.

Adverse Geometry and Environment Warrant

Special crosswalk illumination shall be warranted when roadway geometry, local structures, and/or environmental conditions such as the prevalence of fog, etc., cause reduced pedestrian visibility in the presence of conventional intersection illumination which may be improved by the application of special crosswalk illumination.

Such illumination shall be warranted if the visibility of pedestrians by approaching motorists is limited by adverse geometry, local structures, or environmental conditions to the extent that pedestrians cannot be seen until within the normal safe stopping distance to the crosswalk.* Such reductions in visibility may be the result of horizontal or vertical curvature, or the presence of physical obstructions in the motorist's field of view of the portions of the crosswalk. Further, special crosswalk illumination shall be warranted in locations where it is determined that the presence of background and/or surrounding lighting for advertisement, etc., will distract the motorist so that the effect of conventional illumination is negated.

Special attention should be given to this warrant for proposed installations in CBD and OBD areas because of the relatively high frequency of sites in which such adverse geometry and environment exist.

Pedestrian Behavior Warrant

Special crosswalk illumination shall be warranted when it is determined that a minimum proportion equal to 5% of observed pedestrians using the subject crosswalk are demonstrating inadequate search and detection behavior, show dangerous distraction to surrounding stimuli, or demonstrate erratic or inappropriate crossing behavior as discussed in the ACCIDENT WARRANT, and the VOLUME WARRANT is satisfied to 2/3 of the prescribed level. It is recommended that the behavioral characteristics shown below be conducted as prescribed in the ACCIDENT WARRANT.

- Did the pedestrian cross the street outside of the crosswalk, but within 25 feet of the crosswalk, during any portion of the crossing?
- Was the direction of travel of the pedestrian approach (prior to entering) the crosswalk from any direction other than parallel to the crosswalk (did he turn into the crosswalk?)?
- Was the direction of travel of the pedestrian exiting the crosswalk toward any direction other than parallel to the crosswalk?
- Was pedestrian attention directed other than toward vehicular traffic or traffic signals...
  - in his approach to the crosswalk?
  - in the first half of the crossing?
  - in the second half of the crossing?
- Was the pedestrian motivated to hurry the crossing or run in the crossing for a bus, taxi cab, etc.?

Combined Warrant

Special crosswalk illumination may be warranted if any two of the above warrants are met to 2/3 of the prescribed levels, or responsible traffic engineering and illumination engineering judgment along with local government concurrence indicates the advisability and desirability of such special crosswalk illumination.

A special concept for lighting these type facilities has been developed (6).

*Safe stopping distance to the crosswalk is defined by the formula:

$$Sd = 1.47\,Vt + \frac{V^2}{30\,(f \pm g)}$$

V = velocity in miles per hour
f = coefficient of friction
g = the percent grade divided by 100
t = the perception-reaction time in seconds

APPLICATION OF WARRANTING PROCEDURES

The effective application of a warrant procedure involves the collection of field data for each roadway facility under consideration for lighting. The design engineer utilizes this data as an aid in making decisions. The data obtained in the field eliminates points of guesswork involved in design and/or decision-making.

The field investigation serves a multi-purpose function:

- To develop further driver visual information needs, especially as related to characteristics of specific traffic facilities;
- To validate the traffic facility function;
- To determine subjective comfort benefits of roadway lighting;
- To provide information for warranting conditions and priorities for roadway lighting; and
- To provide information on design guidelines.

It is recommended that the designer develop a checklist and possibly a numerical rating system such as that discussed in NCHRP Report No. 152 for assigning priorities to lighting jobs within his city or area of jurisdiction. At least the following should be included in an evaluation checklist:

A. Description of Roadway or Street
  - Kind of facility
  - Number of lanes and lane width
  - Median type and width
  - Curb type and degree of access
  - Pavement surface type
  - Geometric features (curves, grades, etc.)

B. Traffic Conditions
  - Night traffic volumes
  - Speeds (85 percentile, 15 percentile)
  - Percent of entering and exiting traffic

C. Environmental Conditions
  - Type of lane use (commercial, residential, and subcategories of each that relate to street use)
  - Extent of commercial lighting, including signs, area lighting, novelty lighting, and degree of animation
  - Pedestrian generation potential
  - Traffic generation potential
  - Possible influences of driver condition, principally in regard to alcholoic consumption

D. Accident Conditions
  - Accident rates (night vs. day)
  - Accidents by type
  - Actual or potential pedestrian activity

ESTABLISHING PRIORITIES FOR LIGHTING PROJECTS

The decision-maker, who allocates funds to various competing lighting projects, needs a rational approach to use in allocating funds to maximize benefits to motorists. One such approach is to compute an equivalent priority index, P_x, for any warranting lighting project, X, and to compare it to all other competing projects. If all competing priority indices were ranked in order from highest to lowest, then selections would be made from the top until either all available funds were spent or some minimum acceptable priority spending level was reached based on historical needs. One such procedure is an extension of the warranting method based on driver information needs by Walton and Messer. The formula for calculating the priority index is as follows:

$$P_x = \frac{\sum_{i=1}^{D} I_i Q_i d_i}{C_i}$$

where:

P_x = priority index of warranted lighting project X
I = information index of roadway section i
d = length of roadway section i
Q = ADT on roadway section i
D = number of sections warranted on roadway
C = present cost of lighting operation, and maintaining the complete project

A complete description of this process is given in TRB Record No. 502 (4). Another recommended technique for calculating priority index is given in NCHRP Report No. 152 (2). The formula for priority index is:

$$P_x = \frac{E \times \frac{NADT}{n} \times L \times \frac{F}{W}}{AC}$$

where:

P_x = priority index
E = calculated lighting effectiveness (total warranting points)
NADT = design night average daily traffic (.25 x ADT)
n = number of lanes
L = affected lane miles
F = actual design level of average illumination (fc)
W = warranted design level of average illumination (fc)
AC = annual cost

Neither of these priority index ratings produce absolute conclusions. Many times, other factors are considered in precedence of a cost-effectiveness analysis. Source of funding may dictate priority guidelines based upon traffic facility classification. The environmental ramifications of a lighting project may create a shift in priority.

The utility of energy conservation should be incorporated into any and all priority calculations. Above all, the lighting project must be politically acceptable to the governing authority and populace.

For an example of Priority Index usage, we will compare two different configurations that have been considered for a lighting project. The following information is given:

	Configuration 1	Configuration 2
(1) Initial Capital Cost	18000	25000
(2) Equivalent Capital	1570	2180
(3) Maintenance and Power	1760	2500
(4) Subtotal (2 + 3)	3330	4680
(5) Light Pole Accident	770	1080
(6) Total (4 + 5)	4100	5760
(7) Ave. Footcandles Actual (F)	1.2	1.3
(8) Min. Footcandles	.45	.45
(9) Ave/Min Ratio (7)/(8)	2.7:1	2.9:1

along with:

E = total warranting points from the example form used earlier = 87.3
W = warranted illumination level, ave. maintained footcandles calculated =

$$\frac{\text{Total Warranting Points}}{\text{minimum points}} \times$$

Recommended ave. illumination

$$= \frac{87.3}{85} \times 1$$

NADT = night ADT = 8,000 VEH
n = number of lanes = 4
L = affected lane-miles = 4

Using the following equation for Priority Index (P_x):

$$P_x = \frac{E \times \frac{NADT}{n} \times L \times \frac{F}{W}}{AC}$$

a priority index can be found for each configuration. The one with the largest priority index (P_x) should be considered for installation.

Thus:

$$P_1 = \frac{(87.3)\left(\frac{8000}{4}\right)(4)\left(\frac{1.2}{1}\right)}{4100} = 204$$

$$P_2 = \frac{(87.3)\left(\frac{8000}{4}\right)(4)\left(\frac{1.3}{1}\right)}{5760} = 158$$

P_1 should be considered before P_2. The same procedure may be used for determining the priorities of two separate lighting projects.

Complete details of this procedure is given in NCHRP Report No. 152 by Walton and Rowan (2).

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5. Wortman, R., Warrants for Rural Intersection Lighting, Final Report for Illinois Department of Transportation, University of Illinois, Urbana, Illinois, 1973.

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4

SELECTING LIGHTING EQUIPMENT

SELECTING LIGHTING EQUIPMENT

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

If a lighting system is to serve its intended purpose efficiently and economically, it is very important that the proper equipment be selected and applied correctly. Thus, it is important that the designer be knowledgeable of the fundamental characteristics of lighting equipment and that he be familiar with current hardware and developments within the industry. This chapter will introduce the fundamental equipment characteristics to the reader. To obtain up-to-date product information, the designer should maintain contact with the major lighting equipment manufacturers and/or their product line representatives.

"Lighting Equipment" covers a wide range of items from lamps to luminaires to structural supports. This chapter will describe the major components which make up a lighting system, along with an introduction to the photometric performance and how this performance is described in the photometric test report. The electrical supply system is covered in Chapter 7.

Lighting equipment, for presentation purposes in this book, is divided into four basic elements:

- Light Sources
- Luminaires and Ballasts
- Photometric Data
- Support Hardware

LIGHT SOURCES

The most important element of the illumination system is the light source. It is the principal determinant of the visual quality, economy, efficiency, and energy conservation aspects of the illumination system. Although there are many types of light sources available, major emphasis will be placed on the characteristics of those sources that are currently used for public lighting.

An electric light source is a device which transforms electrical energy, or power (watts), into visible electromagnetic radiation, or light (lumens). The rate of converting electrical energy into visible energy is called "luminous efficacy" and is measured in lumens per watt.

There are two general types of electrical light sources--filament lamps and arc-discharge lamps. Filament lamps include incandescent, tungsten-halogen, and photo-lamps; arc discharge lamps include fluorescent, high intensity discharge (H.I.D.), Xenon, carbon-arc, and other flame-arc lamps. To stay within the scope of this handbook, we will discuss the incandescent and the tungsten-halogen (also known as quartz-iodine) lamps as well as the fluorescent and the H.I.D. lamps. The H.I.D. family is composed of the mercury vapor, the metal halide, the high pressure sodium, and, with some constraints, the low pressure sodium lamps.

Prior to the development of the gaseous discharge lamps, almost all street lighting was done with incandescent lamps. During the past twenty or thirty years, however, a gradual change from this lamp to the discharge type has taken place. Because of ever-increasing power costs and the concern to preserve our energy resources, the trend to these more efficient H.I.D. sources is becoming more and more visible.

Incandescent Lamps

The first major step in the modern technology of illumination was the development of the incandescent lamp. The replacement of the flame type lamp came with the widespread use of electrical energy. Electrical energy provided not only a more efficient light source, but a better method of light control which resulted in many improvements in the visual environment

The incandescent lamp is probably the widest known and most commonly used light source available to us today. Its uses for roadway illumination today is limited to a small percentage of minor roads in the highway network and it is being phased out. Its major parts are the filament, the bulb, the gas fill, and the base (see Figure 3). Light is produced when an electric current of sufficient magnitude passes through the filament and heats it to incandescence. This filament is an electrical resistance element (usually tungsten wire) enclosed in a sealed glass envelope called the bulb. Evaporation of the filament is reduced by operating it in an atmosphere of inert gas, such as nitrogen, or krypton, which also acts as a thermal barrier allowing higher filament operating temperatures than possible in a vacuum. Luminous efficacies of incandescent lamps are between 15 and 25 lumens per watt; in general, the efficacy increases with higher filament operating temperatures and larger wattage lamps. However, an increase in filament temperature and higher luminous efficacy normally results in a somewhat shorter lamp life.

The base is a fabricated metal shell which provides a means of connecting the lamp bulb to the socket. The base is electrically connected to the filament and mechanically attached to the glass envelope.

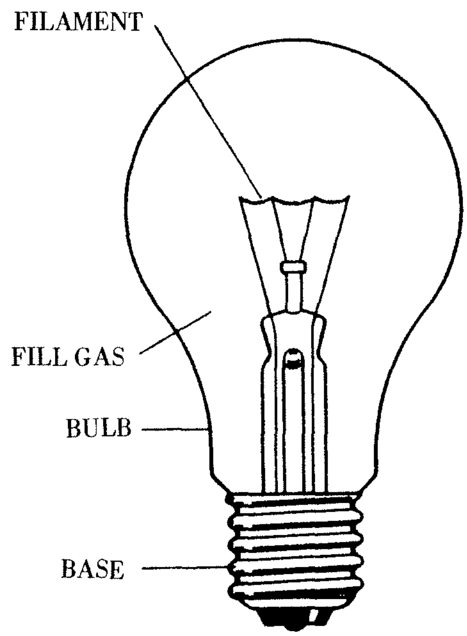

Figure 3. Typical construction of an incandescent lamp.

Tungsten-Halogen Lamps

Tungsten-halogen lamps operate on a principle similar to the incandescent lamps; however, they use a special quartz tubular envelope, are much smaller sized than standard incandescent lamps of the same wattage, and have a halogen (i.e., iodine, fluorine, bromine) added to the standard fill gas.

The quartz envelope is the basis for many advantages over conventional filament lamps. It provides compactness, thermal shock resistance, higher luminous efficacy, and almost perfect maintained light output throughout life. The halogen in the lamp supplies the means for this lamp, along with the high bulb temperature, to work on the principle of a halogen regenerative cycle, which prevents bulb blackening due to evaporated tungsten from the filament.

The principal use of the tungsten-halogen lamp in the context of this handbook is in floodlighting. Its basic construction and parts are shown in Figure 4.

Discharge Lamps

Unlike the filament lamp where light is produced when a wire is headed to incandescence, radiation from an arc- or gas-discharge lamp is produced by the excitation of gas or metal vapors in a lamp or arc-tube. When an electrical potential is applied to the electrodes, the gas in the lamp becomes ionized and starts a current flow between the electrodes. The electrons making up this current or "arc-discharge" transverse through the lamp or arc-tube at tremendous speeds and, when colliding with the atoms of the gas or the metal vapor, momentarily alter the structure of these atoms. When the disturbed atoms return to their normal state, energy is released and, depending on the gas or metal used and the operating conditions of the lamp (internal pressure, temperature, etc.) the energy released is characteristic of the type lamp observed. Fluorescent lamps release mostly ultraviolet (black light) and blue radiation, if no phosphor coating is applied to the bulb. Mercury lamps emit much of their energy in the blue, green, and yellow wavelengths. Sodium lamps radiate most of their energy around the yellow portion of the spectrum.

Since electric discharge lamps exhibit negative resistance characteristics, they require a current limiting device, called a ballast, in their operation. Ballasts are discussed later in this chapter.

Fluorescent Lamps. The fluorescent lamp is an electric discharge source in which light is produced predominantly by fluorescent powders activated by ultraviolet energy generated by a mercury arc. The lamp, usually in the form of a long, tubular bulb with an electrode sealed into each end, contains mercury vapor at low pressure with a small amount of inert gas, principally argon, for starting. The inner walls of the bulb are coated with fluorescent powders, commonly called phosphors. When the proper voltage is applied, an arc is produced by current flowing between the electrodes through the mercury vapor. This discharge generates some visible radiation, or light, but mostly invisible ultraviolet radiation. The ultraviolet radiation in turn activates the phosphors to emit light.

Like most electric discharge lamps, fluorescent lamps must be operated in series with a current regulating device (ballast). The ballast assures that the current flow into each lamp is in accordance

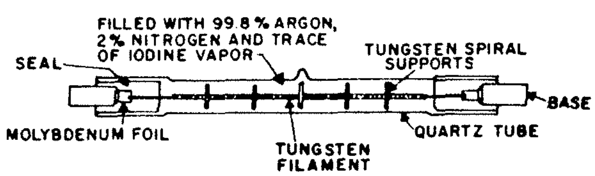

Figure 4. Typical construction of tungsten-halogen lamp.

with manufacturer's design recommendations. It also provides the required starting and operating lamp voltages.

Fluorescent lamps used for roadway lighting are normally 48", 72", or 96" long. Practically all outdoor installations use the higher loaded 800 milliampere (ma) or 1500 ma "High-Output" types. Several are often mounted in one luminaire to achieve a reasonable level of light output or "lumen-package."

Certain inherent characteristics of fluorescent lamps limit or restrict their use for highway lighting. First of all, fluorescent lamps have a relatively large area from which light is radiated. Since the light emitted from such a large source is difficult to control, fluorescent lighting is best suited for floodlighting large areas. The large lamp size requires bulky and heavy luminaires, which often adds to the structural requirements of the pole and mast arms. Also, since the light output of fluorescent lamps is quite susceptible to temperature variations, restrictions are placed on their application in areas where wide variations are encountered.

Figure 5 shows the construction of a typical fluorescent lamp.

Mercury Vapor Lamps. The mercury vapor lamp was invented in the 1930's and with development through the years has become the most widely used street lighting source. The principle of operation of the mercury lamp is typical of all gaseous discharge lamps. The characteristics of the gaseous medium and the operating parameters determine the color of the light and lamp efficacy. Mercury vapor lamps utilize higher arc tube pressures and temperatures than fluorescent lamps.

Most mercury lamps are constructed with two envelopes, an inner envelope (arc tube) which contains the gaseous medium and the electrodes, and an outer envelope which shields the arc tube from outside drafts and changes in temperature. The outer envelope usually contains nitrogen which prevents oxidation of internal parts. The essential construction details shown in Figure 6 are typical of a lamp with fused quartz arc tube within an outer envelope.

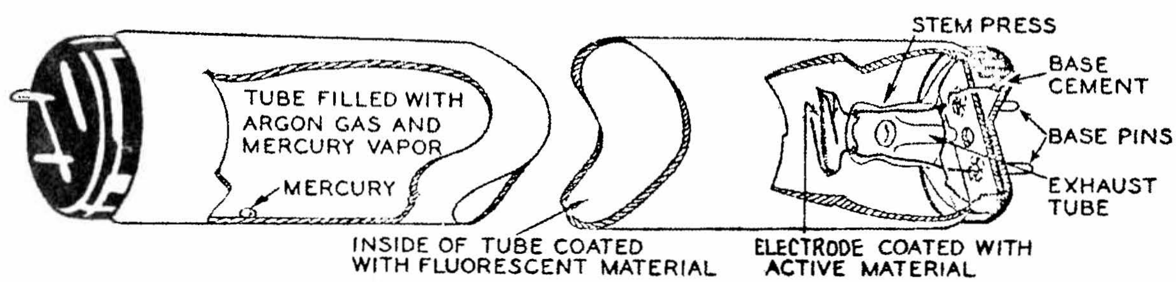

Figure 5. Typical fluorescent lamp construction.

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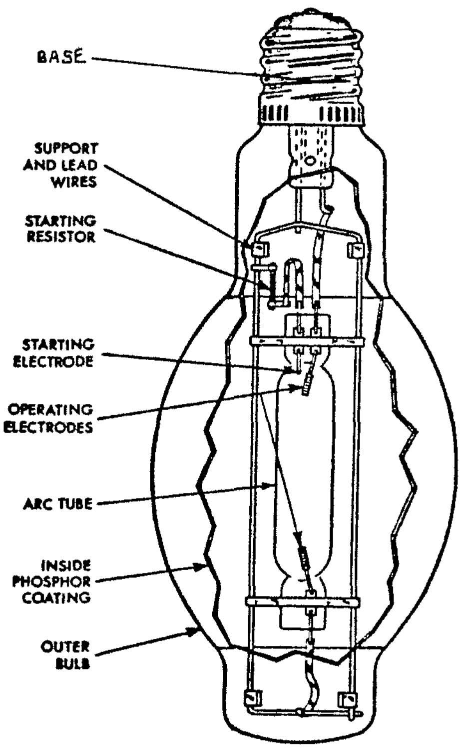

Figure 6. Construction details of the mercury vapor lamp.

The most common form of mercury lamp in roadway lighting is the type using a clear bulb. It produces light at efficacies of 50-65 lumens per watt. While the light source itself appears to be bluish-white, there is an absence of red radiation, and most colored objects appear distorted in color rendition. Blue, green, and yellow colors in objects are emphasized; orange and red colors appear brownish.

This poor color rendition led to the development of mercury lamps with a phosphor coating applied to the inside wall of the outer bulb. Depending on the particular phosphors used, color rendition can be greatly improved and luminous efficacies may be increased somewhat. The phosphors convert the ultraviolet radiation emitted by the arc tube to visible light of selected wavelengths.

Since the phosphor-coated lamp is a larger light source than the clear lamp, the light emitted by it is more difficult to optically control than light emitted by the clear lamp. For roadway lighting where a high degree of optical control is desirable and good color rendition is of secondary importance, clear lamps are normally used. In urban street lighting and area lighting where color is more important and optical control can be somewhat sacrificed, color-corrected lamps are widely used.

Metal Halide Lamps. Metal halide lamps were introduced in the 1960's. Through a combination of metallic vapors in the arc tube, they provide better color with higher efficacies (up to 125 lumens per watt) than mercury lamps. Additives to mercury and argon gas in the arc tube are generally iodide compounds of metals such as sodium, indium, scandium, or thallium.

In general, metal halide lamps are similar in construction to mercury lamps, but a close look will reveal several construction features which are different. The arc tubes in metal halide lamps are smaller than those of mercury lamps for equivalent wattage, with a coating or reflector at the ends of the arc tube. Some metal halide lamps include a system for either shorting the starting electrode to the operating electrode or opening the starting electrode circuit. This is required to prevent electrolysis in the fused silica between the starting and operating electrodes, especially when a halide such as sodium iodine is used in the lamp.

The color rendition produced by metal halide lamps is excellent. Earlier designs did exhibit color variations between individual lamps, but this problem appears to have been corrected. The lamp is available in both a clear and coated version; color rendition of the coated lamp is somewhat better than the clear lamp.

Metal halide lamps are commonly used for lighting sports arenas, major sports stadiums, large interchanges (high mast), downtown areas, and parks.

The recent introduction of a special configuration arc tube designed for horizontal lamp operation may make this a well-suited light source for urban street lighting when good color quality and optical control are required.

High Pressure Sodium Lamps. The most recent addition to the discharge lamp family is the high pressure sodium lamp, with efficacies of up to 140 lumens per watt.

In high pressure sodium lamps, light is produced by passing an electric current through sodium vapor. The sodium vapor emission combined with the mercury emission provides a soft, pinkish-yellow light that is generally well accepted by the driving public.

Since sodium vapor is very corrosive, quartz will not stand up to it. The material used for the arc tube in this lamp is polycristalline alumina oxide, a translucent ceramic material capable of withstanding sodium vapor at high temperatures (see Figure 7).

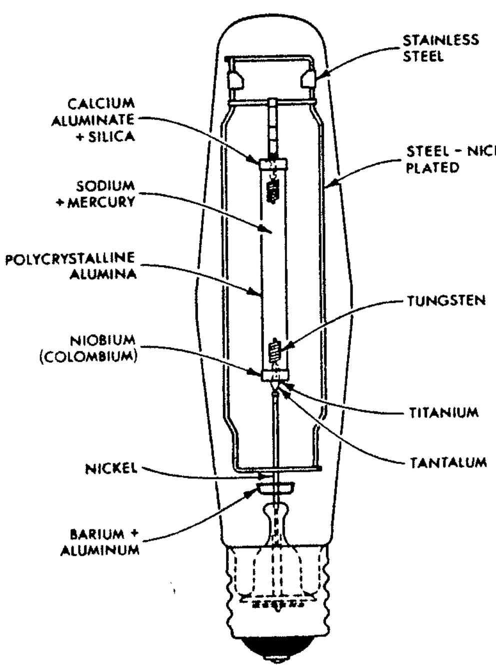

Figure 7. Construction of a typical high pressure sodium lamp.

The arc tube is normally filled with sodium, mercury, and xenon gas. The xenon gas acts as a starting gas and, as the arc tube becomes hotter, the mercury and sodium vaporize and add color to the discharge. Since very little ultraviolet energy is emitted by the high pressure sodium arc, change in color by the addition of a phosphor coating to the outer envelope will not be possible. Diffuse enveloped lamps are available where the distribution characteristics of such lamps are desired.

Since the arc tube of the high pressure sodium lamp has a very small diameter and does not contain a starting electrode, a high voltage low energy pulse is used to ionize the xenon gas. Once the lamp is started, its color will go first through that typical for mercury, then that typical for low pressure sodium. After about 2-3 minutes, when stable operating conditions are reached, the lamp will radiate most of its energy in the green, yellow, and red wavelengths.

To achieve the necessary electrical control for high pressure sodium lamps, special ballasts are required. These ballasts incorporate starting circuits which provide starting pulse voltages in the range of 2250 to 4000 volts. If ballasts for these lamps are mounted remote from the fixtures, care must be taken not to exceed ballast manufacturers' recommended maximum permissible distance between lamp and starter-circuit.

At a slight decrease in lamp efficacy (approximately 25 percent), a second type of high pressure sodium lamp is available which can be retrofitted into conventional roadway luminaires equipped with certain mercury ballasts (reactors or lag-type auto transformers). These lamps do not require the special starting circuit mentioned above.

Low Pressure Sodium Lamps. In low pressure sodium lamps, light is produced by passing electricity through vaporized sodium. It is the most efficient light source available today with a luminous efficacy of up to 183 lumens per watt. The gas used for starting is neon with small additions of argon, xenon, or helium.

Two types of arc tube construction are used in low pressure sodium lamps. In the "U" tube type construction, the arc tube is formed into a hairpin shape with its limbs close together. In the second type, the linear, the arc tube is double ended. Figure 8 shows typical constructions of both the "U" tube and linear tube.

When low pressure lamps are first started, the light output is the characteristic red of the neon discharge and gradually changes to the characteristic yellow as the sodium is vaporized. The warm-up process takes about 10 to 15 minutes. Once the lamp has reached stable operating conditions, the emitted light is monochromatic yellow, resulting in poor color rendition.

Since low pressure sodium lamps are rather large (the 180 watt lamp, for example, is 54" long), optical control is difficult in reasonable sized luminaires, and the coefficient of utilization for roadway lighting is generally lower than that achievable with the mercury, metal halide, or high pressure sodium lamps. This deficiency is similar to that discussed relative to the use of fluorescent lamps.

While all other lamps experience a lumen depreciation over their normal life span, low pressure sodium lamps maintain their light output close to 100 percent of initial. However, power consumption gradually increases during life and, in case of the 180 watt lamp, the energy dissipated at 18000 hours is 241 watts. This fact should be considered when designing an installation using low pressure sodium lamps.

Summary of Light Sources

Each of the light sources discussed has its own unique advantages and disadvantages. These and some of the outdoor applications are summarized here and in Table 5.

Incandescent. The advantages of this lamp are its low initial cost, excellent optical controllability, relatively low fixture cost, good color, "instant-on" characteristic, and no need for a ballast. Its disadvantages are low luminous efficacy and short life. Thus, while a rather poor choice for general roadway lighting, it can be used where its advantages may be utilized, such as, for example, in train-activated spotlighting of rail-highway grade crossings.

Tungsten-Halogen. The advantages and disadvantages of this lamp are similar to those of the incandescent lamp; however, larger lumen packages can be put into a given size lamp. The horizontal optical control is poor, and lamp cost is considerably higher. Principal application is in area floodlighting when initial costs are of primary concern and total operating hours per year are relatively low. They are also often used in conjunction with the H.I.D. lighting systems as emergency lighting providing "instant-on" features.

Fluorescent. Fluorescent lamps have good color characteristics, high luminous efficacies, and long life. Their main disadvantages in outdoor applications are their relatively large size, resulting in poor optical control, and their susceptibility to cold temperatures. Fluorescent street lighting has been successfully used in urban, and especially downtown areas, where high illumination levels were desired and luminaires could be spaced fairly close. With the advent of H.I.D. luminaires, however, fluorescent street lighting has lost many of its advantages. Tunnel and sign lighting, however, are still excellent application areas for fluorescent lighting. Care must be exercised in selecting luminaires having the qualities needed for these applications.

Mercury. The mercury lamp was, during the past 20 or so years, the "workhorse" of street lighting. Its luminous efficacy is quite good, its color is fair to good, its size is small enough to allow good optical control, especially with the clear lamp, and its life is exceptionally long and dependable. It has been used for practically all outdoor applications.

Metal Halide. Metal halide lamps produce better color at higher efficacies than mercury lamps.

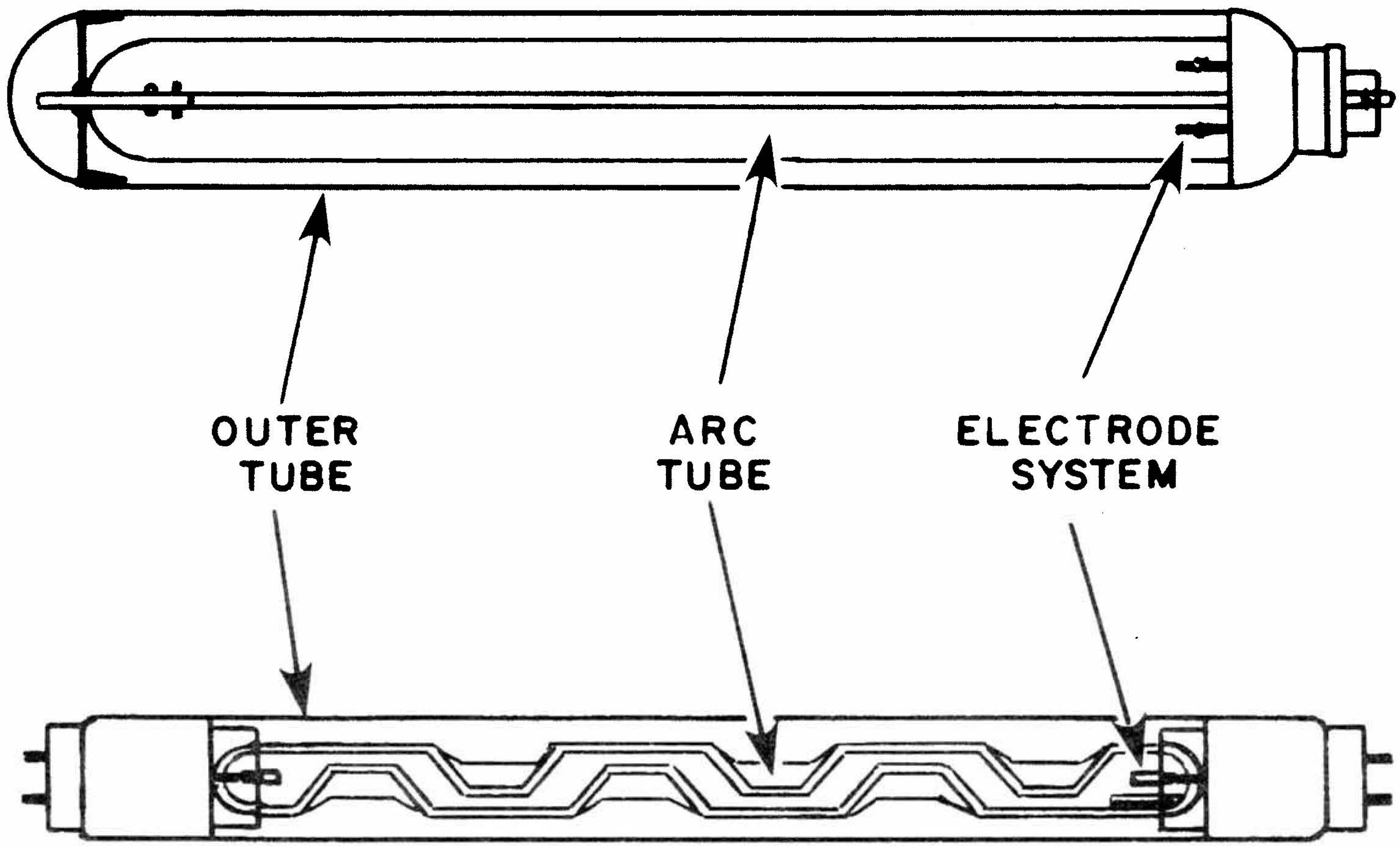

Figure 8. Typical construction of the "U" type (upper) and linear (lower) low pressure sodium lamps.

TABLE 5

TYPICAL AREA AND ROADWAY LIGHTING LAMP CHARACTERISTICS[1]

	Lumens Per Watt								Cost	
	(Includ. Ballast Losses (2.)	Lamp Only	Lumens	Wattage Range	Rated Ave. Life (hrs.) (3.)	% Maint. Output at end of life	Color Rendition	Optical Control	Initial (Lamp)	Opera-tional (Power)
Incandescent[5]	N/A	11-18	655-15300	58-860	1500-12000	82-86	Exc.	Excellent	Low	High
Tungsten-Halogen	N/A	20-22	6000-33000	300-1500	2000	93	Exc.	Exc. Vertical Poor Horiz.	Moder.	High
Fluorescent	58-69	70-73	4200-15500	60-212	10000-12000	68	Good	Poor	Moder.	Moder.
Mercury-Clear	37-54	44-58	7700-57500	175-1000	24000+	62-82	Fair	Good	Moder.	Moder.
Mercury-W/Phosp.	41-59	49-63	8500-63000	175-1000	24000+	50-73	Good	Fair	Moder.	Moder.
Metal Halide	65-110	80-125	14000-125000	175-1500	7500-15000	58-74	Good	Good	High	Low
High Pressure Sodium	60-130	83-140	5800-140000	70-1000	20000-24000	73	Fair	Good	High	Low
Low Pressure Sodium	78-150	131-183	4650-33000	35-180	18000	100[4.]	Poor	Poor	High	Low

NOTES:

1. All figures show operating ranges typical for lamp sizes normally used in area and roadway applications.
2. Ranges shown cover low wattage lamps with regulated type ballasts (worst condition) through high wattage lamps with reactor type ballasts (best condition).
3. Rated average life is based on survival of at least 50% of a large group of lamps operated under specified test conditions at 10 or more burning hours per start.
4. Low pressure sodium lamps maintain initial lumen rating throughout life, but lamp wattage increases. Considering this change in wattage, the luminous efficacy of these lamps (including ballast losses) at 18000 hours is 67-117 lumens per watt.
5. Larger sized incandescent lamps (up to 2000 watts) for floodlighting applications are available. Depending on operating conditions, the luminious efficacy and life change considerably for these lamps from the typical values shown. Lamp schedules should be consulted for details.

Their life, however, is somewhat shorter and they are more sensitive to lamp orientation. Care should be exercised when selecting lamps relative to their burning position. Excellent results have been obtained with these lamps in high mast lighting. If exceptionally good color rendition is required for street lighting, the metal halide lamp should be considered.

High Pressure Sodium. This is the newest addition to the family of H.I.D. lamps and provides excellent luminous efficacy, good lumen-maintenance, long life, and very acceptable color. Higher lamp cost and a more complex ballast could be listed as its disadvantages. This lamp provides a good economic compromise ideally suited for most roadway lighting projects. Normally it should not, however, be used for sign lighting, as the color of the illuminated sign may change considerably from that observed during daylight hours.

Low Pressure Sodium. The principal advantage of this light source is its exceptionally high luminous efficacy. Its disadvantages are its monochromatic color and large size. It is an excellent source where color and optical control are less important than the quantity of light produced per unit of electrical energy, such as in tunnel lighting. It has been successfully used in roadway lighting where high illumination levels are required and the luminaires can be spaced close together so as to achieve good uniformity. Because of its poor color, it is not a very desirable light source for urban street lighting where pedestrians are present.

These are broad generalizations, and it should be noted that, with a wide variety of sources, there is no one best solution for a given lighting application. The requirements should be known; the characteristics of the light sources with these requirements in mind should be reviewed, and the sources that are not suitable should be eliminated.

Table 5 presents various sources and some of their general characteristics. This table should aid the designer in choosing the light source best suited for a given application.

LUMINAIRES

A luminaire is defined as a complete lighting unit consisting of a lamp (or lamps) together with the parts designed to distribute the light, to position and protect the lamp(s), and to connect the lamp(s) to the power supply. It is made up of components grouped together in terms of their functions. They are generally described as the optical system, the electrical system, and the mechanical system. A typical luminaire is shown in Figure 9.

The Optical System

The optical system is made up of a light source, a reflector, and, usually, a refractor.

Light Source. See preceding section on Light Sources.

Reflector. The reflector is one of the devices used in optical control to change the direction of light rays. Its purpose is to take that portion of light emitted by the lamp which otherwise would be lost or poorly utilized, and redirect it into a more desirable distribution pattern. Reflectors are designed to either work alone or in combination with a refractor. Reflectors designed to work with a refractor should never be used alone. While they may still appear to function properly, they usually do not, and generally create high luminaire brightness and very spotty (non-uniform) illumination of the roadway.

Reflectors can generally be classified into two types--specular and diffuse. Specular reflectors are made from a glossy material which provides a mirror-like surface. Light rays reflect from such surfaces with only their directions changed. Most reflectors in use today for street and area lighting applications are complex shapes of formed aluminum sheets. Oftentimes, these reflectors are highly polished, especially their beam-forming sections. Their surfaces are treated to protect the high specularity and reflectivity from deterioration

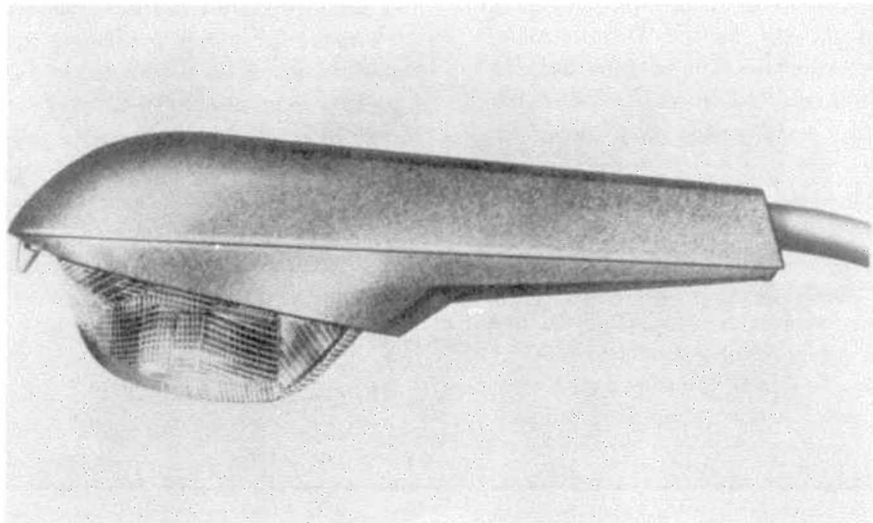

Figure 9. Typical roadway luminaire.

due to dirt, moisture, and industrial and automotive exhaust fumes. Reflectors used in an enclosed optical system are formed with a "lip" at the reflector opening to which a gasket is secured. This provides a seat for the refractor (or lens) and also seals the optical cavity to a certain degree, while still allowing the system to "breathe" and act as a filter during on-and-off cycles. Luminaires using non-breathing type gaskets (i.e., silicone rubber) are usually equipped with a separate filter or a filtering gasket near the lamp socket to provide a path for air to enter or exit the optical chamber.

Diffuse reflectors are used where the intent is to spread the light over a wider area, rather than into a tightly controlled pattern. Materials used for diffuse reflectors may be non-polished (or etched) aluminum sheet, white painted, enamelled, or porcelainized steel, or plastic materials. Light rays from the lamp striking a diffuse reflector are reflected, but the direction of these rays is scattered and may approach a cosine distribution. Although many luminaire designs use a diffuse reflector-refractor combination, this type of reflector is well-suited to be used by itself or with just a plain lens. In some luminaires a small area of the reflector above the lamp may be diffuse. This may accomplish two purposes: to reduce the "hot spot" or high illumination level immediately below the luminaire, or it may be done to reduce the amount of light that is redirected back through the arc tube. Light redirected through the arc tube can cause overheating and reduced lamp life. In some instances, absorption and slotting have been used to correct this problem. Absorption involves placing a black shield above the lamp to absorb rather than reflect the light. Slotting is removal of part of the reflector to permit the light to pass into the housing rather than be reflected back into the arc tube.

Refractor. The refractor is another means in optical control to change the direction of light rays. Refractors are made of a transparent, clear material, usually a high-strength heat and shock resistant glass, such as boro-silicate, or of a plastic material. Plastics used are either acrylic, if luminaire operating temperatures present no problem, or polycarbonate, where higher impact strength is desired, such as in a high-vandalism area, or where higher luminaire operating temperatures are encountered. While glass is chemically stable, the plastic materials undergo a gradual change due to heat and ultraviolet exposure, resulting in a crazing and/or yellowing of the refractor. Because of this, plastic refractors may need to be replaced occasionally.

The refractor serves several functions. First, it controls and redirects the light emitted by the lamp and coming off the reflector by means of its prismatic construction. Both the inside and the outside surfaces of a refractor are normally made up of a large number of prisms, each one of which controls a small portion of the total light passing through it. The second function is, ideally, that of a source-enlarger. The apparent (maximum) brightness created by the lamp and a specular reflector can be considerably reduced if a well-designed and properly applied refractor is used. Another function of the refractor is to close up the optical cavity of an enclosed and gasketed luminaire.

Several types of luminaires use an open refractor, oftentimes without or with just a minimal reflector. In those cases, the lamp is usually operated in a vertical position and located well within the refractor. Almost all the light emitted by the lamp is intercepted by the refractor and shaped into beam patterns to illuminate a given area. While this type of light control provides for high luminaire efficiencies, it causes sometimes a higher degree of "system glare" than luminaires where the lamp is recessed and shielded by a reflector.

The Electrical System

The electrical system of a luminaire consists of the lamp socket, the ballast, a terminal block, a fuse, a lightning arrester, a photoelectric control, and internal wiring. While a lamp socket and some means for connecting the socket to the power supply are always provided, the other items are optional and may not be contained in the luminaire but be located elsewhere (i.e., pole base).

Lamp Socket. The lamp socket serves to hold the lamp securely at its design location and connects it electrically to the power source. It is usually a porcelain shrouded, plated, brass shell, equipped with lamp grips to prevent the lamp from loosening in the socket while in service. Fluorescent luminaires have compression-type sockets, often designed with rubber seals to prevent entry of moisture and dust into the contact area.

In many street lighting luminaire designs, the lamp socket is adjustable, both vertically and horizontally. This allows for a number of socket settings which, for a given optical system, will result in various light distributions. Lowering the lamp in the optical cavity will cause the beams to move upward, permitting wider spacings between luminaires. Conversely, raising the lamp upwards in the luminaire will depress the vertical beam elevation. Moving the lamp downward or upward will also result in a respectively higher or lower brightness of the luminaire, and consequently change the degree of glare. If the lamp is moved horizontally within the optical cavity, the lateral light distribution will be altered. To get a better understanding of the change in light distributions obtainable from a given optical system, the reader is advised to obtain and compare photometric test reports based on identical lamp-luminaire combinations using various socket settings.

Ballast. Unless an incandescent or quartz-halogen lamp is used, a ballast is needed to properly operate the lamp. Basically, the ballast is an assembly consisting of laminated steel and wire coils which performs three functions. First, it provides the proper open circuit voltage to start the lamp. The second function is to keep the lamp operating within its design parameters. Arc-discharge lamps have no inherent resistance or impedance, and lamp current would increase continuously, once the lamp has started, until it destroys itself. This phenomena is called "negative resistance." The ballast provides a control function and limits the power available to the lamp. The third function of the ballast is to adapt the lamp to any one of the line voltages commonly available.

In discussing ballasts, the term "regulation" is frequently used. Regulation expresses the variation in wattage delivered to the lamp as ballast input voltage varies. For example, the nominal line voltage (120, 208, 240, 277, or 480 volts) may change over a given time period or over the length of a given circuit. As this applied voltage varies, the power dissipated by the lamp changes, along with a corresponding change in lamp light output. Ballasts with best regulation characteristics compensate better for these line voltage variations than do the "non-regulating" types. Generally, good regulation is required in roadway lighting when luminaire spacing is large and voltage drops over a given circuit become significant. The reader is advised to fully understand what ballast regulation is and how it is defined. A 400 watt, 240 volt ballast, for example, which has a $\pm 3\%$ lamp regulation for a $\pm 10\%$ line variation will only hold the lamp wattage to within $\pm 3\%$ of that value at which it operates when the supply voltage is 240 volts. If the lamp and the ballast are nominal, the lamp would operate at 388 watts for a 216 volt line, and at 412 watts with 264 volts supplied. In the real world, however, lamps and ballasts, while as a large group have average nominal characteristics, individually deviate somewhat from these nominal values. If a lamp would be tested whose wattage is 390 watts at a nominal line voltage, the $\pm 3\%$ lamp regulation would produce a dissipated lamp power of 401.7 and 378.3 watts, respectively, for the $\pm 10\%$ line voltage change.

In practice, the problem becomes somewhat more complex when performing this type of test with production ballasts. Not only will the lamp deviate from the nominal values slightly, but so will the ballasts. These deviations are expected in manufacturing and follow a normal (Gauss-Laplace) distribution curve. Limits within which a product is considered acceptable are usually specified by standards writing associations (i.e., ANSI), manufacturers or manufacturers' organizations (i.e., NEMA), or, sometimes, a user. The reader should be aware that the tighter these tolerances are, the higher will be the cost of the product. Engineering judgment and experience should be applied when compromising between performance and cost to best satisfy the overall objective in a cost-conscious manner. The point made in this discussion is to provide the reader with enough background to alert him to situations which inevitably will occur in real situations.

Over the years and with the development of various types of discharge lamps, many ballasts have become available. They are categorized by lamp type (i.e., fluorescent, mercury, high pressure sodium), by lamp wattage and line voltage, and by their circuit design. Circuits available for H.I.D. lamps are essentially of four types, each of which has advantages and disadvantages relative to cost and performance which determine its suitability for a particular application. No such distinction is made for fluorescent ballasts in the context of this handbook; therefore, only H.I.D. ballasts are discussed.

- Reactor. The reactor is the simplest, least expensive, smallest, and most efficient ballast available. Its only function is that of controlling the lamp current. For this reason, lamp starting must be accomplished by the line voltage directly, and reactors can only be used on systems having a voltage equal to or higher than the lamp starting voltage.

  The disadvantages of this ballast are its low inherent power factor (around 50%), its high operating current, its still higher starting current, and its poor lamp regulation.

By adding a capacitor across the line side of the reactor, the power factor can be brought up to about 90%. While this will reduce the operating current, the High Power Factor (HPF) reactor retains all the other advantages and disadvantages associated with the normal power factor (NPF) reactor.

- High-Reactance (HR), High Leakage (HX), Lag, or Autotransformer. Anyone of the above names applies to a ballast which is essentially a reactor in series with a step-up transformer. If the line voltage is insufficient to start the lamp, a step-up transformer, wound on the same structure as the reactor coil, is used to bring it up to the necessary value. This voltage is then applied to the lamp through the reactor. Similar to the reactor, this ballast is compact, relatively inexpensive, and efficient. Again, it has an inherently low power factor, but, as in the case of the reactor, a capacitor can be added to give it a high power factor. However, since the additional cost of the capacitor brings this ballast in a price range of ballasts having considerably better performance, it is used very seldom today in the high power factor version.

- Auto-Regulator (AR), Constant Wattage Autotransformer (CWA), Regulated- or Auto-Stabilized Ballast. All of the above designations are synonymous and describe a ballast having better regulation than either type discussed previously. The capacitor in this ballast is no longer an optional element for power factor correction, but an integral part of the ballast, responsible for the amount of power delivered to the lamp. Its characteristics are good lamp regulation over a fairly wide range of line voltage variation, high power factor, and low starting current. Ballast cost, size, weight, and losses are somewhat higher than the reactor or the high-reactance ballast.

- Regulator, Constant Wattage (CW), or Regulated Output (RO) Ballast. There may be a situation calling for a higher degree of lamp wattage stabilization over wider line-voltage variations than possible with the auto-regulator type. For such applications, a regulator, or constant wattage ballast, should be used. Similar to the auto-regulator, it has a primary and secondary coil, but they are not physically connected. The power to start and operate the lamp is generated in the secondary coil by induction only, requiring larger amounts of wire and steel in the construction of this ballast. The physical separation of the secondary side of the ballast also provides electrical isolation of the lamp circuit, a safety feature often desired in roadway lighting applications. As in the auto-regulator ballast, the constant wattage ballast uses a capacitor in the secondary circuit to control lamp wattage.

  This ballast provides the best lamp regulation, a high power factor, low starting current, and electrical isolation of the lamp circuit. It is bulkier, heavier, more expensive, and usually has higher losses than the other ballasts.

So far, the discussion of ballast types and characteristics has dealt with mercury ballasts. In principle, it also applies to other H.I.D. lamps. Metal halide and high pressure sodium lamps have different starting and operating parameters, but the ballast still provides the starting, operating, and voltage adaptation requirements for these lamps. A reactor, designed for high pressure sodium, will still have similar size, weight, power factor, regulation, and cost characteristics as a reactor for mercury lamps. Similarly, an auto-regulator designed for metal halide lamps retains all the advantages and disadvantages of one dedesigned for a mercury lamp. It should be pointed out that a certain degree of interchangeability of ballast types exists. For example, metal halide ballasts operate mercury lamps. However, very few mercury ballasts will operate metal halide lamps properly. Standard high pressure sodium lamps require a starting voltage of between 2500 and 4000 volts--much higher than any mercury or metal halide ballast will provide. For this reason, these lamps must be operated on ballasts designed for them. Some "retrofit" high pressure sodium lamps are available; however, they can only be used with a mercury reactor or high-reactance autotransformer. This allows conversion of existing mercury luminaires to high pressure sodium by only changing the lamp. Care must be taken when making such a conversion to be sure lamps and ballasts are compatible. Manufacturers' representatives and/or literature should be consulted.

- Metal Halide Ballast. While metal halide lamps bear a strong resemblance to mercury lamps, both physically and electrically, the voltage requirements for starting and warm-up are considerably higher than those usually provided by a mercury ballast. A special metal halide ballast has been developed to satisfy these requirements. Basically, the circuit resembles the auto-regulator; a modification in the core-construction (core-slots) provides a highly peaked voltage wave form in the secondary (lamp) winding. Because of this characteristic wave shape, this ballast is also referred to as a "lead-peaked" or "peak-lead" ballast.

  Metal halide ballasts have lamp regulation somewhere between a regulator ballast and a lag or reactor ballast. They have a high power factor, low line starting current, and their sizes, weights, and losses are similar to the mercury regulator ballast.

- High Pressure Sodium Ballast. The physical and electrical characteristics of high pressure sodium lamps are considerably different from all the other H.I.D. lamps, and the ballasts needed to operate them are generally larger, heavier, more complex, and more expensive. The two lamp characteristics responsible for the different ballast requirements are the high starting voltage necessary to strike the arc plus the fact that lamp operating voltage changes considerably during lamp life. In contrast to this, mercury lamps retain essentially constant lamp voltage over their entire life span.

  To provide the starting voltage, a starter circuit, normally of solid state design, is tied into the secondary (lamp) side of the ballast and provides a series of narrow, high voltage pulses to the lamp until an arc has been established. Once the lamp has started, the operation of the starter circuit is blocked. To control the lamp wattage, the ballast decreases lamp current as the lamp voltage increases. Very specific limits are placed on allowable lamp voltages and lamp wattages by the lamp industry to which the ballasts have to be matched.

  Several designs of high pressure sodium ballasts are available, such as reactors, lag autotransformers, auto-regulators, or regulator ballasts. Regulation, power factor, losses, starting current requirements, etc., of these ballasts are similar to the equivalent circuit ballasts for mercury lamps.

- Low Pressure Sodium Ballast. Low pressure sodium lamps require high open circuit voltage (up to 680 volts) for starting. Both the starting and control requirements can be met with a reactor or high-reactance autotransformer type ballast. This ballast also provides satisfactory regulation parameters.

Ballast characteristics are summarized in Table 6.

Other Electrical Components. Luminaire internal wiring usually ends at the terminal block. This is the point where connections to the supply lines are made. Terminal blocks are either of porcelain or a plastic material and contain two or more pressure-type screw terminals, to which the incoming leads are connected. If aluminum wires are used for the incoming leads, the luminaire primary terminals should be suitable for this type of wire. In some designs, luminaires are dual-voltage rated, and care should be taken to connect the line leads to the proper terminals. Whenever

TABLE 6

SUMMARY OF TYPICAL BALLAST ELECTRICAL CHARACTERISTICS *

	Circuit Type	Line Volts	Variation in Lamp Wattage vs. Line Voltage: Line Volts	Variation in Lamp Wattage vs. Line Voltage: Lamp Watts	Power Factor (min.)	Starting Current	Lamp Current Crest Factor	Ballast Losses
Mercury	Reactor (Normal Power Factor)	240 & 277 for 100 - 400W; 480V for 700 & 1000W	± 5%	± 10-12%	50%	Higher than Operating	1.4 - 1.5	5-13%
Mercury	Reactor (High Power Factor)	Same as NPF Reactor	± 5%	± 10-12%	90%	Slightly higher than Operating	1.4 - 1.5	5-13%
Mercury	High Reactance; Lag-Ballast; Autotransformer (NPF)	120V for 100W through 400 watt	± 5%	± 10-12%	50%	Higher than Operating	1.4 - 1.5	9-23%
Mercury	Auto-Regulator; Constant Wattage Autotransformer	Any voltage	± 10%	± 5-6%	90%	Lower than Operating	1.6 - 2.0	8-20%
Mercury	Regulator; Constant Wattage; Regulated Output	Any voltage	± 13%	± 2-3%	90%	Lower than Operating	1.6 - 2.0	12-22%
MH	Lead-Peak; Autotransformer	Any voltage	± 10%	± 10%	90%	Lower than Operating	1.6 - 1.8	7-20%
High Pressure Sodium	Reactor (NPF or HPF)	120V for 70W, 100W; 150W (55V). 480V for 1000W	± 5%	± 10-12%	50% or 90%	Higher than Operating	1.4 - 1.5	5-18%
High Pressure Sodium	Autotransformer; Lag-Ballast (HPF)	70 through 400W Any voltage	± 5%	± 10-12%	90%	Lower than Operating	1.4 - 1.5	10-27%
High Pressure Sodium	Auto-Regulator	Any voltage	± 10%	± 10%	90%	Lower than Operating	1.6 - 1.8	12-25%
High Pressure Sodium	Regulator; Magnetic Regulator Constant Wattage	Any voltage	± 10%	± 3-5%	90%	Lower than Operating	1.6 - 1.8	17-30%
LPS	Reactor (HPF)	480 for 35 through 135W	± 10%	± 5%	90%	Slightly higher than Operating	1.4 - 1.5	22-71%
LPS	High-Reactance Autotransformer (HPF)	Any voltage	±10% up to 90W; -10% to +5% 135 & 180W	±5% up to 90W; -5% to +3% 135 & 180W	90%	Slightly higher than Operating	1.4 - 1.5	22-71%

*Characteristics of equipment made by different manufacturers will vary somewhat. The values shown are typical only. Manufacturers' literature should be consulted for exact performance date.

dual-voltage rated luminaires or luminaires providing for field-changing of the input voltage are used, the internal wiring diagrams and/or instructions supplied with the equipment should be consulted.

Oftentimes, luminaires are fused to protect the supply side of an installation. Thus, if a ballast failure occurs, the fuse disconnects the faulty luminaire from the supply lines and presents no danger to the rest of the circuit. Fuses can be installed in the luminaire itself, either in separate fuse holders, or in a combination fuse holder-terminal block, or they can be placed near the base of the pole where they are accessible through a handhole or a transformer base coverplate. Fuse size and type should be in line with the manufacturer's recommendations for ballast type, lamp wattage, and line voltage.

Luminaires installed in areas subject to electrical storms are often equipped with air-gap or expulsion type lightning arresters to protect ballasts and lamps from damaging voltage surges. Depending on luminaire construction and line voltage, these arresters can be either built into the luminaire housing, or they are attached to the supply leads outside the fixture. The lightning arrester provides a shunt-path for high energy surges to ground.

Photoelectric controls are used extensively to turn lighting equipment on and off automatically at dusk and dawn. They are wired into the circuit between the supply lines and the ballast and open or close one side (usually the "hot" lead) of the luminaire. During daylight hours, the resistance of the photoelectric cell is quite low and allows sufficient current to flow through it to keep a switching element (relay or bimetallic switch) open. As the ambient light level drops to a desired value, the resistance of the cell increases, causing the current-flow to diminish until it no longer is sufficient to hold the switch open. The switch closes, and the ballast and the lamp are connected to the line. The reverse process takes place at dawn. It should be noted that most currently available photoelectric controls fail in a "fail safe" or closed position. Failed photoelectric controls should be replaced promptly. Some agencies group-replace these controls along with every or every second group lamp replacement.

Internal wiring serves to connect the various electrical components. Conductors must be insulated to withstand the high temperatures generated within the luminaire by the lamp and the ballast. All connections must be vibration-proof and insulated to prevent electrical failure.

The Mechanical System

The mechanical system of a luminaire serves to package all of the optical and electrical components in an orderly fashion. A good mechanical design provides for proper positioning and protection of the lamp, ease of luminaire installation and maintenance, minimal weight and windloading, and a pleasing daytime appearance. Generally, the mechanical system consists of the luminaire housing, the lamp socket support, the slipfitter, a hinge and latching mechanism to allow ready access to the luminaire interior, and an assortment of miscellaneous hardware.

The luminaire housing is that mechanism which holds the various optical, electrical, and mechanical elements making up the luminaire in place. The most common material used is cast aluminum, but other materials, including plastic, can be used, provided they are properly finished to protect them in the outdoor environment. The housing should be strong enough to withstand snow, ice, windloads, and vibrations, and constructed to give long, troublefree service. In most designs, the luminaire housing is made of two parts--the housing itself, or the "upper" housing, and a refractor-holding ring. Luminaires with a replaceable ballast mounted on a separate coverplate would have this coverplate make up a third part of the housing.

The lamp support, made of cast or fabricated metal parts, attaches the lamp socket securely either to the reflector or the luminaire housing. In most designs, it is an adjustable device which allows vertical and lateral adjustment of the lamp socket. Different light distribution patterns can thus be achieved. Since a relatively small change in light center position can cause a considerable change in the luminaire's photometric performance, the lamp socket support should be well-designed and sturdy.

A slipfitter is provided to attach and secure the luminaire to the mast arm. Since mast arms and mounting brackets are available in various sizes, most modern luminaire designs have universal slipfitters to fit all 1¼ through 2 inch diameter pipes. Slipfitters usually allow some vertical luminaire adjustment to compensate for small misalignments of the bracket arm or the pole. The design and the materials in the slipfitter greatly influence the ease of installation and the integrity, with which the luminaire is held to the support structure. Because of this, slipfitter design and construction should be included in an overall appraisal or evaluation of a luminaire.

Since the interior of the luminaire needs to be accessible for relamping and routine maintenance work, luminaire doors or refractor holding rings usually are hinged at one end and latched on the other. As is the case with the slipfitter, the hinging and latching mechanism should be sturdy, safe, made from non-corrosive materials, and simple and easy to operate. Some luminaire designs provide for easy removal of the ring; others have it permanently attached. This difference in design may require different approaches for cleaning the glassware. The advantages of one design over another should be evaluated, but in no case should a luminaire be used which allows the refractor holding ring to accidentally drop to the roadway during routine maintenance, or a latch that allows the door to swing open while in service.

The luminaire housing should have a "leveling pad"--a flat surface where the installer can place a leveling device during installation. As an option, most luminaires can be purchased with a permanently attached level, visible from the roadway. Whether or not this item is worth the extra cost is left to the judgment of the specifier.

Most luminaires provide a "bird-stopper"--a "bird-gasket," which is a plastic or metal barrier to be inserted around the bracket-arm near the slipfitter, where it enters the luminaire. This is to block the area otherwise left open when a small pipe bracket is used with a 2 inch slipfitter. It prevents entry and nesting of birds in the luminaire.

In installations subject to steady and severe vibrations, such as those on a bridge, it may be desirable to support the lamp-tip to reduce lamp breakage. An optional metal strap or spring can be installed in the reflector in many luminaire designs.

Finally, the hardware used in the components and the assembly of a luminaire should be made from non-corrosive materials or properly finished to provide protection from the environment and to give long and troublefree service.

CLASSIFICATION OF LUMINAIRE LIGHT DISTRIBUTIONS

The ultimate performance of a lighting system is dependent upon the control of luminous flux from the light source. Manufacturers provide to the designer photometric data for various lamp-luminaire combinations that can be used in determining the amount and direction of luminous flux. For standardization purposes, IES has classified light distributions on the basis of the following:

- Vertical light distribution
- Lateral light distribution
- Control of light distribution above maximum candlepower

The classification of light distributions is made on a plan view of a roadway which has superimposed on it a series of lines parallel with the roadway and another series transverse to the roadway. These lines, which are spaced in multiples and fractions of the mounting height, are referred to as Longitudinal Roadway Lines (LRL), and Transverse Roadway Lines (TRL), as shown in Figure 10.

Vertical Light Distributions

Vertical light distributions are divided into three groups--short, medium, and long, as illustrated in Figure 10. Classification is on the basis of the distance from the luminaire to where the beam of maximum candlepower strikes the roadway surface. The classifications are:

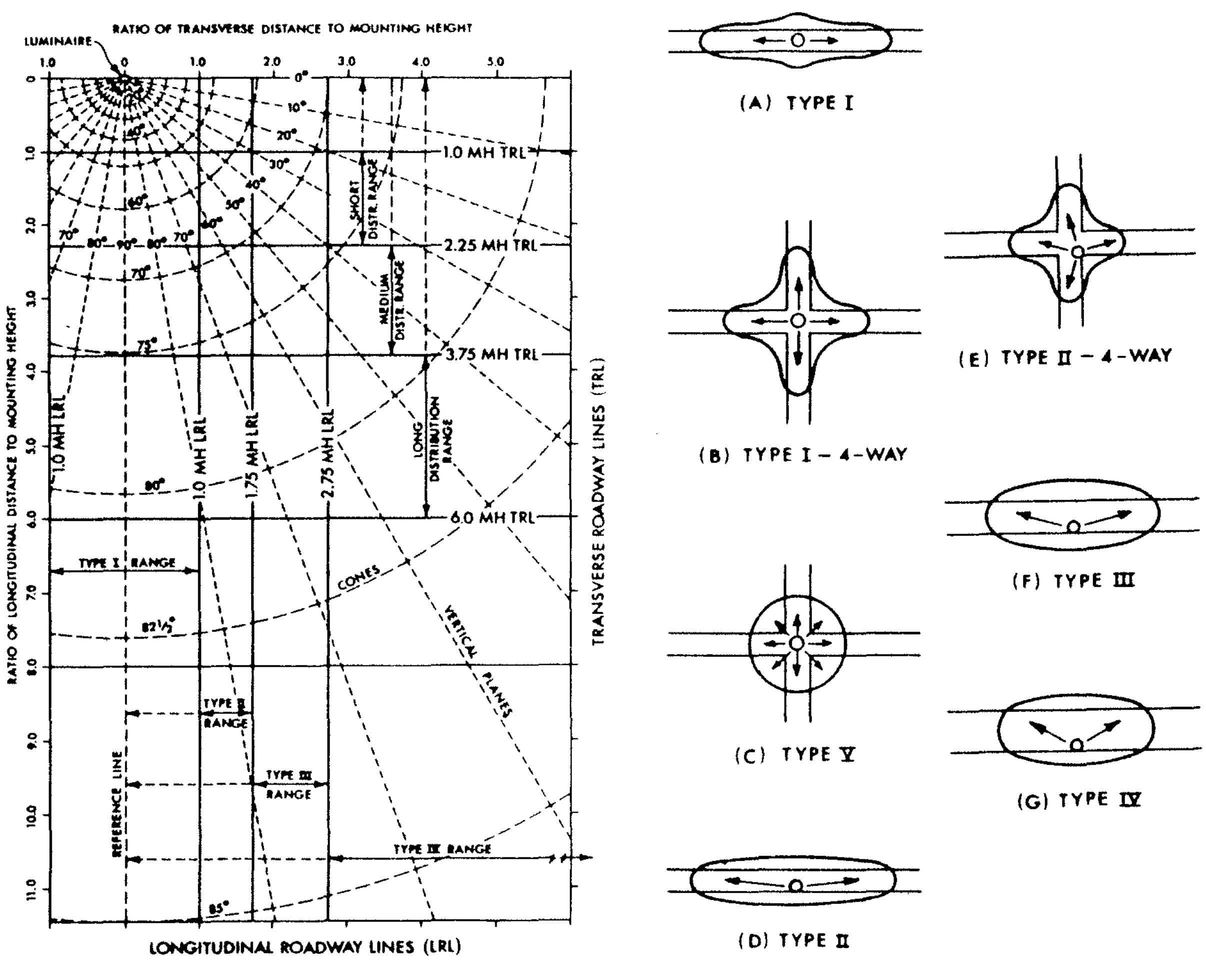

Figure 10. Plan view of roadway coverage for different types of luminaires.

- *Short distribution* - The maximum candlepower beam strikes the roadway surface between 1.0 and 2.25 mounting heights from the luminaire.

- *Medium distribution* - The maximum candlepower beam strikes the roadway at some point between 2.25 and 3.75 mounting heights from the luminaire.

- *Long distribution* - The maximum candlepower beam strikes the roadway at a point between 3.75 and 6.0 mounting heights from the luminaire.

On the basis of the vertical light distribution, theoretical maximum spacing are such that the maximum candlepower beams from adjacent luminaires are joined on the roadway surface. With this assumption, the maximum luminaire spacings are:

- Short distribution - 4.5 mounting heights

- Medium distribution - 7.5 mounting heights

- Long distribution - 12.0 mounting heights

From a practical standpoint, the medium distribution is predominantly used in practice, and the spacing of luminaires normally does not exceed five to six mounting heights. Short distributions are not used extensively for reasons of economy, because extremely short spacing is required. At the other extreme, the long distribution is not used to any great extent because the high beam angle of maximum candlepower often produces excessive glare.

Lateral Light Distributions

The Illuminating Engineering Society established a series of lateral distribution patterns designated as Types I, II, III, IV, and V. These types are described in great detail in the American National Standard Practice for Roadway Lighting (1). In general, we may describe Types I and V as luminaires mounted over the center of the area to be lighted. Type I applies to rectangular patterns on narrow streets, while Type V applies to areas where light is to be distributed evenly in all directions. Type V and a modified Type I are generally the class of luminaire applied in high mast lighting systems.

Types II, III, and IV are classes of luminaires to be mounted near the edge of the area to be lighted. Type II applies to narrow streets, Type III to streets of medium width, while Type IV applies to wide street applications. These are illustrated in Figure 10.

For specific classification, luminaires are described on the basis of where the half maximum candlepower isocandela trace falls. This measure, "the half-maximum candlepower trace," describes the direction of the greatest punch of the luminaire better than just simply describing the direction of the beam of maximum candlepower. The ranges of Types I, II, III, and IV are presented in Figure 10.

Control of Distribution Above Maximum Candlepower

Disability and discomfort glare are largely a result of light emission into the driver's eye. For design purposes, it is necessary that luminaires be classified according to their relative glare effects. Thus, luminaires are classified as cutoff, semi-cutoff, and non-cutoff. IES descriptions of these classification categories are as follows:

- *Cutoff.* A luminaire light distribution is classified as cutoff when the candlepower per 1000 bare lamp lumens does not exceed 25 at an angle of 90 degrees above nadir (a vertical axis through the light source); and 100 at an angle of 80 degrees above nadir.

- *Semi-cutoff.* A luminaire light distribution is classified as semi-cutoff when the candlepower per 1000 bare lamp lumens does not exceed 50 at an angle of 90 degrees above nadir and 200 at a vertical angle of 80 degrees above nadir.

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- *Non-cutoff.* The classification when there is no candlepower limitation in the zone above maximum candlepower.

In lighting practice, the semi-cutoff control is normally used. Adequate glare control may be accomplished without unduly restricting the spacing of luminaire supports.

LUMINAIRE SUPPORTS

The luminaire support includes all of the structural hardware used to hold the luminaire in place. As illustrated in Figure 11, luminaire supports generally consist of 1) a mast arm, 2) a pole (mast), 3) a base, and 4) a foundation. There are exceptions: for example, some decorative lighting is of the post-top style, thus eliminating the mast arm. Other luminaires may be wall-mounted, thus eliminating the entire support. Some poles are buried directly in the soil, and thus eliminate the base and the foundation. Most all of the common alternatives will be discussed in this section.

Mast Arms

Mast arms serve the purpose of supporting the luminaire at a lateral dimension from the pole. Typically, it is desirable to locate the luminaire over the edge of the roadway, but it is also desirable to place the pole at some distance from the roadway to reduce the probability of traffic colliding with the pole. The mast arm makes this possible.

Figure 11. Typical luminaire support with mast, mast arm, base, and foundation.

Mast arms are of many forms dependent upon their length and the type of material used in their fabrication. For metal poles, they usually are fabricated from the same material as used in the pole. For wood and concrete poles, mast arms are generally made of galvanized tubing.

Mast arms may be classified generally as single arm, truss, and davit types (see Figure 12). The single arm is used on relatively short mast arm applications while the truss type is used where longer arms are needed. The single arm and the truss type are generally of an upsweep style to facilitate desired mounting heights without full-height poles.

Davit type mast arms as illustrated in Figure 12 offer a structural shape that has a pleasing appearance. Because davit arms are telescoped onto the top of the pole and eliminate bolted connections, they may be more economical than other types. Davit arms are extremely popular in European countries, but are not used to a great extent here. Davit arms are used, however, on most stainless steel poles in the U.S.

Poles

There are five types of poles utilized for luminaire supports. They are:

- Steel - galvanized, painted, or weathering steel
- Aluminum
- Stainless steel
- Wood
- Concrete

The advantages and disadvantages of each are discussed in the following paragraphs.

Steel. Galvanized steel poles are extremely popular because of comparatively low cost and extended life. Painted poles are less popular because of the continual maintenance problem. Weathering steel poles are popular because of low maintenance, but the rusty runoff can present aesthetic problems. There are a number of designs and devices available to make steel poles breakaway under impact.

Aluminum. Aluminum poles are popular on the basis of three advantages over other types: 1) they are relatively maintenance-free due to their resistance to corrosion when exposed to the natural elements; 2) they are lighter in weight than other types; and 3) they are purported to be safer because the pole should break away easier under the impact of a collision. Such breakaway action may not be as good for the taller poles. The one major disadvantage is that aluminum poles may be more expensive than most others.

Stainless Steel. Stainless steel poles offer some advantages over others. They employ a base that has good breakaway characteristics, the poles are lightweight, and they are corrosion resistant. They are, however, considerably more expensive than other poles.

Wood. Wood is perhaps the most economical of lighting poles, particularly in the regions where trees are plentiful. Wood may be treated to resist rotting and deterioration, and dyed to make them more attractive. The major disadvantage is that they may be installed only by the method of embedment. Direct embedment precludes the possibility of utilizing breakaway features. Preliminary results from a recent research project have indicated that an inexpensive method of making wood poles breakaway is possible.

Concrete. Concrete poles are popular in certain regions where cement and concrete aggregates are plentiful. Thus, the principal advantage of concrete poles is economics. Disadvantages are that concrete poles cannot be effectively made breakaway, and they are extremely heavy even though they are made by prestressing concrete. Collisions with concrete poles may cause failure of the concrete, but the prestressing cables may pull the heavy pole down on to the automobiles.

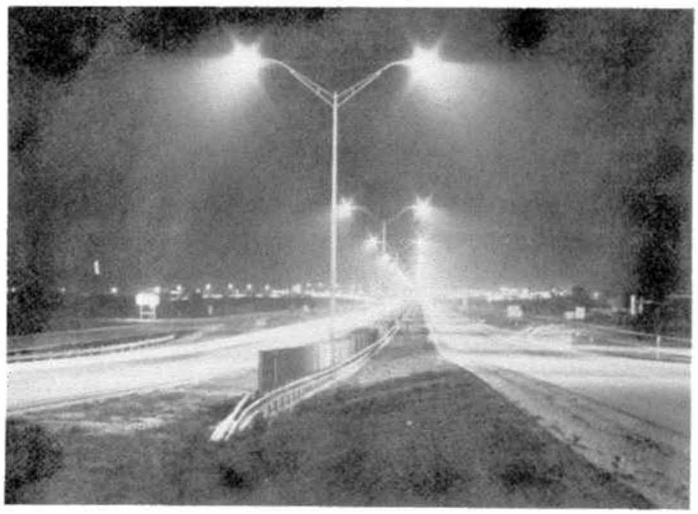

Figure 12. Types of mast arms (above top--single arm; above--truss; right--davit).

Of more importance is the usual heavy damage to colliding vehicles and injury to occupants.

Bases

There are several types of bases currently used to support luminaire poles. There are several factors considered in the selection of a particular type of base: the method of construction, type of pole, funds available, agency policy, and safety. This latter criterion is one of the most important considerations and, in the past, it has frequently received little or no consideration.

As a principal safety consideration, breakaway or frangible luminaire supports should be used wherever the support is exposed to traffic. There are exceptions, however, as outlined in the AASHTO Guide, "Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals" (2). Some of these exceptions are summarized as follows:

- The supports are located well beyond the clear roadside requirements (e.g., high mast lighting);
- The supports are located upon or behind barriers existing or installed for other purposes;
- The supports are located on retaining walls; or
- The relative hazard of a fallen support is greater than the hazard of the vehicle colliding with a fixed base support (e.g., supports in low speed, high pedestrian volume areas and at intersections where the luminaire support is integrated with the signal mast).

The acceptability of breakaway devices for use on all new Federal-Aid projects is determined on the basis of compliance with the AASHTO standard specifications. The dynamic performance of the breakaway supports under automobile impact is the basic measure of satisfactory breakaway characteristics. Satisfactory dynamic performance is indicated when the maximum change in momentum for a standard 2250 pound (1020 kg) vehicle, or its equivalent, striking a breakaway support at speeds of 20 to 60 mph (32 km/h to 96 km/h) does not exceed 1100 pound-seconds (4893 N-sec) but desirably does not exceed 750 pound-seconds (3336 N-sec).

There are other alternatives to full-scale crash testing. The specification permits testing by a method "equivalent" to vehicle (automobile) crash testing. Actually, in the future an equivalent test, or test series, will probably become the preferred method because, presumably, it would eliminate the variation in crush characteristics of crash vehicles. Presently, there is no universally applicable equivalent test for all breakaway roadway hardware. However, test procedures that are considered equivalent have been developed for luminaire supports using a pendulum or a bogie. Vehicle crush characteristics are simulated by the use of an expendable aluminum honeycomb cartridge that is placed between a relatively rigid striking face and the principal mass of the test device. Controlling a relatively few characteristics of such test devices should ensure consistent results between devices.

In determining if an item meets the requirements of the AASHTO specifications, testing and reporting procedures comparable to those given in NCHRP Report No. 153 (3) should be followed. Acceptance may be based on a single test if the test change in momentum and the analytically-inferred changes in momentum over the speed range are less than 750 pound-seconds. If the first dynamic test change in momentum is between 750 and 1100 pound-seconds, a second dynamic test will be needed unless assurance that the test results are representative of what would result from further dynamic tests and can be demonstrated analytically and statically. The results of the second test must also meet the specification requirements.

There are numerous types of luminaire support bases currently in service. Some of the more common types are described in the following paragraphs. Their presentation herein does not imply that they are acceptable for use on Federal-Aid projects. In fact, several are included to emphasize that they are not acceptable and should not be used where they are exposed to traffic.

Butt-Type Bases. Probably the most basic of all support methods is the butt-type base which is embedded directly in the soil. It is by far the most economical in most instances, and the only method applicable to wood. Also, embedment may be used to install concrete and galvanized steel poles. As mentioned previously, breakaway features are not possible when the embedment method is used. Further, poles get out of plumb during the seasons of high rainfall, when the ground is soft, and when the poles are subjected to high winds. Obviously, the butt-type bases do not meet the dynamic requirements of the AASHTO specifications.

Flange Bases. Most steel and aluminum poles are fitted with a plate or a flange at the base of the pole to facilitate bolting to a foundation or to some form of base. On steel poles, this is generally a steel plate that is fitted and welded to the base of the pole prior to galvanizing or painting. On aluminum poles, a cast aluminum shoe base is fitted over the lower end of the pole and is welded to it.

Although flange bases are frequently bolted directly to a foundation without an intermediate breakaway device, they do not meet the dynamic requirements. Such applications should be restricted to locations where they are not exposed to traffic or otherwise excepted in the AASHTO specifications. An aluminum flange base is illustrated in Figure 13.

Figure 13. Aluminum flange base.

Cast Aluminum Transformer Bases. "Serendipity" --the fortune of finding valuable things not sought for--can be used to describe the development of the cast aluminum transformer base as a breakaway device. The T-base originally was devised to house the transformer or ballast. It was made of cast aluminum as one alternate to reduce corrosion effects associated with the steel base. Other T-bases were made of steel plate and galvanized or painted to reduce the corrosion effects. The T-base soon proved to be unacceptable for housing the ballast because of moisture and insect damage to the electrical components. However, the cast base did prove to be a safety device because it would yield and break apart when struck by a vehicle. Today, virtually no one designs a system to use the T-base to house the ballast, but many agencies have specified T-bases as safety devices.

Cast aluminum T-bases are manufactured in various forms, but generally they are square to fit the flange of the pole, and either straight or slightly tapered outward to fit the anchor bolts of a concrete foundation. The earlier T-bases were 20 inches (50 cm) tall, and it has been found that this is an optimum height. It is important that the colliding vehicle strike the T-base rather than the pole. In this manner, the vehicle imparts a certain amount of shock which is desirable in causing a quick, rapid failure and subsequent release of the pole. Experimental versions of shorter bases resulted in extensive damage to the pole and an increased resistance to failure which, in turn, increased the probability of injury to the vehicle occupants.

Cast aluminum T-bases have been used to improve the safety of existing lighting systems. For example, a system which consists of galvanized steel poles flange-mounted to concrete foundations was modified by simply inserting under the flange mounting a transformer base which had the same bolting configuration, both top and bottom.

With the issuance of FHWA Notice N5040.20 of July 14, 1976 (4), T-bases no longer qualified as breakaway devices. Several manufacturers and other agencies are exploring design modifications to bring the T-base into compliance with the AASHTO dynamic requirements. As of this writing, at least one design, utilizing a different manufacturing process, has met the new AASHTO requirements and is acceptable as a breakaway device for use on Federal-Aid projects. Care should be taken to differentiate between the old and new designs.

Frangible Couplings. Several manufacturing companies have developed frangible couplings that improve the impact behavior of the flange-mounted aluminum or steel supports. A typical coupling, illustrated in Figure 14, is simply a short, cast aluminum connector or sleeve that is threaded internally. It is placed on the foundation anchor bolts, and the flange of the support is attached to the top of the coupling. When the support is struck by a vehicle, the coupling breaks and the intensity of the collision is greatly reduced. The fluting of the insert is essential to its satisfactory behavior upon impact. This frangible coupling has been tested and is acceptable for use on Federal-Aid projects.

Multi-directional Slip Base. The multi-directional slip base, illustrated in Figure 15, operates on the breakaway concept of high resistance to overturning and low shear resistance. The base consists of two identical plates, one welded to the support shaft and the other welded to a foundation attachment. These plates are slotted in a triangular or rectangular configuration so that when bolted together they will slip apart regardless of the angular direction of the impact. The multi-direction slip base offers the least resistance to collision of all of the breakaway concepts. As an additional advantage, the pole normally is not destroyed by the impact of collision. With some minor repairs, it generally can be reinstalled, thus reducing the total cost of the installation when all economic factors are considered. The multi-directional slip base has been adopted by quite a number of state agencies as their standard design for luminaire supports.

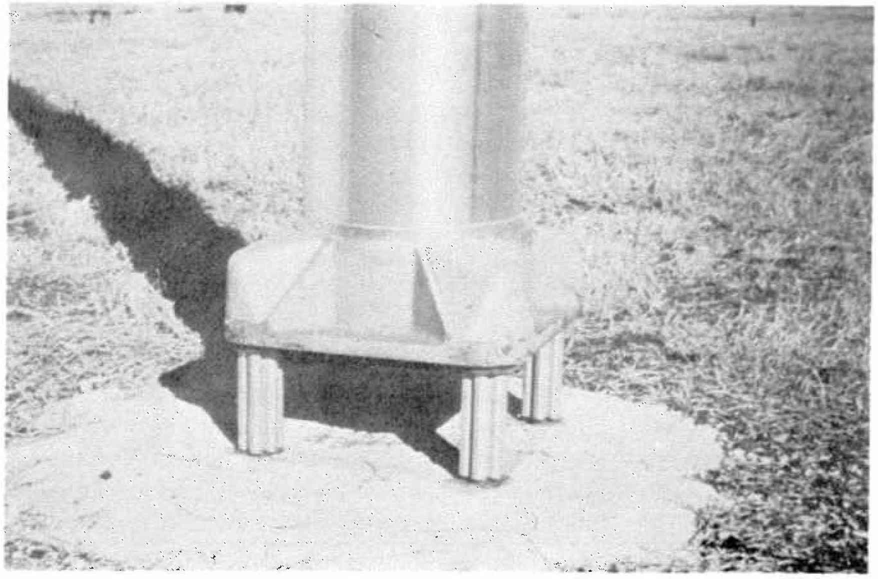

Figure 14. Typical frangible coupling.

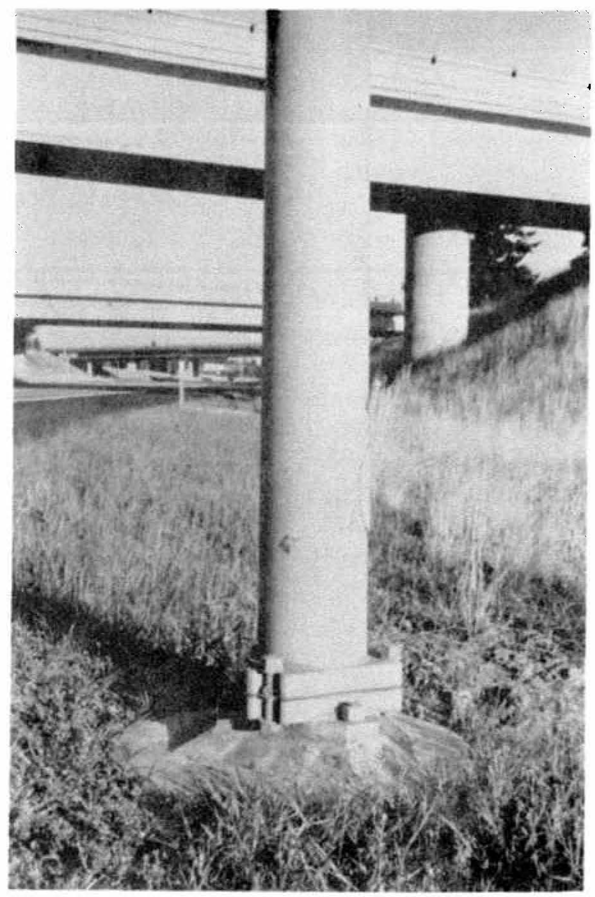

Figure 15. The multi-directional slip base.

The multi-directional slip base has been approved for use on Federal-Aid projects when designed and installed in accordance with requirements outlined in FHWA Notice N5040.20 (July 14, 1976), as follows:

- Weight 1000 pounds or less
- Have a total slip face clamping force less than 45 kips. (A force one-quarter this amount or less would be preferred and should give good service under wind loads.) (The clamping force must be controlled by installing bolts with a torque wrench, using torque limiting nuts, or another acceptable method.)
- Have a 28-gage steel keeper plate or equivalent to prevent "walking"
- Have washers with the clamping bolts of sufficient strength to prevent the washers' cupping into the vee slots
- Have a stub height of 4 inches or less

Stainless Steel Bases. A specially-designed stainless steel base and support has been used extensively as a breakaway design by a number of state agencies. The shaft of the support is fabricated from stainless steel and is welded to a stainless steel base or box as shown in Figure 16. This base is then riveted to a stainless steel base plate which is bolted to a concrete foundation. The failure mechanism is in the area where the box is riveted to the base plate. When a vehicle strikes the box, the rivets are sheared and the support breaks away.

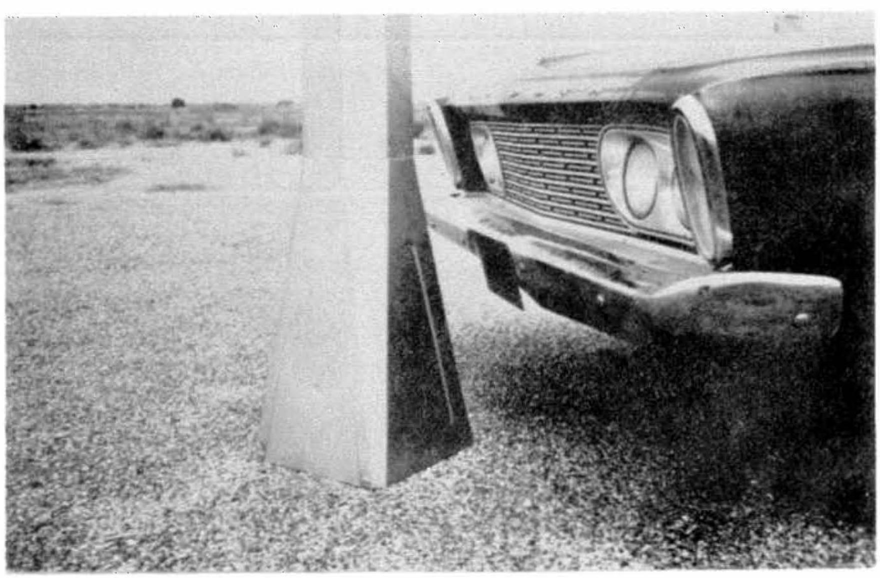

Figure 16. Stainless steel base and support.

Kaiser Anchor Base. The Kaiser Aluminum and Chemical Corporation has developed a family of cast aluminum bases (not a T-base) for use with poles with mounting heights up to 50 feet. The 8-, 9-, and 13-inch bases are acceptable for use on Federal-Aid projects.

Luminaire Pole Foundations

The eventual success and reliability of a lighting system will depend to a great extent on the pole foundation. The foundation must provide for accurate alignment of the luminaire so that the distribution of luminous flux can be maintained as designed. In addition, the foundation must resist overturning movements created by windloads and must be able to withstand considerable impact should a pole be struck. At the same time, the foundation itself must not be a potential hazard.

Most foundations are prepared in drilled shafts with special cage reinforcement, longitudinal reinforcement, and anchor bolt embedment. Quite often, the foundation footing must be replaced at considerable depth. Comprehensive soil information and geographical-weather information are usually necessary to determine foundation designs. Chapter 6 discusses foundation design in greater detail.

HIGH MAST LIGHTING EQUIPMENT

The design of high mast lighting equipment is considerably more complex than the design of conventional roadway lighting equipment discussed in previous sections. In the developmental stage, high mast equipment has taken several forms. Vertical truss type antenna towers were used, as well as straight and tapered steel masts. Methods of installing and servicing luminaires at the top of the pole have ranged from access by climbing, access by special personnel carrier, and finally access by lowering the luminaires to the ground level. From all of these earlier developmental efforts, a common configuration has emerged which consists of the following major elements: (1) luminaires, (2) luminaire mounting assembly, (3) mast, (4) foundation, and (5) raising and lowering assembly (see Figure 17).

High Mast Luminaires

High mast luminaires were discussed earlier and consist primarily of IES Type V, Type IV, Type I, and floodlight type luminaires. The Type I luminaire used in high mast lighting is frequently referred to as Type V assymetric or as a modified Type I. Whereas IES intended a Type I to describe a luminaire to be mounted over the street and to put out a long narrow beam in both directions, the assymetric high mast luminaire is in fact a slightly elongated Type V which will fit a fairly wide freeway section, but yet provide a generally rectangular pattern. Typical high mast luminaires are illustrated in Figure 18.

Floodlights are used where light sources are located along the edge of the roadway and aimed to provide a uniform distribution over the area to be lighted. In general, luminaires used in high mast installations use either 400 or 1000 W high pressure sodium or 1000 W metal halide lamps. Oftentimes, they are designed to allow lateral rotation for easy alignment of the optics with the roadway.

Further discussion relative to the selection of light sources is included in Chapter 5--Selecting the Lighting System Configuration.

The Mounting Assembly

Whereas in conventional lighting the luminaires are attached to a mast arm, in high mast the luminaires are clustered on a mounting ring or assembly which is hoisted to the top of the mast for its normal operating position. This mounting ring is usually fabricated from either square or round steel tubing and hot-dipped galvanized to provide a lasting finish. This mounting ring is fabricated to accept the brackets or slip fitters for luminaires and ballasts. The mounting ring is frequently made in three parts to be bolted together at the lift points; thus, an attachment for

Figure 17. Common high mast configuration.

hooking to the lift cables may be provided at the joint. Also, the mounting ring should have three leveling pads which will be brought into contact with corresponding leveling pads at the top of the mast so that when the mounting ring is raised to its fully elevated position, it will be held firmly in place by tension in the hoisting cables and the luminaires will be positioned in their designed orientation.

In many designs, the ring is held in place by a locking mechanism. The mechanism is similar in concept to the retractor of a ball point pen.

Masts

The masts for high mast lighting are fabricated of steel and are typically round, octagonal, or polygonal in shape. They are almost always tapered from bottom to top in order to proportion the steel cross section to the bending moment of the mast. Masts may be monolithic, that is, made in one piece, or they may be telescoped together in several pieces. Telescoping is a matter of convenience in manufacturing and shipping of the masts. Most manufacturers prefer to work with the mast sections in their manufacturing process up to about 40 feet in length. Thus, a 100 foot mast could easily be made up of three sections each approximately 35 feet in length. These 35-foot sections could be hot-dipped galvanized with no great difficulty and shipped to the job site in sections. At the job site, the three sections would be telescoped together and the mast set in an upright position. Once the mast is upright there is little concern for separation at the telescoped connections.

There are three methods of protecting the surface of the mast. These are hot-dipped galvanizing, painting, and using weathering steels. Painted masts have not proven to be very popular because the paint surface is frequently damaged in transit and field patching of a factory finish has not proven to be satisfactory. The most desirable methods are hot-dipped galvanizing and weathering steels. The designer should contact manufacturers for specific pole design and protection methods.

Masts are typically fitted with a heavy steel flange which is bolted to a reinforced concrete foundation.

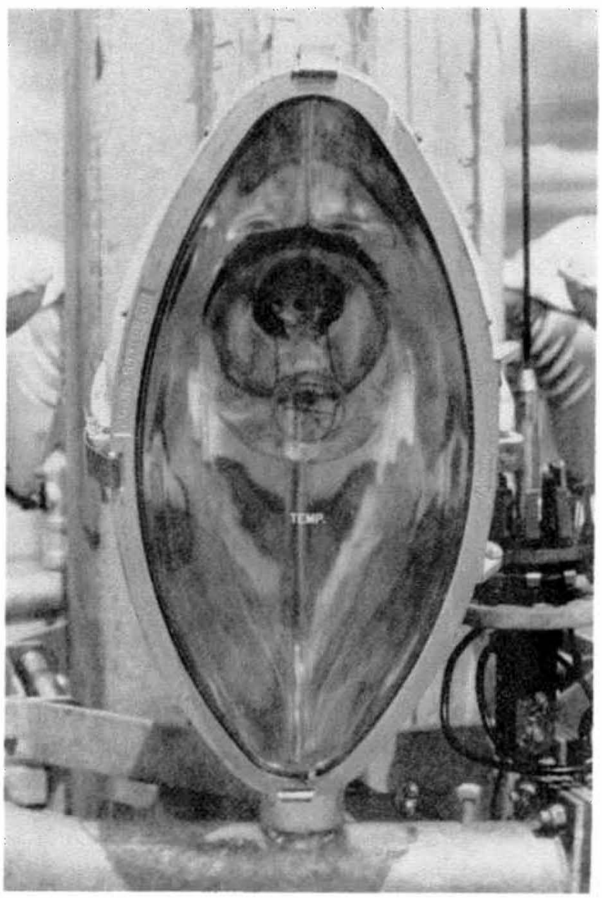

Figure 18. Typical high mast luminaires (floodlight above, Type I right).

The Foundation

The foundations for high mast lighting systems are highly variable, depending on local soil conditions and design procedures used by various foundation designers. Typically, however, the foundation for a high mast unit may be a combination of drilled shaft footing and a spread footing foundation. A drilled shaft footing from three to four feet in diameter may be supplemented by a concrete slab at or near the ground level. Of course, reinforced concrete is used throughout fabrication. It is significant to point out that foundation design for a massive structure such as a high mast lighting assembly is complex and should be performed by those with experience in foundation design.

Raising and Lowering Assembly

The raising and lowering assembly usually consists of a winch at the base of the pole, a mast head with pulleys in each of three arms, and a cable system which fastens to the mounting ring, passes over the pulleys at the mast head, and connects to a winch at the base of the mast. This winch may be powered by a stationary motor or by a portable power source such as a heavy duty drill. The power unit must be able to operate in both directions in order to drive the winch and the assembly either in the up or down direction. In any case, there should be sufficient lead on the control cable to allow personnel to stand free of the moving luminaire assembly.

Typically, the cables that hoist the luminaire ring are ¼" aircraft-type stainless steel cables. Three lift cables are used in order to maintain stability of this ring when it is being raised or lowered. The cables pass over pulleys in a mast head. The pulleys should be stainless steel and should be equipped with roller bearings. Oilite bushings, or grease impregnated bushings, are sometimes used, but it is considered advisable to use sealed bearings because of the relative inactivity of the pulleys. The cables are brought together in a single connection. At this point, a (down) cable hooks to the three lift cables and to the winch at the base of the pole. By winding the down cable onto the winch drum, the ring assembly is lifted to the top of the mast. Correspondingly, unwinding this down cable from the winch drum lowers the ring to the ground. In some designs, counter weights are used in the assembly as an aid to raising and lowering.

Some agencies specify that the down line be a link chain rather than cable. There are no strong reasons as to why a chain should be used in preference to cable, and therefore it is felt that principally this is designer preference.

Some high mast systems require that the luminaires and mounting assembly be supported continuously on the lift cables. In other words, there is no provision to lock the mounting assembly in place once it is hoisted to the top. Other designs do provide a locking mechanism. Regardless of choice, the cables are sufficiently strong to preclude failure under all but the rarest of circumstances.

It is desirable, however, to hold the mounting assembly in place once it is hoisted to the top of the mast. Stability may be provided by a cup and cone arrangement so that the cone mates with the cup and prevents both vertical and horizontal movement of the mounting assembly.

Electrical power is provided to the luminaires through a 3-conductor cable that passes over a large pulley at the mast head. The electrical cable is secured at both ends and runs parallel with the lift cables. When the mounting assembly is hoisted to the top, the cable is plugged into a receptacle at the base of the pole. To lower the assembly, the power is simply unplugged. To energize the luminaires when the mounting assembly is lowered for servicing, an alternate conductor must be provided.

The power source for driving the winch may be the same as used to energize the luminaires. The voltage of the drill must be compatible or a step down transformer must be used. Portable power may also be used and can service a large number of masts. A heavy-duty industrial type drill may be modified for attachment to the winch, as illustrated in Figure 19.

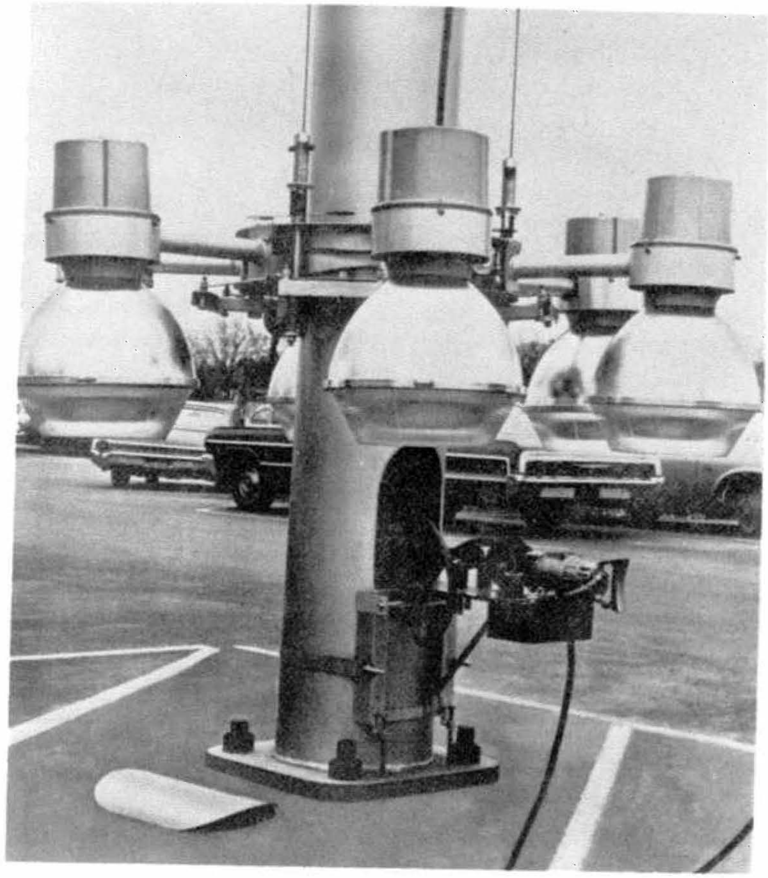

Figure 19. A heavy-duty, industrial-type drill for attachment to high mast winch.

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5

SELECTING THE LIGHTING SYSTEM CONFIGURATION

SELECTING THE LIGHTING SYSTEM CONFIGURATION

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

The previous chapter has provided a review of the various equipment elements such as light sources, luminaires support hardware, and foundations that are combined to comprise the illumination system. This chapter provides an insight to the various ways in which the equipment elements are applied in order to best satisfy the user needs. The combination of equipment elements, referred to as system configuration, is dependent upon a number of factors, but primarily the characteristics of the facility to be lighted and the characteristics and specific needs of the users. As discussed in the introductory chapter, facility characteristics and the characteristics and needs of users vary according to the type or class of facility. A classification of facilities for lighting is presented in the following section and will be used as the framework for discussing system configurations.

CLASSIFICATION OF ROADWAYS, WALKWAYS, BIKEWAYS

Roadway, Pedestrian Walkway, and Bikeway Classifications

Our system of streets and highways is composed of several different types of facilities, each serving a different function. Functional classification of streets and highways then becomes the mechanism by which we are able to communicate the criteria and constraints for the process of planning, designing, and operating these facilities. The functional classification system is especially important to all aspects of the lighting process, and therefore, the classification adopted by the American National Standard Practice is presented below:

- *Freeway.* A divided major roadway with full control of access and with no crossings at grade. This definition applies to toll as well as non-toll roads.
- *Expressway.* A divided major roadway for through traffic with partial control of access and generally with interchanges at major crossroads. Expressways for noncommercial traffic within parks and park-like areas are generally known as parkways.
- *Major.* The part of the roadway system that serves as the principal network for through traffic. The routes connect areas of principal traffic generation and important rural highways entering the city.
- *Collector.* The distributor and collector roadways serving traffic between major and local roadways. These are roadways used mainly for traffic movements within residential, commercial, and industrial areas.
- *Local.* Roadways used primarily for direct access to residential, commercial, industrial,

or other abutting property. They do not include roadways carrying through traffic. Long local roadways will generally be divided into short sections by collector roadway systems.

- *Alleys.* A narrow public way within a block, generally used for vehicular access to the rear of abutting properties.

- *Sidewalks.* Paved or otherwise improved areas for pedestrian use, located within public street rights-of-way which also contain roadways for vehicular traffic.

- *Pedestrian Way.* A public walk for pedestrian traffic not necessarily within the right-of-way for a vehicular traffic roadway. Included are sky walks (pedestrian overpasses), subwalks (pedestrian tunnels), walkways giving access to parks or block interiors and midblock street crossings.

- *Isolated Interchange.* A grade separated roadway crossing which is not a part of a continuously lighted system, with one or more ramp connections with the crossroad.

- *Isolated Intersection.* The general area where two or more non-continuously lighted roadways join or cross at the same level. This area includes the roadway and roadside facilities for traffic movement in that area. A special type is the channelized intersection in which traffic is directed into definite paths by islands with raised curbing.

- *Bikeway.* A public street, highway, or separate path, identified as part of a bicycle travel network. Bikeways may consist of the following:

  Type-A Bikeway. A strip within or adjacent to a public roadway or shoulder, marked for bicycle travel.

  Type-B Bikeway. An improved strip identified for public bicycle travel and located away from a roadway or its adjacent sidewalk system.

Area Classifications

Although the above classifications normally reflect the geometric and operational conditions to be expected on a traffic facility, additional subclassifications by area type and environmental conditions are necessary. The American National Standard Practice recommends the following area classification:

- *Commercial.* That portion of a municipality in a business development where ordinarily there are large numbers of pedestrians during business hours. This definition applies to densely developed business areas outside of, as well as those that are within, the central part of a municipality. Contains land use which attracts a relatively heavy volume of nighttime vehicular and/or pedestrian traffic on a frequent basis.

- *Intermediate.* That portion of a municipality often characterized as in blocks having libraries, community recreation centers, large apartment buildings, or neighborhood retail stores.

- *Residential.* A residential development, or a mixture of residential and commercial establishments, characterized by a few pedestrians at night. This definition includes areas with single family homes, townhouses, and/or small apartment buildings.

- *Rural.* Open land with little or no commercial or residential development.

FREEWAYS, EXPRESSWAYS, AND INTERCHANGES

General Objectives

Although lighting generally serves a multiplicity of functions in its general application, these are

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quickly narrowed almost to a single-purpose function when applied to freeways and expressways--that is, to provide improved driver visibility. When this purpose is satisfied, however, a number of other sub-objectives may be satisfied. By improving driver visibility we may, in turn, improve traffic operations, increase capacity, reduce accidents (improve safety), and, in general, enhance the driving environment. In clarification of this latter point, visualize the driver in the interior lane of a six-lane freeway at night depending on vehicle headlights to light the way. The familiar landmarks by which he normally drives--curbs, shoulders, intersections, driveways, development, controls, and other physical objects--are gone. The driver is in darkness of indeterminate dimensions. Lighting pushes back the darkness, revealing the roadway features that are familiar to the driver and permits perception and judgment similar to that afforded by daylight conditions.

Perhaps the most tangible justification for freeway lighting can be expressed in terms of driver safety. Of interest is a report on freeway illumination by Box (1). The study suggests that the installation of lighting probably is effective in lowering the night accident rate. While no unanimous agreement on the benefits of lighting has been established, the vast majority of studies in the United States and foreign countries show significant reductions in accidents as a result of lighting (2, 3, 4, 5, 6, 7, 8, 9, 10, 11).

Lighting systems for freeways and expressways are divided into two different types of systems for discussion: Continuous Lighting and Interchange Lighting. Within each of these types, there are several different system configurations, dependent upon the characteristics of the facility to be lighted.

Continuous Lighting Systems

"Continuous Lighting" is a term applied to the lighting of the main lanes (and frontage roads, if applicable) on freeways. As the term implies, a continuous "ribbon" of light encompasses the roadway and the area immediately adjacent to the roadway over a substantial distance. In concept, driver information needs are within and contiguous to the freeway, and therefore, that should be the area where the light is concentrated.

Early freeway lighting projects utilized technology and equipment generally available in the area of street lighting. These early experiences indicated, in general, that street lighting technology was inadequate for freeway lighting purpose, and that new technology should be developed.

Because of the wider roadways and higher traffic speeds, light sources were increased in lumen emission and mounted higher above the roadway. This reduced the glare effects, improved uniformity, and permitted improved illumination of larger roadway areas. Specific changes resulted in the mercury vapor light source being increased to 1000 watts (55,000 lumens) and mounting heights being increased to 40 and 50 feet. Since then, technology has permitted the application of metal halide and high pressure sodium sources at lower wattages because of their increased efficacy over the mercury vapor source. It appears that 40 to 50 feet is the acceptable freeway mounting height because it reduces significantly the number of supports required and still provides a mounting height that is accessible for maintenance without highly specialized equipment.

Another carryover from conventional street lighting systems was the "house-side" or side-mounted systems. Because early streets generally did not have medians, the only choices were the mount light sources along the side of the street or suspend them overhead. In fact, early side-mounted systems utilized long mast arms in order to get the light source out over the street. In applying these systems to freeways, it was found that better illumination could be achieved by mounting the luminaire over the shoulder or at the edge of the traveled way rather than over the traffic lanes. Uniformity on the main lanes was improved, and specular reflection was reduced, particularly in wet weather.

Because freeways and expressways were, by design, wide multi-lane roadways within a median strip separating the two directional roadways, the conventional one-side and staggered lighting systems were not applicable to the entire system; each roadway was lighted independently from the outside edge of the roadway. Early considerations of placing luminaire supports in the median were rejected because the median was to remain a clear area for reasons of safety. Accident experience on early freeways indicated a severe problem with vehicles crossing the median, particularly the narrow medians in urban areas, and colliding with vehicles in the opposing direction. Physical barriers were developed to reduce vehicle encroachment. When these barriers became popular, a secondary benefit was derived as protection for the lighting system, or to eliminate or reduce the probability of a collision with a luminaire support. Integrating the luminaire support with the median barrier has become the most common approach to lighting freeways and expressways.

Median Lighting. The popularity of the median lighting configuration is due to several other factors. Perhaps a primary one is economy. Placing the luminaire supports in the median reduces the number of supports required by one-half over that required for side-mounted configurations. Additional supports may be required for supplemental lighting in the areas of ramp terminals and interchanges. Also, as there is only one row of supports, there is need for only one run of electrical conductor. Savings in material and construction costs are substantial. In addition to the economic advantage of median lighting, there is a service advantage; median lighting simply provides better visibility. The illumination level dissipates slowly across the traffic lanes and out into the areas adjacent to the roadway. The highest level of illumination is along the median and inside higher speed lanes. The horizontal light component is proportionately high in the border areas and aids the driver's visibility. This effect is compared by schematic (Figure 20) to show the contrast with side-mounted lighting. In the side-mounted configuration, the highest illumination level is along the edge of the roadway, between the driver and the peripheral area. This is, in effect, a brightness curtain that reduces the driver's ability to see beyond the edge of the roadway. The net result is an "illumination tunnel."

Due to the economic and service factors, median lighting should be the first consideration in lighting the main lanes of freeways and expressways. However, there are several conditions where median lighting may not be the most applicable. Among these are:

- Freeways and expressways where the median is to be used for transit vehicles.
- Freeways and expressways where there is no median barrier and the relative hazard of fixed-object collisions would be increased.
- Freeways and expressways on separate alignment or where the median is too wide for both directional roadways to be lighted from one mast.
- Freeways and expressways in urban areas where the facility is depressed.

Regarding the first of these conditions, freeways in some large metropolitan areas are being designed or redesigned to provide an exclusive travel way for bus or rapid transit in the median area. This may be two-way operation, or one-way reversible to accommodate buses flowing in the peak direction only. Regardless, this type of operation generally precludes the use of the median area for lighting supports. There is one exception, however, where a physical barrier, typically a concrete median barrier, is used to separate the busway from the main traffic lanes. In this instance luminaire supports may be integrated with the median barrier. Understandably, this approach would result in an off-center system with one short and one long mast arm for single luminaires on each side of the busway. The choice between these two alternatives is largely dependent upon the width of the busway and the capability of the median-mounted system to provide complete coverage.

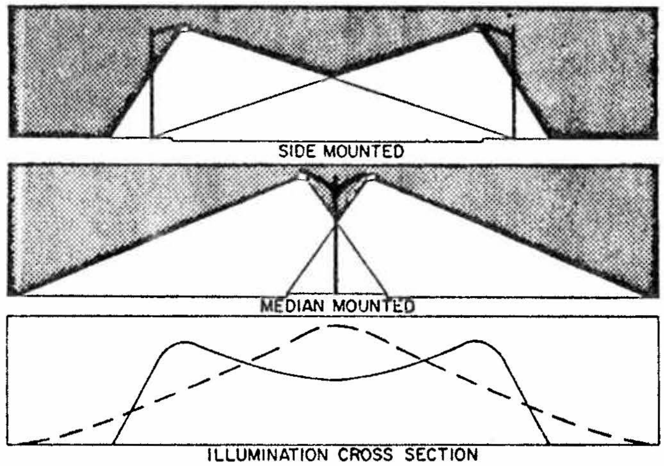

Figure 20. Comparative distribution of illumination for median vs. side-mounted systems.

The second condition which may preclude the use of median lighting is the situation where there is no median barrier, and the placement of luminaire supports would perhaps constitute a greater hazard than if they were side-mounted. The additional hazard one may anticipate is in the case of a luminaire support being driven into the opposing traffic lanes by the impact of a collision. The result of such a collision is largely speculative because speed of the colliding vehicle, the angle of impact, the distribution of the mass of the support, and many other factors determine the post-collision behavior of the support. There are two points to consider in reaching a decision on whether to use median lighting without the protection of a median barrier. First, the current Federal Highway Administration policy permits the use of breakaway luminaire supports in medians when the median contains no barrier and is wider than 40 feet. Thus, on all Federal-Aid projects, this policy will govern.

The second point in determining whether median lighting should be used is provided in Figure 21. The relative hazard of side-mounted vs. median-mounted configurations is compared. In this study conducted by TTI (12), the relative hazard was determined as the product of

- the probability of a vehicle encroaching on the median or roadside far enough to strike a support; by
- the probability of the vehicle actually striking a support; and by
- the probability of the support encroaching upon the opposing traffic lanes.

This study was based on a comparison of a median-mounted system, with the median width as the variable. It should be noted that both systems were mounted 50 feet high. Longitudinal spacing on the two systems resulted in comparable illumination quality (2). The side-mounted system was mounted 15 feet laterally from the edge of the traveled way. Based on these conditions, it may be noted in Figure 21 that, for any median width greater than about 32 feet, it is relatively safer to use a median-mounted system.

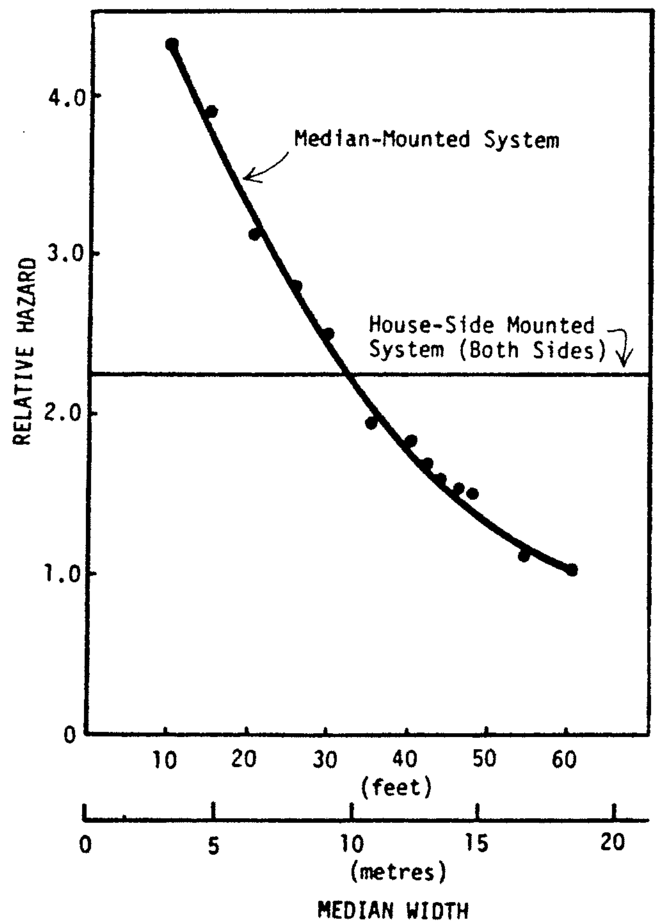

Figure 21. Relative hazard of median vs. side-mounted lighting.

In the third condition (median too wide), there is naturally a limit to the width of a median where median lighting can be utilized effectively. Mast arm lengths greater than about 20 feet are impractical. Thus, if one chooses to place the light source over the edge of an inside shoulder of 6-10 feet, the practical limit on median width would be 52 to 60 feet. There are a number of installations where median lighting is used in median widths in this range, and they provide excellent service. Examples of these installations are illustrated in Figure 22. It should be noted, however, that Type II or Type III luminaires are generally used and they are tilted upward to transverse the roadway by an angle of 5 to 10 degrees, or to their maximum vertical adjustment in the slip-fitter.

In the fourth condition where the freeway is depressed in urban areas, wall-mounted lighting may prove to be the best solution in providing economical lighting. Light units can often be mounted directly to the retaining wall, eliminating the need for poles. The wall-mounted system also provides for high quality visibility.

Figure 22. Example of median-mounted lighting in wide median.

It is a foregone conclusion that breakaway bases should be used when median-mounted lighting is used without a median barrier. Experience throughout the nation has demonstrated an unquestionable safety advantage of breakaway bases on the intermediate to high speed traffic facilities such as freeways and expressways. Their application to arterials and other streets will be discussed later in this chapter.

When luminaire supports are integrated with a median barrier, breakaway bases may or may not be applicable, dependent upon the type and characteristics of the median barrier. Median barriers are normally of three types: flexible, semi-rigid, and rigid, characterized by the amount of deflection permitted during impact. For more detail on median barriers, refer to NCHRP Report No. 118 (13), or FHWA Report No. FHWA-RD-76-504, "Guide for Selecting, Locating, and Designing Traffic Barriers" (14). Typically, allowable deflection for the three types are 8-12 feet, 2 feet, and 0 feet, respectively. Because of the large deflection of the flexible barrier, median-mounted lighting should not be integrated with this type of barrier. The luminaire support would constitute a fixed or semi-rigid object in a flexible system, and the barrier system would simply guide the vehicle into a collision with the luminaire support. If for some reason luminaire supports must be integrated with flexible barriers, they certainly should have breakaway bases.

Luminaire supports are frequently integrated with semi-rigid barriers with a great degree of success. The semi-rigid barrier, typically a double-beam section using two flexbeams or standard W-sections on wood or steel posts, is illustrated in Figure 23. Design standards limit deflection to 2 feet, and the system provides a certain amount of beam action to redirect a vehicle and reduce the effect of "pocketing" the vehicle against the luminaire support. Generally, there are two modifications in the barrier design when luminaire supports

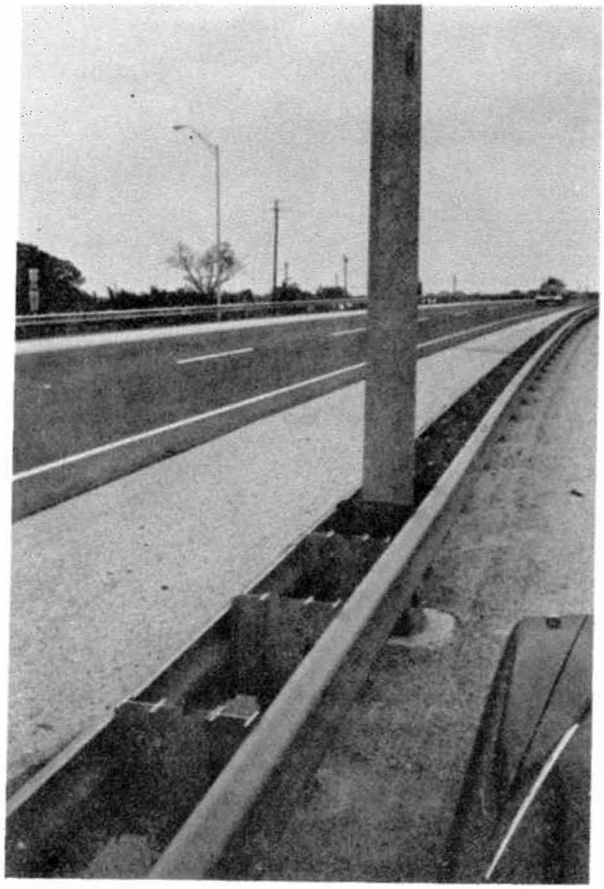

Figure 23. Semi-rigid barrier with luminaire support.

are included: (1) the barrier beams are spread with additional blocking to provide more space between the beam and the luminaire support, and (2) the barrier is stiffened in the vicinity of the support to increase the beam action and further reduce the pocketing effect. For further details, see Reference 13. Some, however, have chosen to continue the normal section of the barrier without widening or stiffening, and simply use breakaway supports.

Integrating luminaire supports with rigid concrete median barriers is perhaps the simplest of all such installations. Several different agencies around the country have chosen different approaches. The main design consideration stems from the barrier design. The standard barrier is 6 inches wide at the top and tapers out toward the base as shown in Figure 24. Because the base plate on the luminaire supports is typically about twice the dimension of the top of the barrier, some modifications are necessary for compatibility.

One alternative is to widen the top of the barrier in the vicinity of the luminaire support. The state of Oregon has used this method and apparently it has been successful. Rather than use localized widening, Texas chose to widen the barriers to

Figure 24. Standard concrete median barrier.

8 inches and redesign the luminaire support to fit the top of the barrier (Figure 25). The round tapered steel pole is forced into an oval shape to fit a base plate 8 inches in width. This design has been tested in full-scale crash tests and installed in a substantial number of locations. It is the standard design for Texas.

It should be noted that in both situations, a drilled-shaft type foundation is placed under the barrier at the support location, and sufficient reenforcement of the concrete is provided. Many rigid barriers today are constructed using prefabricated (pre-cast) sections or slip-forming methods. In both instances, the section to contain the luminaire support is formed and poured by conventional procedures after the other sections have been placed.

In other design variations, some states, including Minnesota, have left an opening in the median barrier to facilitate mounting the luminaire supports flush with the top of the median. Continuity across the opening is provided by a "fish plate," a piece of steel bolted across the opening. In Wisconsin, a split barrier was used to provide protection of luminaire supports as well as sign supports, bridge piers, and other fixed objects. As shown in Figure 26, the two barrier sections are spaced 36 inches apart, and luminaire supports are mounted flush with the median. It is interesting to note also that the electrical conductors are placed within the space between the two barriers, which is not covered.

Side-Mounted Systems. There are certain features of side-mounted systems that should be discussed from the application standpoint. These include location, protection, and application of breakaway bases. Both proven and experimental application will be discussed.

There are two aspects of location of side-mounted luminaire supports: lateral and longitudinal. Lateral location of the support is dictated to a great degree by the location of the light source.

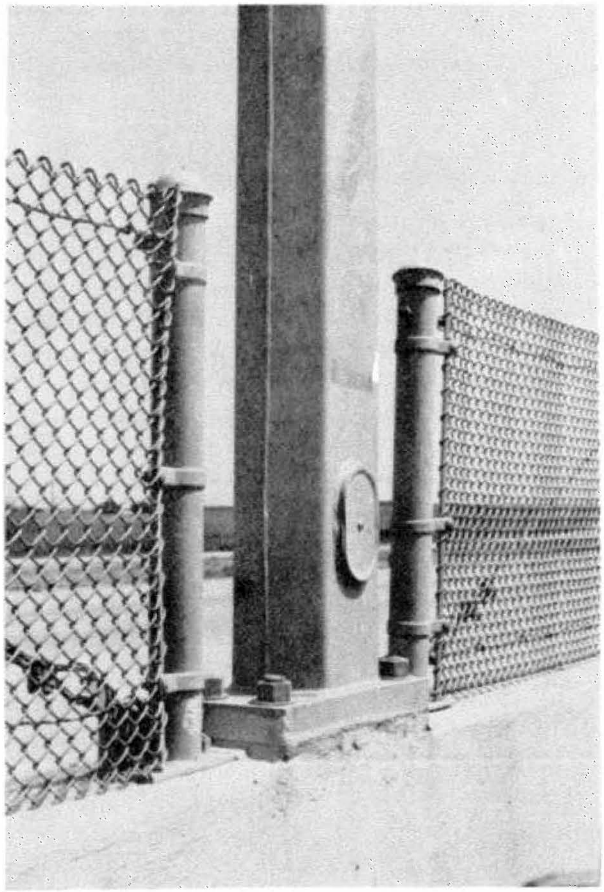

Figure 25. Texas design of the concrete median barrier using a widened top and modified pole.

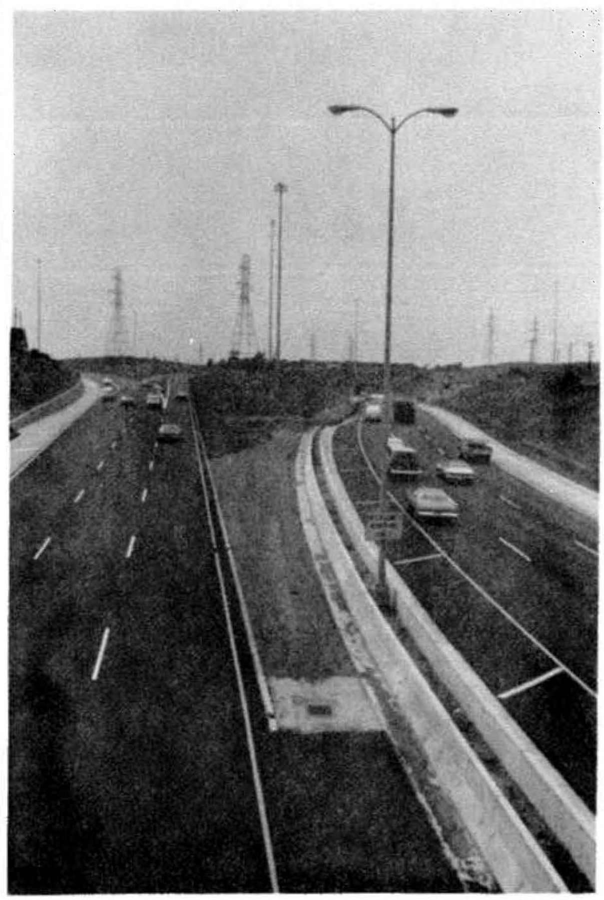

Figure 26. Wisconsin split concrete median barrier.

Some feel that the luminaire should be over the shoulder, while others feel that it should be over the edge of the traffic lanes. Obviously, the choice of luminaire location and the lateral clearance desired for safety will determine the length of mast arm required.

Lengths of 4 to 30 feet have been used, but most designers seem to prefer lengths of 12 to 15 feet for the best aesthetic proportioning with 50-foot mounting heights. Practical lateral positioning of the mast is between 15 and 30 feet from the edge of the traveled way.

The clear roadside concept, established as an FHWA policy, requires that all fixed objects within 30 feet of the traveled way be removed or made breakaway. Otherwise, they are to be protected by guardrail or impact attentuation devices. Research and experience have shown that protection of luminaire supports by guardrail or impact attenuation is not practical, cost-effective, or safe. A section of guardrail has a higher degree of accident incidence and severity than a section of luminaire supports without the guardrail; thus, they must be removed or made breakaway. Most agencies have opted for the breakaway alternative. Still, there is the need to locate the luminaire supports with breakaway devices as far away from the traveled way as practicable, for the probability of impact diminishes as lateral distances increases. A good example is the lighting system on I-5 in Portland, Oregon. A special mast design was utilized to provide maximum lateral clearance as well as slip base breakaway features. Also, luminaire supports were mounted on retaining walls and other structures where possible (Figure 27).

Figure 27. Luminaire supports mounted on retaining walls.

In applying side-mounted lighting, it is important to also consider the safety aspects of the longitudinal location of luminaire supports. The normal spacing must be adjusted in the vicinity of ramps, merge areas, lane drops, and other major maneuver points. The basic rule is to avoid locating a luminaire support in an area that has a high probability of vehicle encroachment. The most common problem is the ramp gore area. Supports in the immediate gore areas should be located on the outside of the ramp and preferably slightly in front of the gore. Then the next support will be located almost a full normal space beyond the point of bifurcation. This should provide sufficient distance for an errant vehicle to avoid a collision with the support or to decelerate appreciably.

In the early stages of implementing the clear roadside concept, some agencies chose to increase the lateral location of luminaire supports rather than use breakaway bases. One innovative alternative, proposed by Ketvirtis and Hobson in 1969, is known as the Offset Luminaire Concept. The authors developed a test installation on the Queen Elizabeth Way, a 6-lane freeway with a 36-foot median in Toronto, Canada. Type III medium cut-off luminaires with 700-watt clear mercury lamps were mounted to 50-foot mounting heights 35 feet from the edge of the traveled way. Approximate luminaire spacing was 185 feet and the illuminated strip along the roadway was approximately 180 feet wide. To light this area, the luminaires were tilted upward at an angle of 15 degrees above normal or horizontal position. Ketvirtis and Hobson reported satisfactory results from the test installation.

A study of the offset luminaire concept was conducted by Wilson and Johnson (5) on I-55 in Southaven, Mississippi. The system utilized a special offset luminaire mounted at a vertical angle of 45 degrees atop a 40-foot pole. The luminaire used a 250 watt high pressure sodium lamp. The beam of maximum candlepower was 72.5 degrees above the vertical. In the test installation, the supports were located 30 feet from the traveled way and spaced 280 feet apart. Wilson claims that the quality of lighting was comparable to conventional lighting with improved aesthetics.

The state of Wisconsin has reported limited experience with offset luminaires and their conclusions are typical. Offset luminaires provide good illumination on the straight sections of roadway, but excessive glare due to source brightness is sometimes experienced on the curves and hills. Recent advancements in breakaway base technology has reduced the need for offset luminaires.

The offset luminaire concept is illustrated in Figure 28.

Specialized Mainlane Systems. There are a number of specialized and innovative systems that have been used to light the main lanes of freeways and expressways. Some are experimental in nature while others are practical expansions of systems already discussed. Most of the specialized systems are designed and utilized for complex highway systems in major metropolitan areas such as dual-dual freeways, partially elevated freeways, mixed mode systems such as the exclusive median busways discussed earlier, and other extremely wide and multiple roadway systems. These systems require specialized and innovative design approaches to achieve effective lighting.

One major consideration of the designer in complex roadway situations should be to minimize the number of luminaire supports while maintaining acceptable illumination and uniformity levels. The reasons are two-fold: economy and improved aesthetics. For the dual-dual type of freeway (that is, two major roadways in each direction), twin mast arm supports may be placed in the outer separation of the roadways in the same manner as median-mounted systems are applied to the basic freeway section. This approach is applicable to the lighting of freeway-frontage road combinations as well.

High Mast Lighting. High mast lighting, commonly applied to the interchange areas, has been used for complex main lane sections. Where conditions

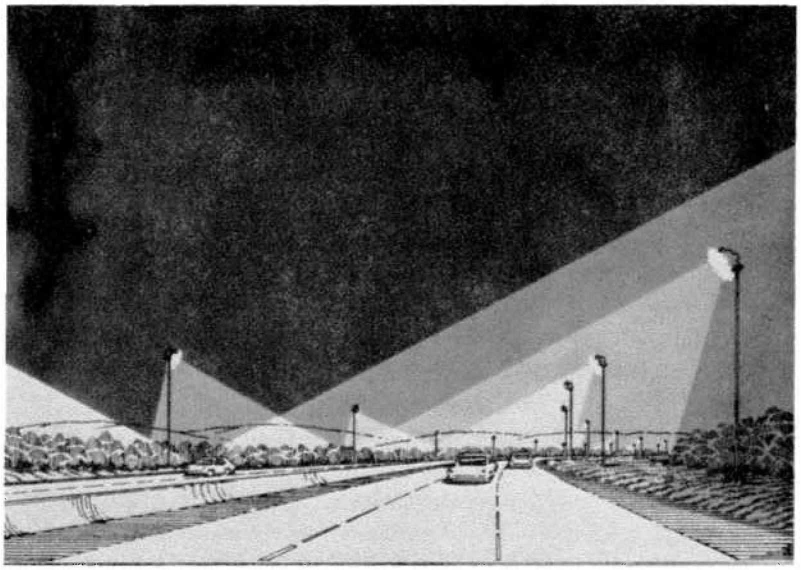

Figure 28. Illustration of the offset luminaire concept (left--concept; below--typical offset luminaire).

permit, the masts are sometimes installed in the median and protected by barriers. Where the median area is being reserved for possible future use for rapid transit, high mast units have been placed on the outer extremes of the freeway system. The re-design of the Gulf Freeway (I-45) in Houston, Texas, is an excellent example of this type of installation. Masts are located in a staggered pattern, nominally 750 feet apart along the right-of-way line. Floodlights on 150-foot masts are used to light two major roadways and a frontage road in each direction.

The re-design of the Gulf Freeway brings up another major point in the lighting of complex systems. Like many other urban freeways that will be rebuilt in years to come, some of the lanes will be elevated while other lanes will be built at grade; this is necessary to fit the total design into existing right-of-way. It is virtually impossible to light these sections with conventional systems because the difference in elevation of the various roadway sections are almost as great as the mounting height of the conventional (40 to 50 foot mounting height) light sources. Glare control, uniformity, and maintenance of illumination levels will be very difficult to achieve. In these instances the only practical approach is to utilize high mast systems which can be designed to accommodate substantial differences in roadway elevations.

Catenary Lighting. Catenary lighting is an innovative system developed and used extensively in Europe, but has not been applied to any specific degree in this country. The system derives its name from the method of construction. A catenary is used to support luminaires evenly spaced along the horizontal cable. Because the number of luminaires that can be used is no longer a function of supports used, numerous smaller luminaires are used to achieve excellent uniformity.

Catenary systems are used primarily in the Netherlands and in Germany. Systems installed in the Netherlands typically are low pressure sodium units mounted at 10 metres. Luminaire spacing is 1.0 to 1.5 mounting heights, and mast spacing is 4 to 6 mounting heights. A dual catenary system was used in a major cloverleaf interchange with collector-distributor roads. A median-mounted catenary system was used on the approach to the interchange. Once in the interchange area, the median system was discontinued and a catenary system was placed in the outer separation between the main lanes and the collector-distributor roads. The loops and turning roadways of the interchange were lighted using low pressure sodium and conventional methods.

Installations in Germany utilized fluorescent fixtures in one and mercury or metal halide sources in the other. Otherwise, system characteristics were essentially the same.

The catenary systems are excellent performers, and one may question why they are not used in this country. Aside from the fact that installation costs are higher, they really are not applicable where an average of only 0.6 to 0.8 horizontal footcandle is the design objective. From another, but similar, viewpoint, catenary lighting is a product of European lighting philosophy where cut-off type fixtures are used to control glare and to increase the level of illumination. Further, they make extensive use of low pressure sodium which is a physically larger area source. Combining all these factors, they depend primarily on reflector control rather than refractor control for light distribution.

In contrast, the American approach to roadway lighting has been more tolerant of luminaire brightness and reduced uniformity of pavement brightness to achieve the economics necessary to light the vast array of urban street and highway networks in this country. Thus, our design technology makes use of the more compact sources which can be controlled optically for maximum distribution of luminous flux, and maximum spacing of light sources.

Other problems that may be anticipated in the application of catenary systems is the difficulty in negotiating curved sections without guy wires, and the lack of aesthetic quality due to the overhead cables and electrical conductors.

Unidirectional Lighting. A great deal of experimentation with unidirectional systems has been done in the Chicago area. The state of Illinois and at least two manufacturers have been involved. The unidirectional system is designed to direct most of the illumination down the roadway in the direction of traffic flow; very little light is directed upstream into the driver's eye. As a result, pavement luminance is comparatively low, and seeing is by surface detail or reverse silhouette rather than by normally anticipated silhouette.

The unidirectional lighting experiments utilize 1000 watt mercury sources at 50-foot mounting heights and 250-foot longitudinal spacings in the median.

Results of the unidirectional lighting system tests indicate good visibility in the direction of traffic flow. The chief disadvantage of the unidirectional concept is the glare experienced by opposing traffic within approximately 1.6 mounting heights from the luminaire. Also, the glare problem is intensified by horizontal and vertical curves in the roadway.

Interchange Lighting

The freeway or expressway interchange is perhaps the most critical element of the road system, particularly from an operational viewpoint, because it is the area in which driver informational needs are greatest. The driver is confronted with decisions relative to navigational and situational tasks as well as maintaining lane position. These decisions are influenced to a great degree by the physical or geometric characteristics of the interchange and the potential conflicts of other traffic. The cues are usually off-axis from the area illuminated by headlight beams. The accuracy and, in fact, the success of the driver decision process is a function of how well he can "read" the conditions, i.e., see and judge the geometric and operational influences on the decision-making process. On this basis, lighting of interchanges is frequently of even greater importance than lighting the main lanes.

Interchange lighting may take a number of different forms, dependent upon the type and complexity of the interchange, the nature of land development surrounding the interchange, and the presence or absence of lighting on the main lanes of the freeway. For the purposes of discussing various interchange lighting applications, they will be classified as:

(1) Partial lighting

(2) Continuous or complete lighting

Partial Interchange Lighting. Partial lighting, as the name implies, is the process of illuminating only the parts of the interchange that are considered most critical to the night driver. The parts most frequently lit are the merge-diverge areas of the ramp connections, intersections, and critical roadway features. An illustration of partial lighting applications to the basic diamond interchange is shown in Figure 29.

The situation is further complicated when the diamond interchange involves frontage roads or service roads. This adds to the situation four more points to be lighted. Further, if the service roads are two-way operation, critical geometry at the ramp-service road terminals needs lighting. Figure 29 illustrates the critical points on a diamond interchange with two-way service roads.

Partial lighting is applied to other types of rural interchanges in much the same manner as it is

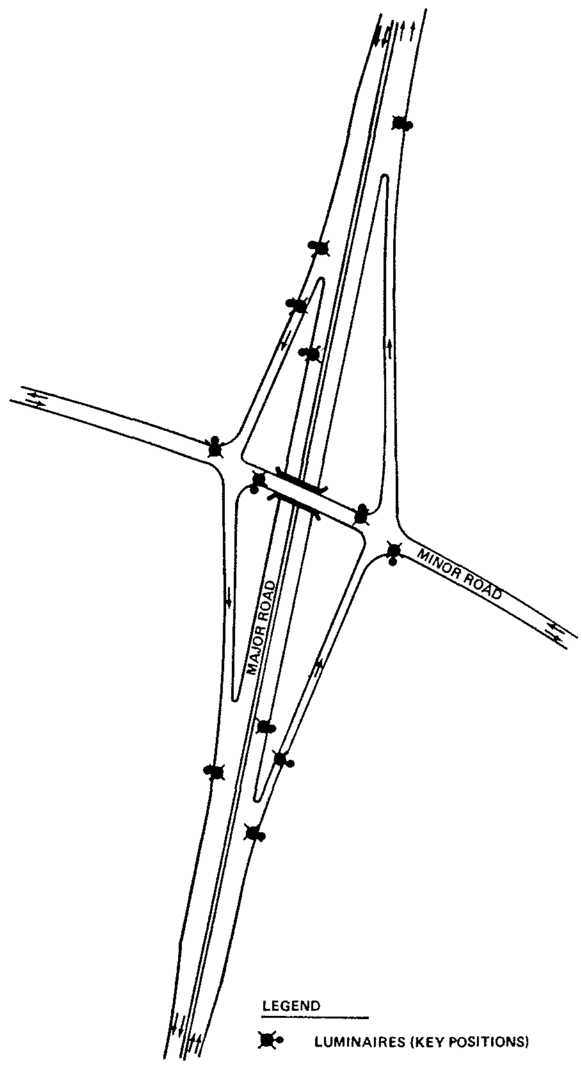

Figure 29. Illustration of partial lighting applications to the basic diamond interchange.

applied to the diamond. Differences arise primarily in the increased need for navigational information and more critical geometry. A very common rural interchange is the partial cloverleaf illustrated in Figure 30. In addition to the merge-diverge areas, critical points are the sharp curves in the off-ramps and the intersections with the highway. The problem with the curve is one of critical geometry. This can be alleviated in design by reversing the design so that the entrance rather than the exit

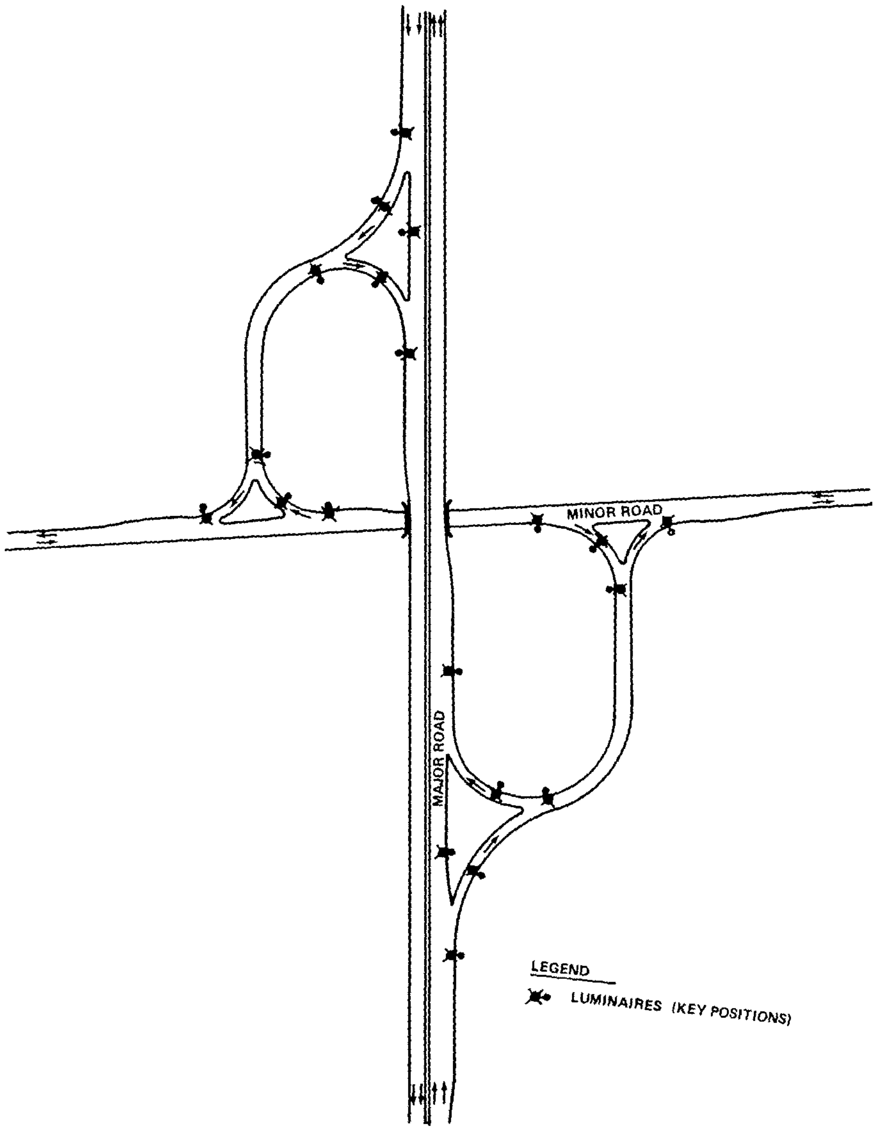

Figure 30. Partial cloverleaf interchange with partial lighting (19).

ramp has the critical curve. The problem with the ramp-highway intersection is one of driver orientation. Drivers may be confused and enter the exit ramp. Good directional signing is necessary, but it is more essential that the driver be able to see the geometry of the intersection. This illustrates a point in driver communication: for these intersection points to work best, they should be designed properly with channelization to prohibit or discourage wrong movements, signing to confirm the design, and lighting to give the driver the proper picture or perspective of the situation.

Partial lighting applications are generally limited to the simpler forms of interchanges where acceptable driver communications may be achieved by illumination of only the critical points of the interchange. One should keep in mind, however, that there are two major objectives in interchange lighting: one is to give the driver the overall picture of the interchange, and the second is to identify those critical points. On the simpler interchanges, it is assumed that the driver will be able to visualize the layout of the interchange by viewing the critical points. When the interchanges become more complicated such that the driver will need to be able to see the ramps, turning roadways, and the various elements of the interchange to get the visual picture, then it may be necessary to light the entire interchange. This is known simply as complete interchange lighting.

Complete Interchange Lighting. Complete interchange lighting is used to describe the process of applying lighting to the interchange in such a manner as to achieve illumination of all roadways in the interchange. Generally, complete interchange lighting is supplemental to the application of continuous lighting on the main lanes of various freeways or expressways. Commonly, luminaires in side-mounted configurations are located at regular spacings along the ramps and turning roadways of the interchange. Thus, by lighting the entire interchange, the visual picture is provided as well as the lighting of the critical points.

Complete interchange lighting is generally, but not necessarily, associated with freeways and expressways where the main lanes are lighted. It can be used in rural or suburban locations where there is a need for lighting the interchange, but not necessarily a need for lighting the main lanes. In such instances, the need generally arises from the complicated nature of the interchange. The designer must decide whether lighting at the critical points is sufficient or whether there is a need for lighting the entire area. This is a decision that the designer must make on the basis of a detailed analysis of driver informational needs relative to the actual interchanging conditions.

High Mast Interchange Lighting. Another method of interchange lighting is one commonly referred to as high mast area lighting. In high mast lighting, light sources are mounted on masts 80 feet or taller and located such that a uniform distribution of light is provided over the entire area. Most high mast illumination systems today range on the order of 100 to 150 feet in mounting height and utilize all types of lighting used to illuminate large interchanges or complex roadway systems which are amenable to the area lighting concept rather than conventional lighting as used on normal roadway sections.

The first applications of high mast lighting to the modern freeway interchange were in Europe. The Heerdter Triangle in Duesseldorf, Germany, the Brienenoord Interchange near Rotterdam, Holland, and others in England, France, and Italy were experimental ventures for the development of technology that is in general application today.

High mast applications in the U.S. were prompted by the apparent success of the experimental systems in Europe. Almost simultaneously, systems were installed in the states of Texas, South Dakota and Washington. The installations in Texas and South Dakota were the results of preliminary research at the Texas Transportation Institute to identify suitable high mast luminaires and to develop suitable mounting arrangements and support hardware. The preliminary studies at TTI were conducted using a portable antenna-type telescoping tower (Figure 31) to support floodlight systems up to 100-foot mounting heights. Once acceptable luminaires were identified and mounting arrangements were developed, the trial installations were made using microwave-type antenna towers that facilitate climbing for installation and maintenance (Figure 32).

The high mast lighting installation at the Auburn interchange in the state of Washington was the result of several years of study by engineers of the Washington Department of Highways and various lighting equipment manufacturers.

These early installations of high mast lighting represented the two different design concepts of the time. The installations in Texas and South Dakota utilized floodlights that produce a long, narrow banana-shaped distribution pattern when equipped with a clear lamp. These floodlights are aimed separately to produce the desired distribution on the roadway. In contrast, the installation at the Auburn interchange in Washington

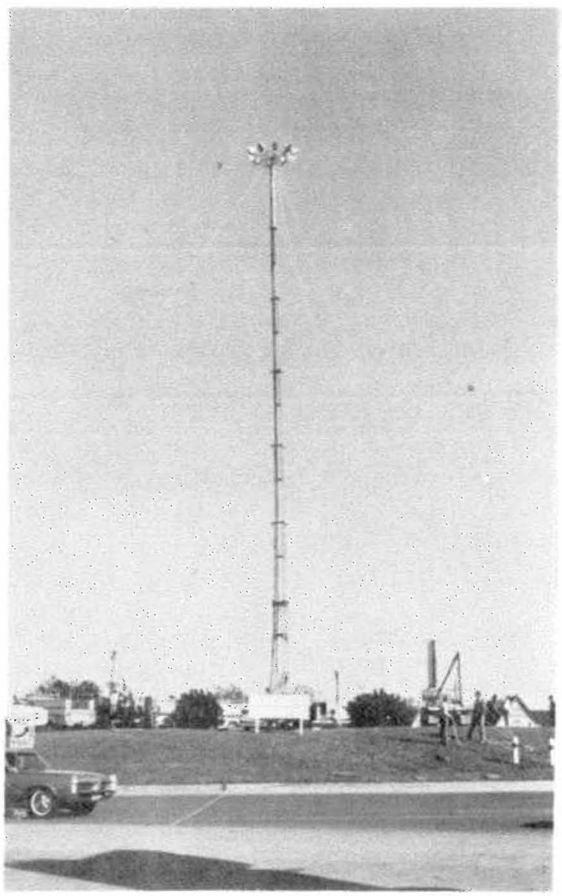

Figure 31. Portable telescoping tower used for high mast studies.

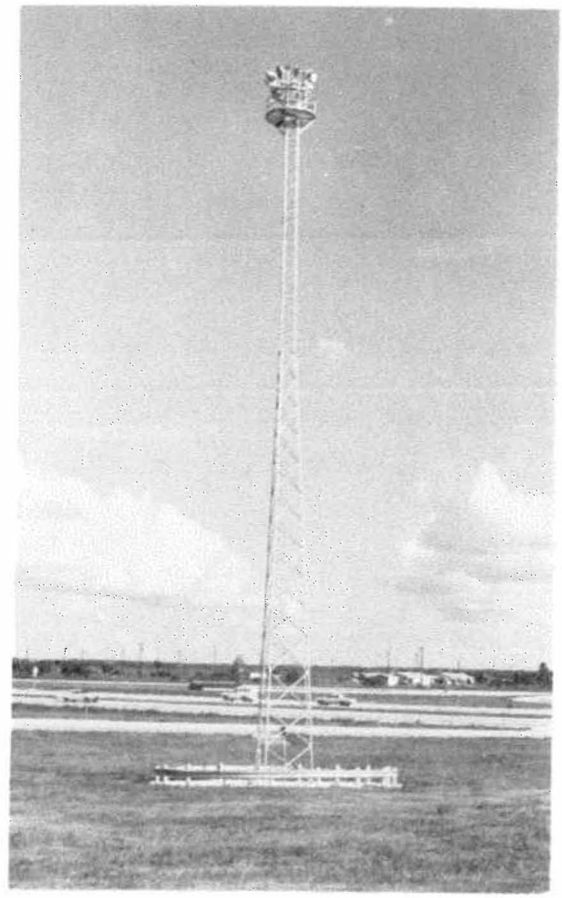

Figure 32. Early high mast lighting installation using microwave-type antenna towers.

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utilized a Type V distribution luminaire, installed in multiples to achieve the desired level of illumination at the roadway level. In all installations, mounting heights were nominally 100 feet above the main roadway. Access to luminaires for service and maintenance in all installations was provided by climbing the tower or mast.

Since those early installations, some form of high mast lighting has been applied in practically every state of the nation. In these applications, some common characteristics have emerged. Luminaire mounting heights of 100 to 150 feet appear to be most common. Some have used mounting heights of 175 feet, but the apparent increase in the cost of the mast offsets any economic gain. Therefore, these higher mounting heights are justified on the basis of extreme differences in elevation of the interchanging roadways. For example, the four-level directional interchanges in Dallas and Houston justify the use of 175-foot masts in the general vicinity of the 4-level stack. Luminaires most commonly used in high mast lighting are the Type V circular distribution and an asymmetric distribution that closely approximates the IES Type IV or Type I. The intent is to achieve a wide but rectangular distribution that can be integrated into an interchange lighting system more efficiently. Floodlight units are still used to some extent, but are generally applied to situations where masts must be located at the periphery of the roadway, and all light directed in toward the roadway.

There is no doubt that high mast lighting is an effective concept in illumination of highway interchanges and complex roadway systems. However, it should not be considered as a solution to all illumination problems, for there are certain types of interchanges that are more adaptable to conventional forms of illumination. The illumination of each interchange should be considered separately, and decisions made on the basis of providing the best lighting system in the most economical manner.

The geometric configuration of the interchange should be a major factor in deciding the type of lighting system to be used. For diamond, cloverleaf, and partial cloverleaf interchanges, high mast lighting has worked very well. Further, high mast lighting is quite effective in the compact, multilevel directional interchanges. In all of these, it is of some informational value to the driver to have a panoramic view of the interchange with all visible elements in proper perspective as in daylight conditions.

To summarize, the designer of high mast or continuous lighting in interchanges must answer these basic questions:

- Will the driver be able to gain additional useful visual information if the entire interchange area is lighted?
- Will there be an illumination quality and visual comfort advantage to high mast lighting?
- Will there be a safety advantage to having fewer luminaire supports near the roadway?
- Is there an economic advantage to the installation, operation, and maintenance of high mast lighting?

A negative response to the last question should not rule against high mast lighting; rather, the designer should compare the added cost to the benefits identified in the first three questions.

Transitional Lighting. Drivers entering a lighted section from darkness experience physiological shock that is psychologically related to glare. This is due to a lag in response of the eye to the change in light level. Research has shown the effects are discomfort rather than disability veiling brightness. The effect of rapidly changing light-to-dark conditions is of much greater consequence to the driver because the adjustment of the eye from a light to dark condition is more critical and takes more time than does the adjustment from dark to light. Thus, it would be desirable to provide a transitional lighting section in which the illumination level is decreased gradually to transition the driver to the darkened conditions. Ideally, the transitional effect would be one of continually changing from the illumination level of the lighted section down to zero. Practically, however, it is most difficult to provide a continuously changing illumination level. Thus, the transitional effect is accomplished in stages by simply changing the lumen output of the light source. IES recommendations on transitional lighting suggest that this be handled in a step up or step down process. Specifically, it is recommended that the illumination level be reduced by 50% within a 15-second section. In other words, the reduction of illumination is one-half; the distance over which this transition is provided is the distance that would be traveled in fifteen seconds by the traffic using the facility. There may be a one- or two-stage transition, depending upon the level of illumination in the standard section of the roadway. This is governed by the requirement that the illumination level in the beginning of the transition section be somewhere between .25 and .50 average horizontal footcandle. As an example, consider a roadway section being lighted to an average of 1.5 footcandles and the operating speed is 50 mph. Using the criteria outlined above, a transition section adjoining the conventional lighting section would provide an average illumination level of .75 horizontal footcandle over a distance of 1100 feet. Then, for the next transition section, the average illumination level would be 0.37 footcandle again over a distance of 1100 feet. Many feel that the second transition section is not completely necessary; thus, transition would be achieved with only one section 1100 feet long. There are others who question the needs for any transition (15).

ARTERIAL URBAN AND SUBURBAN STREETS

The arterial street is a principal traffic artery that must serve moderately high volumes of traffic at night as well as in the daytime. Speeds are somewhat lower than for freeways, but direct access to abutting property more than offsets any safety advantage gained in the lower speeds. Whereas freeways and expressways serve the primary purpose of moving traffic, the urban arterial serves numerous functions; thus, the illumination system for an arterial must be designed to accommodate the multiplicity of street functions. Several of these functions are listed and discussed briefly as follows:

- Arterials frequently must provide direct access to abutting property. The availability of this access creates a rather intensive development which, in turn, generates traffic maneuvers. These traffic maneuvers are in direct conflict with through traffic and constitute a need for greater driver visibility.

- Most arterials have frequent at-grade intersections. At-grade intersections result in crossing and turning conflicts which, in turn, require special design features and/or traffic control devices. These changes increase the driver's workload and constitute a greater need for visual information.

- Intensive commercial development along arterials results in extraneous lighting. Lighting of business establishments along an arterial generally has a detrimental effect on visibility on the arterial. This effect must be overcome in the design of lighting along the arterial.

- Pedestrian movements along and across arterials are quite prevalent. Integrated pedestrian and vehicle facilities place a great demand on driver (and pedestrian) vision to insure safety.

- Arterials must accommodate bicycles unless specifically restricted. If bicycles are a part of the traffic stream, or if bike lanes are a part of the arterial street, driver visual information needs are intensified significantly.

- Arterials must accommodate public transportation. Frequent stops and the loading and unloading of passengers at night increases driver informational needs.

All of these functions of the arterial are associated with driver information needs which constitute objectives that are to be achieved in arterial lighting. It is the responsibility of the designer to recognize the needs that are to be served by specific lighting systems and to maintain a proper balance of serving these needs in the final result of a lighted arterial.

Arterial System Configuration

Because of intensive land development and limited right of way, the designer is restricted to a much greater degree in the development and application of the lighting system configurations on arterial streets. Generally, those configurations that are available to the designer are median lighting where medians exist and the conventional one side, staggered, and opposite arrangements.

Median Systems on Arterials. From the standpoint of economics and aesthetics, median lighting is the preferred configuration for arterials where there is an acceptable median. For the median configuration to be applicable to arterial streets, the median should have a barrier type curb that prohibits voluntary crossing of the median, and further, there should be a minimal number of intersections. In some instances, however, this latter constraint has not been considered to be important; designers have simply located the luminaire supports on the median nose adjacent to auxiliary turning lanes with very little lateral clearance. There is no doubt that placing luminaire supports in medians on arterial streets constitutes an increased exposure to fixed object hazards. Vehicles going out of control can impact luminaire supports located in the median. In the same manner, however, vehicles going out of control to the right can strike luminaire supports located in the side-mounted configuration. The only difference is in terms of the trajectory of the pole after impact of a collision. If the luminaire support is broken loose by the impact, it can be driven into the opposing lanes of traffic. Although there is considerable controversy throughout the nation in regard to whether or not to place supports in the medians of arterial streets, it is done with considerable regularity. Apparently, those people responsible for the design of lighting in the urban area do not consider it to be a greater hazard than locating the supports in a side-mounted configuration. An example of installations of the median-mounted configuration is presented in Figure 33. It should be noted that median lighting applications range from arterials in high developed commercial areas with frequent intersections or breaks in the median to arterials through residential areas. Only on extremely narrow medians should the practice be avoided.

Side-Mounted Systems. The "one-side," "staggered," and "opposite" systems (Figure 34) are utilized when it is impossible or inadvisable to use the median-mounted configuration. The choice among the 3 depends mainly on the width of the roadway to be lighted. The "one-side" system is applied to narrow roadways which can be easily lighted from the single row of luminaires. Streets adaptable to this configuration are narrow one-way streets, and two-lane, two-way streets, and other situations where the street is no wider than 1 to 1½ times the mounting height of the luminaire. The "staggered" arrangement should be used on streets of medium width, that is 1½ to 2 mounting heights. The "opposite" system is used where streets are extremely wide and where medians are too wide to effectively accommodate median lighting. In this latter case, the system is actually two independent "one-side" systems.

A number of factors are involved in the selection of luminaire mounting heights. They are mounted low to facilitate ease of maintenance; they are mounted high to reduce source brightness and reduce the effects of discomfort and disability glare. The mounting height is one means available to the designer to control the illumination level on the roadway. With a given light source, the average illumination level on the roadway is an inverse function of the mounting height. Of course, another means of controlling the illumination level is through the selection of the light source. In practice, the lighting engineer uses four variables--light source, mounting height, spacing, and beam control--to achieve a design that is acceptable from

Figure 33. Median-mounted lighting on arterial street.

the standpoint of illumination and glare control.

In practice, mounting heights for major arterials range from 30 to 50 feet with 40 feet perhaps being the most practical. Thirty-foot mounting heights result in excessive source brightness near the central field of view of the driver, while 50-foot mounting heights with common sources do not provide sufficient illumination levels for the highly developed arterial streets. Where arterial streets are in the outlying areas with a minimum amount of development and extraneous light, 50-foot mounting heights are actually preferable.

There are instances where other factors will preclude the installation of luminaires at the mounting heights recommended above. One which is perhaps not associated with arterials to a great degree is when lighting is installed among trees. Compromises are necessary in these instances, and further discussion of mounting heights on tree-lined arterials is to be presented later.

On some downtown streets, particularly the semi-malls where a specific appeal is made to attract the pedestrian, ornamental type lighting is used to appeal to the visual aesthetics. Many times, these ornamental systems must be supplemented with standard roadway lighting equipment in order to achieve an acceptable visual environment. Note in Figure 35 that the ornamental lighting unit is supplemented with still another attractively finished roadway luminaire mounted at normal height for an intensely developed downtown area.

The technique of suspending luminaires from buildings in downtown areas is not practiced to a great degree, but has great potential for the removal of fixed objects (the luminaire supports) from the already crowded street margin. A difficulty noted immediately in most areas is that most buildings do not have the same setback from the curb line and, in many instances, buildings are often too low to provide the necessary mounting height. However, one excellent example is greater

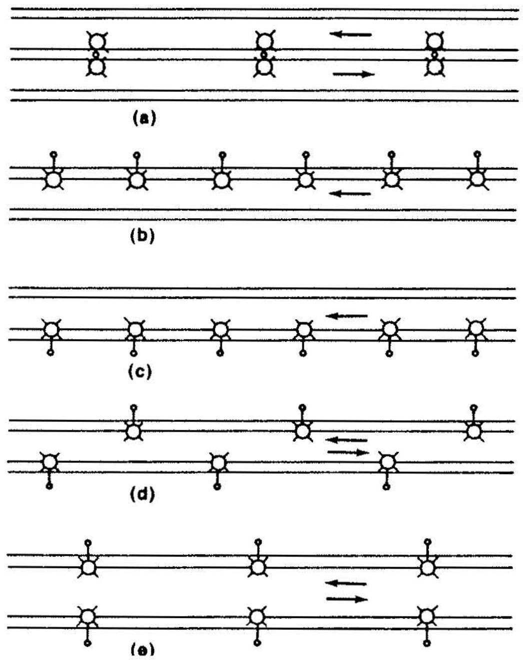

Figure 34. Luminaire mounting arrangements: (a) median, (b) right-side, (c) left-side, (d) staggered, and (e) opposite (19).

London where, in a one square mile area of intensely developed activity, virtually all of the luminaires are mounted on mast arms that are fastened to the facades of the buildings. The area is very attractive at night and the mounting does not reduce the aesthetics of the area during the daylight. It is a technique that should be explored more fully for applicability in this country.

Light Sources for Arterial Streets

The selection of light sources for arterial streets should be made on the basis of efficacy and color quality. The two sources that should be considered in current designs are high pressure sodium and metal halide lamps. Mercury lamps perhaps may be ruled out because of their relatively low efficacy, and low pressure sodium lamps perhaps may be ruled out because of the lack of good color quality, except in areas where appearance is of little importance and where there is little nighttime pedestrian activity (industrial and warehouse districts).

From the standpoint of color quality, the first two sources have their advantages. High pressure sodium, frequently considered as a utilitarian, high-efficacy light source, is not without aesthetic quality. In reality, it is superior to white light sources when applied in areas where the predominant colors in the lighted area are browns and

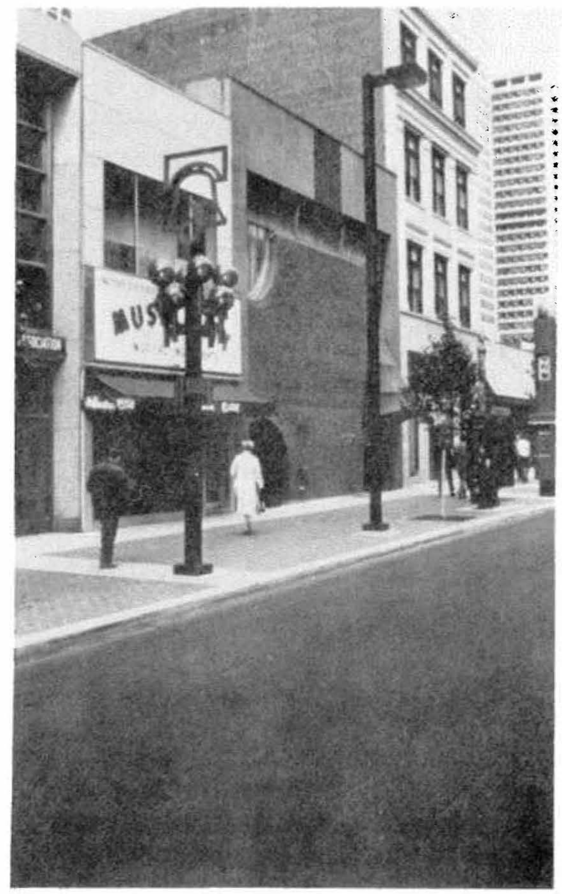

Figure 35. Ornamental lighting supplemented with roadway lighting.

grays such as pavements, sidewalks, and buildings. An excellent example is the area referred to as greater London, a one-mile square area encompassing the major government and business operations. This area is a combination of stone, concrete, brick, and other earthy hues and colors. The lighting system was modernized in 1970, replacing a fluorescent system with high pressure sodium sources. The change greatly enhanced the nighttime appearance of the area. The same can be said for many downtown areas in the United States where high pressure sodium sources have been utilized.

At the other end of the scale, white light sources, such as color-corrected mercury vapor, and metal halide sources seem to enhance the colors of the lighted area when the predominant colors are green and other pastels. These are colors that are normally found in park and recreational areas.

Luminaire Supports for Arterial Streets

Even a limited observation shows that virtually every type of luminiare support is used on arterial streets. The various types and their characteristics are discussed in Chapter 4. Here, the intent is to discuss the application of various support types to arterial lighting systems, giving advantages and disadvantages where appropriate.

Supports may be classified by material type (steel, aluminum, concrete, etc.), or configuration (mast arm, davit, etc.), or dynamic behavior (breakaway or non-breakaway). Material types are selected on the basis of economics, maintenance, local preferences, and performance requirements. For example, direct burial poles such as wood and concrete cannot be used where breakaway performance is required. Where breakaway performance is required, one of the materials adaptable to breakaway designs must be used.

There is no true consensus on the conditions that justify or require the use of breakaway supports on urban arterials. Many designers are strongly opposed to breakaway supports, while others feel that they should be used exclusively. Further, there has been very little research directed specifically to resolving the question. Therefore, any guidelines that may be set forth must be drawn from current practice. Many designers claim that breakaway supports should not be used where there is emminent danger of an impacted support striking a pedestrian, private property, or other traffic. Thus, the use of breakaway devices in very confined areas with high pedestrian activity such as the downtown area is ruled out. Also, breakaway supports should not be used on the corner near signalized intersections and other high-volume cross street locations where an impacted support would have a high probability of striking another vehicle or traffic control devices.

One of the principal considerations in the application of breakaway supports is the speed of traffic that may strike the support. Because the severity of impact is proportional to the square of the speed, the importance of breakaway devices increases greatly as the speed on a facility increases. On this basis, there should be some speed threshold on which the designer can base his decision whether to use breakaway supports. Unfortunately, such a speed threshold has not been established at this time. Rationally, a threshold speed of 30 mph seems appropriate. The logic behind this statement is as follows:

- The normal "urban speed limit" is 30 mph in most states; thus, a speed limit or normal operating speed greater than 30 mph would mean that the arterial has better than normal operational features and reduced conflicts with pedestrians.

- An impact speed of 30 mph appears to be the maximum speed for a high probability of serviceability without very serious injury. This threshold speed is determined on the basis of assuming that 12 g's is the maximum tolerable deceleration rate for crash survivability. By assuming that the vehicle and support together will crush a distance of 2.5 feet, the impact speed can be computed as 30 mph.

In summary, the designer must seek an acceptable balance between safety, economy, and local preference in the selection and application of luminaire supports.

Coordination of the Arterial Lighting System and Traffic Controls

The lighting system should be designed in such a manner that the lighting serves to enhance rather than detract from the traffic control system. Major points of consideration are that luminaires should not reduce the night visibility of signs, signals, markings, and channelization. Further, luminaire supports should not add to the already congested conditions of hardware blocking pedestrian movements on many street corners. When luminaires are placed behind overhead signs and signals, they may at some point be in a direct line of sight with the sign or signal. This makes it virtually impossible to see them. One way of avoiding the problem is to locate the sign or signal directly under the luminaire. Research has shown that there is no effect of reduced visibility (16). Further, combined use supports may be employed to reduce the hardware required and to reduce the congestion at the sidewalk level. An illustration of a combined use signal-luminaire support is illustrated in Figure 36, and a combined use luminaire-signal-sign support is illustrated in Figure 37.

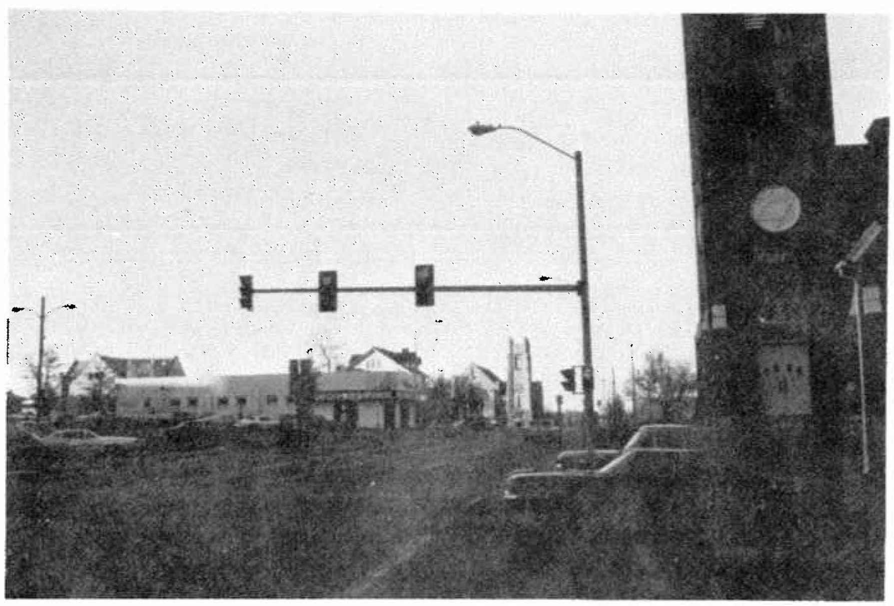

Figure 36. Combined use signal-luminaire support.

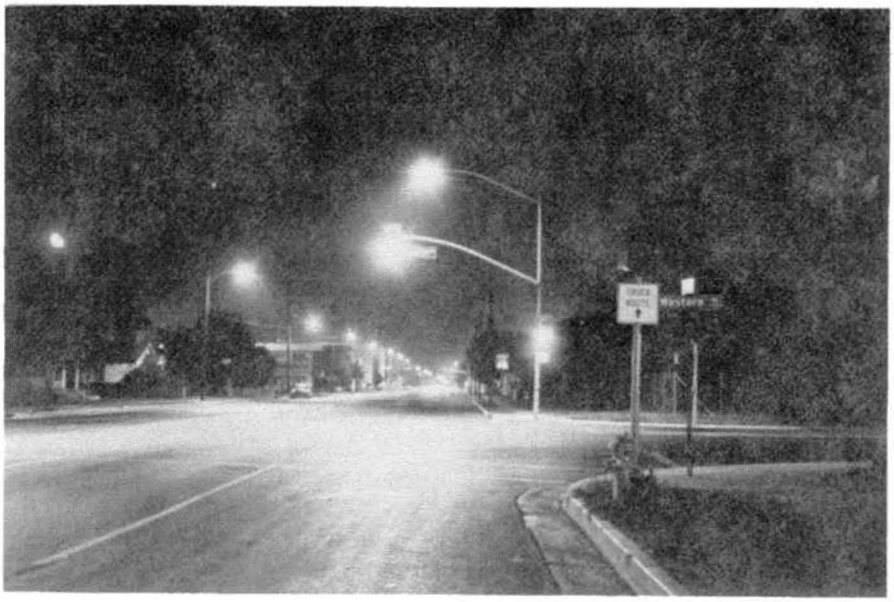

Figure 37. Combined use luminaire-signal-sign support.

Pedestrian Lighting on Arterials

Because of the relatively high speed operating conditions on most urban and suburban arterial streets, specific attention should be given to lighting the areas of potential conflict between pedestrians and vehicles. Luminaires may be located in such a manner that the highest illumination levels are achieved in the crosswalk area, and so that pedestrians may be viewed by surface detail rather than by silhouette.

The illumination of sidewalks can be achieved with backlight from the luminaires. The current standard practice is to light sidewalks to an average maintained horizontal illumination of 0.9 footcandle (9 lux) in commercial areas and 0.6 footcandle (6 lux) in intermediate locations.

Sidewalk lighting should be integrated directly with the design of lighting for the parallel street. This can be handled in two ways. First, the width of the street in the design equation (Chapter 6) is selected to include the sidewalk. This simply establishes the same criteria for the pedestrian way as that used for the roadway. Second, the design of lighting for the sidewalk area may be handled as a separate computational procedure, utilizing IES criteria established specifically for sidewalk lighting (see Table 11). The latter method would be applicable to normal sidewalk lighting while the first approach should be used in situations where there is a great deal of nighttime pedestrian activity.

Transitional Lighting for Arterials

When an urban or suburban arterial is lighted, it should be lighted along its entire length or at least to an outlying point where traffic volumes are low and/or the warranting conditions no longer exist. At these points, it is reasonable and practical to use the step down procedure for transitional lighting that was presented earlier in this chapter.

Ideally, the designer will be able to maintain a uniform spacing of luminaire supports and vary the size of the light source in effecting the transition. Later, when the lighting system is extended, only the fixtures will need to be replaced in order to achieve continuity in the system.

Intersection Lighting

Accident experience has shown that intersection lighting on urban arterials is usually justified. In suburban areas where complete lighting of the arterial may not be warranted, at least the intersections should be lighted. Thus, certain forms of partial lighting are recommended as minimum requirements. Partial lighting will alert the driver to an approaching intersection. Luminaires at partially lighted intersections should be placed at or near prominent conflict points, such that they illuminate by surface detail the most important visual elements of the intersection.

On an arterial that is continuously lighted, intersection lighting may be of a higher intensity than the roadway lighting in order to alert the driver of possible conflicts. If both intersecting roadways are lighted, the intersection illumination level should be equal to the sum of the illumination levels on the intersecting roadways.

Summary

Although freeways are important to most metropolitan areas, the arterial is the principal transportation system in the city. Practically all urban trips make use of at least part of the arterial system. Pedestrians, bicycles, buses, trucks--all of these in addition to the automobile make use of it. If the arterial is to function both night and day, the lighting system must be designed in such a manner that all transportation modes may use the facility effectively. Thus, the design and operation of functional lighting for the arterial is even more important than perhaps for the freeway. To achieve an effective lighting system, the designer must first identify the visual needs of the various users of the street facility and then identify from the various acceptable alternatives the system configuration. Finally, it is necessary that the designer make a cost-effectiveness analysis of the various alternatives that are available to him, and arrive at the one that best satisfies the need of the community.

RESIDENTIAL STREET LIGHTING

Roadway or street lighting serves a multitude of functions in the residential area. Further, residential street lighting relates less to the driver and more to the residents of the area than any system discussed to this point. A well-lighted residential street does provide driver information relative to the street geometry, to objects or activities within the street, and to objects or activities in areas adjacent to the street. However, travel speeds on residential streets are low and the vehicle headlights could conceivably provide sufficient illumination for driver information needs. Thus, it is the other, the non-driver, benefit that really justifies residential street lighting. These include lighting for pedestrian activities, bicycling activities, activities in and around the home, personal security, and other elements of neighborhood enhancement.

"Residential Street Lighting" is a broad term that covers a wide range of conditions from single unit dwellings on large lots, to duplexes, townhouses, and low density apartments to high-rise apartments in high density areas. Certainly, the need for lighting becomes more intense as the density of residential development increases. General provisions for lighting residential areas should be based on the density and activity levels. For example, lighting a street in an area containing single-family units or duplexes should conform to the "local street-residential area" recommendations by IES which is an average maintained horizontal illumination of 0.4 footcandle (4 lux). Streets in low density apartment and townhouse areas should be lighted according to IES recommendations for "collector street-residential area" which is 0.6 footcandle (6 lux) as a minimum. Lighting on streets in high-rise, high density residential areas should conform to the major street requirements in residential areas which is 1.0 footcandle (11 lux) as a minimum.

The system configuration of a residential street depends to a great degree on the area served. In any case, however, aesthetics is extremely important. In the medium and high density residential areas, the lighting system configuration should be similar in most respects to configurations used on collectors and arterials in the commercial areas of the city. That is, steel or aluminum poles, 30-50 feet high, should be used in the appropriate one-side or staggered arrangement. The lighting hardware should blend in with the surrounding area as much as practicable.

Figure 38. Classic (antique) lighting unit.

In the single-family type residential neighborhood, more emphasis may be placed on aesthetics. For example, some neighborhoods have gone to considerable expense to preserve the appearance of various antique or classic lighting units such as those illustrated in Figure 38. For the modern look, some neighborhoods utilize aesthetically pleasing lighting units like those illustrated in Figure 39. Still others with an eye for economy use luminaires mounted on wood poles that have been dyed or stained to a pastel color. Also, direct burial (butt-type concrete poles) are very popular supports for roadways lighting in residential areas.

In many residential areas, street lighting consists of a small luminaire such as a Type I or Type V "Security Light" attached to an electrical distribution line pole at each residential street intersection. Such a practice generally does not comply with the minimum illumination recommendations

Figure 39. Modern look lighting unit.

of IES. Such an installation may be better than nothing, but it should not be expected to fully satisfy the neighborhood lighting needs. In addition, an inferior system may result in a negative attitude toward the value of lighting in the neighborhood. Wherever possible, the lighting agency should strive to meet the minimum illumination levels recommended by IES.

The most common light source for the residential area is probably the color-corrected mercury lamp. It provides a reasonable efficacy and a pleasing color rendition. The color-corrected mercury source provides the greatest practical enhancement for pastel colors normally predominant in the residential areas.

High pressure sodium sources are being used in residential neighborhoods to a greater degree. Certainly, they offer twice as much light for the same amount of energy expended. However, one should consider the color characteristics in reaching a decision relative to the type of source for residential lighting.

Funding for Residential Lighting

In most instances, residential lighting is funded through local sources. Ideally, lighting will be included in the subdivision development costs and prorated to the prospective homeowner in the same manner as the street, water, and sewer systems. When lighting is added after the subdivision is developed, it may be paid for by direct assessment, general obligation bonds, or from the general funds of the city. However, one should not overlook the possibility of funding residential lighting installation through the various Federal sources such as revenue sharing, urban renewal, and others.

RURAL ROADS AND AT-GRADE INTERSECTIONS

Webster defines rural as "relating to the country, country people or life, or agriculture." These are indicative of openness, low population densities, and little traffic. There is an absence of the hustle and bustle typical of the city. These characteristics tend to reduce lighting needs of roads. On the other hand, some characteristics tend to increase operating speeds and reduce driver alertness. These conditions intensify the importance of lighting where it is needed for driving visibility.

It should suffice to say that economics and available resources prohibits the application of fixed source lighting to all rural roads. Further, it is not necessary because, in most instances, vehicle headlights do a reasonably good job of lighting the roadway ahead. There are instances, however, where the vehicle headlights may be inadequate and should be supplemented with fixed source lighting. Identifying these locations and selecting proper equipment and system configurations is the challenge.

Lighting in the rural area consists primarily of lighting critical intersections, major physical features, and rural developments where conflicts with pedestrians, bicycles, autos, and other objectives may arise. The warranting aspects of these situations are discussed in more detail in Chapter 3.

Rural Intersection Lighting

Rural intersections are frequently illuminated when there is a substantial probability for a vehicular conflict in the intersection during night hours. There are three major benefits to be derived:

- the presence of a luminaire in the dark area establishes a discrete uniqueness to the area, alerts the driver, and draws attention to the intersection,
- the light reveals the physical features of the roadway so that the driver may plan the driving task more deliberately, and
- other vehicles and pedestrians in the intersection will be visible to an approaching driver.

Most studies have shown that the principal warranting criterion for intersection lighting is accident experience. Accordingly, an intersection lighting system could be configured to provide visibility of other traffic and physical features that are potential collision objects. On this basis, a simple intersection may be lighted using as a minimum two luminaires (Figure 40). Although many intersections may be lighted with one luminaire, two are better because of the combination of silhouette and surface detail methods of seeing made available. As noted in Figure 40, the luminaire on the near side of the intersection will provide surface detail visibility of objects within the intersection. If, on the other hand, a pedestrian may be in the near side crosswalk, then he or she would be revealed by silhouette made possible by the bright pavement due to the far side luminaire.

Using a single light source at an intersection is generally undesirable because it may create a "brightness barrier," particularly when it is low-mounted near the driver's normal line of sight. This "brightness barrier" is the same problem that we experience in other instances such as attempting to see beyond the headlights of an oncoming vehicle. Multiple light sources at the intersection increase the lighted area and reduce the need to see beyond until we are inside the lighted area looking out.

The exact configuration of the rural intersection lighting system is dependent upon the configuration of the intersection. In complex intersections with auxiliary lanes, channelization, ramps, and turning roadways, all major decision points and points of critical geometry should be lighted. In many instances this may be accomplished by "partial lighting" (lighting only the critical points). In some instances where intersections are compact, the difference in partial and full illumination may be negligible in cost. In such cases, full illumination should be considered.

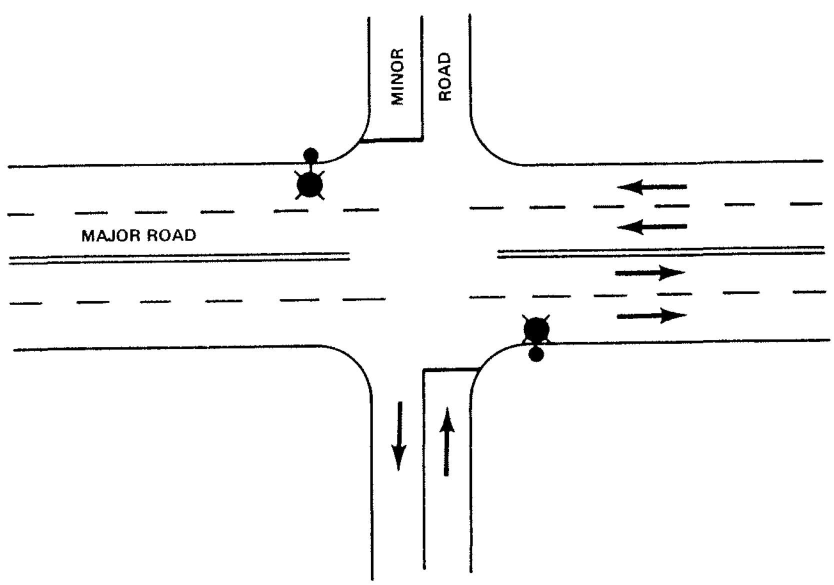

Figure 40. Lighting of intersection with two luminaires (19).

Lighting of Other Critical Locations on Rural Roads

As indicated previously, lighting of rural roads is not the normal practice. However, lighting may be used to draw attention and to reveal critical points on the roadway. These points may be geometric features such as sharp curves, narrow bridges, and changes in cross section. Also, critical points may be isolated commercial and residential developments. In all of these instances, the designer should decide upon the area to be lighted and utilize luminaires in strategic locations so that a combination of silhouette and surface detail visibility may be provided.

A number of factors should be considered in placing luminaires relative to the roadway. First, they should be placed such that they will create a desired pavement brightness pattern. Most generally, luminaires on both sides of the roadway in a staggered arrangement is preferred over a single side mounting. The location of supports for illumination purposes must be balanced against the safety aspects of the roadway. Luminaire supports should not be placed in a location where there is a higher than average probability of a vehicle leaving the roadway.

Mounting height is very important in rural illumination because of the high glare and brightness contrasts with the relatively dark environment. The relationship between source brightness and mounting height must be controlled closely. Briefly stated, if mounting heights must be low, use small sources; if it is desirable to use large sources, then provide mounting heights accordingly. For specific relationships, refer to Figure 47, Chapter 6.

Continuous lighting in rural areas normally is limited to what might be termed suburban; that is, sections of highways near the city where the development process is well underway. These roadway sections should be classified as urban arterial, and fall within a category previously discussed.

Recommended Illumination Levels

Neither the IES or AASHTO recommendations are specific in the average illumination levels for rural systems. A study conducted by Wortman showed that states with rural intersection illumination programs designed for 0.6 to 1.5 maintained horizontal footcandles (6 to 16 lux). This compares favorably with recommended standards for collectors and major arterials in residential areas.

SPECIALIZED TRAFFIC FACILITIES

This section deals with illumination practices for those facilities that complement the ordinary street system discussed in previous sections. A discussion of illumination systems is necessary because the illumination criteria and/or the methods of illumination are different in comparison to the normal roadway or street treatment. Included in this section are the illumination systems for tunnels and underpasses, roadway signs, parking lots, pedestrian ways, bike paths, and rest areas.

Tunnels and Underpasses

Material in this section is taken from the 1976 edition of AASHTO's "Informational Guide for Roadway Lighting" (17).

> *Underpasses.* An underpass is defined as a portion of a roadway extending through and beneath some natural or man-made structure which, because of its limited length to height ratio, requires no supplementary daytime illumination. Length to height ratios of approximately 10:1 or lower will not, under normal conditions, require daytime underpass illumination. Underpasses of multiple highway structures, where the space between these structures permits good penetration of daylight on the underpass roadways, will normally be treated separately rather than as

one single, composite length. In cases where the overhead structure results in one or more sides of the roadway beneath being open to relatively direct daylight, such as a building extending over the highway to the median area and supported by columns (which permit light to reach the roadways), the structure may be of considerable length, yet require no daytime lighting.

When the length to height ratio exceeds about 10:1, it is necessary to analyze the specific geometry of roadway conditions, including vehicular and pedestrian activity, to determine the need for daytime illumination. These features are more fully covered in the tunnel lighting section.

Roadways which are not continuously lighted warrant underpass lighting in areas having frequent nighttime pedestrian traffic through the underpass, or where unusual or critical roadway geometry occurs under or adjacent to the underpass area.

Roadways having continuous lighting warrant the use of underpass illumination. Favorable positioning of luminaires adjacent to the underpass can often provide adequate lighting of relatively short underpass areas without the need for supplemental lighting.

Underpass lighting levels and uniformities should duplicate, to the extent practical, the illumination values on the adjacent roadways. Because of luminaire mounting height and spacing limitations it is sometimes difficult to achieve the required underpass uniformity values. Increased levels should not exceed approximately twice that of the roadways adjacent to the underpass.

Underpass lighting, if warranted on otherwise lighted roadways, should be illuminated in the range of 0.6 to 0.8 horizontal footcandle (6-9 lux) maintained with a 3:1 to 4:1 uniformity of illumination. Special conditions of high nighttime ambient brightness produced by lighting competition from other nearby sources may justify higher illumination levels to the extent required to produce the necessary underpass roadway visibility.

Luminaires attached to the structure along the roadside in full or partial view of the motorist must exhibit a high degree of source brightness glare control. It is generally a better practice to minimize source glare by use of several lower output luminaires than to provide one or two high output luminaires of the same type. The use of lower lumen output fixtures tends to improve uniformity of illumination while maintaining lighting levels commensurate with the approach and exit roadways.

Tunnel - General. A tunnel is defined as a structure of any type surrounding a vehicular roadway which requires the use of artificial illumination or equivalent means to provide adequate roadway visibility necessary for safe and efficient daytime traffic operation. The recommendations presented in this section apply to all vehicular tunnels designed to provide an uninterrupted flow of traffic into the entrance portals and through the tunnel.

It is the purpose of this section to provide a basis for an engineering investigation of motorist tunnel visibility needs and methods appropriate to accomplish these needs. Literature is available on the technical aspects of visibility and lighting of vehicular tunnels. A review of the referenced material included in this as well as other research efforts is encouraged and will provide considerably more detailed information than is possible in this section.

A tunnel is classified as short if its length from portal to portal is equal to or less than the wet pavement minimum stopping sight distance as recommended by the latest American Association of State Highway and

Transportation Officials design standards for the vehicle operating speeds of the tunnel roadway and approaches. A tunnel zone, as used in this section, is defined as a length of tunnel roadway equal to the wet pavement minimum stopping sight distance. A short tunnel therefore has only one zone, referred to as the entrance zone.

A tunnel is classified as being long if its portal to portal length is greater than the wet pavement minimum stopping sight distance. A long tunnel has two or more zones.

The installation of artificial daytime lighting is warranted when tunnel user visibility requirements are not satisfied without the use of an illumination system supplement to natural sunlight. Overall tunnel visibility varies considerably with such items as the geometry of the tunnel and its approaches, the traffic characteristics, the treatment of roadway and environmental reflective surfaces, the climate and orientation of the tunnel, and with visibility objectives determined to be essential for safe, efficient tunnel operation.

Visibility Optimization of the Tunnel and Approach Features. It is important that the physical design of a tunnel structure and its environs be given due consideration to illumination needs, particularly in the early stages of tunnel and roadway design.

Existing tunnels may not have favorable physical characteristics from the aspect of optimizing visibility conditions on tunnel approaches and within the tunnel structure. The physical features of a tunnel, if properly considered, can have a significant effect in reducing the artificial lighting needs required, and enhancing tunnel visibility conditions. Often these physical features, favorable to lighting needs, contribute little or nothing to initial tunnel structure costs, and can be easily incorporated into existing tunnels.

The following items list those factors considered to contribute to improved tunnel visibility conditions and should be fully explored as a prerequisite to the development of supplementary daytime tunnel illumination designs:

Reduction of
Ambient Daytime Brightness

Tunnel portals, adjacent walls, approach pavement, and other external features in the motorist's field of view should be darkened to the extent possible. The use of surface treatments, admixtures, overlays, vegetation, or other methods which result in low reflectance, non-specular surfaces are recommended. The darkening of these features serves to increase the degree of advance eye adaptation of the entering motorist and improves contrast with the lower luminance levels in the tunnel interior. Tunnels having a predominant sky background immediately above their entrance portals should be reviewed for the possibility of using plantings, screens, or panels to increase the size of the darkened area above the portals.

Portal Design Factors

The amount and extent of natural daylight concentration in the tunnel entrance is largely dependent upon the orientation of the tunnel with respect to the sun's path in the sky. The orientation of a tunnel is dictated by criteria other than illumination considerations, and consequently, the tunnel lighting system must be able to accommodate the entrance orientation conditions.

The use of upsweep ceilings in the portal entrance areas may result in increasing the length and amount of daylight penetration by means of increased height at the entrance. The upswept ceiling may, however, result in increased tunnel structure costs.

Screens or louvers placed over tunnel entrance roadways at, and in advance of, the entrance portal for the purpose of progressively reducing ambient brightness to levels commensurate with tunnel entrance portal conditions have been effectively used. The sun screen through the use of perforations or louvers permits a gradual reduction in ambient light levels rather than competing with ambient light levels through the development of high brightness of the tunnel interior. The design of the louvers requires a highly sophisticated technique in developing proper sunlight penetration through the louvers at various sun angles during the year.

Sun screens are not at this time in common use in this country. Tunnels located on high speed, multi-lane facilities will require long length screen structures of considerable width. The resulting high installation and maintenance costs and the space occupied by the screen structure may preclude use of the screen as an alternate to high level tunnel entrance illumination. Energy considerations, roadway geometrics, and aesthetics should also be examined in detail before considering the installation of screens or louvers.

Visibility Optimization of Tunnel Interiors

To effectively use natural and artificial lighting, it is recommended that ceiling and wall surfaces be of an easily maintained, highly reflective, nonspecular finish having a reflective efficiency of at least 70 percent initially. In tunnels having curved roadways or tunnels having curved approach roadways, development of high wall brightness is of great value in meeting visibility needs. Relatively narrow tunnels where the width to height ratios are approximately 3 or less will normally develop good tunnel visibility as a result of reflected light from highly reflective walls. Tunnels having higher width to height ratios will normally require supplementary illumination of the roadway surface. Interior roadways having a light color will enhance tunnel roadway visibility.

In entrance portal areas, natural penetration can be improved by use of wall, ceiling, and roadway surface texture control. The use of vertical wall corrugations, coarse finished pavements, or other treatments which produce surface relief, increases the retroreflection of light entering the portal over that of smooth surfaces.

Short Tunnels-Silhouette Visibility. Vehicular tunnels of short length, having straight, relatively level approach alignment with corresponding straight and level tunnel roadways may, without artificial lighting, offer adequate visibility to the entering motorist by silhouette viewing of other vehicles and objects on the roadway against the far side exit portal and consequently are treated as underpasses. Silhouette visibility must be carefully evaluated with respect to tunnel geometry to insure visibility of objects within the tunnel that may exist at any location on the traveled roadway.

Under silhouette seeing, the roadway surface details will normally be indiscernible to the motorist. In multi-lane, one-way tunnels, or unseparated two-way tunnels, illumination should be provided to the extent the motorist can distinguish lane markings or other delineation important to safe travel through the tunnel.

Entrance Portal Illumination. The most critical portion of a tunnel as affects visibility occurs just prior to entering the tunnel portal. This is commonly called the "black hole" effect. Visibility of this first entrance zone, while still outside the tunnel, is essential to the motorist in identifying and safely reacting to the presence of vehicles and objects that may be present on the tunnel

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roadways. This is accomplished only by providing illumination of the tunnel entrance zone interior in proper proportion to the outside ambient brightness to which the motorists' eyes are adapted. It is recommended the first tunnel entrance zone be illuminated to a brightness between 1/10th and 1/15th of the ambient brightness level to which the entering motorist is adapted. A 10:1 ratio of brightness does not necessarily imply that an ambient illumination level of 10,000 horizontal footcandles (107,600 lux) requires at least 1,000 horizontal footcandles (10,760 lux) in the tunnel entrance zone. The ratio applies only to the brightness level the motorist views in the entrance zone. The luminance of the approach pavement, adjacent landscape, sky, and the portal area itself, are all integrated over time by the motorist's eye in adapting to overall ambient conditions. It is required that an evaluation of brightness conditions be made for the actual roadway and tunnel prior to establishing a lighting design. On new facilities, this may not be possible and a model simulation may be necessary to duplicate the anticipated tunnel approach conditions. The motorist's field of view of adapted brightness should be evaluated at a location along the approach roadway equal to the minimum stopping sight distance in advance of the portal.

Two- and three-lane one-way tunnels having favorable alignments of the approaches and tunnel structure, and which are of relatively short length have been adequately lighted with relatively low artificial illumination levels. The optimization of portal entrance conditions in some cases has produced adequate entrance visibility at artificial illumination levels in the range of about 100 to 200 horizontal footcandles (1100-2200 lux) maintained. Highly favorable approach conditions on long or on curbed tunnels and approaches can have a similar effect, requiring only modest levels of illumination to achieve the 1/10th to 1/15th brightness ratio from the combination of sunlight and artificial lighting systems. Tunnels where physical features and surrounds are not favorable in producing good pre-adaption conditions, such as very wide, multiple lane, high speed tunnels having predominant bright sky or other bright background, can require considerably higher artificial lighting levels.

Entrance zone lighting levels should be designed to accommodate the greatest ambient brightness expected at the location. The length of entrance zone lighting should be determined by use of the stopping sight distance defined previously. Except for extreme cases of vertical and horizontal curvature, most tunnel approach roadways have entrance characteristics such that, at a point relatively close to the tunnel portal, the motorist's view is confined to the predominance of the darkened tunnel structure. It is an acceptable practice to include this "fixation" distance in the minimum stopping sight distance to reduce the length of the entrance interior lighting. Preadaption should not normally be used to reduce portal illumination levels.

Lighting Beyond the Entrance Zone. If the tunnel is classified as a short tunnel, the entrance zone lighting level in the tunnel should be continued throughout its entire length. However, in long tunnels, lighting beyond the minimum stopping sight distance should be reduced progressively until an established minimum level is reached. It is recommended that beginning at the end of the entrance zone lighting, the levels be reduced in steps to a level not less than 1/15 the previous higher level. Minimum daytime levels in long tunnels should not be less than 5 horizontal footcandles (54 lux) on the roadways. Each stepped zone should have a length of at least equal to the minimum stopping sight distance.

Nighttime Tunnel Lighting. Nighttime lighting should, if practical, make use of a portion of the daytime lighting system rather than be a separate system. Nighttime levels in a tunnel should be approximately 2 times but not exceeding 3 times that of the lighting requirements for the roadways adjacent to the tunnel. Uniformity of illumination should closely match that of the requirements for the adjacent roadways.

Tunnels located on non-continuously lighted roadways should be lighted to the minimum standards required for the highway type.

Selection and Placement of Tunnel Lighting. The choice of particular types of tunnel luminaires and light sources should be made by considering such items as luminous efficacy, source glare, light distribution characteristics, physical placement limitations, ease and frequency of maintenance, and resistance to damage. In addition to these, an important consideration in the choice of a particular system for both daytime and nighttime lighting in long tunnels is the stroboscopic effect of alternate bright-dark areas where luminaires do not form a continuous line of luminance. Frequencies in the range of 5 to 10 cycles per second have been observed to result in eye annoyance (and other physiological problems for drivers), and should be avoided at the particular design speed of the tunnel.

Tunnel Lighting Control Systems. Because of varying ambient light levels from season to season and during cloudy or inclement weather, the illumination levels of the entrance zone can be adjusted to match the ambient conditions. If such system variances are determined to be economical and feasible, in recognition of the more complex control equipment and system maintenance required, lighting levels in subsequent tunnel zones above the 5 horizontal footcandles (54 lux) minimum level should vary in the same proportion. Lighting systems for tunnels should be designed as fail-safe as practical to reduce the possibility of a total tunnel outage in the event of a circuit failure or other malfunction.

Maintenance Factor for Tunnel Illumination Design. The reduction with time of initial illumination levels becomes an important factor in tunnel lighting design. Initial illumination design levels must consider the frequency and degree of maintenance which the operating agency tends to perform. It is essential to assign a reasonable value for maintained illumination to be integrated into initial lighting design level determinations. Factors in the range of 25-60 percent are commonly applied to tunnel lighting where moderate frequency of maintenance, heavy dirt accumulation, and climatic conditions result in rapid luminaire and reflective surface efficiency depreciation. A detailed cost analysis should be conducted comparing the initial installation and energy costs using various schedules of routine maintenance and subsequently select the system offering the greatest economy of maintained illumination.

Roadway Signs

Night sign visibility is achieved in one of two ways:

- retroreflection of vehicle headlights from a reflectorized sign face, or
- illumination of the sign face by fixed-source sign lighting.

The retroreflection concept is used almost universally for roadside signs while external illumination has generally been added when signs are placed overhead. It has been a general practice to utilize fluorescent fixtures mounted at the bottom of the sign. However, there have been some major changes in sign lighting practices in recent years.

Perhaps the greatest change in sign lighting is the use of mercury vapor and metal halide sources in some states. Mercury vapor and metal halide luminaires designed specifically for sign lighting applications are available from several manufacturers, and several studies around the country have demonstrated excellent results. High pressure sodium luminaires and low pressure sodium luminaires should not be used for sign lighting because of the color shift in the appearance of the sign at night.

Guidelines for luminance and illumination levels for signs recommended by AASHTO are presented in Table 7. These values should be applied using a uniformity ratio (maximum/minimum) of 6:1, preferably 4:1.

At least two recent studies have demonstrated the use of high intensity sheeting in sign construction as an alternative to sign lighting. Several state agencies have adopted this as standard practice. There are certain conditions that must be met in order to eliminate the necessity for lighting.

- The overhead sign must be in the area of a low to intermediate ambient light level; i.e., this alternative is applicable mainly to rural areas.

- There must be no major alignment changes within a distance of 1,000 to 1,200 feet in advance of the sign; i.e., if the approach to the sign is in horizontal or vertical curvature, the headlights may not produce sufficient retroreflectivity for visibility and target value.

Major Traffic Generators

This category of specialized traffic facilities includes the driveways, walkways, parking lots, and other traffic ways in major shopping centers, parks and recreation areas, civic centers, and university campuses.

Major Shopping Centers. Most major shopping centers are auto-oriented with a network of driveways, circulation roadways, and vast parking areas.

TABLE 7

LUMINANCE AND ILLUMINATION FOR SIGN LIGHTING

The following may be used as a guide for luminance and illumination levels.

Ambient Luminance	Low	Medium	High
Luminance*	7-14 fl	14-28 fl	28-56 fl
Illumination	10-20 fc	20-40 fc	40-80 fc

*Maintained reflectance of 70 percent for white sign letters.

Frequently, the pattern of this network is confusing, and there may be limited physical features that help to define the pattern. Further, there is an ever-present vehicle-pedestrian conflict because virtually every auto trip begins and ends with a pedestrian trip. Thus, we identify the major objectives in shopping center lighting as to provide sufficient visibility for:

- easy access and safe circulation by vehicle
- reduced hazard to pedestrians
- improved personal security of pedestrians
- improved security of personal property
- enhancement of the business property

Lighting systems in major shopping centers are more on the order of area lighting systems than roadway lighting systems. It is similar to interchange lighting because it is desirable to achieve a uniform distribution of luminous flux, generally with a minimum number of luminaire supports. It has long been recognized that the fewer number of luminaire supports in a parking area results in fewer collisions and less interference with parking space utilization.

Perhaps the most common configuration for the lighting system is the twin mast arm support placed along the spine of parking rows as shown in Figure 41. An even more efficient utilization of space and support hardware is achieved using the multi-armed support shown in Figure 42. Mounting height for the multi-armed system can be as high as 60 feet. High mast lighting with mounting heights of 100 feet or more is becoming increasingly popular in parking lot applications, as shown in Figure 43. Care must be taken in these applications to reduce "spill light" on neighboring residential areas.

Figure 41. Common twin mast arm support placed along the spine of parking rows in shopping center.

Figure 42. Multi-armed support used for parking lot lighting in shopping center.

Light sources for major shopping centers are color-corrected mercury, metal halide, and high pressure sodium. Obviously, high pressure sodium is more attractive from the economics of operation, but metal halide may provide greater aesthetic balance. A great deal of consideration should be given to the center of shopping activity relative to the outdoor illumination. If the center of activity is inside and there is little more than ingress and egress pedestrian activity outside, then the more economical system would suffice. On the other hand, if the shopping center attracts a great deal of outside activity, and if there is a substantial amount of planting and natural landscaping, then metal halide may be the preferred source.

Roadway lighting guidelines by AASHTO and IES are not specific in recommendations for the minimum illumination levels for major shopping centers. IES has recommended that Pedestrian Ways in commercial areas be lighted to an average maintained illumination level of 2.0 footcandles (22 lux). Since the parking area and the circulation network presents a constant pedestrian-vehicle conflict, it should be lighted to the standards of a pedestrian way. Very frequently, however, minimum illumination levels are of little concern because shopping center developers feel that there is substantial aesthetic quality and attractiveness to a brightly-lighted center.

Regardless of the lighting system selected, the designer must be very careful to design a high utilization, low glare installation. Quite often, the ball-globe type of unit is used where some 50 percent of the luminous flux is emitted upwards (wasted) with the balance of the flux contributing

Figure 43. High mast lighting used in shopping center parking lot.

significantly to glare. Any lighting system, regardless of location, should provide good visibility first and aesthetics second.

University Campus. The lighting of a university campus presents a unique challenge to the designer. The university campus is generally a concentrated development within the limits of an urban area. This area is frequently an architecturally designed system of buildings and other facilities, designed to be served externally by automobiles and to operate internally by pedestrian, bicycle, and possibly shuttle bus movements. Most universities operate a night schedule of classes, many times as extensive as daytime activities. Also, students living on campus present nighttime traffic demands.

The lighting designer should consider two main objectives in lighting a university campus:

- The interior of the campus should be lighted principally to satisfy the safety, security, and orientation of pedestrians and bicyclists, with due consideration to on-campus auto traffic.
- Streets on the periphery of the campus should be lighted to high standards in view of the frequent pedestrian movements on and off campus.

This latter objective is no different from lighting an arterial in a commercial area. Lighting the inner portion of the campus presents more complex problems. Certainly, parking lots for students should be lighted dependent upon their use. If the parking lot is a high turnover lot with service to off-campus students, then it should be lighted to high standards, probably 1.0 to 2.0 footcandles (11 to 22 lux). If, on the other hand, the lot is used principally as storage for vehicles for on-campus students, then average horizontal illumination should be on the order of 0.6 to 1.0 footcandle (6 to 11 lux)..

The lighting system for the interior of the campus should be designed as a two-stage system. The entire area should be lighted to a low illumination level to provide general security and orientation. This may be achieved by locating floodlights on buildings, and by the selective placement of luminaires. As the second stage, a higher level of illumination should be provided along the walkways and bikeways. Post-top luminaires with optical control are frequently used to light these facilities because of their decorative benefits; however, excellent service and high efficiency may be realized from the use of standard roadway lighting hardware in the lighting of pedestrian and bicycle facilities.

Bicycle Facilities

The entire concept of providing a system of bicycle facilities separately and/or integrated with the street system is new. Planning, design, and operational procedures are not well defined at this time, so it is understandable that procedures relative to lighting these facilities are even less defined. However, a recent FHWA document (18) sets forth standards of geometric design for various types of classes of bicycle facilities. These classes are based on functional characteristics of the facilities and will relate to the illumination requirements and design procedures. Bicycle facilities may be classified into one of the three following categories:

> *Class I - Bikeways.* These are facilities provided exclusively for bicycle travel. They may be adjacent (but separate) to streets or highways or they may be on non-contiguous rights-of-way (see Figure 44). This classification is similar to the IES Type B Bikeway.
>
> *Class II - Bike Lanes.* These are lanes within the street that are reserved for the exclusive or semi-exclusive use of bicycles. Bike lanes are generally designated with markings, but may be outlined by physical barriers (see example, Figure 45). This classification is similar to the IES Type A Bikeway.
>
> *Class III - Bike Routes.* Streets that are shared

Figure 44. Example of Class I bikeway.

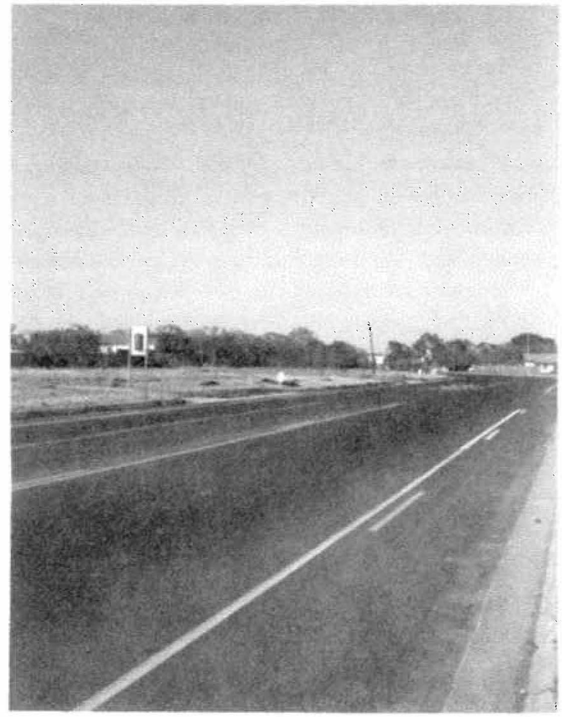

Figure 45. Example of Class II bikelane.

by bicycles and other vehicles, but are designated as bike routes by signs to attract bicyclists and to warn motorists of the potential presence of the bicycles. This classification does not have an IES equivalent.

Consideration for lighting each of the classes of bike facilities will be discussed in reverse order.

Class III bike facilities are almost always residential or collector streets. The lighting practices for these streets have been discussed previously and no special consideration should be given to lighting for bicyclists unless there is an unusually high number of bike trips made at night. On streets adjacent to night recreation areas, parks, and universities, greater than minimum illumination levels should be provided.

On Class II bicycle facilities, the lane reserved for bicycles is normally at the curbside, and the bike lanes are lighted by the same system that lights the street. Where bike lanes are used at night, lighting should be installed, and it should meet and preferably exceed, the minimum requirements for that class of street. Where side-mounted systems are used, the highest levels of illumination are generally along the curb where the bike lane is located.

Where median lighting is used, special consideration should be given to methods of increasing the illumination of the bike lane by changing the type of luminaire or increasing the overall illumination level. Separate luminaires for the bikeway may also be considered.

Serious conflicts arise at intersections on streets with Class II bike lanes. Vehicle-vehicle conflicts are compounded by vehicle-bicycle conflicts. The problems at these intersections are very similar to those related to pedestrian crosswalks discussed previously.

Class I bicycle facilities generally fall within one of two categories; they are continuous with a given facility, that is, parallel but separate, like the pedestrian sidewalks, or they are built through a park or otherwise undeveloped area. Where these facilities are contiguous to traffic facilities, the lighting system for the traffic facility should be expected to serve the bikeway. There are no explicit criteria for lighting bikeways except for those occupying a portion of a vehicular roadway. Until such criteria are established, bikeways should be lighted to the same standards as pedestrian ways.

Where bikeways are located in parks or undeveloped areas, lighting becomes extremely important if the bikeway is to serve its function at night. Most bicycles do not have headlights, and therefore, bike riders are toally dependent upon fixed source lighting for information relative to operating the bicycle. Further, criminal assault and robbery becomes of great concern in urban areas as the bikeways are removed from the sight of nearby streets.

As indicated earlier, there are no separate standards for bikeway lighting, particularly those on independent rights-of-way. Experience with bikeway lighting will be necessary before such standards can be established. In the meantime, it appears logical that independent bikeways should be lighted at least to the minimum standards for pedestrian ways in an intermediate area, that is, 0.6 footcandle (6 lux) maintained and an average-to-minimum uniformity ratio of 4:1. This should be achieved using luminaires mounted at least 17 feet (5 metres) above the bikeway. The type of light source should be one of the high intensity discharge type sources such as high pressure sodium, mercury, or metal halide.

Roadway Safety Rest Areas

Safety Rest Areas offering complete rest facilities (i.e., including comfort station and picnic area) are a comparatively recent addition to the national freeway and expressway system. By their very nature, these facilities incorporate both vehicular and pedestrian usage, and constitute an important highway feature to the traveling public. They are available for use at night as well as by day, and their general appearance should generate a feeling of safety and security. This condition can exist only if the facility is adequately lighted for nighttime use.

Properly designed lighting will enhance the architecturally and landscape features on the facility, promote safety by easing the task of policing, and contribute to the rest and relaxation of the motorist by completely delineating the driving, parking, and walking areas of the facility.

One of the prime concerns is that the motorists traveling along an unlighted main highway do not have their vision adversely affected by glare or by spill light from luminaires placed adjacent to the roadway within the rest areas. Adverse glare within all areas should also be given consideration. As the motorist on the main roadway traverses the entire length of the adjacent rest area, he should be able to discern any vehicle leaving the rest area, as well as the traffic traveling along the main roadway.

The overall design of rest area lighting should be divided into general areas which are described in the following paragraphs. It should be noted that recommended illumination levels presented in Chapter 6 are divided according to these same areas.

Entrance and Exit. These are defined as the deceleration and acceleration lanes adjacent to the main roadway, leading to and from the gore areas. The entrance and exit lanes may be lighted so that the driver desiring to enter or leave the rest area can safely make the transition from the main roadway to the rest area and vice versa.

When the lanes of the major roadway are not lighted, the illumination along the deceleration lane into the rest area may be transitional, and an average maintained illumination of 0.6 footcandle (6 lux) should occur at the gore point between the deceleration lane and the beginning of the interior roadways. This is based on the use of from 3 to 5 luminaire locations along the length of the speed change lanes.

Similarly, 0.6 average maintained footcandle (6 lux) should occur at the exit gore and may be transitional to a point where a motorist can merge into the through traffic lanes. The motorist on the through lanes should be able to see the merging vehicle, make a proper decision, and, if necessary, adjust to the traffic flow.

In the event that the main roadway is continuously lighted beyond the confines of the rest area, deceleration and acceleration lanes should be lighted to a level equal to that of the main roadway.

Interior Roadways. These are roadways between the entrance gore point and the parking areas and from the parking areas to the exit. It is recommended that the average maintained illumination be 0.6 footcandle (6 lux) with a uniformity ratio of 3:1 to 4:1. This continues the illumination level obtained at the gore points.

Parking Areas. Illumination of the parking areas, both automobile and truck, should be such that the motorist, while still in his vehicle, can distinguish features of the area, as well as see pedestrians moving about the area. An average maintained lighting level of 1.0 footcandle (11 lux) with a uniformity ratio of 3:1 to 4:1 should be used over the entire parking facility.

Attention should be given to special areas, such as handicap ramps, sanitary disposal stations, and other items which may require special detailing. This may be done by placing a luminaire in close proximity to a particular spot so that maximum visibility may be obtained.

Activity Areas. The activity areas are those areas designed for pedestrian use. The major activity areas are those which include such facilities as restrooms, information centers, etc., as well as the walkways to and from these locations and to the parking area. The minor activity areas are those which include picnic tables, dog walks, etc., and their associated walkways and facilities.

It is recommended that the main walkways around the structures and major walkways leading to and from the parking facilities be lighted to 1.0 average maintained footcandle (11 lux) with a 3:1 to 4:1 uniformity. This is in keeping with the recommendations for the parking areas.

Those walks leading to the shelter table, picnic tables, dog walks, etc., should be lighted to 0.5 average maintained footcandle (5 lux) utilizing a 6:1 or better uniformity ratio.

Should the designer desire, for architectural or other reasons, area floodlighting may be utilized in order to accomplish the desired results. Caution should be observed, not only from the design standpoint, but in final setting of the luminaires, that no objectionable glare be created for the passing motorist on the main roadway.

Maintenance. Safety Rest Areas are frequently in remote, isolated areas and require more rigid maintenance and supervision than areas having highway lighting. Because of the remoteness of these areas, luminaires and related equipment should be selected and utilized to provide maximum protection against vandalism and the least maintenance.

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6

DESIGNING THE LIGHTING SYSTEM

DESIGNING THE LIGHTING SYSTEM

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

This chapter begins with a discussion of the general and specific design criteria which are input for the design of a lighting system. This is followed by the step-by-step design process including the selection of light source, luminaire type, mounting height, luminaire spacing, and location. Procedures are given for checking the adequacy of a design once a tentative design is chosen.

DESIGN CRITERIA

Design criteria may be in two forms: (1) general criteria which are in essence the general objectives to be achieved by the lighting system, and (2) specific criteria which define or describe the situation or operational characteristics of the lighting system. Each of the two types of design criteria are discussed in the subsequent paragraphs.

General Criteria

The general design criteria for roadway lighting are visibility, safety, energy consumption, and economics. All of these must be considered in designing lighting systems. It is recognized that visibility is the principal objective of any lighting system, while safety, energy consumption, and economics are conditional criteria that have no meaning until the decision is made to provide visibility through illumination.

The criterion of visibility describes how well the lighting system performs in revealing the roadway, objects within the roadway, and the surroundings of the roadway to the driver. Current practice in the United States assumes that visibility is related to the amount of light reaching a horizontal surface, typically assumed to be the roadway surface, and the uniformity of light on the surface. Lighting design experience in the United States has been reasonably successful in providing good visibility, particularly when the latest design standards have been satisfied.

Safety as a design criterion for roadway lighting has both positive and negative aspects. From the positive point of view, improved visibility results in increased safety. The negative aspect involves the installation of fixed objects near the roadway.

A driver's ability to perform his driving task is a function of how well he recognizes his surroundings and how well he reacts to these visual stimuli. Stated another way, drivers who can see better perform better. Pedestrians and bicyclists are also provided with a safer travel environment. The negative aspects may reduce the safety of the roadside by the physical existence of the lighting system. A luminaire and its support constitutes a fixed object and, in order for the luminaire to accomplish its task, it must be placed reasonably close to the roadway. There are methods, however, through the design process by which the designer may reduce the negative safety effects of the lighting system. These are: (1) use the fewest number of poles possible, and (2) locate them where they are least likely to be struck.

The overall objective criterion of lighting should be to achieve good visibility through effective utilization while minimizing energy consumption to provide that illumination. The designer has essentially three means by which he can accomplish this objective. The first of these is the use of light sources exhibiting high efficacy, such as metal halide and high pressure sodium vapor. A second means of conserving energy involves using the minimum illumination needed. Over-lighting can be wasteful from an economic standpoint and offset the gains which may be realized. The third consideration should be that of using lighting only where needed. The designer should weigh carefully alternative methods of achieving improved visibility and safety. Perhaps delineation or signing improvements will suffice. Or perhaps fewer and more strategically located luminaires can replace a continuous system.

Specific Criteria

While the general criteria discussed above are important design considerations, specific criteria are needed to define the objectives in designing a roadway lighting system. These criteria establish the quantity and quality of illumination based on environment, type of roadway, area, and other factors. Environment, type of roadway, area, and other factors were discussed in Chapter 5.

The current criteria are:

1. Quantity of Illumination. The quantity of illumination is that average illumination level which has been established through experience and compromises in the lighting profession that represent economic and practical restraints. The quantities are a function of the classification of the roadway and the area which is served by the lighting system. The quantity of light is referred to as the average maintained horizontal illumination according to current practice in the United States. Breaking this term up into its parts, the first term, average, refers to the method of measuring the illumination level, and means that this is a mean value of all points within the area being lighted. The second term, maintained, refers to the illumination value at some point in time after the system is installed. Maintained illumination takes into account reductions in luminous output due to factors such as lamp lumen depreciation and dirt accumulation. Thus, a lighting system begins within an initial illumination level and depreciates to some level less than this. For this reason, the initial design level of illumination is higher than the maintained value. The final term, horizontal, refers to the surface on which the illumination is measured, in this case a horizontal plane such as the roadway surface.

Average maintained illumination levels currently recommended by the IES for various areas and facilities are shown in Table 8.

2. Quality of Illumination. The illumination concept of lighting design defines an average quantity of illumination over the pavement surface. This average quantity of illumination can, however, be accomplished by either producing a generally uniform level of illumination over the area or by producing relatively high and low areas of illumination. The latter is not desirable. As a driver passes through areas of relatively high and low illumination levels, his eyes must adapt. Reducing these adaptations reduces psychological and physiological stress.

The uniformity of illumination is considered a qualitative means of defining roadway lighting. The term used to quantitatively describe uniformity is the *uniformity ratio.* As the name implies, it is a ratio of various illumination values. Current practice makes use of the Average Level-to-Minimum Point method (average-to-minimum ratio) of calculating uniformity in which the average illumination is divided by the lowest illumination point encountered within the area of roadway being lighted. For example, a street with an average illumination level of 2.0 footcandles (22 lux) and a minimum point of 0.5 footcandle

TABLE 8

RECOMMENDATIONS FOR ROADWAY AVERAGE MAINTAINED HORIZONTAL ILLUMINATION (Reference 2)

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

NOTE: The recommended illumination values shown are meaningful only when designed in conjunction with other elements. The most critical element as described in this practice are as follows:

(a) Illumination depreciation
(b) Quality
(c) Uniformity
(d) Luminaire mounting heights
(e) Spacing
(f) Transverse location of luminaires
(g) Luminaire selection
(h) Traffic conflict areas
(i) Border areas
(j) Transition lighting
(k) Alleys
(l) Roadway lighting layouts

*Both mainline and ramps

(5 lux) would have a uniformity ratio of 4 to 1. Current recommended average-to-minimum ratios are shown in Table 9.

Some in the lighting field would argue that the use of a maximum-to-minimum ratio more accurately portrays the degree of uniformity because it takes into account the full effects of the differences of illumination on the lighted roadway. In this regard, Ketvirtis suggests maximum-to-minimum values in the range of 6:1 for freeways to 10:1 for local streets in outlying areas (1). To date, the maximum-to-minimum ratio has yet to be widely accepted in lighting design standards, but it has been used to obtain excellent results in some recent designs.

TABLE 9

RECOMMENDED AVERAGE-TO-MINIMUM UNIFORMITY RATIOS

For Roadways in	Recommended Ratios IES/ANSI (2)	FHWA/AASHTO (3)
Commercial Areas	3:1	4:1
Intermediate Areas	3:1	4:1
Residential Areas	6:1	6:1

The uniformity ratio may be utilized in one of two ways: as a design check, or as a performance measurement of a lighting system in the field. The design application requires comparison of the average illumination value used in design to an anticipated minimum point on the roadway estimated from photometric data supplied by luminaire manufacturers. Further explanation of this procedure is contained in the illumination design procedures section of this chapter. Field measurement requires an illumination meter to make detailed measurements or spot checks.

In summary, specific design criteria are related to (1) the area and roadway to be lighted, and (2) the recommended quantity and quality of lighting. Additional factors such as disability glare and discomfort glare enter into the design process and are treated as they are encountered in the following explanation of the design process.

LIGHTING DESIGN PROCEDURES

Lighting design is concerned with the selection and location of lighting equipment so as to provide improved visibility and increased safety while making the most efficient use of energy and accomplishing this with a minimum expenditure. There are two basic concepts of lighting design, i.e., the illumination concept and the luminance concept. The illumination concept, which is almost universally used in the United States, is based on the premise that, by providing a given level of illumination and a uniformity of distribution, satisfactory visibility can be achieved.

The luminance concept, which is fairly popular in parts of Europe and is promoted by some people in the United States, is based on the premise that visibility is related to the luminance of the pavement and the objects on the pavement. This, in

285-027 O - 79 - 9

turn, is related to the reflectance properties of the pavement and the objects on the pavement. The primary obstacle to implementing the luminance design concept is that of estimating pavement reflectivity for a wide variation of pavement types and ambient conditions. Estimation of the reflective properties of the objects which drivers must see is also difficult. Information of this type is needed because the luminance measurement is made of light flux reflected from the pavement and the object to an observer. With further development, it is expected that luminance design procedures, or more appropriately, visibility design procedures, will be incorporated into the recommended practice by the early 1980's. This handbook, however, will only address the illumination design process.

ILLUMINATION DESIGN PROCEDURE

By definition, lighting design according to the illumination method relies on the amount of light flux reaching the pavement and the uniformity of the light on the pavement surface. The steps in the design process which form the outline for the material presented below are as follows:

- Assessing the facility to be lighted (see Chapters 2 and 3)
- Selection of type of light source (see Chapter 4)
- Selection of light source size and mounting height
- Selection of luminaire type
- Luminaire spacing and location
- Checking for design adequacy

These steps are arranged in the order in which they are usually encountered in the design process. The context in which they are presented is that of a completely new design to be accomplished by an individual with an adequate engineering background, but less than average lighting experience.

Step 1. Selection of Type of Light Source

The type of light source selected determines the lumen output, efficacy, energy requirements, lamp life, color, optical controllability, temperature sensitivity, and environmental effects. The type of light source selected in this first step will, of course, affect the rest of the design process. The various sources used in roadway applications are discussed in detail in Chapter 4.

Incandescent, fluorescent, mercury vapor, metal halide, high pressure sodium, and low pressure sodium lamps have all been used for roadway lighting. During the past few years, high pressure sodium lamps and metal halide lamps have been developed and have gained popularity due to their high luminous efficacy. Low pressure sodium lamps are also highly efficient and have been used at a limited number of locations in the United States. The use of the more efficient light sources is most critical when lighting relatively large areas such as arterial streets, freeways and interchanges, where the amount of light and utilization are more critical than other factors, such as color rendition.

In addition to efficacy, lamp life, color, optical controllability, and temperature sensitivity of light sources should also be considered. While some lamps have lives as short as 2000 hours (6 months operation for average streetlighting use), other types are rated at up to 24,000 hours (6 years). Rated lamp life refers to the period of time beyond which at least 50% of the lamps will still operate. However, permitting such a large outage to occur will greatly detract from the appearance and effectiveness of the system. Frequent relamping may quickly exceed initial savings made on an inexpensive system using short-life lamps.

Color must also be considered. To have good color rendition, luminous efficacy or one of the other parameters usually becomes a secondary consideration. Many installations are not "color-critical," and the most energy-efficient sources can be used. Other applications require a high degree of true color rendition at night, and lamps should be selected from that viewpoint. For example, in freeway lighting, the major concern is that of providing a relatively high level of illumination with good uniformity at the lowest energy cost. In this case, the pinkish-orange color of high pressure sodium lamps is not considered detrimental to performance of the system. On the other hand, this color of light may not be deemed desirable for a city street which is lined with trees because the high pressure sodium source causes the green tree leaves to take on a faded and brownish appearance. In this case, a slightly less efficient light source such as metal halide or mercury vapor tends to accentuate the greenness of the foliage and may be selected for just this reason. Parks are another lighting application where color may be critical.

Optical controllability, or the ability of a lamp-luminaire combination to put the light where it is needed, is to a large degree a function of the light source. In general, we can say that the smallest size light sources are easiest to control. Fluorescent lamps are somewhat temperature-sensitive, and, when considering an installation using this source, especially in areas having very low ambient temperature, this fact must be kept in mind. A reduction in light output of up to 50 percent or more may be expected in below zero temperatures.

Thus, we see that a variety of factors enter into the selection of the type of light source. Generally speaking, high pressure sodium lamps are becoming the most popular light sources used in new roadway lighting designs. Where color is critical, metal halide may be preferred.

Step 2. Selection of Light Source Size and Mounting Height

Light source size and mounting height are directly related and are, therefore, selected as a combination rather than individually. Information concerning utilization of the actual light output of a given light source used in a specific luminaire at a particular mounting height can be determined from photometric data available from the various lighting equipment manufacturers. An example of one such set of data is shown in Figure 46.

Mounting heights have generally increased over the past few years due mainly to the development of more efficient and larger lumen output lamps and the availability of service equipment to service the increased heights. Mounting height enters into several considerations including safety, economics, and aesthetics. Increased mounting heights used with higher output lamps can be used to produce the same level of illumination as provided by lower mounting heights and smaller lumen output lamps. As the mounting height is increased, larger spacings between the luminaire supports may also be used as long as uniformity and level of illumination are maintained. Greater spacings provide safety benefits by reducing the number of roadside objects exposed to the motorist. Economic benefits may also be accrued because the primary cost of a lighting system is based on the number of poles and the accompanying equipment that is needed. Thus, a substantial savings may be realized even though taller poles are more expensive to purchase. When considering converting to increased mounting heights, the cost of new service vehicles needed for maintaining luminaires may be recouped by savings related to the fewer luminaires required because of the increased mounting heights.

Increased mounting height may, but will not necessarily, reduce direct glare, discomfort glare, and disabling veiling luminance. It increases the angle between the luminaire and the line of sight to the roadway; however, luminaire light distributions and candlepower also are significant factors. Glare is dependent on the flux reaching the observer's eye from all luminaires in the visual scene. Glare is not, however, a function only of the size and height of the light source. Luminaire construction and offset from the roadway are also important in controlling glare from lighting systems.

The relationship of light source size (lumen output) and mounting height can be determined from some general guidelines. The basis for these guidelines is the inverse square function which says the

PHOTOMETRIC DATA

Lumen rating of lamp in specified position 100C

*To obtain actual candela and footcandle values, multiply the values shown by the factor: ______

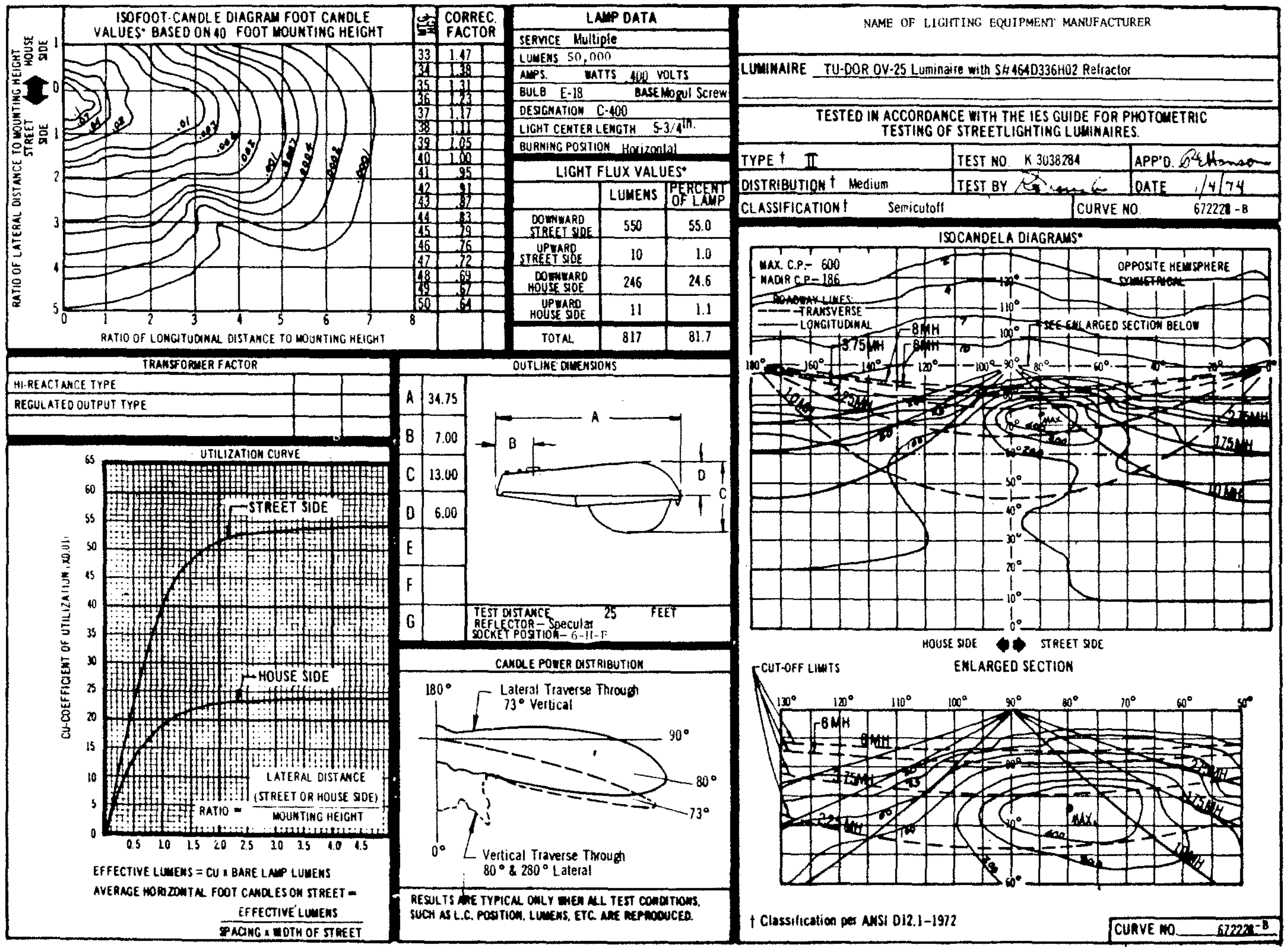


Figure 46. Example of a photometric test report for a Type II, medium, semi-cutoff luminaire.

flux density is inversely proportional to the square of the distance to the source. Thus, it is obvious that, as light sources increase in output, the mounting height can be increased while maintaining the same level of illumination on the roadway. Figure 47, adapted from the IES (2), lists minimum mounting heights for maximum candlepower values provided by certain lamp/luminaire combinations. The maximum candlepower value is a function of the size of the light source and the construction of the luminaire. Luminaires which tend to concentrate the emitted light flux in a smaller area will usually have a higher maximum candlepower value. The three curves in Figure 47, labeled "long, medium, and short distribution," refer to the longitudinal distance that the point of maximum candlepower lies from the luminaire. (A more extensive discussion of luminaire light distribution may be found in Chapter 4.) While Figure 47 provides minimum mounting heights for various maximum candlepower levels, it should be emphasized that these are indeed minimum mounting heights, and larger values are usually used in actual design. Bare lamp lumens, the measure of luminous flux emitted by a light source, can also be used to estimate a beginning mounting height in design. Figure 48 may be used for this purpose; however, ambient conditions must be considered.

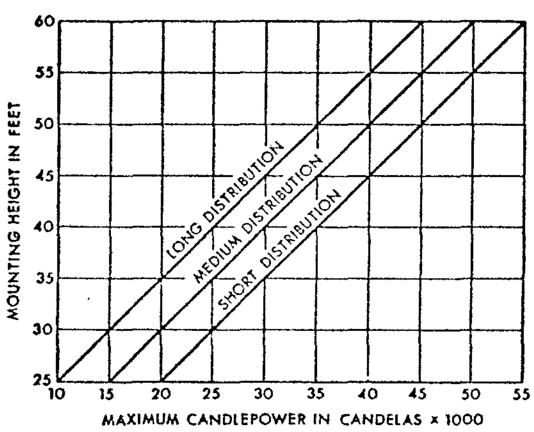


Figure 47. Minimum luminaire mounting heights based on current practice (for roadway lighting only).

A discussion of mounting heights also requires some discussion of the concept of high mast lighting. Larger light sources have made the use of higher mounting heights in the range of 80 to 150 feet feasible. High mast lighting systems, composed usually of 200,000 or more lumens, are used for lighting large areas such as interchanges, intersections, toll plazas, and parks. The justifications for high mast lighting for roadway application pertain mainly to providing a panoramic view of an entire area that would be similar to daylight conditions, and to the removal of luminaire supports from near the traffic area for safety reasons.

In summary, the correct matching of mounting height with light source size should result in meeting minimum illumination and uniformity criteria while being responsive to economic and safety criteria.

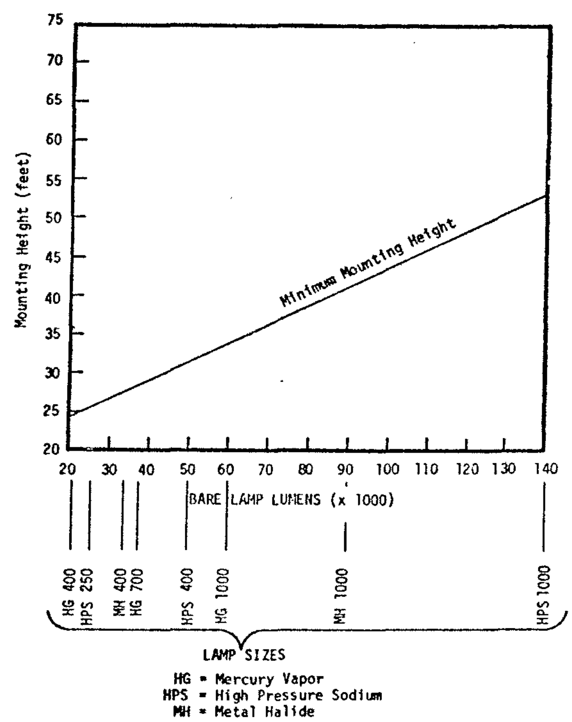


Figure 48. Suggested minimum mounting heights for various light source sizes.

Step 3. Selection of Luminaire Type

In the previous design step the type and size of light source and mounting height were chosen. This establishes the number of lumens which can be expected. In step three of the design process, we are concerned with selecting a type of luminaire which will distribute the luminous flux over the pavement in a desired pattern. Luminaire construction is discussed in some detail in Chapter 4; however, it may be well to restate here that most luminaires make use of a reflector and a refractor to produce a particular light distribution. Modification of the reflector and refractor and altering the position of the lamp within the luminaire can be accomplished by the manufacturer to attain various light distributions.

In the selection of luminaire type, the main factors are the width of the roadway to be lighted and the location of the luminaire relative to the roadway. The lighting industry through the IES has developed a method for classifying luminaires in terms of lateral and vertical distributions. Different lateral distributions are available for different street width-to-mounting height ratios. Different vertical distributions are available for different spacing-to-mounting height ratios.

The vertical distributions referred to as Short, Medium, and Long refer to how far down the roadway the main beam of light from the luminaire reaches. The selection of vertical distribution is largely controlled by the amount of source glare which is to be permitted. Long distributions produce the most glare because the main beam of light is emitted at a rather high vertical angle. Distances are measured in terms of mounting heights (MH) (see Chapter 4).

Lateral light distributions are referred to as Type I through Type V, and are based on the width of the roadway to be lighted. Types I, I Four-Way, and V are intended for use at or near the center of the area to be lighted. Types II, II Four-Way, III, and IV are used near the edge of the area. The 4-way types produce four beams and are normally used at intersections where two crossing roadways should be illuminated by one luminaire. A plan view of the shapes of light provided by these various distributions was included in Chapter 4. A general guide for the selection of lateral distribution type and placement is shown in Table 10. The types of mounting configurations (side, staggered, etc.) listed in this table are discussed in Chapter 5 and are illustrated in Figure 34.

In summary, the width of the area to be lighted, the configuration of luminaires, and the mounting height all affect the type of light distribution which will produce the best uniformity of lighting while attempting to minimize glare. Much of the lighting design process is involved with trying various combinations of these factors in an effort to identify the best combination. Referring again to Figure 46, we see specific information by a lighting equipment manufacturer regarding one particular lamp/luminaire combination.

Step 4. Luminaire Lateral Location and Spacing

Thus far in the design process, a lamp/luminaire combination has been selected and a tentative mounting height has been chosen. The next step is to select the lateral and longitudinal mounting dimensions. The lateral dimension, or the distance from the roadway edge to the luminaire, is mainly governed by the need to place the luminaire over the roadway edge or slightly inset from the roadway edge. Safety considerations and right-of-way restrictions require the use of various length mast arms in order to correctly locate the luminaire support while leaving the luminaire at its desired position.

In designing a lighting system, maximizing spacing of luminaires consistent with good illumination design, should be emphasized. From the standpoint of economy and safety, the minimum number of luminaires and luminaire supports should be used while satisfying the illumination quantity and quality criteria.

The first three steps in the design process were primarily judgment decisions related to the selection of light source, luminaire type, and mounting height. In the fourth step, the luminaire spacing is calculated by using the following equation:

$$\text{Luminaire Spacing} = \frac{LL \times CU \times LLD \times LDD}{E_h \times W}$$

where:

LL = Initial lamp lumens
CU = Coefficient of utilization
LLD = Lamp lumen depreciation factor
LDD = Luminaire dirt depreciation factor
E_h = Average maintained level of illumination (footcandle for U.S. system, lux for metric [SI] system)
W = Width of lighted roadway (feet for U.S. system, metres for metric [SI] system)

As this formula is usable in both the U.S. and the SI system of measures, either units can be used. The resultant luminaire spacing will of course be obtained in units corresponding to the system units used.

Other factors also exist which may affect the spacing, but are excluded from normal calculations. The first of these is a temperature correction factor for light sources such as fluorescent lamps which are sensitive to ambient temperatures. This factor is negligible with incandescent and high intensity discharge light sources and is usually eliminated from these calculations. Another factor generally used only in sports lighting is the over voltage factor. This applies mainly to filament type lamps where the lumen output is directly related to the voltage at which the lamp is operated. In sports lighting, it is not uncommon to use higher than rated lamp voltages in order to increase the light output. While this practice severely reduces lamp life, it is of only minor significance due to the relatively few hours of operation per year. As with the temperature factor, the over voltage factor is not applicable to roadway lighting calculations based on the use of high intensity discharge lamps.

In the luminaire spacing formula, the desired average level of illumination is a function of the roadway type and area, while the roadway width is the width of the facility under consideration. The other factors are dependent on the characteristics of the light source, the luminaire, and the expected ambient conditions. Photometric data regarding light source/luminaire combinations are provided by lighting equipment manufacturers. The designer should insist on specific information for a particular lamp/luminaire combination rather than accepting a generalized curve for a luminaire type. Photometric data is usually arranged in the following groups:

- *Lamp Lumen Output.* The initial lumen output of a lamp (LL) is used in the spacing calculations and represents the lamp performance in terms of bare lamp lumens. Note that for many lamp types, operating position (vertical, horizontal, etc.) will alter the initial lamp lumen rating. Also, lumen ratings of lamps are subject to change with lamp improvements.

- *Isofootcandle (Isolux) Diagram.* The isofootcandle diagram, photometric data unique to a specific luminaire, is also available to the designer. A typical isofootcandle curve is illustrated in Figure 49. The isofootcandle curve gives the level of illumination on the roadway at various distances from the luminaire. Note that the distances are given as a ratio to mounting height. This permits the same curve to be used for various mounting heights as long as height correction factors are used. Isofootcandle curves have in the past been prepared for a particular luminaire/lamp combination in terms of actual lamp lumens, but the trend is to report luminaire performance in terms of 1000 bare lamp lumens. The latter is recommended by the IES and allows for change as lamp performance improves. The isofootcandle diagram is useful in the study of uniformity of horizontal illumination and in the determination of the level of

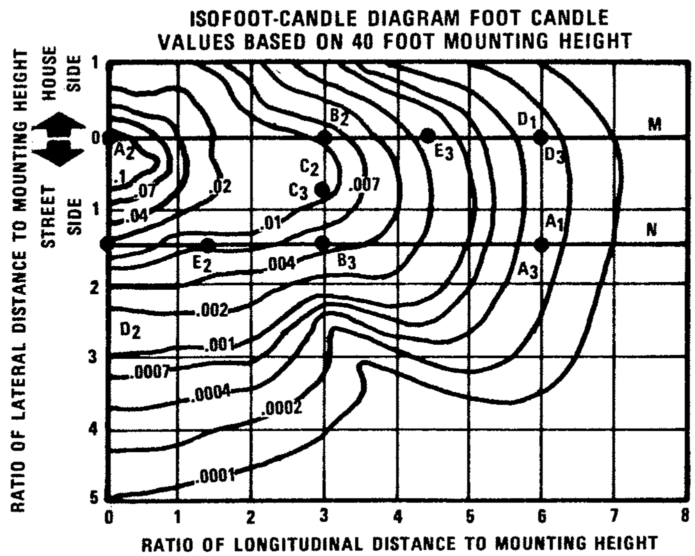
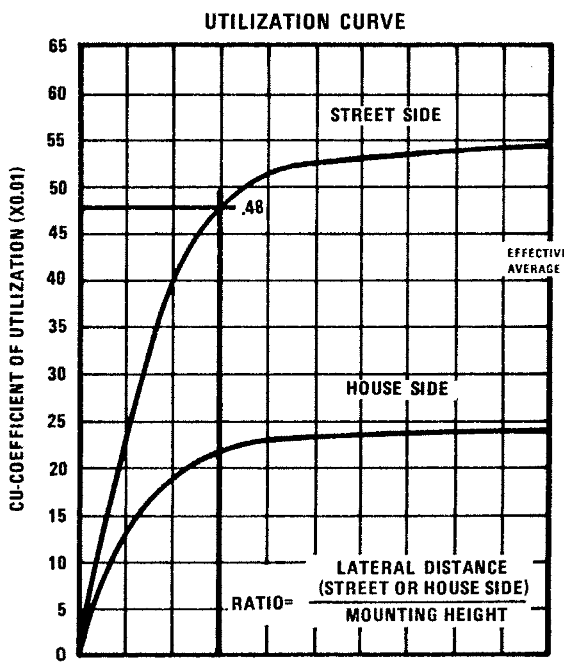


Figure 49. Isofootcandle curve (see first example problem--Roadway Lighting Design).



EFFECTIVE LUMENS=CU X BARE LAMP LUMENS
AVERAGE HORIZONTAL FOOT CANDLES ON STREET= EFFECTIVE LUMENS / SPACING X WIDTH OF STREET

Figure 50. Example of coefficient of utilization curve (see first example problem--Roadway Lighting Design).

horizontal illumination at any specific point.

- *Utilization Curve.* The utilization curve from which we derive the coefficient of utilization (CU) is illustrated in Figure 50. This utilization relates to the luminaire rather than the light source and gives us at any roadway width the percentage of bare lamp lumens which are utilized to light the pavement surface. If the luminaire is placed over the traffic way, out from the curb or edge of pavement, the total lumen utilization is determined by adding the street side light and curb side (house side) light. In essence, the utilization curve defines how much of the total lumen output reaches the area being lighted.

- *Isocandela Diagram.* An isocandela line is a line, plotted on appropriate coordinates to show directions in space, about a source of light, for which the candlepower is constant. A series of such curves, usually for approximately logarithmic increments of candela values, makes up an isocandela diagram. As for the isofootcandle diagram, the values of the isocandela lines can either be a function of the assigned bare lamp lumens or they can be expressed in terms of 1000 bare lamp lumens. The isocandela diagram is used to determine the lateral and vertical light distributions, as well as the vertical control (classification) of the luminaire. It provides candela values in any direction about the source, useful in point-by-point calculations. Candela values in tabular format are commonly used for computer application.

- *Light Flux Value Table.* This table lists the total light output of the luminaire subdivided into four sectors of space surrounding the luminaire. The light output is expressed as a percentage ratio, and often also in lumens, either in terms of the assigned lamp lumen rating, or in terms of 1000 bare lamp lumens. The "downward street side" and "downward house side" values represent how much of the light produced by the lamp would fall onto the street side and the house side, provided the street and house sides were infinite in size.

Lamp lumen depreciation curves and luminaire dirt depreciation curves are not normally contained in a photometric report. However, values applicable must be determined and used in the Spacing Formula. Lamp lumen depreciation values are usually found on technical lamp data sheets or in lamp schedules. The luminaire dirt depreciation curves are published in IES/ANSI RP-8, 1977, and discussed below.

- *Lamp Lumen Depreciation Curve.* The lumen output of a lamp decreases as the lamp progresses through life. This decrease is called lumen depreciation and is an inherent characteristic of all lamps. Thus, in the design process, the initial lamp lumen value (LL) is factored by a lamp lumen depreciation factor (LLD) to compensate for the anticipated lumen reduction. This assures that a minimum level of illumination will be provided at the end of some assumed lamp life even though lamp lumen depreciation has occurred. An example of a lamp lumen depreciation curve is shown in Figure 51. The designer should refer to manufacturer's data for depreciation curves for specific lamp types and sizes.

- *Luminaire Dirt Depreciation Curve.* Dirt on the exterior and interior of the luminaire, and to some extent on the lamp, reduces the amount of light reaching the roadway. Various degrees of dirt accumulation may be anticipated depending on the area in which the luminaire is located. The relationship between area and luminaire dirt depreciation according to the IES is shown by the Luminaire Dirt Depreciation Curve in Figure 52. As shown in this figure, the amount of dirt is highly related to the amount of particulate material in the atmosphere, as in the vicinity of heavy industry. Some dirt accumulation is also produced by the exhaust of vehicles, especially large diesel trucks. Higher mounting heights, however, tend to reduce vehicle related dirt accumulation.

In summary, the lamp lumen output (LL), coefficient of utilization (CU), lamp lumen deprecia-

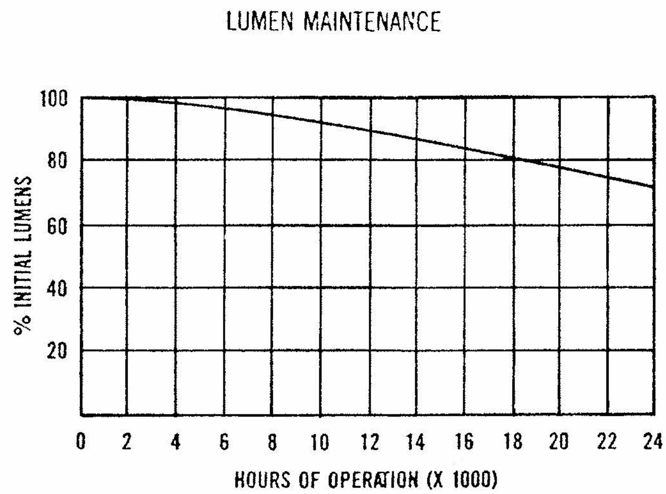
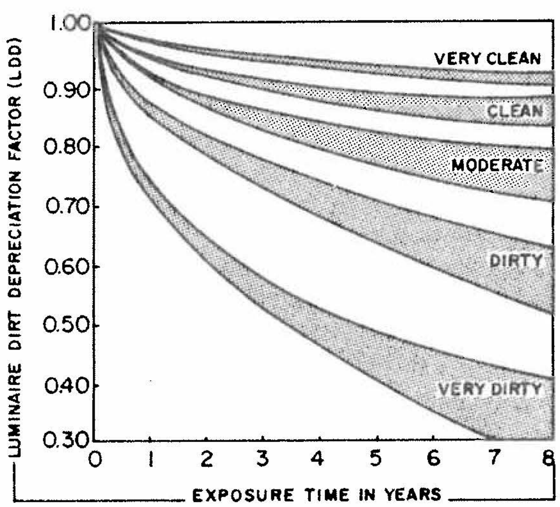


Figure 51. Typical lamp lumen maintenance curve.



SELECT THE APPROPRIATE CURVE IN ACCORDANCE WITH THE TYPE OF AMBIENT AS DESCRIBED BY THE FOLLOWING EXAMPLES:

VERY CLEAN--No nearby smoke or dust generating activities and a low ambient contaminant level. Light traffic. Generally limited to residential or rural areas. The ambient particulate level is no more than 150 micrograms per cubic meter.

CLEAN--No nearby smoke or dust generating activities. Moderate to heavy traffic. The ambient particulate level is no more than 300 micrograms per cubic meter.

MODERATE--Moderate smoke or dust generating activities nearby. The ambient particulate level is no more than 600 micrograms per cubic meter.

DIRTY--Smoke or dust plumes generated by nearby activities may occasionally envelope the luminaires.

VERY DIRTY--As above but the luminaires are commonly enveloped by smoke or dust plumes.

Figure 52. IES luminaire dirt depreciation curve.

tion value (LLD), and luminaire dirt depreciation value (LDD) must be determined in order to find the luminaire spacing. The quantity of illumination (fc), as determined by the type of roadway and area, and the roadway width (W) to be lighted must also be known to use the luminaire spacing equation.

Step 5. Checking for Design Adequacy

The luminaire spacing equation as defined earlier is based on the average level of illumination or lumens per square foot or square metre on the area of roadway under consideration. This establishes the quantity of illumination. Up to this point, nothing has been calculated regarding the quality of illumination. As defined in a previous section, the uniformity ratio relating the average illumination level to the point of minimum illumination is used as one way of specifying the quality of lighting. Because the average level of illumination is already defined by the design process, the next step involves finding the minimum point of illumination. This can be determined by inspection of the isofootcandle diagram contained in photometric data for the particular luminaire. Referring to the isofootcandle diagram in Figure 49, the lines in this curve define the level of illumination that will occur at various mounting heights from the luminaire. Several correction factors must be applied to the values of these lines before they are in a usable form. These are summarized below:

- Correction for light source size. The values in the isofootcandle diagram are based on 1000 bare lamp lumens. Thus, for a 50,000 lumen lamp, each of the curve values would need to be multiplied by a factor of 50.

- Correction for mounting height. The curve values are typically shown for one mounting height. Because the level of illumination is inversely proportional to the distance from the source, correction factors are given for adapting the curve values for various mounting heights. These are illustrated in the right hand column of Figure 49.

- Correction for maintenance factors. In the luminaire spacing equation, factors for lamp lumen depreciation (LLD) and luminaire dirt depreciation (LDD) are used to convert the initial illumination values into maintained illumination values or that which is expected to exist after the system has been operating for some period of time. Because this maintenance correction factor is used in calculating the average illumination, it must also be used in finding the value for minimum illumination.

Thus, the above correction factors make possible the use of the following uniformity equation:

$$\text{Uniformity Ratio} = \frac{\text{Average Maintained Illumination Value}}{\text{Minimum Maintained Illumination Value}}$$

Once it is understood how these values are defined, the remaining step is to locate the point of minimum illumination expected to occur on the roadway. Depending on the roadway width, mounting height, type of luminaire, and mounting configuration, the minimum point will usually occur at one of several typical locations. These locations are shown in Figure 53. After checking the illumination at each of the anticipated low points, the minimum illumination is used to determine the uniformity ratio. If this value is within the acceptable range for the particular area and type of roadway, the illumination design is acceptable. If the calculated uniformity ratio exceeds the given value, the design process should be repeated using other combinations of luminaire distributions, socket setting in the same luminaire, different mounting heights, luminaire types, and configurations. One step is to decrease the luminaire spacing; however, this tends to increase the average level of illumination above the desired minimum value. In this situation, an increase in mounting height may be a better choice in attempting to improve uniformity as the increased height will cause the light to be more evenly spread out. Luminaire type and distribution, and spacing configuration may also be altered. For example, if the far side of the roadway in a one-side system is too dark, the use of either a staggered configuration or a luminaire type with a wider light distribution would be possible solutions. The use of electronic computers discussed in a later section greatly speeds up this process.

Examples of Illumination Design

In order to understand the principles of illumination design, one must participate in the design process. The inexperienced reader should review each of the following examples and actually solve the problems so that he can understand the source of the data and the ramifications of the various design decisions. Then the reader should select a different problem with different design criteria and follow through the design process. Having followed such a procedure, the reader should then be ready to tackle a roadway lighting design problem.

EXAMPLE PROBLEM ROADWAY LIGHTING DESIGN

Design the illumination for an arterial collector street in a city of 125,000 people. The street is 60 feet wide, and has four 12-foot lanes and a 12-foot two-way left turn lane. For a metric example, we will use a street 18 m wide, consisting of four 3.5 m lanes and a 4 m, two-way left turn lane.

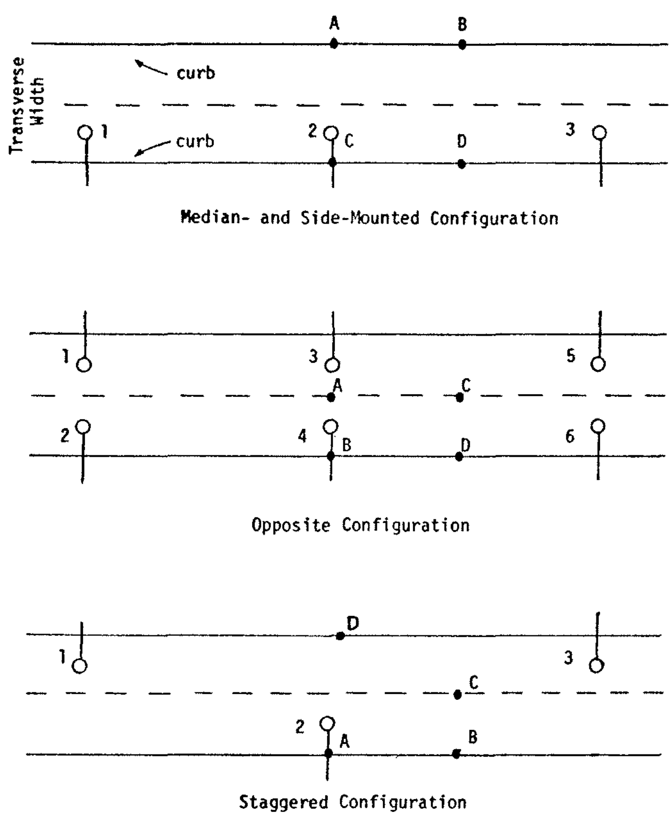


Figure 53. Locations of possible minimum intensity.

Step 1. Selection of Light Source. Based on current practice, a high intensity discharge type lamp should be used. Mercury vapor, metal halide, and high pressure sodium are all of this type. From the three high intensity discharge sources, high pressure sodium would be desired because of its high efficacy, good controllability, good lumen maintenance, long life, and acceptable color. The second most efficient source, metal halide, would probably be preferred if color rendition were important.

Step 2. Selection of Light Source Size and Mounting Height. The size of light source is dependent on the level of illumination desired and the mounting height. Mounting height must be consistent with the area in which the lighting is to be placed and maintenance capability of the lighting agency. In this example problem let's assume that we select a 400-watt high pressure sodium unit at 40-foot mounting height emitting 50,000 lumens.' If height restrictions are present, a smaller source such as 250 watts could be mounted at 30- or 35-foot height. If we have no maintenance capability problem, we could mount the 400-watt source at 40 feet. In general, increased mounting heights and larger light sources should be used to reduce the number of luminaires and luminaire supports. For this example problem, 400-watt high pressure sodium units are used at 40-foot mounting heights. In the metric example, we will use a 12 m mounting height.

Step 3. Selection of Luminaire Type. Keeping in mind the source and mounting height already selected, the next step is the selection of the luminaire type and mounting configuration. For a mounting height of 40 feet, a street width of 60 feet would result in 60 ft. ÷ 40 ft. = 1.5 mounting heights. In the metric example, a 12 m mounting height and an 18 m road width will also result in a ratio of 18 m ÷ 12 m = 1.5. From Table 10 we see that Type II could be used for a street width of 1.5 MH. To provide reasonable glare control, a semi-cutoff distribution is selected.

Step 4. Spacing Calculations. Up to this point, a trial combination of light source, luminaire type, and mounting height has been selected based on general guidelines and recommendations resulting from existing lighting practice. It should be noted that many other combinations could also have been selected. This step involves calculation of the luminaire spacing using the spacing equation:

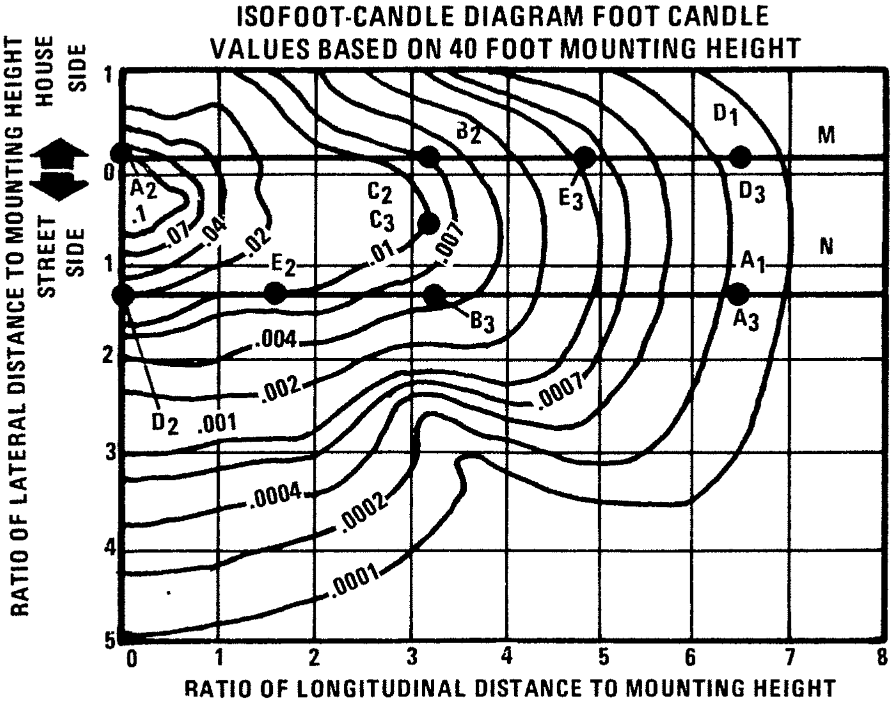
Luminaire Spacing =

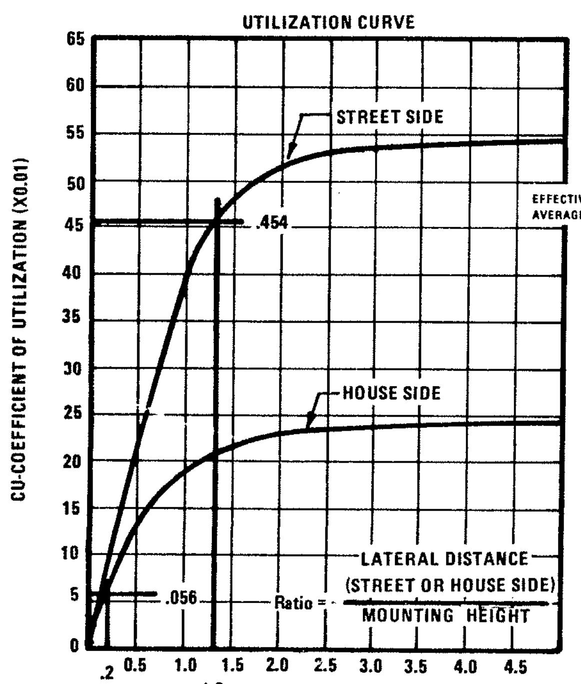
$$\frac{LL \times CU \times LLD \times LDD}{E_h \times W}$$

Values for LL and LLD are dependent on the particular light source chosen. For a 400-watt high pressure sodium light source, a LL value of 50,000 lumens would be typical. The lamp depreciation factor (LLD) is related to the amount of time the lamp is left in service. A typical LLD value after four years (based on an average operation of 4000 hours/year) would be 84% as shown in Figure 51. This says that after four years the average lamp will still be producing 84% of the lumens it was producing initially. If the decision was made to replace the lamps within a shorter time period, the respective value for LLD would be higher. The luminaire dirt depreciation factor is dependent on the cleaning schedule and the ambient contaminant level. Assuming for this example a two-year cleaning schedule and a moderate area as defined by the IES in Figure 52, the LDD factor would be about 0.87. It should be noted that the maintenance schedule establishing luminaire washing intervals determines the value of LDD used in the calculations. The result of this is a trade-off between design and anticipated maintenance. If maintenance is to be infrequent, a higher initial illumination level must be designed for. The opposite is true if frequent maintenance can be expected.

The coefficient of utilization (CU) defines how much of the total light emitted by the luminaire will be utilized in lighting the roadway. If the luminaire is mounted at the roadway edge, the ratio of transverse distance to mounting height becomes 60 feet ÷ 40 feet = 1.5. From Figure 50, the corresponding CU value taken from the street side utilization curve would be 0.480.

The final piece of information needed for the spacing equation is the level of illumination





EFFECTIVE LUMENS=CU X BARE LAMP LUMENS

AVERAGE HORIZONTAL FOOT CANDLES ON STREET= $\frac{\text{EFFECTIVE LUMENS}}{\text{SPACING X WIDTH OF STREET}}$

Figure 54. Photometric data for ANSI/IES Type II, medium, semi-cutoff luminaire used in second design problem.

TABLE 10

GUIDE FOR LUMINAIRE LATERAL LIGHT TYPE AND PLACEMENT

Side of the Roadway Mounting			Center of the Roadway Mounting		
One Side or Staggered	Staggered or Opposite	Grade* Intersection	Single Roadway	Twin Roadways (Median Mounting)	Grade* Intersections
Width up to 1.5 MH	Width beyond 1.5 MH	Width up to 1.5 MH	Width up to 2.0 MH	Width up to 1.5 MH (each pavement)	Width up to 2.0 MH
Types II, III, IV	Types III and IV	Type II 4-way	Type I	Types II and III	Types I 4-way and V

NOTE: In all cases, suggested maximum longitudinal spacings and associated vertical distribution classifications are: Short distribution = 4.5 MH, Medium distribution = 7.5 MH, and Long distribution = 12.0 MH.
*Local street intersection.

desired. For this case, a collector roadway in a commercial area would require 1.2 fc (13 lux) as a minimum (Table 8).

At this point the values can be substituted into the spacing equation as follows:

Spacing =

$$\frac{LL \times CU \times LLD \times LDD}{E_h \times W}$$

Spacing =

$$\frac{50{,}000 \text{ lumens} \times 0.48 \times 0.84 \times 0.87}{1.2 \text{ lumens/sq. ft.} \times 60 \text{ ft.}} = 244 \text{ ft.}$$

For simplification of the example, we will use a 240 ft. spacing. This equation can be used equally well in the metric system:

Spacing =

$$\frac{50{,}000 \text{ lumens} \times 0.48 \times 0.84 \times 0.87}{13 \text{ lumens/sq. m} \times 18 \text{ m}} = 75 \text{ m}$$

The arrangement and spacing of luminaires are shown in Figure 55.

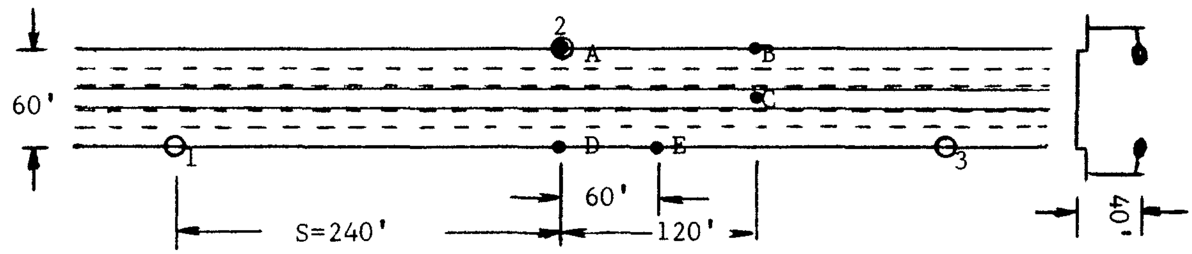


Figure 55. Luminaire arrangement for first design.

Step 5. Checking for Design Adequacy. The spacing equation as used above pertains only to the average quantity of light on the pavement. It does not tell us how uniformly this light is distributed. In Step 5 we will determine the uniformity ratio and check if it meets the IES/ANSI uniformity ratio requirement of 3:1 found in Table 9 for commercial areas. Because the uniformity ratio is the ratio of average-to-minimum illumination, these values must be determined. The average maintained illumination level used in the spacing formula was 1.2 fc (13 lux). The minimum values must now be found. To do this we use the isofootcandle diagram (Figure 49) and check the points shown in Figure 53 where minimum illumination is most likely to occur. Since a number of luminaires contribute to the illumination of any one point, we take a typical section of roadway and evaluate it. Depending on the luminaire mounting arrangement (Figure 34), the contributions of 2, 3, or 4 luminaires are normally considered.

We will first lay out the roadway geometrics on the isofootcandle diagram.The luminaire is mounted over the edge of the roadway, and we can lay the curb line longitudinally in line with the luminaire position (line M). Since the lateral width of the road is 60 ft. and the mounting height is 40 ft., the lateral (or transverse) ratio of roadway width to mounting height is 60 ft. ÷ 40 ft. = 1.5. We can now mark the opposite curb line (line N) on the isofootcandle diagram. We will initially only consider luminaire no. 2 (Figure 55). Point A is located directly beneath the luminaire. Point B is along the curb line (line M) 120 ft. from the luminaire. Its transverse distance from the luminaire location is zero, its longitudinal distance 120 ft. The ratio of longitudinal distance to mounting height for point B is 120 ft. ÷ 40 ft. = 3. Point C is located at a longitudinal distance of 120 ft. and a transverse distance of 30 ft. from the luminaire. The ratios for point C, therefore, are 120 ft. ÷ 40 ft. = 3 (longitudinally) and 30 ft. ÷ 40 ft. = 0.75 (transversely). Point D is at a transverse distance of 60 ft. and a longitudinal distance of zero from the luminaire. The ratios for point D are 60 ft. ÷ 40 ft. = 1.5 (transverse) and 0 (longitudinally).

Since in our actual design light from adjacent luminaires contributes to the illumination of points A, B, C, and D, we must find the relative locations of points A, B, C, and D to luminaires no. 1 and no. 3.

We will first consider luminaire no. 1. Point A is 240 ft. longitudinally and 60 ft. transversely from luminaire 1. The ratios are 240 ft. ÷ 40 ft. = 6 (longitudinally) and 60 ft. ÷ 40 ft. = 1.5 (transversely). This point is shown on the isocandela diagram as A_1. Point D_1 is 240 ft. longitudinally, but transversely in line with luminaire 1. The ratios are 6 (longitudinally) and 0 (transversely).

Similarly, points B_1 and C_1 are found. Since B_1 and C_1 are at a longitudinal distance of 360 ft. (9 mounting heights), and the isofootcandle diagram provides no values at these distances, we can neglect contributions from luminaire 1 to these points.

The last luminaire to be evaluated is no. 3. By symmetry, we see point A_3 is to luminaire 3 the same as to luminaire 1. The same is true for point D_3. Point B_3 is 120 ft. longitudinally and 60 ft. transversely from luminaire 3. The ratios are 120 ft. ÷ 40 ft. = 3 (longitudinally) and 60 ft. ÷ 40 ft. = 1.5 (transversely). Point C_3 is 120 ft. longitudinally and 30 ft. transversely from luminaire 3. By inspection, we can see again that point C_3 has the same relative position to luminaire 3 as to luminaire 2.

Having identified all points in question and the relative contributions made to each from the 3 luminaires, we now can read the raw data from the isofootcandle diagram and tabulate it into a table such as Table 11.

To find the average-to-minimum uniformity ratio, we now have to adjust the minimum illumination value found in Table 11.

LL = 50 (50,000 lamp lumens; values on isocandela diagram in terms of 1000 lamp lumens)
MH = 1 (Mounting height correction factors for a 40 ft. mounting height and isocandela values based on 40 ft. mounting height)
LLD = 0.84
LDD = 0.87

TABLE 11

INITIAL UNADJUSTED ILLUMINATION VALUES

Check Point	Luminaire	Trans. Distance (ft.)	TR	Long. Dist.	LR	Illumination Contribution	Illumination Total
A	1	60	1.5	240	6.0	.0003	
	2	0	0	0	0	.1162	
	3	60	1.5	240	6.0	.0003	.1168
B	2	0	0	120	3.0	.0095	
	3	60	1.5	120	3.0	.0040	.0135
C	2	30	.75	120	3.0	.01	
	3	30	.75	120	3.0	.01	.02
D	1	0	0	240	6.0	.0003	
	2	60	1.5	0	0	.0150	
	3	0	0	240	6.0	.0003	.0156

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Thus, the minimum illumination becomes:

Min. Illum. =

$$.0135 \times 50 \times 1 \times .84 \times .87 = .49 \text{ fc}$$

Then the uniformity ratio is

Uniformity ratio =

$$\frac{\text{Ave. maintained fc}}{\text{Min. maintained fc}} = \frac{1.2}{.49} = 2.5{:}1$$

Although the metric units for this layout would differ from the units used, the ratios would be almost the same, resulting in basically identical results. The values of the isofootcandle lines, of course, would have to be multiplied by 10.57 to convert fc to lux.

This would be an acceptable design based on the assumption that the minimum illumination does occur at points A, B, C, or D.

Once sufficient familiarity has been developed in reading isofootcandle diagrams, it might be seen by inspection that a relatively low level of illumination exists along the curb opposite the luminaire at a longitudinal distance of between 1 and 2 mounting heights. Since this is quite far from the next luminaire, we should check total contributions at an additional point E located at a transverse and longitudinal distance of 60 ft., or a 1.5 mounting height ratio from luminaire 2.

Contribution from luminaire 1 is beyond the values shown on the isofootcandle diagram (long. R = 7.5, transv. R = 0). Contribution from luminaire 2 is .007, and contribution from luminaire 3 is .0015. Total contribution, therefore, is .0085 unadjusted fc, or, after converting, .31 fc. Thus, evaluating point E, we find that the actual uniformity is only 1.2:03 = 4:1 and does not meet our 3:1 criteria.

Several options are available to correct this problem. We can use a different luminaire, possibly a wider (IES Type III) distribution, or locate the luminaires differently. We will use the last option and use longer bracket arms to move the luminaires 8 feet out over the roadway (Figure 56).

We now must start again with redetermining the utilization factor to check if our previous luminaire spacing can still be used. Figure 54 shows the basic isofootcandle diagram and utilization curves used in the previous example problem, but layed out for the new mounting arrangement.

With the luminaire mounted 8 feet from the curb over the roadway, the lateral (or transverse) distance from the luminaire to the far curb is 52 feet. This gives as a street-side to mounting height ratio of 52 ft.÷ 40 ft. = 1.3. From the utilization curve we obtain a coefficient of utilization (CU) for the "Street Side" of 0.454. We also utilize some of the light emitted towards the near curb (in back of the luminaire, or, the "House Side"). Our ratio of house-side to mounting height is 8 ft. ÷ 40 ft. = 0.2. The CU, read off the "House Side" curve of the utilization curve is about 0.056. Since both the house and street sides are additive, we have a total CU of

$$CU = CU_{SS} + CU_{HS} = .454 + .056 = .51$$

Using this value in the spacing formula, we obtain our new spacing:

Spacing

$$= \frac{LL \times CU \times LLD \times LDD}{E_h \times W}$$

$$= \frac{50{,}000 \text{ lumens} \times .51 \times .84 \times .87}{1.2 \text{ lumens/sq. ft.} \times 60 \text{ ft.}}$$

$$= 259 \text{ ft.}$$

To simplify the arithmetic, we will use a spacing of 260 ft.

We now can go to the isofootcandle diagram and check for design adequacy (Figure 54).

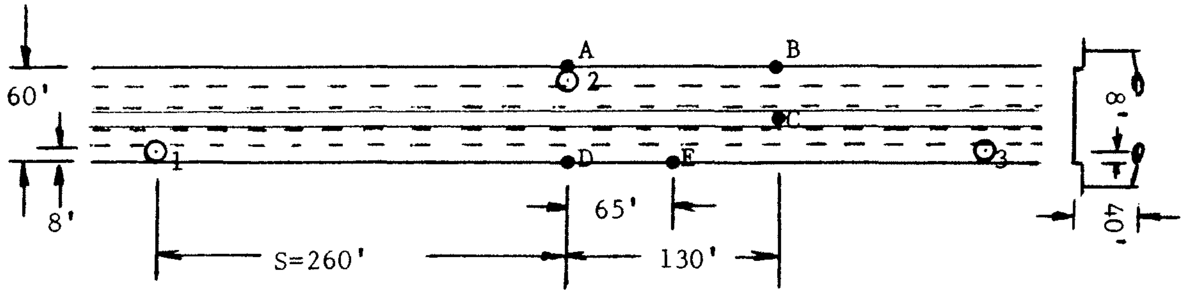


Figure 56. Luminaire arrangement for second design.

The curb lines (M and N) are at a transverse distance of 8 ÷ 40 = 0.2 and 52 ÷ 40 = 1.3, respectively. Since we have moved the luminaire out toward the street by 8 feet, the 0.2 (M) line is behind the luminaire. The distance between curb lines has not changed -- 60 ft. at a 40 ft. mounting height -- still provides a ratio of 1:5.

We again can lay out points A, B, C, D, and E and tabulate the raw data. This is done on Table 12. Distances from luminaire 2 to the various points are as follows:

Longitudinally: A (0); B (130 ft.); C (130 ft.); D (0); E (65 ft.).

Transversely: A (-8 ft.); B (-8 ft.); C (22 ft.); D (52 ft.); E (52 ft.).

The ratios are:

Longitudinally: A (0); B (3.25); C (3.25); D (0); E (1.625).

Transversely: A (-.2); B (-.2); C (.55); D (1.3); E (1.3).

Raw values read off the isofootcandle diagram are:

A = .08; B = .006; C = .009; D = .025; E = .01.

The next step is to evaluate contributions made to these points by luminaires 1 and 3.

Locations of points A, B, C, D, and E relative to luminaire 1:

Longitudinally: A_1 (260 ft.); B_1 (390 ft.); C_1 (390 ft.); D_1 (260 ft.); E_1 (325 ft.).

Transversely: A_1 (52 ft.); B_1 (52 ft.); C_1 (22 ft.); D_1 (-8 ft.); E_1 (-8 ft.).

The ratios are:

Longitudinally: A_1 (6.5); B_1 (9.75); C_1 (9.75); D_1 (6.5); E_1 (8.125)

Transversely: A_1 (1.3); B_1 (1.3); C_1 (0.55); D_1 (-.2); E_1 (-.2).

Raw values read off the isofootcandle diagram are:

A_1 = .00018; B_1 (off isofootcandle diagram); C_1 (off diagram); D_1 = .00015; E_1 = (off diagram).

Next, we find the location of points A, B, C, D, and E relative to luminaire 3:

Longitudinally: A_3 (260 ft.); B_3 (130 ft);

TABLE 12

INITIAL UNADJUSTED ILLUMINATION VALUES

Check Point	Luminaire	Trans. Distance (ft.)	TR	Long. Dist.	LR	Illumination Contribution	Illumination Total
A	1	52	1.3	260	6.5	.00018	
	2	-8	-.2	0	0	.08	
	3	52	1.3	260	6.5	.00018	.0804
B	2	-8	-.2	130	3.25	.006	
	3	52	1.3	130	3.25	.0055	.0115
C	2	22	.55	130	3.25	.009	
	3	22	.55	130	3.25	.009	.018
D	1	-8	-.2	260	6.5	.00015	
	2	52	1.3	0	0	.025	
	3	-8	-.2	260	6.5	.00015	.0253
E	2	52	1.3	65	1.625	.01	
	3	-8	-.2	195	4.875	.0009	.0109

C_3 (130 ft.); D_3 (260 ft.); E_3 (195 ft.).

Transversely: A_3 (52 ft.); B_3 (52 ft.); C_3 (22 ft.); D_3 (-8 ft.); E_3 (-8 ft.).

The ratios are:

Longitudinally: A_3 (6.5); B_3 (3.25); C_3 (3.25); D_3 (6.5); E_3 (4.875).

Transversely: A_3 (1.3); B_3 (1.3); C_3 (0.55); D_3 (-.2); E_3 (-.2).

Raw values read off the isofootcandle diagram are:

$$A_3 = .00018; B_3 = .0055; C_3 = .009$$
$$D_3 = .00015; E_3 = .0009.$$

We can now assemble the contributions made by each luminaire in Table 12.

From Table 12 we see that point E has again the lowest uncorrected illumination value. Correcting this raw data, we find the minimum footcandle level for our second solution to be

min. fc =

$$.0109 \times 50 \times 1 \times .84 \times .87 = .40 \text{ fc}$$

The uniformity ratio for this design is

$$\frac{1.2 \text{ fc}}{.40 \text{ fc}} = 3.0:1$$

and meets the requirements specified.

In comparing the two solutions, we find that different results can be obtained in a design problem using identical equipment, road geometry and mounting height. Moving the luminaire somewhat we were able to provide the specific average-to-minimum ratio. At the same time, we also found we could increase the luminaire spacing somewhat. While longer bracket arms will add to the initial cost, the increased spacing can offset this cost and may actually result in lower operating and maintenance costs (fewer luminaires). The point made in this illustration is that changing just one variable may yield noticeably different results. When all variables are considered, such as luminaire light distribution, lamp size, mounting height, luminaire arrangement, etc., it becomes obvious that, except for small or simple designs, the use of a computer is highly desirable as a design aid.

SPECIALIZED SYSTEMS

Up to this point the discussion of roadway lighting design has dealt primarily with what is referred to as conventional lighting. In systems of this type, luminaires are usually located near the edge of the roadway or over the roadway at mounting heights of 30 to 60 feet on street lighting poles. Several other types of lighting systems are also prominent in roadway lighting. Two of these are high mast lighting and tunnel and underpass lighting.

High mast lighting differes from conventional lighting mainly in the approach to lighting the roadways and the hardware used. As the name suggests, high mast lighting uses mounting heights of 80 to 175 feet and larger total lumen packages to light a large area such as an intersection, interchange, or toll plaza. As compared to conventional lighting which attempts to focus the light within the narrow confines of the roadway, high mast lighting illuminates the entire area, thus presenting a panoramic view of an area such as a complex interchange.

Tunnels and underpasses present yet another set of design criteria and constraints. In contrast to conventional lighting, tunnel and underpass lighting systems have definite constraints. A large number of small light sources may be used rather than a few larger ones. In addition, tunnel lighting is unique in the fact that daytime illumination levels inside the tunnels must be considerably higher than nighttime levels in order to match outdoor, daytime conditions. Because the design of lighting for tunnels is quite different from that emphasized on other parts of the lighting system, it will not be discussed further here, but will be the subject of a future FHWA handbook.

High Mast Systems

The illumination design procedure for high mast lighting is comprised of the same general steps encountered in conventional roadway lighting design. These are:

- Assessing the area to be lighted (Chapters 2 and 3)
- Selection of light source
- Selection of luminaire type
- Selection of mounting height
- Luminaire support spacing and location
- Checking for design adequacy

These design steps are discussed in detail in the following section:

Step 1. Selection of Light Source

Due to the additional mounting height as compared to conventional lighting, only the larger light sources can be used effectively. Even with these larger light sources, it is not practical to place only one luminaire on a single pole; thus, several luminaires are usually used in one assembly. This type of configuration provides lumen packages ranging from a minimum of 200,000 lumens up to 800,000 or more lumens.

For an initial approach to selecting a lumen package for high mast lighting, 400,000 lumens (3-1000 W HPS or 4-1000 W MH) at 100-foot mounting height, about 600,000 lumens at 120-130 feet, and about 800,000 lumens for a height of 150 feet have been used and have given good results. Due to its rather low efficacy, mercury vapor has been eliminated from consideration as a light source for new high mast lighting systems.

Generally, color is not critical in high mast lighting for interchanges where the need is to provide visibility of vehicles and the elements of the interchange. Other high mast applications such as parking lots may prove to be more color critical.

Step 2. Selection of Luminaire Type

High mast lighting systems have been designed to use both floodlights and roadway luminaires. Floodlights have been adapted from fixtures used for sports lighting and can be aimed to achieve the desired illumination distribution and level. One of the problems with a floodlighting system is that each luminaire has a particular portion of the area to light. An outage in one floodlight will produce a noticeable illumination drop in the area being lighted by that particular floodlight.

Another approach is to use multiple luminaires (such as the Type V) to build up illumination to the desired level. This approach requires that the luminaire support be spaced properly to achieve a uniform lighting system. No aiming capability is provided; thus, the location and spacing of luminaires is more critical than with floodlighting systems. Type V systems provide the advantage of "redundancy" due to the fact that all of the luminaires are aimed at the same location, i.e., the base of the luminaire support. If an outage does occur in one out of six luminaires, for example, the illumination level will be decreased by one-sixth overall, but will not result in greatly reduced illumination on a single section of roadway or produce spotiness. Floodlight systems produce some overlapping of luminaires, but do not provide complete redundancy.

Type V luminaires with modified optics resulting in an oval shaped light pattern have also been used in high mast lighting. Thus, instead of using several Type V luminaires which essentially all form coincidental circular light patterns, several asymmetric luminaires may be oriented so as to provide one oval shaped light pattern. The asymmetric pattern or possibly a Type IV luminaire may be preferable to the Type V distribtuion in lighting rectangular shaped areas. When used in freeway interchange lighting, for example, this can reduce the amount of spill light on private property abutting the freeway.

Both floodlight and roadway luminaires have been used and continue to be used in high mast lighting. The decision to use one or the other of these types rests with the designer and the particular design requirements and restraints with which he is presented.

Step 3. Selection of Mounting Height

High mast lighting installations have been built using mounting heights from 80 to 175 feet. Mounting heights associated with current roadway lighting practice are predominantly in the range of 100 to 175 feet. To a large degree, pole height, pole spacing, and light source size are interrelated. Assuming that high efficacy, large light sources will be used, mounting height considerations become primarily a function of luminaire support spacing. To envision this relationship, imagine a 100-foot pole with a moderately large circle light distribution. As the pole height is increased, the periphery of the illuminated area becomes larger. At the same time, the illumination level at a point below the luminaire assembly decreases because of the inverse relationship between illumination and mounting height. To rebuild the illumination level to what it was at the lower mounting height, additional luminaires must be added. Thus, increased mounting heights spread the light over a greater area, but additional luminaires must be added to preserve the level of illumination. While the number of luminaires per pole is increased, the number of poles is decreased resulting in approximately the same number of luminaires being used. The benefit accrued by the increased mounting height is improved uniformity by spreading the light from each luminaire assembly over a larger area.

The cost of high mast luminaire supports has a definite effect on the heights used. Costs vary from one region to another, and designers have different ideas from one geographical area to another. What is important in these design considerations is the conservation of funds while still providing the best lighting possible. No real clear-cut value exists for the most efficient high mast mounting height. An economic analysis should always be conducted to assure that a cost-effective design has been established.

Step 4. Luminaire Support Spacing and Location

In conventional street lighting design, much of the luminaire location problem deals with selecting the spacing between successive luminaires in order to provide a required level of illumination and an acceptable degree of uniformity. While luminaire support spacing is also important in high mast lighting, the location of the luminaire supports within the lighted area relative to the nearby roadways is also important. Good high mast lighting design should begin with focusing attention on critical areas where luminaire supports should or should not be placed. Once this step has been completed, other less critical poles may be fitted in to complete the total design. The designer should begin with a plan view of the area to be lighted and should tentatively locate the luminaire supports according to the following design considerations:

- Masts should be located so that the highest localized levels of illumination fall in the traffic conflict areas; for example, ramp terminals. Otherwise, masts should be located a sufficient distance from the roadway in order to position the greatest uniformity of illumination on the pavement surface. This is done by using plastic overlays of isofootcandle curves of the light units to be used. This will normally result in the masts being placed a sufficient distance from the roadway so that the probability of collision is virtually eliminated.

- Masts should be located so that the driver's line of sight is not directly toward the light source when he is within 1,500 feet of the mast. More specifically, the driver's line of sight should not be above the lower third of the mast when he is within 1,500 feet of the mast. This rule is applicable when the driver's line of sight is within 10° on either side of the mast.

- Masts should be located so 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.

- 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 protection should be provided.

Preliminary spacing of masts in the interchange area should be made on a maximum spacing-to-mounting height ratio of about 5:1 if the same cut-off characteristics that result from medium distribution luminaires in conventional lighting are desired. A trial number of total luminaires can be estimated by a computational process involving total lamp lumens, a coefficient of luminaire utilization, the area to be lighted, and an assumed maintenance factor (LLD and LDD). The equation would be:

$$E_h = \frac{N_{lum} \times LL \times CU \times LLD \times LDD}{A}$$

where:

N_{lum} = number of luminaires

LL = initial lamp lumens

CU = coefficient of utilization

LLD = lamp lumen depreciation factor

LDD = luminaire dirt depreciation factor

E_h = maintained level of illumination (footcandles or lux)

A = area to be lighted (ft^2 or m^2)

Solving for N_{lum}

$$N_{lum} = \frac{E_h \times A}{LL \times CU \times LLD \times LDD}$$

Thus, an early estimate of the number of luminaires once the light source has been chosen would be as follows:

LL = 100,000 lumens (1000 W metal halide)

CU = 0.61 from photometric data

LLD = 0.72 assumed for light source

LDD = 0.87 from IES curves

E_h = 0.60 fc maint. level of illumination

A = 3,000,000 ft^2 for design example

Substituting into the equation,

$$N_{lum} = \frac{E_h \times A}{LL \times CU \times LLD \times LDD}$$

$$= \frac{0.60 \times 3{,}000{,}000}{100{,}000 \times 0.61 \times 0.72 \times 0.87}$$

= 47.11 luminaires

Assuming the use of 100-foot poles, a lighting package of 500,000 lumens would be appropriate. Using a 100,000 lumen light source would result in 5 luminaires per pole. For initial design purposes, 5 luminaires per pole would result in 47.11 ÷ 5 = 10 poles. These are only rough estimates of the number of poles and luminaires per pole needed and are intended as a starting point for one of the design procedures described below.

Step 5. Checking for Design Adequacy

Two primary methods exist for the completion of the high mast lighting design process. The point-by-point method uses photometric data and illumination formulae to determine the illumination at critical areas such as travel lanes and decision points. The template method utilizes scaled-down templates to represent the area illuminated by one luminaire assembly. These two methods are described below as Steps 5a and 5b.

Step 5a. Point-by-Point Method

This computational process utilizes a candlepower distribution curve as illustrated in Figure 57. The inverse square law is used to determine from the values on the candlepower distribution curve the levels of illumination at various points on the interchange or area to be lighted. This curve can be developed for all symmetrical high mast systems, whether they consist of Type V units or individual floodlights arranged in a symmetrical pattern. Curves for asymmetrical luminaires require additional information because the pattern varies in the third dimension also.

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

$$E_h = \frac{cp \cos \theta}{d^2}$$

where:

E_h = illumination at the point in horizontal footcandles

cp = candlepower at angle θ

= the angle from the vertical axis through the system to the point in question (Figure 58)

d = the distance from the light source to the point in question (Figure 58)

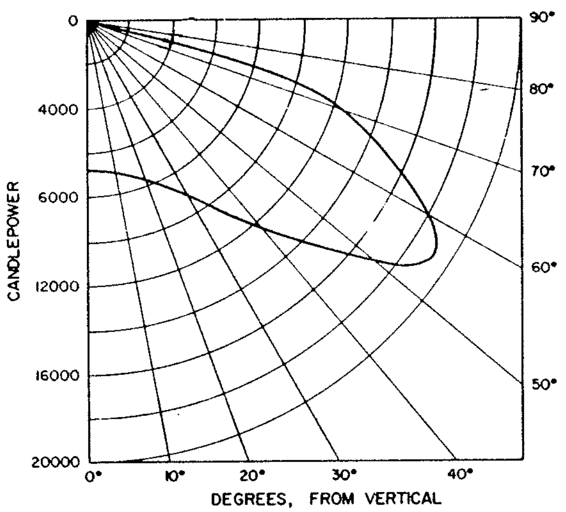


Figure 57. Example of candlepower distribution curve used for making point-by-point illumination calculations.

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 58.

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

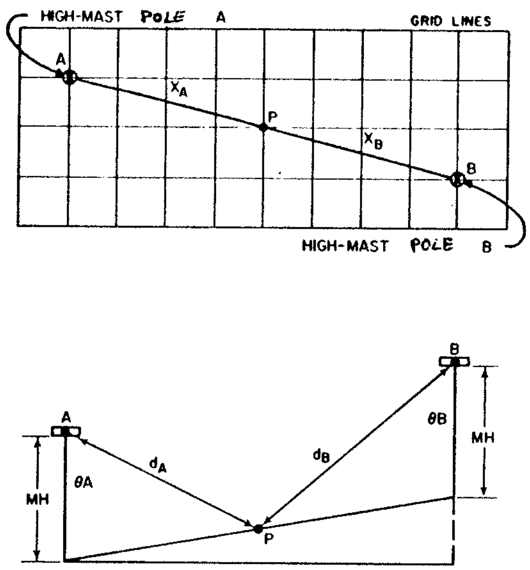
For a more specific appraisal, the designer should plot an illumination profile for each section of roadway in the interchange. For wider roadways, it may be necessary to plot two or more profiles in order to fully represent the traveled way. These profiles are plotted either by using the contour values 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. The average illumination values and uniformity ratios are computed from the illumination profile. A typical illumination profile is illustrated in Figure 59. 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.

Because of the time involved with hand calculations in the point-by-point method and due to the number of trials which may be required, the point-by-point method is usually accomplished by electronic computer. Generally, computer programs are built around the point-by-point method. Manufacturers have these type programs available and will normally provide design layouts.

Step 5b. Template Method

In this method templates drawn to the scale of the highway plans are used to simulate the pattern of light that will result from a luminaire at a particular mounting height. Before proceeding with the actual computation, the required average-to-minimum uniformity ratio has to be known and the number of luminaires per pole has to be tentatively selected.

To keep the computations simple and to allow the use of data from the isofootcandle diagram directly, portions of this method are carried out in terms of one luminaire per pole. The required



$$d_A = \sqrt{\bar{X}_A^2 + (\text{ELEV. A} - \text{ELEV. P})^2} \text{ AND}$$

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

$$\text{THEN } EH_P = \frac{CP_{\theta A} \cos\theta_A}{\bar{X}_A^2 + (\text{ELEV. A} - \text{ELEV. P})^2} + \frac{CP_{\theta B} \cos\theta_B}{\bar{X}_B^2 + (\text{ELEV. B} - \text{ELEV. P})^2} + \cdots$$

Figure 58. Illustration of the point-by-point process of illumination computations.

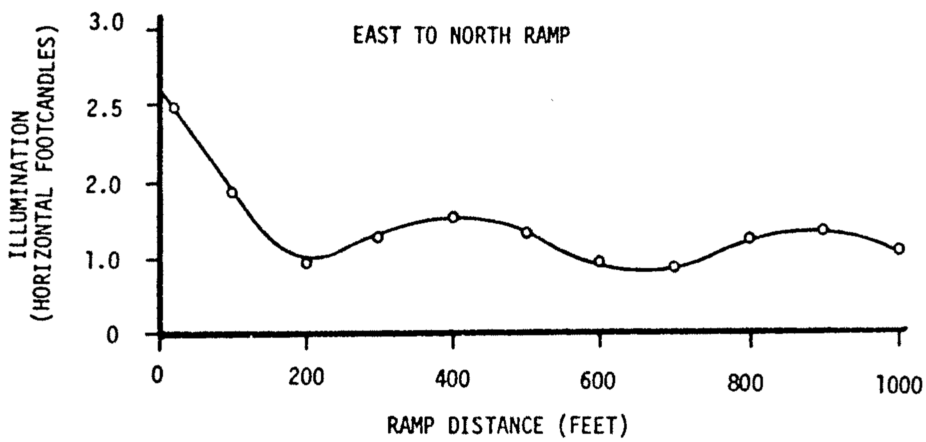


Figure 59. Typical profile of illumination level at ramp centerline.

number of luminaires is determined in the last step.

Step 1. Design a template which shows minimum initial illumination required from one luminaire and whose perimeter is one-half of that value.

A. Determine the minimum maintained illumination by dividing average maintained illumination by the average-to-minimum ratio:

$$\text{Min. Maint. Illum.} = \frac{\text{Ave. Maint. Illum.}}{\text{Ave.-to-Min. Ratio}}$$

B. To obtain minimum initial illumination required, divide the minimum maintained illumination value obtained in Step A by the total maintenance (or light loss) factor, which is a combination of lamp lumen depreciation and lamp dirt depreciation factors.

$$\text{Min. Init. Illum.} = \frac{\text{Min. Maint. Illum.}}{\text{LLD x LDD}}$$

C. To obtain the minimum initial illumination required from one luminaire, divide the minimum initial illumination obtained in Step B by the tentative number of luminaires (N) per pole selected from typical lumen packages of numbers of luminaires and mounting heights.

$$\text{Min. Init. Illum. Per Luminaire} = \frac{\text{Min. Init. Illum.}}{\text{Number of Lum. per Pole}}$$

D. Since usually at least two poles contribute to the minimum illumination, determine

½ Min. Init. Illum. per Luminaire

E. From an isofootcandle diagram of the type shown in Figure 60, obtain isofootcandle line representing the values:

- Min. Init. Illum. per Luminaire, and
- ½ Min. Init. Illum. per Luminaire

Note: If the mounting height selected for the installation differs from that on the photometric test report, the proper correction factor has to be applied. Also, if the values on the test report are per 1000 lamp lumens, a factor for actual initial lamp lumens has to be included in the computations.

F. Using the longitudinal or transverse distance to mounting height ratio of the isofootcandle diagram as scale, make a template to fit the scale of the plans used for the lighting layout. Use ½ Min. Init. Illum. per Luminaire as perimeter of the template and show Min. Init. Illum. per Luminaire as a broken line on the template.

Step 2. Determine pole locations

A. Use the master template as a pattern and make several templates of transparent material.

B. Superimpose these templates on the layout, making sure that all roadways are covered by the minimum illumination boundaries (line on the template) or by the overlap of two one-half minimum illumination boundaries (perimeter of the template).

If the area to be illuminated consists of a complex road system, the first poles (origin of template) should be placed at the most critical points, such as the gores in case of an interchange. Position these templates so as to assure light on these critical areas, but not in direct line of the driver's vision. Next, place additional templates so the entire area is covered, making sure the minimum lighting requirements are satisfied by all roadways being covered by the minimum illumination lines of the templates or by the overlap of two one-half minimum illumination boundaries (the perimeters of adjacent templates).

Step 3. Determine the coefficient of utilization

A. Obtain the longitudinal and transverse distance to mounting height ratios for one-half the minimum initial illumination per luminaire from the isofootcandle diagram (Figure 60).

B. Take the average of these two ratios. In case of a symmetrical light distribution (Type V), these values are identical.

C. Enter the value obtained in Step B on the coefficient of utilization curve and read the CU. Since both street and house side are fully utilized, add the CU for both sides to obtain the total CU.

Step 4. Determine average maintained illumination

Count the number of poles (templates) and calculate the average maintained illumination based on one luminaire per pole.

$$\text{Ave. Maint. Illum.} = \frac{(\text{number of poles}) \times (\text{lamp lumens}) \times \text{CU} \times (\text{total light loss factor})}{\text{total area}}$$

Step 5. Check minimum maintained illumination

To make sure the minimum requirements are met, several points of the roadway which, by inspection of the layout appear to have the lowest illumination, can now be checked. The values are obtained from the isofootcandle diagram. Add the contributions from each pole and multiply the total by the total light loss factor to obtain the illumination at the point investigated.

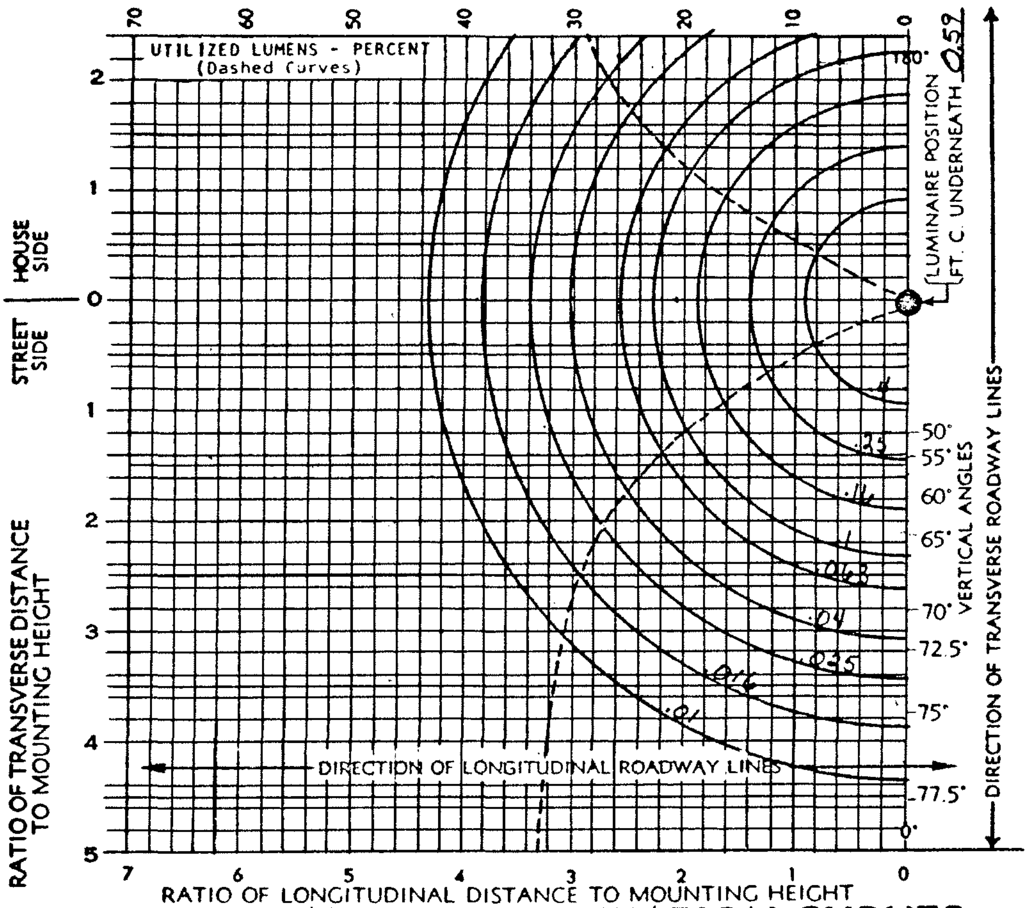
Step 6. Check uniformity

Divide the average maintained illumination found in Step 4 by the lowest value found in Step 5. If the uniformity requirement is not met, the pole locations (templates) should be readjusted.

Step 7. Final check

To make sure the number of luminaires per pole selected initially is correct, multiply the average maintained illumination found in Step 4 by the number of luminaires per pole. If it is necessary to either increase or decrease the number of luminaires per pole by one luminaire, this can be done witout affecting the uniformity.

This concludes the steps used in completing a high mast lighting design by use of the template method. The following is an example problem of the template method.



ISOFOOTCANDLE & UTILIZATION CURVES

100,000·LUMENS

FOOTCANDLE DATA IS BASED ON A LUMINAIRE MOUNTING HEIGHT OF 100 FEET. FOR OTHER MOUNTING HEIGHTS MULTIPLY THE VALUES OF FOOTCANDLES SHOWN BY THE FACTORS IN THE FOLLOWING TABLE. THE UTILIZATION CURVE (DASHED) IS CORRECT FOR ALL MOUNTING HEIGHTS AND DOES NOT REQUIRE CORRECTION.

MOUNTING HEIGHT - FT.	60	70	80	90	100	110	120	130	140	150	175	200
FACTOR	2.78	2.04	1.56	1.23	1.00	0.83	0.69	0.59	0.51	0.44	0.33	0.25

PHOTOMETRIC DATA

TYPE - V

1000 WATT METAL HALIDE

Figure 60. Photometric data for high mast luminaire.

EXAMPLE PROBLEM
HIGH MAST LIGHTING - TEMPLATE METHOD

Design the illumination of an Interstate Highway interchange using the high mast system.

Design Data:

Interchange layout per Figure 61

Maintained illumination = 0.6 fc

Uniformity ratio (avg.-to-min.) = 3:1

Light source: 1000 W metal halide (100,000 lumens)

Photometric data: curves, Figure 60

Mounting height: 100 feet

Total light loss factor (maintenance factor, LLD x LDD) = .63

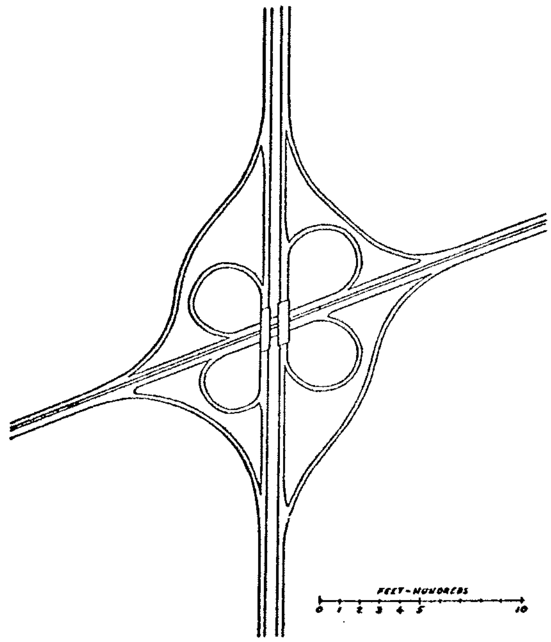


Figure 61. Highway lighting design, typical cloverleaf interchange.

Solution:

Since the selected mounting height is 100 feet and the light source is a 1000 W metal halide lamp, initial layout is based on 4 luminaires per pole.

Step 1. Design template for minimum and one-half minimum illumination required per luminaire per pole.

A. Min. Maint. Illum.

$$= \frac{\text{Ave. Maint. Illum.}}{\text{Ave.-to-Min. Ratio}}$$

$$= \frac{0.6 \text{ fc}}{3:1}$$

$$= 0.2 \text{ fc}$$

B. Min. Initial Illum.

$$= \frac{\text{Min. Initial Illumination}}{\text{Total light loss factor}}$$

$$= \frac{0.2 \text{ fc}}{.63}$$

$$= 0.32 \text{ fc}$$

C. Min. Init. Illum. per Lum.

$$= \frac{\text{Min. Init. Illum.}}{\text{Number of Luminaires per Pole}}$$

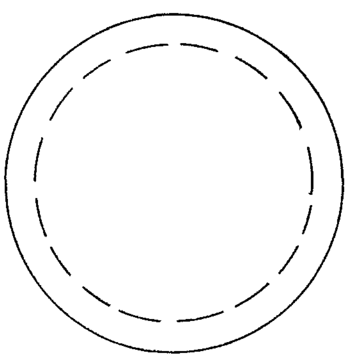
$$= \frac{0.32 \text{ fc}}{4}$$

$$= 0.08 \text{ fc}$$

D. ½ Min. Init. Illum. per Lum. = 0.04 fc

E. On isofootcandle diagram (Figure 60), locate the lines having a value of 0.08 and 0.04 fc. Since the test report is for a mounting height of 100 feet and the lumen rating of the lamp is nominal, no correction factors have to be applied.

F. The 0.04 fc line is found at a distance of 3.05 mounting heights, the 0.08 fc line a distance of 2.5 mounting heights from the origin of the isofootcandle diagram. Therefore, the template has a radius representing 3.05 x 100 feet, or 305 feet, for the perimeter, representing ½ Min. Init. Illum. per Lum., and a line with a radius of 2.5 x 100 feet, or 250 feet, representing Min. Init. Illum. per Lum. The template is shown in Figure 62.



Scale: 1" = 350'

Figure 62. Template used for design.

Step 2. Determine pole location

Figure 63 shows poles located at critical points.

Figure 64 shows additional poles placed over the area.

Figure 65 shows an alternate layout, adding one pole to the layout shown in Figure 64. This layout favors the overpass, but also covers all road sections.

Step 3. Determine the CU

½ Min. Init. Illum. per Lum. = 0.04 fc (Step I-E).
From the utilization curves (Figure 60), the CU is .305 for both the street and the house side. Total CU, therefore, is 0.61.

Step 4. Determine average maintained illumination

Figure 65 shows 12 poles.

Ave. Maint. Illum. =

$$\frac{(\text{number of poles}) \times (\text{lamp lumens}) \times CU \times (\text{total light loss factor})}{\text{total area covered}}$$

The total area covered by templates can either be measured with a planimeter or other means. In the template method, the area is determined by the 4 gore circules (4¶ r^2) plus the area of the square equal to the remaining area covered by overlapping circules (1330' x 1330'). Inspection will show that areas not covered, areas covered twice, and open areas will balance.

Total area = (4¶ x 305^2) + (1330^2) = 2,940,000 square feet

Ave. Maint. Illum. per One Lum. per pole

$$= \frac{12 \times 100{,}000 \times .61 \times .63}{2{,}940{,}000}$$

$$= .157 \text{ fc}$$

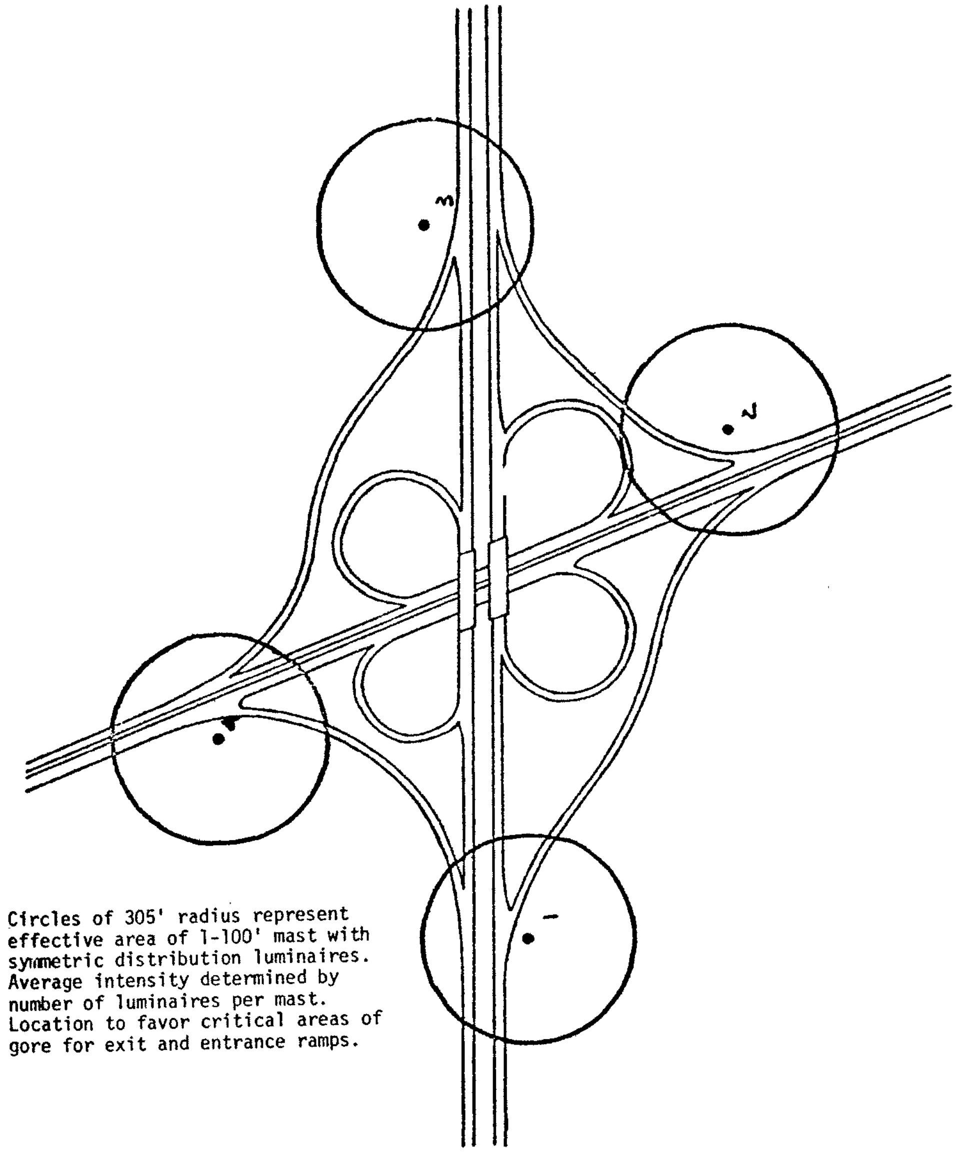


Figure 63. Highway lighting design, typical cloverleaf interchange with initial poles located.

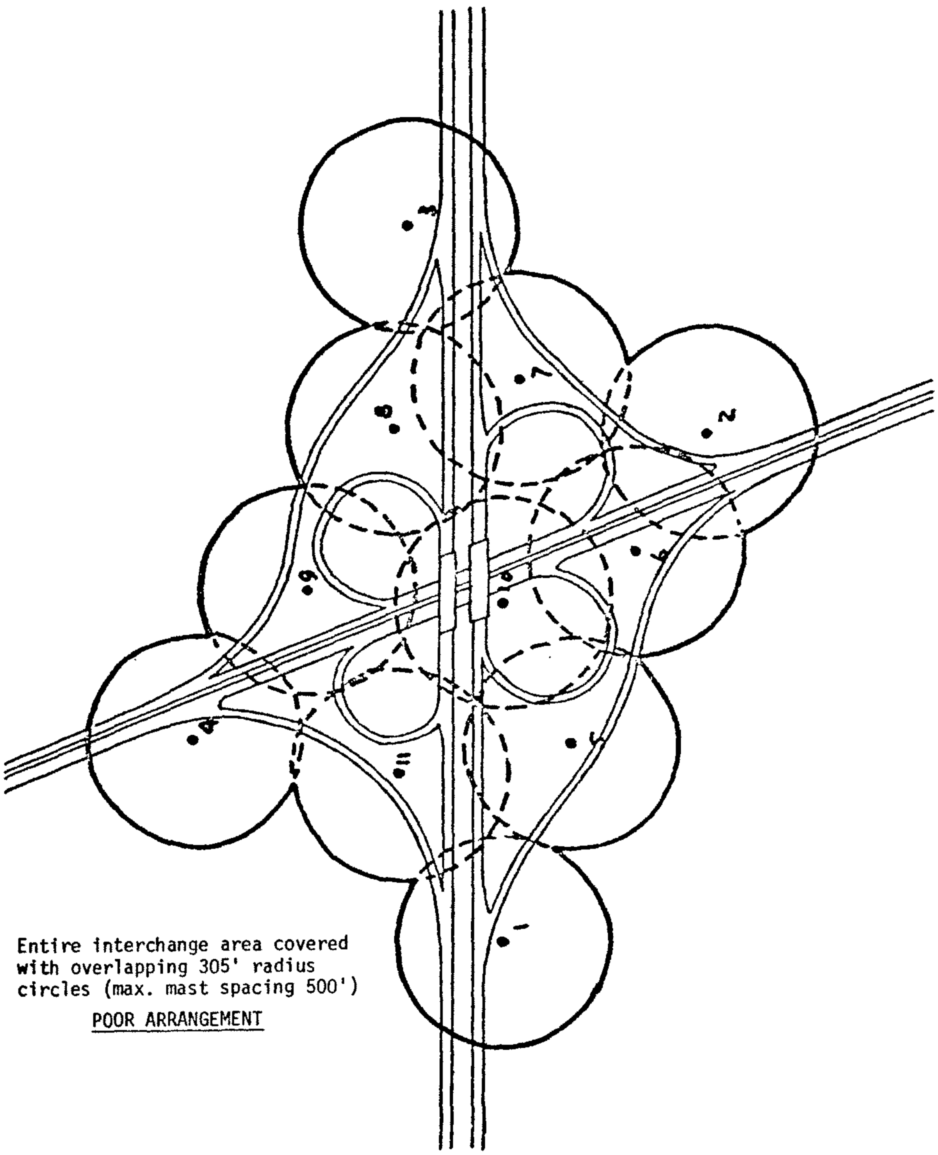


Figure 64. Highway lighting design, typical cloverleaf interchange with less than optimal mast locations.

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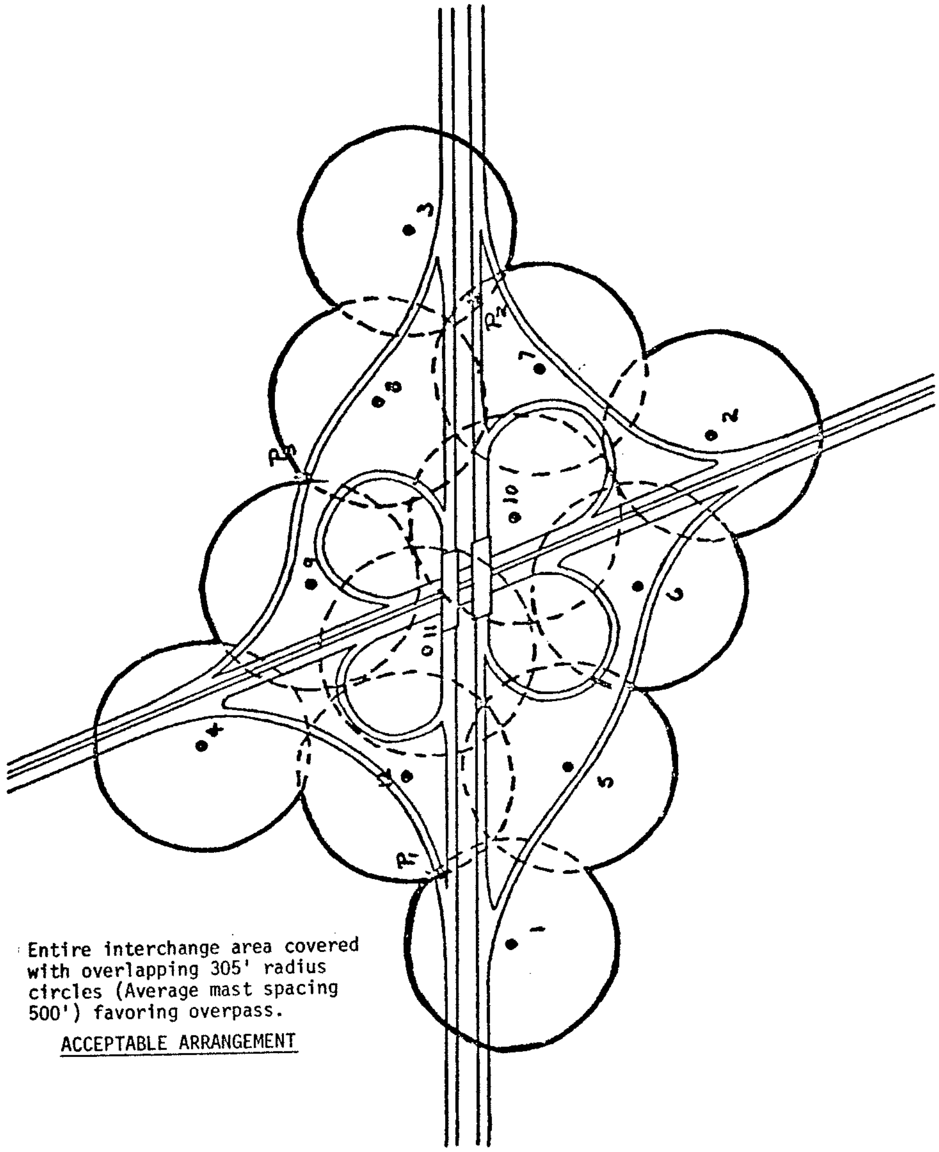

Figure 65. Highway lighting design, typical cloverleaf interchange improved design over previous one.

Step 5. Check minimum illumination

Point P_1 (Figure 65)

From mast No. 1 (305') - 0.044

From mast No. 2 (500') - 0.005

From mast No. 12 (305') - 0.044

Total 0.093
x 0.63

= 0.059 fc

Point P_2

From mast No. 3 (280') - 0.056

From mast No. 7 (280') - 0.056

From mast No. 8 (400') - 0.016

Total 0.128
x 0.63

= 0.081 fc

Point P_3

From mast No. 8 (320') - 0.042

From mast No. 9 (320') - 0.042

Total 0.084
x 0.63

= 0.053 fc

Step 6. Check uniformity

$$\text{Uniformity} = \frac{\text{Average Illumination}}{\text{Minimum Illumination}}$$

$$= \frac{.157 \text{ fc}}{.053 \text{ fc}}$$

Uniformity = 2.96:1, O.K., less than 3:1

Step 7. Final check

Since 4 luminaires per pole were selected initially, average maintained illumination is:

4 x .157 fc = 0.63 fc, O.K.

If this value had been less than .6 we would need to add an additional luminaire.

CONTROL OF GLARE

The lighting designer should always be conscious of glare in the design of a roadway lighting system. As discussed previously, two types of glare are of concern:

- disability glare
- discomfort glare

With the advent of higher mounting heights (greater than 40'), glare is reasonably easy to control. Most designers use a semi-cutoff luminaire, a compromise between the cutoff and non-cutoff types. This selection, in conjunction with reasonable care in placing the light source, can result in good glare control.

COMPUTER APPLICATIONS IN ILLUMINATION DESIGN

The digital computer has become very popular in the illumination design process because it can perform very rapidly the laborious and repetitive calculations involved in illumination design. Most illumination design utilizes the inverse square law (illumination varies inversely as the square of the distance from the source) in determining the distribution of illumination on a point-by-point basis. By hand, these calculations are long and laborious, but by computer they are minor.

Computers may be programmed to interpolate, to make comparisons, to perform trial and error procedures, and to plot results in various forms. Because of their flexibility in application, computers have been applied to lighting very extensively. Applications may be categorized into three major areas for the purposes of discussion.

- Roadway Lighting Programs
- Area Lighting Programs (High Mast)
- Cost Comparison Programs

Each of these is discussed below.

Roadway Lighting Programs

This type of program may be used in either one of two ways shown as Case A or B in Table 13. The Case A mode of the program would typically be used for a relighting job where pole location is already set and an estimate of a new illumination level and uniformity ratio would be desired. Case B is typical of new lighting design where a design standard for illumination level and uniformity ratio have been established and the pole spacing is required.

In either case this type of program usually makes use of stored photometric data for a particular lamp/luminaire combination. Various configurations, such as staggered opposite or one-side, may be experimented with to find the best illumination results with the fewest number of luminaires.

Some agencies involved in lighting designs such as state highway departments or larger cities may have the computer capability to program and run their own lighting programs. Smaller agencies

TABLE 13

ROADWAY LIGHTING PROGRAM PARAMETERS

CASE	GIVEN	CALCULATED
A	Pole Spacing Roadway Width Lamp/Luminaire Comb. Mounting Height Offset from Pavement Configuration Maintenance Factor	Average Illumination Uniformity Ratio
B	Average Illumination Uniformity Ratio Roadway Width Lamp Luminaire Mounting Height Offset from Pavement Configuration Maintenance Factor	Pole Spacing

should investigate the use of remote computer terminals and programs provided by lighting equipment manufacturers.

Area Lighting Programs

The design of high mast lighting systems for freeway interchanges is greatly expedited by the use of computer programs. Essentially, the programs do point-by-point calculations of illumination levels using either stored data for the luminaire or an equation for the photometric data. Mounting height relative to the various roadway surfaces and distance from the pole to the roadway are taken into account. The location of the roadways relative to the lighting pole are established by first utilizing a traverse (horizontal and vertical alignment) program to establish a grid system for the entire interchange. Thus, the lighting designer may ask for a printout of the illumination at a given interval along the centerline and pavement edges of each of the roadways and ramps within the interchange. Trial and error location of a pole is accomplished by changing the information input to the machine. More sophisticated versions of these programs are capable of plotting isofootcandle curves for the entire interchange.

Cost Comparison Programs

Cost programs, developed primarily by manufacturers, are useful in calculating the return on investment for various lighting schemes. These programs take into account fixture, labor, replacement, maintenance, and energy costs in comparing two or more lighting systems. An example would be the comparison of a low first cost, high energy consumption luminaire/lamp combination with one that initially costs more but requires less maintenance and/or energy. While this type of program may be quite useful and timesaving, it should be noted that the results are only as good as the input data. Estimating what energy and labor costs may be over the life of the system may not always be the easiest task. For this reason, several computer runs with values that are likely to bracket the future unknown values may be desirable.

Limitations of Computer Lighting Programs

As stated previously, the computer may be used as a method for quickly analyzing lighting schemes with a large number of variables. Caution, however, should be taken in converting the computer results directly into design standards and plans. Experience on the part of the lighting engineer is still needed to assure that things such as glare minimization, aesthetics, and other special considerations are made.

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2. American National Standard Practice for Roadway Lighting, RP-8, 1977, Illuminating Engineering Society-American National Standards Institute, New York, N.Y., 1977.

3. An Informational Guide for Roadway Lighting, American Association of State Highway and Transportation Officials, Washington, D.C., March 1976.

7

DESIGNING THE LIGHTING HARDWARE

DESIGNING THE LIGHTING HARDWARE

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

The total design of a roadway lighting system entails more than simply the selection and location of the luminaires. An important consideration must be the method by which electrical energy is supplied to the individual luminaires. Also, pole foundations and mounting hardware must be chosen which will support the luminaire and pole under anticipated loading conditions. These topics are addressed in the following paragraphs.

ELECTRICAL DISTRIBUTION SYSTEMS

The electrical distribution system encompasses the equipment which performs the following functions:

- Distributing electrical energy to individual luminaires
- Energizing and de-energizing the system or portions of the system
- Transforming commercial power where necessary into a form usable by the luminaires

A description of the essential components, their functions, and some suggestions for equipment selection and sizing are given below.

Roadway Lighting Circuits

A roadway lighting circuit can be as simple as a single luminaire attached to a utility pole or as complex as the illumination system for an entire interchange or section of freeway. Beginning with the single luminaire installation, we will look at the equipment and design considerations of various lighting systems.

The majority of residential street lighting utilizes luminaires mounted on power poles. Power for these luminaires is usually provided by secondary power transformed for other commercial users along the roadway. A typical installation of this type is shown in Figure 66, and simple circuit diagrams for a single luminaire or a small group of luminaires are shown in Figure 67.

Equipment needed for this type of installation is minimal. Switching the luminaire on and off is typically accomplished by a photoelectric cell mounted on the luminaire thereby eliminating the need for more complicated switching equipment. The electrical load imposed by a single luminaire is usually quite small compared to the commercial load for which the transformer and other equipment have been sized, and therefore can be added with little or no problem.

Larger systems such as continuous street lighting or interchange lighting involves numerous luminaires which cannot feasibly be fed by existing,

Figure 66. Power pole-mounted luminaire.

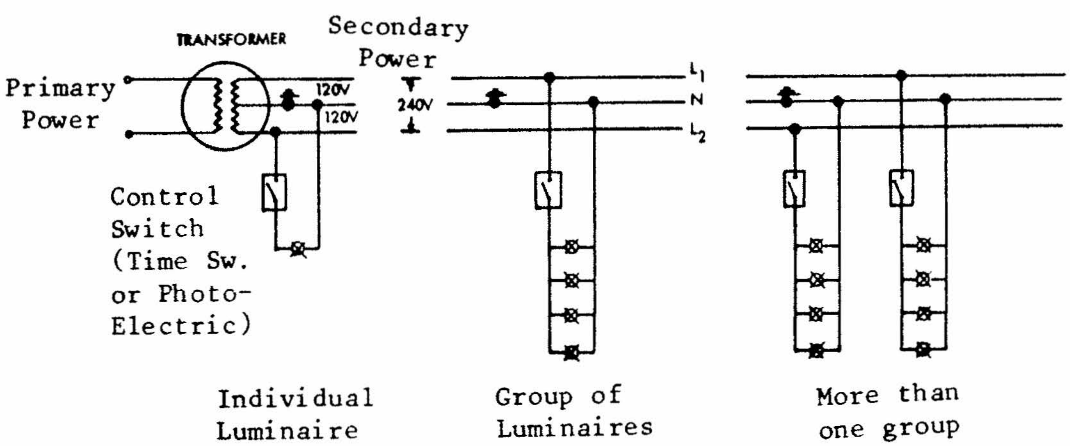


Figure 67. Simple street lighting circuit diagram.

nearby secondary power. Instead, heavy duty type transformers, switching gear, and other equipment must be used. Power in this case is typically purchased from a utility company in un-cut or primary form somewhere in the range of 2500 to 7500 volts. This power is usually furnished to the roadway right-of-way line and from there the lighting authority must provide the transmission lines and transformers needed to transmit the power to the lighting control center(s) and step the voltage down to some usable level such as 240 or 480 volts. Step-down transforming of the power is accomplished at a substation which, in turn, feeds one or more lighting control centers. The substation may also house a lighting control center.

Secondary feeder circuits connect the luminaires to the lighting control center. Secondary circuits are generally referred to as series or multiple circuits. The series system employing a constant current supply is far less popular today than it was in the early days of street lighting. There were two main reasons for the series circuit--the adaptability to early, constant wattage arc lamps, and the fact that a circuit over a large area could be controlled from one point. Briefly, the series system is designed so that a wire begins at a regulating transformer, wanders up and down the various streets, and finally ends up back at the other terminal of the transformer. The wire is interrupted by the inclusion of lamps resulting in a series circuit with a constant current throughout the system.

Multiple circuits, on the other hand, provide constant voltage to the lamps. Filament-type lamps can be used directly on multiple circuits while discharge lamps can be used with suitable ballasts. In the multiple system, the lamps or ballasts are connected directly across a source of constant voltage and the current will be different for each lamp rating. Multiple circuits did not become widely used due to the difficulty of control until low-cost time switches and later even lower-cost photoelectric controls were developed.

The present trend is toward the conversion to multiple lighting for new and upgraded installations. Several of the factors that have dictated this trend are:

- Multiple distribution facilities are now generally in place where street lighting is proposed.
- The growth of overhead distribution lines is crowding pole space. The elimination of series power lines results in additional room for transformer, primary capacities, and other devices necessary to carry the new load.
- With multiple lighting, outages may be limited to a few isolated lamps, whereas it is not uncommon for an entire series circuit from 40 to 300 lamps to be out for extended periods.
- Multiple circuits require minimum maintenance.

For these reasons, the secondary lighting circuit discussed and illustrated in this section will be of the multiple circuit type.

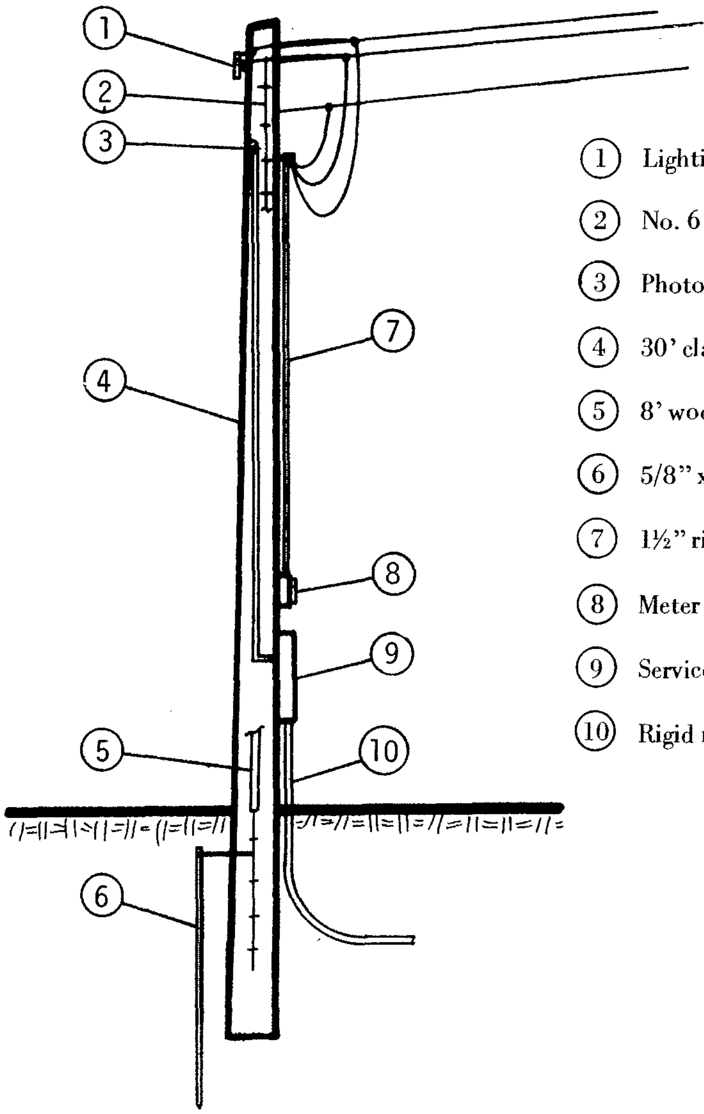
Lighting Control Center Equipment

Except for the single luminaire attached to a utility pole and operating off of available secondary power, each lighting system requires a certain amount of equipment at the control center. This equipment is listed and discussed below.

Lighting Control Center Enclosure. Selection of the type of control center is dictated by the size of the project, road location, aesthetic requirements, methods of primary feeder installation, local practices, and predominant climatic conditions. The principal types of lighting control centers used are:

- Pole mounted type
- Kiosk type
- Building type
- Undergound vault type

Pole type substations are used in cases where the lighting load and required equipment are not excessively large. In general, a pole type substation consists of a pole, switching gear, and a set of secondary equipment. In addition, transformers may be needed depending on the voltage of the power source. Figure 68 is an example of a pole type control center operated from a secondary power source, thus eliminating the need for a transformer. As would be expected, the cost of this type of installation is relatively low.



(1) Lighting arrester

(2) No. 6 AWG bare ground wire

(3) Photo cell and ¾" rigid metal conduit

(4) 30' class 5 pole

(5) 8' wood ground wire molding

(6) 5/8" x 8' copper glad ground rod

(7) 1½" rigid metal conduit

(8) Meter (if required)

(9) Service assembly

(10) Rigid metal conduit--minimum size 2"

Figure 68. Typical example of a pole type control center installation.

The kiosk type of lighting control center is popular due to aesthetics and space considerations. The housing is usually of a rigid welded construction and is placed on a concrete pad. The high voltage and transformer compartments should be bolted together to form a continuous, tamper-proof, weather-proof, dead front enclosure with bulkhead style doors and access panels. Figure 69 shows a typical kiosk type control center.

Building type control centers often including substations are of sufficient size to allow for the inclusion of considerable equipment. Maintenance activities may be conducted inside the weatherproof structure. This type of installation is not usually warranted for small lighting systems. An illustration of a typical building type substation is included in Figure 70.

Underground vault type control centers are primarily used in urban areas where right-of-way space and aesthetics are most important. Underground vault type control centers may cause the designer to consider somewhat different aspects in equipment application, maintenance, and operation. Vault ventilation, drainage, work space, personnel safety, equipment insulations and enclosure, as well as other factors often become considerations which cause underground vault type centers to be less desirable than other types.

Thus, the type, size, and construction of the lighting control center is dependent on a number of items such as cost, space required, and aesthetics. Much of control center selection is dictated by the particular lighting installation being designed for as well as the preferences of the lighting agency involved.

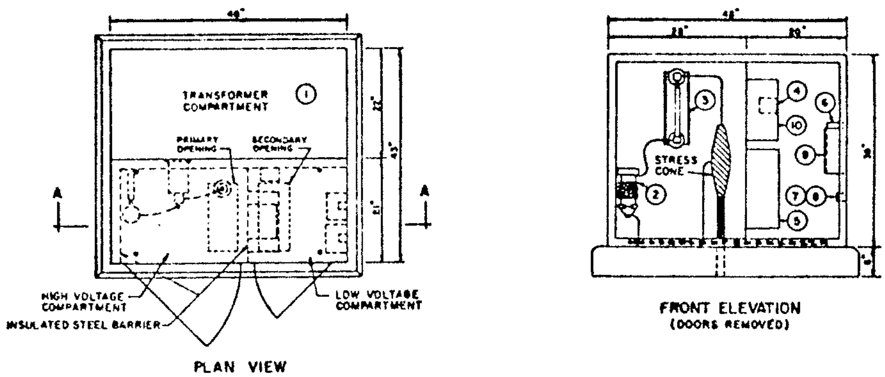
Control Equipment. One item of equipment within the lighting control center is the control by which the luminaire circuits are energized and deenergized. Luminaires may be controlled locally by the use of a photo-switch at every luminaire or an entire circuit may be turned on and off by a switch at the lighting distribution center. Having only a few luminaires controlled by one device results in very limited outages if the device fails. On the other hand, this increases the number of devices and the probability that one will fail. The decision to use single luminaire or circuit control is dependent on the type of control used. The most popular of these are time switches and photo switches. Radio control has also been considered.

A time switch is a device in which an electric clock operates a set of contacts through a turn-on to turn-off cycle with the turn-on and turn-off times preset. Time switches of this type may have a mechanical backup system in case of a power failure. Astronomic-dial time switches are made to compensate for day length, thus resulting in turn-on and turn-off times closely corresponding to light levels. Unless several lights are to be served by one time clock, it may be more economical to control the lights by some other means.

The photoelectric or light sensitive control switch is fast becoming the most widely used control switch for street lighting. It has reached the stage of development where it renders reliable service at very low cost. The main advantages of the photo control can be listed as:

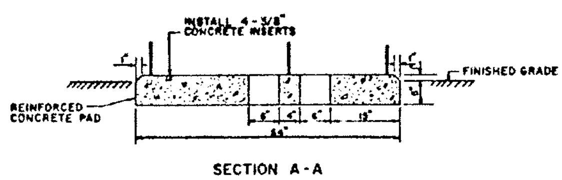
- Operates when illumination levels indicates lights are needed, thus compensating for seasonal variations in day length and for dark or bright days.
- Adapts itself particularly well to integral mounting into the luminaire, thus making installation and maintenance simpler and less expensive.
- Can be used to control entire circuits, thus reducing the total number of photocells.

Other types of control have also been used or experimented with for controlling roadway lighting. For example, the use of radio frequency control could be used for real time control of street lighting. In certain situations, such as those where time clocks are currently being used, a radio-controlled system could effectively reduce the total power consumed by the street lighting system by accurately matching turn-on and turn-off times to



EQUIPMENT LIST

1. TRANSFORMER, 1PHASE, 25KVA. 60 CYCLE, 2.4 KV. PRIMARY/120-240V. SECONDARY, SOLIDLY GROUNDED NEUTRAL,
2. PRIMARY LIGHTNING ARRESTER, DISTRIBUTION TYPE, 3KV. CLASS
3. LOAD INTERRUPTER SWITCH, 1 PHASE, 8KV. WITH HOLDER AND FUSE UNIT
4. SECONDARY LIGHTNING ARRESTER, PELLET TYPE, 2 POLE 115/230 VOLT 3 WIRE, WITH WALL BRACKET
5. PANELBOARD, TYPE 'NOP', 1PHASE 3 WIRE 120/240 VOLT, 8-30 AMP. 'EA' FRAME CIRCUIT BREAKERS
6. CIRCUIT BREAKER, 225 AMP., 2 POLE 600 VOLT, 'JA' FRAME
7. RELAMP SWITCH, 1 POLE, 10 AMP. 125 VOLT
8. 30 AMP. 250/600 VOLT FUSE HOLDER, FRONT CONNECTED WITH 5 AMP FUSES
9. CONTROL RELAY, 110 VOLT WITH ONE N/C CONTACT
10. CONTACTOR, OPEN TYPE, 135 AMP., 2 POLE 600 VOLT, SIZE 4



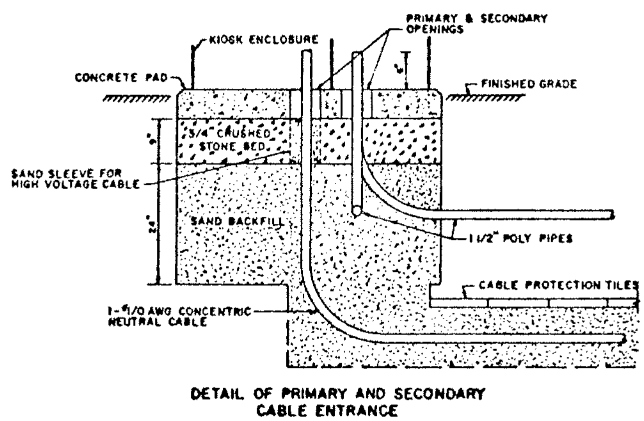
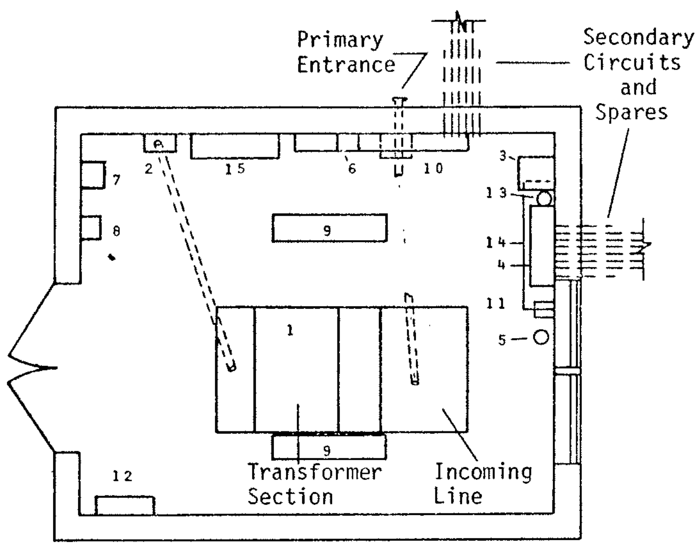


Figure 69. Kiosk type control center installation (3).

ambient light conditions.

Other Lighting Control Center Equipment. In addition to some type of control to turn the lights on and off according to the natural light conditions, other equipment is also needed in the roadway lighting circuit to perform a variety of functions. A simplified schematic of this equipment, usually referred to as a one-line electrical diagram because one line is used to represent all of the necessary conductors, is shown in Figure 71.



Equipment List

1. Unit Substation, Metal Enclosed, 15 KV Class
2. Safety Switch with Fuses
3. Combination Starter
4. Panelboard
5. Photoelectric Cell
6. Safety Switch with Fuses
7. Transformer, Air Cooled
8. Load Center
9. Industrial Fluorescent Luminaire
10. Combination Starter
11. Secondary Lightning Arrester
12. Spare Parts Cabinet
13. Secondary Lightning Arrester
14. Wiring Trough
15. Metering Equipment

Figure 70. Plan view of building type control center installation.

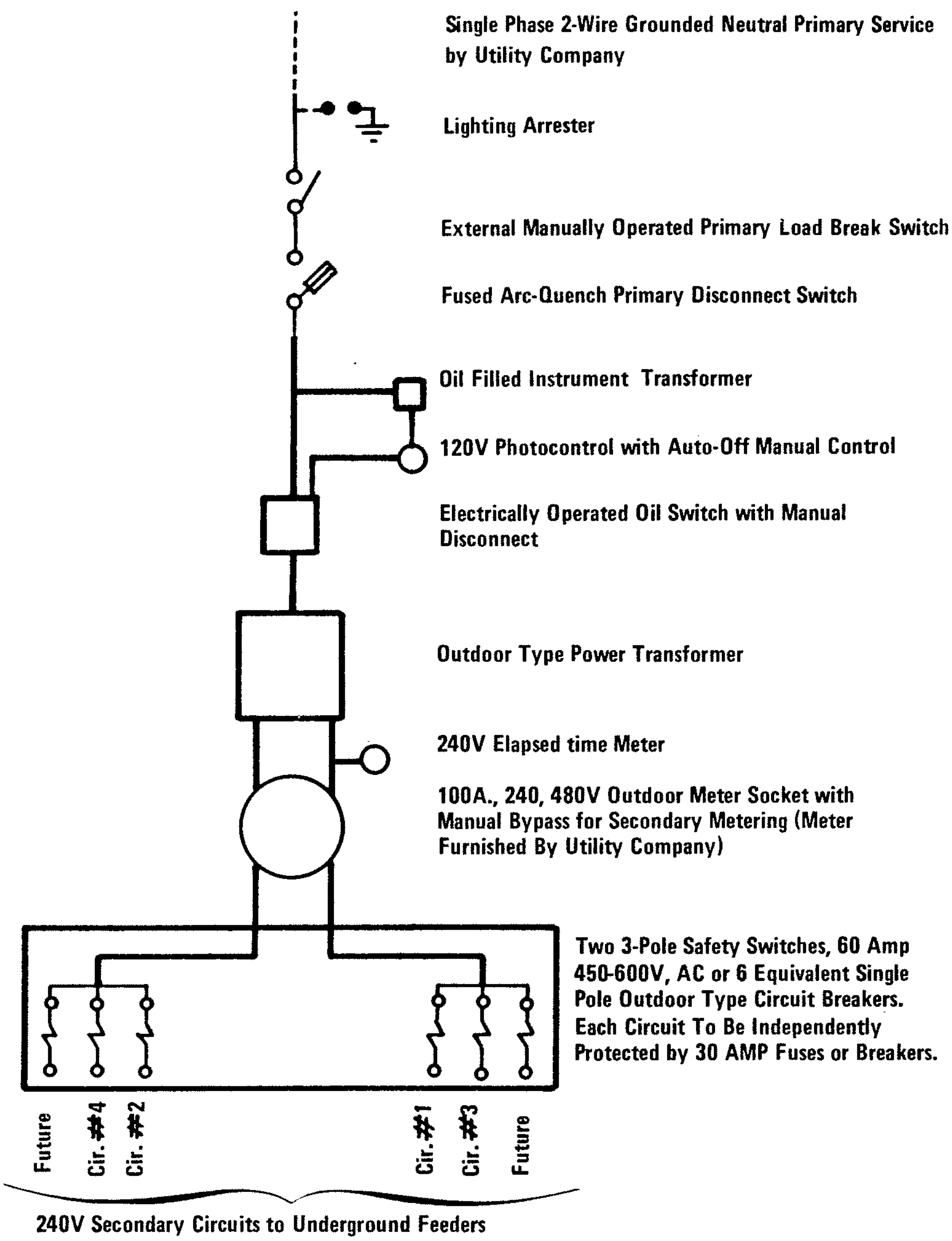


Figure 71. One line electric diagram of lighting control equipment.

The first device usually encountered before reaching the control center is a lightning arrester. Basically, a lightning arrester provides a direct path to ground for lightning that may be attracted by overhead wires or other equipment. The grounding circuit is usually open due to a gap in the contacts; however, this gap is small enough for the electrical charge to jump, thereby closing the circuit until the lightning surge has been dissipated.

Next in line is a switch which is used to de-energize the entire control center. Referred to as a primary break switch or similar term, this device is usually located externally to the control cabinet to provide ease of access and protection from electrical shock. Provision is usually made for locking the handle of this switch in either the "ON" or "OFF" position.

The next piece of equipment shown in Figure 71 is a primary disconnect switch. This switch is fused to protect the equipment within the control center.

Following these switches are the photocontrol and the transformer needed to power the photocontrol. This equipment and the accompanying, electrically-operated, oil switch are used when an entire circuit or circuits are to be controlled from the lighting control center. Should the luminaires be controlled by individual photocells, these three pieces of equipment would be eliminated. A three position switch is usually included with "AUTO" for photocell control of the luminaires, "OFF" for complete shut-off during maintenance periods, and "MANUAL" for bypassing the photocell during the day to energize the circuits and look for individual lamp outages.

Up to this point the power is still at the primary voltage. This has allowed the contactors and other equipment used thus far to be of a high voltage, low amperage type. The next device that is needed is a power transformer used to reduce several thousand volts down to the voltage suitable for the luminaires (240 volts in the case of Figure 71). As illustrated, two separate power taps were taken off the transformer at this point to prevent all of the subsequent circuits from being on one set of conductors. This not only cuts down on the conductor size, but also reduces the number of outages that will occur should this circuit fail.

Also shown in Figure 71 is an elapsed time-meter which may be used to determine how many hours per month or year the luminaire circuits are energized. Readings which are too high for a city at a particular latitude would indicate that either turn-off time is too late or turn-on time is too early.

A meter socket is usually also included to accept the utility company's meter. This socket will be on the outside of the distribution and control center enclosure in order to allow reading of the meter from outside the enclosure.

The bottom section of equipment shown in Figure 71 is a bank of switches or circuit breakers. In the example shown, each set of three circuits can be controlled by either one 3-pole safety switch or three single-pole circuit breakers, the only difference being the capability of controlling each circuit individually with the single-pole circuit breakers.

Sizing of this type of equipment depends largely on the primary and secondary voltages and the anticipated load imparted by the luminaires. An example of this is included in another section of this chapter.

Secondary Lighting Circuit Equipment

The secondary lighting circuit transmits the power from the lighting control or distribution center to each of the luminaires. The principal types of equipment necessary to accomplish this task are the cables, conduit, and junction boxes.

Lighting Cables. Underground cable systems have generally replaced aerial cable systems on new roadway lighting installations. This is mainly because of the hazard to the public should a pole be knocked down and for aesthetic considerations. Street lights added to existing overhead, secondary distribution systems are an exception to this trend.

Because of this trend toward underground transmission lines, the emphasis in conductor specification has shifted from mechanical strength to improved insulation types suitable for underground installations. Conductors are usually specified to be of annealed copper meeting standards such as ASTM B-3 or B-33. Stranded rather than solid conductors are usually specified according to ASTM B-8. An exception is the use of grounding conductors where solid copper wires in the range of No. 8 may be used.

Conductors should have a high quality, tough, heat- and moisture-resistant type of insulation suited for application in dry or wet applications. These include NEC Type THW and cross-linked polyethylene insulation types.

Cables may be installed in the following ways:

- Direct burial
- Polyethylene duct
- Cable in duct (pre-conduitized)
- Rigid metal duct

Each of these methods is discussed briefly below.

Direct burial cable probably requires the least construction cost. By use of a vibratory plow the cable is usually placed 18 to 24 inches below ground level. Backfilling is not required because no trench is required. The direct burial method is not used in many states and local jurisdictions because of the damage that can occur to the cable insulation and conductors if a heavy load passes over the conductor.

The most common type of cable installation in roadway lighting systems makes use of polyethylene conduit. This type of conduit is lightweight, easy to work with, and still provides reasonable protection to the enclosed conductors. The conduit is usually buried to a depth of 18 to 24 inches by standard trenching methods. After all of the conduit is in place, the cables are pulled through the conduit and the necessary connections are made. Care should be taken during cable pulling to prevent mechanical damage to the conductors or insulation. This involves making proper connection of the pulling device to the cables, gauging the amount of tension applied to the cables, and installing a sufficient number of pull boxes to prevent pulling cables around unprotected corners or over extremely long distances.

Poly-type conduit is usually not permitted under roadways where anticipated loading may crush this type of conduit. In this case, rigid metal conduit is usually specified.

Cable in duct or pre-conduitized cable is gaining popularity in underground distribution systems. This method of installation is similar to that above except that the cables are placed in the conduit at the time of manufacture. The cable and conduit arrive at the job site in coils to be fed off a spool directly into the trench. This eliminates the need for pulling the cables through the conduit and possible damage which might occur. This type of conduit is made to still allow for removing the existing cables and pulling new ones at a later date.

Rigid metal conduit is used primarily under roadways or attached to structures such as bridge underpasses. Metal conduit may also be placed in bridge or other structures at the time of construction for later use in lighting circuits.

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Conduit placed under roadways is usually accomplished either by jacking or boring. Jacking is better suited for short runs, as pressure alone is used to force the conduit through the soil. In the boring method an auger is used to drill a hole for the conduit. In sandy soils the auger is often placed inside the conduit and both are advanced together, the auger bit being slightly ahead of the leading conduit edge. In heavy clay soils the hole is usually drilled in the soil first and after the auger is removed the conduit is jacked under the roadway.

Junction Boxes. Junction boxes, also referred to as pull boxes, are installed in the underground system where connections and splices need to be made. Planning for a sufficient number of pull boxes during the design process will assure that workmen will have adequate room for splicing and connecting cables. This also provides the locations from which cable pulls will originate and terminate, thus relieving the temptation of contractors to make overly long cable pulls. Pull boxes are also used where cables cannot be pulled around sharp corners.

Pull boxes are constructed of a variety of materials such as asbestos, cement, or corrugated metal as illustrated in Figure 72. Other organizations use precast concrete pull boxes of the design shown in

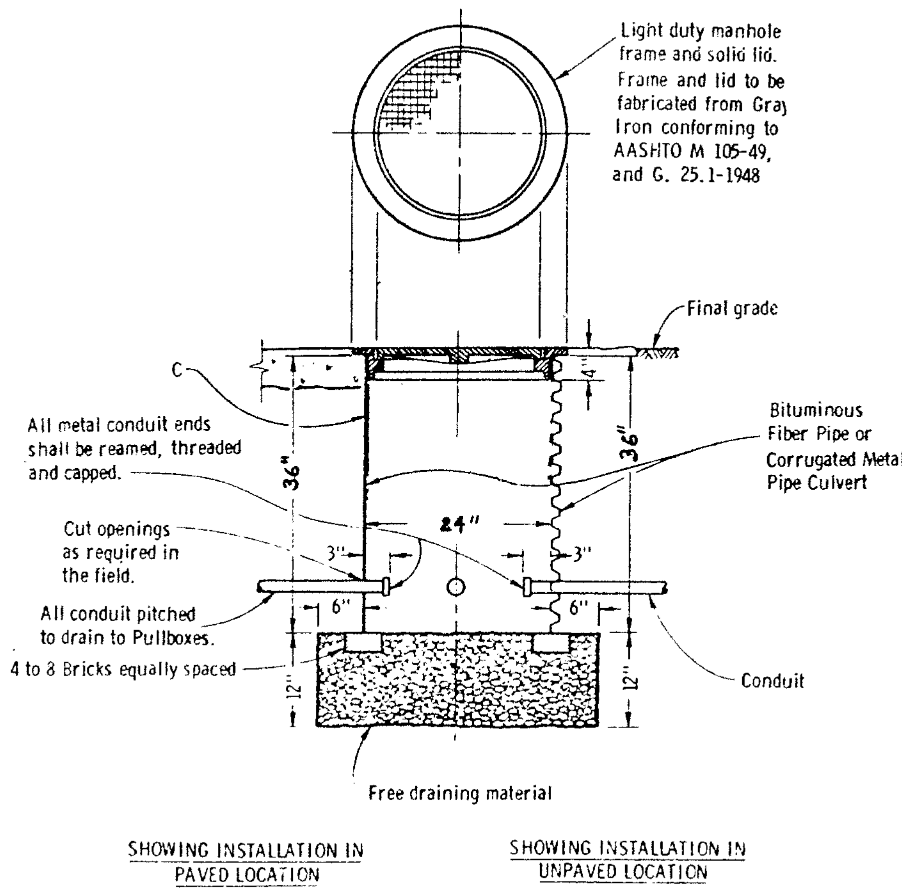


Figure 72. Typical bituminous fiber or corrugated metal pipe pull box.

Figure 73. The size of the pull box depends primarily on the number of conductors. When installing pull boxes, care should be taken to orient the cover away from the road to reduce the amount of dirt, ice, snow, etc., that can enter, and so that it can be easily serviced.

Grounding

A roadway lighting system includes transformers, cable, auxiliary equipment, and luminaires--all sensitive to voltage fluctuation. Voltage stresses caused by transient conditions or ground faults

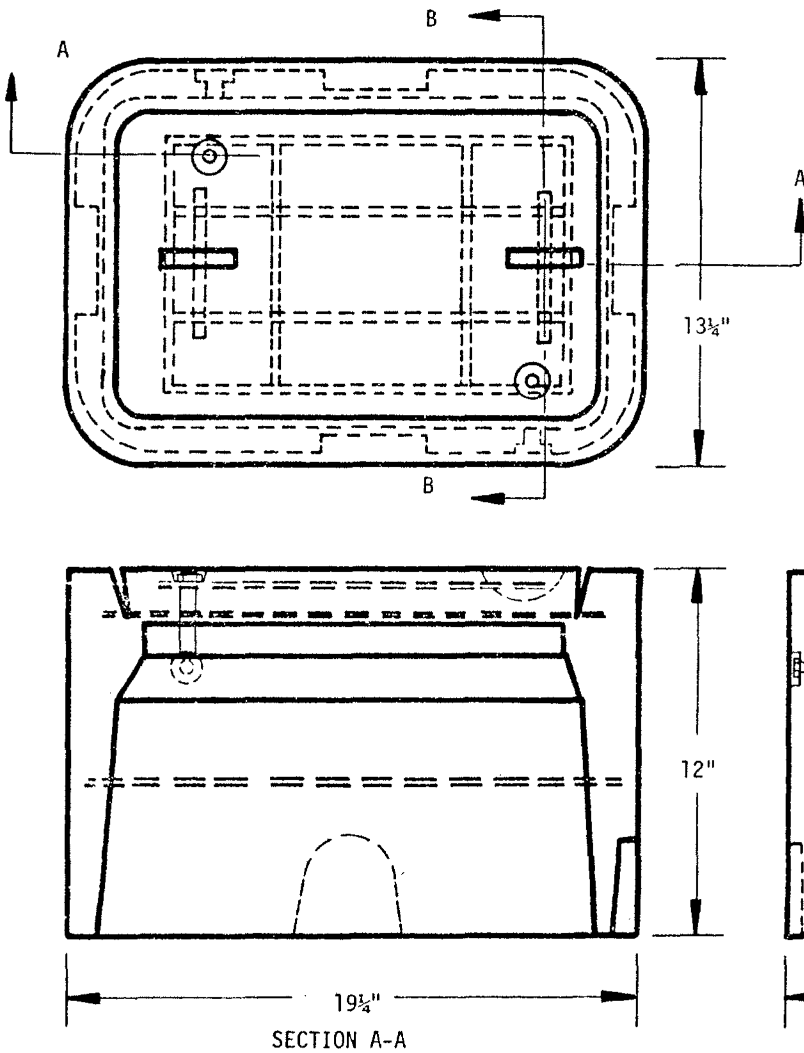


Figure 73. Typical reinforced concrete pull box.

can seriously affect the life of the equipment or wiring. An effective method of reducing any possible hazard resulting from high voltage is to ground all metal parts which might be energized by a failure of insulation. Grounds are especially effective for series circuit because the current is limited.

It is advisable that the lighting system secondary neutral be solidly grounded wherever this does not conflict with local Utility practice. The primary neutral grounding must be coordinated with the policies of the local Utility.

Equipment grounding is required to maintain low potential differences between metal components and ground for the protection of personnel. For this reason, all electrical equipment enclosures or housings, motor frames, structures, and substation equipment should be interconnected and effectively grounded. The housings of luminaires and other devices individually supported should be connected to a ground cable.

Grounding of the system or equipment would have no significance if the connection to earth did not provide low values of resistance. For lighting system equipment in individual substations or for the system neutral grounding, the value should not exceed 10 ohms where possible.

The ground conductors should be, in general, soft-drawn stranded copper wire at least No. 8 AWG, except when connected to luminaires in which case No. 12 AWG wire is quite acceptable. Where the conductor is insulated, the color of the insulation should comply with local regulations.

The ground rods should be of copper clad steel. The tops of the rods should be at least one foot below finished grade. Copper plates not less than 1/8" thick should be used where conditions do not permit the use of rods.

The copper wire used as a ground conductor should be buried not less than one foot below finished grade. Bare aluminum wire should not be used as a ground wire.

The connections to ground rods should be made with thermit welds where possible. If mechanical connections are used, these should be accessible for inspection.

Most roadway light poles are grounded to some degree through the anchor rods or embedded steel base. However, dry concrete is a poor conductor and it is necessary to make more definitive provisions for grounding. Most companies use a single ground rod driven adjacent to the pole or extending into permanently moist earth below the base. In some cases, a copper plate or coil of wire is buried immediately below the pole foundation. The ground connection is permanently connected to the metal lamp pole and is often connected to a grounding conductor or to the metal sheath of the street light cable.

A stranded soft-drawn bare copper ground wire not smaller than No. 8 AWG should be installed in the same trench as the secondary wiring. Ground rods should be driven at every fifth pole or approximately 800 feet apart and thermit welded to the ground wire. The ground wire should be kept in direct contact with the earth. At each pole the ground wire should be tapped off, using a thermit weld connection and installed up the pole to the ground stud. A No. 12 AWG stranded insulated ground wire of the approved color should be installed from the ground stud in the pole to the luminaire ground stud as shown in Figure 74. Figure 75 illustrates another alternative.

CODES AND STANDARDS

Roadway lighting systems are usually designed and built to meet state and local standards, especially when state or federal funds are involved. Standard specification, special provisions, and plan sheets describe the items and procedures to be used in completing the contracted work. These documents usually make further reference to industry codes and standards which describe how a particular piece of equipment is to be made and how it functions. Some of these publications are:

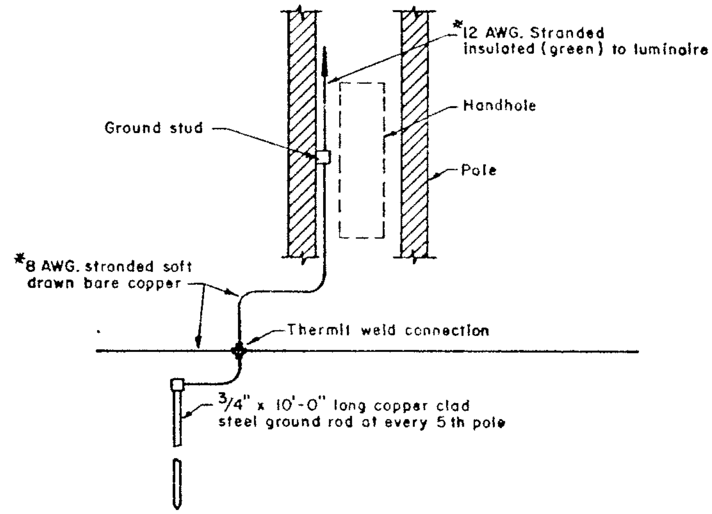


Figure 74. Lighting pole grounding assembly (3).

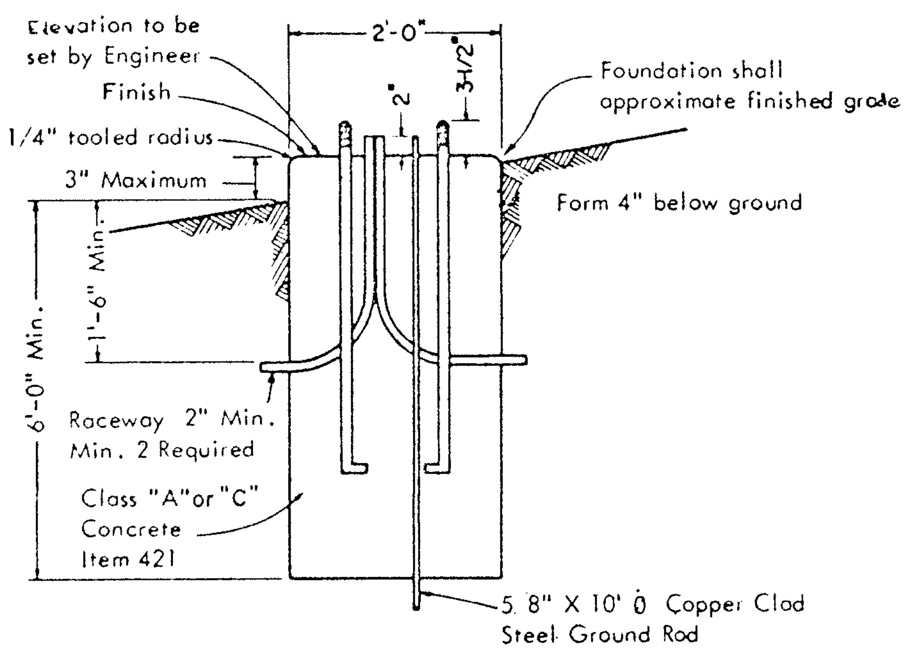


Figure 75. Grounding scheme using rod in foundation.

- National Electrical Code (NEC)
- National Electrical Manufacturers Association (NEMA)
- American Society for Testing Materials (ASTM)
- Underwriters Laboratories (U.L.)
- American National Standards Institute (ANSI)

The use of these codes and standards in specifying materials to be used in a lighting installation will assure that inferior and possibly hazardous equipment will not be used.

EXAMPLE CIRCUIT DESIGN PROBLEMS

The electrical design of a roadway lighting system involves the selection and sizing of the conductors, transformers, and other equipment required by the system. Some knowledge of electricity and power distribution must be commanded by the lighting engineer if he is to perform his own electrical design. Equipment manufacturers can provide valuable information on equipment selection while electrical engineering consultants are available for the more extensive lighting jobs. Therefore, due to the complexity of situations which may arise in lighting design, the following is given only as an example of some of the considerations which must be attended to in the electrical design.

The load imparted on the electrical system is the result of the following luminaires:

40 units - 700 w mercury vapor

75 units - 400 w mercury vapor

20 units - 250 w mercury vapor

The first step is the calculation of the total load. Because high intensity discharge lamps require ballasts for operation, the ballast losses must be considered in calculation of the total load. Information concerning ballast losses is provided by the manufacturers. In this example, the total loading would be:

$$40 \times (700 + 72) = 30880 \text{ w}$$

$$75 \times (400 + 60) = 34500 \text{ w}$$

$$20 \times (250 + 35) = 5700 \text{ w}$$

71080 or 71.1 kw

While this gives the total load in watts or kilowatts, most power distribution equipment is rated in kilo-volt-amperes (kva). To convert kilowatts to kva, we must know the "power factor" of the load. Simply stated, power factor, or pf, relates real power (watts) to apparent power (volt-amperes). For a purely resistive load, such as an incandescent lamp or a heating coil, the real power and the apparent power are identical. For most loads, however, which have, in addition to their resistive characteristic, an inductive or a capacitive component, the real and the apparent power are not the same. Power factor is that number obtained when the real power is divided by the apparent power.

$$\text{Power Factor} = \text{pf} = \frac{P}{VI}$$

To illustrate, we calculate the power factor of an incandescent lamp and a mercury luminaire. Assume the incandescent lamp is a 500 watt, 120 volt lamp which draws 4.17 amperes. The mercury luminaire dissipates 460 watts (400 watts in the lamp and 60 watts ballast losses), and operates on a line voltage of 120 volts, drawing a line current of 4.2 amperes.

pf of the incandescent lamp is:

$$\frac{500}{120 \times 4.17} = 1.0$$

pf of the mercury luminaire is:

$$\frac{460}{120 \times 4.2} = .91$$

To convert kilowatts, or real power, to kva, or apparent power, we simply divide the real power by the power factor.

$$kva = \frac{kw}{pf}$$

In case of our incandescent lamp, therefore, the kva rating is:

$$\frac{.5\ kw}{1} = .5\ kva$$

and the rating of our mercury luminaire would be:

$$\frac{.460\ kw}{.91} = .505\ kva$$

Using a power factor of .8 for our circuit design problem, we now can determine the kva rating of the transformer:

$$kva = \frac{71.1\ kw}{.8} = 88.87\ kva$$

Assuming the system is three-phase, the transformer rating should be three-30 kva single-phase or one-90 kva three-phase.

In illustrating an example to determine the cable size for a lighting circuit, the following data is given:

Total circuit 1 mile long, center-fed, each branch circuit ½ mile long
Power supply: 240V, single-phase, 2-wire
Luminaires: 700W mercury, 240V, 72W ballast losses, power factor = .97
Luminaire spacing = 220 ft.
Permissible voltage drop = 10%

The current in the individual line conductors of the distribution system must be known and may be calculated from the following forumlas:

Single-phase, 2-wire: $I = \frac{W}{Ep \times pf}$

Single-phase, 3-wire: $I = \frac{W}{2Eg \times pf}$

3-phase, 3-wire: $I = \frac{W}{\sqrt{3} \times Ep \times pf}$

3-phase, 4-wire: $I = \frac{W}{\sqrt{3} \times Ep \times pf}$

or: $I = \frac{W}{3Eg \times pf}$

where:

I = conductor current
W = power in watts
pf = power factor
Ep = voltage between wires
Eg = voltage between phase wire and neutral

Once the line current has been determined, voltage-drop tables, curves, mechanical computers of the slide-rule type, or electronic computers can be used in the circuit design. The voltage-drops of Table 14 can be used where power-factor is close to 100% and can be neglected. For lower power factors, other tables or curves, found in Electrical Engineering Handbooks, should be used.

To determine the required conductor size, the following steps are taken:

1. Permissible voltage drop = .10 x 240V = 24V

2. Total number of luminaires on branch-circuit =

$$\frac{2640 \text{ ft.}}{220 \text{ ft.}} = 12$$

3. Total load per branch circuit: (700w + 72w) x 12 = 9264w

4. Line current per branch circuit at feeder point:

$$\frac{9264}{240 \times .97} = 39.8 \text{ amps}$$

We can now find the wire size required to stay within the permissible voltage-drop.

To find wire size for a given voltage-drop:

a. Find ampere-feet by multiplying current in amperes by length of one wire in feet.

b. Divide the amp-ft. by the permissible voltage-drop to obtain amp-ft./one-volt-drop.

c. For uniformly distributed loads (such as is the case in many roadway lighting systems), halve the calculated amp-ft./one-volt-drop value. For loads concentrated at the end of the distribution system, use the amp-ft./one-volt-drop value without modification.

d. Follow column down to the number of amp-ft./one-volt-drop nearest to the number calculated. Find the correct size at the left hand column.

e. With short runs, table may indicate a size of wire smaller than permitted by code regulations. In such cases, the wire size must be increased to meet the code requirement.

5. Determine amp-ft.: 39.8 amps x 2640 ft. = 105100 amp-ft.

6. Determine amp-ft./one-volt-drop:

$$\frac{105100 \text{ amp-ft.}}{24 \text{ volts}} = 4380 \text{ amp-ft./one-volt-drop}$$

7. Since we have a uniformly distributed load, we use half the value found in step 6 to find recommended wire size:

$$\frac{4380}{2} = 2190$$

The nearest value found in Table 14 is 2880. The wire size to be used is no. 2.

To check for actual drop in no. 2 wire, divide calculated amp-ft. value by amp-ft. value from Table 14 and multiply by the allowable voltage drop:

$$\frac{2190}{2880} \times 24\text{V} = 18.2\text{V}$$

This says the last luminaire will be supplied with a line voltage of 240V - 18.2V, or 221.8 volts, provided the supply voltage actually is 240 volts, and all luminaires dissipate nominal power.

If the voltage drops were checked between luminaires, we would see that the highest drop occurs between the feeder and the first luminaire. At that point, the current flowing to the rest of the luminaires is reduced by the amount taken by the first unit. A similar reduction in current occurs at every luminaire. Since voltage-drop is a function of cable impedance and current, and the current through the cables becomes less and less as the last luminaires are approached, the voltage drop from the second-last to the last luminaire is much smaller than what is found at the start of the circuit. For this reason, long lighting circuits are sometimes wired using a heavier cable for the first section of a circuit, and a smaller diameter cable for the end section. A cost analysis should be made, however, to check the justification of such a configuration.

TABLE 14

VOLTAGE DROP TABLE
1.0 Power Factor

CONDR. SIZE AWG	Voltage Drop at 49 C per Ampere-Feet
14	177
12	282
10	448
8	712
6	1110
4	1760
2	2880
1	3540
1/0	4460
2/0	5620
3/0	7080
4/0	8920

LUMINAIRE SUPPORT HARDWARE DESIGN

The luminaire is supported by several pieces of hardware, the mast or pole, the mast arm, the pole foundation, and a transformer base which is used between the foundation and the mast. Each of these components must be of sufficient design to support its own weight and the weight of the luminaire under a variety of loading conditions. These design considerations are discussed below.

Mast Design

The loads that should be considered in the design of luminaire masts are: dead load, live load, ice load, wind load, or a combination of loads. The dead load consists of the weight of the luminaire, the mast arm, the mast itself, and any other device that is attached to the mast. In simple terms, the dead load is the total of the weight of the mast and any object that it supports.

The live load that should be considered is the weight of maintenance personnel that maintains the luminaires. With the present widespread use of high-reach service vehicles, loading of this type is less prevalent than in the days of maintenance personnel climbing poles for maintenance purposes. Should this type of loading be anticipated at some time in the life of the installation, however, it should be included in design calculations.

The ice load should be a load of 3 pounds/foot^2 applied around the surfaces of the structural support, the horizontal support (mast arm), and the luminaire. Figure 76 shows the locations within the United States where an ice load should be considered.

The wind load is the pressure of the wind on the horizontal and vertical supports and the luminaire that is derived from the following formula. This formula was developed by the American Association of State Highway Officials.

$$P = 0.00256\ (1.3V)^2\ C_d\ C_h$$

where:

P = wind pressure in pounds per square foot
V = wind speed in mph from map, n-year recurrence interval (see maps--Figures 77, 78, and 79)
C_h = coefficient for height above ground measured to the centroid of the corresponding limits of the loaded area (see Table 15)
C_d = drag coefficient (see Table 16)

The loads described above should be combined in groups and the mast and mast arm should be proportioned for the combination producing the

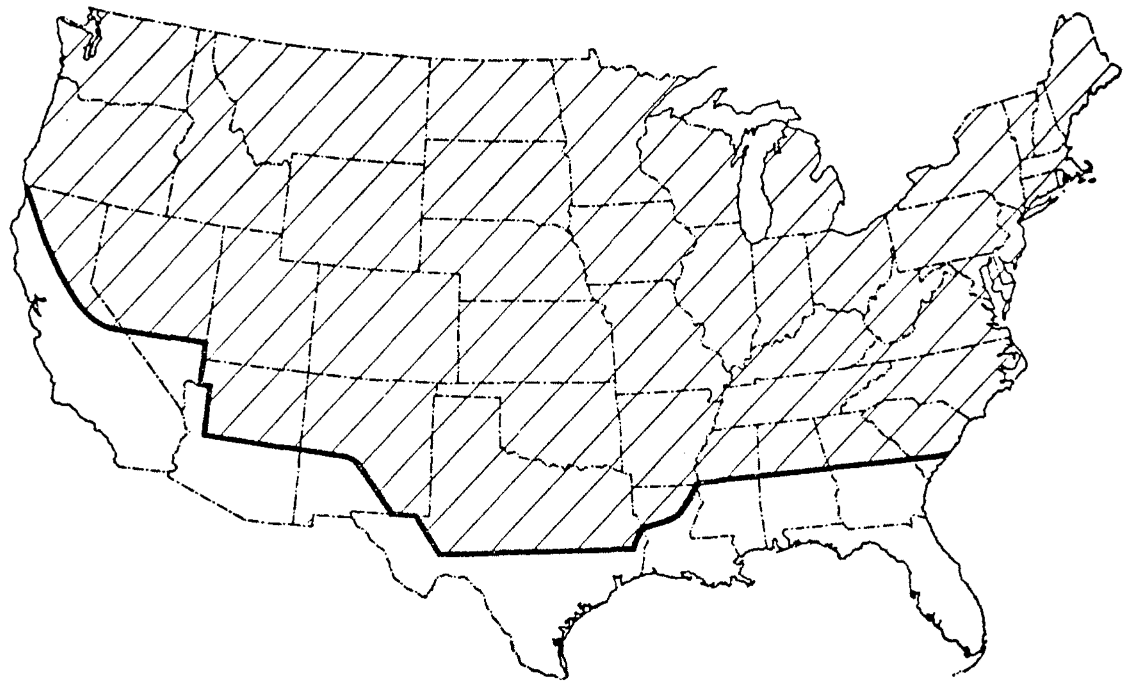


Figure 76. Ice load areas.

TABLE 15

COEFFICIENTS FOR VARIOUS HEIGHTS ABOVE THE GROUND (C_h)

Height (ft.) (m)	C_h
0-15 (0-4.57)	0.80
15-30 (4.57-9.14)	1.00
30-50 (9.14-15.24)	1.10
50-100 (15.24-30.48)	1.25
100-150 (30.48-45.72)	1.40
150-200 (45.72-60.96)	1.50
200-300 (60.96-91.44)	1.60

TABLE 16

DRAG COEFFICIENTS (C_d) FOR LUMINAIRE SUPPORTS

Shape	C_d
Luminaires (with generally rounded surfaces)	0.5
Luminaires (with rectangular flat side shapes)	1.2

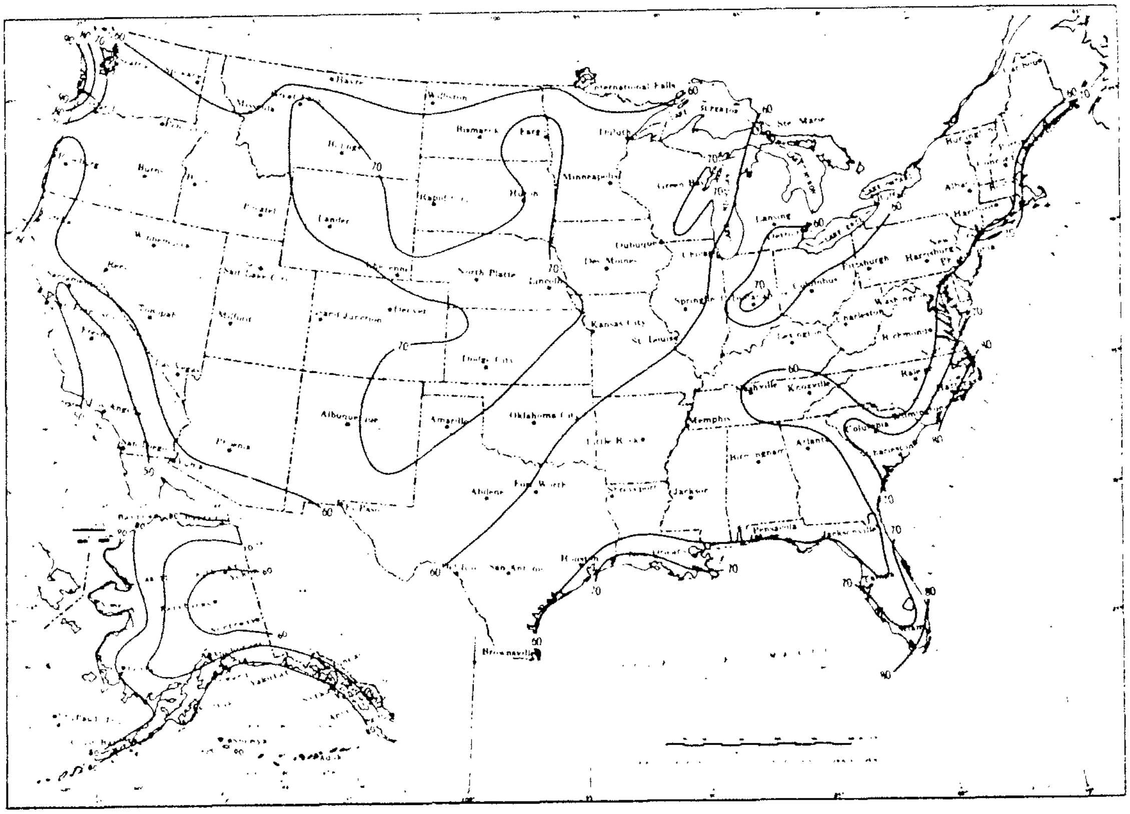


Figure 77. Isotach 0.10 quantiles, in miles per hour: annual extreme-mile 30 feet above ground, 10-year mean recurrence interval.

maximum effect. In addition, other requirements may be specified as to the pole's performance under certain loading conditions. One state (1) uses the following:

> "The complete lighting standard, including luminaire, shall sustain a vertical load of 200 pounds applied at the point of luminaire attachment. Deflection of the shaft center line shall be not more than 5 percent of the shaft length when a load of 500 pounds is applied in any direction 18 inches from the top of the pole."

A good reference on this subject is the current issue of AASHTO's "Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals" (2).

Mast Arm Design. Mast arm design is to some extent governed by the required overhang over the street and the desired amount of upsweep (the extra mounting height gained by curving the mast arm upward from its point of attachment to the mast). Other considerations are aesthetics and the desirability of using as few mast arm types as possible to reduce the inventory of replacement mast arms. In general, the mast arm must be able to withstand the weight of the luminaire and the accompanying ice and wind loads. One state (1)

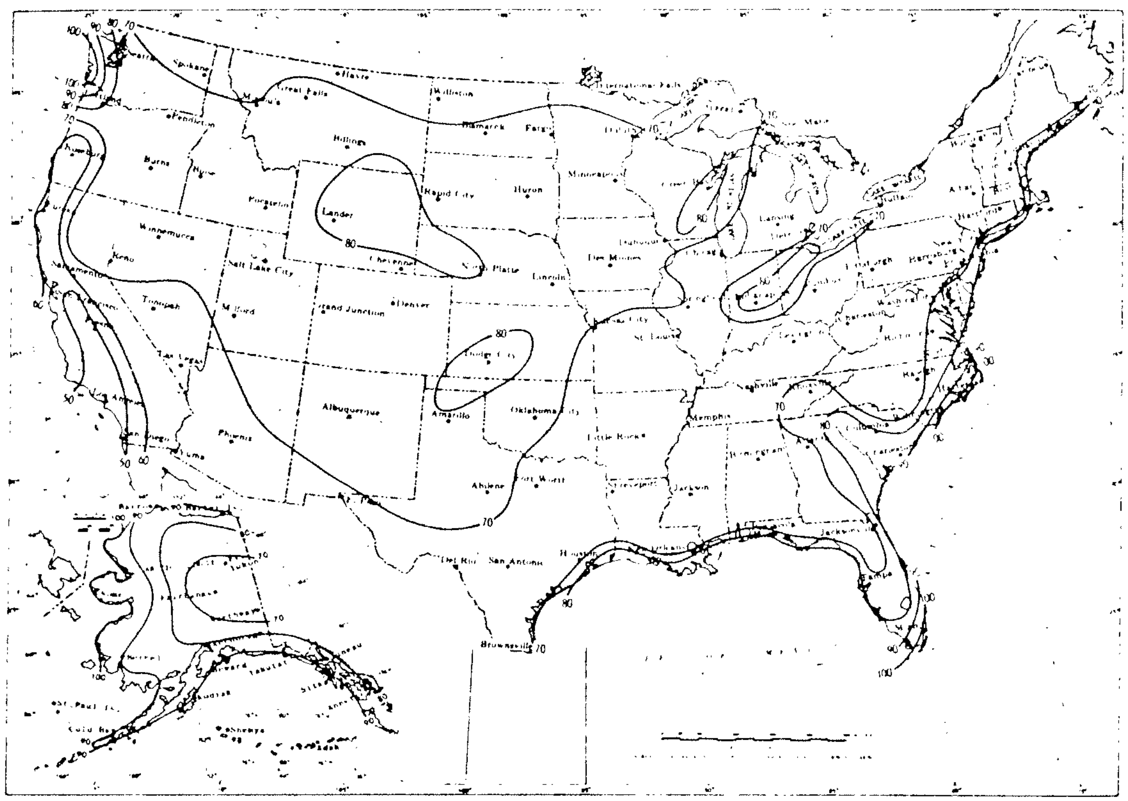


Figure 78. Isotach 0.04 quantiles, in miles per hour: annual extreme-mile 30 feet above ground, 25-year mean recurrence interval.

requires that all mast arms be designed for a 66-pound luminaire having a projected area of 2.7 square feet.

Pole Foundation Design. Regardless of the type of foundation used, comprehensive soil information is valuable information for foundation designs. Investigations should include the type and density of each material encountered and ground water conditions. In-place strength tests are very beneficial for determining the soil strength required for design. The soil strengths resisting lateral movement are very critical. Adequate information on the type soil is essential before actual design of the luminaire support foundation can begin.

Consideration should also be given to the geographical area in which the luminaire foundation is to be located. In temperate latitudes, foundations are commonly located at a depth not less than that of normal frost penetration. In warmer climates, and especially semi-arid regions, the minimum depth of footings may be governed by the greatest depth at which seasonal changes in moisture cause appreciable shrinkage and swelling of the soil.

The elevation at which a footing is established depends on the soil type, the load supported, and the cost of the foundation. Generally, the luminaire footing should be located at the level where adequate supporting material can be found. In some

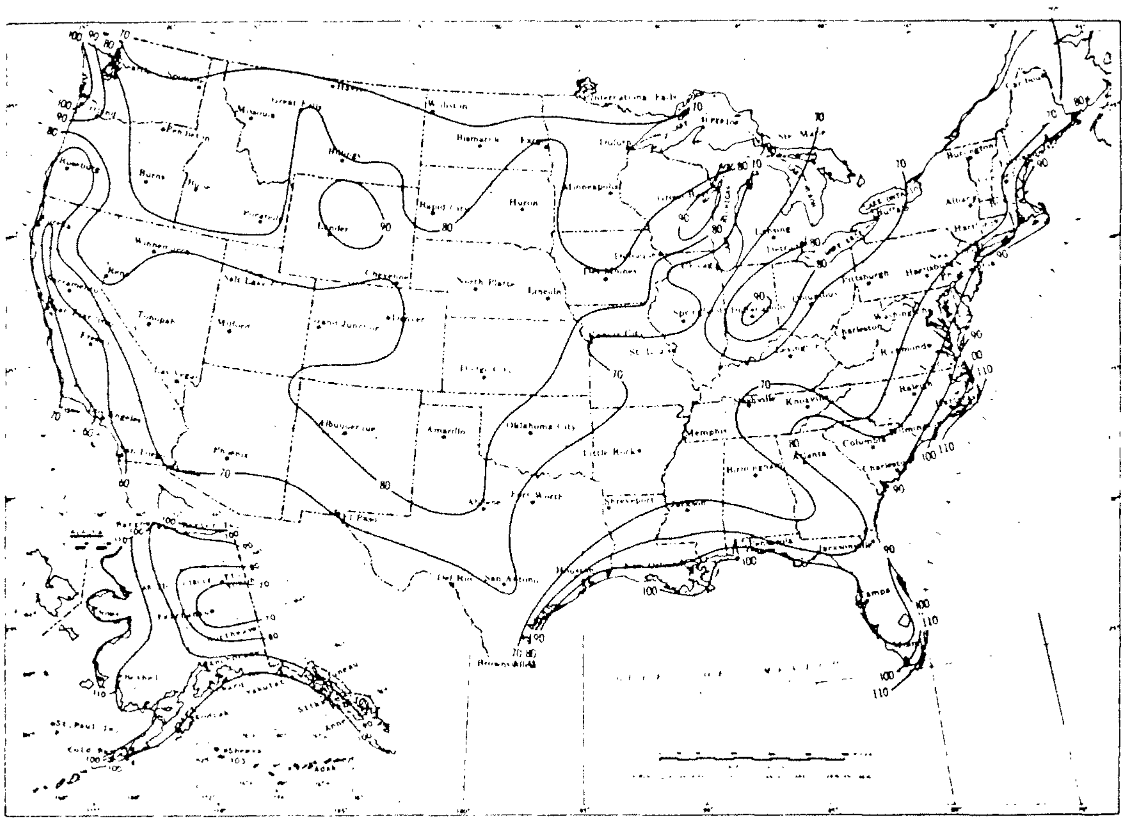


Figure 79. Isotach 0.02 quantiles, in miles per hour: annual extreme-mile 30 feet above ground, 50-year mean recurrence interval.

instances, if a supportive layer is encountered at greater depth, it may be economical to combine two of the types of foundations. For instance, pilings can be poured down to a firm soil layer and then a slab can be poured in place on these pilings to support the mast.

The foundation should also be strong enough to withstand the moment created by wind loads on the mast. Refer to the formula used in the section on Mast Design.

The two design criteria discussed above--soil characteristics and wind loads--should be considered in any foundation design. It is recommended that, first of all, a foundation expert be consulted for the initial design, and, secondly, that a standard luminaire foundation design be developed by the agency responsible for roadway lighting. The standard foundation should be designed to meet the existing local conditions.

Base Design

In order to adequately support the luminaire, the lighting pole must be strong to resist wind loads, steady to reduce the effects of vibrations, well-proportioned for aesthetics, low in initial cost, and low in maintenance costs. From the safety standpoint, however, additional criteria must be considered. Where the pole is not sheltered and breakaway performance is required, the support must yield to vehicular impact, either by progressive failure, fracture, or slippage--any means to reduce the transfer of energy from fixed object to vehicle to occupant. The support must behave after the impact in such a manner that it will not constitute undue hazard to the vehicle occupants in a secondary impact with the vehicle, or by falling on a pedestrian, or by falling within the traveled way to be struck by another vehicle.

There are two basic requirements that should be considered when designing breakaway luminaire supports. Primarily, the base must have the ability to fracture, yield, or slip when struck by a colliding vehicle. This characteristic is measured in terms of change in momentum of the colliding vehicle. This characteristic is influenced by the type of base, vehicle speed, vehicle weight, and orientation. Table 17 gives the acceptance criteria for the dynamic behavior of breakaway bases.

The second design consideration for breakaway luminaire supports is the behavior of the support after impact. It is desirable to know where the support falls after it breaks away and whether or not it strikes the automobile in a secondary collision. The behavior of the support after impact is dependent upon the base fracture energy, the vehicle speed and weight, the weight and the distribution of the weight of the support, and the angle at which the base is struck.

TABLE 17

ACCEPTANCE CRITERIA
DYNAMIC BEHAVIOR OF BREAKAWAY LUMINAIRES

Vehicle Weight:	2250 lbs (1020 kg)
Vehicle Speed:	20 to 60 mph (32 to 97 kmh)
Change in Momentum:	
Desirable:	750 lb-sec (3336 N-Sec)
Acceptable:	1100 lb-sec (4893 N-Sec)

The two basic requirements used above constitute the minimum design requirements for breakaway bases. The following design criteria are recommended to assure that these requirements are met.

- The base should be selected or designed on the basis of an acceptable base fracture energy. Consideration should also be given to the requirement that the base and the support must withstand the static and wind loads with a suitable factor of safety.

- If the base is of the slip type, the supported shaft must possess sufficient strength to resist crushing or denting in the vehicle contact area.

- The lowest base fracture energy, consistent with static and wind strength requirements, should be used.

- In those cases where low velocity collisions are most probable, the base fracture energy must be a minimum, and the shaft should be as light in weight as possible.

- Where higher mounting heights (40 feet to 50 feet) are used, the multi-directional slip base design is preferred due to the low base fracture energy.

PLANS AND SPECIFICATION

A set of engineering drawings and specifications is a visual presentation of the solution to a particular engineering problem. The documents outline the responsibilities of the parties involved, list the amount of material required, describe methods of installation, and define the method of measurement and compensation for work completed. These documents not only assist the contractor in scheduling his activities, but also serve as a guideline for the inspector in determining the adequacy of work completed.

A complete set of engineering documents covering all phases of the project will usually consist of:

- Layout drawings and diagrams
- Special provisions
- Standard specifications

These items are discussed in the following paragraphs.

Layout Drawings and Diagrams

Engineering drawings should include clear and concise instructions in order to convey the information needed to carry out construction work. The first sheet in a set of plans usually includes the project number, a small map showing the location of the roadway within the city and state, a legend of symbols used throughout the following sheets, and the signatures of those responsible for the design and construction of the system.

On the following pages layout drawings should clearly locate poles, road crossings, substations, manholes, pull boxes, overhead signs, and other stationary lighting components which require electrical wiring. Information on circuit arrangement, trenching, and methods of erection of all equipment should be shown.

Drawings are usually made to a scale of 50 or 100 feet per inch on standard plan size sheets that are 24 x 36 inches. Many agencies now prepare standard plan sheets and then have them photographically reduced to one-half size for ease of use and storage. Drawings should be made large enough to prevent loss of details when reduced. Also, a graphic scale rather than a numerical scale which reads, for example, 1" = 50', should be used on sheets that are to be reduced.

Layout drawings of the lighting system are usually placed on a strip map of the roadway prepared from existing plans and surveys for the area. For lighting on roadways to be constructed, the construction plans are usually available from the roadway designer. A problem in designing lighting from plans for older existing roadways is that the designer must rely on the accuracy of these plans and also he cannot be certain that minor improvements to the roadway or development of the abutting property have not occurred. One method of overcoming these problems is the use of a montage of current aerial photographs of the area as a base on which lighting poles, conduit runs, and other equipment are located. The use of photographs such as this greatly reduces both the number of trips to the field during the design process and the number of field adjustments during construction.

In addition to the layout sheets, standard detail drawings are included which describe the hardware to be used and construction practices to be followed. These sheets are not always drawn for each lighting job, but rather may be used for similar types of lighting jobs with modifications to fit the particular situation. Jobs will require different standard detail drawings and general notes depending on the types of lighting involved, i.e., conventional, high mast, underpass, etc. A portion of a standard detail drawing for conventional lighting is shown in Figure 80.

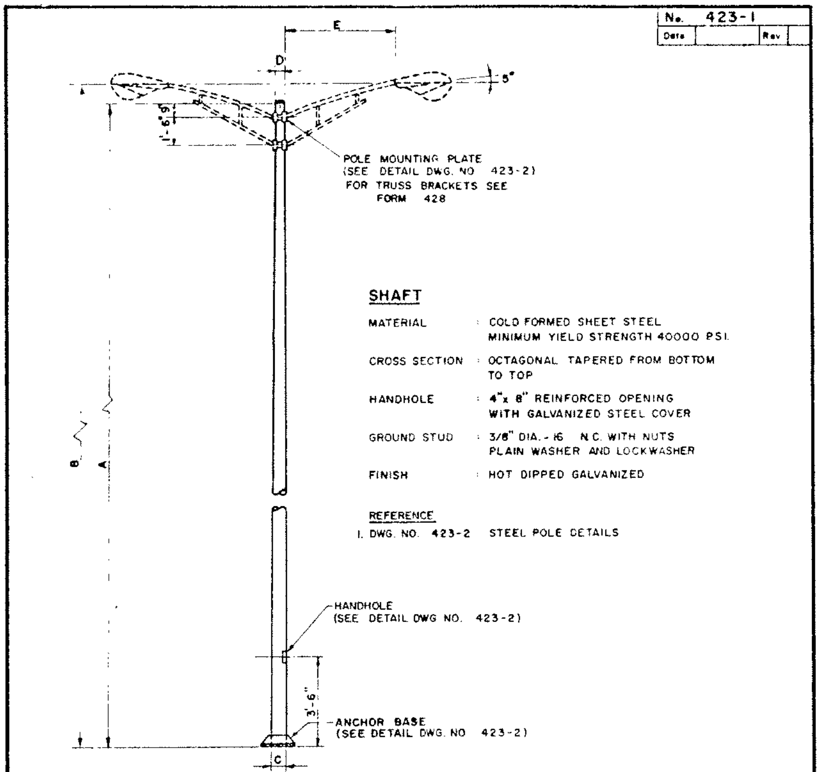
Other sheets are included which list in tabular form quantities of lighting fixtures, poles, conduit, wire, pull boxes, and other materials to be used on the job. An example of one of these sheets is shown in Figure 81.

Standard Specifications

Many governmental organizations have some form of standard specifications which explain in detail the standards by which work is to be done. Usually included in these publications is a description of pay quantities listing how a particular item will be paid for (i.e., whether it is on a unit, cubic yard, square foot, mile, or some other basis). These are usually standard specification and are changed on a yearly or greater basis.

Special Provisions

Special provisions contain information peculiar to the job and may further explain or add to the standard specifications. This document usually has



POLE LENGTH A	LUM MTG HEIGHT B *	BOTTOM DIA. C	TOP DIA. D	BRACKET LENGTH E	BASE PLATE F	BOLT CIRCLE G	ANCHOR BOLT DIA.
24'-6"	25'-0"	7.43"	4"	6 FT	12"	11 1/2"	1"
29'-6"	30-0"	8.13"	4"	6 FT. 9 FT.	12"	11 1/2"	1"
34'-6"	35'-0"	8.83"	4"	6 FT 9 FT	12"	11 1/2"	1"
39'-6"	40'-0"	9.53"	4"	6 FT.	16"	16"	1 1/4"
44'-6"	45'-0"	10.0"	4"	6 FT	16"	16"	1 1/4"
49'-6"	50'-0"	10.0"	4"	6 FT	16"	16"	1 1/4"

* LUMINAIRE MOUNTING HEIGHT BASED ON A 6'-0" MERCURY LUMINAIRE BRACKET

NOTES

1 SHAFTS UP TO & INCLUDING 34 FEET 6 INCHES IN LENGTH SHALL BE FABRICATED IN ONE SECTION OF # 7 GA STEEL.

2 SHAFTS ABOVE 34 FEET 6 INCHES IN LENGTH SHALL BE FABRICATED IN TWO SECTIONS WITH ONE HORIZONTAL JOINT

UPPER SECTION - # 7 GA STEEL
LOWER SECTION - # 3 GA STEEL

STEEL POLE

THIS DRAWING FORMS PART OF SPECIFICATION FORM 423

Figure 80. Portion of standard detail drawing for conventional lighting (3).

sections regarding a general description of where the work is to be performed and what type of work is expected. Procedures may be outlined for the handling of traffic within the construction area. The remainder and the bulk of the special provisions deals specifically with the materials and procedures to be used in installing the lighting system. Materials are listed according to their size

DETAIL SUMMARY OF MISCELLANEOUS QUANTITIES
LIGHTING

CIR & UNIT NO	STATION	SHAFT LENGTH (FT)	BREAKAWAY BASE	LUMINAIRE 250 W	LUMINAIRE 400 W	LUMINAIRE 1000 W	LUMINAIRE	BRACKET LENGTH	TYPE OF FOOTING GND	TYPE OF FOOTING STRUCT	UNDERGROUND CABLE: THREE CONDUCTOR CABLE - IN DUCT #8	#6	#4	2-#8 1-#6	2-#6 1-#2	2-#4 1-#1	1-#8 1-#6 1-#4	1-#4 1-#6 1-#2	1-#8 1-#4 1-#2	MEDIAN BARRIER CABLE: TWO CONDUCTOR CABLE - IN - DUCT #8	#6	#4	MEDIAN BARRIER CABLE: THREE CONDUCTOR CABLE - IN - DUCT 2-#8 1-#6	2-#6 1-#2	2-#4 1-#1	1-#8 1-#6 1-#4	1-#4 1-#6 1-#2	1-#8 1-#4 1-#2
DIST. CTR. "CB"															200													
PULL BOX	68+92																							210				
D CB 1-E CB 1	70+92	47			2			TWIN 4	STD.															275				
D CB 2-E CB 2	72+54	23*			2			TWIN 4	NO FTG.															120				
UNDERDECK	74+65																							180				
D CB 3-E CB 3	76+32	47			2			TWIN 4	STD.															290				
D CB 4-E CB 4	79+08	47			2			TWIN 4	STD.															290				
D CB 5-E CB 5	81+84	47			2			TWIN 4	STD.														280					
D CB 6-E CB 6	84+55	47			2			TWIN 4	STD.														290					
D CB 7-E CB 7	87+24	47			2			TWIN 4	STD.														105					
NEW SIGN BRIDGE	88+30																						195					
D CB 8-E CB 8	90+13	47			2			TWIN 4	STD.														215					
PULL BOX	92+20																						80					
D CB 9-E CB 9	92+92	47			2			TWIN 4	STD.														290					
D CB 10-E CB 10	95+71	47			2			TWIN 4	STD.														290					
D CB 11-E CB 11	98+50	47			2			TWIN 4	SPEC.														110					
UNDERDECK	99+50 ±																											
PULL BOX	92+20										230																	
D CB 12	EXISTING																											
D CB 14	EXISTING										170																	
D CB 15	85+80	45			1			SINGLE 20	STD.																			
PULL BOX	92+20										175																	
E CB 12	91+60	40			1			SINGLE 20	STD.		210																	
E CB 13	EXISTING																											
DIST. CTR. "CA"											80																	
SIGN BRIDGE	S-40-42																											
DIST. CTR. "CA"	EXISTING										280																	
A CA 1	EXISTING										210																	
A CA 4	3+50 "D"	42			1			SINGLE 20	STD.		230																	
UNDERDECK	1420+80 ±										260																	
SIGN BRIDGE	S-40-41																											
DIST. CTR. "CA"																150												
PULL BOX	1427+50																								95			
B CA 1-C CA 1	1426+68	47			2			TWIN 4	SPEC.																290			
B CA 2-C CA 2	1423+59	47			2			TWIN 4	SPEC.																155			
UNDERDECK	1422+45 ±																								225			
B CA 3-C CA 3	1420+32	47			2			TWIN 4	SPEC.																		270	
B CA 4-C CA 4	1417+71	47			2			TWIN 4	STD.																		260	

Figure 81. Typical quantity sheet for plans.

and the standards they must meet. Certification procedures are given for items that are subject to compliance testing. Items cleared for use on the project are often listed by brand name and model (catalog) number along with the words "or equal." This allows the contractor to substitute another brand of material as long as the item meets the approval of the project engineer. In addition to the specifying of materials to be used, construction methods are also set forth for a variety of activities such as pole foundation installation, concrete work, handling of materials, etc.

Special provisions are the final word concerning the conduct of a construction project and have precedence over the standard specifications where a conflict exists.

In summary, the engineering documents discussed above list the materials and labor that the contractor is required to supply. Careful and thorough preparation of these documents will serve to eliminate confusion and misunderstandings as well as reduce the number of decisions that must be made by the engineer as inspector in the field.

REFERENCES

1. "Roadway Illumination Details," RID(1)-76, Texas State Department of Highways and Public Transportation, Austin, Texas, July 1976.

2. Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, American Association of State Highway and Transportation Officials, Washington, D.C., 1975.

3. Ketvirtis, Antanas, Highway Lighting Engineering, Foundation of Canada Engineering Corporation, Ltd., Toronto, Canada, 1967.

8

OPERATING AND MAINTAINING THE LIGHTING SYSTEM

OPERATING AND MAINTAINING THE LIGHTING SYSTEM

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *l lerstanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

LIGHTING SYSTEMS OPERATION AND MAINTENANCE

The continued effectiveness of a lighting system is as much a result of good operation and maintenance procedures as it is of good design in its initial development. The acquisition of a lighting system is in many respects similar to the purchase of an automobile. One simply does not purchase an automobile and receive utilitarian benefits without some input commonly referred to as operation and maintenance. The lighting system and the automobile alike require a constant provision of energy for their operation. Furthermore, neither will continue to operate efficiently unless each receives both routine and emergency maintenance. Another similarity is that routine maintenance can reduce the probability of emergency maintenance. In summary, the agency which is responsible for the operation of a lighting system must provide certain functions. These are:

- Provide for power to be supplied to the system
- Monitor the system
- Maintain the system

These three functions are the basis of discussion for this chapter.

PROVIDING POWER FOR THE SYSTEM

The major ongoing function of a lighting agency is the provision of electrical energy to the roadway lighting system. There are several ways in which these provisions are handled. The first of these is the purchase of primary power by the lighting agency from the local utility company. Primary or un-cut power is at a relatively high voltage and is usually cheaper because the utility company does not have to transform it to the voltage required for operating the luminaires. Billing for the electrical energy is based on the metered consumption.

A second method of providing electrical energy is to purchase secondary power which has already been transformed to the voltage at which the luminaire operates. As with primary power, the electrical consumption is metered and billed on a kilowatt-hour basis.

In the previous case, power was purchased according to the actual metered consumption. Another arrangement exists in which a periodic payment is made for power to the luminaire. This is primarily used where only one luminaire may be hooked into a circuit already established to provide power to a residence or business. This system alleviates the need for an individual meter at each isolated luminaire such as in a residential area.

In the methods for purchasing power discussed thus far, the lighting agency is assumed to own the luminaires and accompanying lighting equipment. An alternate to these schemes involves the utility company owning, operating, and maintaining the luminaire. In this case, the utility company receives a per unit payment for operating the luminaire, a portion of which is for the electrical energy consumed.

In summary, the method by which electrical energy is provided depends to a large degree on the size of the lighting system. A continuous freeway lighting system extending several miles would probably warrant the inclusion of primary power transformers in order to reduce the cost of energy as much as possible. On the other hand, a per unit cost for electricity at an isolated luminaire on a residential street corner would alleviate the need for a power meter.

MONITORING THE SYSTEM

The second most important element of operating a lighting system is continued monitoring to assure the system is performing as intended. To return to the automobile analogy, the owner does not simply drive an automobile without monitoring its performance. From time to time he checks the gasoline consumption and oil level, and in general determines whether the car is performing properly. In a similar manner, the lighting agency must periodically check the system to determine if the lights are coming on and going off at the correct time and note any single or multiple outages which may exist. Unlike the automobile which will eventually stop from lack of attention, thereby calling attention to itself, a roadway lighting system may continue to operate in a sub-optimal condition until someone discovers it. Meanwhile, the energy consumption of the system may continue to be high even though output is severely curtailed. For this reason the lighting agency should provide for a method of periodically inspecting the lighting system looking for individual lamp outages or entire circuit outages. In addition, the circuit should be checked during the daytime for malfunctioning controls which cause the lamps to be on during the day. Although night patrols established solely for lighting system maintenance are probably the most ideal method of locating and correcting outages, another proven and effective method of providing good lighting maintenance is the combination of traffic signal and lighting system maintenance activities during night. When each of these functions are under the same department, monitoring efforts and maintenance equipment can be shared, thus resulting in fewer individuals required to monitor traffic signal and lighting systems.

In addition, a convenient system should be established whereby motorists and private citizens can report outages and pole knockdowns. Thus, we can see that a monitoring procedure should be established for checking the lighting system in order to preserve its appearance and assure that electrical energy is being used efficiently.

MAINTAINING THE SYSTEM

Proper maintenance of a lighting system is important for several reasons. The first of these is that through good maintenance practices we can be assured that the system is performing as designed. Secondly, the maintenance state of the lighting system reflects the civic concern shown by the lighting agency. A lighting system is highly visible in the roadway environment, thus a system containing many uncorrected faults such as lamp outages, dirty luminaires, and unreplaced, knocked down poles reflects a poor attitude on the part of the lighting agency.

Another incentive for roadway lighting maintenance involves the legal aspects of allowing a system to operate at a substandard level. Current tort claims laws in many states require the responsible agency to correct a fault within a reasonable amount of time after notice of the fault has been given. It could be argued that if an agency deems the installation of a lighting system necessary to improve the safety aspects of a roadway or intersection and if the lighting system is allowed to operate with a number of deficiencies past a reasonable time, then this constitutes a hazard and could be the basis for a legal claim against the lighting authority. Finally, economics also come to bear on the maintenance policy of a roadway lighting agency. Once a roadway lighting system is initially energized, a gradual reduction in light output of the luminaires begins to occur for a variety of reasons previously discussed. Meanwhile, the electrical energy needed to power the system remains more or less constant or even may increase. Thus, a reduced output with nearly the same input results in decreased efficiency. For this reason, certain maintenance procedures and schedules as discussed in the following sections can improve the efficiency and the economic return of a lighting system.

Types of Lighting Maintenance

The types of activities usually thought of as roadway lighting maintenance generally fall within either one of two categories: *demand (emergency)* or *routine* maintenance. The main difference is the time at which these activities are conducted. Demand responsive maintenance is generally related to more or less random occurrences such as pole knockdowns, lamp or circuit outages, or other equipment failures. Routine maintenance, on the other hand, refers to scheduled activities such as luminaire washing or group lamp replacements which are intended to retain a level of performance of the system while at the same time eliminating the need for some demand responsive maintenance. The activities suggested for possible inclusion in both demand responsive and routine maintenance are discussed below.

Demand responsive maintenance includes all of the various efforts needed to keep the system operating as it was intended. Some of these maintenance needs such as pole knockdowns, exposed wires, and other threats to the public's safety can be referred to as emergency maintenance, and must be attended to within minutes or hours after notice has been received. This is because failure to respond within a reasonable amount of time is hazardous to the public and may be used as a basis for legal action against the lighting authority should injury or accident occur. Thus, the lighting authority must either have at its disposal the crews and equipment required to perform these activities or contract with other governmental or private agencies for this type of work.

Other demand responsive maintenance items which do not require the response time dictated by emergency activities include lamp and circuit outages and other random events. While the correction of these deficiencies are not as time-critical as emergency items, they should be corrected as soon as it is economically feasible to dispatch a work crew to the area. For example, a single outage may not be corrected until one or more other outages occur within the same general area. In a similar manner, a single outage may not be corrected immediately if the luminaire is soon to be serviced as part of a routine washing and relamping schedule. Thus, for non-emergency items, demand responsive maintenance should be planned to minimize travel and time spent by work crews while at the same time making corrections within a reasonable amount of time.

Routine maintenance, also referred to as scheduled or preventive maintenance, is performed on a regular basis in order to maintain the light output of a roadway lighting system. This maintenance stems from two primary factors, each of which reduce the output of a lighting system over a period of time. These are lamp lumen depreciation and luminaire dirt depreciation. Lamp lumen depreciation in high intensity discharge lamps such as mercury vapor, metal halide, and high pressure sodium sources occurs as metal oxides on the electrode are slowly evaporated or spattered onto the inner surface of the arc tube. As this irreversible process occurs, lumen output of the lamp steadily decreases and only replacement of the lamp will result in regaining the original lumen output level.

Older types of light sources such as incandescent lamps had relatively short lives in the range of 6 months to a year resulting in frequent replacement. With the advent of high intensity discharge lamps, lamp life has been extended to as much as 24,000 hours (6 years). Thus, the tendency by lighting agencies may be to allow the lamp to continue to operate until the end of its life. As can be seen in Figure 82, the typical life for a high pressure sodium lamp is 24,000 hours, based on a mortality of 50% at the end of this time. Therefore, approximately one-half the lamps will continue to operate beyond this time. At the same time the lumen maintenance, as shown in Figure 83, gradually decreases to a little over 70% of the initial value at 24,000 hours. We can also see from Figure 83 that those lamps still operating after their rated life will exhibit even more lamp lumen depreciation (lower lumen maintenance). The result of this is the need to consider whether it is advisable to allow each lamp to operate until it expires resulting in a larger amount of lumen depreciation, or replace all lamps at one time resulting in a higher lumen maintenance factor. This decision is also related to the illumination design procedure described in Chapter 6. Because the design value used in illumination design is expressed in terms of maintained footcandles, the anticipated lamp lumen depreciation must be used to convert initial lamp lumens to maintained lamp lumens. The spacing formula given in Chapter 6 includes the lamp lumen depreciation (LLD) and the luminaire dirt depreciation (LDD). The effect of these two factors on maintenance can be visualized by considering the following.

Referring to Figure 83, the LLD values for 16,000 hours (4 years) and 24,000 hours (6 years) are 0.84 and 0.73, respectively. For example purposes

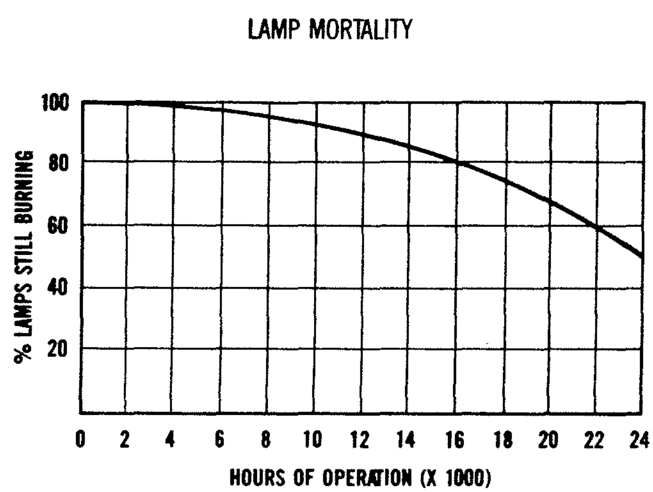


Figure 82. HPS lamp mortality curve.

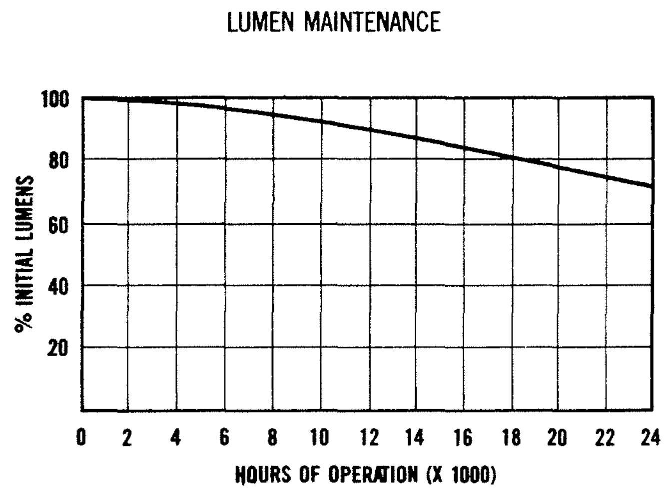


Figure 83. Typical HPS lamp lumen maintenance curve.

let us say that the decision was made to relamp every 6 years (LLD = 0.73) and the calculations resulted in a spacing of 200 feet. If, on the other hand, a 4-year relamping schedule were adopted (LLD = 0.84), the calculated spacing would be 200 x 0.84/0.73 = 230 feet. This example shows that relamping at the end of 4 rather than 6 years will result in approximately 3½ fewer luminaires per mile of roadway. Whether the initial savings in hardware is greater than the cost of more frequent relamping and additional energy consumption depends on a variety of factors which should be considered by the lighting agency.

The second major factor causing a reduction in light emitted by a luminaire is dirt accumulated on the interior and exterior of the luminaire and on the lamp. This reduction in light output is referred to as luminaire dirt depreciation (LDD) and is usually related to the amount of time between washings and the type of area in which the luminaire is located. The current curves developed by the IES and ANSI for luminaire dirt depreciation are illustrated in Figure 52. As with the lamp lumen depreciation factor, a similar factor is used in the luminaire spacing equation for luminaire dirt depreciation. More frequent maintenance, which of course costs more to perform, results in lower initial illumination design values (greater luminaire spacing). Again, as with the decision regarding when to relamp, washing schedules are dependent on various factors. It is, however, advisable to have the group relamping and luminaire washing schedules coincide where possible (4-year relamping and 2-year washing, for example) in order to make the fewest possible trips to each luminaire.

Maintenance Activities

Routine maintenance, whether it is accomplished by lighting agency work forces or on a contract basis by a private firm, may include a variety of activities. As discussed above, probably the least activity which will be undertaken consists of washing the glass refractor in the luminaire and replacing the lamp. A more complete lighting maintenance program may consist of the steps or tasks discussed below.

- *Lamps.* Group replace lamps on a given-number-of-years cycle depending on the mortality rate and lamp lumen depreciation for the particular type of light source.

- *Glassware.* Glassware should be washed, clear rinsed, and dried. Glassware or plastic should be checked for cracks or breakage and replaced where necessary. Care should be taken to make sure that the replacement glass has the same optical properties as the original glass.

- *Reflector.* Reflector should be cleaned by washing with a mild soap solution and rinsed with clean water. Reflectors which are beyond reconditioning by cleaning should be replaced.

- *Gaskets.* Synthetic rubber gaskets should be cleaned and treated with preservative liquid to keep the gasket from sticking, and keep it in good condition over an extended period of time.

- *Re-leveling.* Mast arms and fixtures which obviously are out of adjustment should be re-leveled where necessary. If the pole needs leveling, then adjustments and/or shimming at the foundation may be necessary.

- *Photocell.* Photocells should be checked to be sure that they are neither staying on all of the time or are failing to energize the luminaire. Defective photocells may be replaced when they are detected, or the photocells may be replaced on a group basis.

- *Other Activities.* Other miscellaneous activities such as replacing worn wires, replacing damaged luminaires, pole painting, and minor tree trimming are also items included in roadway lighting maintenance. In the case of contract maintenance, these items may either be handled under the basic contract or may be performed on an individual cost basis.

Designing for Maintainability

The experience of those individuals responsible for roadway lighting maintenance indicates a need to consider future maintenance needs during the design and specification of lighting system components. Cutting corners or attempting to sub-optimize during the design of a lighting system may seriously affect the cost involved in later maintaining the system. The following is a discussion of some of the more prevalent maintenance problems and how they may be averted.

Lighting Cables. Underground lighting cables have traditionally been installed by first burying the conduit and then pulling the wires through the conduit. This process, when performed carefully, provides a satisfactory cable installation. Pulling the cable around tight corners or exerting extreme tensions on the cable may, however, damage the insulation or fatigue the metal in the conductors. As a method of preventing this problem, the use of cable in duct has become popular. In this technique, the cables come from the factory already placed in a duct and wound on reels. Cables may be pulled from the duct and replaced if necessary at a later time.

The choice of insulation may also reduce future maintenance costs. Cross link polyethylene insulation may be substituted for rubber insulation due to its superior durability.

Grounding wires should be a separate insulated conductor to prevent the attraction of stray ground currents. The insulation also prevents electrolytic corrosion at the wires due to a particular soil condition. Lightning protection of underground cables may be improved by placing the ground wire approximately six inches above the power cables.

Another critical point is where the cables pass from the pole interior into the luminaire bracket. Due to the weight of the cable which must be supported inside the pole, care should be taken to prevent damage to the conductor insulation at this point. This is usually accomplished by rounding off sharp burrs and either using a rubber grommet or by supporting the cable from the top of the pole.

Pole Installation. Where breakaway bases are not used for safety purposes, either butt-type or poured foundation poles may be used. Soil conditions should be checked to determine that butt-type installations will not shift, causing the pole to lean after a period of time. In these situations, deep, poured foundations may be needed.

Fuses. The need to fuse every pole appears to be gaining widespread acceptance. This not only protects the ballast, but also allows maintenance crews to isolate and repair an outage. Fuse holders should contact the fuse firmly such as by the use of spring tension in order to prevent arcing and heat buildup. Some lighting agencies prefer to use fused connectors or quick disconnect fuse holders which will separate when the pole is knocked down. These fuse holders are constructed so that, should the holder be pulled apart, the line side of the connector is insulated to reduce the potential for electric shock. Other lighting agencies prefer a screw type fuse holder, arguing that the tensile strength of the wire pole may not be sufficient to pull apart the fused disconnect in the event of a pole knockdown.

Compatability of Replacement Parts. The number of different sizes and types of lighting components used in lighting design and equipment specification will greatly affect the inventory of replacement parts. Reducing the number of parts in the inventory not only decreases the capital outlay, but also reduces delays in maintenance activities should an unusually high demand for a relatively seldom used part deplete the inventory of this particular part.

Another facet of stocking replacement parts involves the inventory of the lighting equipment contained in the total lighting system. This allows maintenance supervisors to predict according to the number and age of equipment components how many replacement parts will be needed during the year and how many should be stockpiled. The City of Philadelphia uses a card file system, as illustrated in Figure 84, to record the location and type of each luminaire. Systems such as this can also be computerized which are capable of sorting data concerning the number of each type of luminaire, the average age of each type of luminaire, and other pertinent information used in estimating the need for replacement parts and in optimizing maintenance schedules. Still other inventory systems may use sectional maps of the city on which the location, age, type, etc., of luminaires are recorded.

In summary, the important point is to have a supply of spare parts so that a breakdown can be corrected quickly. These parts include ballasts, luminaires, lamps, glassware, photo controls, and poles. An inventory of the type and age of fixtures in use in the system can be used to determine the approximate number of parts which may be needed during the year.

Troubleshooting. The correction of problems affecting the output of a lighting system can be greatly facilitated by knowing what problems are likely to occur and their probable cause. A troubleshooting guide is shown in Table 18.

This table is only a partial listing. To include all of the problems, possible causes, and corrective maintenance for each type of light source is beyond the scope of this publication, especially in view of ever-advancing lighting technology. Two

<table>
<tr><td colspan="4">STREET</td><td colspan="2">NUMBER</td><td>A or U</td><td>SIZE</td></tr>
<tr><td>SIDE</td><td>FT. or P.</td><td>N. or W.</td><td colspan="4">CROSS ST.</td><td>PLATE</td></tr>
<tr><td colspan="2">INST. ORDER NO.</td><td>DATE</td><td colspan="3">REM. ORDER No.</td><td>DATE</td><td>WARD</td></tr>
<tr><td colspan="2">LUMINAIRE</td><td>BRACKET</td><td>M.H.</td><td>S. or M.</td><td colspan="2">BALLAST</td><td>CIRCUIT</td></tr>
<tr><td colspan="2">POLE</td><td>TYPE</td><td colspan="3">BASE</td><td>P.E. BILL</td><td>POLE NO.</td></tr>
</table>

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PHILA. STREET LIGHT LOCATION RECORD

Figure 84. Philadelphia street light location record (source: City of Philadelphia, Pennsylvania.

primary information sources that are of considerable value in relating maintenance experience with various light sources are the trade magazines and informational brochures published by the various lamp manufacturers. Regarding the latter of these, several of the major lighting companies now have or are in the process of preparing troubleshooting brochures to aid their customers in lighting maintenance. Examples of these are "Troubleshooting Fluorescent Lighting," Sylvania Engineer Bulletin 0-330 (1) and "Troubleshooting Mercury-Metal Halide Lighting," Bulletin 0-345 (2). The General Electric Company has a similar publication entitled "Troubleshooting Guide for High-Intensity Discharge Lamps" (3). These publications are currently available, and indications are that other publications by these and other companies are being prepared. Looking to a particular manufacturer for information of the type discussed here will usually bring favorable results.

TABLE 18

TROUBLESHOOTING GUIDE*
(FOR H.I.D. LAMPS)

LAMP WILL NOT START

Possible Causes	*Corrective Maintenance*
1. Lamp loose in socket.	1. Screw lamp firmly into socket until good contact is made. STOP! Excess torque may cause lamp to shatter at neck.
2. Incorrect lamp.	2. Check and compare data on ballast or fixture nameplate with lamp electrical characteristics.
3. Incorrect or loose wiring.	3. With power off, check wiring against wiring diagram; check for loose connectors and loose terminal screws; check for broken insulation. Check circuit continuity with ohmmeter.
4. End of ballast life.	4. Check for charred spots and/or swollen capacitors.
5. Photoelectric control inoperative	5. With power ON, cover photocell. Wait the few minutes generally required for an operative photocell to apply power to the fixture. Replace if inoperative.
6. Supply voltage to fixture or ballast output voltage is low.	6. Check supply voltage and ballast-output voltage.

*Adopted from G.E. Troubleshooting Guide (Ref. 3)

TABLE 18 (continued)
TROUBLESHOOTING GUIDE

Possible Causes	*Corrective Maintenance*
7. HPS starter circuit failure	7. Check lamp on DLC* or try known good lamp. Replace starter circuit.
8. Ambient temperature too high or low for ballast.	8. Check ballast specifications. Indoor and outdoor specs differ with respect to ambient operating-temperature range.
SHORT LAMP LIFE	
9. Incorrect lamp.	9. Check and compare data on ballast or fixture nameplate with lamp electrical characteristics.
10. Shorted ballast.	10. Check electrically for a shorted ballast. For mercury lamp systems, use MCT**. If defective, replace.
11. Incorrect lamp operating position.	11. Check lamp operating specifications for BU (base up) or BD (base down) operation. Use ONLY as specified.
12. Over-wattage operation.	12. Check ballast or fixture rating for lamp type and wattage. Check operation for correct voltage and current at socket terminals.

*DLC -- Discharge Lamp Checker
**MCT -- Mercury Circuit Tester

TABLE 18 (continued)
TROUBLESHOOTING GUIDE

FLICKERING

Possible Causes	*Corrective Maintenance*
13. Overheated arc tube, possibly caused by reflector focusing heat energy back onto arc tube.	13. Repositioning the lamp in the reflector *may* correct the condition.
14. Supply voltage to fixture is low.	14. Check both supply and ballast output voltage with lamp operating.
15. Incorrect ballast.	15. Check and compare data on ballast or fixture nameplate with lamp electrical characteristics.
16. High operating voltage.	16. Check lamp voltage at socket terminals while operating.
17. Low ballast-output voltage.	17. Check ballast output and supply volts without lamp in circuit.
18. Variable voltage.	18. Use recording voltmeter to check degree and duration of voltage variation. Check to determine other electrical loads on lamp circuit. Remove lighting circuit from lines with large electrical loads.

TABLE 18 (continued)
TROUBLESHOOTING GUIDE

BLOWN FUSES

Possible Causes	*Corrective Maintenance*
19. High momentary line current at turn "ON."	19. Check ballast literature for recommended rating of circuit protective devices. Circuit protective devices should have time delay elements when used with reactor or autotransformer ballasts.
20. Over-wattage operation.	20. Check ballast or fixture rating for lamp type and wattage. Check operation for proper voltage and current at socket terminals.
21. Overloaded circuit.	21. Check total load on circuit; lamps and ballasts, plus other connected equipment.

LAMP LIGHT OUTPUT LOW

22. Lamps near end of life.	22. Check burning time. If near end of life, replace lamp.
23. Supply voltage to fixture is low.	23. Check both supply and ballast output voltage with lamp operating.
24. Incorrect ballast.	24. Check and compare data on ballast or fixture nameplate with lamp electrical characteristics.

TABLE 18 (continued)
TROUBLESHOOTING GUIDE

Possible Causes	*Corrective Maintenance*
25. Low ballast voltage.	25. Check ballast output and supply volts without lamp in circuit.
26. Dirt accumulation.	26. Clean luminaires and lamps.
LAMP STARTS SLOWLY	
27. Supply voltage to fixture is low.	27. Check both supply and ballast output voltage with lamp operating.
28. Low ballast output voltage.	28. Check both ballast output and supply volts without lamp in circuit.
29. Lamp is a hard starter.	29. Replace lamp *IF* other system components are OK.
BLACKENED ARC TUBE	
30. Incorrect ballast.	30. Check and compare data on ballast or fixture nameplate with lamp electrical characteristics.
31. Partially shortened ballast.	31. Check electrically for a shorted ballast. For Mercury lamp system, use MCT. If defective, replace.

TABLE 18 (continued)
TROUBLESHOOTING GUIDE

Possible Cause	*Corrective Maintenance*
32. Over-wattage operation.	32. Check ballast or fixture rating for lamp type and wattage. Check operation for correct voltage and current at socket terminals.
33. Overheated arc tube, possibly caused by reflector focusing heat energy back onto arc tube.	33. Repositioning the lamp in the reflector *may* correct the condition.
ABNORMAL LAMP COLOR DIFFERENCE	
34. Low supply voltage.	34. Check supply voltage and ballast output voltages with lamp operating.
35. Low ballast output voltage.	35. Check ballast output and supply volts without lamp in circuit.
36. Overheated arc tube, possibly caused by reflector focusing heat energy back onto arc tube.	36. Repositioning the lamp in reflector *may* correct the condition.
37. Variation in light distribution.	37. Check luminaire. To test, interchange lamps between suspected and normally performing luminaires.

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TABLE 18 (continued)
TROUBLESHOOTING GUIDE

Possible Causes	*Corrective Maintenance*
38. Dirt accumulation.	38. Clean luminaires and lamps.
39. Illumination color differences.	39. Variations in environmental color--walls, ceilings, etc.--can cause illumination-color illusions.

REFERENCES

1. "Troubleshooting Fluorescent Lighting," Sylvania Engineering Bulletin 0-330, Sylvania Lighting Center, Danvers, Mass.

2. "Troubleshooting Mercury-Metal Halide Lighting," Sylvania Engineering Bulletin 0-345, Sylvania Lighting Center, Danvers, Mass.

3. "Troubleshooting Guide for High-Intensity Discharge Lamps," Lamp Business Division, General Electric.

9

ANALYZING THE ECONOMICS OF THE LIGHTING SYSTEM

ANALYZING THE ECONOMICS OF THE LIGHTING SYSTEM

The overall process of designing and operating a roadway lighting system consists of several well-defined steps as listed below. These steps are utilized as the subject matter for the principal chapters of this handbook. They are presented here and at the beginning of each of the principal chapters to indicate the continuity of the handbook.

- *Understanding Visibility Requirements*
- *Analyzing Lighting Needs*
- *Selecting Lighting Equipment*
- *Selecting the Lighting System Configuration*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

Economic analyses are applied to all proposals for highway improvements. Roadway lighting proposals are not excluded from analyses. We must always strive to give the public the best possible return for their investment. This chapter addresses the economics of lighting improvements. But before these are discussed, a few words about alternatives to lighting are necessary.

ALTERNATIVES TO LIGHTING

One of the first economic analyses a lighting designer or administrator should perform is the relative cost-effectiveness analysis of all reasonable alternatives, short of lighting. If the objective is better visual guidance at night, delineation and signing alternatives may satisfy the objective at a more economical cost. In many cases, roadway lighting improvements have been used where more reasonable alternatives would have sufficed. It is sufficient to note that this problem must be carefully analyzed.

COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness analysis can be used to choose preferred lighting designs for different situations in which lighting is warranted. It also can be used to set priorities for the expending of public funds.

In general, the cost-effectiveness procedure involves a detailed economic evaluation of the following:

- Level of illumination
- Type of light source
- Type of support
- Electrical materials and installation
- Mounting height
- Energy requirements
- Maintenance schedule

The procedure may be summarized as:

- Specifying several lighting designs that give the desired level of lighting effectiveness, illumination level, and uniformity. For a more complete optimization procedure, consider several levels of effectiveness.
- Specifying circuit alternatives that are feasible for each lighting design. Estimate the cost of each of the circuits and suboptimize by choosing the least costly circuit for each design. It

is also possible to further suboptimize by considering different user-utility ownership arrangements for each circuit and to choose the least costly (or "best" in some other sense) ownership arrangement for each circuit. Then compare these least-costly ownership arrangements to obtain the least costly circuit for each lighting configuration.

- Summarizing the effectiveness and cost for each feasible lighting design and choosing, using judgment, the best design. The best design, together with its effectiveness and cost, is the design selection for priority competition with other improvements.

The cost-effectiveness procedure for analyzing roadway lighting alternatives may follow the style suggested by Cassel and Medville (1), and Walton (2). There are five forms which are used in the procedure for each warranting facility (e.g., each continuous section of roadway, interchange, intersection). Each specific facility is assigned an Identification Number which appears on each form corresponding to that facility. Form 1 gives identifying characteristics and design variables and also has a space for identifying the "best" design, chosen at the completion of the analysis. Form 2 is for summarizing the cost and effectiveness of each feasible design. Various roadway lighting design configurations are summarized on Form 3. Form 4 provides for the presentation of equipment and costs of each circuit that is considered for each feasible configuration. A separate Form 5 is completed for each different circuit appearing in Form 4. Forms 4 and 5 are in costs per mile of continuous lighting, but can easily be modified to calculate the cost per facility, interchange, intersection, etc.

There are three primary ways in which feasible lighting configurations can be determined. (A feasible lighting configuration is one that provides the minimum desired illumination, w, as shown in Item (10) in Form 1, and also provides a uniformity ratio, or ratios, that are equal to or less than the desired ratio.) These three ways of determining feasible designs are: (1) through the use of a formula that relates unit spacing to average illumination, (2) through the use of empirically-derived iso-footcandle overlays, and (3) through the use of point-by-point calculations. After unit spacing that provides desired illumination is derived, the uniformity ratio is checked. If it is acceptable, then the design is feasible. If it is not, then the spacing is reduced until the ratio is acceptable, at which point the design is feasible.

For example, using the spacing formula, initial design and roadway conditions are specified; these include most items shown in Forms 3 and 4, and are as follows: lamp type and characteristic, luminaire mounting height, luminaire overhang, and luminaire. The required light distribution is determined and a luminaire arrangement is chosen. Next, calculate or obtain: the coefficient of utilization, the maintenance factor, and other correction factors. Then, spacing in feet, S, is calculated using an appropriate formula. The formula can be used to calculate spacing for a desired intensity; or, it can be used to calculate intensity for a given spacing. Next, the uniformity ratio is checked and, if not met, spacing is changed until it is met.

The above steps are completed several times, generating feasible lighting configurations and different arrangements, spacings, mounting heights, lamp wattages, etc. Columns (9), (10), and (11) of Form 2 and all of Form 3 are completed for each feasible configuration. It is important to consider several different configurations so that "best" designs are considered in the cost-effectiveness comparisons.

After different feasible configurations have been determined, it is necessary to specify equipment and determine lighting circuit for each configuration.

Each alternative lighting configuration can have several different circuits; these different circuits

FORM 1

Identification Number: ____
SUMMARY

(1) Facility Location: ________

(2) Facility Type: ________

(3) Road Length: ________

(4) Road Width(s): ________

(5) Number of Lanes (n): ________

(6) Affected Lane Miles (L): ________

(7) Design Average Daily Traffic: ________

(8) Design Night Average Daily Traffic: ________

(9) Warranted Illumination Level, ave. maintained footcandles (w): ________

(10) Calculated Lighting Effectiveness or total warranting points (E): ________

(11) Multiplier = (E x NADT x L) / (n x w): ________

(12) Analysis Period (years): ________

(13) Interest Rate (%): ________

(14) Desired Uniformity Ratio(s): ________

Best Design

(15) Configuration Number: ________

(16) Priority Index(es): ________

(17) Annual Cost: ________

(18) Ave. Maintained Footcandles: ________

(19) Uniformity Ratio(s): ________

FORM 2

IDENTIFICATION NUMBER: ___
COST AND EFFECTIVENESS SUMMARY FORM

			Annual Cost***					Effectiveness				
											Priority Indexes****	
(1) Configuration Number	(2) Circuit Number*	(3) Initial Capital Cost	(4) Equivalent Capital**	(5) Maintenance and Power	(6) Subtotal (4) + (5)	(7) Light Pole Accident	(8) Total (6) + (7)	(9) Ave. Footcandles Actual (F)	(10) Min. Footcandles	(11) Ave./Min. Ratio (9)/(10)	(12) Multiplier x Col. (9) = Col. (6)	(13) Multiplier x Col. (9) = Col. (8)
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												

*Circuit number chosen as best for given configurations.
**Column (3) multiplied by capital recovery factor for chosen analysis period and interest rate.
***For "best" ownership arrangement considered.
****"Multiplier" is taken from Form 1.

FORM 3

IDENTIFICATION NUMBER: ____

ROADWAY LIGHTING CONFIGURATION SUMMARY FORM

Configuration Number	Lamp Characteristics				Pole Characteristics			Light Distribution Type	Arrangement	Spacing (feet)	Illumination (footcandles)		Uniformity Ratio
	Type	ANSI Designation	Light Output (lumens)	Power (Watts)	Mounting Height (feet)	Overhang (feet)	Luminaire Type				Average	Minimum	
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													
13													
14													
15													
16													
17													

FORM 4

IDENTIFICATION NUMBER:___
EQUIPMENT SPECIFICATION AND COST SUMMARY FORM

ITEM	CONFIGURATION NUMBER						
	CIRCUIT NUMBER**						
a. Basic Data							
1. Lamp type 2. ANSI designation 3. Initial lumens 4. Wattage 5. Mounting height (feet) 6. Overhang (feet) 7. Luminaire type 8. Light-distribution type 9. Arrangement 10. Spacing (feet) 11. Average horizontal footcandles 12. Minimum footcandles 13. Uniformity ratio 14. Total kw per luminaire 15. Distribution system 16. Lamps per mile 17. Lamps/circuit 18. Burning hours per year 19. Adjustment factor*							
b. Cost Summary (dollars)							
OMC I: User Ownership and Maintenance 1. Initial cost 2. Equivalent annual cost 3. Annual maintenance cost 4. Annual power cost 5. Total annual cost							
OMC II: User Ownership, Utility Maintenance 6. Total annual cost							
OMC IIIa: Utility Ownership and Maintenance, aggregate 7. Total annual cost							
OMC IIIb: Utility Ownership and Maintenance, detail 8. Total annual cost 9. Annual cost/average horizontal foot-candle (OMC I)							

*Lamps/mile / Lamps/circuit

**There may be several circuits for each configuration number.

FORM 5

IDENTIFICATION NUMBER:____
CONFIGURATION NUMBER:____
CIRCUIT NUMBER:____

COST DATA FORM

Completion Instructions:

Ownership/Maintenance Configuration (OMC)	Complete Lines
I	1 through 45
II	1-26, 31-35, 46, 47
IIIA	48, 49
IIIB	42-44, 50-55

Equipment-Specification Summary:

i.	distribution cable / circuit	=	______
ii.	connection cable / circuit	=	______
iii.	poles per mile	=	______
iv.	adjustment factor	=	______
v.	total kw per lamp	=	______
vi.	burning hours per year	=	______

OMC I: User Ownership and Maintenance

a. Initial Costs

(1) Per Pole

Item	Unit cost (dollars)	
	Equipment	Labor
1. Pole		
2. Foundation		
3. Luminaire		
4. Lamp		
5. Bracket arm		
6. Ballast		
7. Photoelectric control		
8. Cable		
Total		

9. Total initial cost per pole $______

10. Initial cost per mile of pole items $______

(2) Per-Circuit Distribution

(a) Circuit

Item	Cost per foot (dollars)	
	Equipment	Labor
11. Trench & backfill		
12. Cable		
13. Total		

14. Cost per distribution circuit $______

(b) Connection to Poles

Item	Cost per foot (dollars)	
	Equipment	Labor
15. Trench & backfill		
16. Cable		
17. Total		

18. Cost of connection per circuit $______

19. Total distribution cost per circuit $______

COST DATA FORM (continued)

OMC I, continued

20. Control Equipment

Equipment Item	Initial Cost per Circuit (dollars)	
	Equipment	Labor
Time Controls: Photoelectric control and receptacle Time switch		
Transformers: Constant-current Distribution Hanger irons		
Group-Control: Protective relay Multiple relay Oil switch Multiple control switch Power-factor-correcting capacitor Mounting bracket for capacitor Potential transformers Time-delay-lockout relay Fuse cutouts Other		
21. Total		

22. Total distribution and control cost per mile . . . . $ ______

23. Total initial cost per mile . . . . $ ______

OMC I, continued

24. Interest rate used . . . . ______ %

25. Time period used . . . . ______ years

26. Equivalent annual cost per mile . . . . . $ ______

b. Maintenance and Power Costs

(1) Per Pole

Mainten-ance Item	Mainten-ance Frequency	Cost (dollars)			
		Equipment		Annual Labor	Total Annual
		Unit	Annual		
27. Replace lamp 28. Replace refractor 29. Wash luminaire					
30. Total lamp and luminaire					
31. Replace ballast 32. Paint pole 33. Remove damaged pole 34. Install new pole					
35. Total ballast and pole					

36. Total annual maintenance cost per pole, "per-pole" items . . . . $ ______

37. Total annual maintenance cost per mile, "per-pole" items . . . . $ ______

COST DATA FORM (continued)

OMC I, continued

b. Maintenance and Power Costs, cont.

(2) Per Circuit

38. Equipment

Type	Maintenance Cost per circuit per year (dollars)
Time Controls:	
Photoelectric control and receptacle	
Time Switch	
Transformers:	
Distribution	
Hanger irons	
Group-Control:	
Protective relay	
Multiple relay	
Oil switch	
Multiple control switch	
Power-factor-correcting capacitor	
Potential transformer	
Time-delay-lockout relay	
Fuse cutouts	
Other	
39. Total	

OMC I, continued

40. Total annual control equipment cost per mile . . . . $ ______
41. Total annual maintenance cost per mile . . . . $ ______
42. Energy rate per kwh . . . . $ ______
43. Kilowatts per mile . . . . ______
44. Total annual energy cost per mile . $ ______
45. Total annual cost per mile . . . . . $ ______

OMC II: User Ownership, Utility Maintenance

46. Cost per lamp per year . . . . $ ______
47. Total annual cost per mile . . . . . $ ______

OMC IIIA: Utility Ownership and Maintenance, Aggregate

48. Cost per lamp per year. . . . . . . $ ______
49. Added costs . . . . $ ______
50. Total annual cost per mile . . . . . $ ______

OMC IIIB: Utility Ownership and Maintenance, Detail

51. Cost per lamp per year . . . . $ ______
52. Added costs . . . . $ ______
53. Cost per pole per year . . . . $ ______
54. Total cost per unit per year . . . . $ ______
55. Total annual facility cost. . . . . . $ ______
56. Total annual cost per mile . . . . . $ ______

are determined, and Parts (a) and (b) of Form 4 are completed for each circuit.

Form 5 is completed for each circuit, and the costs are summarized in Part (b) of Form 4. Comparing the different circuits and their costs under different ownership arrangements, the designer chooses a preferred circuit and ownership arrangement and enters the number of this circuit in Column (2) of Form 2, and enters the critical costs in maintenance and power costs in Columns (3) and (5). Using the analysis period and interest rate from Form 1, a uniform series capital recovery factor is obtained from a table and multiplied by initial costs in Column (3) to obtain equivalent capital costs which are entered in Column (4). Columns (4) and (5) are added to obtain Column (6). Then, Column (9) is divided by Column (6) and the quotient is multiplied by the "multiplier" [Item (11) in Form 1] to obtain a priority index which is entered in Column (12).

It is also desirable to calculate expected accident costs for vehicles hitting lighting installations. To do this, the following formula is used:

$$AC = (ADT/XDT)\ EA \times C$$

where:

- AC = the expected average accident cost from vehicle hitting lighting units, in dollars per mile per year
- ADT = the design average daily traffic - Item (7) in Form 1
- XDT = the number of vehicles of ADT that it takes to generate one out-of-control vehicle running off the road per mile per year
- EA = the expected numbers of lighting units per vehicle running off the road for the appropriate spacing and width of units from nearest traffic lane
- C = the average cost of a vehicle-lighting unit accident

Tables 19 and 20 provide the basic input information. The cost AC is calculated for one mile of road and should be multiplied by the number of miles in the facility to get total annual lighting-unit accident cost which is entered in Column (7) of Form 2. Column (7) is then added to Column (6) to get Column (8). The "multiplier" from Form 1 is multiplied by average footcandles from Column (9) and divided by Column (8) to get the Priority Index which is entered in Column (13).

COMPUTER COST ANALYSIS

Several computer programs involving cost analysis of lighting designs have been formulated by various concerns both in industry and government. These programs can significantly reduce the time required for a lighting engineer to determine comparative costs associated with a particular lighting application. One such program, termed COST$$, was developed by General Electric and is available as a customer service. COST$$ compares the initial cost and the operating and maintenance cost of up to three indoor or outdoor lighting systems. There are over 70 types of lighting systems stored with the program. These "standard" systems can be compared or the program can be run with cost values available for the specific lighting installation. An optional life cycle cash flow-present worth analysis can be outputted.

Similar programs can be obtained from other manufacturers. It is suggested that the lighting designer contact the various manufacturer's representatives.

VALUE ENGINEERING

A more complex procedure for making lighting decisions is the value engineering procedure. This procedure is especially effective for larger jobs. Value engineering is the systematic application of recognized techniques which identify the function of a design or system, establish a value for that function, and provide the necessary function reliably at the lowest overall cost. Details of the value engineering process may be found in the

TABLE 19

EXPECTED NUMBERS OF LIGHTING POLE ACCIDENTS PER MILE OF ROADWAY PER YEAR, FOR EXPOSED ILLUMINATING UNITS, BY UNIT SPACING AND DISTANCE FROM EDGE OF TRAFFIC LANE

Unit Spacing (feet)	Distance of Units from Edge of Traffic Lane (ft) 0	10	15	20	25	30
100	1.31	1.18	1.03	.83	.59	.33
150	.88	.79	.70	.57	.40	.22
200	.66	.59	.52	.43	.30	.17
250	.53	.48	.42	.34	.24	.13
300	.44	.40	.35	.29	.20	.11
350	.38	.34	.30	.25	.17	.10

*Expected accidents per mile per year: 5,000 vehicles of two-way ADT for median or opposite arrangement; per 10,000 vehicles of two-way ADT for one-side and staggered arrangement; per 2,500 vehicles of two-way ADT for median-opposite arrangement.

TABLE 20

AVERAGE ACCIDENTS 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 Cost	Average Total Accident Cost
Aluminum	Aluminum Transformer	$174	$381	$221	$776
Steel	Aluminum Transformer	272	400	313	985
Steel	Steel Transformer	603	501	231	1335
Steel	Steel Shoe	823	541	103	1467

*These costs do not include cost of pain and suffering. Also, the costs used do not fully reflect the increasing severity of injuries (including death) associated with non-breakaway bases (steel transformer, steel shoe). Therefore, the injury costs for steel transformer and steel shoe bases probably are considerably larger than the values shown. In addition, all of these values should be updated continuously to reflect current costs.

FHWA course manual on value engineering (3). The manual was written for FHWA by the Olympic Engineering Corporation for application in highway engineering. The concepts from the manual can be applied in the evaluation of public roadway lighting designs. The reader is referred to the manual for applications.

REFERENCES

1. Cassel, A., and Medville, D., "Economic Study of Roadway Lighting," NCHRP Report No. 20, National Research Council, Washington, D.C., 1966.

2. Walton, Ned E., and Rowan, N. J., "Warrants for Highway Lighting," NCHRP Report No. 152, National Research Council, Washington, D.C., 1974.

3. "Value Engineering for Highways," Federal Highway Administration, Washington, D.C., 1975.

METRIC CONVERSION TABLE

285-027 O - 79 - 15

METRIC CONVERSION TABLE *

Illumination Conversion Factors

1 lumen = 1/673 lightwatt
1 lumen-hour = 60 lumen-minutes
1 footcandle = 1 lumen/ft^2
1 watt-second = 10^7 ergs
1 phot = 1 lumen/cm^2
1 lux = 1 lumen/m^2 = 1 metercandle

Multiply number of → / To obtain number of ↓ / By ↘	Foot-candles	Lux	Phot	Milliphot
Footcandles	1	0.0929	929	0.929
Lux	10.76	1	10,000	10
Phot	0.00108	0.0001	1	0.001
Milliphot	1.076	0.1	1,000	1

Luminance (Photometric Brightness) Conversion Factors

1 nit = 1 candela/m^2
1 stilb = 1 candela/cm^2
1 apostilb (international) = 0.1 millilambert = 1 blondel
1 apostilb (German Hefner) = 0.09 millilambert
1 lambert = 1000 millilamberts

Multiply number of → / To obtain number of ↓ / By ↘	Foot-lambert	Nit	Milli-lambert	Candela/in^2	Candela/ft^2	Stilb
Footlambert	1	0.2919	0.929	452	3.142	2,919
Nit	3.426	1	3.183	1,550	10.76	10,000
Millilambert	1.076	0.3142	1	487	3.382	3,142
Candela/in^2	0.00221	0.000645	0.00205	1	0.00694	6.45
Candela/ft^2	0.3183	0.0929	0.2957	144	1	929
Stilb	0.00034	0.0001	0.00032	0.155	0.00108	1

Conversion Factors for Units of Length

Multiply number of → / To obtain number of ↓ / By ↘	Centi-meters	Meters	Kilo-meters	Inches	Feet	Miles
Centimeters	1	10^2	10^5	2.540	3.048×10	1.609×10^5
Meters	10^{-2}	1	10^3	2.540×10^{-2}	3.048×10^{-1}	1.609×10^3
Kilometers	10^{-5}	10^{-3}	1	3.048×10^{-5}	3.048×10^{-4}	1.609
Inches	3.937×10^{-1}	3.937×10	3.937×10^4	1	12	6.336×10^4
Feet	3.281×10^{-2}	3.281	3.281×10^3	8.333×10^{-2}	1	5.280×10^3
Miles	6.214×10^{-6}	6.214×10^{-4}	6.214×10^{-1}	1.578×10^{-5}	1.894×10^{-4}	1

*From IES Lighting Handbook

GLOSSARY

GLOSSARY*

absorptance: the ratio of the flux absorbed by a medium to the incident flux.

Note: The sum of the hemispherical reflectance, the hemispherical transmittance, and the absorptance is one.

accommodation: the process by which the eye changes focus from one distance to another.

adaptation: the process by which the retina becomes accustomed to more or less light than it was exposed to during an immediately preceding period. It results in a change in the sensitivity of the eye to light.

atmospheric transmissivity: the ratio of the directly transmitted flux incident on a surface after passing through unit thickness of the atmosphere to the flux that would be incident on the same surface if the flux had passed through a vacuum.

ballast: a device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current, and waveform) for starting and operating.

bikeway: a public street, highway, or separate path identified as part of a bicycle travel network.

Type A bikeway -- a strip within or adjacent to roadway or shoulder, marked for bicycle travel.

Type B bikeway -- an improved strip identified for public bicycle travel, and located well away from a roadway or its adjacent sidewalk system.

blinding glare: glare that is so intense that for an appreciable length of time no object can be seen.

bracket (mast arm): an attachment to a lamp post or pole from which a luminaire is suspended.

brightness: see *luminance* and *subjective brightness.*

candela, cd: (formerly candle) the unit of luminous intensity.

candlepower, cp: luminous intensity expressed in candelas. It is no indication of the total light output.

candlepower distribution curve: a curve, generally polar, representing the variation of luminous intensity of a lamp or luminaire in a plane through the light center.

Note: A vertical candlepower distribution curve is obtained by taking measurements at various angles of elevation in a vertical plane through the light center; unless the plane is specified, the vertical curve is assumed to represent an average such as would be obtained by rotating the lamp or luminaire about its axis. A horizontal candlepower distribution curve represents measurements made at various angles of azimuth in a horizontal plane through the light center.

central (foveal) vision: the seeing of objects in the central or foveal part of the visual field, approximately two degrees in diameter. It permits seeing much finer detail than does peripheral vision.

coefficient of utilization, CU: the ratio of the luminous flux (lumens) from a luminaire received on the surface of the roadway to the lumens emitted by the luminaire's lamps alone.

constant-current transformer: a device (sometimes erroneously referred to as a constant-current regulator) that automatically maintains a constant current in its secondary circuit under varying conditions of load impedance when supplied from a constant potential source.

contrast sensitivity: the ability to detect the presence of luminance differences. Quantitatively, it is equal to the reciprocal of the contrast threshold.

contrast threshold: the minimal perceptible contrast for a given state of adaptation of the eye. It also is defined as the luminance contrast detectable during some specific fraction of the times it is presented to an observer, usually 50 percent.

cutoff: a luminaire light distribution is designated as cutoff when the candlepower per 1000 lamp lumens does not numerically exceed 25 (2½ percent) at an angle of 90 degrees above nadir

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*From American National Standard Practice for Roadway Lighting, RP-8, 1977, Illuminating Engineering Society - American National Standards Institute, New York, N.Y., 1977.

(horizontal); and 100 (10 percent) at a vertical angle of 80 degrees above nadir. This applies to any lateral angle around the luminaire.

diffuse reflectance: the ratio of the flux leaving a surface or medium by diffuse reflection to the incident flux.

diffuser: a device to redirect or scatter the light from a source, primarily by the process of diffuse transmission.

direct glare: glare resulting from high luminances or insufficiently shielded light sources in the field of view or from reflecting areas of high luminance. It usually is associated with bright areas, such as luminaires, that are outside the visual task or region being viewed.

disability glare: glare resulting in reduced visual performance and visibility. It often is accompanied by discomfort. See *veiling brightness.*

discomfort glare: glare producing discomfort. It does not necessarily interfere with visual performance or visibility.

fixture: see *luminaire.*

footcandle, fc: the unit of illumination when the foot is taken as the unit of length. It is the illumination on a surface one square foot in area on which there is a uniformly distributed flux of one lumen, or the illumination produced on a surface, all points of which are at a distance of one foot from a directionally uniform point source of one candela. See Figure 1.

footlambert, fL: a unit of luminance (photometric brightness) equal to $1/\pi$ candela per square foot, or to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square foot, or to the average luminance of any surface emitting or reflecting light at that rate.

Note: The average luminance of any reflecting surface in footlamberts is, therefore, the product of the illumination in footcandles and the luminous reflectance of the surface.

glare: the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility. See *blinding glare, direct glare, disability glare, discomfort glare.*

Note: The magnitude of the sensation of glare depends upon such factors as the size, position and luminance of a source, the number of sources, and the luminance to which the eyes are adapted.

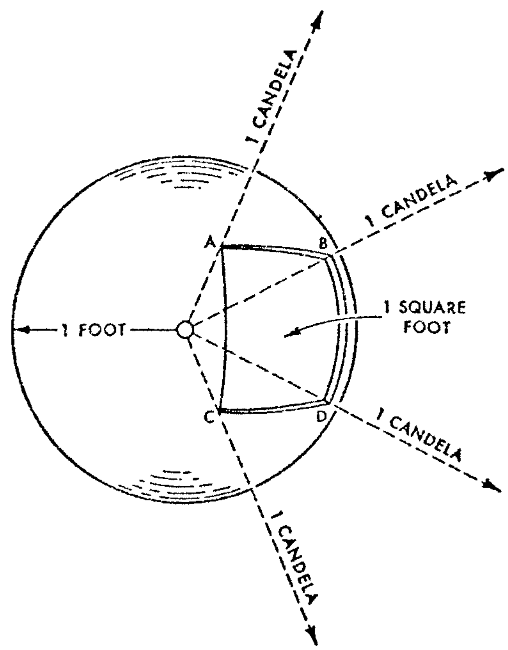

Figure 1. Relationship between candelas, lumens, and footcandles. A uniform point source (luminous intensity or candlepower = 1 candela) is shown at the center of a sphere of one-foot radius. It is assumed that the sphere surface has zero reflectance. The illumination at any point on the sphere is one footcandle (one lumen per square foot). The solid angle subtended by the area A, B, C, D is one steradian, which corresponds to a luminous intensity of one candela, as originally assumed. The sphere has a total area of 12.57 (4π) square feet, and there is a luminous flux of one lumen falling on each square foot. Thus, the square provides a total of 12.57 lumens.

high-intensity discharge lamps: a general group of lamps consisting of mercury, metal halide and high pressure sodium lamps.

high mast lighting: illumination of a large area by means of a group of luminaires which are designed to be mounted in fixed orientation at the top of a high mast [generally 80 feet (25 meters) or higher].

high pressure sodium lamp: a sodium vapor lamp in which the partial pressure of the vapor during operation is of the order of 10^4 N · m^{-2} (0.1 atmosphere).

illumination: the density of the luminous flux incident on a surface; it is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated.

Note: The term illumination also is commonly used in a qualitative or general sense to designate the act of illuminating or the state of being illuminated. Usually the context will indicate which meaning is intended, but occasionally it is desirable to use the expression *level of illumination* to indicate that the quantitative meaning is intended.

illumination (footcandle) meter: an instrument for measuring the illumination on a surface. Most such instruments consist of one or more photovoltaic cells connected to a meter calibrated in footcandles.

infield: the portion of an interchange area exclusive of roadways and shoulders. Such portions may be either landscaped or unimproved.

intensity: a shortening of the terms *luminous intensity* and *radiant intensity.* Often misused for level of illumination.

insulating transformer: an auxiliary device for use with mercury or fluorescent lamps or incandescent lamps in series circuits to insulate the lamp from the high-voltage series circuit. It may also transform current and limit peak open circuit voltage across the lamp socket.

isocandela line: one plotted on any appropriate coordinates to show directions in space, about a source of light, in which the candlepower is the same. For a complete exploration the line always is a closed curve. A series of such curves, usually for equal increments of candlepower, is called an isocandela diagram.

isolux (isofootcandle) line: one plotted on any appropriate coordinates to show all the points on a surface where the illumination is the same. For a complete exploration the line is a closed curve. A series of such lines for various illumination values is called an isolux (isofootcandle) diagram.

lambert, L: a unit of luminance (photometric brightness) equal to $1/\pi$ candela per square centimeter.

lambert surface: a surface that emits or reflects light in accordance with Lambert's cosine law. A lambert surface has the same luminance regardless of viewing angle.

lamp: a generic term for a man-made source of light which is produced either by incandescence or luminescence.

lamp lumen depreciation factor, LLD: the multiplier to be used in illumination calculations to relate the initial rated output of light sources to the anticipated minimum rated output based on the relamping program to be used.

lamp post: a standard support provided with the necessary internal attachments for wiring and the external attachments for the bracket and luminaire.

lateral width of a light distribution: (in roadway lighting) the lateral angle between the reference line and the width line, measured in the cone of maximum candlepower. This angular width includes the line of maximum candlepower.

light center (of a lamp): the center of the smallest sphere that would completely contain the light-emitting element of the lamp.

light center length (of a lamp): the distance from the light center to a specified reference point on the lamp.

lighting unit: the assembly of pole or standard with bracket and luminaire.

longitudinal roadway line, LRL: may be any line along the roadway parallel to the curb line.

low pressure sodium lamp: a sodium vapor lamp in which the partial pressure of the vapor during operation is of the order of 30 millimeters of mercury (0.04 atmosphere).

lumen, lm: the unit of luminous flux. It is equal to the flux through a unit solid angle (steradian), from a uniform point source of one candela (candle), or to the flux on a unit surface all points of which are at unit distance from a uniform point source of one candela. See Figure 1 for a diagrammatic representation.

luminaire: a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

luminaire efficiency: the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein.

luminance (photometric brightness): luminance in a direction, at a point on the surface of a source of a receiver, or of any other real or virtual surface is the quotient of the luminous flux leaving, passing through, or arriving at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction; or it is the luminous intensity of any surface in a given direction per unit of projected area of the surface as viewed for that direction.

Note: In the defining equation, θ is the angle between the direction of observation and the normal to the surface.

In common usage, the term *brightness* usually refers to the intensity of *sensation* resulting from viewing surfaces or spaces from which light comes to the eye. This sensation is determined in part by the definitely measurable luminance defined above and in part by conditions of observation such as the state of adaptation of the eye.

In much of the literature the term brightness, used alone, refers to both luminance and sensation. The context usually indicates which meaning is intended.

luminance ratio: the ratio between the luminances (photometric brightnesses) of any two areas in the visual field.

Note: See last paragraph of the note under *luminance.*

luminous efficacy of a source of light: the quotient of the total luminous flux emitted by the total lamp power input. It is expressed in lumens per watt.

Note: The term luminous efficiency has in the past been extensively used for this concept.

lux, lx: the International System (SI) unit of illumination. It is the illumination on a surface one square meter in area on which there is a uniformly distributed flux of one lumen, or the illumination produced at a surface all points of which are at a distance of one meter from a uniform point source of one candela.

maintenance factor, MF: a factor formerly used to denote the ratio of the illumination of a given area after a period of time to the initial illumination on the same area.

mean lamp lumens: the mean lumen output of a lamp is calculated by determining the area beneath the lumen maintenance characteristic curve of that source over a given period of time and dividing that area by the time period in hours.

mercury lamp: an electric discharge lamp in which the major portion of the radiation is produced by the excitation of mercury atoms.

metal halide lamp: a discharge lamp in which the light is produced by the radiation from a mixture of a metallic vapor (for example, mercury) and the products of the disassociation of halides (for example, halides of scandium or sodium).

mounting height, MH: the vertical distance between the roadway surface and the center of the apparent light source of the luminaire.

non-cutoff: the luminaire light distribution category when there is no candlepower limitation in the zone above maximum candlepower.

overhang: the distance between a vertical line passing through the luminaire and the curb or edge of the roadway.

point of fixation: a point or object in the visual field at which the eyes look and upon which they are focused.

polarization: the process by which the transverse vibrations of light waves are oriented in a specific plane.

pole: a standard support generally used where overhead lighting distribution circuits are employed.

primary line of light: the line connecting the point of observation and the point of fixation.

rapid start fluorescent lamp: a fluorescent lamp designed for operation with a ballast that provides a low-voltage winding for preheating the electrodes and initiating the arc without a starting switch or the application of high voltage.

reaction time: the interval between the beginning of a stimulus and the beginning of the response of an observer.

reference line: either of two radial lines where the surface of the cone of maximum candlepower is intersected by a vertical plane parallel to the curb line and passing through the light center of the luminaire.

reflectance of a surface or medium: the ratio of the reflected flux to the incident flux.

Note: Measured values of reflectance depend upon the angles of incidence and view, and on the spectral character of the incident flux. Because of this dependence, the angles of incidence and view and the spectral characteristics of the source should be specified.

reflector: a device used to redirect the luminous flux from a source by the process of reflection.

refractor: a device used to redirect the luminous flux from a source, primarily by the process of refraction.

regular (specular) reflectance: the ratio of the flux leaving a surface or medium by regular (specular) reflection to the incident flux.

semi-cutoff: a luminaire light distribution is designated as semi-cutoff when the candlepower per 1000 lamp lumens does not numerically exceed 50 (5 percent) at an angle of 90 degrees above nadir (horizontal); and 200 (20 percent) at a vertical angle of 80 degrees above nadir. This applies to any lateral angle around the luminaire.

shielding angle (of a luminaire): the angle between a horizontal line through the light center and the line of sight at which the bare source first becomes visible.

spacing: for roadway lighting the distance between successive lighting units, measured along the center line of the street.

spacing-to-mounting height ratio, S/MH: the ratio of the distance between luminaire centers to the mounting height above the roadway.

street lighting luminaire: a complete lighting device consisting of a light source together with its direct appurtenances such as globe, reflector, refractor, housing, and such support as is integral with the housing. The pole, post, or bracket is not considered part of the luminaire.

street lighting unit: the assembly of a pole or lamppost with a bracket and a luminaire.

subjective brightness: the subjective attribute of any light sensation giving rise to the percept of luminous intensity, including the whole scale of qualities of being bright, light, brilliant, dim, or dark.

Note: The term brightness often is used when referring to the measurable "photometric brightness." While the context usually makes it clear as to which meaning is intended, the preferable term for the photometric quantity is *luminance,* thus reserving *brightness* for the subjective sensation.

transverse roadway line, TRL: may be any line across the roadway that is perpendicular to the curb line.

tungsten-halogen lamp: a gas-filled tungsten incandescent lamp containing a certain proportion of halogens.

Note: The tungsten-iodine lamp (UK) and quartz-iodine lamp (USA) belong to this category.

utilization efficiency: a plot of the quantity of light falling on a horizontal plane both in front of and behind the luminaire. It shows only the percent of bare lamp lumens which fall on the horizontal surface, and is plotted as a ratio of width of area to mounting height of the luminaire.

veiling brightness: a brightness superimposed on the retinal image which reduces its contrast. It is this veiling effect produced by bright sources or areas in the visual field that results in decreased visual reflected glare.

veiling reflection: regular reflections superimposed upon diffuse reflections from an object that partially or totally obscure the details to be seen by reducing the contrast. This sometimes is called reflected glare.

visibility: the quality or state of being perceivable by the eye. In many outdoor applications, visibility is defined in terms of the distance at which an object can be just perceived by the eye. In indoor applications, it usually is defined in terms of the contrast or size of a standard test object, observed under standardized view-conditions, having the same threshold as the given object.

visual acuity: a measure of the ability to distinguish fine details. Quantitatively, it is the reciprocal of the angular size in minutes of the critical detail that is just large enough to be seen.

visual angle: the angle subtended by an object or detail at the point of observation. It usually is measured in minutes of arc.

walkway: a sidewalk or pedestrian way.

width line: the radial line (the one that makes the large angle with the reference line) that passes through the point of one-half maximum candle-power on the lateral candlepower distribution curve plotted on the surface of the cone of maximum candlepower.

zonal constant: a factor by which the mean candlepower emitted by a source of light in a given angular zone is multiplied to obtain the lumens in the zone.

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285-027 O - 79 - 17

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ALPHABETICAL INDEX

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