ADDENDUM TO CHAPTER SIX OF THE

Addendum to
Implementation Package 78-15

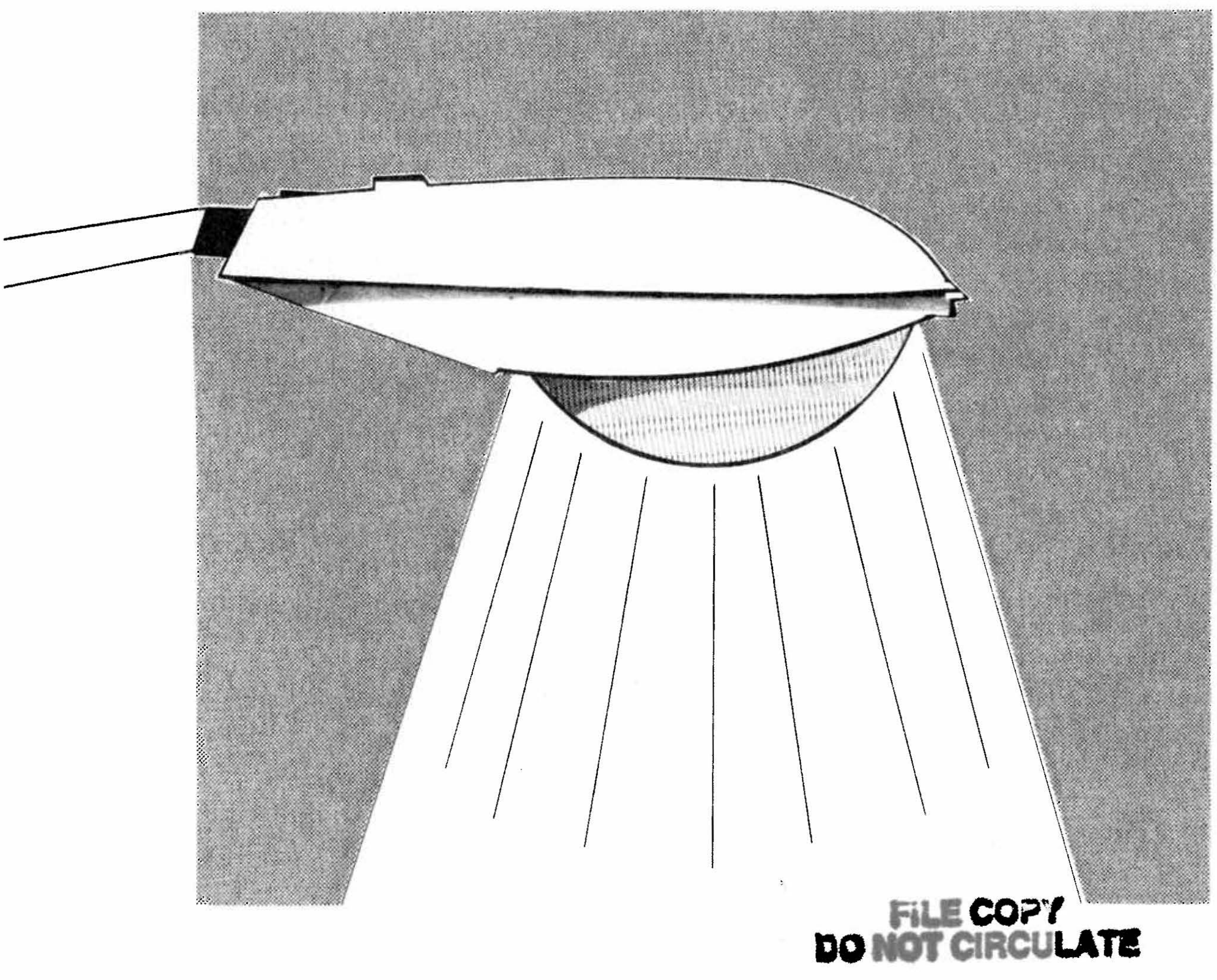
# ROADWAY LIGHTING HANDBOOK

## DESIGNING THE LIGHTING SYSTEM

## —Using Pavement Luminance

September
1983

U.S. Department
of Transportation
Federal Highway
Administration



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# ROADWAY LIGHTING HANDBOOK ADDENDUM TO CHAPTER SIX

## Designing the Lighting System Using Pavement Luminance

September 1983

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
WASHINGTON, D. C. 20590

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# DESIGNING THE LIGHTING SYSTEM
## Using Pavement Luminance

*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 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*
- *Designing the Lighting System*
- *Designing the Lighting Hardware*
- *Operating and Maintaining the Lighting System*
- *Analyzing the Economics of the Lighting System*

This chapter assumes that the engineer or designer has access to and is familiar with the other chapters listed above even though this chapter is printed and distributed separately from the previously published handbook. This chapter begins with a discussion of Pavement Luminance which is followed by the specific design criteria, the process of creating a tentative design, evaluating that design and then revising the tentative design until the evaluation technique indicates that a final design has been achieved. The chapter concludes with appendix material for those who desire specific background material in selected areas.

## LUMINANCE vs ILLUMINANCE

The chapter on "Designing the Lighting System" in the *Roadway Lighting Handbook* as originally published (Implementation Package 78-15) was based on Illuminance. This has been the traditional lighting criteria in North America for both interior and outdoor lighting design. In 1983 the Illuminating Engineering Society, sponsor of the *American National Standard Practice for Roadway Lighting* recommended the use of pavement surface Luminance as the preferred design criteria.

Illuminance is the amount of light falling on the pavement, it is also often called illumination or incident light. It is measured by inserting a meter between the pavement and the light striking the pavement. Luminance, on the other hand, refers to the light that is reflected from the pavement towards the eye of the observer. It is measured by inserting a meter between the eye and the light reaching it from the pavement.

Luminance is preferred as a criteria since many of the functions of the eye are goverened by the adaptation level under which we find ourselves. With the high adaptation levels of daylight our eyes can see colors, detect low contrast detail, and see small objects at a distance. Under the low adaptation level of moonlight our eyes cannot see colors, we cannot read a newspaper, or detect a brick on the roadway in the distance. The primary source of our adaptation level when driving at night is the brightness or luminance of the roadway ahead. A system which produces a higher pavement luminance permits us to see lower contrast detail at a greater distance. The system with the most incident light striking the pavement does not necessarily produce the highest pavement luminance.

### Principles of Producing Luminance

In order to make a small area of pavement ahead of us bright, it is necessary to have light fall upon it, and for that pavement to posesss the characteristics to reflect some part of that light which falls upon it. Figure 1 shows the three angles that govern the prediction of the luminance of a small area of the pavement from a particular observer position. Gamma ($\gamma$) is the angle from the vertical at which the light strikes the pavement. Beta ($\beta$) is the angle between the plane of light incidence and the plane of obseration. Alpha ($\alpha$) is the observation angle from the pavement surface.

In Figure 2 the angles $\gamma_1$ and $\gamma_2$ are the same, but if the incident light intensity is the same, the pavement at point $P_2$ will always have a higher luminance than that at point $P_1$. This is because of the surface characteristics of the

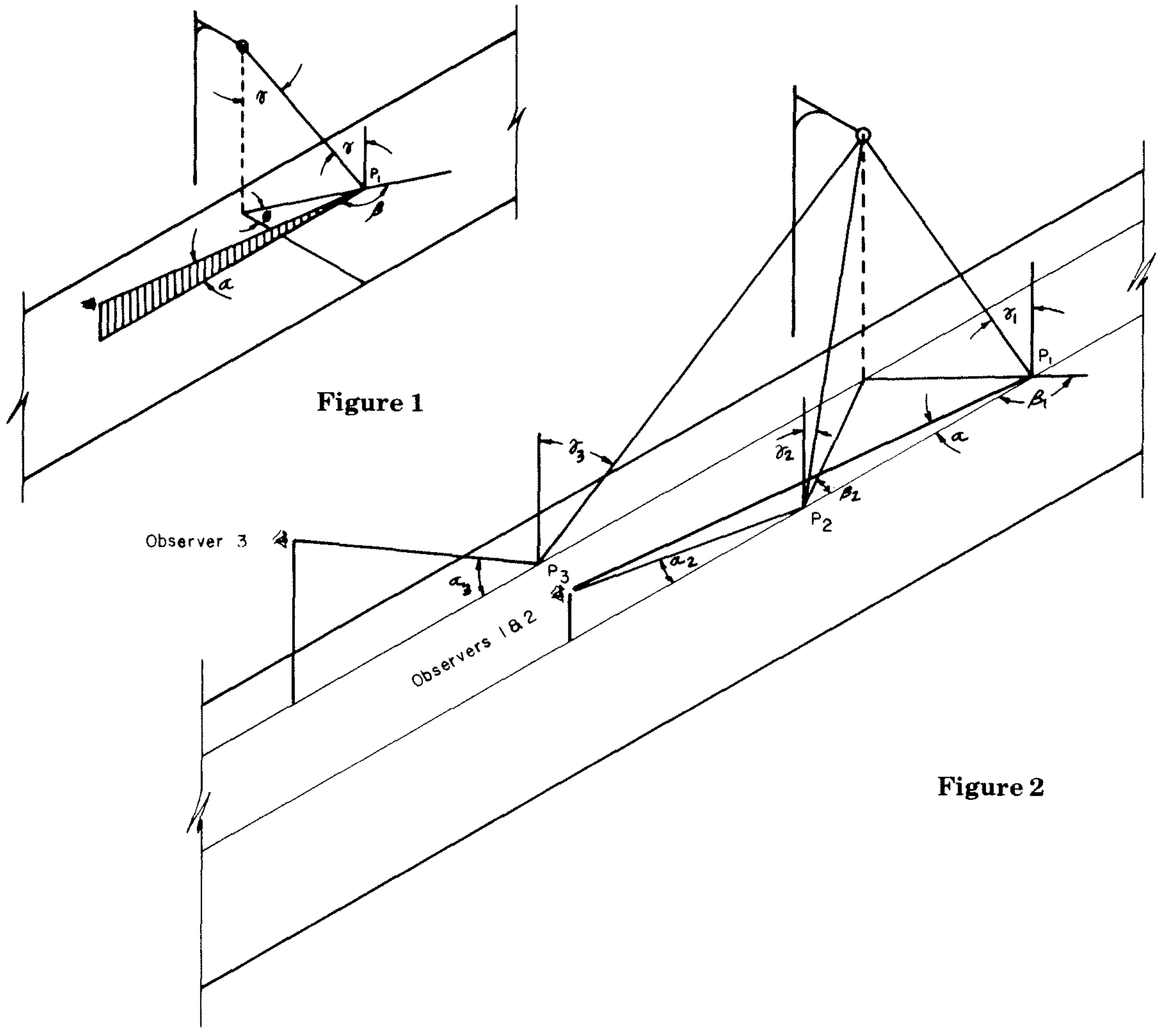



Figure 1

Figure 2

pavement. Like any semi-polished surface the pavement luminance will be highest when $\beta$ is zero degrees and the angle of light incidence is equal to the angle of reflectance. This condition is shown as point $P_3$. In order to achieve this position of maximum pavement luminance at point $P_3$ it has been necessary to move the observer a greater distance from the luminaire and at a considerable height above the roadway.

The intensity of incident light at each of the different pavement points in Figure 2 depends on the relative distribution of light from the luminaire. From a practical point of view the driver of a motor vehicle is never very high above the pavement and an average height of 1.45 meters (57 inches) has been adopted as standard. By using a standard observer height and a standard angle of sight ($\alpha$ equal to one degree) it is possible to reduce the number of angles on which luminance is dependent from three to two (Beta and Gamma) and thus be able to show the pavement reflectance in a two dimensional table, called an R-table.

### Measurement of Pavement Luminance

Luminance is not quite the same as brightness. Luminance can be measured by instruments and as so measured remains constant while brightness is the sensation of what we perceive and depends both upon the adaptation of the eye and on the relative brightness of areas surrounding the small spot whose brightness we are judging. For example the moon looks bright against the dark night sky and dim when seen against the daytime sky but its measured luminance is a constant value.

Luminance is measured with an instrument that has an optical system and internal masks which frame the area to be measured. The instrument then reads the average luminance of the framed area in candelas per square meter (Cd/SqM) in SI* units or in footlamberts (fL). In this chapter SI units will be used.

### Calculation of Pavement Luminance

The formula for the calculation of luminance at a point is as follows:

$$L = \frac{I \times r}{H^2 \times 10000}$$

where

L is luminance in Cd/SqM

I is the light intensity in candelas

r is the reduced coefficient of pavement reflectance

H is the height of the luminaire above the calculation plane in meters

While this is a very simple formula it should be remembered that to obtain the light intensity it may be necessary to calculate the vertical and lateral angle from the luminaire to the point on the pavement and also to determine r it may be necessary to calculate the angles $\gamma$ and $\beta$. Detailed examples are shown later.

Pavement surface reflectance characteristics (Table III) have been standardized into four catagories and for each a table of reflectance coefficients, called R-Tables, have been compiled. As indicated before these assume that the observer is 1.45 meters (57 in.) above the plane of the pavement and has a direction of view 1 degree downward. This places a certain limitation on the use of R-Table data. If one considers the observer as fixed then observation points should be restricted to those falling within a tolerance of 1/2 degree of the assumed 1 degree downward line of sight. Beyond this tolerance excessive error may occur. Two observer concepts are in use in various parts of the world. The fixed observer concept permits the observer to be located anywhere on the pavement surface and a calculation of the pavement luminance can be made at any other point in the same lane or another lane as long as the limitations noted above are observed. It does mean, however, that if two different people are going to calculate the luminance at a given point (or points) that they must have some preagreement as to the observer location they intend to use, otherwise they may choose different observer locations and obtain different correct answers. In many countries such a preagreed location of the observer is used and this is called the CIE** method.

The North American countries of Canada, Mexico and the United States have adopted a somewhat different concept. In this concept the observer is considered to always be on a line parallel to the centerline of the roadway thru the calculation point at such a distance from the calculation point that his angle of view is 1 degree downward. As various calculation points are chosen down the roadway and across it the observer moves so that he is always looking parallel to the centerline of the roadway and always at the proper distance away to be looking downward at exactly 1 degree. This is called the IES† or "moving observer" method.

In this chapter the IES or "moving observer" method will be used exclusively. All examples will be shown without fixing the observer. Grid points located in a lane of oncoming traffic are calculated as if the observer is using that lane as a passing lane.

## DESIGN CRITERIA

Each vehicle licensed to operate on this Nation's roadways is required to be equipped with headlights. These are deemed to be sufficient to permit the vehicle operator to safely drive his

* Standard International (SI)

** Commission Internationale d'Eclairage (CIE)

† Illuminating Engineering Society of North America (IES)

**TABLE I**
**Design Criteria**

| ROAD Classification | | $L_{avg}$ Cd/SqM | $L_{avg}$ to $L_{min}$ | $L_{max}$ to $L_{min}$ | Maximum Ratio $L_v$ to $L_{avg}$ |
|---|---|---|---|---|---|
| Freeway Class "A" | | 0.6 | 3.5 to 1 | 6 to 1 | 0.3 to 1 |
| Freeway Class "B" | | 0.4 | 3.5 to 1 | 6 to 1 | |
| | Commercial | 1.0 | 3 to 1 | 5 to 1 | |
| Expressway | Intermediate | 0.8 | 3 to 1 | 5 to 1 | 0.3 to 1 |
| | Residential | 0.6 | 3.5 to 1 | 6 to 1 | |
| | Commercial | 1.2 | 3 to 1 | 5 to 1 | |
| Major | Intermediate | 0.9 | 3 to 1 | 5 to 1 | 0.3 to 1 |
| | Residential | 0.6 | 3.5 to 1 | 6 to 1 | |
| | Commercial | 0.8 | 3 to 1 | 5 to 1 | |
| Collector | Intermediate | 0.6 | 3.5 to 1 | 6 to 1 | 0.4 to 1 |
| | Residential | 0.4 | 4 to 1 | 8 to 1 | |
| | Commercial | 0.6 | 6 to 1 | 10 to 1 | |
| Local | Intermediate | 0.5 | 6 to 1 | 10 to 1 | 0.4 to 1 |
| | Residential | 0.3 | 6 to 1 | 10 to 1 | |

Source: ANSI/IES RP-8, 1983

vehicle. The objective of a fixed lighting system is to supplement the headlights and render objects, which are distant, complex, or which have low contrast, more visible to the motorist and pedestrian. The result of making such objects more visible is expected to be less accidents, improved traffic flow, and increased motorist confidence. In order to achieve these positive effects from a fixed lighting system it is necessary to install supports for the luminaires. These supports can be hazardous in themselves for a motorist who has lost control of his vehicle. For a more complete discussion of the costs, benefits, and operating economics of a fixed lighting system see other chapters of the Roadway Lighting Handbook.

Specific criteria keyed to the type of roadway and the area through which it passes have been developed by the Illuminating Engineering Society and adopted by the American National Standards Institute as a guide in determining the appropriate enegry levels and quality acceptability for fixed lighting systems in the United States. Four criteria as follows are specified in Table I.

1. ***Average Maintained Pavement Luminance*** ($L_{avg}$). This criteria sets both the basic energy level and the visual adaptation level. It is the average over the roadway surface, at a point in time when the decline in light level, due to light source aging and luminaire dirt accumulation, has occured. It is specified for dry pavement.

2. ***Minimum Pavement Luminance*** ($L_{min}$). The allowable minimum is specified in terms of a ratio that relates it to the average value. This ensures that the contrast sensitivity of the eye as determined by the adaptation level, never falls below the specified level.

3. ***Maximum Pavement Luminance*** ($L_{max}$). The allowable maximum is specified as a ratio that relates it to the minimum. The purpose in limiting this ratio is to control the limits of transient adaptation (the momentary reduction in contrast sensitivity of the eye as it is subjected to a substantial change in adaptation).

4. ***Maximum Veiling Luminance*** ($L_v$). Maximum $L_v$ is specified as a ratio that relates it to the average pavement luminance. Veiling

luminance is a measure of the amount of light entering the eye which causes a reduction in contrast due to its interaction with minute irregularities in the optical media of the eye. In a streetlighting installation the amount of $L_v$ varies as the observer moves from point to point over the grid. This is due to the changing intensity of the luminaires and their changing angular relationship to the observer. While $L_v$ is produced by every luminous object in the field of view (such as the white shirt of a pedestrian) the effect of light producing sources predominates and light from reflected sources is normally not included in $L_v$ calculations. The effect of a given level of $L_v$ on the visibility of a target depends on the adaptation level of the eye. An example is the obvious reduction in visibility from the headlights of an approaching vehicle at night on an unlighted roadway as compared to an unnoticable effect from approaching headlights during daytime hours.

To use Table I it is necessay to determine the Road Classification of the roadway to be lighted. For an indepth discussion of road classifications refer to Chapter 5 of the Roadway Lighting Handbook. A brief definition of the classifications follows:

- ***Freeway Class "A" and "B":*** Freeways are divided major roadways with full control of access and no crossings at grade. Freeway "A" are those freeways with higher traffic volumes and greater visual complexities. Such freeways will usually be found in major metropolitan areas in or near the central core of the city and will operate at or near the design capacity through part of the early evening or morning hours of darkness. Freeway "B" are all others where lighting is warranted.

- ***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:*** That part of the roaday system which serves as the principle network for through traffic flow. The routes connect areas of principle traffic generation and important highways entering the city.

- ***Collector:*** The distributor and collector roadways servicing traffic between major and local roadways.

- ***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.

- ***Area Classifications: Commercial.*** A business area of a municipality where ordinarily there are many pedestrians during a part of the night hours. ***Intermediate.*** Those areas of a municipality often characterized by moderately heavy nighttime pedestrian activity such as in blocks having libraries, recreation centers, apartment buildings, industrial buildings and neighborhood retail stores. ***Residential.*** A residential development, or a mixture of residential and small commercial establishments, characterized by few pedrestrians at night.

Criteria in Table I can be exceeded and it is unlikely that a design can be made which meets the exact value of all criteria without exceeding some. No one criteria is considered more important than another and exceeding one does not indicate that the requirements of another can be waived. All criteria must be met or exceeded.

Verification of meeting the design criteria is difficult to determine by field measurement and installations are usually verified by indirect means. A discussion of recommended methods of verifing installation performance appears later in this chapter.

## DESIGN vs DESIGN EVALUATION

The *design* of a lighting system involves the selection of equipment and locating it in space with relationship to the roadway. This selection includes the pavement type. In creating a lighting design, consideration must be given to changes that will occur during the anticipated design life. These include but are not limited to light source changes over life, lamp burnout

**TABLE II**
**Luminaire Classification System (note 1, 2, 3)**

| Width Classification | Mounted at pavement | Normally used for |
|---|---|---|
| Type I | Center | Roadways up to 2 times the MH in width. |
| Type II | Edge | Up to 1 times the MH for one side mtg.<br>Up to 2 times the MH for both side mtg. |
| Type III | Edge | Up to 1.5 times the MH for one side mtg.<br>Up to 3.0 times the MH for both side mtg. |
| Type IV | Edge | Up to 2 times the MH for one side mtg.<br>Up to 4 times the MH for both side mtg.; |
| Type V | Center | Up to 4 times the MH in total width. |

| Spacing Classification | Definition | Normally used for |
|---|---|---|
| S | Short | Spacings up to 4 times Mounting Height |
| M | Medium | Spacings up to 5 times Mounting Height |
| L | Long | Spacings over 5 times Mounting Height |

| Glare Control Classification | Definition | Normally used for |
|---|---|---|
| CO | Cutoff | Strict control of light above 80 deg. V. |
| SCO | Semicutoff | Medium control of light above 80 deg. V. |
| NCO | Noncutoff | No contol requirements above 80 deg. Vert. |

Note 1 — The complete luminaire classification consists of the three terms in sequence. Example: Type II-M-SCO

Note 2 — There is no assurance that the criteria values will be achieved by a luminaire which meets the classification requirements and is used as shown above.

Note 3 — The method of classifying a particular luminaire distribution is to be found in ANSI/IES RP-8, 1983

and replacement, dirt accumulation, cleaning schedules, vibration, rain, snow, pavement wear, patching and resurfacing. The *evaluation* of a lighting design involves the calculation or measurement of the lighting criteria parameters. This can be done under one or more conditions that can be expected to occur during the life of the installation. At the present time insufficient data is available to predict pavement luminance data as the result of varying amounts of moisture on the pavement, or changes in luminaire distribution.

### Elements of a Lighting System Design.

The elements of a lighting design can be chosen by experience, dictated by other factors in the overall roadway design, or by calculations made to determine an optimum trial selection. The initial tentative design is then evaluated, modified and then re-evaluated. This reiterative process is followed until a final design is achieved. The elements of a lighting design that must be selected are:

1. ***System Configuration.*** Different luminaire optical designs have been created for luminaires intended to be located over the center of the roadway, over the pavement but near the edges, or at some distance off roadway. Typical configurations are shown in Figure 3 with spacing defined as the distance between luminaires along the centerline of the roadway.

**Figure 3**

TYPICAL MOUNTING CONFIGURATIONS
(LUMINANCE PATTERNS REPEAT AT SPACING BOUNDARIES INDICATED)

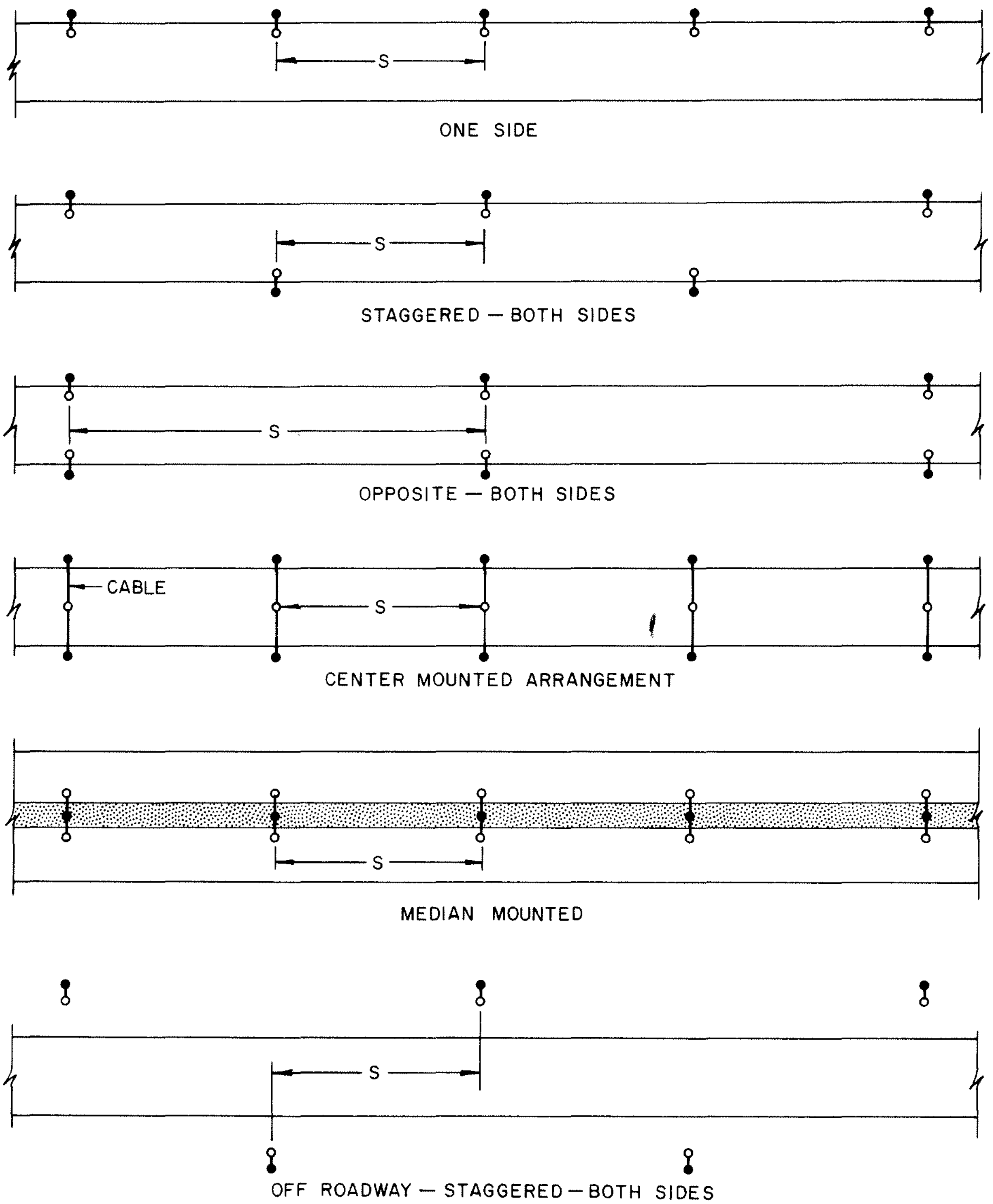
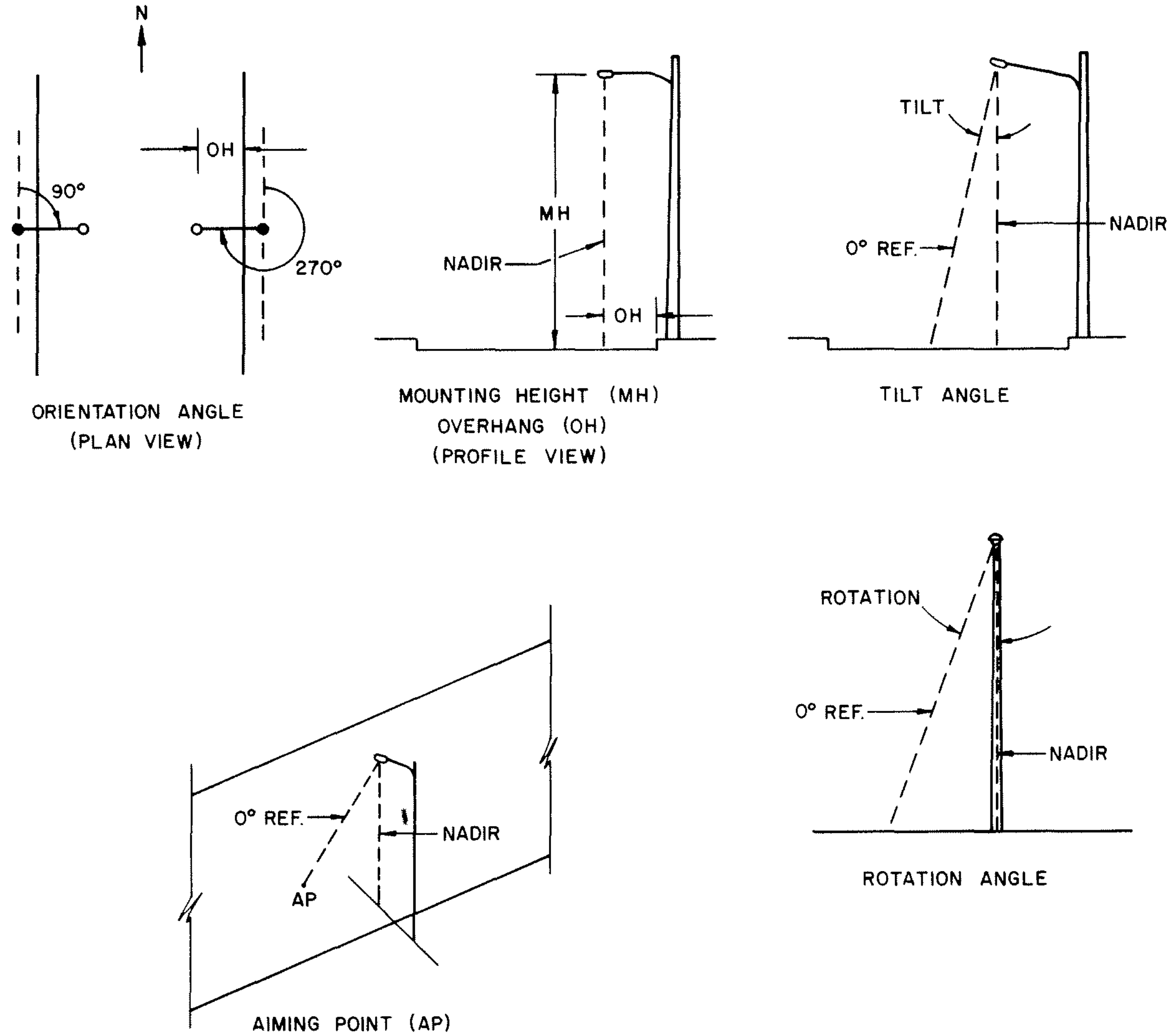


**Figure 4 Mounting Height, Overhang, Tilt, Rotation and Aiming**




2. ***Luminaire and Light Source.*** The luminaire and light source are inseparable in terms of producing the optimum amount of light in a particular intensity distribution. Luminaire optical systems are created by the design of reflector contours that interact within limits to changes in light source size and location. In some designs, refractors are used to modify light ray directions by selective prismatic action on transmitted rays. Changing the light source type or wattage can, by modifying the location, size and shape of the emitting source; cause either a minor or major change in the light distribution.

A standardized light distribution system designation established by the IES is widely used and is shown in Table II. In this system the roman numerals indicate the mounting location and width of street on which the distribution was designed to be used. The letter (S, M, or L) indicates the spacing between luminaires for which the distribution is best suited and the abbreviations (CO, SCO, NCO) indicate the degree of glare control included in the design. Knowledge of this classification system is helpful in selecting a trial luminaire and light source for use in a tentative design.

**TABLE III**
**Road Surface Classifications**

| Class | Description | Reflectance |
|---|---|---|
| R-1 | Portland cement concrete road surface. Asphalt road surface with a minimum of 15% of the aggregates composed of artificial brightner (e.g., Synopal) aggregates (e.g., labradorite, quartzite). | Mostly Diffuse |
| R-2 | Asphalt road surface with an aggregate composed of a minimum 60% gravel (size greater than 10 milimeters). and Asphalt road surface with 10 to 15% artificial brightener in the aggregate mix. (Not normally used in North America). | Mixed Diffuse and Specular |
| R-3 | Asphalt road surface (regular and carpet seal) with dark aggregates (e.g., trap rock, blast furnace slag); rough texture after some months of use. (Typical Highways) | Slightly Specular |
| R-4 | Asphalt road Surface with very smooth texture. | Mostly Specular |

Source: ANSI/IES RP-8, 1983

3. ***Luminaire Geometry.*** This is the term used to describe the location of the luminaire within the system and relative to the roadway. The individual luminaires must be located as to mounting height, spacing between luminaires, overhang, orientation tilt and rotation. See Figures 3 and 4 for a graphical understanding of these terms. For normal installations, with the luminaires level, tilt and rotation will be zero.

4. ***Pavement Classification.*** Four classifcations of pavement as standardized by the Commission Internationale d'Eclairage (CIE) have been adopted by the countries of North America. They are designated and described in Table III. The most commonly used type in the USA is type R-3 which is representative of asphaltic concrete pavement, reasonably worn, with medium aggregates.

### Elements of a Design Evaluation

To evaluate a tentative design it is necessary to calculate the criteria listed before. The design is considered to be a straight level roadway of infinite length. In such a case the luminance pattern repeats in the same manner that the configuration repeats but not in exactly the same manner as incident illumination repeats. It is only necessary to explore the luminance pattern over the area between lines dividing the repeating pattern. The spacing boundries in Figure 3 are also boundries of the repeating patterns. It is not necessary to search at great length for the maximum and minimum points. A suitable grid of points should be set up and the average, maximum and minimum values from that grid can be used as the system average, maximum and minimum values. Information as to recommendations for a suitable grid will be found in appendix A. In order to make a complete evaluation of a tentative or final design the following need to be calculated.

- System average pavement luminance.
- Ratio of average pavement luminance to minimum luminance. $L_{avg}/L_{min}$
- Ratio of maximum pavement luminance to minimum luminance. $L_{max}/L_{min}$
- Ratio of maximum veiling luminance to average pavement luminance. $L_v/L_{avg}$

From a complete or partial evaluation of a tentative design, determinations can be made to improve the tentative design. Either small improvements or major changes may be indicated by a design evaluation.

## PROCEDURE FOR CREATING A TENTATIVE DESIGN

To illustrate the details of creating a tentative design an example will be used. The problem will be to design a fixed lighting system for a collector street in a commercial area. The street is 18 m (59 ft) wide, consisting of four 3.5 m (11.5 ft) lanes and a 4 m (13 ft) two-way left turn lane. Each criteria will be selected in turn, with comments, to form a tentative design. That design will then be evaluated, improved, and evaluated again in a reiterative cycle until it is finalized.

**Step 1. Selection of Criteria.** From Table I the following criteria are found.

- $L_{avg}$ = 0.8 Cd/SqM
- $L_{avg}$ to $L_{min}$ = 3 to 1 The min is to be 0.8/3 = 0.27 Cd/SqM maintained
- $L_{max}$ to $L_{min}$ = 5 to 1 The max is to be 0.27 × 5 = 1.4 Cd/SqM maintained
- Max $L_v$ to $L_{avg}$ = 0.4 to 1 The $L_v$ is to be 0.8 × 0.4 = 0.32 Cd/SqM maintained

**Step 2. Select a System Configuration.** Experience indicates that a 18 m (59 ft) street is too wide to achieve satisfactory luminance uniformity from a one-side arrangement therefore the luminaires will be located on both sides of the street. A staggered arrangement will be chosen since this always provides superior luminance uniformity as compared to an opposite arrangement when using the same lamp and luminaire and equal average luminance.

**Step 3. Select a Pavement Reflectance Type.** The city street is now paved with asphalt and city policy is expected to be to continue to repave with the same type of material. From Table III it is logical to select R-3 as the pavement reflectance type.

**Step 4. Select a Luminaire and Light Source.** This is a somewhat difficult step and the decision can best be made by using a semi-evaluation process. A logical light source is High Pressure Sodium which has a high luminous efficacy (about 100 lumens per watt compared to 55 for mercury and 20 for incandescent sources), a small source size for good optical control, and a yellow white color that has been widely accepted. The 200 watt size was developed for roadway lighting and is a good place to start. From Table II it appears logical to select a Type II-Med-SCO luminaire. It is now necessary to take from the file the photometric data sheet for this lamp and luminaire combination. Appendix B has a discussion of photometric data and the various ways it is presented.

The photometric data sheet for the luminaire of this example is shown in Figure 5a and 5b. Its first page (Fig.5a) contains general data at the top and data for designing for illuminance in the lower section. The second page of the data sheet (Fig.5b) shows data for designing by the luminance method for R-3 pavement. The luminaire is located with a "P" and the observer is on the upstream side looking toward the luminaire. Both the point on the pavement where maximum pavement luminance occurs from the normal observer location (83 meters upstream) (272 ft) and the point where the observer would be located to experience maximum veiling luminance ($L_v$) are marked with a symbol. The values for each are shown in the legend below the isoluminance chart. From it (Fig.5b) we can locate the single luminaire maximum pavement luminance value and location. The value on the curve is for a 9.1 m (30 ft) mounting height so a correction must be applied per Appendix C. In this case it is 2.4 Cd/SqM for a mounting height of 10 m (33 ft). which is above the maximum criteria value of 1.4 as found in Step 1. However the value shown on the curve is an initial value while the criteria value is a "maintained in service value". One or the other should be adjusted by selecting a Light Loss Factor (LLF), a discussion of light loss factor selection is found in Appendix D. In this case a LLF of 0.7 will be selected and the criteria values adjusted upward by this amount. The new maximum luminance criteria value will be 1.9 Cd/SqM. A listing of the revised criteria values (initial values) are as follows.

- $L_{avg}$ = 1.14 initial vs 0.8 maintained. (Fixed value)

Figure 5a Example of a Photometric Test Report

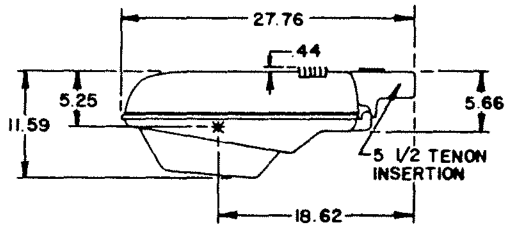
# PHOTOMETRIC DATA SHEET

TEST NO 734313

LUMINAIRE OV-15 SINGLE DOOR

LAMP C-200 200W HPS H

SOCKET POSITION:. A-2
REFLECTOR:......... SPECULAR
REFRACTOR:........ GLASS
LCL:............... 5.25
OTHER VARIABLES:. 5/17/79




CLASSIFICATION: II MEDIUM SEMI CUTOFF
(ANSI 1977)

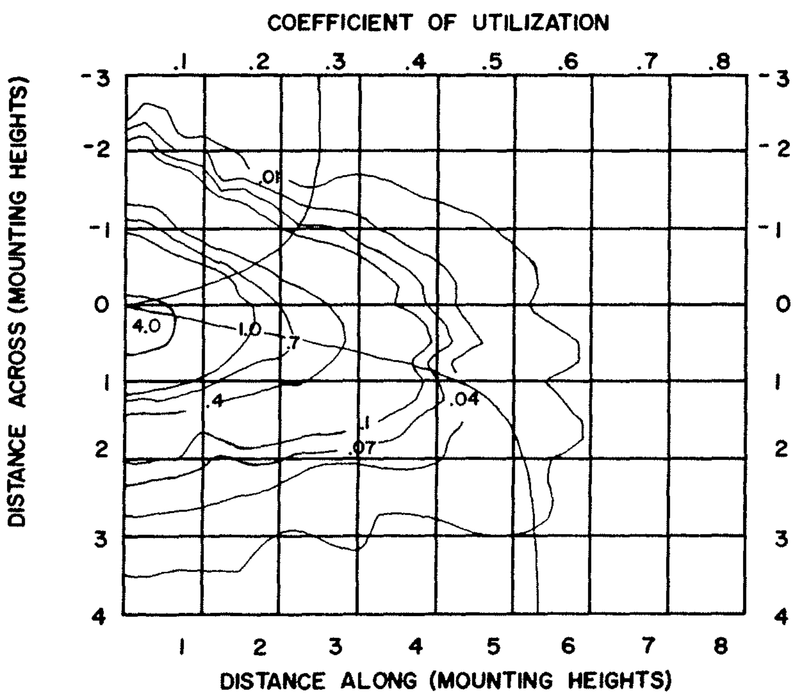
DISTRIBUTION BY ZONES (% OF LAMP LUMENS)

| | | |
|---|---|---|
| DOWNWARD STREET SIDE: | 55.6 | % |
| DOWNWARD HOUSE SIDE: | 24.7 | % |
| UPWARD STREET SIDE: | 0.7 | % |
| UPWARD HOUSE SIDE: | 0.6 | % |
| TOTAL EFFICIENCY | 81.6 | % |

CANDELA *DATA
MAX CD. 10313 AT 80.8 H 70.0 V
NADIR CD. 4193

*NOTE: ISO FOOTCANDLE AND CANDELA VALUES ARE PER 22000 LAMP LUMENS

COEFFICIENT OF UTILIZATION AND ISO FOOTCANDLE* PLOT BASED ON MOUNTING HEIGHT OF 30. FT.




| MTG. HT. | CORR. FACTOR |
|---|---|
| 15. | 4.000 |
| 20. | 2.250 |
| 25. | 1.440 |
| 30. | 1.000 |
| 35. | 0.735 |
| 40. | 0.562 |
| 45. | 0.444 |
| 50. | 0.300 |
| 55. | 0.298 |
| 60. | 0.250 |

734313

APPROVED:
DATE:

THIS TEST WAS MADE IN ACCORDANCE WITH THE IES APPROVED METHOD FOR PHOTOMETRIC TESTING

**Figure 5b Example of a Photometric Test Report**

# PHOTOMETRIC DATA SHEET

TEST NO. 734313

LUMINAIRE

LAMP

SOCKET POSITION: . A-2
REFLECTOR: . . . . . . SPECULAR
REFRACTOR: . . . . . . GLASS
LCL: . . . . . . . . . . . . 5.25
OTHER VARIABLES: . 5/7/79

DATE:

APPROVED:

CLASSIFICATION: II MEDIUM SEMI CUTOFF
(ANSI 1977)

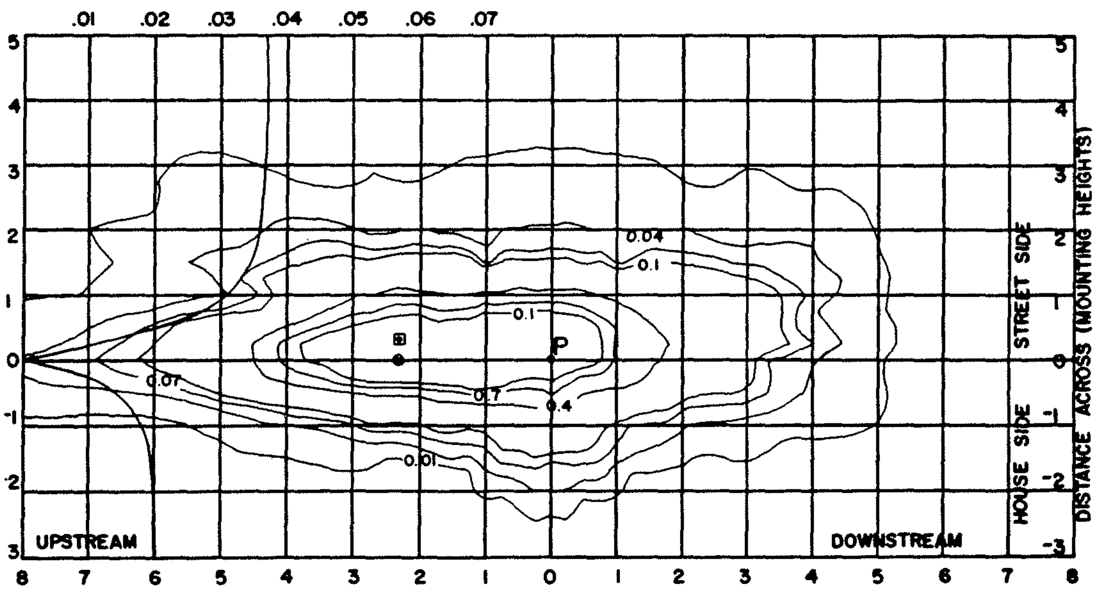
DISTRIBUTION BY ZONES (% OF LAMP LUMENS)

| | | |
|---|---|---|
| DOWNWARD STREET SIDE: | 55.6 | % |
| DOWNWARD HOUSE SIDE: | 24.7 | % |
| UPWARD STREET SIDE: | 0.7 | % |
| UPWARD HOUSE SIDE: | 0.6 | % |
| TOTAL EFFICIENCY | 81.6 | % |

CANDELA * DATA
MAX CD. 10313 AT 80.8 H 70.0 V
NADIR CD. 4193

*NOTE ISO FOOTCANDLE AND CANDELA VALUES ARE PER 22000 LAMP LUMENS

FOR CIE TYPE R3 PAVEMENT
COEFFICIENT OF LUMINANCE UTILIZATION AND
ISO-LUMINANCE PLOT BASED ON 30 FT. MH.




P-FIXTURE LOCATION
——►-OBSERVERS DIRECTION OF VIEW
⊙-MAX. PAVEMENT LUMINANCE POINTS = 2.89 cd/m²
⊞-MAX. VEILING LUMINANCE POINTS = 0.328 cd/m²

THIS TEST WAS MADE IN ACCORDANCE WITH THE IES APPROVED METHOD FOR PHOTOMETRIC TESTING

- $L_{min}$ = 0.38 initial vs 0.27 maintained.)
- $L_{max}$ = 1.93 initial vs 1.35 maintained.)
- $L_v$ = 0.46 initial vs 0.32 maintained.)

Since the maximum single luminaire value of 2.4 is still greater than the initial criteria value of 1.9 we will either have to use a higher mounting height or select a similar luminaire with a smaller wattage lamp. In this example we will utilize a higher mounting height. The mounting height will be determined in Step 5.

From the photometric data sheet of Figure 5b find the maximum single luminaire veiling luminance $L_v$. It is 0.33 Cd/SqM for a 9 m (30 ft) mounting height. Since this is less than the 0.46 maximum initial criteria value and since this will decline further with a higher mounting height it poses no problem.

In the event the photometric curve did not list the single luminaire maximum pavement luminance and veiling luminance; values and location it would have been worthwhile to calculate the values and permanently mark the file copy of the curve so that it would be readily available for future reference. This calculation can be done in several ways as indicated in Appendix F and G.

**Step 5. Select the Luminaire Locations.** There are four items to be determined: Orientation, Overhang, Mounting Height, and Spacing. Each will be decided in turn.

1. ***Orientation:*** Experience indicates that except in unusual circumstances luminaires should be mounted level and at right angles to the centerline of the roadway since the luminaire distribution was designed to perform best with this position.

2. ***Overhang:*** The luminaire should be over the pavement since maximum pavement luminance, per unit of luminaire candlepower, will be produced (due to pavement reflectance charcteristics) along and near a line directly under the luminaire and parallel to the centerline. This must be balanced against the cost of long mast arms necessary to keep poles a safe distance from the paved surface. For this example we will initially locate the luminaires about 1/4 of the lane width from the edge of the pavement. The lane width is 3 1/2 m (11.5 ft) and we will locate the luminaires 1 m (3.3 ft) from the edge of the pavement.

3. ***Mounting Height:*** Experience indicates that a mounting height of approximately 10 m(33 ft) is frequently satisfactory. However, in Step 4 it was found that the maximum pavement luminance from a single luminaire (of the type selected) would exceed the criteria maximum value. Pavement luminance decreases as the mounting height increases and is proportional to the square of the mounting height. Since from Step 4 the desired maximum is 1.9 Cd/SqM and a single luminaire mounted at 10 m (33 ft) will produce 2.4 Cd/SqM we can set up a ratio to select the mounting height. In as much as over 90% of the maximum system luminance will be produced by a single luminaire we will choose 1.8 as the desired single luminaire maximum. The ratio then is the existing MH squared (100) divided by the desired MH squared ($MH^2$) to the desired max. luminance (1.8) divided by the existing max. luminance (2.4).

$$\frac{100}{MH^2} = \frac{1.8}{2.4} \qquad MH = 11.5$$

The mounting height for the tentative design will be 11.5 m (37.8 ft).

4. ***Spacing:*** With the type of photometric data shown in Figure 5b, optimum spacing can be calculated using the "Luminance Coefficient of Utilization Curve". On the data sheet of Figure 5b the curve is printed on the same grid as the isoluminance curves and for clarity it is extracted and shown alone as Figure 6. The relationships to be calculated are shown on the profile illustration of Figure 7 and plotted on the extracted curve of Figure 6. They are as follows:

**Figure 6**

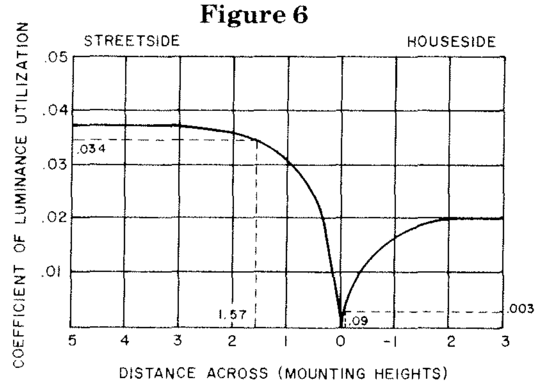
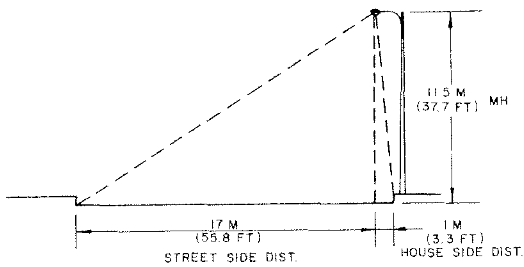


Figure 7




a. Street Side (SS) ratio which is the distance at pavement level from a point directly under the luminaire to the far edge of the pavement related to the mounting height (MH). This is 17/11.5 = 1.48.

b. House Side (HS) ratio which is a similar ratio from the same point to the near edge of the pavement. This is 1/11.5 = 0.09.

Using these ratios the SS coefficient and HS coefficient are read from the curve, added, and used in the formula below. From Figure 6 the coefficients are SS = 0.034; HS = 0.003; and the total is 0.037

Spacing =

$$\frac{\text{Lp. Lumens} \times \text{No. of Luminaires} \times \text{CofU}}{L_{avg} \times \text{Width}} =$$

$$\frac{22000 \times 1 \times .037}{1.14 \times 18} = 40$$

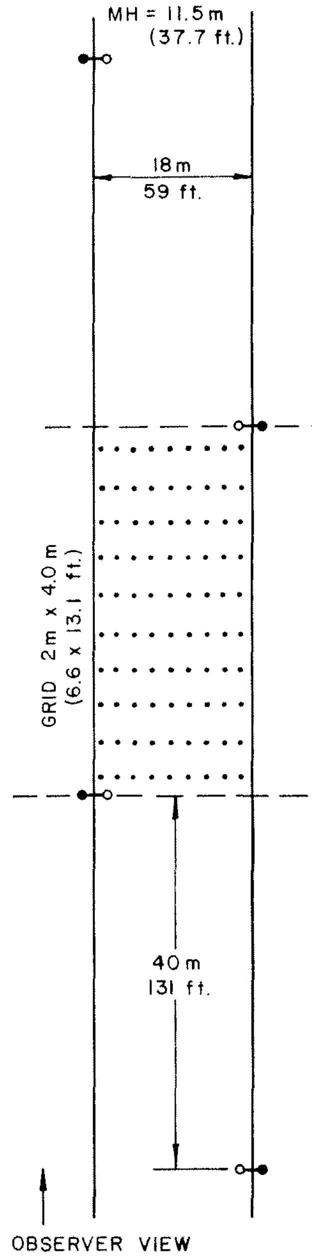
Substituting values results in a calculated spacing of 40m (131 ft). Note that the initial level is being used as there is no Light Loss Factor in the formula.

## EVALUATION OF A TENTATIVE DESIGN

The first tentative design for a system to light the 18 m (59 ft) wide street of our Example Problem is now complete and is shown in Figure 8. It is now time to evaluate that design. Let us assume that we have access to a computer program and utilize it to do the necessary calculations.

**Step 1. Selection of a grid.** For a discussion of grid selection refer to Appendix A. The grid selected is shown in Figure 8 and is 2m × 4m

Figure 8




and consists of 90 points. To calculate manually the pavment luminance at each of the 90 points requires a great deal of time but can be done by a computer in a few seconds of calculation time. In this example a computer print out will be shown and the alternate method of manual evaluation discussed in each step. A grid is required for both methods.

# TABLE IV
# SUMMARY LISTING FOR FIRST EVALUATION

| | |
|---|---|
| Street Width — 18 m (59 ft) | Photometrics — Fig. 5 |
| Mtg. Height — 11.5 m (37.7 ft) | Arrangement — Stagg. |
| Overhang — 1 m (3.3 ft) | Luminaire Level |
| Spacing — 40 m (131 ft) | |

| | DESIRED INITIAL | | | CALCULATED INITIAL | |
|---|---|---|---|---|---|
| Criteria | Value | Max Ratio | | Value | Max Ratio |
| Avg. Pav. Lum. | 1.14 | — | | 1.06 | — |
| Min. Pav. Lum. | .38 | 3 | Avg/Min | .31 | 3.4 |
| Max. Pav. Lum. | 1.9 | 5 | Max/Min | 1.95 | 6.3 |
| Max. Veiling Lum. | .46 | 0.4 | Lv/Lavg | .25 | 0.24 |

**Step 2. Determine Average Luminance.** A computer printout of the grid with pavement luminance values is shown in Figure 9. The average pavement luminance ($L_{avg}$) is the average of all these points provided the grid has been properly chosen so that each reading is the value at the center of equal area rectangles. If not, each value must be weighted according to the area of its rectangle. See Appendix E.

*Alternate Manual Method.* The average pavement luminance calculated from the formula and Coefficients of Luminance Utilization as shown in Step 5 above can be used or a similar calculation made as shown in Appendix E. Note that the agreement between the graphical method and the computer printout of this example is not perfect. Agreement to about 5 to 10% can be expected from such small scale curves.

**Step 3. Determine Avg to Min Ratio.** The location of the minimum luminance grid point on the printout can be determined by inspection and the ratio calculated. Most printouts also list this ratio. It is advisable to locate the actual minimum point to better visualize what corrective action, if any, needs to be taken.

*Alternate Manual Mehod.* The most likely location of the minimum luminance point for various configurations is discussed on page 30. The luminance of this most likely point can be calculated using the graphical method as shown on page 22. The ratio can then be easily calculated.

**Step 4. Determine Max to Min Ratio.** The location and value of the maximum luminance point can be found on the computer printout and ratio calculated.

*Alternate Manual Method.* The single luminaire maximum point value and location shown on the photometric curve as used in selecting the luminaire and lamp locates this point accurately and gives the value for the dominant luminaire contribution. For many evaluations this value, which is normally about 90% of the system maximum is all that is required to determine acceptability of the system. The most likely location of the maximum pavement luminance of the system is discussed on page 30.

**Step 5. Determine Max—$L_v$** and Ratio. Some computer programs search for and print out only the maximum value of $L_v$ while others print out a value of $L_v$ for the observer as if he was located at some place related to each of the grid points. An example of the latter is shown in Figure 10. The maximum point is then found by inspection and the ratio computed.

*Alternate Manual Method.* The single luminaire maximum point value and location shown on the photometric curve

## Figure 9

FIRST EVALUATION
STAGG SPACING 10 LUMINAIRES

**** PAVEMENT LUMINANCE ( CD /SQ. M. ) FOR R3 CIE ROAD SURFACE ****

VALUES ARE NORMALIZED TO A Q-ZERO VALUE OF 0.07
OBSERVER VIEWS NORTH
VIEWING ANGLE = 1.0 DEGREE BELOW HORIZONTAL

| Y CO-ORD. METERS | 1.0 | 3.0 | 5.0 | 7.0 | 9.0 | 11.0 | 13.0 | 15.0 | 17.0 |
|---|---|---|---|---|---|---|---|---|---|
| 38.0 | 0.66 | 0.59 | 0.52 | 0.78 | 1.06 | 1.38 | 1.49 | 1.38 | 1.18 |
| 34.0 | 0.31 | 0.62 | 0.58 | 0.74 | 0.98 | 1.39 | 1.73 | 1.91 | 1.64 |
| 30.0 | 0.48 | 0.63 | 0.66 | 0.71 | 0.92 | 1.15 | 1.28 | 1.51 | 1.59 |
| 26.0 | 0.50 | 0.60 | 0.68 | 0.72 | 0.85 | 1.00 | 1.19 | 1.62 | 1.78 |
| 22.0 | 0.50 | 0.57 | 0.65 | 0.68 | 0.79 | 0.97 | 1.25 | 1.57 | 1.75 |
| 18.0 | 0.49 | 0.57 | 0.65 | 0.71 | 0.84 | 1.02 | 1.41 | 1.74 | 1.83 |
| 14.0 | 0.60 | 0.66 | 0.71 | 0.81 | 0.95 | 1.13 | 1.44 | 1.80 | 1.95 |
| 10.0 | 0.68 | 0.74 | 0.79 | 0.89 | 0.98 | 1.10 | 1.42 | 1.77 | 1.78 |
| 6.0 | 1.00 | 1.22 | 1.23 | 1.20 | 1.08 | 1.05 | 1.30 | 1.51 | 1.32 |
| 2.0 | 1.00 | 1.21 | 1.37 | 1.32 | 1.12 | 0.97 | 0.95 | 1.03 | 0.96 |

X CO-ORDINATE - METERS

TABLE IS NOT TO SCALE

| LONGITUDINAL MAX/MIN: | 3.2 | 2.1 | 2.6 | 1.9 | 1.4 | 1.4 | 1.8 | 1.9 | 2.0 |
|---|---|---|---|---|---|---|---|---|---|

AVERAGE CD /SQ. M. = 1.06

MAXIMUM CD /SQ. M. = 1.95

MINIMUM CD /SQ. M. = 0.31

MAX./MIN. RATIO = 6.2 : 1

AVG./MIN. RATIO = 3.4 : 1

## Figure 10

FIRST EVALUATION
STAGG SPACING 10 LUMINAIRES

DISABILITY GLARE (VEILING LUMINANCE IN CD. /SQ. M. X 100)
FOR POINTS 1.45 METERS ABOVE PAVEMENT LEVEL
OBSERVER VIEWS NORTH

| Y CO-ORD. METERS | 1.0 | 3.0 | 5.0 | 7.0 | 9.0 | 11.0 | 13.0 | 15.0 | 17.0 |
|---|---|---|---|---|---|---|---|---|---|
| 38.0 | 8.81 | 8.82 | 8.70 | 8.61 | 8.71 | 9.76 | 9.25 | 7.25 | 5.53 |
| 34.0 | 6.5 | 9.4 | 11.6 | 9.5 | 8.4 | 11.2 | 12.5 | 12.3 | 10.2 |
| 30.0 | 5.5 | 7.7 | 10.0 | 9.7 | 10.2 | 12.3 | 12.8 | 12.9 | 12.1 |
| 26.0 | 5.1 | 7.3 | 9.1 | 9.7 | 10.8 | 12.8 | 14.9 | 16.2 | 14.8 |
| 22.0 | 4.6 | 6.6 | 8.9 | 10.7 | 12.6 | 14.8 | 17.8 | 19.1 | 18.2 |
| 18.0 | 4.6 | 6.7 | 9.3 | 12.5 | 16.1 | 19.4 | 22.6 | 22.0 | 21.2 |
| 14.0 | 4.8 | 7.0 | 9.7 | 13.1 | 16.5 | 20.7 | 24.1 | 24.9 | 21.8 |
| 10.0 | 4.9 | 7.0 | 10.1 | 14.1 | 18.0 | 20.7 | 23.4 | 23.3 | 16.9 |
| 6.0 | 5.1 | 7.0 | 9.5 | 13.1 | 15.4 | 16.4 | 15.7 | 14.9 | 13.2 |
| 2.0 | 4.8 | 6.4 | 8.7 | 11.6 | 11.5 | 10.2 | 6.2 | 7.2 | 12.0 |

X CO-ORDINATE - METERS

TABLE IS NOT TO SCALE

AVERAGE = 11.99

MAXIMUM = 24.93

MINIMUM = 4.60

MAX/MIN RATIO = 5.4 :1

AVG/MIN RATIO = 2.6 :1

** ALL DISABILITY GLARE VALUES HAVE BEEN MULTIPLIED BY 100 **

**TABLE V**
**EFFECT OF LUMINAIRE LOCATION CHANGE**

| | $L_{avg}$ | $L_{min}$ | $L_{max}$ | $M_{ax}$ $L_v$ |
|---|---|---|---|---|
| Decrease Spacing | II | II | I | I |
| Increase Overhang | II | II | — | — |
| Decrease Mounting Height | I | DD | II | I |
| Increase Lamp Size | I | I | I | I |
| CO to SCO Classification | D | — | — | I |
| SCO to NCO Classification | D | I | — | I |
| Short to Med. Classification | D | II | D | I |
| Med. to Long Classification | D | I | D | I |
| Staggered to Opposite Arrangement | — | D | — | D |

I Increase in absolute value.
D Decrease in absolute value.
II or DD Faster increase or decrease than single letter.
— Little or no change with moderate variation.

as used in the selection of the luminaire and lamp locates this point accurately and gives the value for the dominant luminaire contribution. For many evaluations this value, which is normally about 95% of the system maximum is all that is required to determine acceptability of the system. The most likely location of the maximum veiling luminance of the system is discussed on page 30 and a method of calculation is given in Appendix G.

**Step 6. Summary Listing:** The values of the criteria, and the values and ratios found for the tentative system should be listed in a table and studied before proceeding to the next topic. Such a table for the example is shown in Table IV. Note that the tentative design fails in terms of meeting the criteria. It fails in two of the ratio requirements and is about 7% deficient in terms of the average pavement luminance.

## IMPROVEMENT OF A TENTATIVE DESIGN

Table V lists the effects of changing the variables affecting the location of the luminaires of the system. Using the data of Table IV and the principles shown in Table V the options for improving the tentative design, *regardless of whether or not the criteria are met*, should be listed and considered. In the case of the example, first priority should be given to increasing the average pavement luminance while improving the ratios of avg/min and max/min. It is important to correct the average luminance before correcting the ratios. From Table V consideration should be given to those factors which cause an increase (I or II) in the column labeled "$L_{avg}$". They are: Decrease Spacing, Increase Overhang, Decrease Mounting Height, and Increase Lamp Size. Each option will be discussed below.

- ***Option 1.*** Decrease the spacing. More poles per mile would increase capital equipment and maintenance costs. It will increase $L_{avg}$, increase $L_{max}$ slightly, increase $L_{min}$ and increase $L_v$ very slightly. The ratios will improve.
- ***Option 2.*** Increase Overhang. Longer mast arms will increase the capital costs. If the poles are set close to the curb this may not be significant since the tentative overhang was only 1 m (3.3 ft). An increase in the overhang will increase $L_{avg}$, increase $L_{min}$

have little effect on $L_{max}$, and have little effect on $L_v$. Ratios will improve.

- ***Option 3.*** Decrease the mounting height. This would reduce capital equipment costs. It would increase $L_{avg}$, increase $L_{max}$ (which might cause it to exceed the criteria ratio), reduce $L_{min}$, and increase $L_v$. Ratios will become worse.
- ***Option 4. Increase Lamp Size.*** Using a larger lamp does not usually change luminaire output uniformly in proportion to the ratio of the change in lamp lumens. Modern "arc tube lamps" such as mercury, medal halide, HPS and LPS change the dimensions of the arc tube to change lamp output (and wattage). This changes the relative distribution of light from the luminaire. In general all luminance values will increase and ratios will tend to remain relatively constant.
- ***Option 5.*** Select a different luminaire and light source. Such a selection should be made with the expectation that the changes in luminaire distribution will improve both the absolute value of $L_{avg}$ and the ratios. The present system of luminaire classification is of little help in selecting an improved luminaire in these terms. This subject is discussed on page 20. In this example it will be assumed that no more likely candidate luminaire can be found.

The luminaire spacing of the tentative design is 40m (131 ft) more than enough to allow for a cross street of normal width between pole locations. If this were not the case then the configuration would have to be changed to opposite to allow the normal pole spacing to "jump" the cross street. The tentative system design is reasonably close to the criteria so Option 2 will be selected and tried. In some cases changes in more than one parameter will have to be made but unless one has considerable experience it is best to change only one parameter at a time.

Since the coefficient of utilization curve is steeper on the HS than on the SS (for the ratios being used) we know that $L_{avg}$ can be improved by increasing the overhang (less luminance will be lost on the SS than will be gained on the HS). The present overhang is 1 m (3.3 ft). Let us consider the effect of a 2 m (6.6 ft) overhang. From an inspection of the curve (Fig. 6) it can be seen that increasing the HS ratio by 0.1 and decreasing the SS ratio a like amount will result in a CofU change of about 10%, see below:

| Present | CofU | Proposed | CofU |
|---|---|---|---|
| HS ratio of 0.1 | 0.003 | HS Ratio of 0.2 | 0.008 |
| SS ratio of 1.48 | 0.034 | HS Ratio of 1.39 | 0.033 |
| TOTAL | 0.037 | TOTAL | 0.041 |

This is an increase of 11% in coefficent of utilization and should allow a slight increase in spacing and an experienced designer would undoubtedly increase the spacing at the same time that the overhang is increased. In this example, only one parameter at a time will be changed so that the effects of each can be observed. The second tentative design and its summary evaluation data is shown in Table VI. The pavement luminance values from the computer are as shown in Fig. 11.

The summary data indicates that the changes made in the overhang from 1 to 2 meters was successful in improving the system design. All ratios are now better than required by the criteria and the average pavement luminance has been increased by 9% (from 1.06 to 1.16). It is now possible to increase the spacing slightly by the ratio of the criteria desired (1.14) divided by the achieved value (1.16) to the present spacing (40) divided by the desired spacing (s).

$$\frac{1.14}{1.16} = \frac{40}{s} \qquad s = 41 \text{ m } (134.5 \text{ ft})$$

The proportional method used above gives better accuracy than using the small scale CofU curve of Fig. 5b.

A third evalulation can now be made and Table VII gives both the design paramerters and calculated luminance values. A computer print out of this design is not shown. It should be realized that incremental increases in the overhang will permit incremental increases in the spacing until the optimum overhang is reached. The optimum overhang will occur when the incremental gain in CofU on the House Side is exactly offset by the incremental loss on the Street Side. This is the point where the slope of the two curves is equal. The designer must also consider the costs of increasing the mast arm

## Figure 11

SECOND EVALUATION
STAGG SPACING 10 LUMINAIRES

**** PAVEMENT LUMINANCE ( CD /SQ. M. ) FOR R3 CIE ROAD SURFACE ****

VALUES ARE NORMALIZED TO A Q-ZERO VALUE OF 0.07
OBSERVER VIEWS NORTH
VIEWING ANGLE = 1.0 DEGREE BELOW HORIZONTAL

| Y CO-ORD. METERS | 1.0 | 3.0 | 5.0 | 7.0 | 9.0 | 11.0 | 13.0 | 15.0 | 17.0 |
|---|---|---|---|---|---|---|---|---|---|
| 38.0 | 0.75 | 0.76 | 0.66 | 0.87 | 1.22 | 1.49 | 1.57 | 1.32 | 1.16 |
| 34.0 | 0.53 | 0.62 | 0.74 | 0.82 | 1.25 | 1.57 | 1.90 | 1.85 | 1.42 |
| 30.0 | 0.51 | 0.65 | 0.75 | 0.89 | 1.14 | 1.29 | 1.35 | 1.67 | 1.55 |
| 26.0 | 0.49 | 0.63 | 0.75 | 0.86 | 1.01 | 1.13 | 1.42 | 1.84 | 1.80 |
| 22.0 | 0.49 | 0.59 | 0.70 | 0.79 | 0.94 | 1.14 | 1.44 | 1.74 | 1.63 |
| 18.0 | 0.50 | 0.62 | 0.71 | 0.83 | 0.99 | 1.25 | 1.62 | 1.86 | 1.66 |
| 14.0 | 0.62 | 0.72 | 0.79 | 0.91 | 1.10 | 1.33 | 1.69 | 2.01 | 1.69 |
| 10.0 | 0.69 | 0.79 | 0.83 | 0.99 | 1.17 | 1.35 | 1.69 | 1.94 | 1.59 |
| 6.0 | 0.89 | 1.17 | 1.33 | 1.32 | 1.32 | 1.29 | 1.56 | 1.58 | 1.25 |
| 2.0 | 1.01 | 1.15 | 1.44 | 1.43 | 1.28 | 1.15 | 1.12 | 1.12 | 0.93 |

X CO-ORDINATE - METERS

TABLE IS NOT TO SCALE

| LONGITUDINAL MAX/MIN: | 2.1 | 2.0 | 2.2 | 1.8 | 1.4 | 1.4 | 1.7 | 1.8 | 1.9 |
|---|---|---|---|---|---|---|---|---|---|

AVERAGE CD /SQ. M. = 1.16

MAXIMUM CD /SQ. M. = 2.01

MINIMUM CD /SQ. M. = 0.49

MAX./MIN. RATIO = 4.1 : 1

AVG./MIN. RATIO = 2.4 : 1

## TABLE VI
## SUMMARY LISTING FOR SECOND EVALUATION

| | |
|---|---|
| Street Width — 18 m (59 ft) | Photometrics — Fig. 5 |
| Mtg. Height — 11.5 m (37.7 ft) | Arrangement — Stagg. |
| Overhang — 2 m (6.6 ft) | Luminaire Level |
| Spacing — 40 m (131 ft) | |

| Criteria | DESIRED INITIAL Value | DESIRED INITIAL Max Ratio | | CALCULATED INITIAL Value | CALCULATED INITIAL Max Ratio |
|---|---|---|---|---|---|
| Avg. Pav. Lum. | 1.14 | — | | 1.16 | — |
| Min. Pav. Lum. | .38 | 3 | Avg/Min | .49 | 2.4 |
| Max. Pav. Lum. | 1.9 | 5 | Max/Min | 2.01 | 4.1 |
| Max. Veiling Lum. | .46 | 0.4 | Lv/Lavg | .25 | 0.22 |

## TABLE VII
## SUMMARY LISTING FOR THIRD EVALUATION

| | |
|---|---|
| Street Width — 18 m (59 ft) | Photometrics — Fig. 5 |
| Mtg. Height — 11.5 m (37.7 ft) | Arrangement — Stagg. |
| Overhang — 2 m (6.6 ft) | Luminaire Level |
| Spacing — 41 m (134.5 ft) | |

| Criteria | DESIRED INITIAL Value | DESIRED INITIAL Max Ratio | | CALCULATED INITIAL Value | CALCULATED INITIAL Max Ratio |
|---|---|---|---|---|---|
| Avg. Pav. Lum. | 1.14 | — | | 1.13 | — |
| Min. Pav. Lum. | .38 | 3 | Avg/Min | .47 | 2.4 |
| Max. Pav. Lum. | 1.9 | 5 | Max/Min | 2.0 | 4.1 |
| Max. Veiling Lum. | .46 | 0.4 | Lv/Lavg | .25 | 0.22 |

length (and possibly pole shaft strength) as opposed to the reduced number of luminaires and poles per mile.

It is now important to look at how the tentative design can be adapted to commercially available product. Pole heights come in definite increments and we find poles that provide 30, 35, and 40 ft mounting heights but none that provide 37.7 ft. In a like manner we find mast arms with lengths of 6, 8, 10, and 12 ft. It should also be noted that the light center of the luminaire will be about 12 inches beyond the end of the mounting tennon of the mast arm (Fig. 5a), and other factors in the total design dictate that the poles will be placed 2 ft from the edge of the pavement. Our calculations have indicated that to reduce the mounting height to 35 ft would mean exceeding the min to max ratio of luminance. One possibility is to use a lower wattage lamp and luminaire with attendent closer spacings and more poles per mile which is not desirable. Raising the mounting height to 40 ft is thus necessary in order to use a commercially available pole. From Table V and our previous experience we know

## TABLE VIII
## SUMMARY LISTING FOR FOURTH EVALUATION

Street Width — 18 m (59 ft)
Mtg. Height — 12.19 m (40 ft)
Overhang — 2.74 m (9 ft)
Spacing — 41 m (134.5 ft)

Photometrics — Fig. 5
Arrangement — Stagg.
Luminaire Level

| Criteria | DESIRED INITIAL Value | DESIRED INITIAL Max Ratio | | CALCULATED INITIAL Value | CALCULATED INITIAL Max Ratio |
|---|---|---|---|---|---|
| Avg. Pav. Lum. | 1.14 | — | | 1.15 | — |
| Min. Pav. Lum. | .38 | 3 | Avg/Min | .49 | 2.3 |
| Max. Pav. Lum. | 1.9 | 5 | Max/Min | 1.84 | 3.8 |
| Max. Veiling Lum. | 0.4 | 0.4 | Lv/Lavg | .22 | 0.19 |

this will reduce the average luminance slightly. With this is mind let us look at the mast arm length. A mast arm length of 10 ft will mean an actual overhang of 9 ft (10 ft arm − 2 ft from the curb + 1 foot added by the luminaire). This added length (the third tentative design used an overhang of 2 m (6.6 ft) should offset the rise in mounting height up to 40 ft, in its effect on average luminance. This then will be the fourth tentative design which, if it meets the criteria, will become the final design. Figure 12 shows a print out of the pavement luminance for this design and table VIII shows the results of the evaluation of the fourth tentative design. It exceeds all ratio criteria and meets the average pavement luminance requirement. It thus becomes the final design.

It is worthwhile to evaluate the system maximum pavement luminance as shown in Table VIII of 1.84 and compare it to the single luminaire $L_{max}$ as shown on the photometric data sheet (1.63 when corrected for MH) and realize that it is 89% of the system maximum. Likewise the single luminaire max $L_v$ of .215 (when corrected for MH) is 97% of the system maximum of .22 as shown in the same table.

## VARIOUS MEANS OF OBTAINING EVALUATION DATA

There are three means of obtaining data for evaluating a tentative or final design:

- Computer printout
- Graphical from specialized data presentations.
- Manual calculations from candlepower data.

Each will be discussed in turn and examples used so that a comparison of the difficulty and accuracy is shown.

***Computer printout.*** All of the evaluations used in the examples thus far have used the computer printout method. Such printouts are shown in Figures 9, 10, 11 and 12. At this time all known programs require inputs of the selections of Step 2, 3, 4, and 5 of the "Procedure for Creating a Tentative Design" plus selection of the grid. The luminaire photometric data, in terms of a candela table (see Appendix C), must be entered or be accessed from a photometric data base available to the computer. True "design" programs that will select the best luminaire and its best location are not yet available.

***Graphical.*** Two special photometric data presentations are required to evaluate a tentative design by this method. A background discussion on photometric presentations is contained in Appendix C.

The "Coefficient of Utilization for Luminance Curve" is shown in Figure 6 and its use was described in Step 5 of the "Procedure for Creating a Tentative Design" to determine the

**Figure 12 Pavement Luminance — Fourth Evaluation**

| Y CO-ORD. METERS | 1.0 | 3.0 | 5.0 | 7.0 | 9.0 | 11.0 | 13.0 | 15.0 | 17.0 |
|---|---|---|---|---|---|---|---|---|---|
| 38.9 | 0.77 | 0.92 | 0.96 | 1.08 | 1.35 | 1.44 | 1.35 | 1.17 | 1.04 |
| 34.8 | 0.70 | 0.63 | 0.80 | 0.93 | 1.31 | 1.60 | 1.81 | 1.58 | 1.11 |
| 30.7 | 0.57 | 0.61 | 0.81 | 0.96 | 1.15 | 1.26 | 1.46 | 1.53 | 1.31 |
| 26.6 | 0.51 | 0.65 | 0.79 | 0.96 | 1.04 | 1.12 | 1.46 | 1.70 | 1.49 |
| 22.5 | 0.49 | 0.60 | 0.72 | 0.88 | 1.02 | 1.22 | 1.45 | 1.60 | 1.38 |
| 18.4 | 0.52 | 0.64 | 0.75 | 0.87 | 1.04 | 1.35 | 1.59 | 1.70 | 1.36 |
| 14.3 | 0.61 | 0.74 | 0.83 | 0.95 | 1.16 | 1.43 | 1.68 | 1.84 | 1.34 |
| 10.2 | 0.66 | 0.79 | 0.90 | 1.01 | 1.22 | 1.50 | 1.76 | 1.79 | 1.31 |
| 6.1 | 0.76 | 1.06 | 1.30 | 1.35 | 1.40 | 1.52 | 1.64 | 1.54 | 1.18 |
| 2,0 | 0.93 | 1.03 | 1.25 | 1.42 | 1.44 | 1.45 | 1.40 | 1.12 | 0.89 |

X CO-ORDINATE - METERS

TABLE IS NOT TO SCALE

| LONGITUDINAL MAX/MIN: | 1.9 | 1.8 | 1.8 | 1.6 | 1.4 | 1.4 | 1.3 | 1.6 | 1.7 |
|---|---|---|---|---|---|---|---|---|---|

AVERAGE CD /SQ. M. = 1.15

MAXIMUM CD /SQ. M. = 1.84

MINIMUM CD /SQ. M. = 0.49

MAX./MIN. RATIO = 3.8 : 1

AVG./MIN. RATIO = 2.4 : 1

spacing between poles. To determine the average pavement luminance during the evaluation process the same general procedure is used except the formula is as follows:

$$L_{avg} = \frac{\text{Lp. Lumens} \times \text{No. of Luminaires} \times \text{CofU} \times (\text{LLF})}{\text{Area}}$$

The use of LLF (light loss factor) in the above formula is optional. If LLF is not used then the result will be initial luminance. The result is given in Cd/SqM if width and spacing (area) are in meters. This can then be converted to Footlamberts (fL) if desired but the result of the calculation will not be fL if feet are used for the width and spacing. The accuracy of the calculation will depend on the scale of the data presentation and the care used in reading the curve but will usually be within 10% of a computer printout.

An isoluminance plot, shown on Figure 5b, (also occasionally called an isonit plot) is required for graphically determining the luminance at a point. Figure 13 is the same isoluminance plot as the one shown on the curve of Figure 5 except it has been extracted for easier reference. In this example we will use a luminaire arrangement as shown on Figure 14, and will calculate the luminance of point P. Figure 14 shows, on the left, a relativly long stretch of the roadway with 10 luminaires and the location of the grid area. Note that the grid area is located between luminaires #2 and #7 since the contributions of luminaires to pavement luminance are greater from the luminaires beyond the grid area than from those on the same side of the grid as the observer. On the right side of Figure 14 there is an enlarged view of the grid area. Note that the X axis of the coordinate system is directly under luminaire #2 and the Y axis is located along the left edge of the pavement. The location of the axes is purely arbitrary but this is a convenient location and often used. The Z axis is perpendicular to the plane of the paper and located at the 0,0 intersection of the X and Y axis. (Appendix B)

The isoluminance plot (Fig.13) is not symmetrical about the luminaire location "L" (on Fig. 5b this mfg. shows it as "P") and the four quadrants are identified from the fact they are either on the "house side" (HS) or "street side" (SS) of the luminaire or "upstream" (US) (towards the observer) or "downstream" (DS) of the luminaire. The location of each luminaire and the pavement point (P) (see Fig. 14) is tabulated as follows:

| | | | |
|---|---|---|---|
| Point P | x=1<br>y=34.8<br>z=0 | Lum. 6 | x=15.3<br>y=−41<br>z=12.19 |
| Lum. 1 | x=2.7<br>y=−82<br>z=12.19 | Lum. 7 | x=15.3<br>y=41<br>z=12.19 |
| Lum. 2 | x=2.7<br>y=0<br>z=12.19 | Lum. 8 | x=15.3<br>y=123<br>z=12.19 |
| Lum. 3 | x=2.7<br>y=82<br>z=12.19 | Lum. 9 | x=15.3<br>y=205<br>z=12.19 |
| Lum. 4 | x=2.7<br>y=164<br>z=12.19 | Lum. 10 | x=15.3<br>y=287<br>z=12.19 |
| Lum. 5. | x=2.7<br>y=146<br>z=12.19 | | |

Next the ratios to locate the grid point will be calculated in terms of the HS, SS, US, and DS of each luminaire. The sequence will be in terms of the probability that the luminaire will contribute a significant amount of light to the grid point. As the two ratios are calculated the location of the point relative to each luminaire for example $P_1$, $P_2$, etc. should be plotted onto Figure 13. It will become apparent as this is done that not all ten of the points can be plotted on the diagram and those that cannot, of course contribute an insignificant amount to the total luminance at point P.

For Luminaire #2:

$$HS = \frac{P_x - L_x}{L_z} = \frac{1 - 2.7}{12.19} = -.14$$

$$DS = \frac{P_y - L_y}{L_z} = \frac{34.8 - 0}{12.19} = 2.85$$

For Luminaire #7:

$$SS = \frac{L_x - P_x}{L_z} = \frac{15.3 - 1}{12.19} = 1.17$$

$$US = \frac{P_y - L_y}{L_z} = \frac{34.8 - 41}{12.19} = -0.51$$

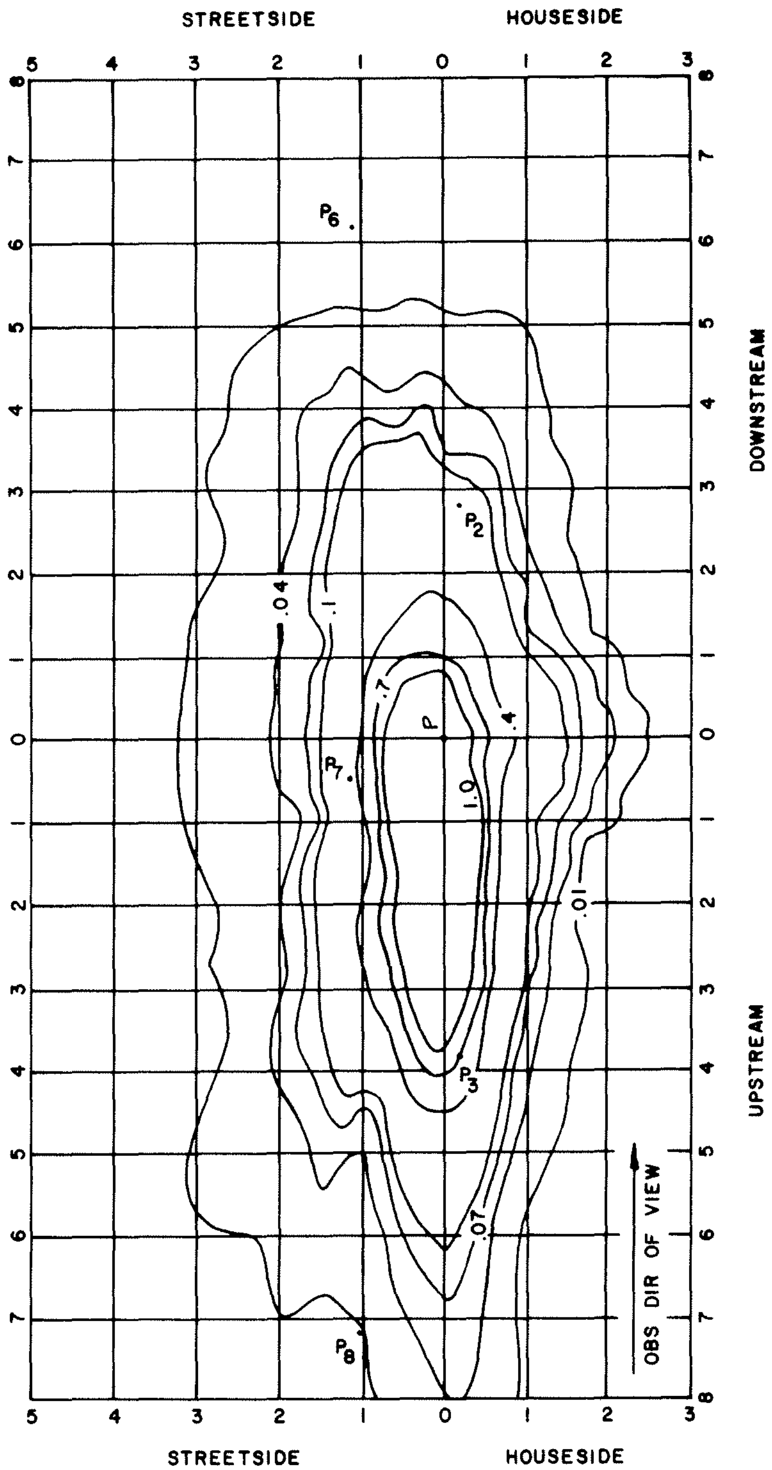



**Figure 13 Isoluminance Plot**

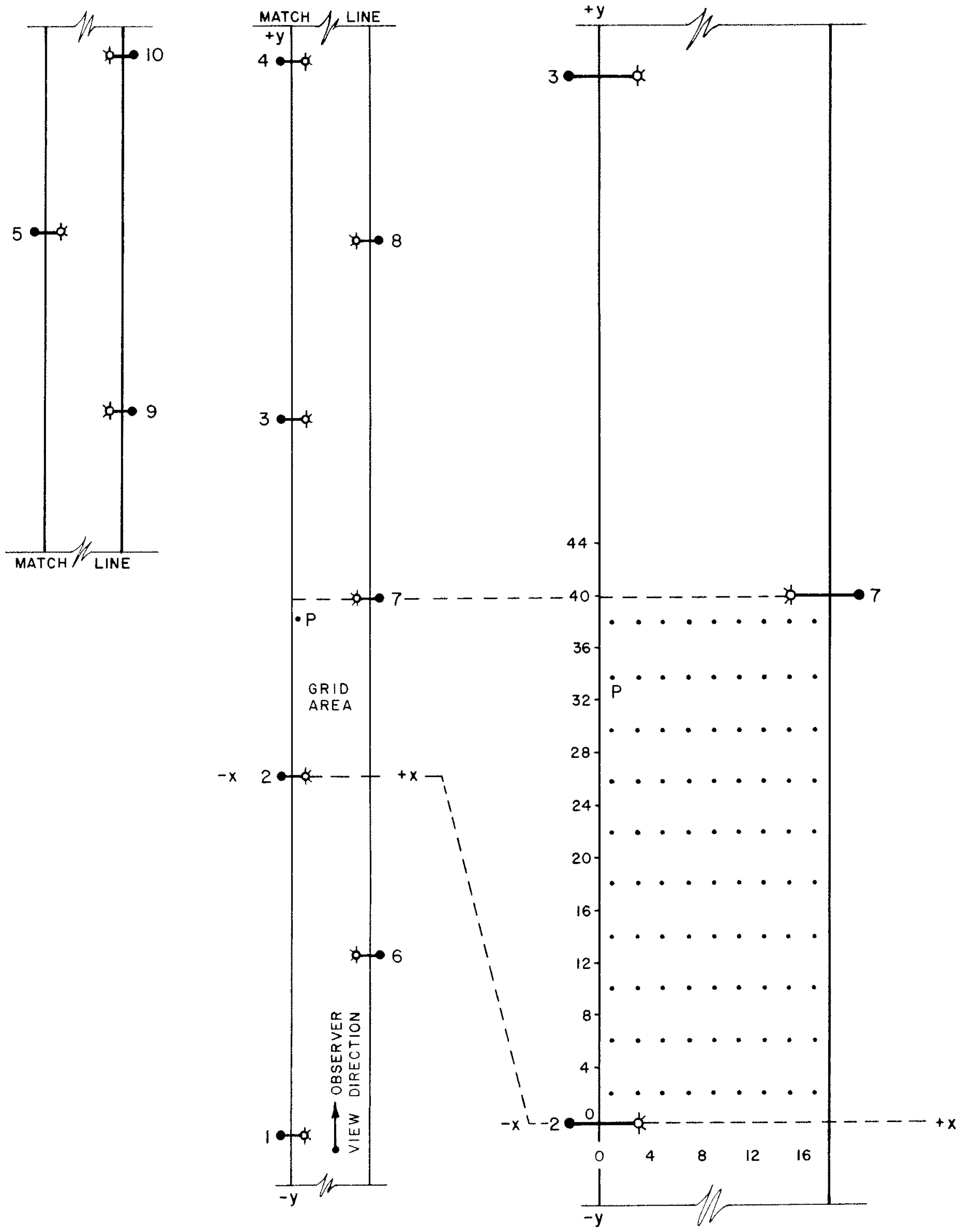



Figure 14 Luminaire and Grid Locations — Final Design

For Luminaire #3:

$$HS = \frac{P_x - L_x}{L_z} = \frac{1 - 2.7}{12.19} = -.14$$

$$US = \frac{P_y - L_y}{L_z} = \frac{34.8 - 82}{12.19} = -3.87$$

For Luminaire #6:

$$SS = \frac{L_x - P_x}{L_z} = \frac{15.3 - 1}{12.19} = 1.17$$

$$DS = \frac{P_y - L_y}{L_z} = \frac{34.8 + 41}{12.19} = 6.22$$

For Luminaire #8:

$$SS = \frac{L_x - P_x}{L_z} = \frac{15.3 - 1}{12.19} = 1.17$$

$$US = \frac{P_y - L_y}{L_z} = \frac{34.8 - 123}{12.19} = -7.24$$

For Luminaire #4:

$$HS = \frac{P_x - L_x}{L_z} = \frac{1 - 2.7}{12.19} = -.14$$

$$US = \frac{P_y - L_y}{L_z} = \frac{34.8 - 164}{12.19} = -11.42$$

After the points $P_1$ thru $P_6$ are plotted on Figure 13 the values should be read from the plot and listed as follows:

Luminance at $P_2$ = 0.17

Luminance at $P_7$ = 0.35

Luminance at $P_3$ = 0.70

Luminance at $P_6$ = — cannot be read.

Luminance at $P_8$ = 0.01

Luminance at $P_4$ = — point falls off plot.

TOTAL 1.23 × .56 = .69

A correction factor for mounting height of 0.56 has been applied since the isoluminance plot from the data sheet (Fig. 5) was created for a 9.1 m (30 ft) mounting height and we are using a 12.19 m (40 ft) mounting height. The graphical calculation of the pavement luminance at grid point X = 1, Y = 34.8 is 0.69 Cd/SqM while the computer printout (Figure 12) shows 0.70 for the same point which is excellent agreement, much better than normally expected. It is interesting to analize the relative contributions of the various luminaires to the total luminance of this grid point. Luminaire #3 is by far the largest contributer even though it is much more distant than Luminaire #7 which contributes only half as much to the total.

**Manual Calculations.** Manual calculations use the formula first shown on Pg. 3 and are based on the assumption that an engineering calculator with trig functions and at least one memory is available. It is also necessary to have some photometric data for the luminaire available, preferably the candela table (Fig. 15) although a conventional Isolux or Isofootcandle chart can be used with some additional loss of accuracy. The method to be described can be adapted to a computer program or to a programable hand held calculator.

The method uses a work sheet with column headings, Figure 16. In the first five columns at the left of the page enter the x, y, z coordinates of the point on the pavement and the luminaire as called for at the top of the column. Then fill out each column in turn, using the formula at or referenced by the column heading. The work sheet is so designed that each column can be calculated with a one memory engineering calculator with no additional written notes required. Angles are denoted by greek letters and their relationship to the pavement point and luminaire are shown in Fig. 1. After angles Gamma ($\gamma$), Beta ($\beta$), and Phi ($\phi$) are calculated it is necessary to use the candela table and angles $\gamma$ and $\phi$ to find the light intensity (I) in candepower, and angle $\beta$ and tangent $\gamma$ with the proper R-Table to find the reduced coefficient of reflectance (r). These tables for the four classifications of pavement are printed at the end of this chapter. Interpolation is usually necessary with both tables if accuracy is to be achieved.

After entering the Cp. and r values into their respective columns then fill out the remaining column and determine the luminance. The first few lines of the work sheet are filled out with the calculation of luminance for the same grid point (X =1, Y = 34.8) and Luminaire as was used in the graphical example. The sum of the luminaces is also shown on the work sheet. These can be compared with the luminances as found by the graphical method. In the event a candela table is not available for the luminaire that you wish to use, candlepower can be calculated from the illuminance (incident light) value of footcandles taken from an isofootcandle

Figure 15

## CANDELA TABLE for EXAMPLE LUMINAIRE

| DEG H<br>deg v | 0.0 | 5 | 15 | 25 | 35 | 45 | 55 | 65 | 75 | 85 | 90 | 95 | 105 | 115 | 125 | 135 | 145 | 155 | 165 | 175 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 | 4193 |
| 5.0 | 4960 | 4560 | 5011 | 4150 | 5001 | 4283 | 4581 | 4242 | 4191 | 4140 | 4191 | 4212 | 4150 | 4171 | 4119 | 4119 | 4171 | 4140 | 4263 | 4119 | 4283 |
| 10.0 | 5226 | 5165 | 5257 | 5093 | 5124 | 5124 | 5021 | 4263 | 4222 | 4181 | 4150 | 4212 | 4140 | 4201 | 4212 | 4242 | 4099 | 4263 | 4140 | 4119 | 4201 |
| 15.0 | 6087 | 5195 | 5575 | 5195 | 5267 | 5308 | 5236 | 5185 | 5093 | 4990 | 4704 | 4550 | 4191 | 4171 | 3996 | 3699 | 3218 | 3576 | 3074 | 4017 | 3177 |
| 20.0 | 6333 | 6169 | 6271 | 6118 | 6292 | 6189 | 6118 | 5657 | 5216 | 4755 | 5021 | 4622 | 4119 | 3658 | 3207 | 3146 | 3115 | 3197 | 3136 | 3115 | 3177 |
| 25.0 | 7317 | 6702 | 6702 | 6610 | 7173 | 7009 | 6271 | 6241 | 6169 | 5626 | 5185 | 5134 | 4140 | 3525 | 3074 | 2992 | 2213 | 2705 | 2644 | 3095 | 3177 |
| 30.0 | 7214 | 7142 | 6732 | 6732 | 7255 | 7214 | 7296 | 7265 | 7163 | 6138 | 6220 | 5728 | 4519 | 3187 | 2941 | 2172 | 2121 | 2183 | 2101 | 3023 | 2951 |
| 35.0 | 6230 | 6732 | 6118 | 6732 | 7255 | 7255 | 7163 | 7296 | 7091 | 6968 | 6241 | 5738 | 4704 | 3146 | 2500 | 2172 | 2090 | 2172 | 2070 | 2552 | 2869 |
| 40.0 | 5165 | 5165 | 5195 | 6159 | 6251 | 7276 | 6763 | 6702 | 6220 | 5677 | 5236 | 5216 | 4632 | 3146 | 2593 | 2121 | 2121 | 2142 | 2162 | 2531 | 2910 |
| 45.0 | 4099 | 4171 | 4191 | 5062 | 5124 | 6189 | 6261 | 6220 | 5195 | 5165 | 5236 | 5165 | 4704 | 3218 | 2121 | 2162 | 1988 | 2049 | 2121 | 2459 | 2152 |
| 50.0 | 3074 | 3136 | 2654 | 4068 | 4242 | 5021 | 6722 | 6046 | 5185 | 6241 | 6169 | 6169 | 4663 | 3607 | 2090 | 1886 | 1137 | 1496 | 1670 | 2234 | 2049 |
| 55.0 | 2049 | 2142 | 2070 | 2316 | 3115 | 4099 | 5124 | 6138 | 6148 | 6241 | 5708 | 5657 | 4160 | 2705 | 1117 | 1168 | 1137 | 1476 | 1148 | 1957 | 1168 |
| 60.0 | 1209 | 1117 | 1086 | 1701 | 1168 | 3177 | 4109 | 5626 | 6220 | 6804 | 6650 | 5800 | 3546 | 2121 | 1117 | 1096 | 1014 | 1137 | 1096 | 1076 | 1168 |
| 65.0 | 1107 | 1066 | 1066 | 1148 | 1025 | 2972 | 4048 | 6210 | 8761 | 7849 | 7603 | 5728 | 2623 | 1527 | 1066 | 861 | 113 | 840 | 143 | 1014 | 861 |
| 67.5 | 963 | 1035 | 953 | 1117 | 1127 | 2131 | 3658 | 6773 | 9786 | 9110 | 8075 | 5708 | 2623 | 1148 | 892 | 143 | 133 | 92 | 20 | 461 | 82 |
| 70.0 | 861 | 912 | 892 | 1025 | 1168 | 1926 | 3095 | 6251 | 9243 | 9796 | 7624 | 6159 | 2726 | 1168 | 92 | 41 | 123 | 72 | 123 | 41 | 184 |
| 72.5 | 820 | 840 | 820 | 963 | 1066 | 1209 | 2183 | 5216 | 9755 | 9243 | 4683 | 5165 | 2121 | 1014 | 113 | 164 | 92 | 102 | 61 | 143 | 102 |
| 75.0 | 102 | 164 | 143 | 564 | 143 | 1066 | 1629 | 4642 | 7696 | 7655 | 4242 | 4058 | 1455 | 553 | 123 | 102 | 41 | 61 | 0 | 61 | 41 |
| 80.0 | 143 | 72 | 20 | 92 | 143 | 102 | 635 | 2582 | 2675 | 2183 | 1045 | 1096 | 92 | 72 | 41 | 0 | 164 | 92 | 143 | 184 | 143 |
| 85.0 | 0 | 61 | 61 | 72 | 100 | 143 | 200 | 625 | 656 | 553 | 72 | 51 | 102 | 61 | 184 | 143 | 102 | 123 | 102 | 102 | 102 |
| 90.0 | 143 | 164 | 143 | 164 | 143 | 143 | 143 | 143 | 41 | 92 | 41 | 20 | 92 | 184 | 143 | | | | | | |

## Work Sheet for Manual Calculation of Luminance at a Point

| Lum. | $P_x$ | $P_y$ | $L_x$ | $L_y$ | $L_z$ | $L_x - P_x$ | $L_y - P_y$ | Tan $C_a$ $\frac{L_y - P_y}{L_x - P_x}$ | Note 1 Calc Angle | $\phi$ | Tan $\gamma$ Formula #1 | $\gamma$ | $\beta$ Note 2 | CP Note 3 | r Note 4 | $L_p$ Formula #2 | Lum. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1 | 34.8 | 2.7 | 0 | 12.19 | 1.7 | -34.8 | -20.5 | 87.2° | 92.8° | 2.86 | 70.7° | 87.2° | 6048 | 16.5 | .067 | 2 |
| 7 | 1 | 34.8 | 15.3 | 41 | " | 14.3 | 6.2 | .43 | 23.4° | 23° | 1.28 | 52.0° | 67.0° | 3529 | 77 | .183 | 7 |
| 3 | 1 | 34.8 | 2.7 | 82 | " | 1.7 | 47.2 | 27.76 | 87.9° | 92.1° | 3.87 | 75.5° | 2.1° | 4144 | 169 | .471 | 3 |
| 6 | 1 | 34.8 | 15.3 | -41 | " | 14.3 | -75.8 | -5.3 | 79.3° | 79.3° | 6.32 | 81° | 169.3° | 2093 | 0 | 0 | 6 |
| 8 | 1 | 34.8 | 15.3 | 123 | " | 14.3 | 88.2 | 6.17 | 80.8° | 80.8° | 7.33 | 82.2° | 9.2° | 1672 | 9.9 | .011 | 8 |
| 4 | 1 | 34.8 | 2.7 | 164 | " | 1.7 | 129.2 | 76 | 89.2° | 90.8 | 10.6 | 84.6° | 0.8° | 75 | 48.2 | .002 | 4 |
| | | | | | | | | | | | | | | | Total | 0.73 | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

Formula #1 $\text{Tan}\ \gamma = \frac{\sqrt{(L_y - P_y)^2 + (L_x - P_x)^2}}{L_z}$

Formula #2 $L_p = \frac{CP \times R}{L_z^2 \times 10000}$

Note #1: Draw sketch to determine $\phi$ from Calculated Angle.

Note #2: Draw sketch to determine $\beta$ from $\phi$.

Note #3: Read from Candela Tables.

Note #4: Read from R-Tables.

Figure 16

**Figure 17**
**Work Sheet for Determing Candlepower from Iso-Lux Plots**

| Luminaire | $\gamma$ Note 1 | $Cos^3\gamma$ | $L_z$ | LUX Note 3 | CP Formula #1 |
|---|---|---|---|---|---|
| #2 | 70.7° | .036 | 12.17 | 1.69 | 6975 |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

Note 1. Find $\gamma$ from column of Fig. 16

Note 2. Find $L_z$ from column of Fig. 16.

Note 3. Read Lux from iso-lux plot on photometric data sheet. If data sheet has only iso-foot candle plot then read and convert to lux. Lux = FC × 10.76

Formula 1. $CP = \frac{Lux \times L_z^2}{Cos^3 \gamma}$

diagram of the type shown on the photometric data sheet of Fig. 5a. A work sheet for this is shown as Figure 17 but only the top line is filled in to show the calculation procedure and the comparative accuracy to that obtained from a candela table as used in line 1 of Figure 16.

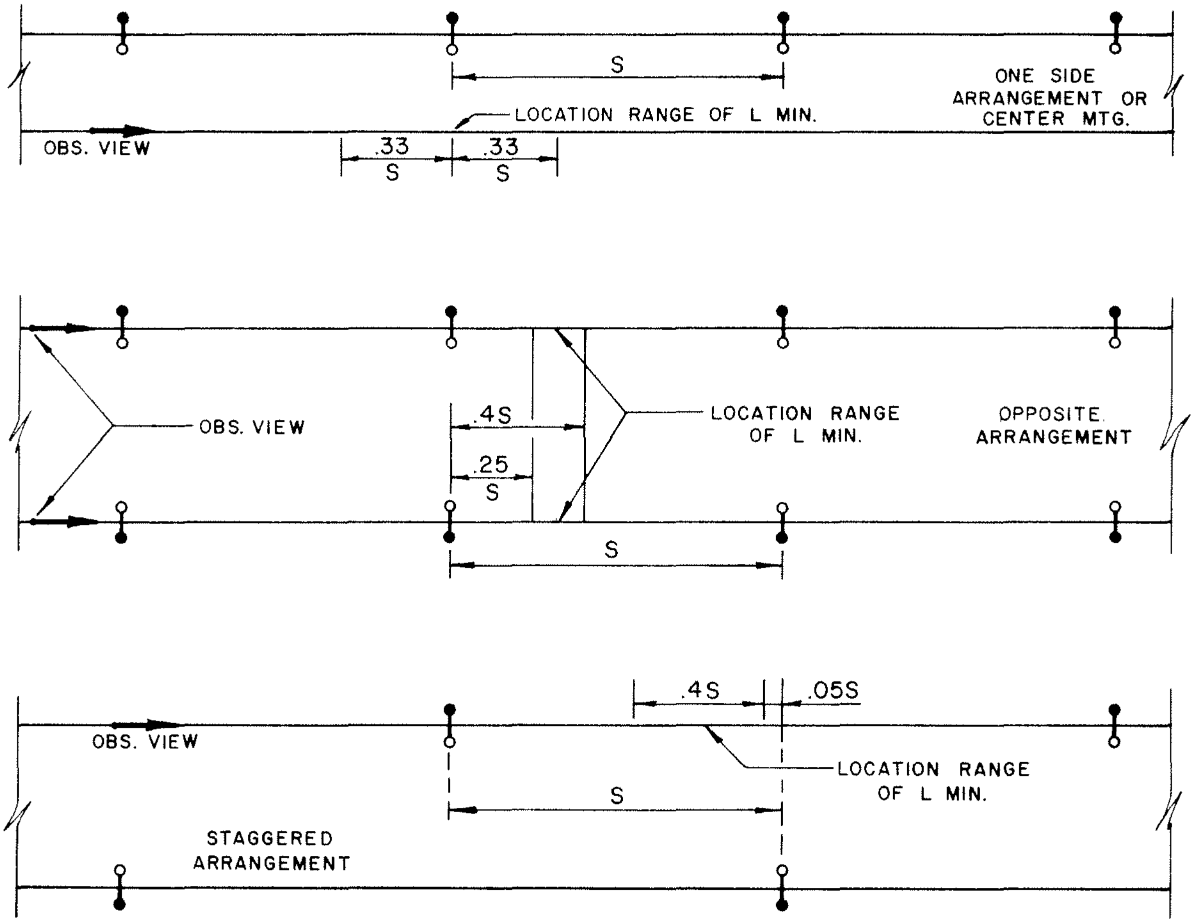
## MOST LIKELY LOCATION OF MAXIMUMS AND MINIMUMS

The manual or graphical calculation of the pavement luminance at all the grid points of a typical installation takes a great deal of time, for that reason it is very desirable to know where to expect the maximums and minimums to occur so that only a few points need to be calculated. The following information is based on a systematic exploration using typical luminaires of the type on the market in 1982. All have light distributions that are symmetrical in the downstream, upstream directions and all were first marketed when the standards were based on illuminance and not luminance. Whether or not this information will remain valid if luminaires are introduced that have distributions designed for more efficient production of luminance is difficult to forecast. The study was confined to spacings between 3.5 and 5 MH and may not hold at spacings less than 3.5 MH. With the luminaires investigated it is seldom possible to meet the criteria ratios with spacings over 5 MH.

***Maximum Veiling Luminance.*** Maximum $L_v$ occurs when the observer is located at the grid point closest to where the luminaire maximum candlepower would strike his eye. This is not at the same location where the max. Cp. strikes the pavement since the observer's eye is considered to be 1.45 m (57 in) above the pavement. The angular location and value of the luminaire max. Cp. is normally given on the photometric curve (Fig.5). Manufacturers are encouraged to place the value and location of the maximum single luminaire $L_v$ (Fig.5b) on the photometric curve and if this is given it will also be the system max $L_v$ location.

***Maximum Pavement Luminance.*** This will most likely occur on a line, parallel with the roadway centerline, that passes directly under-

**Figure 18 Probable Location of Minimum Pavement Luminance Point**




neath the luminaire. A grid point closest to this line and and slightly closer to the luminaire than the grid point closest to the vertical angle of maximum candlepower will be both the single luminaire and the system location for maximum luminance. See Appendix F (long method) for a means of accurately locating the maximum point along this line. Again manufacturers are encouraged to place this value and its location on the photometric curve (Fig. 5b) and if this is given it becomes unnecessary to manually calculate either the exact location or the value of the dominant contributor to the system maximum luminance.

***Minimum Pavement Luminance.*** The exact location of the minimum pavement luminance is difficult to precisely predict. Its general location for the various configurations is shown on Figure 18. As indicated it is nearly always located on the line of grid points closest to the edge of the pavement and on the opposite side from the maximum luminance. In a few instances with very wide pavements, narrow luminaire distributions and long spacings it moves to the center of the pavement; but even then it is usually not much lower than the edge of pavement value.

For opposite, one side and staggered spacing (but more drastically with staggered spacings) the minimum moves more towards the observer as spacings are reduced in terms of the MH. A good example of this is shown in the difference in location of the minimum in Fig. 9 and 11 of the example problem computer printouts. It is good practice to first calculate the luminance at a grid point at one end of the range shown on Figure 18 and then move one or two grid points along the range to see if the luminance is increasing or decreasing.

## SELECTING A MORE SUITABLE DISTRIBUTION

After following the example shown previously to a final design, this question often is asked, "How can one find a luminaire with a more suitable light distibution?" In the course of the reiterative design process it usually is obvious as to what is needed to make an acceptable design that would cost less to install and maintain. In the case of the example shown a lower mounting height and a longer spacing would be preferable. In fact, as could be seen from the discussion, a lower mounting height would increase the average pavement luminance and permit a longer spacing. A luminaire with the same wattage lamp and a lower value of maximum pavement luminance would be a characteristic for which one could look. If one were found then the Coefficient of Luminance Utilization should be checked to see if it is reasonably close or exceeds that of the luminaire previously tried.

If such a luminaire can not be found then one with an equal value of maximum luminance but a higher utilization curve would also be preferable.

Initial cost of the installation could also be lowered if less overhang were used. In the example, the overhang was increased in order to raise the CofU (and $L_{avg}$) by gaining more utilization on the house side than was lost on the street side. The characteristic to be looked for is a CofU curve that is lower on the house side and higher on the street side and that rises less steeply near the luminaire nadir position and continues to rise as the distance from the luminaire increases. Such a curve is more likely to be found with a type III or IV distribution than the Type II used in the example.

It is quite possible that the overall performance of a luminaire possessing the last discussed characteristics might transfer the problem from a max to min ratio to an avg to min ratio problem. However it is only by investigating such possiblilities that valuable experience is gained in selecting the best performing luminaire distributions for a particular situation.

## FIELD EVALUATION OF AN INSTALLED SYSTEM

The evaluation of pavement luminance and veiling luminance of an installed system can be done in either of three ways.

- Direct measurement with luminance instruments.
- Measurement of predicted incident light.
- Calculation from photometered luminaires.

Luminance of the pavement can be measured with a telephotometer of a special type. The instrument should be set up at the observer's position and a measurement made at the desired point. If the moving observer method (IES) method of calculation has been used to predict the luminance at the same point, then a different instrument location is required for each point measured. In addition it is very difficult to determine if the difference between calculated and measured values is due to the lighting system or the pavement. While it is necessary to use this method in research investigations it is not recommended as a method to determine if an installation is performing as specified.

Measurement of predicted incident light can be used as a method of determining if an installation is performing as specified. In this method a computer printout of the initial incident light level (Footcandles or Lux) is made at the same time as the printout of the luminance. After the installation is completed and operating the incident light level can be measured at each grid point in the customary manner. This method eliminates the pavement as a variable and will reveal incorrect installation procedures such as leveling, tilt or rotation. These are difficult to separate from the effects of other variables such as dirt, light source output, luminaire and ballast variability, and voltage variations.

Calculation from photometered samples is an excellent way to evaluate the performance of an installation. Several random samples of luminaires (with ballast) and lamps are selected and sent to a competent laboratory to be photometered. The resultant photometric data can be averaged (or analyzed independently) and the luminance calculated by a computer run. If desired, the light sources (lamps) can be photometered separately, dirt can be removed from the submitted luminaires, or they can be photometered twice, once dirty and once clean, to determine its effects. This technique has many variations and is the preferred way to write specifications to permit field evaluation of the performance of an installed system. Random sampling at the rate of one per hundred luminaires installed with a minimum of three per installation is good practice.

## APPENDIX A GRID SELECTION

In the selection of a grid to cover a portion of the roadway it is necessary to consider first the repetitive cycle of the luminance patterns in different configurations. The simple configurations of Figure 3 all repeat at each pole but in the case of the staggered configuration the luminance pattern will be reversed as it repeats. A more complex configuration is shown in Fig. A-1 in which the luminance pattern repeats less frequently as shown. The very complex patterns of intersections, traffic circles, rest areas, and high mast installations often require grids that cover large areas.

Grids do not have to be square or rectangular, they can be triangles, diamonds, or any polygon that will fit with its neighbor with no gaps or overlaps. The principle is that the single cell of the grid represents an area that can be fairly represented by a single value at its center. In roadway lighting rectangles are commonly used with the length of the rectangle running along the street.

Since the average of the values at the centers of all the grid areas is intended to represent the average for the entire grid area it is important to either have all grid cells the same area or to weight them according to area. In the case of curved roadways weighting is usually necessary to find the correct average.

Grids can be arranged in different ways and yet yield equally valid data. Figure A-2a and b show equally valid grid arrangments while c is an invalid grid since the value is not at the

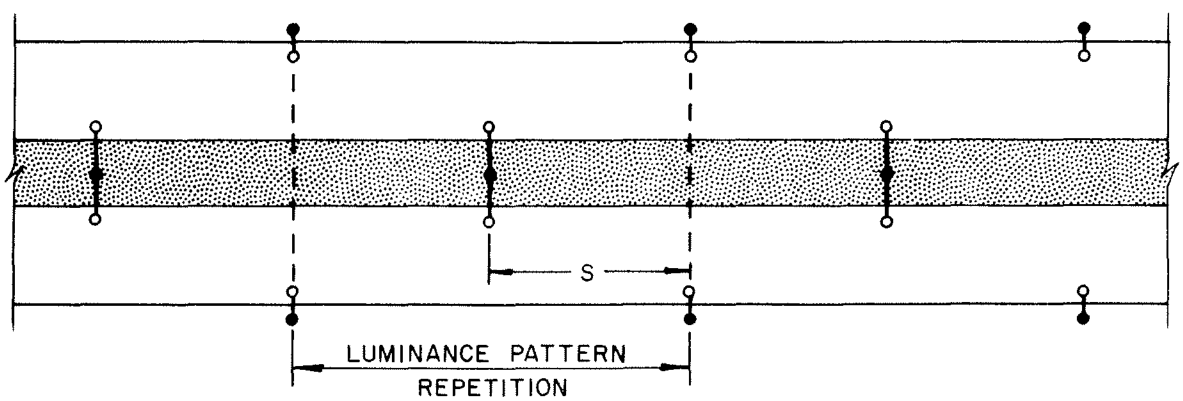
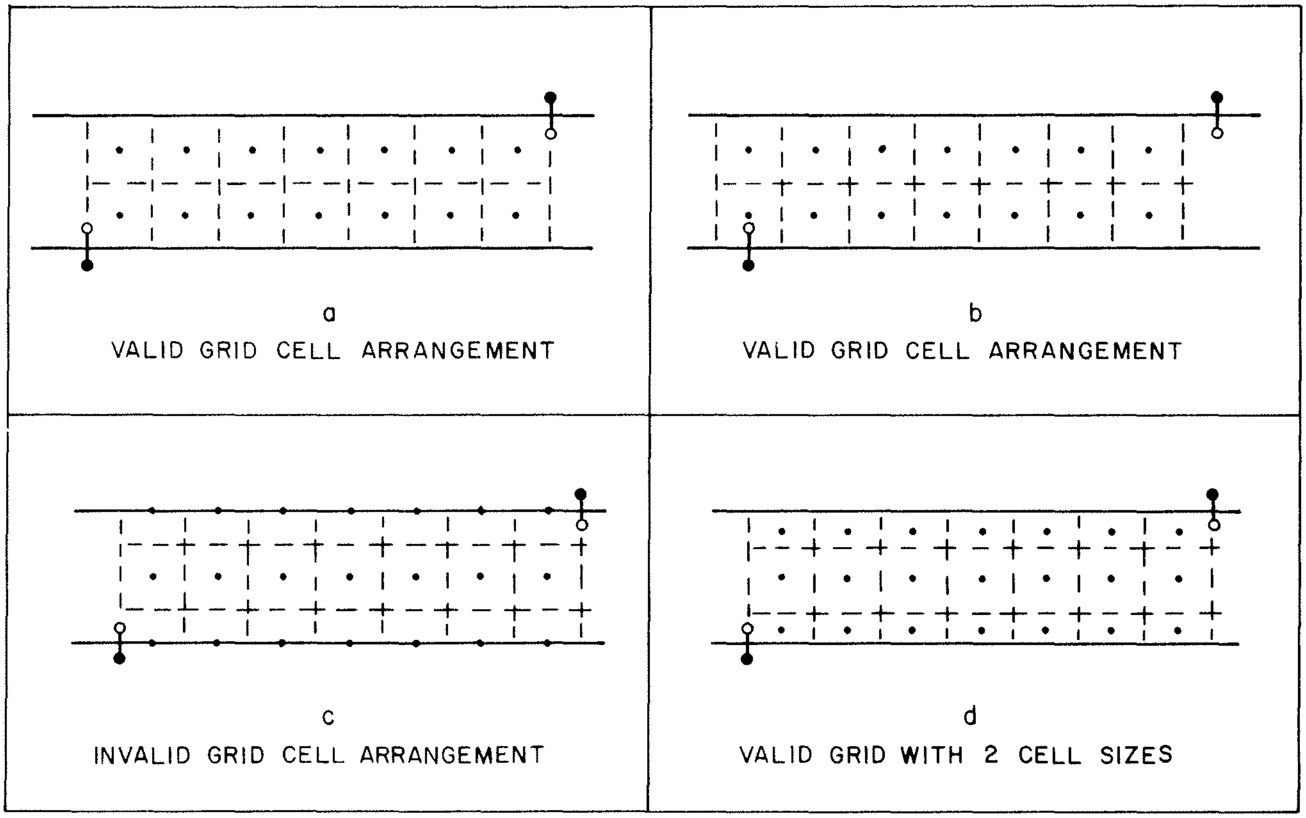



**Figure A-1**

**Figure A-2**




center of the area. Fig. A-2d is a valid grid but since it has two different cell sizes a weighted averaging method must be used (see appendix D).

The IES has made the following recommendations as to grid size for straight roadways. In the transverse direction (across the roadway) grid cell width is to be 1/2 the lane width. In the longitudinal direction grid cell length should be such that it is no greater than 1/10th the spacing between poles or 5 meters whichever is greater. In the example used in this chapter the lane widths were not equal but equal area grids were used, this is better practice than to have used a grid with a variable cell size.

## APPENDIX B
## USE OF X, Y, Z AXES

It is very convenient to use the "X, Y, Z" axes method to locate a point in space and to express the location of that point. Virtually all entry into a computer program utilizes this method of expressing the location of a point and the method is used in all the examples in this chapter.

The three axes are at right angles to each other and are as shown on figure B-1. The location of any point P, at any location in space, can be expressed as P followed by three subscripts: distance along the X axis; distance along the Y axis; and distance along the Z axis. The distances can be either positive or negative and are always expressed in the order X, Y, Z. In Fig.B-1 the location of P would be designated as $P_{-1,-2,0}$ with the numerical values along each axis separated by commas. Similarly the location of point L would be expressed as $L_{1,0,2}$.

In roadway lighting it is convenient to consider the pavement to be located in the X, Y plane (Z = 0). The distance "a" along the pavement can be expressed as $L_y - P_y$ which in this case is $0 - (-2) = 2$. The distance "c" would be $L_z - P_z$ which is 2. The distance "b" could be expressed as $L_{xy}P_{xy}$ and would be calculated as follows:

$$L_{xy}P_{xy} = \sqrt{(K_y - P_{y})^2 + (P_z - K_{z})^2} \ .$$

This method of expressing distances in formulae has been used throughout this chapter and is the method normally used in computer programs and with programmable calculators. It is also convenient to use in setting up work sheets for use with either engineering calculators or slide rules.

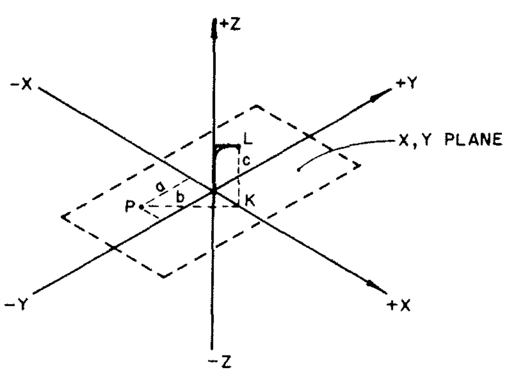



**Figure B-1**

# APPENDIX C PHOTOMETRIC DATA PRESENTATION

Photometric data is taken by placing a luminaire at the center of an imaginary sphere and taking light readings from the inside surface of the sphere. The pattern of readings is described in terms of horizontal and vertical angles. Figure C-1 illustrates this concept. For a roadway luminaire the reference axis (0 deg.V and 0 deg H) runs from the luminaire to a pole of the sphere and the luminaire is positioned on the photometer so that it is in its normally level position and the reference axis goes from the luminaire to a point directly under it. The meridian directly in front of the luminaire is labeled 0 degrees horizontal. These conventions and the maximum spacing between readings have been standardized by the Photometric Testing Procedures Committee of the IES. The light readings of the light intensity (I) are in candlepower and the table containing the readings is called a candela table. The candela table for the luminaire used in the examples of this chapter is shown as Figure 15.

There is no standardized format for candela tables and the spacing between values is not always uniform but often is decreased in areas where the candlepower is changing rapidly. Such tables are not normally used by a designer but are the basic data and usually must be entered into a computer by some means before a program can be run. This can be done by typing in the values (an extremely slow process) punched cards, magnetic tape, magnetic disks, or by calling up the data from a file stored in the computer memory and called a "data base" (fastest method).

Photometric data from the candela tables can be manipulated to provide specialized presentations for different uses. For roadway lighting these include the luminaire efficiency, ratio of upward light to downward light, ratio of street side light to houseside light and others. The two we will look at more closely are the Coefficient of Utilization Curve and the Isoluminance Plot.

**Coefficient of Utilization Curve.** Let us consider a very wide street of infinite length to be divided into a number of narrow strips as

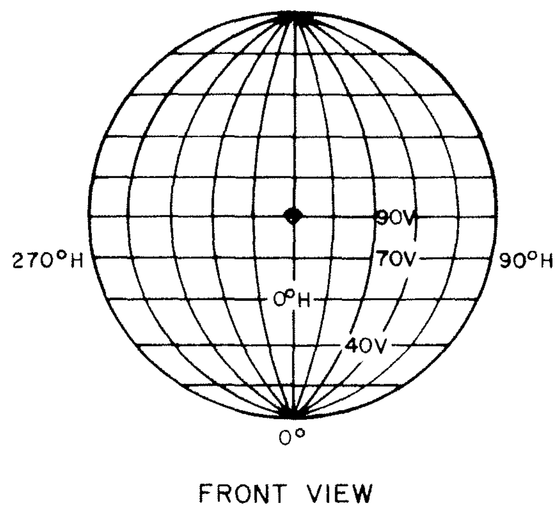



**Figure C-1**

shown in Figure C-2. If this street is lighted by only one luminaire we can use the candela table data to calculate the average luminance of each strip. By plotting on graph paper the luminance of the strip closest to the luminaire and then plotting the sum of the first and second strip and so on we will create a Coefficient of Utilization (CofU) Curve. The portion of the curve plotted for the strips in front of the luminaire is called the Street Side (SS) and the portion to the rear of the luminaire is called the House Side (HS). Such a curve is shown in Fig. 6 of this chapter.

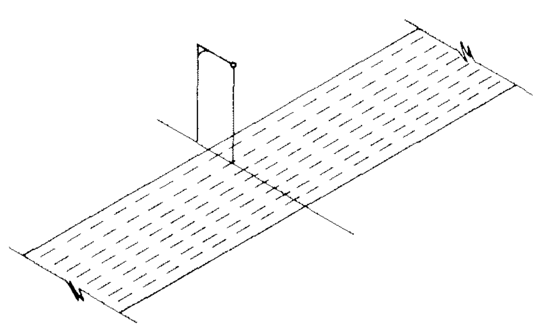


**Figure C-2**

**Isoluminance Plot.** Again let us consider a very wide street lighted by one luminaire. If we use a grid with small cells and plot the luminance at each point on the grid and then connect and label points of equal luminance we will have an isoluminance plot. Again we will use the SS and HS convention but since the plot is not symetrical about the luminaire along the street we use the terms Upstream and Downstream to denote the difference. Such a curve is shown as Figure 13 of this chapter.

The scales along these curves are marked in mounting heights (MH). This is a convenient method and if the mounting height is 10 m (33 ft) then the location on the pavement 20 meters from the luminaire will be found at grid line 2. The CofU has no dimensions but the values on the Isoluminance plot are in Cd/SqM. The values will be different as the mounting height is changed. This is taken care of with a mounting height correction factor. This is a ratio of the mounting height squared at which the data was plotted to the mounting height squared at which it is to be used. As the MH *increases* the value *decreases*.

The candela table data, as the direct output of what is measured on the photometer, is the most accurate data. As each type of specialized data is computed many interpolations have to be made from the basic data of the candela table. Thus the specialized data presentation itself is subject to some error and this is increased by the scale of the curve or plot and by human errors in reading it. In a similar sense the data produced by a computer using interpolated data is subject to error and one can expect small differences between programs. This is because interpolations must be made, and the method of interpolation can be varied as well as the detail selected from the candela table. For example the candela table shown in Figure 15 utilizes 5 degree increments for its vertical values over most of the range but drops to 2.5 degree increments near the areas of maximum candlepower. If the computer program is written to make all interpolations from a 5 degree increment table then it will ignore the 2.5 degree data and not achieve maximum accuracy.

Specialized photometric data presentations are not standardized and different laboratories present similar data in slightly different formats. Study it carefully and do not assume that it is exactly the same as the data from the one used a few moments before. Most CofU and isoluminance curves are superimposed as shown in Figure 5. Similar specialized presentations of CofU and IsoFC or IsoLux plots are published for incident light calculations. Luminance curves and plots look very similar to incident light (illuminance) curves and plots and it is easy to make a mistake.

## APPENDIX D LIGHT LOSS FACTOR

Any lighting parameter, and this includes both luminance and veiling luminance, can be calculated in terms of either an initial or maintained value. It is generally assumed (but not always true) that the highest light level in the life of the installation will be found when the system is first energized and that all effects of system aging will cause the light level to decrease. For this reason any compensation for system aging is part of the term "Light Loss Factor" (LLF). LLF is usually considered to be made up of these factors:

- Reduced output from the light source due to aging.
- Reduced output from the light source due to dirt accumulation on it.
- Reducted output from the luminaire due to dirt accumulation on and in it.
- Changes in relative light intensity due to dirt accumulation altering the characteristics of lamp, reflector and enclosure surfaces.
- Changes in relative light intensity due to changes in reflector and enclosure characteristics with time.
- Changes in ballast characteristics with time.
- Changes in lamp characteristics with time.

With regard to pavement luminance, the effects of wear, patching, moisture, and repaving must be added to the above list.

Many of the above factors are complex in nature and are interrelated. Most will not be discussed here but additional information can be found in other chapters of this Handbook and in publications of the IES. A few important points will be discussed.

The high pressure sodium lamp is the most common energy source used in new roadway lighting installations in this country and the relationship between the lamp and ballast is very complex. It is not usually recognized that these lamps, when used on the most common types of ballast, produce less light when first installed than after several thousand hours of operation. This is not the fault of the ballast or lamp but due to the fact that the lamp voltage rises during life of the lamp and the lower cost type ballasts are not capable of compensating for this lamp change. This means that for luminaires operating in clean conditions the light level is likely to increase for some time after initial installation.

The surface finish of both metal reflectors, plastic reflectors, and plastic enclosures can be scratched and dulled by some maintenance techniques. Sandstorms and exposure to ultraviolet light can also affect the transmission of some plastics. This damage is permanent and not reversible.

In general two approaches can be taken to the question of maintained light levels. One is to anticipate the normal maintenance practices and schedules and select a LLF based on estimates of the effects of those schedules and practices. The other is to select an LLF and then monitor the light level and tailor the maintenance schedule and practices to what is occuring at the installation.

## APPENDIX E
## CALCULATION OF AVERAGE PAVEMENT LUMINANCE

Average pavement luminance can be calculated by three methods. By taking the average of values at many grid points; by use of the graphical CofU method; and by the use of an incident light multiplier factor.

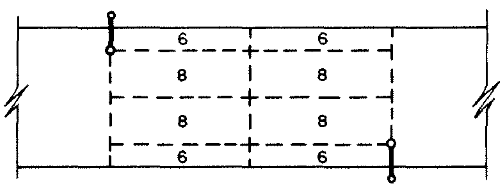



**Figure E-1**

***Average of Grid Points:*** If all the cells of the grid are of the same area then the average can be calculated by adding the values and dividing by the number of values. If the cells are not of the same area then a weighting method can be used. Figure E-1 shows a grid with unequal areas. If the luminance values in each area are as shown, and the areas of the edge grids are 1/2 the areas of the center grids, then the average would be calculated as follows:

| Value | Weight | Weighted Value |
|---|---|---|
| 8 | 1.0 | 8 |
| 8 | 1.0 | 8 |
| 8 | 1.0 | 8 |
| 8 | 1.0 | 8 |
| 6 | .5 | 3 |
| 6 | .5 | 3 |
| 6 | .5 | 3 |
| 6 | .5 | 3 |
| | Tot. 6.0 | Tot. 44 |

Avg. = 44/6 = 7.33

***Graphical CofU Method:*** This method is shown in some detail in the main body of the chapter (page 13) but will be enlarged here with a more complex situation. The example will be for a divided roadway with luminaires both in the median and on the edges. A plan view and an elevation is shown in Figure E-2. This example has been chosen to show various factors and should not be considered as an example of good final design. Note that two different mounting heights have been used and that some of the luminaires are not over the pavement. The design is symmetrical about the centerline of the median so that the CofU of only two luminaires is unique and must be calculated. There are however four ratios to be calculated for each luminaire and four co-efficients to be read from the curve for each of the luminaires. By addition and subtraction of the coefficients the total per luminaire is calculated. The final CofU is the average of the two unique luminaires not the sum. The repetitive pattern of the poles (and luminaires) is shown by dotted lines as occuring midway between poles. This makes it easier to see that four luminaires contribute to the area than if the repetitive pattern dividing lines had split a luminaire. The calculated ratios and coefficients as read from the CofU curve are shown in Table E-I.

The actual calculation of the initial average pavement luminance is made from the formula:

$$\text{Lavg} = \frac{\text{Lp. Lumens} \times \text{No. of Luminaires} \times \text{CofU}}{\text{Area in Sq. Meters}}$$

as follows:

$$\text{Lavg} = \frac{22000 \times 4 \times 0.032}{100 \times 24} = 1.17 \text{ Cd/SqM}$$

***Incident Light Multiplier:*** The least accurate method of determining average pavment luminance is by multiplying the average incident light level by a constant. The chief use of this method is when graphical luminance curves are not available and approximate calculations need to be made in the selection of a tentative design before evaluation of the design is made with a computer run.

The variables that affect the choice of multiplier are the pavement type, luminaire width classification, and luminaire spacing classification. Table E-II gives multiplier ranges for

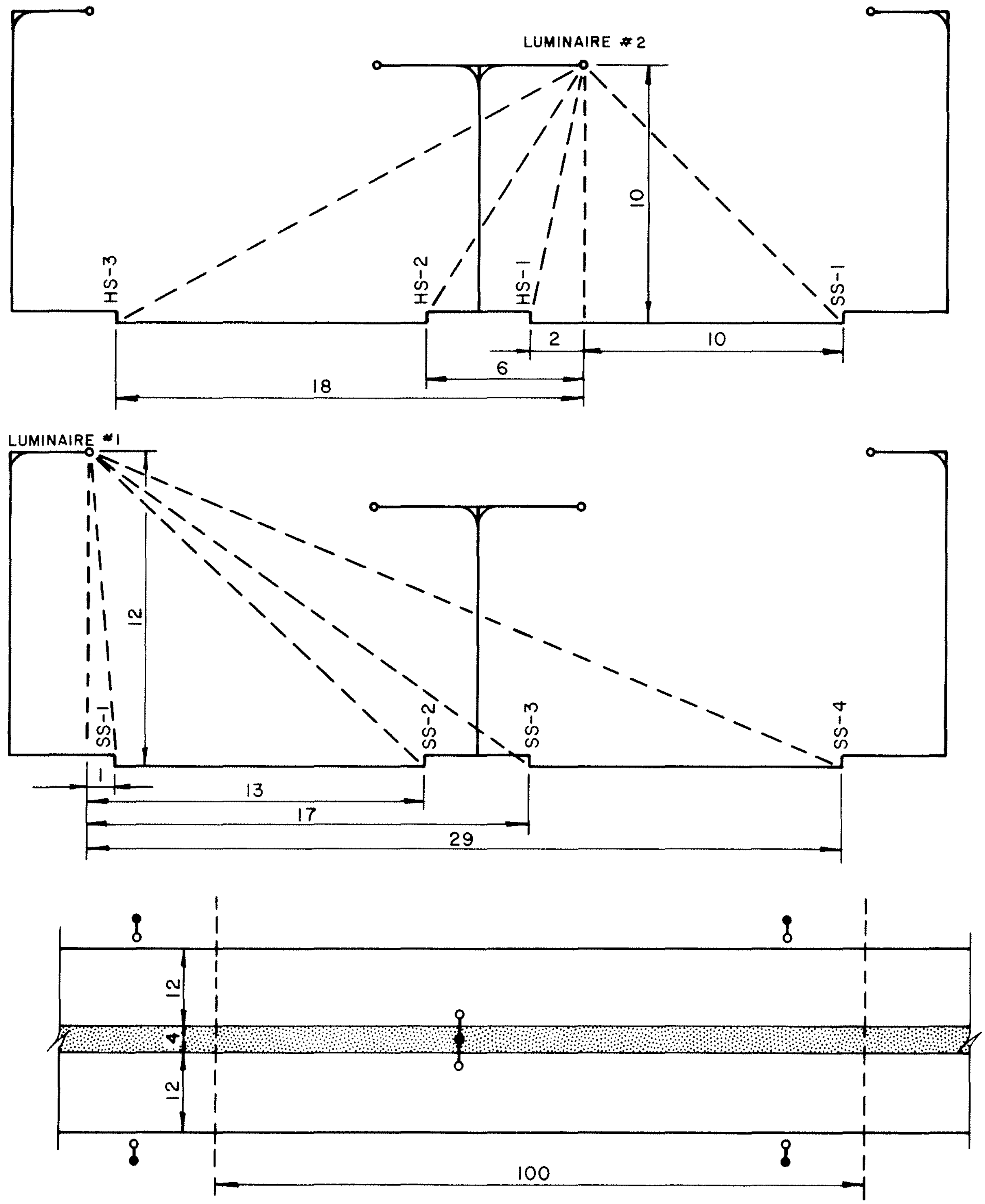



Figure E-2 Relationships for Complex CofU Example

## TABLE E-I
## SUMMARY OF RATIOS AND COEFFICIENTS OF LUMINANCE UTILIZATION

| Location | Luminaire #1 Dist. | MH | Ratio | CofU | Location | Luminaire #2 Dist. | MH | Ratio | CofU |
|---|---|---|---|---|---|---|---|---|---|
| SS-4 | 29 | 12 | 2.42 | .0365 | SS-1 | 10 | 10 | 1.0 | .031 |
| SS-3 | 17 | 12 | 1.42 | .0340 | HS-1 | 2 | 10 | .2 | .003 |
| | CofU North Roadway | | | .0025 | | CofU North Roadway | | | .034 |
| SS-2 | 13 | 12 | 1.08 | .0315 | HS-3 | 18 | 10 | 1.8 | .019 |
| SS-1 | 1 | 12 | .08 | .0015 | HS-2 | 6 | 10 | .6 | .012 |
| | CofU South Roadway | | | .0300 | | CofU South Roadway | | | .007 |
| | Sum of Both Roadways | | | .0325 | | Sum of Both Roadways | | | .041 |
| | | | Average of Both Types of Luminaires .037 | | | | | | |

## TABLE E-II
## INCIDENT LIGHT MULTIPLIERS

| Pavement Class | Range of Multipliers High | Medium | Low |
|---|---|---|---|
| R 1 | 0.18 | 0.16 | 0.13 |
| R 2 | 0.09 | 0.08 | 0.065 |
| R 3 | 0.10 | 0.09 | 0.07 |
| R 4 | 0.13 | 0.11 | 0.09 |

Luminance = Lux × Multipier from table above.

Luminance = Footcandles × 10.76 × Multiplier from table above

each of the four pavement classes. With regard to luminaire distribution types the following rules should be followed:

**RULE 1:** Use the low end of the range if a luminaire with a wide width classification is used on a narrow street and the high end of the range if a luminaire with a narrow classification is used on a wide street.

**RULE 2:** Use the low end of the range with a luminaire classified for long spacings and the high end of the range for a luminaire classified for short spacings.

# APPENDIX F MAXIMUM PAVEMENT LUMINANCE FROM SINGLE LUMINAIRE

In the body of this chapter, we have seen how useful it is to know the location and value of the maximum pavement luminance from a single luminaire. If the photometric data sheet for the luminaire contains the graphic method luminance curves for the luminaire it probably has listed the value and location of the maximum luminance. If it does not, the $L_{max}$ can be calculated by either the long method (most accurate but candela tables are needed), or by a less accurate "short cut" method in which only the angular location and value of the luminaire maximum candlepower is needed.

**Short Cut Method:**

***Step 1:*** From the photometric curve (Fig. 5a) locate and record the angular location and value of the luminaire maximum candlepower. It is 80.8 deg H, 70.0 deg V, and 10313 cp.

***Step 2:*** Determine the tangent of the vertical angle (70.0 deg). It is 2.75.

***Step 3:*** From the R-table (for Standard Surface R3) determine the r value for Beta = 0 and Tan Phi (from step 2, tan $\phi$ = 2.75). The value by interpolation is 271.

***Step 4:*** From the formula

$$L = \frac{cp \times r}{MH^2 \times 10000}$$

and using a height of 10 meters we can calculate $L_{max}$ as 2.79 Cd/SqM.

The value for $L_{max}$ given on the photometric data sheet (Fig.5b) after correcting for a 10 m (33 ft) height is 2.42 Cd/SqM. This method has only fair accuracy but is good enough to accept or reject a luminaire and lamp combination for a tentative design.

**Long Method:** Candela table needed.

***Step 1:*** From an inspection of the candela table (Fig.15) determine the value and vertical angle (Gamma) of the highest candlepower at 90 deg H. In this case it is at 67.5 deg V and has a value of 8075 cp.

***Step 2:*** Determine the tangent of the vertical angle (67.5 deg). It is 2.41.

***Step 3:*** From the R-Table find the r value for Beta = 0 and tan Gamma (from step 2, tan $\gamma$ = 2.41) and r is 296.

***Step 4:*** Using the same formula as in Step 4 above calculate the $L_{max}$ (trial 1) as 2.39 Cd/SqM.

***Step 5:*** Reduce vertical angle by 2.5 deg to 65 deg and find cp from candela table as 7603 cp. Then repeat steps 2 thru 4 and find $L_{max}$ of 2.4 Cd/SqM.

***Step 6:*** Since the value of step 5 is greater than that of step 4, reduce the vertical angle by 2.5 deg to 62.5 deg and find cp of 7127 (by interpolation). Repeat steps 2 thru 4 and calculate $L_{max}$ of 2.35 Cd/SqM. Since this is less than that found in step 5 we conclued that the max is 2.4 Cd/SqM.

In the event the value calculated in step 5 had been less than that of step 4 the proper procedure would have been to go to a higher vertical angle than Step 4 in the next trial. As it is we have located the $L_{max}$ as on a line passing under the luminaire at 2.14 MH from the luminaire (tan of 65 deg) with a value of 2.4 Cd/SqM. This compares very favorably with the value on the data sheet of 2.42 Cd/SqM.

# APPENDIX G CALCULATION OF VEILING LUMIANCE

The example in this appendix will serve three purposes. First, it gives a short cut method of calculating the maximum veiling luminance (max $L_v$) from a single luminaire. Second, a long (but more accurate) method of calculating $L_v$, and third, an example of how a work sheet is set up for calculating $L_v$ at any observer position. It should be remembered that the observer height has been standardized as 1.45 m (57 in) above the pavement. Angles and distances can be visualized as occuring on a plane 1.45 m above the pavement or can be visualized as occuring on the pavement with the luminaire mounting height reduced by 1.45 m. We will assume a plane above the pavement. The angular and distance relationships are shown in figure G-1 and will be used to calculate the maximum $L_v$ for the luminaire of Figure 5 when mounted 10 m above the pavement.

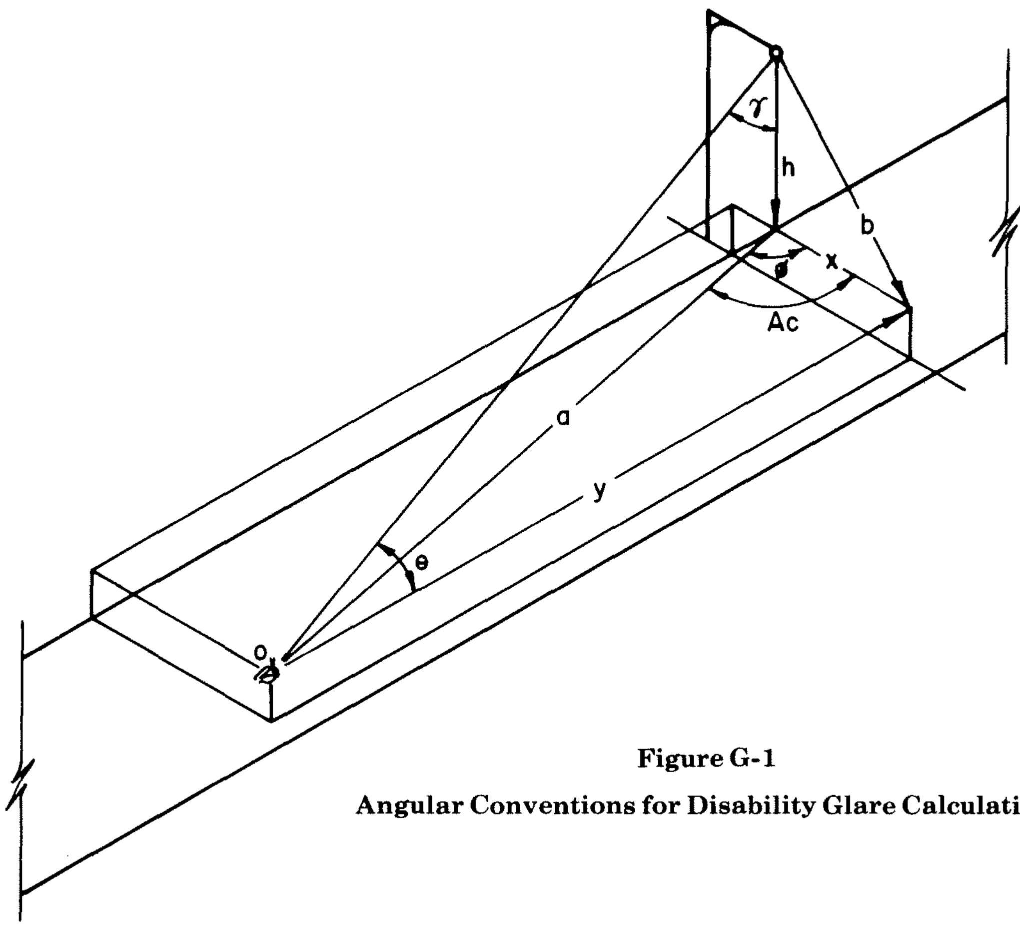



**Figure G-1**

**Angular Conventions for Disability Glare Calculation**

**Short Cut Method For $L_v$ From A Single Luminaire:** The accuracy of this short cut method is fair as long as the observer is at a distance from the luminaire. It must not be used for luminaires that are very close (less than 1.5 MH from the observer). It is useful when the max $L_v$ is not shown on the Photometric curve and is needed to accept or reject a luminaire and lamp combination for a tentative design.

***Step 1:*** From the photometric data sheet of Fig 5a find and record the value and location of the maximum luminaire candlepower. In this case it is 10313 cp at 80.8 deg H (angle Phi) and 70.0 deg V (angle Gamma).

***Step 2:*** Calculate Theta from the following formula:

$$\text{Theta}(\theta) = \sqrt{(90-\gamma)^2 + (90-\phi)^2} = \sqrt{(90-70)^2 + (90-80.8)^2} = 22$$

***Step 3:*** Calculate $L_v$ from the following formula:

$$L_v = \frac{10\left(\dfrac{cp \times \text{Cos}^2\gamma}{h^2}\right)}{\theta^2 + 1.5\ \theta} = \frac{10\left(\dfrac{10318 \times \text{Cos}^2 70}{73.1}\right)}{22^2 + (1.5 \times 22)} = 0.32 \text{ Cd/SqM}$$

Maximum $L_v$ from a single luminaire normally occurs when the observer stands with his eye at the point of maximum candlepower of the luminaire. It may shift slightly towards a line parallel with the roadway center line that passes under the luminaire when the vertical angle of max cp. is low (less than 65 degrees). The point at which the observer is located ($O_x$, y), when

## Work Sheet for Manual Calculation of Veiling Luminance

| Lum. | $O_x$ | $O_y$ | $O_z$ | $L_x$ | $L_y$ | $L_z$ | $L_x-O_x$ | $L_y-O_y$ | Tan $A_c$ $\frac{L_y-O_y}{L_x-O_x}$ | Calc Angle $A_c$ | $\phi$ Note #1 | CP Note #2 | $L_z-O_z$ | Formula #1 | $O_{xz}-L_{xz}$ Formula #2 | Formula #3 | $E_v$ Formula #4 | $L_v$ Formula #5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.8 | 23.5 | 1.45 | 1 | 0 | 10 | -3.8 | -23.5 | 8.39 | 80.8° | 80.8° | 10313 | 8.55 | 70° | 9.35 | 21.7° | 15.3 | .31 |
| | | | | | | | | | | | | | | | | | | |
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Formula #1: $\gamma = \tan \frac{\sqrt{(L_x - O_x)^2 + (L_y - O_y)^2}}{(L_z - O_z)}$

Formula #2: $b = \sqrt{(L_z - O_z)^2 + (O_x - L_z)^2}$

Formula #3: $\theta = \tan \frac{(O_{xz}\, L_{xz})}{(L_y - O_y)}$

Formula #4: $E_v = \frac{CP \times \cos^2\gamma \times \sin\gamma \times \cos(90 - \phi)}{(L_z - O_z)^2}$

Formula #5: $L_v = \frac{10\, E_v}{\theta^2 + 1.5\,\theta}$

Note #1: Draw sketch to determine $\phi$ from Calculated Angle.

Note #2: Read CP from Candela tables or Photometric Data Sheet.

Figure G-2 Work Sheet for Manual Calculation of Veiling Luminance his eye is in the max luminaire candlepower (luminaire located at $L_{0,0,10}$) can be calculated as follows:

***Step 4:*** Select Mounting Height (h). In this case 10 m (33 ft).

***Step 5:*** Calculate distance "a" or $O_{xy}L_{xy} = (L_z - O_z) \tan \gamma = 8.55 \times \tan 70 = 23.5$

***Step 6:*** Calculate "x" or $O_x = O_{xy}L_{xy} \times \cos \phi = 23.5 \times \cos 80.8 = 3.8$

***Step 7:*** Calculate "y" or $O_y = O_x \times \tan \phi = 3.8 \times \tan 80.8 = 23.5$

**Long Method For Calculating $L_v$ From Any Point:** In this example let us assume the observer is located at X = 4.8, Y = −23.5 and Z = 1.45; the luminaire is located at X = 1, Y = 0, and Z = 10 which will place the observer at the point of max candlepower (10313 ) as calculated above.

***Step 1:*** The six values of $O_x$, $O_y$, $O_z$, $L_x$, $L_y$, and $L_z$ should be entered in the first six columns of a worksheet. (Fig. G-2)

***Step 2:*** Calculate distances x, y, and y/x. (Next three columns).

***Step 3:*** Calculate the angle $A_c$. In Figure G-1 this angle is equal to and is angle Phi ($\phi$), but in some arrangements of the luminaire and observer this is not the case and Phi must be found by adding or subtracting 90 degrees. This can be determined by making a small drawing such as Fig. G-1 to help in visualizing the situation.

***Step 4:*** Calculate the distance h and the angle gamma using formula 1 on the worksheet and enter in proper column.

***Step 5:*** Calculate the slant distance b using formula 2 from the worksheet and enter in proper column.

***Step 6:*** Calculate angle Theta ($\theta$) from Formula 3 and enter.

***Step 7:*** Calculate $E_v$ from Formula 4 and enter. This is the incident light striking a vertical plane at the eye of the observer and is calculated in lux when the distances are in meters.

***Step 8:*** Calculate $L_v$ from Formula 5 and enter. When $E_v$ is entered in lux, $L_v$ will be in Cd/SqM.

## APPENDIX H
## COEFFICIENT OF REFLECTANCE

The understanding of the calculation and use of pavement luminance will be enhanced if the significance of the coefficient of reflectance r as used in the R-Tables is understood. The explanation will be as simple and non-technical as possible. This is not a derivation of r.

Figure H-1 shows a single ray of light striking a surface, as it does so a portion of the energy is absorbed in the surface, and the remainder is reflected at a variety of angles. We are interested in only one reflected ray, that which will reach the eye of the observer. A coefficient of reflectance (R) can be the multiplying factor to be used in calculating the intensity of the reflected ray as compared to the incident ray. If this concept had been used in the R-Tables then the numbers would have been very small and would have varied greatly as the angle of incident light (Gamma) and as the angle to the line of sight (Beta) change. Such a relationship could be represented by the formula:

Luminance =
Light Intensity (I) × Reflectance Coefficient (R)

The concept used in the "reduced coefficient" r first transforms the incident ray of light into the horizontal incident light value (illuminance) by means of the formula:

$$\text{Lux} = \frac{I \times \text{Cos}^3\gamma}{h^2}$$

and then relates the value of the horizontal illumination at a point on the pavement to the intensity of the relected ray directed towards the observers eye. By mathematically placing the "cosine cubed gamma" into the r value ($r \times \cos^3 \times R$) it is possible to greatly reduce the spread of the size of the numbers in the R-Table. The numbers are still very small and are therefore multiplied by 10,000 before the table is compiled. This technique of transferring the "cosine cubed gamma" results in the formula for Luminance having the term "height sq." in the denominator as follows:

$$\text{Luminance (L)} = \frac{I \times r}{h^2 \times 10000}$$

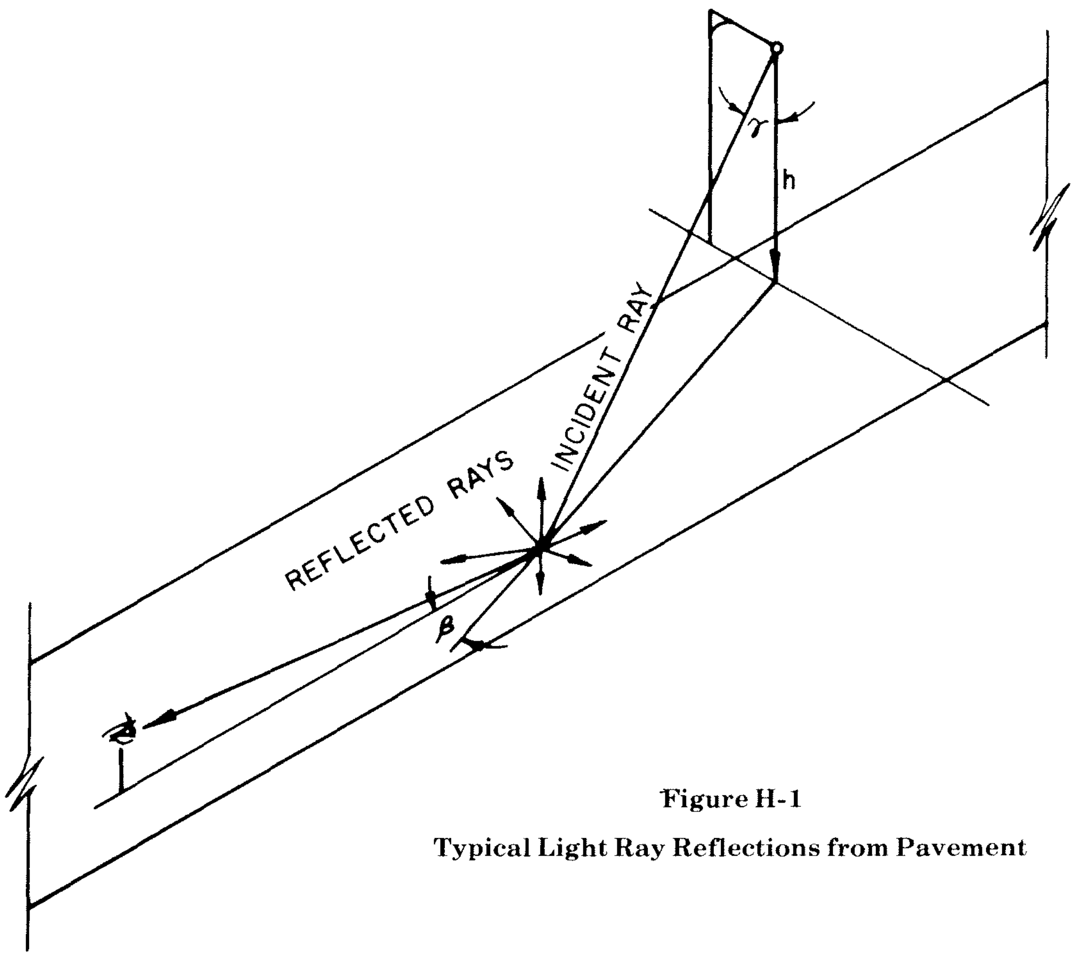


**Figure H-1**

**Typical Light Ray Reflections from Pavement**

It is a very ingenious and useful concept to present the coefficient of reflectance in this manner. The correct terminology is "Reduced Coefficient of Reflectance".

Since the r value is sometimes loosely defined as converting horizontal incident light into luminance the erronious conclusion may be reached that the r value can be used to convert the sum of all horizontal incident light from several luminaires into luminance at a point defined by the angles of the table. This is not the case. The conversion is limited to the horizontal incident light coming from a single direction defined by the angles in the table. The positionof the point on the pavement is defined and specified by the observers location and angular direction of sight.

## R-Table for Standard Surface R1*

| tan γ \ β | 0 | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 | 655 |
| 0.25 | 619 | 619 | 619 | 619 | 610 | 610 | 610 | 610 | 610 | 610 | 610 | 610 | 610 | 601 | 601 | 601 | 601 | 601 | 601 | 601 |
| 0.5 | 539 | 539 | 539 | 539 | 539 | 539 | 521 | 521 | 521 | 521 | 521 | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 | 503 |
| 0.75 | 431 | 431 | 431 | 431 | 431 | 431 | 431 | 431 | 431 | 431 | 395 | 386 | 371 | 371 | 371 | 371 | 371 | 386 | 395 | 395 |
| 1 | 341 | 341 | 341 | 341 | 323 | 323 | 305 | 296 | 287 | 287 | 278 | 269 | 269 | 269 | 269 | 269 | 269 | 278 | 278 | 278 |
| 1.25 | 269 | 269 | 269 | 260 | 251 | 242 | 224 | 207 | 198 | 189 | 189 | 180 | 180 | 180 | 180 | 180 | 189 | 198 | 207 | 224 |
| 1.5 | 224 | 224 | 224 | 215 | 198 | 189 | 171 | 162 | 153 | 148 | 144 | 144 | 139 | 139 | 139 | 144 | 148 | 153 | 162 | 180 |
| 1.75 | 189 | 189 | 189 | 171 | 153 | 139 | 130 | 121 | 117 | 112 | 108 | 103 | 99 | 99 | 103 | 108 | 112 | 121 | 130 | 139 |
| 2 | 162 | 162 | 157 | 135 | 117 | 108 | 99 | 94 | 90 | 85 | 85 | 83 | 84 | 84 | 86 | 90 | 94 | 99 | 103 | 111 |
| 2.5 | 121 | 121 | 117 | 95 | 79 | 66 | 60 | 57 | 54 | 52 | 51 | 50 | 51 | 52 | 54 | 58 | 61 | 65 | 69 | 75 |
| 3 | 94 | 94 | 86 | 66 | 49 | 41 | 38 | 36 | 34 | 33 | 32 | 31 | 31 | 33 | 35 | 38 | 40 | 43 | 47 | 51 |
| 3.5 | 81 | 80 | 66 | 46 | 33 | 28 | 25 | 23 | 22 | 22 | 21 | 21 | 22 | 22 | 24 | 27 | 29 | 31 | 34 | 38 |
| 4 | 71 | 69 | 55 | 32 | 23 | 20 | 18 | 16 | 15 | 14 | 14 | 14 | 15 | 17 | 19 | 20 | 22 | 23 | 25 | 27 |
| 4.5 | 63 | 59 | 43 | 24 | 17 | 14 | 13 | 12 | 12 | 11 | 11 | 11 | 12 | 13 | 14 | 14 | 16 | 17 | 19 | 21 |
| 5 | 57 | 52 | 36 | 19 | 14 | 12 | 10 | 9.0 | 9.0 | 8.8 | 8.7 | 8.7 | 9.0 | 10 | 11 | 13 | 14 | 15 | 16 | 16 |
| 5.5 | 51 | 47 | 31 | 15 | 11 | 9.0 | 8.1 | 7.8 | 7.7 | 7.7 | | | | | | | | | | |
| 6 | 47 | 42 | 25 | 12 | 8.5 | 7.2 | 6.5 | 6.3 | 6.2 | | | | | | | | | | | |
| 6.5 | 43 | 38 | 22 | 10 | 6.7 | 5.8 | 5.2 | 5.0 | | | | | | | | | | | | |
| 7 | 40 | 34 | 18 | 8.1 | 5.6 | 4.8 | 4.4 | 4.2 | | | | | | | | | | | | |
| 7.5 | 37 | 31 | 15 | 6.9 | 4.7 | 4.0 | 3.8 | | | | | | | | | | | | | |
| 8 | 35 | 28 | 14 | 5.7 | 4.0 | 3.6 | 3.2 | | | | | | | | | | | | | |
| 8.5 | 33 | 25 | 12 | 4.8 | 3.6 | 3.1 | 2.9 | | | | | | | | | | | | | |
| 9 | 31 | 23 | 10 | 4.1 | 3.2 | 2.8 | | | | | | | | | | | | | | |
| 9.5 | 30 | 22 | 9.0 | 3.7 | 2.8 | 2.5 | | | | | | | | | | | | | | |
| 10 | 29 | 20 | 8.2 | 3.2 | 2.4 | 2.2 | | | | | | | | | | | | | | |
| 10.5 | 28 | 18 | 7.3 | 3.0 | 2.2 | 1.9 | | | | | | | | | | | | | | |
| 11 | 27 | 16 | 6.6 | 2.7 | 1.9 | 1.7 | | | | | | | | | | | | | | |
| 11.5 | 26 | 15 | 6.1 | 2.4 | 1.7 | | | | | | | | | | | | | | | |
| 12 | 25 | 14 | 5.6 | 2.2 | 1.6 | | | | | | | | | | | | | | | |

Q0 = 0.10, S1 = 0.25, S2 = 1.53

* All values have been multiplied by 10,000. For angles, see Figure 1.

## R-Table for Standard Surface R2*

| tan γ \ β | 0 | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 | 390 |
| 0.25 | 411 | 411 | 411 | 411 | 411 | 411 | 411 | 411 | 411 | 411 | 379 | 368 | 357 | 357 | 346 | 346 | 346 | 335 | 335 | 335 |
| 0.5 | 411 | 411 | 411 | 411 | 403 | 403 | 384 | 379 | 370 | 346 | 325 | 303 | 281 | 281 | 271 | 271 | 271 | 260 | 260 | 260 |
| 0.75 | 379 | 379 | 379 | 368 | 357 | 346 | 325 | 303 | 281 | 260 | 238 | 216 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 |
| 1 | 335 | 335 | 335 | 325 | 292 | 291 | 260 | 238 | 216 | 195 | 173 | 152 | 152 | 152 | 152 | 152 | 141 | 141 | 141 | 141 |
| 1.25 | 303 | 303 | 292 | 271 | 238 | 206 | 184 | 152 | 130 | 119 | 108 | 100 | 103 | 106 | 108 | 108 | 114 | 114 | 119 | 119 |
| 1.5 | 271 | 271 | 260 | 227 | 179 | 152 | 141 | 119 | 108 | 93 | 80 | 76 | 76 | 80 | 84 | 87 | 89 | 91 | 93 | 95 |
| 1.75 | 249 | 238 | 227 | 195 | 152 | 124 | 106 | 91 | 78 | 67 | 61 | 52 | 54 | 58 | 63 | 67 | 69 | 71 | 73 | 74 |
| 2 | 227 | 216 | 195 | 152 | 117 | 95 | 80 | 67 | 61 | 52 | 45 | 40 | 41 | 45 | 49 | 52 | 54 | 56 | 57 | 58 |
| 2.5 | 195 | 190 | 146 | 110 | 74 | 58 | 48 | 40 | 35 | 30 | 27 | 24 | 26 | 28 | 30 | 33 | 35 | 38 | 40 | 41 |
| 3 | 160 | 155 | 115 | 67 | 43 | 33 | 26 | 21 | 18 | 17 | 16 | 16 | 17 | 17 | 18 | 21 | 22 | 24 | 26 | 27 |
| 3.5 | 146 | 131 | 87 | 41 | 25 | 18 | 15 | 13 | 12 | 11 | 11 | 11 | 11 | 11 | 12 | 14 | 15 | 17 | 18 | 21 |
| 4 | 132 | 113 | 67 | 27 | 15 | 12 | 10 | 9.4 | 8.7 | 8.2 | 7.9 | 7.6 | 7.9 | 8.7 | 9.6 | 11 | 12 | 13 | 15 | 17 |
| 4.5 | 118 | 95 | 50 | 20 | 12 | 8.9 | 7.4 | 6.6 | 6.3 | 6.1 | 5.7 | 5.6 | 5.8 | 6.3 | 7.1 | 8.4 | 10 | 12 | 13 | 14 |
| 5 | 106 | 81 | 38 | 14 | 8.2 | 6.3 | 5.4 | 5.0 | 4.8 | 4.7 | 4.5 | 4.4 | 4.8 | 5.2 | 6.2 | 7.4 | 8.5 | 9.5 | 10 | 11 |
| 5.5 | 96 | 69 | 29 | 11 | 6.3 | 5.1 | 4.4 | 4.1 | 3.9 | 3.8 | | | | | | | | | | |
| 6 | 87 | 58 | 22 | 8.0 | 5.0 | 3.9 | 3.5 | 3.4 | 3.2 | | | | | | | | | | | |
| 6.5 | 78 | 50 | 17 | 6.1 | 3.8 | 3.1 | 2.8 | 2.7 | | | | | | | | | | | | |
| 7 | 71 | 43 | 14 | 4.9 | 3.1 | 2.5 | 2.3 | 2.2 | | | | | | | | | | | | |
| 7.5 | 67 | 38 | 12 | 4.1 | 2.6 | 2.1 | 1.9 | | | | | | | | | | | | | |
| 8 | 63 | 33 | 10 | 3.4 | 2.2 | 1.8 | 1.7 | | | | | | | | | | | | | |
| 8.5 | 58 | 28 | 8.7 | 2.9 | 1.9 | 1.6 | 1.5 | | | | | | | | | | | | | |
| 9 | 55 | 25 | 7.4 | 2.5 | 1.7 | 1.4 | | | | | | | | | | | | | | |
| 9.5 | 52 | 23 | 6.5 | 2.2 | 1.5 | 1.3 | | | | | | | | | | | | | | |
| 10 | 49 | 21 | 5.6 | 1.9 | 1.4 | 1.2 | | | | | | | | | | | | | | |
| 10.5 | 47 | 18 | 5.0 | 1.7 | 1.3 | 1.2 | | | | | | | | | | | | | | |
| 11 | 44 | 16 | 4.4 | 1.6 | 1.2 | 1.1 | | | | | | | | | | | | | | |
| 11.5 | 42 | 14 | 4.0 | 1.5 | 1.1 | | | | | | | | | | | | | | | |
| 12 | 41 | 13 | 3.6 | 1.4 | 1.1 | | | | | | | | | | | | | | | |

Q0 = 0.08, S1 = 1.55, S2 = 3.03

* All values have been multiplied by 10,000. For angles, see Figure 1.

## R-Table for Standard Surface R3*

| tan γ \ β | 0 | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 | 294 |
| 0.25 | 326 | 326 | 321 | 321 | 317 | 312 | 308 | 308 | 303 | 298 | 294 | 280 | 271 | 262 | 258 | 253 | 249 | 244 | 240 | 240 |
| 0.5 | 344 | 344 | 339 | 339 | 326 | 317 | 308 | 298 | 289 | 276 | 262 | 235 | 217 | 204 | 199 | 199 | 199 | 199 | 194 | 194 |
| 0.75 | 357 | 353 | 353 | 339 | 321 | 303 | 285 | 267 | 244 | 222 | 204 | 176 | 158 | 149 | 149 | 149 | 145 | 136 | 136 | 140 |
| 1 | 362 | 362 | 352 | 326 | 276 | 249 | 226 | 204 | 181 | 158 | 140 | 118 | 104 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1.25 | 357 | 357 | 348 | 298 | 244 | 208 | 176 | 154 | 136 | 118 | 104 | 83 | 73 | 70 | 71 | 74 | 77 | 77 | 77 | 78 |
| 1.5 | 353 | 348 | 326 | 267 | 217 | 176 | 145 | 117 | 100 | 86 | 78 | 72 | 60 | 57 | 58 | 60 | 60 | 60 | 61 | 62 |
| 1.75 | 339 | 335 | 303 | 231 | 172 | 127 | 104 | 89 | 79 | 70 | 62 | 51 | 45 | 44 | 45 | 46 | 45 | 45 | 46 | 47 |
| 2 | 326 | 321 | 280 | 190 | 136 | 100 | 82 | 71 | 62 | 54 | 48 | 39 | 34 | 34 | 34 | 35 | 36 | 36 | 37 | 38 |
| 2.5 | 289 | 280 | 222 | 127 | 86 | 65 | 54 | 44 | 38 | 34 | 25 | 23 | 22 | 23 | 24 | 24 | 24 | 24 | 24 | 25 |
| 3 | 253 | 235 | 163 | 85 | 53 | 38 | 31 | 25 | 23 | 20 | 18 | 15 | 15 | 14 | 15 | 15 | 16 | 16 | 17 | 17 |
| 3.5 | 217 | 194 | 122 | 60 | 35 | 25 | 22 | 19 | 16 | 15 | 13 | 9.9 | 9.0 | 9.0 | 9.9 | 11 | 11 | 12 | 12 | 13 |
| 4 | 190 | 163 | 90 | 43 | 26 | 20 | 16 | 14 | 12 | 9.9 | 9.0 | 7.4 | 7.0 | 7.1 | 7.5 | 8.3 | 8.7 | 9.0 | 9.0 | 9.9 |
| 4.5 | 163 | 136 | 73 | 31 | 20 | 15 | 12 | 9.9 | 9.0 | 8.3 | 7.7 | 5.4 | 4.8 | 4.9 | 5.4 | 6.1 | 7.0 | 7.7 | 8.3 | 8.5 |
| 5 | 145 | 109 | 60 | 24 | 16 | 12 | 9.0 | 8.2 | 7.7 | 6.8 | 6.1 | 4.3 | 3.2 | 3.3 | 3.7 | 4.3 | 5.2 | 6.5 | 6.9 | 7.1 |
| 5.5 | 127 | 94 | 47 | 18 | 14 | 9.9 | 7.7 | 6.9 | 6.1 | 5.7 | | | | | | | | | | |
| 6 | 113 | 77 | 36 | 15 | 11 | 9.0 | 8.0 | 6.5 | 5.1 | | | | | | | | | | | |
| 6.5 | 104 | 68 | 30 | 11 | 8.3 | 6.4 | 5.1 | 4.3 | | | | | | | | | | | | |
| 7 | 95 | 60 | 34 | 8.5 | 6.5 | 5.2 | 4.3 | 3.4 | | | | | | | | | | | | |
| 7.5 | 87 | 53 | 21 | 7.1 | 5.3 | 4.4 | 3.6 | | | | | | | | | | | | | |
| 8 | 83 | 47 | 17 | 6.1 | 4.4 | 3.6 | 3.1 | | | | | | | | | | | | | |
| 8.5 | 78 | 42 | 15 | 5.2 | 3.7 | 3.1 | 2.6 | | | | | | | | | | | | | |
| 9 | 73 | 38 | 12 | 4.3 | 3.2 | 2.4 | | | | | | | | | | | | | | |
| 9.5 | 69 | 34 | 9.9 | 3.8 | 3.5 | 2.2 | | | | | | | | | | | | | | |
| 10 | 65 | 32 | 9.0 | 3.3 | 2.4 | 2.0 | | | | | | | | | | | | | | |
| 10.5 | 62 | 29 | 8.0 | 3.0 | 2.1 | 1.9 | | | | | | | | | | | | | | |
| 11 | 59 | 26 | 7.1 | 2.6 | 1.9 | 1.8 | | | | | | | | | | | | | | |
| 11.5 | 56 | 24 | 6.3 | 2.4 | 1.8 | | | | | | | | | | | | | | | |
| 12 | 53 | 22 | 5.6 | 2.1 | 1.8 | | | | | | | | | | | | | | | |

Q0 = 0.07, S1 = 1.11, S2 = 2.38

* All values have been multiplied by 10,000. For angles, see Figure 1.

## R-Table for Standard Surface R4*

| tan γ \ β | 0 | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 60 | 75 | 90 | 105 | 120 | 135 | 150 | 165 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 | 264 |
| 0.25 | 297 | 317 | 317 | 317 | 317 | 310 | 304 | 290 | 284 | 277 | 271 | 244 | 231 | 224 | 224 | 218 | 218 | 211 | 211 | 211 |
| 0.5 | 330 | 343 | 343 | 343 | 330 | 310 | 297 | 284 | 277 | 264 | 251 | 218 | 198 | 185 | 178 | 172 | 172 | 165 | 165 | 165 |
| 0.75 | 376 | 383 | 370 | 350 | 330 | 304 | 277 | 251 | 231 | 211 | 198 | 165 | 139 | 132 | 132 | 125 | 125 | 125 | 119 | 119 |
| 1 | 396 | 396 | 396 | 330 | 290 | 251 | 218 | 198 | 185 | 165 | 145 | 112 | 86 | 86 | 86 | 86 | 86 | 87 | 87 | 87 |
| 1.25 | 403 | 409 | 370 | 310 | 251 | 211 | 178 | 152 | 132 | 115 | 103 | 77 | 66 | 65 | 65 | 63 | 65 | 66 | 67 | 68 |
| 1.5 | 409 | 396 | 356 | 284 | 218 | 172 | 139 | 115 | 100 | 88 | 79 | 61 | 50 | 50 | 50 | 50 | 52 | 55 | 55 | 55 |
| 1.75 | 409 | 396 | 343 | 251 | 178 | 139 | 108 | 88 | 75 | 66 | 59 | 44 | 37 | 37 | 37 | 38 | 40 | 41 | 42 | 45 |
| 2 | 409 | 383 | 317 | 224 | 145 | 106 | 86 | 71 | 59 | 53 | 45 | 33 | 29 | 29 | 29 | 30 | 32 | 33 | 34 | 37 |
| 2.5 | 396 | 356 | 264 | 152 | 100 | 73 | 55 | 45 | 37 | 32 | 28 | 21 | 20 | 20 | 20 | 21 | 22 | 24 | 25 | 26 |
| 3 | 370 | 304 | 211 | 95 | 63 | 44 | 30 | 25 | 21 | 17 | 16 | 13 | 12 | 12 | 13 | 13 | 15 | 16 | 17 | 19 |
| 3.5 | 343 | 271 | 165 | 63 | 40 | 26 | 19 | 15 | 13 | 12 | 11 | 9.8 | 9.1 | 8.8 | 8.8 | 9.4 | 11 | 12 | 13 | 15 |
| 4 | 317 | 238 | 132 | 45 | 24 | 16 | 13 | 11 | 9.6 | 9.0 | 8.4 | 7.5 | 7.4 | 7.4 | 7.5 | 7.9 | 8.6 | 9.4 | 11 | 12 |
| 4.5 | 297 | 211 | 106 | 33 | 17 | 11 | 9.2 | 7.9 | 7.3 | 6.6 | 6.3 | 6.1 | 6.1 | 6.2 | 6.5 | 6.7 | 7.1 | 7.7 | 8.73 | 9.66 |
| 5 | 277 | 185 | 79 | 24 | 13 | 8.3 | 7.0 | 6.3 | 5.7 | 5.1 | 5.0 | 5.0 | 5.1 | 5.4 | 5.5 | 5.8 | 6.1 | 6.3 | 6.9 | 7.7 |
| 5.5 | 257 | 161 | 59 | 19 | 9.9 | 7.1 | 5.7 | 5.0 | 4.6 | 4.2 | | | | | | | | | | |
| 6 | 244 | 140 | 46 | 13 | 7.7 | 5.7 | 4.8 | 4.1 | 3.8 | | | | | | | | | | | |
| 6.5 | 231 | 122 | 37 | 11 | 5.9 | 4.6 | 3.7 | 3.2 | | | | | | | | | | | | |
| 7 | 218 | 106 | 32 | 9.0 | 5.0 | 3.8 | 3.2 | 2.6 | | | | | | | | | | | | |
| 7.5 | 205 | 94 | 26 | 7.5 | 4.4 | 3.3 | 2.8 | | | | | | | | | | | | | |
| 8 | 193 | 82 | 22 | 6.3 | 3.7 | 2.9 | 2.4 | | | | | | | | | | | | | |
| 8.5 | 184 | 74 | 19 | 5.3 | 3.2 | 2.5 | 2.1 | | | | | | | | | | | | | |
| 9 | 174 | 66 | 16 | 4.6 | 2.8 | 2.1 | | | | | | | | | | | | | | |
| 9.5 | 169 | 59 | 13 | 4.1 | 2.5 | 2.0 | | | | | | | | | | | | | | |
| 10 | 164 | 53 | 12 | 3.7 | 2.2 | 1.7 | | | | | | | | | | | | | | |
| 10.5 | 158 | 49 | 11 | 3.3 | 2.1 | 1.7 | | | | | | | | | | | | | | |
| 11 | 153 | 45 | 9.5 | 3.0 | 2.0 | 1.7 | | | | | | | | | | | | | | |
| 11.5 | 149 | 41 | 8.4 | 2.6 | 1.7 | | | | | | | | | | | | | | | |
| 12 | 145 | 37 | 7.7 | 2.5 | 1.7 | | | | | | | | | | | | | | | |

Q0 = 0.08, S1 = 1.55, S2 = 3.03

* All values have been multiplied by 10,000. For angles, see Figure 1.

## APPENDIX J
## USE OF PROGRAMMABLE HAND HELD CALCULATORS

The engineering calculator has superseded the slide rule in the colleges today due to its superior speed, accuracy and digital readout. The simplest and cheapest of these have most mathematical functions but only limited memory capability. The work sheet examples are all based on the use of a calculator with only one memory. With such calculators only a limited amount of a complex formula can be completed before it is necessary to write down part of the calculation for future reference.

The next step is the programmable calculator with many memories and the ability to retain a complex equation or series of equations in memory, with such a calculator the work sheets can be simplified. Programmable calculators must be re-programmed each time they are turned on and this can be a time consuming operation if only a few repetitive calculations are made before the calculator is turned off.

The magnetic card programmable calculator overcomes this problem by retaining the program on a magnetic card that is inserted each time that the program is to be used. Such calculators can be considered as a limited capacity hand held computer. At this time they do not have the capacity to hold and refer to large tables of data such as the candela tables or the R-Tables so that it is necessary to interrupt the calculation and manually look up such data and enter it into the calculator before proceeding with the calculator run. Programs for calculating luminance on such calculators have been written by several people but are not known to be available commercially.

## APPENDIX K
## USE OF COMPUTERS

The computer itself, its peripheral equipment such as printers, magnetic memories, tape memories, monitors and keyboards are referred to as "hardware." The particular coded directions to enable it to perform certain tasks is known as "software." Computers come in all sizes and prices. Large computers are capable of handling the inputs from a number of sources at the same time and are normally operated from several separate work stations called terminals. A terminal may be as simple as a teletypewriter (or equivalent) or as complex as another computer which holds the information and transmits it partly preprocessed to the main computer. Terminals may be located at a distance and use a telephone connection to the large computer.

Small computers under the complete control of one person at a time are often called "Personal Computers" since there are no time sharing costs and constraints. After a personal computer is bought and paid for, the only expense is the electricity and maintenance costs. By contrast a large computer operated from a number of remote terminals will likely charge both a "connect time fee" and "compute time fee" and if a remote terminal is used the cost of the telephone call while connected must be considered. These constraints generally mean that the programs (software) used to operate large computers are less "friendly" than the programs written for personal computers. For example, the input to a large high speed remote computer for the street width, mounting height, spacing, grid size, grid starting point, grid ending point, etc. may be input as a string of numbers separated by commas, thus reducing connect time costs. With a personal computer, the input may be answers to individual questions, asked by the computer in sequence, which takes a longer time but is more "friendly". This is also called "conversational mode" or "menu input." The instructions of how to use and send input, and receive output from a program are called the "documentation."

While a few individuals have written programs for personal computers to calculate pavement luminance none are known to be commercially available at this time. The chief problem with regard to making available and using such "personal computer programs" is that of inputing the candela table data. At this time, it can be done only by typing the candela table into the computer. It can then be stored on tape or disk and easily entered the next time needed but for every different candela table needed it must be typed in once. With each brand of personal computer using a slightly different dialect of the "basic" language, manufacturers of luminaires can hardly be expected to supply or sell their data on disk or tape in the many different formats required by the different brands of personal computers. This problem in standardization will be solved in the future.

A solution currently in use is the photometric data base concept offered by time sharing computer services. The photometric data of several manufacturers, in the form of candela tables, is stored in the data base and programs run on the time sharing service may access the data base thru the use of manufacturer and luminaire code numbers.

Just as slide rules superseded pad and pencil, and calculators have superseded slide rules, we can feel certain that the personal computer, or terminal work station, will supercede the calculator for various forms of engineering calculations. The calculation and prediction of pavement luminance was put off for years because of the complexity of the many repetitive calculations required. In a similar manner the calculation of the visibilty of a target requires repetitive calculations even more complex than those for pavement luminance but they can be handled by computers. With the coming ability to calculate and predict the visibility of a target on the roadway under various conditions the relationship between the criteria specified, accident reductions, and traffic flow will be more closely related. The result may well be that the cost of a fixed lighting system will go down while its benefits increase.

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3. C.I.E., "Publication 30: Calculation and Measurement of Luminance and Illuminance in Road Lighting," CIE (1976)

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15. Supplementary Notes

FHWA Contract Manager: William L. Williams (HRT-20)

16. Abstract

The Roadway Lighting Handbook (IP-78-15) deals with all aspects of visibility requirements, equipment, system design, operation and maintenance of a roadway lighting system. A major change from illuminance to pavement luminance as a criteria for lighting design has been made in ANSI RP-8, 1983. This addendum to the chapter on lighting design (Chapter 6) explains the meaning of the new terminology, gives luminance criteria and explains design procedures. Alternate methods of design using either a hand calculator, graphical aids, or computer printouts are included.

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