A Microcomputer Program for Use with the American National Standard Practice for Roadway Lighting

L. ELLIS KING

ABSTRACT

Recommended roadway lighting practices are set forth in the 1983 American National Standard Practice for Roadway lighting. In the past, horizontal illuminance has been recognized in the 1983 Standard Practice as the basis for design of roadway lighting. However, lighting engineers have long known that pavement luminance and veiling luminance criteria provide a better correlation with roadway lighting as perceived by the driver. In the 1983 Standard Practice, luminance is recognized as the primary and preferred basis for design, and values for luminance and veiling luminance are recommended. Illuminance criteria are retained as an acceptable alternative. A microcomputer program has been developed for use with the Standard Practice. The program calculates values for illuminance, luminance, and veiling luminance by using input data that include pavement directional reflectance factors, lamp/luminaire candlepower arrays, and geometry of the lighting system. These values are calculated at regularly spaced test points between two adjacent luminaires. For luminance and veiling luminance calculations, the observer moves through the system viewing the roadway at a fixed distance ahead. All calculations are carried out by using formulas and procedures recognized in the Standard Practice, and the output includes values for both the illuminance and luminance design criteria that are contained in the Standard Practice. Written in Microsoft BASIC-80, the program requires a control program for microcomputers, a disk operating system, a RAM of at least 64K, and two disk drives.

The principal purpose of roadway lighting, as stated in the 1983 American National Standard Practice for Roadway Lighting, is "to produce quick, accurate, and comfortable seeing at night" (1). The ability to see at night contributes to the safe and efficient flow of traffic on highways during the hours of darkness. However, in many instances, limitations of the human eye prevent vehicle headlights alone from completely satisfying visual nighttime driving requirements. In these cases, fixed roadway lighting aids the driver by providing earlier warnings of hazards on or near the highway. The driver can then use this early information to formulate his response to any unsafe condition. Fixed roadway lighting also contributes to a more pleasant and comfortable night-driving environment, which, in turn, reduces driver fatigue and improves driver efficiency.

Recommended roadway lighting practices for North America are set forth in the Standard Practice. The Standard Practice is revised approximately every 5 years under the sponsorship of the Illuminating Engineering Society of North America. The latest version (1983) has been revised from the previous 1977 version to include a luminance method for design that also considers veiling luminance (glare). Although the new luminance method is the preferred method for design, it is recognized in the Standard Practice that because of complexity, the calculation and measurement of pavement luminance may be difficult and burdensome for some agencies. For this reason, the older illuminance design procedures have been retained in the 1983 revision as an acceptable alternative.

Also in the Standard Practice, pavement luminance is recognized as the critical design variable as follows:

> The criteria for roadway lighting in North America have been based on horizontal illuminance. However, it is known that pavement luminance and veiling luminance (glare) criteria provide a better correlation with the visual impression of roadway lighting quality. It is possible to satisfy illuminance criteria and fall far short of the luminance criteria.

The importance of pavement luminance in roadway lighting design has been known to illuminating engineers for many years and has been the subject of numerous research projects and reports, many of which are listed in the bibliography of the Standard Practice. For readers unfamiliar with the illuminance versus luminance concept, the following section provides an update of a previous report on the subject (2).

ILLUMINANCE VERSUS LUMINANCE

Illuminance is the measure of the amount of light flux striking a surface. It is independent of (a) the direction from which the light comes, (b) the number of light sources and their locations, (c) the type of light source, and (d) the type of surface it strikes. A surface may be illuminated to a given level by one concentrated light source placed perpendicular to the surface or by several less intense sources placed at an angle to the surface. The illuminance is the same whether the surface is a traffic-polished asphalt pavement or a new, rough-finished concrete pavement. For roadway lighting, illuminance is a widely understood and easily calculated quantity. However, it has very little value in describing the actual observed highway situation.

Luminance is a measure of the amount and concentration of light flux leaving a surface and is the only light by which an object is seen. It is the luminance that controls the magnitude of the sensation that the brain receives of an object. The luminance of a surface depends on all of the quantities of which illuminance is independent, including the direction from which the light comes, the directions from which the surface is viewed, and the light-reflecting characteristics of the surface itself. The amount of light falling on a small area of a surface may be measured as the illuminance on that area. For a highway pavement, this incident light is generally reflected in all directions and its directional distribution is determined by the properties of the surface and the manner in which the light strikes the surface. The apparent luminance of the surface is determined by the amount of light reflected toward the observer's eye.

All surfaces, including roadway surfaces, may be classified into three major groups according to the way in which they reflect light. The ideal specular surface is one that reflects all the luminous flux received by a point at an angle of reflection exactly equal to the angle of incidence. The reflected ray, the normal to the surface at the point of incidence, and the incident ray all lie in the same plane. An observer looking at a perfect specular surface along the direction of the reflected light will see an undistorted image of the object, and the image will be the same size as the object. The luminance of the image will be proportional to the luminance of the object. Some practical surfaces, such as mirrors, highly polished metal surfaces, and the surface of liquids, closely approximate the ideal specularly reflecting surface.

The perfectly diffuse surface is at the opposite pole from the ideal specular surface. The diffuse (or mat) surface reflects light as a cosine function of the angle from the normal, regardless of the angle of incidence. Because the luminance of the surface is equal to the intensity divided by the projected area that is also a cosine function of the angle from the normal, the perfectly diffuse surface appears equally bright to an observer from any viewing angle. The luminance of this surface is nearly independent of the luminance of the source of light but proportional to the illuminance of the surface. Photometric test plates exhibit the characteristics of almost uniform diffusion for most practical purposes.

Many surfaces, such as a mirror or highly polished steel plate, closely approximate the ideal specular surface, and many surfaces, such as white mat-finished paper or walls finished with flat white paint, would appear to closely approximate the perfectly diffuse surface at first glance. However, closer inspection reveals that these surfaces behave as diffuse surfaces only if the angle of incidence is close to 0 degrees as measured from the normal to the surface. Large angles of view will also cause these surfaces to exhibit properties unlike those of a diffuse surface.

Most surfaces encountered in everyday life fall between the ideal specular and ideal diffuse surfaces and exhibit properties of mixed reflection. These surfaces form no geometric image but act somewhat as a diffuse surface, showing some preference as to direction of reflection. The luminance of such a surface changes with changes in angle of incidence and observer viewing angle. The larger these angles become, the more noticeable are their effect.

Roadway surfaces where observer viewing angles and angles of incident light (as measured from the normal) range from 86 to 89 degrees and from 0 to 87 degrees, respectively, exhibit characteristics of mixed reflection. A single luminaire suspended over a roadway produces a single luminous patch on the surface of the roadway. To the observer traveling on the roadway, this luminous patch has the form of a T with the tail extending toward the observer. The luminous patch is almost completely on the observer's side of the luminaire because the reflecting properties of the pavement surface are such that only a small amount of the light striking the surface in a direction away from the observer is reflected back toward the observer. The tail of the T always extends toward the observer regardless of his position on the roadway. The size, shape, and luminance of the T depends to a great extent on the surface characteristics of the pavement. For a mat surface, the head of the T predominates, and only a short tail is evident; a surface polished smooth by traffic, however, exhibits a long tail and a small head. On a wet roadway, the head may completely disappear and the tail may become very elongated.

VEILING LUMINANCE

Roadway lighting designers must also take into consideration the veiling luminance (glare) produced by the lighting system itself. A discontinuity of brightnesses within the field of view is caused by the luminaires for most roadway lighting conditions. This results in stray light within the eye, which, in turn, produces a veiling luminance that is superimposed on the retinal image of the object to be seen, thus reducing the apparent brightness of the object as well as the background against which it is viewed. The ability of the driver to perform visual tasks is thereby reduced (1).

ROADWAY LIGHTING CALCULATIONS

Levels of illuminance are relatively easy to determine either by measurement or calculation. In the past, the derivation of roadway luminance data from photometric data required time-consuming and tedious measurement of pavement reflectance factors as well as a great number of calculations. However, recent technical developments have greatly simplified the data collection task and laboratory reflectance data are now available for a wide variety of pavement surfaces (3). Calculation procedures and computer programs have also been developed and reported together with methods for determining glare (4-8). However, the programs have often been limited to mainframe computers, and there has been no universal agreement with regard to computational methods.

The Standard Practice includes procedures and formulas for calculating illuminance, luminance, and veiling luminance. The critical expressions are given in the following text. (Appendixes B and C of the Standard Practice may be referred to for their derivation and a more detailed discussion.)

The unit of measurement of illuminance (E) is the lux, which is equal to 1 lumen per m^2. As previously stated, illuminance is the measure of the amount of light flux striking a surface. When the incident light strikes the surface an at angle, the horizontal component of the illuminance (E_h) can be expressed as

$$E_h = [I (\cos \gamma)]/D^2 \qquad (1)$$

where

I = luminous intensity in candelas,
γ = angle of incidence, and
D = distance from the source.

The surface luminance (L) is the luminous flux per steradian reflected by a unit area of surface in the direction of an observer. In general terms, the surface luminance can be expressed as

$$L = [(1/\pi)E_h]\ [q(\beta, \gamma)] \quad (2)$$

where E_h is the horizontal illuminance in lux, and $q(\beta, \gamma)$ is the directional reflectance coefficient for angles of incidence β and γ.

The preceding equations may be applied to the typical roadway lighting situation shown in Figure 1. For the single luminaire shown, the horizontal illuminance at point P can be expressed as

$$E_h = [I(\phi, \gamma)]\ [\cos\gamma]/D^2 \quad (3)$$

and

$$D^2 = H^2/(\cos^2\gamma) \quad (4)$$

where H is the mounting height of the luminaire. Substitution for the D^2 value in Equation 3 gives

$$E_h = [I(\phi, \gamma)]\ (\cos^3\gamma)/H^2 \quad (5)$$

Further substitution of E_h of Equation 5 into Equation 2 gives the following expression for calculating luminance:

$$L = (1/\pi)[q(\beta, \gamma)]\ [I(\phi, \gamma)]\ (\cos^3\gamma)/H^2 \quad (6)$$

In practice $[q(\beta, \gamma)][\cos^3\gamma]$ is expressed as a single luminance coefficient r, and is usually given in tabular form for various types of road surfaces. The luminous intensity $[I(\phi, \gamma)]$, may be determined from published candela tables or obtained from luminaire manufacturers. A simplified expression for L can then be written as:

$$L = (1/\pi)\ [r(\beta, \gamma)]\ [I(\phi, \gamma)]/10{,}000\ H^2 \quad (7)$$

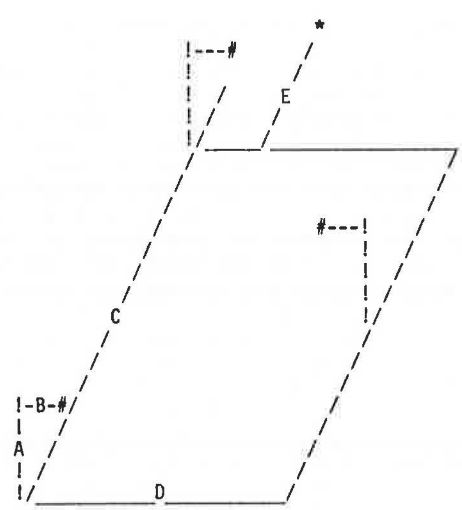
The angles β, γ, and ϕ are as shown in Figure 1. The 10,000 in the denominator of Equation 7 reflects the fact that tabulated r values are multiplied by 10,000 for ease of manipulation.

For a typical roadway lighting situation, both the illuminance and luminance at point P is contributed to by several luminaires. When this is the case, the illuminance and luminance values at point P represent the sum of contributions from all luminaires.

Appendix C of the Standard Practice gives a brief description of both discomfort glare and disability glare, which are the two types of glare encountered in most roadway lighting systems. While discomfort glare produces a sensation of ocular discomfort, it does not reduce the ability to see. No system for evaluating discomfort glare has been universally adopted and there is no widely accepted procedure for calculating discomfort glare. However, agreement has been reached with regard to calculating disability glare or veiling luminance (6). The veiling luminance (L_v) for the single luminaire shown in Figure 2 can be expressed as follows:

$$L_v = 10\ E_v/(\theta^2 + 1.5\ \theta) \quad (8)$$

where E_v is the vertical illuminance in the plane of the pupil of the observer's eye, in luxes, and θ is the angle between the line of sight and the luminaire, in degrees.



A Mounting Height
B Overhang
C Spacing
D Roadway Width
E Viewing Distance
* Observer
# Lamp

FIGURE 1 Reflectance angles.

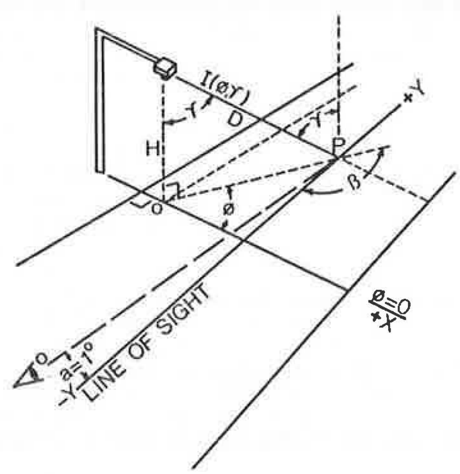


FIGURE 2 Veiling luminance angles.

This empirically derived expression can then be used to calculate the total veiling luminance for a system of luminaires by summing the individual contributions.

THE MICROCOMPUTER PROGRAM

The previously mentioned formulas have been used to develop a roadway lighting program that is compatible with the design and evaluation procedures recommended in the Standard Practice. The program calculates values for illuminance, luminance, and veiling luminance by using input data that includes pavement directional reflectance factors, lamp/luminaire candela arrays, and geometry of the system. These values are determined at regularly-spaced calculation points between two adjacent luminaires for a dynamic observer moving through the system while maintaining a fixed viewing distance of 83m.

Written in Microsoft's BASIC-80 language, the program requires a control program for microcomputers (CP/M), a disk operating system, a minimum random-access memory (RAM) of 64K, and two disk drives. The Microsoft BASIC and program are stored on the first disk while the second disk contains pavement reflectance factor tables and candela arrays. The program's versatility and flexibility are shown by the functions it performs:

1. The program calculates values for the parameters: illuminance; luminance; and veiling luminance, including average values, maximum and minimum values, and ratios of these.
2. A grid system of calculation points on the roadway is established for the moving observer in accordance with Standard Practice procedures.
3. The lighting systems being evaluated may include one side, opposite, or staggered luminaire arrangements. A single luminaire can also be evaluated for area lighting.
4. Roadway width, lane width, and number of lanes may be specified and a median may be included.
5. Values for luminaire spacing, mounting height, and overhang may be specified as well as a light loss factor.
6. The results of the calculations are presented in the form of a printout of the highway grid calculation points and summary tables.

On initiation, the program gives an introduction and then displays the roadway lighting system diagram shown in Figure 3. A brief description of each

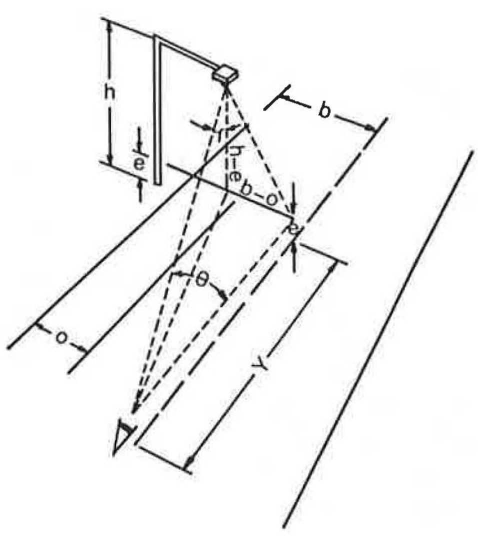


FIGURE 3 Lighting system diagram.

of the input parameters is given and the user is asked to supply a value for each. If needed, the lighting system diagram can be recalled at any time for review. After all input parameters have been assigned a value, they are listed as shown in the following table:

Input Parameter	Assigned Value
Road surface	R3
Luminaire number	1
Light loss factor	0.8
Configuration	Opposite
Spacing	45
Mounting height	12.0
Overhang	3.0
Roadway width	24.0
Lane width	4.0
Number of lanes in direction of travel	3
Viewing distance	83
Longitudinal grid spacing	4.5

If so desired, the user may change any of the values before proceeding. The following input parameters are defined in accordance with the Standard Practice, and metric units are used exclusively:

1. Road surface--The user may select any of the four standard road surfaces for which reflectance data are given in the Standard Practice. The corresponding r-Tables are stored within the program and additional tables may be added.
2. Luminaire number--The example luminaire/lamp intensity distribution shown as Table B5 in the Standard Practice is stored within the program. The user may add additional candela arrays in the same format.
3. Light loss factor--The total light loss factor should include all factors that reduce the original output of the selected luminaire/lamp. This factor may range from 0.1 to 1.0.
4. Configuration--One-sided, staggered, and opposite arrangement, as shown in Figure 2 of the Standard Practice, are provided for within the program. The median arrangement is not directly provided for, but can be produced by manipulation of the one-sided arrangement. A single luminaire configuration is also included for area lighting.
5. Spacing--Luminaire spacing is the longitudinal distance measured between adjacent luminaires, as shown in Figure 2 of the Standard Practice. This distance may range from 5 to 300 m.
6. Mounting height--Mounting height is measured from the luminaire light center to the pavement surface, as shown in Figure 2 of the Standard Practice. This distance may range from 3 to 20 m. At the present time, no provision is made for high mast cluster lighting.
7. Overhang--Luminaire overhang is measured transversely from the pavement edge or curb, as shown in Figure 2 of the Standard Practice. This distance may range from 0 to 15 m.
8. Roadway width--The roadway width is the transverse distance between pavement or curb edges. If a median is present, it is included in this total distance, which may range from 2 to 60 m.
9. Lane width--All lanes are assumed to be of equal width, ranging from 1 to 60 m. The total width of all lanes, plus any median, cannot exceed the roadway width upper limit of 60 m.
10. Number of lanes in direction of travel--This parameter provides for highways with an unequal number of lanes in each direction.

The following two parameters are not input by the user; however, they are included in the preceding table as a reminder.

1. Viewing distance--The observer viewing distance is fixed at 83 m. This corresponds to an eye height of 1.45 m and a line of sight downward 1 degree below horizontal that is parallel to the

roadway edge along quarter-points as shown in Figure B7 of the Standard Practice.

2. Grid spacing--The number shown here is the longitudinal distance between calculation points. In accordance with the Standard Practice, it is determined by dividing the space by 10, not to exceed 5m between points, with a minimum of 10 points.

All calculations are carried out by using procedures and formulas recognized in the Standard Practice. Illuminance values for a given point are calculated with the user-specified lamp/luminaire candela array and the user-specified system geometry. At least 1 luminaire behind and at least 3 luminaires ahead of a test point are considered to contribute to the illuminance at that point. Pavement luminance values are calculated by using reflectance values for the user-specified road surface, geometry of the lighting system, and Standard Practice observer position. As in the illuminance calculations, at least 1 luminaire behind and at least 3 luminaires ahead of a calculation point are considered to contribute to the luminance of the point. The calculations for veiling luminance (a) are based on the total amount of light from all luminaires directed toward the eye as the observer moves through the system, and (b) include consideration of any shielding provided by the roof of the automobile. The program calculates (a) values for individual test points between adjacent luminaires, and (b) average values for the test points, and (c) various ratios of interest.

PROGRAM RESULTS

Figures 4 through 6 show the program's output for the roadway lighting system listed in Table 1. The luminaires are located on a 24-m-wide, 6-lane roadway in an opposed arrangement. The spacing between luminaires is 45 m, the mounting height is 12 m, and the overhang is 3 m. The moving observer is viewing the roadway 83 m ahead as he travels through the system. The light loss factor is 0.8 and calculation points are at longitudinal intervals of 4.5 m. The candela array is from Table B5 of the Standard Practice and the road surface is Standard Surface R3 from Table 1 of the same document. This is a typical system for a major street located in a commercial area.

The illuminance values shown in Figure 4 are acceptable for a major street in a commercial area, as recommended in Table 2 of the Standard Practice.

ILLUMINANCE (LUX)

PAVEMENT NO = 3 LUMINAIRE NO = 1 LIGHT LOSS = 0.8

OPPOSITE ARRANGEMENT DYNAMIC OBSERVER

LUMINAIRE SPACING	MOUNTING HEIGHT	OVERHANG	ROADWAY WIDTH	LANE WIDTH
45.0	12.0	3.0	24.0	4.0

	TRANSVERSE DISTANCE					
	Lane # 1		Lane # 2		Lane # 3	
LONGITUDINAL DISTANCE	1.0	3.0	5.0	7.0	9.0	11.0
0	27	29	30	35	35	34
4.5	18	25	30	33	30	31
9	15	18	22	22	20	18
13.5	12	13	14	14	14	12
18	9	11	11	12	12	11
22.5	7	10	10	11	12	12
27	9	11	11	12	12	11
31.5	12	13	14	14	14	12
36	15	18	22	22	20	18
40.5	18	25	30	33	30	31
45	27	29	30	35	35	34

AVERAGE ILLUMINANCE = 20
MAXIMUM ILLUMINANCE = 35
MINIMUM ILLUMINANCE = 7
MAXIMUM / MINIMUM = 4.7
AVERAGE / MINIMUM = 2.7

FIGURE 4 Illuminance values.

LUMINANCE (CD/SQ.M.)

PAVEMENT NO = 3 LUMINAIRE NO = 1 LIGHT LOSS = 0.8

OPPOSITE ARRANGEMENT DYNAMIC OBSERVER

LUMINAIRE SPACING	MOUNTING HEIGHT	OVERHANG	ROADWAY WIDTH	LANE WIDTH
45.0	12.0	3.0	24.0	4.0

	TRANSVERSE DISTANCE					
	Lane # 1		Lane # 2		Lane # 3	
LONGITUDINAL DISTANCE	1.0	3.0	5.0	7.0	9.0	11.0
0	0.731	0.730	0.936	1.058	1.334	1.383
4.5	0.502	0.552	0.747	0.988	0.983	1.024
9	0.613	0.672	0.865	0.957	0.928	0.884
13.5	0.605	0.659	0.750	0.808	0.839	0.755
18	0.570	0.625	0.705	0.753	0.803	0.785
22.5	0.579	0.756	0.793	0.884	0.935	0.992
27	0.840	1.063	1.008	1.092	1.135	0.965
31.5	1.002	1.120	1.151	1.185	1.167	1.138
36	0.876	0.919	1.159	1.241	1.238	1.287
40.5	0.718	0.791	1.065	1.339	1.357	1.449
45	0.731	0.730	0.936	1.058	1.334	1.383

AVERAGE LUMINANCE = 0.9
MAXIMUM LUMINANCE = 1.4
MINIMUM LUMINANCE = 0.5
MAXIMUM / MINIMUM = 2.9
AVERAGE / MINIMUM = 1.9

FIGURE 5 Luminance values.

VEILING LUMINANCE (CD/SQ.M.)

PAVEMENT NO = 3 LUMINAIRE NO = 1 LIGHT LOSS = 0.8

OPPOSITE ARRANGEMENT DYNAMIC OBSERVER

LUMINAIRE SPACING	MOUNTING HEIGHT	OVERHANG	ROADWAY WIDTH	LANE WIDTH
45.0	12.0	3.0	24.0	4.0

	TRANSVERSE DISTANCE					
	Lane # 1		Lane # 2		Lane # 3	
LONGITUDINAL DISTANCE	1.0	3.0	5.0	7.0	9.0	11.0
0	0.119	0.142	0.127	0.097	0.088	0.095
4.5	0.171	0.205	0.171	0.129	0.118	0.121
9	0.244	0.289	0.222	0.163	0.138	0.111
13.5	0.318	0.337	0.257	0.180	0.119	0.084
18	0.017	0.025	0.030	0.028	0.019	0.012
22.5	0.022	0.030	0.036	0.033	0.024	0.017
27	0.032	0.036	0.042	0.038	0.029	0.021
31.5	0.039	0.046	0.051	0.042	0.034	0.029
36	0.059	0.068	0.069	0.057	0.049	0.048
40.5	0.084	0.095	0.091	0.073	0.065	0.071
45	0.119	0.142	0.127	0.097	0.088	0.095

AVERAGE VEILING LUMINANCE = 0.095
MAXIMUM VEILING LUMINANCE = 0.337
MINIMUM VEILING LUMINANCE = 0.012
MAX VEILING/AVG LUMINANCE = 0.359

FIGURE 6 Veiling luminance values.

TABLE 1 Calculated Luminance Values for Standard Road Surfaces

	Pavement Classification				
Luminance	R1 (cd/m^2)	R2 (cd/m^2)	R3 (cd/m^2)	R4 (cd/m^2)	Recommended Value
Average	0.9	0.8	0.9	1.2	1.2
Maximum	1.4	1.3	1.4	1.9	
Minimum	0.4	0.5	0.5	0.6	
Maximum to minimum	3.2	2.8	2.9	2.9	5 to 1
Average to minimum	2.0	1.8	1.9	1.9	3 to 1
Veiling to average	0.395	0.411	0.359	0.280	0.3 to 1

The average illuminance of 20 lux is greater than the recommended value of 17 lux for an R3 pavement classification and the average-to-minimum illuminance uniformity ratio of 2.7 is less than the recommended ratio of 3 to 1. On the basis of an illuminance method for design, this would be an acceptable lighting system for the specified conditions; however, the luminance and veiling luminance values shown in Figures 5 and 6 do not meet the Standard Practice recommended values. Although the maximum to minimum luminance value of 2.9 and average-to-minimum luminance value of 1.9 are acceptably less than the recommended ratios of 5 to 1 and 3 to 1, respectively, the average luminance of 0.9 cd/m^2 is unacceptable when compared to the recommended value of 1.2 for an R3 pavement classification. In addition, the veiling luminance-to-average luminance value of 0.359 exceeds the recommended ratio of 0.3 to 1.

COMPARISON OF STANDARD SURFACES

In view of the previously mentioned results and as a further demonstration of the program, the output for these results and three additional runs are summarized in Table 1. The geometry of the system and the luminaire/lamp were held constant and only the road surface was varied for each run. In each case, the lighting system would be acceptable based on an illuminance method for design; however, acceptable levels of luminance would be produced only with Standard Pavement Surface R4. This is attributable to the mostly specular mode of reflectance for the smooth textured asphalt surface as compared with the slightly specular, mixed, or diffuse mode of reflection for the other three standard surfaces.

SUMMARY

With the standardization of computational methods and procedures and the ever-increasing availability of the microcomputer, it is now possible to eliminate compromises and shortcut procedures previously used in designing and evaluating roadway lighting systems. Thus, it is practical for engineers involved in roadway lighting design and evaluation to base their recommendations on luminance considerations, rather than on illuminance. The microcomputer program presented here combines readily available lamp/luminaire candela arrays with pavement directional reflectance factor data to calculate illuminance, luminance, and veiling luminance in accordance with the Standard Practice. It is anticipated that this design and evaluation program will be of use to the practicing engineer in providing a better night driving environment through improved roadway lighting.

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