decreases, the rain rate increases because the amount of water in the air at any instantaneous time also increases. And at 0-deg windshield rake angle an increase in velocity has no effect on effective rain rate.

Figure 9 shows a plot of effective rain rates versus vehicle speed for selected rainfall rates. This plot makes two significant assumptions: (a) that the vehicle velocity vector and the rainfall were at 90 deg to each other and (b) that the effects of wind could be ignored. The curves show that the rain produced by the simulator accurately reflects rain rates that are typically encountered. For example, to simulate the condition of a vehicle having a velocity of 88 km/h (55 mph) in a rainfall of 3.8 cm/h (1.5 in/h) requires a static rain rate of 10.80 cm/h (4.25 in/h). The dotted lines in the figure show this relation.

CONCLUSIONS

The significant results of this research can be summarized as follows:

1. During rain conditions, the primary factor that reduces visibility is the film of water on the windshield, which impairs vision by reducing the optical resolution. The S-1 studies, when compared to the S-2 studies (no rain on the windshield versus rain on the windshield), demonstrate this point. At a 2.5-cm/h (1-in/h) simulator rain rate [equivalent to a 0.75-cm/h (0.30-in/h) effective rate at 88 km/h (55 mph)], vision through the windshield is reduced to the point that acuity decreases to 10 min of visual arc, which corresponds to a static visual acuity of 20/200. However, the daylight visual acuity through a 10.2-cm/h (4-in/h) simulator rain, with no water on the windshield, produced a visual degradation equivalent to only 2.5 min of visual arc, which corresponds to a static visual acuity of 20/50.
2. The simulator results showed a precipitous decrease in the detection and identification of pertinent targets (i.e., a man or an automobile) between the 5.1 and 10.2-cm (2 and 4-in/h) simulated rain rates.
3. Windshield wipers restore visual acuity to approximately the same level as would be expected if the vehicle remained outside the rain and the driver looked through it. Higher windshield-wiper speeds do not significantly improve visibility at speeds above 50 cpm.
4. A regression model of visual degradation in terms of the increase in threshold visual angle as a function of the rain rate is given by Equation 1.
5. There are significant interactions between rain and the glare from oncoming vehicles.
6. Raindrop size distribution is a significant factor in visibility reduction, especially at low levels of illumination. A concentration of smaller drop sizes, i.e., those less than 0.5 mm in diameter, causes serious visual degradation through reduction of contrast and the decrease in the quality of the texture background.

ACKNOWLEDGMENT

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Computer Program for Roadway Lighting

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The development of a computer program for the design and evaluation of fixed highway lighting is reported. The program calculates the illuminance, luminance, and disability veiling brightness in each lane at specified grid points on the road surface for regular, straight rows of luminaires, for a straight highway up to six lanes wide. Isoilluminance and isoluminance diagrams can also be obtained. The program can be used as a design tool in the following way: For a chosen road geometry and a selected luminaire type, the designer can determine the performance of a proposed lighting design by calculating the relevant performance measures and comparing the results with the current accepted, or the proposed new standards. Many different designs can be rigorously evaluated in a short time. In conjunction with photometric measurements, the program was used to evaluate the performance of the existing design on the Toronto Bypass. Lighting designs based on calculations of luminance and disability veiling brightness are preferable to those based on illuminance because nighttime visibility is determined by the former rather than the latter.

Modern electronic computer methods are entering the field of outdoor lighting and assisting and improving the design and management of lighting systems. This paper presents a model for a computer program that combines the design tasks of luminaire selection, performance evaluation, and, at a later stage, economic comparison of various alternative systems. The domain of this model is limited to straight, regular systems of roadway lighting, but similar models can be used for other lighting systems, such as parking lots, shopping plazas, or curves and intersections of highways (although the higher costs of developing these programs may be justified only if their potential users join in the effort).

Lighting design by computer methods is cost-effective for two reasons: First, there is a saving in labor costs

when computers are used efficiently and, second, more efficient designs will be developed because computer methods permit more rigorous analysis of the performance of more alternatives than is possible with conventional methods. Thus, future lighting systems may have improved luminance uniformity on the street or roadway and also reduced consumption of electrical energy.

There is another long-range benefit from a computational approach. The computer program described here has been modeled with performance parameters that are oriented toward the visual task of night driving. The use of these parameters can avoid overdesign of lighting systems if standards are adopted that are more relevant to the night-driving task than those traditionally used. For example, lighting systems can be designed for contrast sensitivity by using background luminance rather than roadway illuminance. Or, the system might be designed for an acceptable glare level rather than by using cutoff specifications. The use of the computer program will therefore permit lower illuminance levels that have less glare and are more uniform.

In developing this approach to roadway-lighting design, previous results in the fields of visibility, pavement reflectance, and glare have been considered. Much of this research has been done in Europe, where the problems of energy conservation and the quality of roadway lighting have been more acute than in North America.

SYSTEM LAYOUT AND INPUT SUBPROGRAM

The overall layout of the illumination-design program is shown in Figure 1. The first part of the program (numbers 1 through 7) contains the technical evaluation of alternative lighting designs and is the subject of this paper. The second part of the program contains an economic cost model and will be added later. The design procedure is as follows: A list of suitable luminaires and design arrangements for a particular project (i.e., for a cross section of a given road) is assembled by means of a subprogram (number 2 of Figure 1). The designer establishes the input data for the road section and then, sitting at a terminal, selects various luminaires and suitable arrangements by typing values and code numbers in response to questions asked by the computer program. The illumination levels are determined, and the spacings or uniformities are calculated by the computer as in a conventional design method, except that the computer uses digitized photometric data stored in a luminaire data bank. Whenever a suitable luminaire is selected and a design that has a sufficient average level and uniformity of illuminance is found, these data are added to the input for the part of the program designated Illum 1, which calculates the performance parameters and evaluates the performance of each design.

In this first subprogram, the uniformity is calculated as the ratio of the average to the minimum illuminance. The minimum value of illuminance is chosen from a limited number of point-by-point calculations that use digitized luminous-intensity data for each type of luminaire. The average level of the illuminance or the spacing is computed on the basis of digitized data for the coefficient of utilization. Thus, computerized forms of traditional design procedures (numbers 1 and 2) are used to preselect feasible luminaires and arrangements for the more rigorous performance-evaluation subprogram Illum 1 (number 4 in Figure 1).

The input subprogram and the Illum 1 subprogram use the same data bank input for photometric luminaire data. The most important data needed are the light distribution of the luminaires, i.e., the luminous-intensity distribution function [$I(\gamma, \phi)$], which is usually available on photometric data sheets issued by the manufacturers. Figure 2 illustrates the variable angles (ϕ and γ) of the luminaire-intensity function. These angles are defined by the equations below.

$$\phi = \arctan [a/(b - o)] \quad (1)$$

$$\gamma = \arctan \left\{[a^2 + (b - o)^2]^{1/2}/h\right\} \quad (2)$$

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

The manufacturers' data sheets usually contain the function (I) in the form of various diagrams, but the computerized method requires a format in which I is given in tabular form as a two-dimensional matrix corresponding to the two variables, the horizontal angle (ϕ) and the vertical angle (γ). (Between the discrete values given by the matrix or table, other values can be determined by parabolic interpolation.) A format for a symmetrical luminaire [$I(\gamma, \phi) = I(\gamma, -\phi)$] is given in Figure 3 for vertical angles below the horizon ($\gamma \leq 90$). The format for the coefficient of utilization is given in terms of the ratios (b - o):h for the street side or o:h for the house side, where either ratio can vary between 0.0 and 6.0.

ILLUM 1: CALCULATION OF PERFORMANCE PARAMETERS, ILLUMINANCE, AND DISABILITY VEILING BRIGHTNESS OR GLARE

Single values of illuminance, luminance, and disability veiling brightness or glare (DVB) are calculated for selected grid points on, or over, the road surface for one section between a repetitive arrangement of luminaires. The grid points represent the point (P) on the road surface in Figure 2, or the position of the driver's eyes as shown in Figure 4. The following equations are used for the calculation of the illuminance and the DVB (1).

$$\Theta = \arctan [(h - e)^2 + (b - o)^2]^{1/2}/d \quad (4)$$

$$-\phi = \arctan [d/(b - o)] \quad (5)$$

$$\gamma = \arctan \left\{[d^2 + (b - o)^2]^{1/2}/(h - e)\right\} \quad (6)$$

$$R = (h - e)/\cos \gamma \quad (7)$$

$$E_\nu = [I(\phi, \gamma) \cos \Theta]/R^2 \quad (8)$$

$$DVB = 10E_\nu/\Theta^2 \quad (9)$$

The arrays of single values are then added and averaged, or scanned for maximum or minimum values, as required.

LUMINANCE OR REFLECTED LIGHT

Luminance is calculated from the corresponding illuminance values for the same grid points (P), but only the portion of the light that is reflected toward the driver's eyes is considered. As shown in Figure 5, the illuminance contribution (E_p) from each luminaire is multiplied by a coefficient (q) that depends on the light-reflection properties of the pavement surface (4). For each driver position, or each lane, the calculated luminance arrays are different (unlike the illuminance arrays, which remain the same).

The reflection of light from a road surface ranges from complete specularity (the mirror effect), when the surface is flooded with water, to almost complete diffusion for a nonglossy, dry pavement. However, dry or almost dry conditions prevail most of the time, and the increase in glossiness of damp pavements usually in-

Figure 1. Overall flow diagram for illumination-design program.

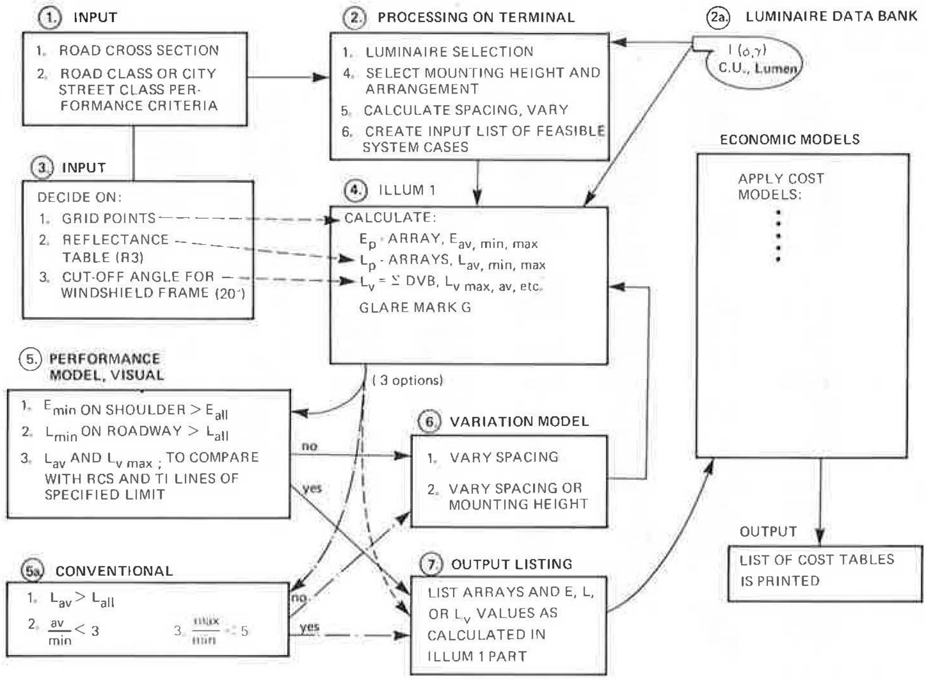
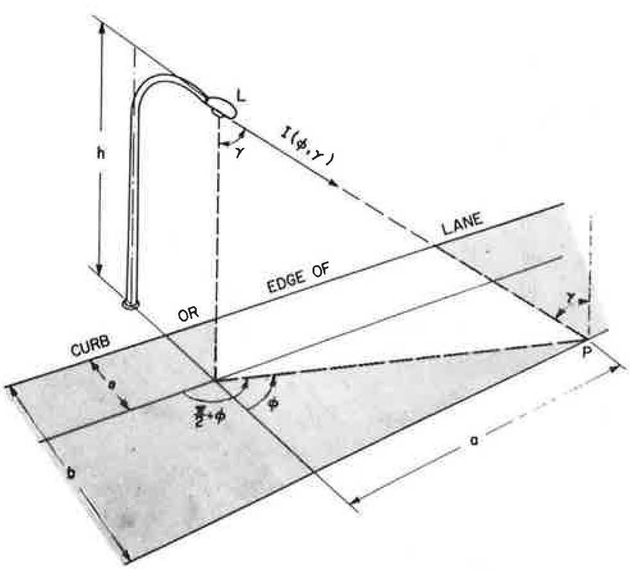


Figure 2. Illuminance.



creases both the average luminance (5) and the difference between the average and minimum luminances. Since it is difficult to include all of these factors in the calculations, highway lighting is usually designed and evaluated for dry (to be eventually supplemented by inclusion of moderately wet) pavements, which permits classification of the degree of glossiness into a few standard categories. The number of categories would increase considerably if moist pavements were included.

On wet pavements, visibility, although diminished, is available from the familiar blurred and streaky image of the reflected luminaires. Under these conditions, laterally extended light sources, such as fluorescent or low-pressure sodium-vapor luminaires, installed above the roadway improve visibility because they generate wider streaks of blurred images.

As illustrated in Figure 5, the luminance coefficient is a function of four angles (α, β, γ, and δ) and of the average luminance coefficient (q_0), which depends on the color of the pavement surface. Thus,

$$L = q_0 \times [\bar{q}(\alpha, \beta, \gamma, \delta)] \times E_p \quad (10)$$

where

- q_0 = average luminance coefficient derived from a specified road area,
- $\bar{q}$ = luminance-coefficient function for a tabulated q_0 that is a function of the angles α, β, γ, and δ, and,
- E_p = illuminance.

The luminance coefficient (q) is defined as the factor by which the illumination (E_p) must be multiplied to obtain the luminance (L). The luminance values must be calculated for each luminaire and then summed. The luminance created by a luminaire at point i is

$$L = q_0 \times [\bar{q}(\alpha_i, \beta_i, \gamma_i, \delta_i)] \times [E_p(\phi_i, \gamma_i)] \quad (10a)$$

If the values for n luminaires are added, Equation 3 is substituted for E_p, the influence of δ is neglected, and $\alpha = 1°$, the following equation for the luminance can be derived.

$$L = \sum_{i=1}^{n} \{q_0 \times \bar{q}(\beta_i, \gamma_i) \times [I(\phi_i, \gamma_i) \times \cos^3 \gamma_i]/h^2\} \quad (11)$$

Standard reflectance tables (4) have been established in the form of reduced coefficients ($R = \bar{q} \cos^3 \gamma$) for $\alpha = 1°$, which simplifies the reflectance measurements. The combination $R = \bar{q} \cos^3 \gamma$ leads to table values of R that decrease with increasing γ or $\tan \gamma$, whereas the pure reflectance function ($\bar{q}$) or (q) alone increases greatly [Figure 6 (6)].

The number of luminaires (n) to be included are those within a longitudinal distance of 12 h beyond P; additional luminaires beyond this range contribute insignificantly. By the substitution of $R = \bar{q} \times \cos^3 \gamma$, Equation 11 can be rewritten as

Figure 3. Format for luminous-intensity distribution function.

Vertical Angle

Horizontal Angle Φ \ γ	0°	2.5°	5°	7.5°	10°	12.5°	15°	17.5°	20°	22.5°	25°	27.5°	30°	32.5°	35°	37.5°	40°	42.5°	45°	47.5°	50°	52.5°	55°	57.5°	60°	62.5°
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125°																										
1?																										

Figure 4. Disability veiling brightness.

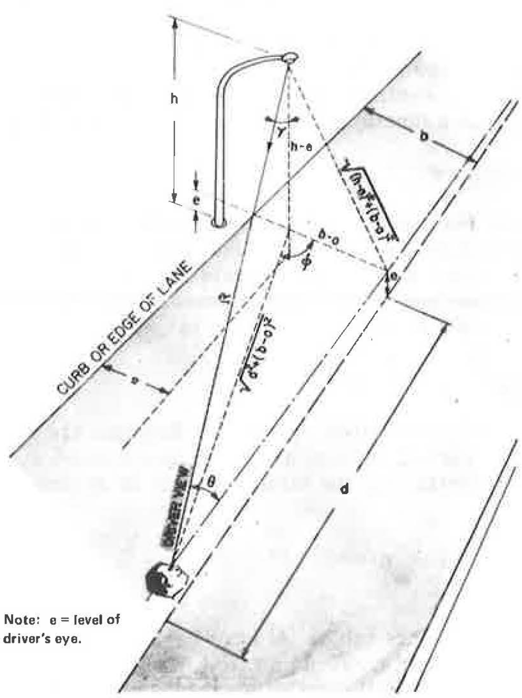
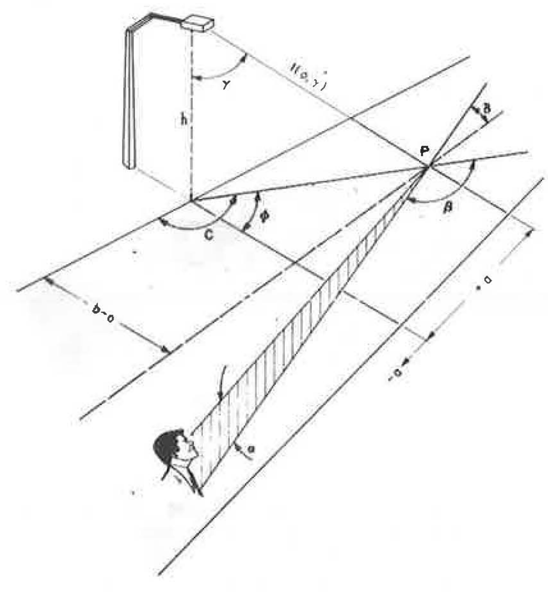


Figure 5. Luminance.



$$L = \sum_{i=1}^{n} \left\{ [I(\phi_i, \gamma_i) \times R(\beta_i, \tan \gamma_i)] / h^2 \times q_0 \right\} \qquad (12)$$

An example of an abridged R-table, which tabulates values of R versus β and tan γ, is given in Table 1. Other examples are those of the Commission Internationale de l'eclairage (4) and Erbay (7).

Equations 11 and 12 represent a point-by-point method of calculating the luminance of a road surface as it appears to a driver in a particular lane who is looking ahead 90 m (300 ft). The first calculations must be carried out for all points on a perpendicular line across the pavement at this distance ahead of the driver. The next calculations assume that the driver has moved forward and is now looking at a line approximately 6.1 or 9.2 m (20 or 30 ft) ahead of the original line. Moving ahead in this way, the driver is assumed to maintain a constant,

standard viewing angle of $\alpha = 1°$. Thus, all of the grid points on a road surface have as many arrays of luminance values as there are lanes for a driver to use, and the luminance values at these points are dynamic values of brightness successively reflected to the driver as he or she moves along. These values are not exactly the same as those seen by an observer from a stationary position.

OUTPUT OF PERFORMANCE VALUES

At this point, printouts for the calculated performance parameters—one array (per road side) of illuminance values for the specified grid points, arrays of luminance values for the grid points and each lane position, and one row of DVB values for each lane—can be obtained. Optionally, the array printouts can be converted into isoilluminance and isoluminance diagrams for more con-

Figure 6. Reflectance function.

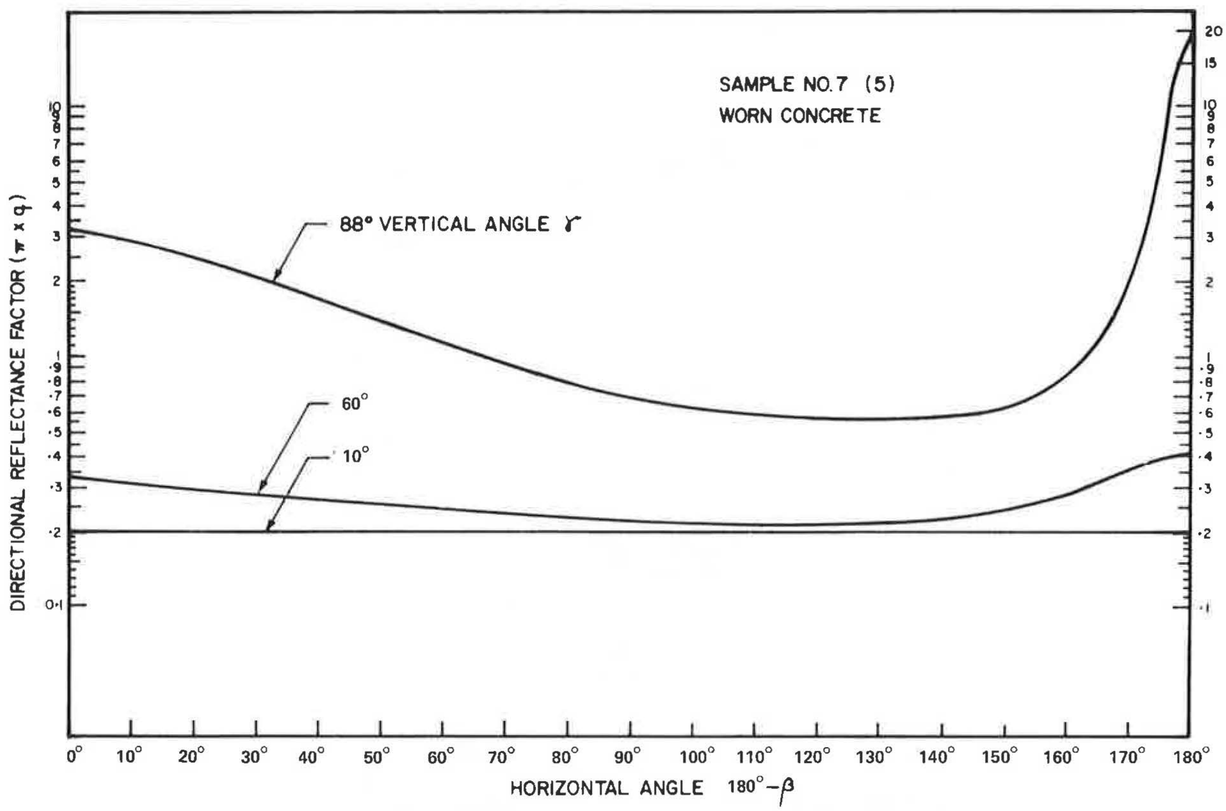
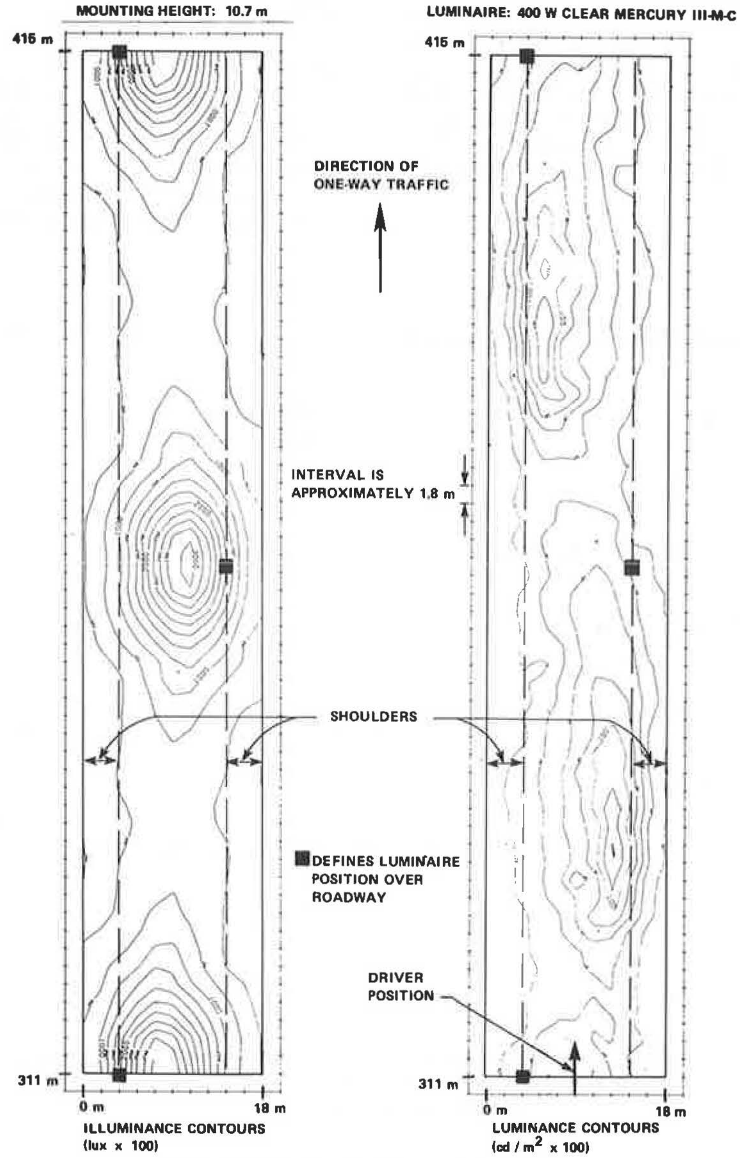


Table 1. Standard reflectance table R-3 (abridged).

Tan γ[a]	β[b] 0	2	5	10	15	25	35	45	60	75	90	120	150	180
0.00	426	426	426	426	426	426	426	426	426	426	426	426	426	426
0.50	498	498	491	491	471	445	419	380	367	321	295	288	288	282
1.00	524	524	511	472	400	328	262	203	197	157	144	144	144	144
1.50	511	504	472	386	314	210	144	118	109	89	83	86	86	89
2.00	472	465	406	275	197	119	89	69	62	54	48	51	52	55
2.50	419	406	321	183	124	77	55	43	39	34	31	34	35	37
3.00	367	341	236	123	76	45	33	26	24	21	20	22	24	25
3.50	314	282	177	86	51	31	24	18	16	14	13	16	17	18
4.00	275	236	131	62	38	24	17	13	12	0	0	12	13	14
4.50	236	197	106	45	29	17	13	10	0	0	0	9	10	12
5.00	210	157	85	34	24	13	10	9	0	0	0	0	0	0
5.50	183	131	68	26	20	10	8	0	0	0	0	0	0	0
6.00	164	111	52	21	16	9	7	0	0	0	0	0	0	0
6.50	151	98	43	16	12	8	5	0	0	0	0	0	0	0
7.00	138	86	35	12	9	7	0	0	0	0	0	0	0	0
7.50	128	76	30	10	8	5	0	0	0	0	0	0	0	0
8.00	121	68	25	9	7	4	0	0	0	0	0	0	0	0
8.50	113	60	21	8	5	4	0	0	0	0	0	0	0	0
9.00	106	55	17	7	5	3	0	0	0	0	0	0	0	0
9.50	100	50	14	5	4	3	0	0	0	0	0	0	0	0
10.00	94	46	13	5	4	3	0	0	0	0	0	0	0	0
10.50	89	42	12	4	3	0	0	0	0	0	0	0	0	0
11.00	85	38	10	4	3	0	0	0	0	0	0	0	0	0
11.50	81	34	9	4	3	0	0	0	0	0	0	0	0	0
12.00	77	31	8	3	3	0	0	0	0	0	0	0	0	0

[a] Tan γ = R/H values corresponding to the listed numbers of reflection values.
[b] All values of β have been multiplied by 1000.

Figure 7. Example graph plots.



Note: 1 m = 3.3 ft; 1 lx = 0.093 ft·c; 1 cd/m² = 0.29 ft·L.

Figure 8. Diagram of visibility criteria.

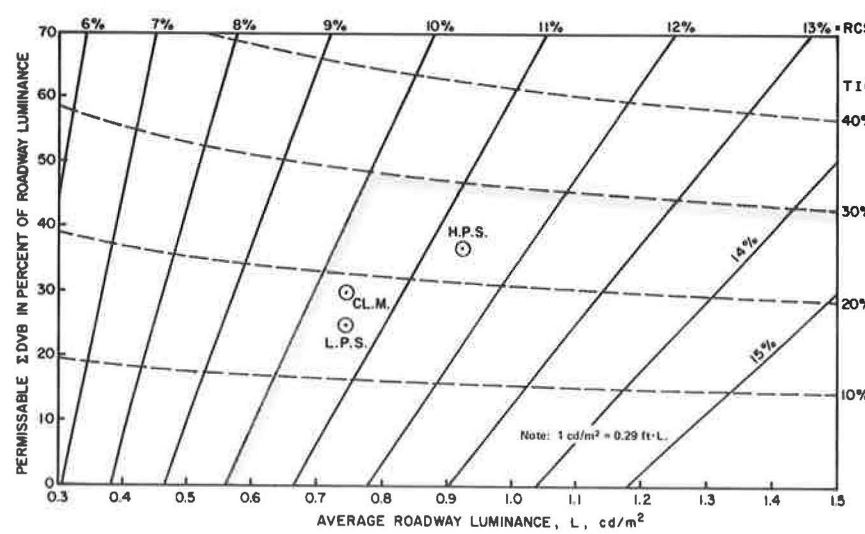
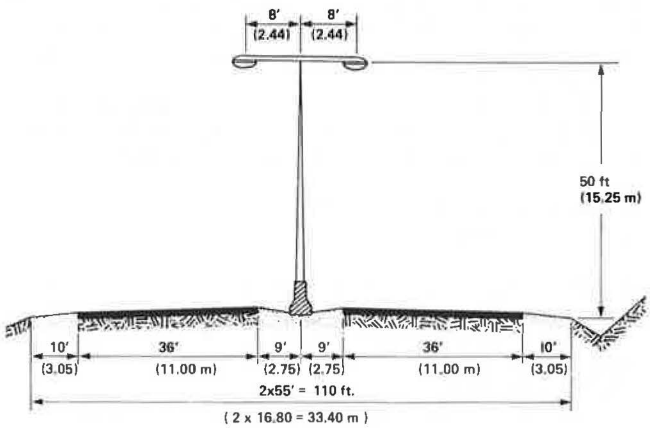


Figure 9. Design example.



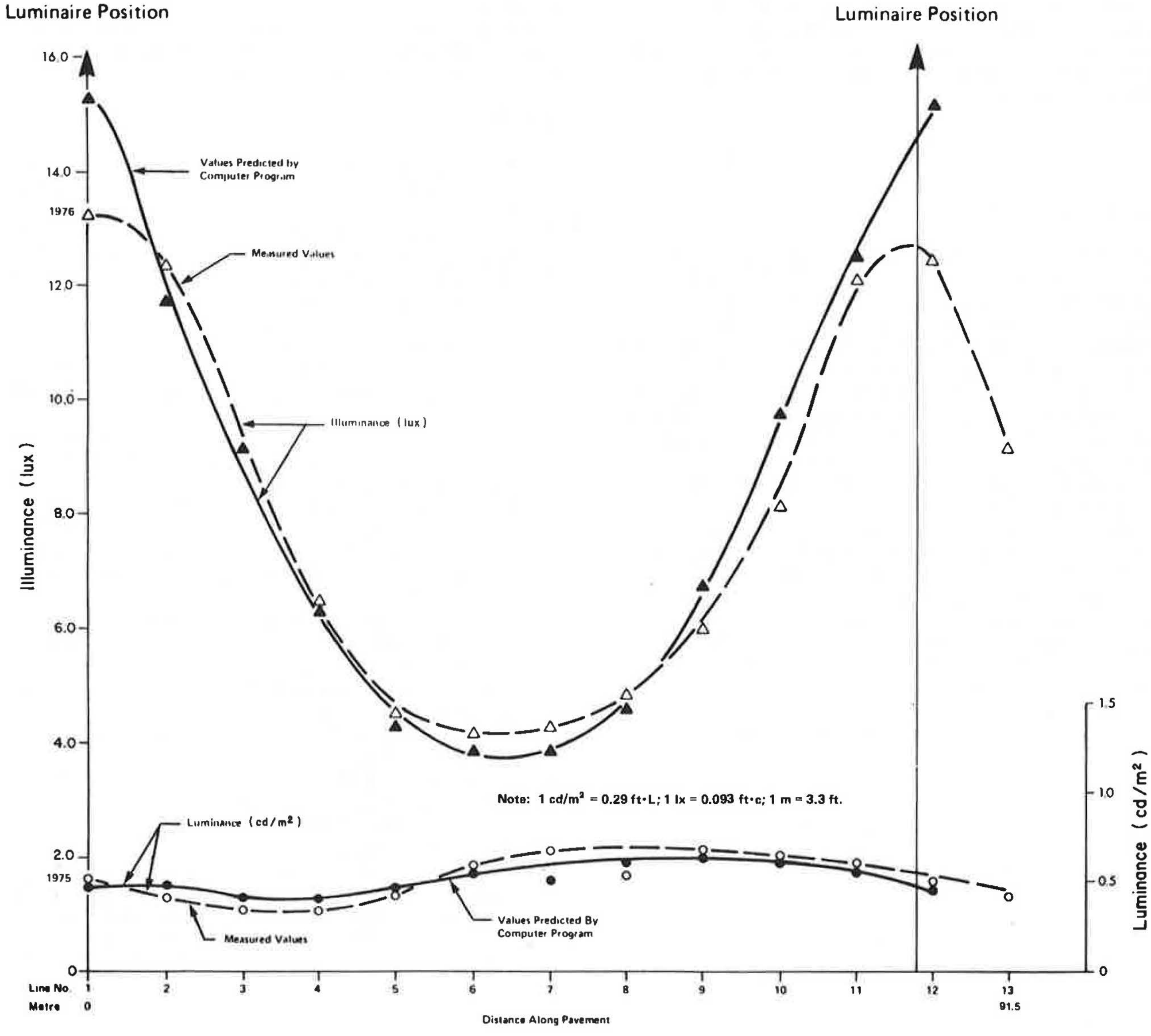
venient study by using a separate computer program. An example for a simple three-lane road is shown in Figure 7.

MODELING OF PERFORMANCE EVALUATION

The performance of a design traditionally has been evaluated by specifying limiting conditions for average values, uniformity ratios, or maximum and minimum values of the illuminance or incident light on the road surface, and correcting for glare by rigid cutoff specifications. This approach wastes an enormous amount of electrical energy, since much of the light is radiated toward places where it is not really needed. Traditional lighting standards are more concerned with maintaining good visibility than with saving energy.

The cost of lighting installations and the use of elec-

Figure 10. Comparison of measured and calculated values of illuminance and luminance (test area 4, bituminous overlay).



tric energy can both be reduced without reducing the level of service by redefining lighting standards in terms of the visual requirements of the night-driving task. The computer program, as it has been developed, can be modeled with traditional standards, or the performance evaluation could be modeled with the concept of relative contrast sensitivity (RCS), as discussed by Jung in the following paper. The RCS provided by fixed lighting at any important spot on the road surface must be larger than the specified minimum value required for the visual task of night driving. The following equation for RCS has been derived from standard values for lighting performance (8).

$$RCS = 13.7(L - 0.06)^{1/2} \quad (13)$$

This equation is valid for a luminance range of 0.15 to 2.5 cd/m² (0.044 to 0.73 ft•c) and for glare-free lighting installations. This value of RCS is reduced when DVB is present because the required contrast for the same visual task is increased by the presence of a veiling luminance (L_v), which is the sum of the DVB contributions from all of the luminaires in the visual field of the driver (Equation 9). The coefficient 10 in this equation corresponds to an average value for 60 to 65-year-old people (9); it would be much smaller for younger people.

The effective RCS is

$$RCS^* = 1.074L/(L + L_v) \times 13.7\left\{[(L + L_v)/1.074] - 0.06\right\}^{1/2} \quad (14)$$

where $L_v = \sum_{i=1}^{n} (DVB)_i$.

The alternative possible design criterion, that of limiting the visual threshold increment (TI) (9), can be combined with the RCS standard into one diagram as shown in Figure 8. For example, the luminance values of acceptable lighting installations will be below the shaded line in Figure 8 if the requirements are RCS* ≥ 10 percent and TI ≤ 30 percent. This line is tentatively proposed as a standard for major highways and expressways that justify fixed lighting. The only additional specifications would be those of minimum point values of luminance on the traveled road surface and of illuminance on the edge of a paved shoulder.

Figure 9 presents a typical design. The performance parameters calculated for three possible lighting configurations [CL.M. = 700-W, clear mercury-vapor (type III, medium-distribution, cut off) lamps spaced 73.2 m (240 ft) apart; H.P.S. = 400-W, light-pressure sodium-vapor (type III, medium-distribution, cut off) lamps spaced 88.4 m (290 ft) apart; and L.P.S. = 180-W, low-pressure sodium-vapor (type IV, medium-distribution, cut off) lamps spaced 70.1 m (230 ft) apart] are given below (1 km = 0.6 mile, 1 lx = 0.093 ft•c, and 1 cd/m² = 0.29 ft•L).

	Lighting Configuration		
Performance Parameter	CL. M.	H.P.S.	L.P.S.
Avg illuminance on roadway, lx	11.6	14.3	11.85
Min illuminance on outer edge of shoulder, lx	3.7	4.3	5.6
Avg luminance on roadway, cd/m²	0.76	0.90	0.74
Min luminance on roadway, cd/m²	0.295	0.28	0.27
DVB (inner lane), cd/m²	0.23	0.32	0.18
Relative energy consumption per km, W	19 140	9050	5140

The veiling luminance percentages for the three configurations are given in Figure 8. All of them are well below the shaded line. The values of the average illuminance or average luminance should not by themselves be regarded as critical.

The dimensions, such as spacing or mounting height, of the design layout should also be varied in the modeling calculations to optimize performance parameters.

COMPARISON WITH FIELD MEASUREMENTS

The Illum 1 program was used to simulate the performance of a test area of the Toronto Bypass (10). The input data used the standard reflectance surface given in Table 1, q_0 = 0.07 cd/m² (0.029 ft•L), which is representative of moderately old black asphalt surfaces having good skid resistance, and an estimated maintenance factor of 0.8. The values calculated were in close agreement with those measured in the field (Figure 10). This comparison is more valuable in respect to the shape of the curves than to the actual magnitudes of the luminance and illuminance because of uncertainties in the initial lamp ratings and the maintenance factor. The actual installation represents practical field conditions without very accurate alignment of luminaires.

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