Effects of Asymmetric Distributions on Roadway Luminance

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The current recommended practice (ANSI/IESNA RP-8) calls for uniform luminance on the roadway surface. This paper summarizes the results of an investigation to determine the effects on the luminance-producing ability of luminaire distributions as various distribution factors were changed while other variables were held constant. It was concluded that (a) the luminance-producing ability of the distribution increases as the vertical angle of the beam maximum increases; (b) in a bidirectional distribution, the maximum luminance-producing ability was obtained when the luminaire, the point to be lighted on the roadway, and the driver were all in line; (c) as the lateral angle of the beam maximum decreases, the luminance-producing ability of the system decreases; and (d) the luminance-producing ability of light toward the driver is much greater than that of light away from the driver (as much as 10 times under certain circumstances), which makes a "counterbeam" system practical.

Before 1983, horizontal illuminance (the amount of light falling on a square unit of horizontal roadway surface) had been the main criterion for roadway lighting in North America. Since that time (and much earlier in Europe), the preferred method has been to light the roadway surface in such a way that the driver sees a uniformly lighted roadway. This method, known as uniform luminance, is specified by *ANSI/IESNA RP-8* (*1*). The rationale for this recommendation is that a uniformly lighted roadway is the best way to reveal objects on the roadway. The objects are revealed in silhouette, with a dark object on a light background.

This theory has several flaws, including the following:

- Headlights from the driver's vehicle "fight" with this system by lighting up the object, which changes the seeing condition to reverse silhouette (with the object brighter than the background).
- On a busy highway, the driver mostly sees the backs of other cars rather than the roadway surface.

Some experts argue that roadway luminance is good but should not be uniform (in other words, it should have bands of light and dark).

The luminance concept causes some design complications that do not exist with illuminance. For example, the observer location, the lightness of the roadway surface, the reflection characteristics of the roadway surface, and the system layout geometry must be considered. Therefore, a computer is necessary to deal properly with the increased number of variables and the complexity of the calculations.

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More important, however, is the need for the lighting system designer to choose the optimum luminaire distribution for each situation. This is not an easy task; it is not always obvious which way the distribution variables should move to achieve the desired results. In addition, because the variables are interactive, optimizing one variable may be disastrous to another. Optimizing the many variables is a serious problem for the luminaire designer, who attempts to produce the ideal luminaire distribution to gain the maximum luminance per watt of electricity.

Nevertheless, *ANSI/IESNA RP-8* calls for uniform luminance on the roadway surface, so this investigation was conducted to determine the effects on the roadway luminance-producing ability of luminaire distributions as various distribution factors were changed while other variables were held constant. It is emphasized that this investigation did not try to optimize all variables or predict what the various changes would do to all variables. Only the effects on pavement luminance were considered.

VARIABLES INVESTIGATED

The following variables in the distributions were changed over as large a range as available photometric data would permit (while holding all other variables constant):

- Vertical angle of beam maximum (max),
- Lateral angle of beam max, and
- Effect of moving the luminaires off the roadway.

Most of the photometric data were on conventional bidirectional luminaires with the upstream and downstream beams symmetrical (the same maximum candela, same vertical angle of beam max, and same lateral angle of beam max). Other distributions were investigated as follows:

- Conventional symmetrical bidirectional;
- Bidirectional with the upstream and downstream beams being drastically different (counterbeam): (a) with a strong beam in the direction of driver motion and (b) with a strong beam against the driver; and
- Unidirectional lighting: (a) with the direction of driver motion and (b) against the driver.

Also investigated was the nature of the bidirectional reflectance characteristics of the typical pavement surface (an asphalt surface designated in *ANSI/IESNA RP-8* as an "R3" surface).

PAVEMENT REFLECTANCE CHARACTERISTICS

Pavement reflectance characteristics are critical for producing luminance. Therefore, they are explored in some detail in this paper. First, however, a diagram of reference angles is explained along with a definition of how pavement luminance is calculated.

If Figure 1 is used as a frame of reference, then roadway luminance at point $P(L_p)$ with respect to the observer (driver) can be defined as

$$L_p = \frac{1}{\pi} \times \frac{q(B,Y) \times \cos^3 Y \times I_p(B,Y)}{H^2}$$

where

q = pavement reflectance at the point,
I_p = candlepower from a luminaire to the point,
H = mounting height of the luminaire, and
π = 3.14159.

Luminances at point P on the pavement surface would then be a summation of L_p from all luminaires in the system.

The R tables in *ANSI/IESNA RP-8*, such as R3 for asphalt (*1*,p. 29), take a portion out of the above equation and multiply all numbers by 10,000 as follows:

$$\text{R-table} = q(B,Y) \times \cos^3 Y \times 10{,}000$$

so that the simplified luminance calculation is

$$L = \frac{1}{\pi} \times \frac{\text{R-table}}{10{,}000} \times \frac{I}{H^2}$$

Figure 2 shows a plot of the R3 table in terms of iso-coefficient lines and illustrates the directionality of pavement reflectance.

Luminance Production Versus Vertical Angle of Beam Max

The R3 table is reproduced in this paper as Table 1. The first column is in a longitudinal vertical plane parallel to the roadway direction. If that column is plotted, the values peak out at about 45° vertical (see Figure 3). This may be somewhat

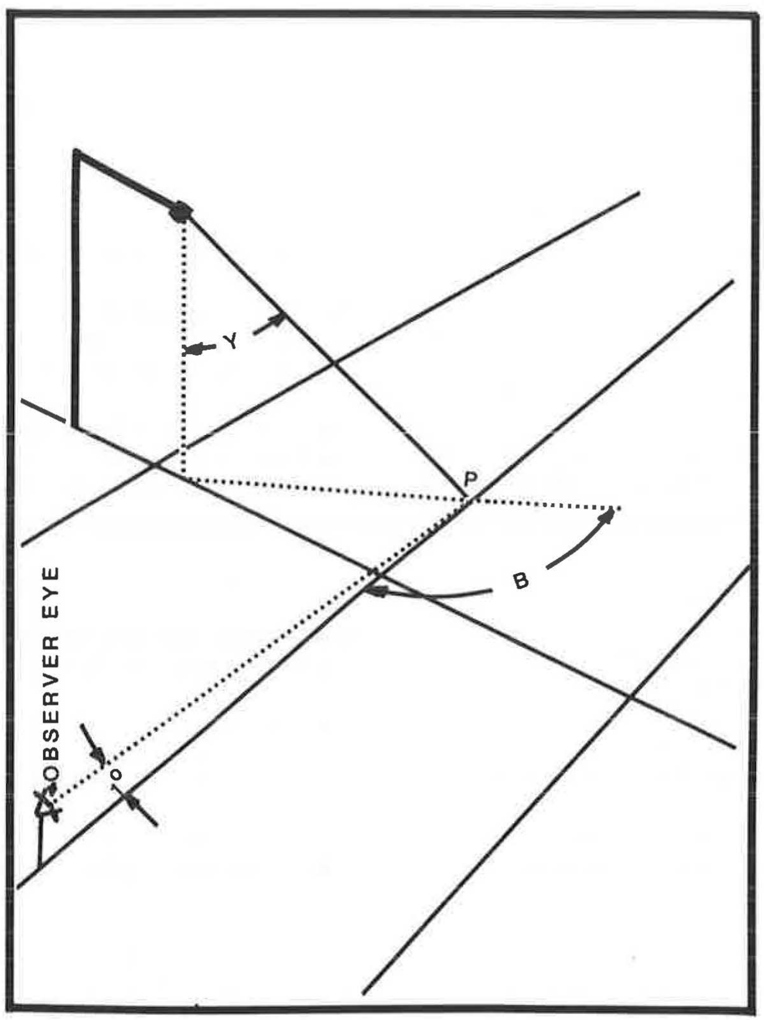

FIGURE 1 Reference angles per RP-8 (*1*).

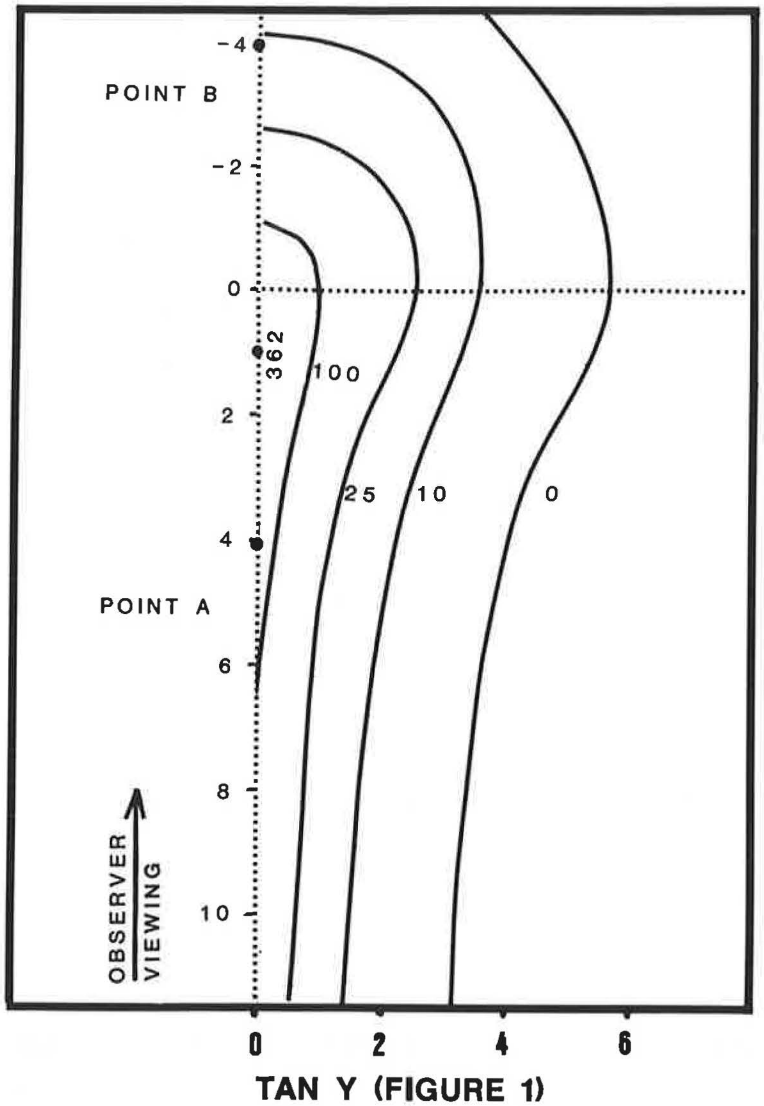

FIGURE 2 Plot of R3 table isocoefficient lines.

misleading unless it is noted that the cube of the cosine of the vertical angle has been included in the R-tables because it is used in every luminance calculation. This means that, as the vertical angle Y gets bigger, the value of $\cos^3 Y$ gets much smaller. The actual reflectance values of the pavement surface become quite large at higher vertical angles, so the R-table depicts the value of pavement reflectance multiplied by the cube of the cosine. Figure 4 compares these values.

Because this multiplication peaks at about 45°, it can be concluded that a single luminaire will produce the maximum luminance per watt input if its beam peaks at 45°. In other words, above 45°, the cube of the cosine gets smaller at a faster rate than pavement reflectance gets larger (all other factors held constant).

Calculations using single luminaires on a roadway proved that, as the beam angle is raised from 45°, the ability to produce luminance drops off, following Figure 3 almost exactly. However, when a complete system of luminaires was used, the trend reversed. As the vertical angle of beam max increased (all other factors held constant), the average luminance on the roadway surface increased rather dramatically, as shown in Figure 5.

The answer to this apparent contradiction seems to be that, as the vertical angle of beam max increases in a system, more luminaires in front of the driver contribute to the luminance at each point. The luminance program calculates contributions from 10 luminaires ahead of each point.

Luminance Production Versus Lateral Angle of Beam Max

In the R3 table (Table 1), the leftmost column represents values where the luminaire, the point under consideration on the roadway, and the driver are all in line as the driver looks straight ahead. If the lateral angle of beam max is in this 90° lateral plane, then this should be the condition of maximum luminance production because the leftmost column in the R-tables has larger numbers than any other column. Figure 6 shows this to be the case.

TABLE 1 R3 TABLE FROM RP-8 (ALL VALUES MULTIPLIED BY 10,000) (*1*)

β tan γ	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	24	8.5	6.4	5.1	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															

$Q0 = 0.07$; $S1 = 1.11$; $S2 = 2.38$

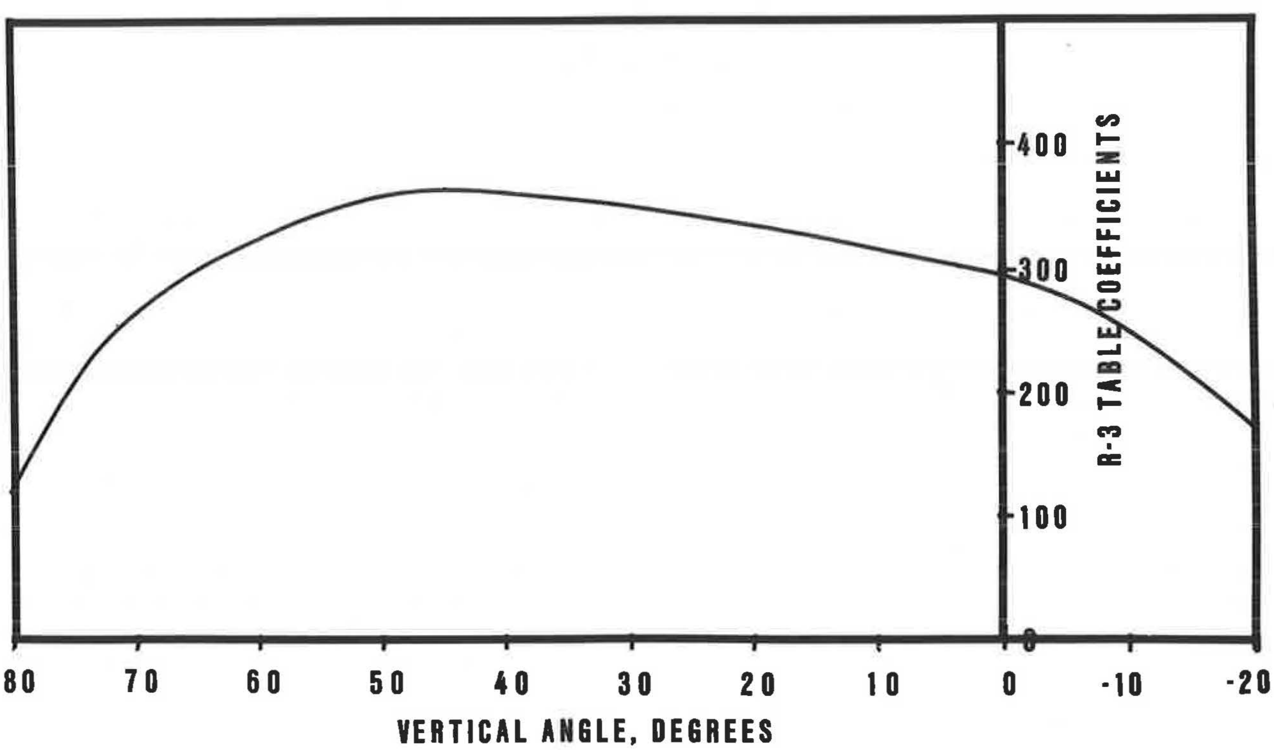

FIGURE 3 R3 coefficient in vertical plane of observer, pavement point, and luminaire.

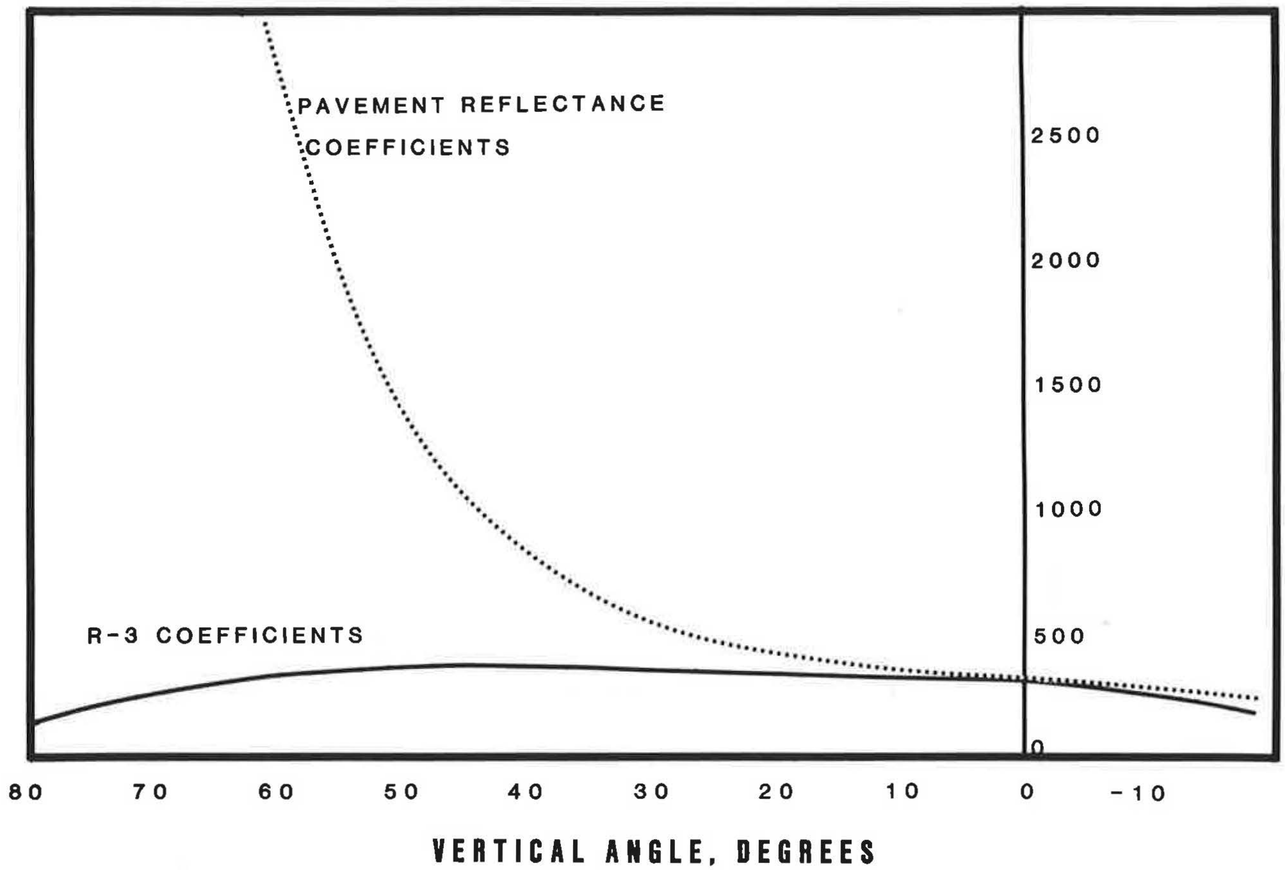

FIGURE 4 Comparison of R3 coefficients with reflectance coefficients.

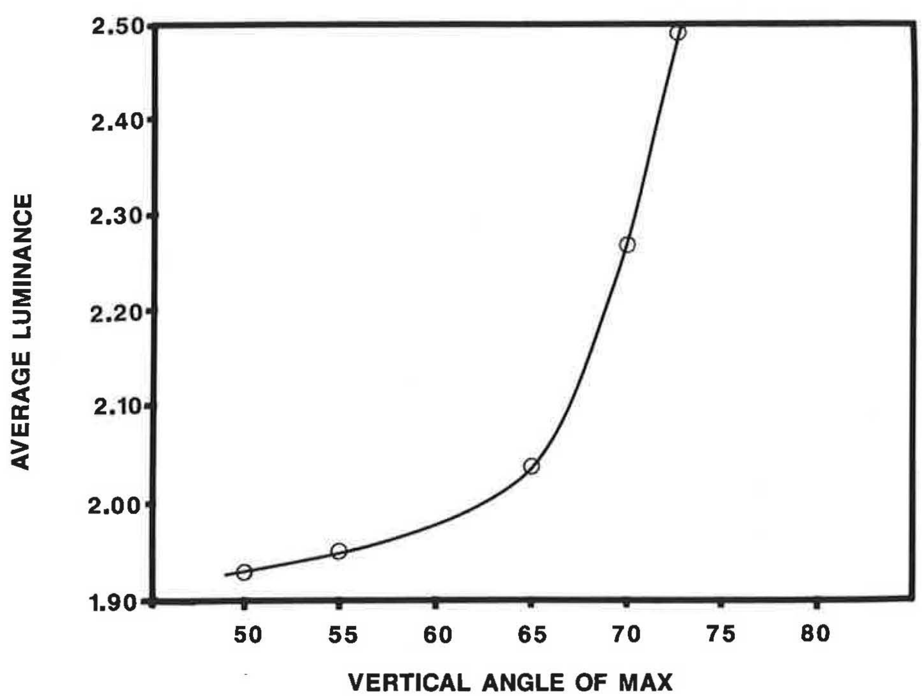

FIGURE 5 Average luminance on roadway surface versus vertical angle of beam max.

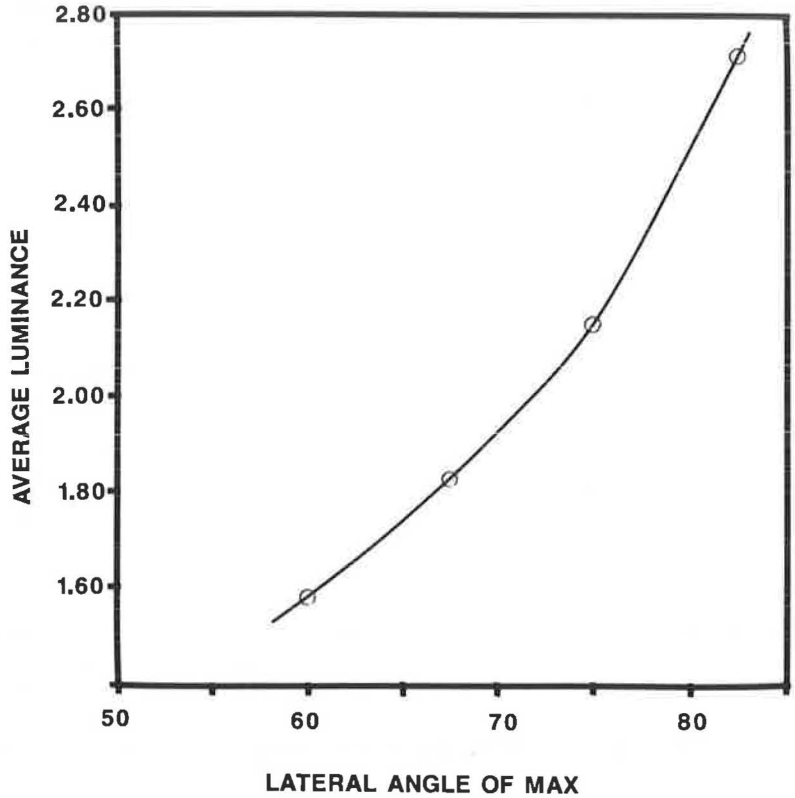

FIGURE 6 Average luminance on roadway surface versus lateral angle of beam max.

Unidirectional Lighting

So far, this paper has focused on bidirectional distributions, which have all had upstream and downstream symmetry. An obvious variation from the bidirectional luminaire distribution is the unidirectional distribution, and this can be further broken down as being either against the driver or in the direction of driver travel. Many experiments and trial installations, as well as some real installations, have been conducted using unidirectional distributions.

Unidirectional Lighting in Direction of Driver Travel

This type of lighting has the advantage of making all objects appear in reverse silhouette (bright against a darker background). In addition, the use of headlights enhances visibility by making objects still brighter against their background.

This method also has several disadvantages. For example, the reflectance coefficient of the roadway surface is quite low, so luminance on the roadway surface is not produced efficiently. Also, those who use unidirectional lighting in the direction of driver travel tend to use beams at high vertical angles to permit longer spacings. However, Figure 7 shows that raising the beam offers no advantage from a luminance-producing standpoint. Also, when using distributions with very strong beams (high candela), an annoying phenomenon takes place. At a certain point in the system, depending on the vertical angle of the beam, the inside of the car is suddenly lighted to a high level. Since this occurs once each luminaire cycle, it becomes an irritating flashing.

It should be obvious that a unidirectional system can only be effective when the light can be completely shielded from drivers traveling in the opposite direction.

Unidirectional Lighting Against the Driver

The advantage of this type of lighting is that the directional reflectance factor of the roadway surface is much higher than it is with the beam going in the direction of driver travel. Therefore, luminance is produced much more efficiently. In addition, there is a tendency among those using this type of system to raise the vertical angle of beam max to produce luminance more efficiently. As shown in Figure 7, when the vertical angle of the beam is as high as 80°, the luminance-producing capability is as much as 10 times that produced when the beam is in the direction of driver travel.

However, this highly efficient luminance-producing system is not without drawbacks. When the vertical angle of beam max becomes large, the glare of the system becomes prohibitive. (This aspect of the two systems was not analyzed in this investigation.) Another disadvantage is that, under the fixed lighting, all objects appear in silhouette (dark against a light background). When the object comes within the effective range of headlights, it disappears at a certain point (the object and background have equal luminance), then appears again in reverse silhouette as the headlights make the object lighter than its background.

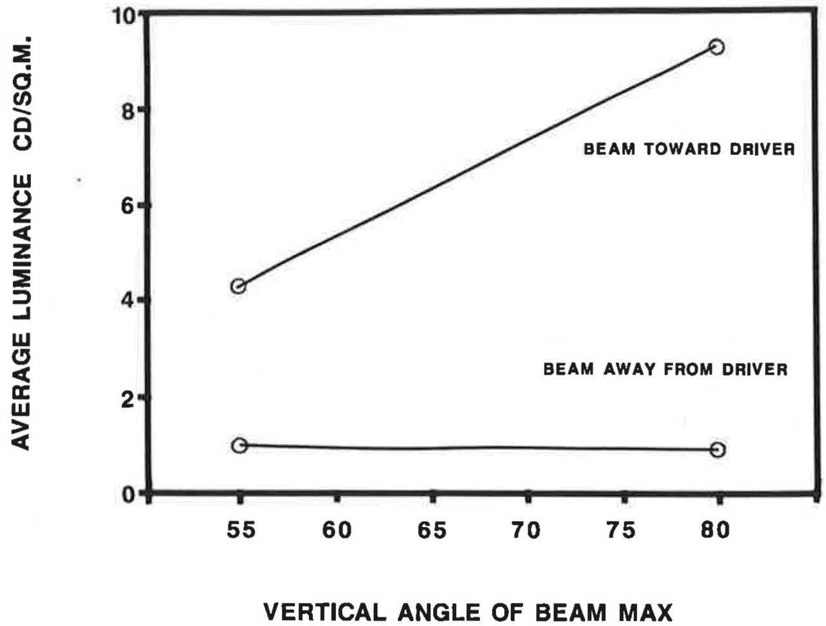

FIGURE 7 Effect on luminance of raising the beam.

A Reasonable Compromise

Assuming there are real advantages in having light in the direction of driver travel, and at the same time realizing the greater luminance-producing potential of light toward the driver, some sort of bilaterally asymmetric distribution would perhaps yield results superior to either bilaterally symmetric distribution or either unidirectional distribution.

Some experimenting has already been done with this concept. A distribution called "counterbeam" is currently being used in the tunnels of Switzerland and is specified for tunnels now being built in Seattle, Washington. Figure 8 illustrates a typical counterbeam distribution. Table 2 shows that, with the beam toward the driver, more than twice the luminance is produced than if the beam were in the direction of driver travel.

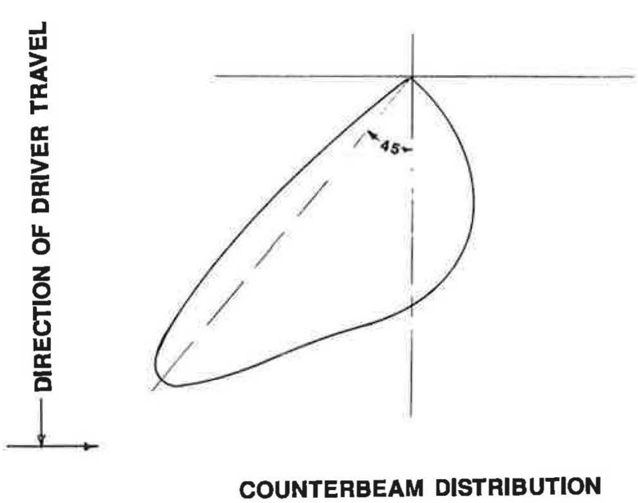

FIGURE 8 Counterbeam distribution.

SUMMARY

All luminance calculations in this investigation were performed using a fixed geometry of a 40-ft roadway, 4-ft overhang, and 40-ft mounting height, spaced 160 ft on one side only. The luminaires used a 400-watt, clear high pressure sodium, 50,000-lumen lamp, and all calculations used a maintenance factor of 1. Table 2 shows a summary of the luminances produced in each computer run. While it lacks the rigor of having all coefficients of utilization exactly equal, the luminance produced in each case is probably a fair represen-

TABLE 2 PAVEMENT LUMINANCE VALUES

Type of Distribution	Average Luminance (cd/m²)
Bidirectional (with symmetry)	
50°V beam (75°L)	1.93
55°V beam (75°L)	1.98
65°V beam (75°L)	2.04
70°V beam (75°L)	2.27
72°V beam (75°L)	2.49
60°L beam (67-½°V)	1.59
67.5°L beam (67-½°V)	1.82
75°L beam (67-½°V)	2.15
82.5°L beam (67-½°V)	2.71
Unidirectional	
With driver	
55°V beam	1.02
80°V beam	0.91
Against driver	
55°V	4.33
80°V	9.30
Counterbeam (50°V)	
With driver	0.95
Against driver	2.84

tation of the particular system's luminance-producing ability in terms of system watts.

CONCLUSIONS

Several conclusions can be drawn from this investigation:

- In a bidirectional distribution system, the luminance-producing ability of the distribution increases as the vertical angle of beam max increases.
- In a bidirectional distribution, the maximum luminance-producing ability is obtained when the luminaire, the point to be lighted, and the driver are all in line.
- In a bidirectional distribution, the luminance-producing ability of the system decreases as the lateral angle of beam max decreases (with the beam angled more into the street).
- In a unidirectional system, the luminance-producing ability of the distribution toward the driver is much greater than the system aimed in the direction of driver travel (up to 10 times as much depending on the vertical angle of the beam). With the beam toward the driver, an increase in the vertical angle of beam max increases the luminance-producing ability of the system; with the beam in the direction of driver travel, the vertical angle of beam max makes no appreciable difference in luminance-producing ability.
- In a counterbeam system with a distribution similar to the prototype shown in Figure 8, the resulting luminance-producing ability is approximately 45 percent higher than in a typical bidirectional system with the beams at about the same vertical angle as the toward-the-driver beam of counterbeam.

REFERENCE

1. *American National Standard Practice for Roadway Lighting, ANSI/IESNA RP-8*. Illuminating Engineering Society of North America, New York, 1983.