Roadway Brightness and Illumination As Related to Luminaire Distributions

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Instead of specifying only light/brightness values for roadway lighting, the authors propose the development of application charts to be derived from a series of system data for pavement brightness, obstacle brightness, veiling brightness and illumination values, plotted vs. varying street width and spacing conditions to enable the over-all quality of the installation to be judged.

MOST STREET LIGHTING engineers have probably heard a number of expressions of the need for adequate pavement brightness data from which a standard might be developed for lighting (or "brightening") of roadways. The authors were made quite aware of the widespread interest in this when a previous paper[1] recommended that horizontal footcandles together with uniformity of horizontal footcandles be used as the most practical single criterion because of the ease of calculating results on horizontal road surfaces.

Many expressed their opinion then, and others later, that classifications for roadway lighting should be based solely on brightness values of the roadway, on the apparent assumption that we see by brightness and not by illumination. Some even believe the footcandle to be hopelessly outmoded and feel that this standard for specifying a roadway lighting system should be abandoned entirely.

The purpose of this paper is to discuss both footcandles and footlamberts as related to the problem of proper roadway lighting. There is no intent to prove an incompability of one criteria with the other. Instead, it is hoped the paper will disclose some additional facts about the many complex relationships between illumination, road brightness and distribution of light flux from the luminaires in roadway lighting systems.

There is, of course, a definite relationship between footlamberts brightness and footcandles illumination because, before a surface can appear bright (by reflected flux), there must have been light flux directed to the surface. Evaluating these relationships is by no means a new problem. It was so well stated back in 1914 by Dr. C. H. Sharp, in a discussion[2] of a paper by Dr. H. Ives, that it bears repeating here: "It should be emphasized that brightness data and illumination data cannot be made to replace each other. They ca nonly supplement each other. The illumination data show only the light flux received and give, only by implication or interpretation, an idea of how bright the surfaces receiving it appear. Brightness data, on the other hand, show how actual natural objects look in a given case and do not show how much illumination has been required to produce the observed effect."

Perhaps little more than this needs to be said, except there is still the question—in what manner does the distribution of light flux directed to the roadway influence the roadway brightness, and how might this brightness data be used for specifying roadway conditions once it becomes available? Proposals have been made simply to substitute an average footlamberts brightness value in place of an average horizontal footcandle value, based on a well selected multiplying factor, that would convert one to the other. One example of where this has been done is in the "Recommendation on Public Lighting" prepared by the Netherlands Foundation on Illumination.[3] In these recommendations an average factor was developed and when converted to our system of units becomes a Footlambert/Footcandle factor of 0.217. This is based on the results of a large number of measurements of illumination and brightness of several systems with customary dry road surfaces used in the Netherlands. The type of luminaire used was fairly uniform with respect to light distribution, generally being a "cut-off" type. It was felt that an average conversion factor was justified for this purpose, at least for important traffic routes where this type of luminaire is used.

A similar factor could be developed here by taking many types of systems and averaging the ratios of Footlamberts/Footcandles for each system. The

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A paper presented at the Natonal Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHORS: Holophane Co., Inc., Newark, Ohio.

authors did not have facilities for making measurements, as was done in the Netherlands, but did investigate this relationship using the calculation method for several different types of lighting systems and light distributions. To obtain these data many point by point calculations of individual brightness values contributed by all significant luminaires in the system were required. The brightness values were calculated using the Reid-Channon pavement reflectance data,[4] the only complete data available at this time. The eye level height and observer position with respect to the pavement brightness location was similar to that shown in Fig. 1 except for a variety of system arrangements. The over-all average brightness results obtained for each type of luminaire, lamp and system combination, together with the resultant average footcandles are shown in Table I. The computed Ratio of Average Footlamberts/Average Footcandles is also shown for each case.

The average of all of the Footlambert/Footcandle factors for the first 17 systems is 0.285. This figure is a weighted average which is dependent upon the number of different types of systems used in making a table of this type. Nevertheless, there seems to be a relationship between road brightness and road illumination that could easily lead to the premise that a brightness value could be substituted for the average horizontal footcandle value now used in roadway lighting practice.

The range of Footlambert/Footcandle factors for the examples used are as much as 3 to 1 between the lowest and the highest value. There is a reason for this. In order to explain this variation it is necessary to examine the various components that affect the relationship between brightness and illumination. These data differ from that obtained by the Netherlands study in that there is a wide range of vertical distributions involved, in line with the general practice in this country. The range is from quite ''low vertical angle'' to ''high vertical angle'' distributions. Table I indicates that the low angle type of distribution generally seems to produce the smallest ratio factor or the smallest average footlamberts brightness per average horizontal footcandle. On the other hand, the high angle distributions generally produce the largest ratio of average footlamberts per average horizontal footcandles. This is the result that might be expected on the basis that the higher emission angle light flux is worth more in producing pavement brightness than flux at lower emission angles, all other things being equal.

This relationship was further explored in a special study in systems 18 through 29. Both pendant incandescent and horizontal mercury luminaires were tested with different light center settings to produce different vertical angles of maximum candlepower. The average illumination level lowered slightly as the vertical angle raised but, at the same time, the average roadway brightness increased. The resulting Footlamberts/Footcandles ratio factor increased as the vertical angle increased. This same relationship held for both types of luminaires and two different spacing conditions.

If this were a direct relationship in all cases it might be possible to class the different light distribution patterns into some type of ''low,'' ''high'' and ''medium'' category, with an appropriate multiplying factor applying for each one.

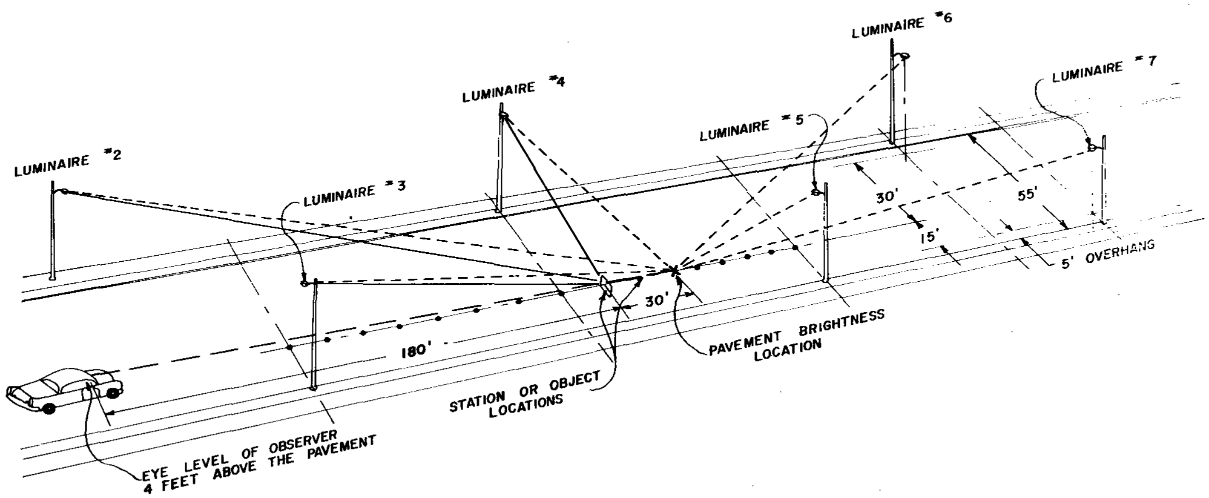


Figure 1. Layout of roadway lighting systems No. 18 through 29 showing observer position with respect to brightness location and contributing luminaires. This layout also refers to contrast data computed for Figs. 2, 3 and 4, showing object station in relation to observer and pavement brightness location.

TABLE I—Average Horizontal Illumination and Pavement Brightness Results from Several Lamp and Luminaire Combinations and Different Roadway Lighting Systems.

System No.	Luminaire and Lamp	Spacing	Vertical Angle of Maximum Candlepower	Average Horizontal Illumination fc	Average Pavement Brightness fL	Ratio fL/fc	Uniformity Footcandles	Uniformity Footlamberts
1	Small Enclosed 2500-Lumen Filament	220′	77½°	.093	.038	.41	2.9/1	2.0/1
2	Open Asymmetric 2500-Lumen Filament	220′	72°	.13	.039	.30	13.0/1	2.0/1
3	Small Enclosed 2500-Lumen Filament	160′	77½°	.13	.05	.38	1.9/1	1.6/1
4	Small Horizontal 175-Watt Mercury	160′	79°	.615	.162	.264	2.9/1	1.9/1
5	Small Horizontal 175-Watt Mercury	160′	75°	.72	.13	.18	3.3/1	2.6/1
6	Open Asymmetric 2500-Lumen Filament	160′	72°	.20	.055	.275	5.0/1	2.1/1
7	Radial Wave 2500-Lumen Filament	120′	0°	.20	.05	.25	3.3/1	1.7/1
8	Medium Pendent 6000-Lumen Filament	120′	74°	.50	.14	.28	1.9/1	1.6/1
9	Medium Pendent 6000-Lumen Filament	120′	78°	.47	.24	.51	1.5/1	1.6/1
10	Medium Pendent 6000-Lumen Filament	300′	77°	.20	.055	.275	5.0/1	2.1/1
11	Horizontal Mercury 400-Watt Clear Mercury	120′	75°	1.32	.407	.308	2.8/1	—
12	Parallel Fluorescent 2-Lamp	120′	45°	.75	.127	.17	4.8/1	—
13	Transverse Fluorescent 4-Lamp	120′	55°	.973	.239	.246	5.5/1	—
14	Parallel Fluorescent 2-Lamp	75′	45°	1.04	.183	.175	—	1.4/1
15	Transverse Fluorescent 2-Lamp	75′	62½°	.56	.145	.26	—	1.1/1
16	Horizontal Mercury 700-Watt Improved-Color	140′	67°	1.98	.53	.268	3.2/1	1.8/1
17	Horizontal Mercury 700-Watt Improved-Color	140′	67°	1.74	.50	.289	2.6/1	1.7/1
Medium Pendent 6000-Lcmen Filament:								
18	Low Angle	140′	66°	.45	.092	.204	3.0/1	1.3/1
19	Medium Angle	140′	73°	.39	.103	.264	2.5/1	1.4/1
20	High Angle	140′	77½°	.35	.106	.33	3.0/1	1.3/1
21	Low Angle	180′	66°	.32	.071	.222	6.6/1	1.9/1
22	Medium Angle	180′	73°	.30	.079	.264	3.5/1	1.5/1
23	High Angle	180′	77½°	.27	.081	.30	3.5/1	1.3/1
Horizontal Mercury 400-Watt Clear:								
24	Low Angle	140′	69°	1.61	.344	.214	4.3/1	1.9/1
25	Medium Angle	140′	74°	1.50	.373	.249	3.8/1	1.8/1
26	High Angle	140′	77°	1.37	.398	.291	3.3/1	1.5/1
27	Low Angle	180′	69°	1.36	.265	.195	5.5/1	2.0/1
28	Medium Angle	180′	74°	1.17	.289	.247	3.9/1	1.7/1
29	High Angle	180′	77°	1.07	.309	.289	3.6/1	1.5/1

With such factors available, it would be possible to determine, quickly, the average footcandles needed to produce the required average pavement brightness condition when the type of vertical distribution is known. However, this is not the only modifying influence on the relationship of footlamberts to footcandles.

There is also the complex situation by which light flux at different vertical angles produces varying amounts of roadway brightness. A given light distribution in one case may have considerably more light flux in one vertical zone than another light distribution, although both may have maximum candlepower at the same vertical angle and even the value of maximum candlepower might be the same.

The distribution with greater flux content at the higher vertical angles, with all other zones being equal, will produce greater pavement brightness average. On the other hand, a distribution with equal flux content in the upper zones but greater flux in the lower zone will also produce greater average brightness.

Another modification comes from different types of pavement surfaces used, some more diffuse than others. The diffuse surfaces are not as responsive to high angle light flux as the more specular surfaces. The paper by Ruff and Lambert[5] presents a wide variety of pavement reflection factors for different pavement surfaces. The sensitivity to high angle illumination appears to have a range of almost 100 to 1 at near grazing angles, that is,

TABLE II—Typical Pendant Filament Luminaire, IES Type III, With 6000-Lumen Street Series Lamp, 140-Foot Staggered Spacing. Data from Systems 18, 19 and 20, For One Longitudinal Roadway Line.

	Low Anqle 66 Degrees					Medium Angle 73 Degrees					High Angle 77½ Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.068	.0096	.0035	.817	.61	.080	.012	.0085	.768	.60	.098	.0136	.0235	.695	.52
2	.070	.0372	.004	.443	.57	.084	.0332	.010	.540	.48	.0895	.0312	.0255	.507	.44
3	.070	.0564	.005	.315	.41	.093	.0371	.012	.532	.35	.0885	.0326	.0295	.474	.30
4	.0695	.0316	.006	.502	.25	.081	.0334	.016	.491	.28	.085	.0248	.0335	.508	.22
5	.072	.0165	.009	.685	.23	.072	.0226	.022	.526	.28	.087	.0186	.038	.547	.21
6	.077	.0074	.0125	.777	.34	.079	.0136	.028	.611	.28	.098	.0128	.040	.617	.28
7	.080	.0028	.0105	.853	.61	.091	.0074	.021	.746	.48	.110	.0083	.031	.721	.46
8	.0835	.0132	.0025	.817	.89	.1095	.0105	.008	.843	.51	.114	.0124	.0205	.755	.50
9	.103	.0406	.0035	.586	.61	.139	.0328	.010	.713	.48	.1255	.0320	.023	.630	.46
10	.133	.0378	.0035	.697	.34	.163	.0342	.0115	.738	.28	.133	.0298	.024	.657	.28
11	.1545	.0270	.004	.804	.23	.152	.0326	.014	.719	.28	.1295	.0248	.027	.669	.21
12	.1415	.0152	.0065	.853	.25	.121	.0220	.016	.723	.28	.1175	.0204	.032	.649	.22
13	.096	.0082	.010	.823	.41	.095	.0134	.0195	.713	.35	.107	.0156	.037	.635	.30
14	.074	.0034	.007	.872	.57	.087	.007	.014	.792	.48	.111	.0118	.034	.684	.44
15	.068	.0096	.0035	.817	.61	.080	.012	.0085	.768	.60	.098	.0136	.0235	.695	.52
Avg.	.092	.0212	.0063	.703	.45	.103	.0223	.0150	.675	.39	.1067	.0206	.0299	.625	.35
Unif.	1.35/1	2.57/1	2.52/1	2.23/1	1.96/1	1.43/1	3.19/1	1.88/1	1.37/1	1.39/1	1.26/1	2.48/1	1.46/1	1.32/1	1.67/1

the most responsive types will produce 100 times more brightness per footcandle than the least responsive types. On the other hand, at that point on the pavement where the lower emission angles are effective, the reverse is true, and the diffuse type pavement produces more brightness per horizontal footcandle than the more specular pavement.

Since the average Footlamberts/Footcandles factor is obtained by averaging several points on a roadway, each of which receives illumination from different angles, the low, medium and high angle distributions will produce a different range of results on different pavements. Also, the variable amounts of light flux above and below maximum, with different luminaire and lamp combinations, will further contribute to widening the range of Footlamberts/Footcandles factors.

Spacing of luminaires and other parts of the system geometry will also influence the Footlamberts/Footcandles ratio factor. For example, ratio values were computed at different spacing conditions for some of the distributions in Table I. In some cases, the factor increased as the spacing increased; in other cases the reverse was true. There was not enough statistical data here to come to any conclusion except that it is probably a minor influence on the ratio factor.

If all of the constituents of the relationship between candlepower distribution, roadway brightness and average horizontal footcandles are considered, it becomes too complex to define and therefore difficult to give exact meaning to a single ratio factor. It might eventually be possible to establish a category for all influencing elements and develop, by an enormous amount of calculations, a ratio factor applying to each case. However, this ratio factor would still simply be a means of transferring an average roadway horizontal illumination value to an average roadway brightness value or vice versa.

Up to this point the discussion has been confined to the relationships between pavement brightness and horizontal illumination. Neither of these will provide a means of determining the seeability in

TABLE III—Typical Pendant Filament Luminaire, IES Type III, with 6000-Lumen Street Series Lamp, 180-Foot Staggered Spacing. Data from Systems No. 21, 22 and 23, For One Longitudinal Roadway Line.

	Low Angle 66 Degrees					Medium Angle 73 Degrees					High Angle 77½ Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.061	.0008	.0035	.933	.60	.057	.0024	.0098	.817	.58	.063	.0036	.013	.782	.49
2	.052	.037	.0045	.265	.55	.056	.0312	.0099	.376	.46	.062	.0288	.0145	.434	.41
3	.0415	.044	.005	.054	.39	.055	.0348	.0120	.301	.31	.065	.0294	.016	.440	.26
4	.0395	.032	.006	.165	.19	.060	.0328	.015	.363	.21	.067	.0240	.020	.494	.16
5	.049	.016	.007	.589	.10	.068	.0486	.020	.220	.14	.069	.0164	.025	.560	.13
6	.060	.0072	.011	.744	.09	.063	.0130	.027	.556	.14	.070	.0112	.032	.576	.13
7	.067	.0028	.010	.834	.16	.056	.0076	.017	.663	.21	.071	.0080	.022	.677	.16
8	.062	.0012	.002	.950	.32	.063	.0040	.0051	.866	.24	.073	.006	.011	.798	.25
9	.052	.0006	.003	.935	.60	.064	.0022	.0052	.893	.46	.079	.004	.011	.833	.43
10	.057	.0056	.003	.857	.40	.060	.0016	.0095	.840	.50	.075	.0089	.013	.751	.48
11	.048	.040	.0035	.155	.60	.068	.0308	.010	.477	.46	.082	.030	.0135	.545	.43
12	.054	.0378	.004	.279	.32	.093	.0280	.010	.631	.24	.092	.0288	.017	.580	.25
13	.080	.264	.0045	.634	.16	.122	.0324	.013	.664	.21	.1075	.0230	.0235	.645	.16
14	.117	.0144	.0055	.838	.09	.143	.0212	.015	.771	.14	.1185	.0198	.0265	.681	.13
15	.147	.0082	.009	.890	.10	.138	.0132	.018	.800	.14	.1135	.0149	.029	.692	.13
16	.136	.0034	.0075	.924	.19	.113	.0072	.015	.827	.21	.102	.0103	.023	.734	.16
17	.089	.0014	.0025	.957	.39	.086	.0048	.007	.873	.31	.083	.007	.014	.784	.26
18	.069	.0008	.0025	.954	.55	.065	.0028	.0085	.846	.46	.069	.0052	.012	.788	.41
19	.061	.0008	.0035	.933	.60	.057	.0024	.0098	.817	.58	.063	.0036	.013	.782	.49
Avg.	.071	.0155	.0052	.664	.32	.079	.0177	.0126	.655	.30	.081	.0155	.0187	.655	.27
Unif.	1.80/1	25.8/1	2.60/1	12.3/1	3.56/1	1.41/1	11.06/1	2.47/1	2.98/1	2.14/1	1.31/1	4.31/1	1.70/1	1.51/1	2.08/1

TABLE IV—Typical Horizontal Mercury Luminaire, IES Type III, with 400-Watt H1LS (E-H1) Clear Mercury Lamp, 140-Foot Staggered Spacing. Data from Systems No. 24, 25 and 26, For One Longitudinal Roadway Line.

	Low Angle 69 Degrees					Medium Angle 74 Degrees					High Angle 77 Degrees				
Station	B_1	B_2	B_v	C′	E_h	B_1	B_2	B_v	C′	E_h	B_1	B_2	B_v	C′	E_h
1	.220	.0076	.013	.912	4.27	.315	.0214	.030	.851	3.74	.318	.0357	.098	.679	3.68
2	.260	.1664	.016	.339	2.15	.257	.1540	.040	.347	2.04	.308	.1195	.110	.451	1.87
3	.290	.1366	.016	.501	1.02	.220	.1512	.053	.252	1.17	.302	.1395	.121	.384	1.01
4	.218	.1259	.023	.382	1.01	.222	.1037	.076	.400	.71	.294	.1066	.133	.439	.73
5	.192	.0858	.040	.458	.85	.275	.0779	.099	.527	.62	.312	.0719	.156	.513	.60
6	.308	.0444	.062	.713	.87	.365	.0557	.110	.651	.90	.418	.0520	.183	.609	.74
7	.332	.0160	.041	.847	1.64	.415	.0390	.069	.777	1.90	.468	.0422	.125	.718	1.53
8	.282	.0079	.011	.935	3.13	.410	.0240	.028	.881	2.57	.400	.0326	.080	.765	2.60
9	.438	.1095	.014	.727	1.64	.463	.1080	.035	.713	1.90	.406	.1162	.097	.576	1.53
10	.528	.0888	.015	.809	.87	.482	.1086	.038	.718	.90	.454	.0842	.104	.663	.74
11	.482	.0921	.019	.778	.85	.462	.1047	.053	.694	.62	.461	.0697	.119	.590	.60
12	.405	.0927	.029	.720	1.01	.438	.1065	.091	.627	.71	.459	.0655	.129	.669	.73
13	.486	.0314	.040	.864	1.02	.468	.0523	.096	.737	1.17	.528	.0498	.131	.726	1.01
14	.368	.0159	.030	.885	2.15	.426	.0284	.055	.827	2.04	.450	.0462	.111	.721	1.87
15	.220	.0076	.013	.912	4.27	.315	.0214	.030	.851	3.74	.318	.0357	.098	.679	3.68
Avg.	.344	.0729	.026	.705	1.61	.373	.081	.062	.643	1.50	.398	.0737	.121	.607	1.37
Unif.	1.8/1	9.6/1	2.36/1	2.08/1	1.9/1	1.7/1	3.8/1	2.2/1	2.55/1	2.4/1	1.35/1	2.26/1	1.51/1	1.58/1	2.28/1

a roadway lighting system since seeing is a matter of brightness *contrasts*. These are, however, part of the data needed to compute the ability of the system to reveal an object in contrast with its pavement background. In order to further study the relationships of pavement brightness and illumination, the apparent contrast, C', of an object silhouetted against the pavement was computed for all of the systems 18 through 29 listed in Table I, using the formula:[6]

$$C' = \frac{B_1 - B_2}{B_1 + B_v}$$

Where: B_1 = Pavement Brightness, in footlamberts, behind the object

B_2 = Brightness of a standard test object, in footlamberts, having a reflection factor of eight per cent

B_v = Disability veiling brightness, in footlamberts (from luminaires only)

The object was set up as shown in Fig. 1 and moved down the roadway in 20-foot steps. Object brightness, B_2, was obtained by multiplying the vertical footcandles, E_v, by eight per cent. All brightness values, together with the resultant contrasts, C', and the related horizontal footcandle values along the line shown in Fig. 1 are tabulated in Tables II through V.

Three typical sets of these data have been plotted in Figs. 2, 3 and 4, showing the results of a low, medium and high angle vertical distribution. There are some interesting relationships here. The highs and lows of C' do not necessarily follow those of pavement brightness, B_1, all the way through the system. In fact, the relation of E_h and C' seems to be somewhat closer. Actually C' is related to the differences between B_1 and B_2 rather than B_1 alone. B_2 is directly proportional to E_v. There is no definite conclusion to be drawn except that E_h and B_1 and the other brightnesses are not directly related to each other, but all of them are used to obtain a more important and meaningful factor, C'.

This contrast value has not been introduced to represent a measure of effective visibility or visi-

TABLE V—Typical Horizontal Mercury Luminaire, IES Type III, with 400-Watt H1LS (E-H1) Clear Mercury Lamp, 180-Foot Staggered Spacing. Data from Systems No. 27, 28 and 29, For One Longitudinal Roadway Line.

	Low Angle 69 Degrees					Medium Angle 74 Degrees					High Angle 77 Degrees				
Station	B_1	B_2	B_v	C′	E_h	B_1	B_2	B_v	C′	E_h	B_1	B_2	B_v	C′	E_h
1	.184	.0025	.013	.921	4.24	.220	.0069	.030	.852	3.64	.250	.0175	.087	.690	3.57
2	.150	.1636	.013	.083	2.10	.202	.1469	.037	.231	1.83	.240	.1424	.097	.290	1.76
3	.140	.1351	.015	.032	.92	.220	.1471	.048	.272	1.03	.220	.1299	.109	.274	.92
4	.190	.1251	.022	.306	.65	.248	.1018	.069	.461	.60	.210	.1001	.122	.331	.59
5	.228	.0853	.035	.543	.43	.208	.0765	.090	.441	.55	.230	.0677	.124	.458	.40
6	.163	.0441	.060	.533	.54	.180	.0546	.101	.446	.48	.215	.0493	.122	.492	.40
7	.160	.0158	.040	.721	.57	.184	.0382	.070	.574	.51	.248	.0401	.095	.606	.44
8	.240	.0077	.006	.944	.74	.280	.0234	.018	.861	.69	.341	.0311	.051	.791	.64
9	.260	.0033	.009	.954	1.60	.315	.0126	.022	.897	1.54	.359	.0230	.059	.804	1.44
10	.150	.0022	.010	.924	3.10	.224	.0074	.022	.880	2.92	.280	.0171	.066	.760	2.52
11	.159	.1075	.011	.303	1.60	.258	.1044	.024	.545	1.54	.288	.1044	.071	.512	1.44
12	.242	.0876	.014	.603	.74	.340	.0838	.036	.681	.69	.328	.0755	.099	.591	.64
13	.396	.0915	.019	.734	.57	.406	.0732	.048	.733	.51	.358	.0636	.105	.636	.44
14	.460	.0922	.026	.757	.54	.413	.0717	.060	.712	.48	.388	.0610	.110	.657	.40
15	.420	.0311	.037	.851	.43	.400	.0754	.083	.672	.55	.407	.0465	.112	.695	.40
16	.382	.0157	.025	.900	.65	.400	.0383	.069	.706	.60	.390	.0439	.090	.721	.59
17	.470	.0076	.010	.963	.92	.402	.0213	.022	.898	1.03	.440	.0352	.068	.797	.92
18	.370	.0044	.012	.955	2.10	.298	.0111	.029	.877	1.88	.370	.0250	.078	.770	1.76
19	.184	.0025	.013	.921	4.24	.220	.0069	.030	.852	3.64	.250	.0175	.087	.690	3.57
Avg.	.265	.0568	.021	.668	1.36	.289	.0608	.049	.652	1.17	.309	.0596	.093	.604	1.07
Unif.	1.89/1	25.8/1	3.5/1	20.9/1	3.16/1	1.61/1	8.81/1	2.72/1	2.82/1	2.44/1	1.47/1	3.49/1	1.82/1	2.20/1	2.68/1

TABLE II—Typical Pendant Filament Luminaire, IES Type III, With 6000-Lumen Street Series Lamp, 140-Foot Staggered Spacing. Data from Systems 18, 19 and 20, For One Longitudinal Roadway Line.

	Low Angle 66 Degrees					Medium Angle 73 Degrees					High Angle 77½ Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.068	.0096	.0035	.817	.61	.080	.012	.0085	.768	.60	.098	.0136	.0235	.695	.52
2	.070	.0372	.004	.443	.57	.084	.0332	.010	.540	.48	.0895	.0312	.0255	.507	.44
3	.070	.0564	.005	.315	.41	.093	.0371	.012	.532	.35	.0885	.0326	.0295	.474	.30
4	.0695	.0316	.006	.502	.25	.081	.0334	.016	.491	.28	.085	.0248	.0335	.508	.22
5	.072	.0165	.009	.685	.23	.072	.0226	.022	.526	.28	.087	.0186	.038	.547	.21
6	.077	.0074	.0125	.777	.34	.079	.0136	.028	.611	.28	.098	.0128	.040	.617	.28
7	.080	.0028	.0105	.853	.61	.091	.0074	.021	.746	.48	.110	.0083	.031	.721	.46
8	.0835	.0132	.0025	.817	.89	.1095	.0105	.008	.843	.51	.114	.0124	.0205	.755	.50
9	.103	.0406	.0035	.586	.61	.139	.0328	.010	.713	.48	.1255	.0320	.023	.630	.46
10	.133	.0378	.0035	.697	.34	.163	.0342	.0115	.738	.28	.133	.0298	.024	.657	.28
11	.1545	.0270	.004	.804	.23	.152	.0326	.014	.719	.28	.1295	.0248	.027	.669	.21
12	.1415	.0152	.0065	.853	.25	.121	.0220	.016	.723	.28	.1175	.0204	.032	.649	.22
13	.096	.0082	.010	.823	.41	.095	.0134	.0195	.713	.35	.107	.0156	.037	.635	.30
14	.074	.0034	.007	.872	.57	.087	.007	.014	.792	.48	.111	.0118	.034	.684	.44
15	.068	.0096	.0035	.817	.61	.080	.012	.0085	.768	.60	.098	.0136	.0235	.695	.52
Avg.	.092	.0212	.0063	.703	.45	.103	.0223	.0150	.675	.39	.1067	.0206	.0299	.625	.35
Unif.	1.35/1	2.57/1	2.52/1	2.23/1	1.96/1	1.43/1	3.19/1	1.88/1	1.37/1	1.39/1	1.26/1	2.48/1	1.46/1	1.32/1	1.67/1

the most responsive types will produce 100 times more brightness per footcandle than the least responsive types. On the other hand, at that point on the pavement where the lower emission angles are effective, the reverse is true, and the diffuse type pavement produces more brightness per horizontal footcandle than the more specular pavement.

Since the average Footlamberts/Footcandles factor is obtained by averaging several points on a roadway, each of which receives illumination from different angles, the low, medium and high angle distributions will produce a different range of results on different pavements. Also, the variable amounts of light flux above and below maximum, with different luminaire and lamp combinations, will further contribute to widening the range of Footlamberts/Footcandles factors.

Spacing of luminaires and other parts of the system geometry will also influence the Footlamberts/Footcandles ratio factor. For example, ratio values were computed at different spacing conditions for some of the distributions in Table I. In some cases, the factor increased as the spacing increased; in other cases the reverse was true. There was not enough statistical data here to come to any conclusion except that it is probably a minor influence on the ratio factor.

If all of the constituents of the relationship between candlepower distribution, roadway brightness and average horizontal footcandles are considered, it becomes too complex to define and therefore difficult to give exact meaning to a single ratio factor. It might eventually be possible to establish a category for all influencing elements and develop, by an enormous amount of calculations, a ratio factor applying to each case. However, this ratio factor would still simply be a means of transferring an average roadway horizontal illumination value to an average roadway brightness value or vice versa.

Up to this point the discussion has been confined to the relationships between pavement brightness and horizontal illumination. Neither of these will provide a means of determining the seeability in

TABLE III—Typical Pendant Filament Luminaire, IES Type III, with 6000-Lumen Street Series Lamp, 180-Foot Staggered Spacing. Data from Systems No. 21, 22 and 23, For One Longitudinal Roadway Line.

	Low Angle 66 Degrees					Medium Angle 73 Degrees					High Angle 77½ Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.061	.0008	.0035	.933	.60	.057	.0024	.0098	.817	.58	.063	.0036	.013	.782	.49
2	.052	.037	.0045	.265	.55	.056	.0312	.0099	.376	.46	.062	.0288	.0145	.434	.41
3	.0415	.044	.005	.054	.39	.055	.0348	.0120	.301	.31	.065	.0294	.016	.440	.26
4	.0395	.032	.006	.165	.19	.060	.0328	.015	.363	.21	.067	.0240	.020	.494	.16
5	.049	.016	.007	.589	.10	.068	.0486	.020	.220	.14	.069	.0164	.025	.560	.13
6	.060	.0072	.011	.744	.09	.063	.0130	.027	.556	.14	.070	.0112	.032	.576	.13
7	.067	.0028	.010	.834	.16	.056	.0076	.017	.663	.21	.071	.0080	.022	.677	.16
8	.062	.0012	.002	.950	.32	.063	.0040	.0051	.866	.24	.073	.006	.011	.798	.25
9	.052	.0006	.003	.935	.60	.064	.0022	.0052	.893	.46	.079	.004	.011	.833	.43
10	.057	.0056	.003	.857	.40	.060	.0016	.0095	.840	.50	.075	.0089	.013	.751	.48
11	.048	.040	.0035	.155	.60	.068	.0308	.010	.477	.46	.082	.030	.0135	.545	.43
12	.054	.0378	.004	.279	.32	.093	.0280	.010	.631	.24	.092	.0288	.017	.580	.25
13	.080	.264	.0045	.634	.16	.122	.0324	.013	.664	.21	.1075	.0230	.0235	.645	.16
14	.117	.0144	.0055	.838	.09	.143	.0212	.015	.771	.14	.1185	.0198	.0265	.681	.13
15	.147	.0082	.009	.890	.10	.138	.0132	.018	.800	.14	.1135	.0149	.029	.692	.13
16	.136	.0034	.0075	.924	.19	.113	.0072	.015	.827	.21	.102	.0103	.023	.734	.16
17	.089	.0014	.0025	.957	.39	.086	.0048	.007	.873	.31	.083	.007	.014	.784	.26
18	.069	.0008	.0025	.954	.55	.065	.0028	.0085	.846	.46	.069	.0052	.012	.788	.41
19	.061	.0008	.0035	.933	.60	.057	.0024	.0098	.817	.58	.063	.0036	.013	.782	.49
Avg.	.071	.0155	.0052	.664	.32	.079	.0177	.0126	.655	.30	.081	.0155	.0187	.655	.27
Unif.	1.80/1	25.8/1	2.60/1	12.3/1	3.56/1	1.41/1	11.06/1	2.47/1	2.98/1	2.14/1	1.31/1	4.31/1	1.70/1	1.51/1	2.08/1

TABLE IV—Typical Horizontal Mercury Luminaire, IES Type III, with 400-Watt H1LS (E-H1) Clear Mercury Lamp, 140-Foot Staggered Spacing. Data from Systems No. 24, 25 and 26, For One Longitudinal Roadway Line.

	Low Angle 69 Degrees					Medium Angle 74 Degrees					High Angle 77 Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.220	.0076	.013	.912	4.27	.315	.0214	.030	.851	3.74	.318	.0357	.098	.679	3.68
2	.260	.1664	.016	.339	2.15	.257	.1540	.040	.347	2.04	.308	.1195	.110	.451	1.87
3	.290	.1366	.016	.501	1.02	.220	.1512	.053	.252	1.17	.302	.1395	.121	.384	1.01
4	.218	.1259	.023	.382	1.01	.222	.1037	.076	.400	.71	.294	.1066	.133	.439	.73
5	.192	.0858	.040	.458	.85	.275	.0779	.099	.527	.62	.312	.0719	.156	.513	.60
6	.308	.0444	.062	.713	.87	.365	.0557	.110	.651	.90	.418	.0520	.183	.609	.74
7	.332	.0160	.041	.847	1.64	.415	.0390	.069	.777	1.90	.468	.0422	.125	.718	1.53
8	.282	.0079	.011	.935	3.13	.410	.0240	.028	.881	2.57	.400	.0326	.080	.765	2.60
9	.438	.1095	.014	.727	1.64	.463	.1080	.035	.713	1.90	.406	.1162	.097	.576	1.53
10	.528	.0888	.015	.809	.87	.482	.1086	.038	.718	.90	.454	.0842	.104	.663	.74
11	.482	.0921	.019	.778	.85	.462	.1047	.053	.694	.62	.461	.0697	.119	.590	.60
12	.405	.0927	.029	.720	1.01	.438	.1065	.091	.627	.71	.459	.0655	.129	.669	.73
13	.486	.0314	.040	.864	1.02	.468	.0523	.096	.737	1.17	.528	.0498	.131	.726	1.01
14	.368	.0159	.030	.885	2.15	.426	.0284	.055	.827	2.04	.450	.0462	.111	.721	1.87
15	.220	.0076	.013	.912	4.27	.315	.0214	.030	.851	3.74	.318	.0357	.098	.679	3.68
Avg.	.344	.0729	.026	.705	1.61	.373	.081	.062	.643	1.50	.398	.0737	.121	.607	1.37
Unif.	1.8/1	9.6/1	2.36/1	2.08/1	1.9/1	1.7/1	3.8/1	2.2/1	2.55/1	2.4/1	1.35/1	2.26/1	1.51/1	1.58/1	2.28/1

a roadway lighting system since seeing is a matter of brightness *contrasts*. These are, however, part of the data needed to compute the ability of the system to reveal an object in contrast with its pavement background. In order to further study the relationships of pavement brightness and illumination, the apparent contrast, C', of an object silhouetted against the pavement was computed for all of the systems 18 through 29 listed in Table I, using the formula:[6]

$$C' = \frac{B_1 - B_2}{B_1 + B_v}$$

Where: B_1 = Pavement Brightness, in footlamberts, behind the object
B_2 = Brightness of a standard test object, in footlamberts, having a reflection factor of eight per cent
B_v = Disability veiling brightness, in footlamberts (from luminaires only)

The object was set up as shown in Fig. 1 and moved down the roadway in 20-foot steps. Object brightness, B_2, was obtained by multiplying the vertical footcandles, E_v, by eight per cent. All brightness values, together with the resultant contrasts, C', and the related horizontal footcandle values along the line shown in Fig. 1 are tabulated in Tables II through V.

Three typical sets of these data have been plotted in Figs. 2, 3 and 4, showing the results of a low, medium and high angle vertical distribution. There are some interesting relationships here. The highs and lows of C' do not necessarily follow those of pavement brightness, B_1, all the way through the system. In fact, the relation of E_h and C' seems to be somewhat closer. Actually C' is related to the differences between B_1 and B_2 rather than B_1 alone. B_2 is directly proportional to E_v. There is no definite conclusion to be drawn except that E_h and B_1 and the other brightnesses are not directly related to each other, but all of them are used to obtain a more important and meaningful factor, C'.

This contrast value has not been introduced to represent a measure of effective visibility or visi-

TABLE V—Typical Horizontal Mercury Luminaire, IES Type III, with 400-Watt H1LS (E-H1) Clear Mercury Lamp, 180-Foot Staggered Spacing. Data from Systems No. 27, 28 and 29, For One Longitudinal Roadway Line.

	Low Angle 69 Degrees					Medium Angle 74 Degrees					High Angle 77 Degrees				
Station	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h	B_1	B_2	B_v	C'	E_h
1	.184	.0025	.013	.921	4.24	.220	.0069	.030	.852	3.64	.250	.0175	.087	.690	3.57
2	.150	.1636	.013	.083	2.10	.202	.1469	.037	.231	1.83	.240	.1424	.097	.290	1.76
3	.140	.1351	.015	.032	.92	.220	.1471	.048	.272	1.03	.220	.1299	.109	.274	.92
4	.190	.1251	.022	.306	.65	.248	.1018	.069	.461	.60	.210	.1001	.122	.331	.59
5	.228	.0853	.035	.543	.43	.208	.0765	.090	.441	.55	.230	.0677	.124	.458	.40
6	.163	.0441	.060	.533	.54	.180	.0546	.101	.446	.48	.215	.0493	.122	.492	.40
7	.160	.0158	.040	.721	.57	.184	.0382	.070	.574	.51	.248	.0401	.095	.606	.44
8	.240	.0077	.006	.944	.74	.280	.0234	.018	.861	.69	.341	.0311	.051	.791	.64
9	.260	.0033	.009	.954	1.60	.315	.0126	.022	.897	1.54	.359	.0230	.059	.804	1.44
10	.150	.0022	.010	.924	3.10	.224	.0074	.022	.880	2.92	.280	.0171	.066	.760	2.52
11	.159	.1075	.011	.303	1.60	.258	.1044	.024	.545	1.54	.288	.1044	.071	.512	1.44
12	.242	.0876	.014	.603	.74	.340	.0838	.036	.681	.69	.328	.0755	.099	.591	.64
13	.396	.0915	.019	.734	.57	.406	.0732	.048	.733	.51	.358	.0636	.105	.636	.44
14	.460	.0922	.026	.757	.54	.413	.0717	.060	.712	.48	.388	.0610	.110	.657	.40
15	.420	.0311	.037	.851	.43	.400	.0754	.083	.672	.55	.407	.0465	.112	.695	.40
16	.382	.0157	.025	.900	.65	.400	.0383	.069	.706	.60	.390	.0439	.090	.721	.59
17	.470	.0076	.010	.963	.92	.402	.0213	.022	.898	1.03	.440	.0352	.068	.797	.92
18	.370	.0044	.012	.955	2.10	.298	.0111	.029	.877	1.88	.370	.0250	.078	.770	1.76
19	.184	.0025	.013	.921	4.24	.220	.0069	.030	.852	3.64	.250	.0175	.087	.690	3.57
Avg.	.265	.0568	.021	.668	1.36	.289	.0608	.049	.652	1.17	.309	.0596	.093	.604	1.07
Unif.	1.89/1	25.8/1	3.5/1	20.9/1	3.16/1	1.61/1	8.81/1	2.72/1	2.82/1	2.44/1	1.47/1	3.49/1	1.82/1	2.20/1	2.68/1

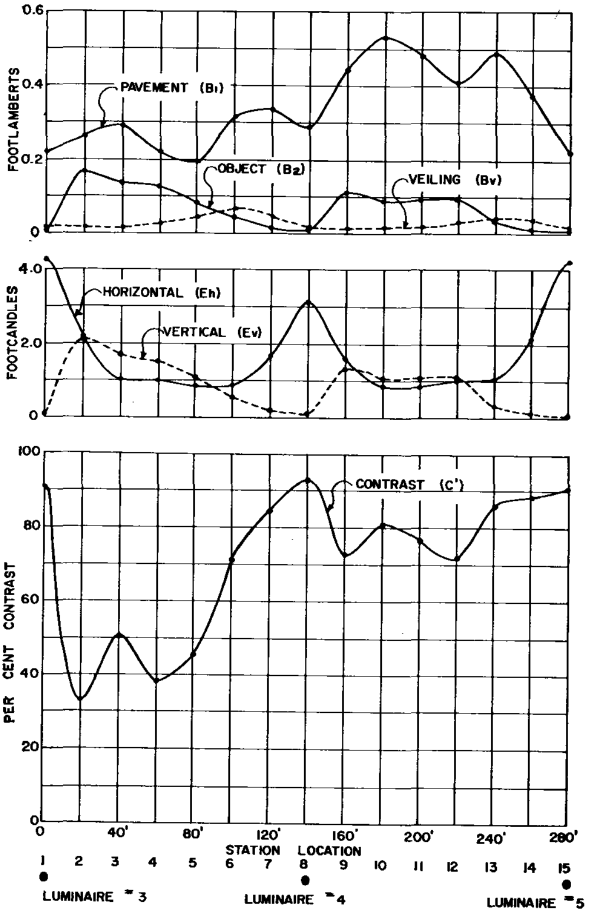


Figure 2. Pavement brightness, object brightness disability veiling brightness, vertical and horizontal illumination and contrast computed for different positions along one driving lane as illustrated in Fig. 1. Data are from System No. 24, horizontal 400-watt mercury, 140-foot spacing, low-angle distribution.

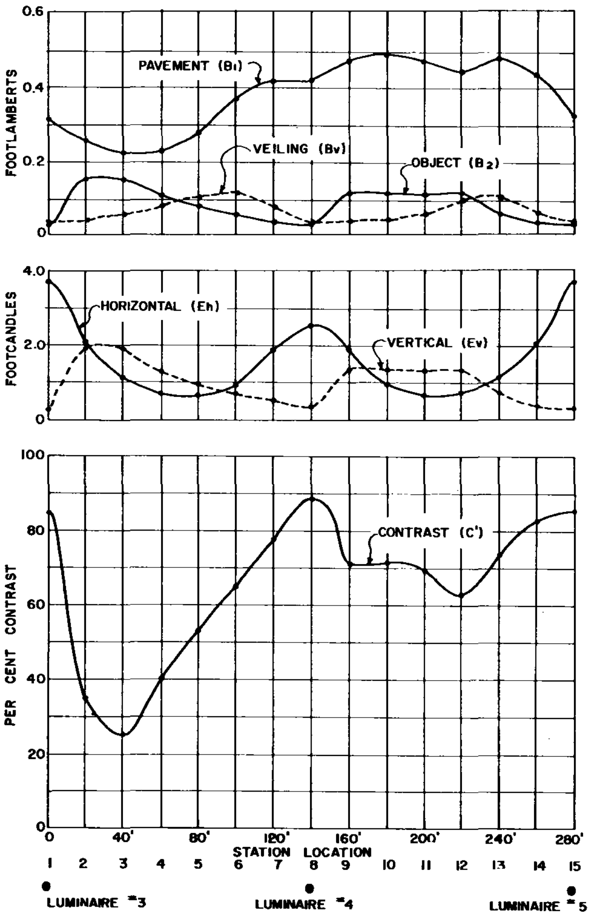


Figure 3. Pavement brightness, object brightness, disability veiling brightness, vertical and horzontal illumination and contrast computed for different positions along one driving lane as illustrated in Fig. 1. Data are from System No. 25, horizontal 400-watt mercury, 140-foot spacing, medium angle distribution.

bility distance because there is no indication of an obstacle size, exposure time, motion or any other extenuating factors that might apply in determining "visibility" by one means or another. It is, however, felt to be a value that relates the potential ability of one system with another in revealing the presence of an object on the roadway. Furthermore, the task of calculating these contrast values is perfectly straightforward, although time consuming, if the system design, light distribution and pavement characteristics are known.

If the object reflection factor were to be much higher than eight per cent, for example, on the order of 20 or 30 per cent, and the object were large enough to protrude above the horizon, it would not be seen in contrast against the pavement but against some darker surround such as sky, building fronts, etc. Here the pavement reflection factor would be of little value. The important data would be vertical footcandles on the object at some distance above the road surface and brightness of the surround.

No one can yet establish a particular condition of seeability or road brightness and determine the luminaire, lamp and system design necessary to obtain it. It is possible, however, to determine a horizontal footcandle level, and select conditions to produce a given uniformity ratio of illumination. While this is no guarantee of the seeability of a system, neither is any other illumination or brightness factor. They must all be considered together and carefully examined in relation to one another. The horizontal footcandle is the one element that can be readily computed and related to, or from, the horizontal geometry of the roadway lighting system. The quality aspects and refinements of a lighting system can be judged by examining the level and uniformity of illumination, as well as brightness of the roadway, level of veiling glare, etc. No one factor alone will give the true answer.

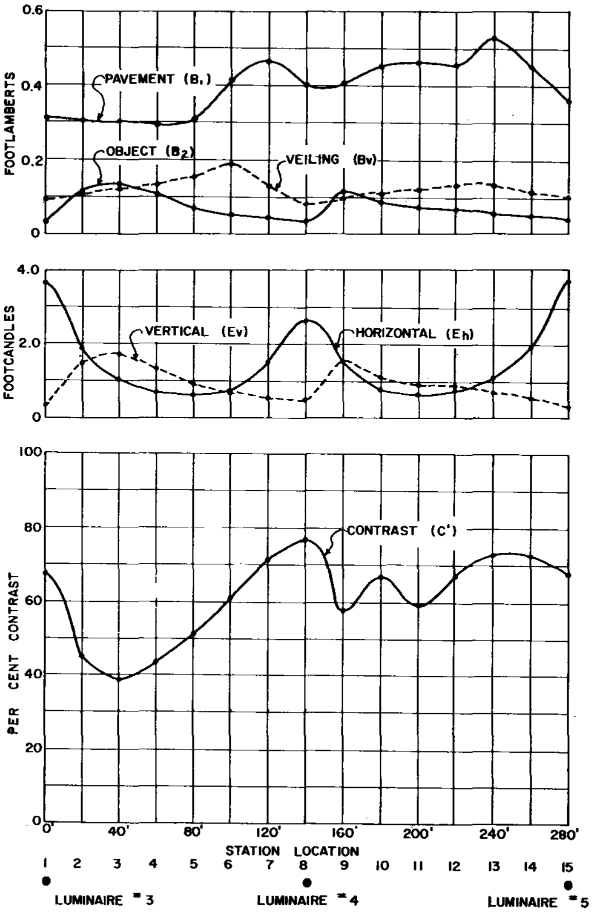


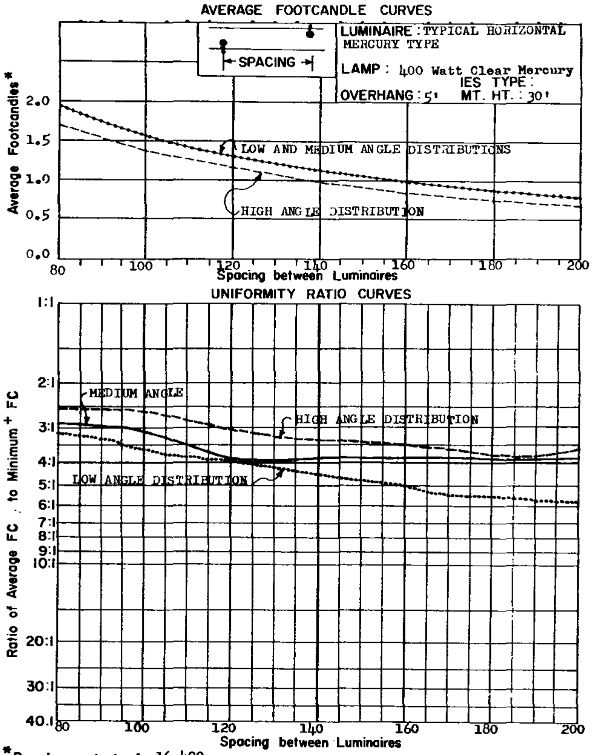
Figure 4. Pavement brightness, object brightness, disability veiling brightness, vertical and horizontal illumination and contrast computed for different positions along one driving lane as illustrated in Fig. 1. Data are from System No. 26, horizontal 400-watt mercury, 140-foot spacing, high angle distribution.

If a Footlambert/Footcandle factor were to be used in luminaire and system design, it would be necessary to explore all possible relationships to determine the effect each has on this ratio factor. This would be a highly impractical solution, since the end result would still be only a multiplying factor between footcandles and footlamberts.

Instead, it is suggested that a series of system data be developed for pavement brightness values and illumination values both near the road surface and at some height above the roadway from which obstacle brightnesses and veiling brightness can be calculated. These could be computed and plotted for varying spacing and street width conditions in the form of an application guide similar to that now used for footcandle level and uniformity ratio charts (Fig. 5). These are now used to relate different items of equipment, or light distributions and system designs to average horizontal footcandles and uniformity of illumination.

It is believed similar information on brightness data would be very helpful in assisting the application engineer in selecting various types of luminaires and light distributions for other system effects than horizontal illumination. Knowing, for example, that a particular kind of low angle or high angle distribution would produce different average levels of road brightness per system horizontal footcandle, the application engineer could apply this knowledge of the equipment accordingly.

If the application engineer is more concerned with higher levels of vertical illumination than with pavement brightness levels, then perhaps a different type of light distribution should be used. If he is concerned with reduction in disability veiling brightness (which will also improve the comfort aspect), then the proper cut-off type distributions would have to be considered. These, in turn, would have to be evaluated along with the other aspects of pavement brightness and vertical footcandles.



*Based on output of 16,400 Lumens MEAN

+ Lowest value on street area.

Figure 5. Average footcandle and uniformity ratio curves. These are plots of the illumination and uniformity ratio values computed for each spacing condition for a given system design. Data for several street widths can be plotted on one chart or, as in this case, data are shown for low, medium and high vertical angle distributions using same luminaire and street width. These curves are for the system represented by Figs. 2, 3 and 4.

The number of computations necessary for preparing such data explain, to some extent, why it has not been done before, but it is hoped this paper will show in a small way the value of eventually going further in this field. Obtaining such information can be facilitated by computer techniques and once obtained the data and charts can be used many times by design and application engineers. It would enable a comparison of the use of different light distributions in different system arrangements from the standpoint of, not only resultant horizontal footcandles and footcandle uniformity, but also pavement brightness and its uniformity, vertical illumination and its uniformity and system veiling brightness. This may further help to lead the way to the ultimate criterion of designing the lighting system according to the effect a particular light distribution will have on the ability to see under that system.

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DISCUSSION

HAROLD F. WALL:* We all know that visibility under street lighting conditions is comprised of many more things than just plain horizontal footcandles. There has been considerable discussion relative to specifying average pavement brightness for street lighting, and although this would seem to be one of the most important factors in visibility, there is as yet no commonly agreed upon method for calculating this average figure. It is entirely possible that the pavement brightness 210 feet in front of the observer might be excellent, resulting in perfect visibility, and yet the brightness 10 feet to the right or left of this location might be zero. We understand that the authors have averaged the brightnesses only of the locations 210 feet in front of the observer in one or more driving lines as described above, and we agree that this cannot fully represent seeability.

From this inadequate calculation of pavement brightness, however, the authors have calculated and introduced contrast as a visibility factor. A comparison of Tables II and IV, representing similar systems of street lighting except with 6000-lumen incandescent and 20,000-lumen mercury lamps, respectively, results in the impossible conclusion that the smaller incandescent lamp provides better visibility in the medium and high-angle distribution categories, inasmuch as the average contrast for the smaller lamps is numerically higher. This same inconsistency is exhibited in in Tables III and V.

More than ever it seems to me that before we can specify average pavement brightness or use it for further investigations such as those in this paper, the IES Roadway Lighting Committee ought to define it in a significant manner. The driver requires good visibility all over the roadway at every instant, and until we get an adequate method for computing average brightness we will not be able to evaluate it satisfactorily.

Since the authors had already calculated pavement brightness, obstacle brightness and veiling brightnesses, all of which are essential to the Reid-Chanon method of computing relative visibility, it might be interesting to show a comparison of this method and the contrast method. Fig. A of this discussion shows the contrasts for the medium-angle luminaires in Tables II and IV, and also the Reid-Chanon visibility ratings for these systems. The contrast method shows the 600-lumen system and 20,000-lumen system to be virtually identical, whereas the Reid-Chanon rating seems

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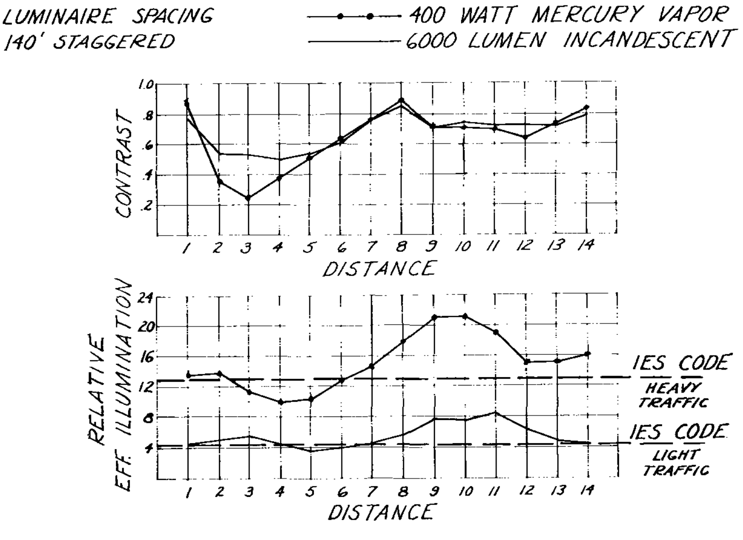

Figure A (Wall discussion).