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Night Visibility

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Dynamic Visual Acuity–Effect on Night Driving And Highway Accidents

J.L. FELDHAUS, JR., Erlton, New Jersey

●IN RECENT MONTHS there have been several instances where an article titled "Study of Visual Acuity during the Ocular Pursuit of Moving Test Objects" has been very briefly noted in the optometric literature. This fine piece of research conducted by Elek Ludvigh of the Kresge Eye Institute and James Miller of the U.S. Naval School of Aviation Medicine, is probably the most important work relating to motorist vision that has been completed in recent years. There is a relationship with the visual problems facing anyone in a moving vehicle.

The following quotation from the summary of the original report serves as an introduction to the calculations and conclusions made herein:

> "Visual acuity may be measured during the voluntary ocular pursuit of moving test objects. This visual function has been referred to as dynamic visual acuity. The apparent movement of the test object is produced by rotating a mirror in the desired plane of pursuit by means of a wheel and disk type variable speed drive. The range of angular velocities utilized is 10°/ to 170°/sec at the nodal point of the tested eye. It is shown that visual acuity deteriorates markedly and significantly as the angular velocity of the test object is increased. It is shown further that the relationship between visual acuity and the angular velocity of the test object may be described satisfactorily by the semiempirical equation $Y = a + bx^3$. It also is pointed out that individuals possessing similar static acuity may differ significantly in their dynamic acuity. The possible causes for the observed deterioration of acuity are discussed and it is concluded that imperfect pursuit movements of the eye result in a continued motion of the image on the retina. This motion results in reduced intensity contrast, which is a factor in producing loss in acuity.
>
> "It was demonstrated that the manner in which visual acuity deteriorates as the angular velocity of the test object increases is similar regardless of whether the motion is produced by moving the target vertically, horizontally, or by rotating the observer in a horizontal plane. It was shown also that the semiempirical equation $Y = a + bx^3$ describes satisfactorily these three types of movement. It was pointed out that individuals having a low acuity threshold in the vertical plane of movement will be likely also to have a low threshold in the horizontal plane. It was shown that although 5 to 10 foot-candles may be sufficient illumination when the test object is stationary, visual acuity is substantially benefitted by increases up to 125 foot-candles when the observer is rotated."

In the foregoing equation Y = visual acuity in minutes of arc, x = angular velocity in degrees per second and a and b are parameters which have been determined by curve fitting using the method of moments (a is a measure of the static visual acuity, b is a measure of the dynamic acuity).

To a person driving a car, all objects outside of his car are moving with a certain angular velocity, the nearer the object the greater the angular velocity. If 60 mph is changed into angular velocity at various distances, there is a vast and rapid drop in visual acuity for approaching objects. This could be a cause for the correlation between increase in driving speed and increase in accident occurence.

The article also points out that there is little if any correlation between static and dynamic acuity—this means that checking the static acuity in relation to driving ability is comparable to checking only the distance acuity in school children when their near vision is very important.

For convenience, the subjects tested were divided into three groups, because the dynamic acuity is not the same for all individuals. To some subjects visual acuity deteriorates very rapidly with increasing angular velocity, whereas in others the deterioration is much less rapid. Table 1 gives the results of calculations changing the velocity of an automobile in miles per hour into various angular velocities. In all cases if the angular velocity is zero, the visual acuity is 20/20 Snellen.

TABLE 1

	60 MPH				30 MPH			
Distance to Object (ft)	Angular Velocity (deg/sec)	Visual Acuity			Angular Velocity (deg/sec)	Visual Acuity		
		GR 1	GR 2	GR 3		GR 1	GR 2	GR 3
1,000	5.0	20/51	20/48	20/38	2.5	20/51	20/48	20/38
500	10.0	20/51	20/48	20/39	5.0	20/51	20/48	20/38
100	47.5	20/64	20/54	20/42	24.75	20/53	20/48	20/29
80	57.5	20/73	20/59	20/45	30.75	20/54	20/49	20/39
60	72.5	20/96	20/70	20/52	40.25	20/59	20/51	20/41
40	95.5	20/154	20/99	20/70	57.5	20/73	20/59	20/45
20	131.0	20/317	20/317	20/121	95.5	20/154	20/99	20/70

These calculations indicate that when driving at 60 mph and looking at an object located 20 ft from the car, the driver's visual acuity will be between 20/121 and 20/317 depending on how rapidly his dynamic acuity changes. When driving at 30 mph, looking at the same object, his visual acuity would be between 20/70 and 20/150. There is a definite advantage to reducing driving speed.

Further investigation by Ludvigh and Miller indicates that dynamic visual acuity is greatly increased by increasing the illumination falling on the object of regard. Under conditions of static vision, increasing illumination more than 10 foot-candles has little value but increases up to 125 foot-candles are usable for increasing dynamic acuity. This information should be very helpful in planning the lighting of streets and highways. Here is dynamic evidence that the proper lighting of streets and highways, by improving dynamic visual acuity, may help to reduce the hazards of night driving. It seems to indicate that roads cannot be illuminated too much to suit the human visual system.

In this age of increasing tempo, dynamic visual acuity—its measurement and implications—may one day replace static acuity in position of importance. Screening out poor driving risks by checking their static acuity only, or increasing static acuity by modification of highway illumination (with no regard to acuity in a moving vehicle or to the increase of dynamic acuity produced by very high foot-candle levels), can no longer be considered adequate.

Dark Adaptation Threshold, Rate, and Individual Prediction

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● THE PURPOSE of this paper is to make a detailed study and interpretation of the relationship between dark adaptation and age. Other studies (1, 3, 4, 9, 11, 12, 17, 19, 20, 21, 27, 30) have demonstrated an association between age and the process of dark adaptation, but an attempt to estimate the extent of the change in the general population from the existing data has proved almost impossible. This is true partly because the experimental conditions, degree and time of presentation, intensity, and color of light under which this phenomenon has been studied have varied widely from one age sample to another and partly because those studies that have shown a relationship have depended on highly select samples that did not represent the general population (19). Such experimental groups have also varied in both composition and size. Furthermore, in some studies an artificial pupil (21) or a mydriatic (23) was used, and in others they were not (27).

The indications are that the range of individual differences in the dark adaptation process as a function of age is considerably greater than has been supposed, and greater than any one study has demonstrated. Therefore, to obtain a better estimate of the influence of age on the dark adaptation process the present study was conducted using a much larger and more representative age sample of the population.

Among those variables which influence rate and the ultimate degree to which the viewer will be able to adapt at low levels of luminance are duration and intensity of pre-exposure illumination (26) and wave length (33).

The variables taken into consideration in the present study were (a) age, (b) dark adaptation thresholds for 21 time intervals, and (c) the intersection of the cone and rod curves.

In an alternative statistical study of the relationship of dark adaptation and age, McFarland and Fisher (21) stated that the dark adaptation curve itself could be described as inversely logarithmic and therefore represented by the general equation

$$y = 10^{a + bx} + C \tag{1}$$

in which

y = $\mu\mu$l luminance;
a = initial level of dark adaptation;
b = drop time (drop time is generally taken to mean the amount of time required to reach some predetermined level of dark adaptation);
x = time; and
C = the asymptote of the curve.

However, it is also possible to compute C (8, 21) by the formula

$$C = \frac{P_1 \times P_2 - P_3^2}{P_1 + P_2 - 2(P_3)} \tag{2}$$

in which

P_1 = a given value of the curve early in time, for example, the 6th minute;
P_2 = a value on the curve late in time, for example, the 30th minute;
P_3 = a value on the curve midway between P_1 and P_2; and
C = the asymptote of the curve.

This method of calculating C, the asymptote of the rod curve, is generally applicable to calculating the asymptote of the cone curve as well.

Hammond and Lee (12) stated that the dark adaptation curve can be represented by

$$\text{Log } I = a + b/t^2 \qquad (3)$$

in which

a = a constant, the general level of the curve at the asymptote;
b = a constant, the rate of adaptation; and
t = the time in minutes from the cessation of the pre-adaptation light stimulus.

In previous investigations the general procedure was to fit curves individually by using various formulas, and then identifying such parameters as the curve intercept, cone-rod curve intersection, drop rate, asymptote of the cone curve, and the asymptote of the rod curve. But dark adaptation is a phenomenon known to vary, relative to a number of conditions of which age is one. It is now certain that as age increases the curve is displaced upward on the y axis. At the same time the cone and rod segments of the curve seem to pivot around their individual focal points near the intercept. The pattern of displacement is extremely orderly.

It is evident that, if the age variable is related to the dark adaptation curve in some lawful manner, then this function could be described mathematically. If this is so, then it should be possible to describe the age curve family. However, this has not been done.

Instead, at this time in the investigation of dark adaptation as a function of age, conventional statistical methods in the study of the age factor were substituted for a more mathematical resolution of the dark adaptation time and age interaction. This approach established beyond a reasonable doubt that dark adaptation becomes a function of age. For example, in 1955 McFarland and Fisher (21) used Eq. 2 for obtaining C and found a correlation of 0.895 between age and C. Inasmuch as the sample of subjects used was composed largely of aircraft pilots who were, by the nature of their occupation, highly selected with respect to visual efficiency, a correlation of this magnitude would not ordinarily have been expected. This is because restricted range of samples tends to lower the magnitude of the conventional product moment, r. The results, r = 0.895, failed to support their inference, because this correlation was one of the highest ever discovered among physiological and psychological relationships.

However, the statistical approach did not fulfill the need for a mathematical model of the dark adaptation, time, and age relationships. Consequently, a search for a general equation was initiated. A model was constructed which made possible the accurate prediction of the mean level of adaptation for any point on the time continuum as a function of age.

METHOD

Subjects

There were 240 male subjects. Thirty subjects were drawn from each decade ranging from the teen-age level through 89 years. The total sample was composed of persons taken from YMCA groups, college-age students, university faculty, taxi drivers, unemployed persons obtained from the USES Agency, and retired men living at home or in private institutions for the aged. All subjects were paid for their services, and after obtaining the data, over one-half the subjects in each decade were then offered and given a complete eye examination free of charge.

Apparatus

The instrument (16) used throughout this study was the Hecht-Schlaer adaptometer which had been rebuilt and recalibrated by the manufacturer. The research was conducted in three different cities to accommodate aged persons for whom traveling was difficult.

Procedure

After each subject was seated in the experimental room, his left eye was covered by a patch, and his head was held steady in a head-chin rest. Vision was uncorrected. The lights in the dark-room were turned off, and after a lapse of approximately 1 min, the retina of the right eye was bleached by exposure to a standard 1,600-millilamberts incandescent light source for 3 min. At the end of the pre-test period, the subject was exposed to a red fixation point 7 deg right of center. The violet light test stimulus of 1 deg (53.0 percent transmission at 405 μ) was then presented. The duration of each flash of light was ⅕ sec. All of the experimental measurements were made by the same person.

TABLE 1

MEAN DARK ADAPTATION AS A FUNCTION OF AGE AND TIME LOG$_{10}$ μμl LUMINANCE[1]

Age (Years)	16-19		20-29		30-39		40-49		50-59		60-69		70-79		80-89	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
0-59 Sec	6.93	0.30	6.78	0.41	6.95	0.32	7.03	0.26	7.06	0.26	7.21	0.24	7.49	0.58	7.67	0.13
Min																
2	6.42	0.32	6.16	0.46	6.37	0.34	6.62	0.27	6.78	0.27	6.94	0.25	7.16	0.57	7.43	0.14
3	5.93	0.39	5.65	0.48	6.05	0.35	6.29	0.32	6.49	0.31	6.73	0.31	7.06	0.17	7.25	0.15
4	5.66	0.39	5.43	0.51	5.85	0.40	5.98	0.35	6.25	0.40	6.59	0.34	6.95	0.22	7.12	0.16
5	5.58	0.40	5.26	0.60	5.67	0.47	5.86	0.37	6.17	0.42	6.50	0.43	6.94	0.23	7.08	0.17
6	5.36	0.41	5.05	0.67	5.45	0.48	5.61	0.33	5.94	0.46	6.27	0.38	6.70	0.29	6.90	0.21
7	5.08	0.45	4.83	0.71	5.17	0.46	5.36	0.34	5.63	0.44	6.02	0.38	6.48	0.29	6.71	0.26
8	4.82	0.46	4.61	0.66	4.86	0.47	5.10	0.38	5.41	0.45	5.76	0.44	6.25	0.32	6.52	0.29
9	4.55	0.52	4.38	0.66	4.84	0.38	4.80	0.38	5.14	0.50	5.51	0.51	5.98	0.43	6.33	0.43
10	4.17	0.48	3.95	0.63	4.17	0.36	4.51	0.39	4.77	0.60	5.24	0.65	5.71	0.44	6.10	0.45
12	3.80	0.40	3.50	0.46	3.87	0.38	4.22	0.34	4.48	0.64	4.99	0.61	5.48	0.46	5.91	0.50
14	3.48	0.43	3.28	0.47	3.62	0.37	3.96	0.35	4.25	0.61	4.78	0.61	5.26	0.45	5.74	0.55
16	3.24	0.41	3.14	0.47	3.44	0.37	3.76	0.31	4.02	0.57	4.50	0.59	5.00	0.48	5.55	0.59
19	3.02	0.35	2.98	0.45	3.23	0.37	3.54	0.31	3.85	0.57	4.27	0.59	4.74	0.48	5.54	0.59
22	2.86	0.35	2.85	0.45	3.04	0.29	3.34	0.29	3.70	0.58	4.05	0.55	4.54	0.47	5.16	0.62
25	2.74	0.32	2.78	0.45	2.93	0.30	3.22	0.29	3.55	0.53	3.88	0.53	4.36	0.46	5.01	0.66
28	2.64	0.30	2.72	0.46	2.87	0.27	3.13	0.30	3.43	0.51	3.74	0.52	4.22	0.46	4.90	0.68
31	2.52	0.30	2.65	0.47	2.81	0.28	3.07	0.31	3.36	0.48	3.67	0.50	4.14	0.47	4.83	0.71
34	2.45	0.23	2.64	0.47	2.77	0.26	3.02	0.29	3.32	0.47	3.63	0.49	4.11	0.47	4.81	0.72
37	2.43	0.17	2.60	0.46	2.76	0.25	3.02	0.29	3.32	0.47	3.62	0.48	4.11	0.48	4.81	0.73
40	2.43	0.17	2.60	0.44	2.76	0.26	3.02	0.29	3.32	0.47	3.62	0.48	4.11	0.48	4.81	0.72

[1] The data for 0-59 seconds were not used in the statistical analysis since they were considered the least reliable.

The first observation was made within the first 59 sec after the termination of the pre-exposure light. Then, beginning with the second observation, one reading was taken every minute for the next 9 min, every 2 min for the next 6 min, and every 3 min for the following 24 min.

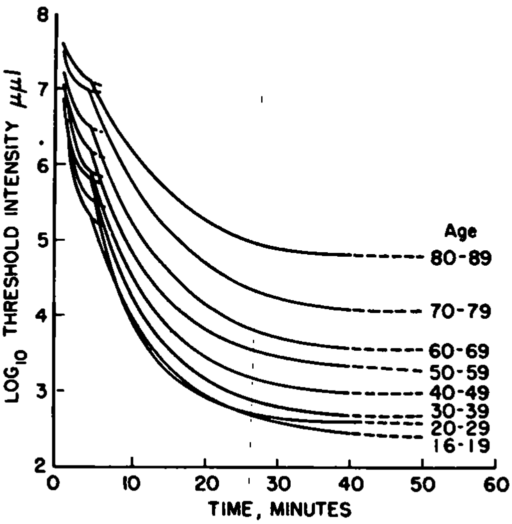

Figure 1. Dark adaptation as a function of age. Age range 16-89 years, N = 240.

RESULTS

Table 1 and Figure 1 show that the family of mean dark adaptation curves obtained as a function of age rises in an orderly manner, suggesting that the differences between their terminal points increases geometrically from one age level to the next. Table 1 also shows the standard deviation for each threshold to be exceedingly small. The intercorrelations among age and thresholds are unusually high (Table 2).

Inasmuch as the curves for the 16- to 19-year old group and the 20- to 29-year old group seemed to be nearly alike, they have been combined for the purpose of simplifying the mathematical process which follows, although plotted independently in Figure 1.

TABLE 2

INTERCORRELATION OF DARK ADAPTATION THRESHOLD FOR EACH TIME INTERVAL AND DARK ADAPTATION THRESHOLDS WITH AGE[1]

	N 240—Age Range 16-89 Years																			
Min	2	3	4	5	6	7	8	9	10	12	14	16	19	22	25	28	31	34	37	40	Age
2		0 87	0 83	0 83	0 81	0 79	0 77	0 76	0 76	0 75	0 75	0 74	0 73	0 73	0 71	0 70	0 69	0 69	0 70	0 70	0.71
3			0 96	0 96	0 94	0 92	0 90	0 88	0 87	0 86	0 85	0 84	0 82	0 82	0 81	0 79	0 79	0 79	0 79	0 79	0 82
4				0 98	0 97	0 94	0 92	0 90	0 89	0 88	0.87	0 85	0 84	0 83	0 82	0 80	0 79	0.79	0 80	0.80	0 80
5					0 98	0 95	0 93	0 91	0 89	0 88	0 86	0 85	0 83	0 83	0 81	0 79	0 79	0 78	0 79	0 79	0.80
6						0 97	0 95	0 93	0 91	0 90	0.89	0 87	0 85	0 85	0 83	0 82	0 81	0.81	0 80	0 81	0.79
7							0 98	0 96	0 93	0 92	0 91	0 89	0 87	0 86	0 86	0 83	0 82	0 82	0 82	0 82	0 79
8								0 99	0 95	0 93	0 92	0 91	0 89	0.88	0 87	0 85	0 84	0 83	0 83	0 83	0 79
9									0 96	0 95	0 94	0 93	0 90	0 89	0 89	0 87	0 86	0 85	0.84	0 85	0 79
10										0 97	0 96	0 95	0 93	0.91	0.91	0.89	0 88	0 87	0 87	0 87	0 79
12											0.98	0 97	0 96	0 94	0 93	0.92	0.91	0 90	0 90	0 90	0 82
14												0.99	0 98	0.96	0 95	0.94	0 92	0 92	0 91	0 92	0 84
16													0 99	0 98	0 96	0.96	0 94	0 93	0 93	0 93	0 83
19														0 99	0.98	0.97	0 96	0 95	0 95	0.95	0 83
22															0 99	0.98	0 97	0 97	0 97	0 97	0 83
25																0 99	0 98	0 98	0.98	0 98	0 83
28																	0 99	0 99	0 99	0 99	0 82
31																		0 99	0 99	0 99	0.82
34																			0 99	0 99	0 83
37																				0.99	0 84
40																					0 84

[1] To be significant at the 0.01 level of confidence r should be 0 155 All the obtained correlations exceeded this value

Model for Dark Adaptation as a Function of Age

For the sake of convenience in examining the level of dark adaptation as a function of age as well as time, the mean data given in Table 3 have been replotted as time curves (Fig. 2). Here age has been entered on the x axis, and $\log_{10}$ $\mu\mu$l luminance entered on the y axis. Each curve in Figure 2 represents the level of dark adaptation as

TABLE 3

DARK ADAPTATION AS A FUNCTION OF AGE AND TIME LOG_{10} $\mu\mu$l LUMINANCE

	Age							
Time	16-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
30 sec	6.9294	6.7803	6.9492	7.0310	7.0590	7.2065	7.4874	7.6174
1 min	6.4198	6.1635	6.3834	6.6640	6.7873	6.9382	7.2554	7.4248
2 min	5.9346	5.6547	6.0472	6.2884	6.4988	6.7261	7.0634	7.2458
3 min	5.6602	5.4286	5.8517	5.9818	6.2562	6.5894	6.9865	7.1198
4 min	5.5830	5.2672	5.8470	5.8701	6.1794	6.4937	6.9687	7.0748
5 min	5.3598	5.0480	5.4505	5.6762	6.9549	6.2732	6.7029	6.9006
6 min	5.0760	4.8323	5.1558	5.4246	5.6407	5.9269	6.2839	6.7056
10 min	3.8543	3.9493	4.1648	4.5095	4.8026	5.2064	5.7469	6.1104
16 min	3.2399	3.1413	3.4364	3.7780	4.2024	4.5028	4.9947	5.5511
22 min	2.8718	2.8450	3.0387	3.3346	3.7404	4.0360	4.6035	5.2667
28 min	2.6422	2.7193	2.8611	3.1334	3.4973	3.7451	4.2207	4.9015
40 min	2.4272	2.6029	2.6945	3.0159	3.3459	3.6419	4.1043	4.8055

a function of age at a given time in log units. The slope of the curves becomes greater as a function of age and time. When plotted in this way, the data appear as a family of positive exponential curves.

A suitable mathematical model (Model A) of dark adaptation as a function of age and time, as plotted in Figure 2, is as follows:

$$\text{Log } y = G^{(Ct)^{f_1(A)}} \qquad (4)$$

A detailed exposition of the method of derivation of this model can be found in (9).

To evaluate the derivation two procedures were devised.

Test Procedure 1.—In procedure 1 Model A (Eq. 4) was used to reconstruct theoretical dark adaptation curves. Then the original data were compared with the theoretical constructs. Both sets of curves are shown in Figure 3. Although the dark adaptation level for the 80- to 89-year old group was slightly overestimated, probably because of the concentration of several cataract defects found in persons who were at the far end of the age range, no serious challenge to the efficiency of the derivation was found. The correspondence of the predicted mean curves with the obtained mean curves is unusually close—so close that one could be substituted for the other without effect on the interaction of the age-time co-variables in the dark adaptation phenomenon. For instance, test retest dark adaptation data often vary by a displacement of one-half of a log value. Model A fits the present data with far greater exactness.

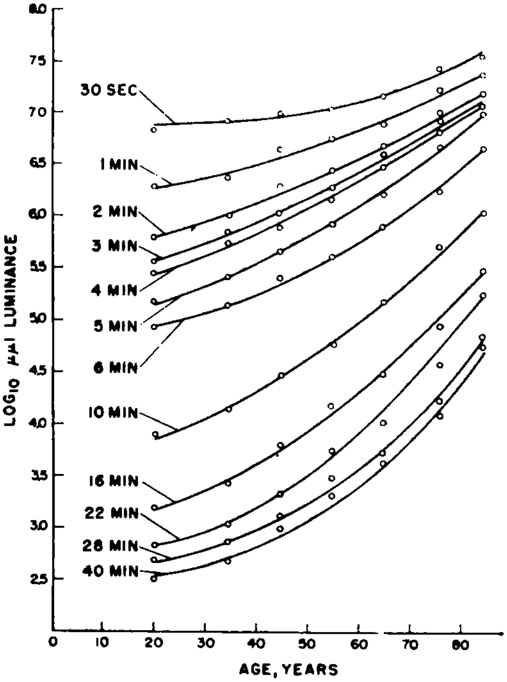

Figure 2. Dark adaptation curves as a function of time plotted against age.

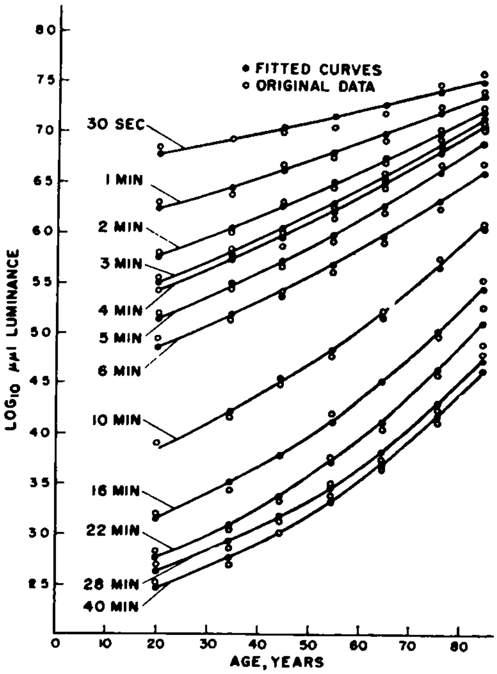

Figure 3. Comparison of the original data as shown in Figure 1 with the reconstructed data obtained from Model A. Model A is shown to fit the original data very closely.

Because the theoretical curves so closely resemble the original distributions, the model was considered valid for the obtained data. What remained was the need to test whether the model could be generalized; that is, extended to alternative independent samples. Test procedure 2 was designed to assist in evaluating this question.

Test Procedure 2.—A more rigid test of the generality of the equations would depend on demonstrating that the model derived from one sample predicted the performance of other independent samples. The present data were treated in the following way to enable approximating the execution of such a test.

The second test procedure was divided into two parts: (a) one part for cone data, and (b) one part for rod data. The reason for treating cones and rods independently was to demonstrate that the stability of the model was not dependent on the method of sampling.

TABLE 4

AGE GROUPS FOR MODEL B

Criterion Category (Cones) Decades	Test Category (Cones) Decades		
	(1)	(2)	(3)
16-29[a]			
	30-39		
40-49			
		50-59	
60-69			
			70-79
80-89			

[a] The 16-19, 20-29 age groups were combined, hence the enlarged range, 16-29.

Test Procedure 2a for Cone Data.—The principle of testing the mathematical model by deriving the data from one group and then predicting the performance of a second independent group was modified in the following way. There were 8 age groups. They were assigned to two general classes: a criterion category, and a test category (Table 4).

TABLE 5

AGE GROUPS FOR MODEL C

Criterion Category (Rods) Decades	Test Category (Rods) Decades		
	(1)	(2)	(3)
	16-29[a]		
30-39			
40-49			
50-59			
60-69			
		70-79	
			80-89

[a] The 16-19, 20-29 age groups were combined, hence the enlarged range, 16-29.

Then using only the data contained within the criterion group, a second model, Model B for cones, was derived independently from Model A. Therefore, there remained three independent test groups, the data from which did not enter into the construction of Model B, and thus could have in no way influenced the new Model. Special attention is called to the fact that the age ranges of the criterion groups are different from the age ranges of the test groups.

Test Procedure 2b for Rod Data.—In the procedure applied to rod data, the age groups were assigned to two categories, a criterion category and a test category, in the following way, as given in Table 5.

Then, using only the data contained within the criterion groups, that is, the middle 50 percent of the age range data, Model C for rods was constructed. There remained three independent test groups, all at the extremes of the age range distribution. The age category 16 to 29 contained 25 percent of the scores, and each of the age range categories, 70 to 79, and 80 to 89 contained 12.50 percent of the scores, respectively. Thus, one-half the data were used for deriving Model C for rods and half for test scores.

Once again there was no modification of the form of the model and practically no change in the coefficients and exponents larger than would be expected within rounding error (9).

It follows that Models B and C are virtually identical to Model A, not only in form but in coefficients and exponents as well. Since Model A fits the data with great fidelity so will Models B and C. Hence, Models B and C will predict the scores of their representative test groups, which are for the cone model the mean scores of age groups 30 to 39, 50 to 59, and 70 to 79, and which are for the rod model the means of the age groups 16 to 29, 70 to 79, and 80 to 89.

To demonstrate the similarity among Models A, B, and C, the curves for all ages at time intervals 30 sec, 2, 10, and 28 min have been calculated, using Models A, B, and C independently. Reproducing the entire range of curves for each model would be redundant, since any possible differences found among the models would remain constant, or approximately so, and thus would be as easily shown at one time interval as another. The graphic results are shown in Figure 4.

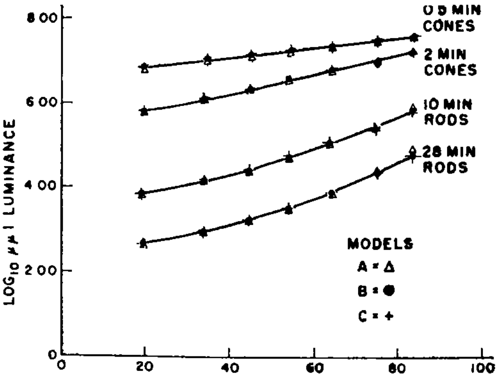

Figure 4. Comparisons of Models A, B, and C.

Rate of Dark Adaptation as a Function of Age

To simplify the mathematical technique in the following analysis, Model A has been used to derive rate of dark adaptation that would appear at the mean ages of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 years. The original data, through the use of the model, have simply been extrapolated to ages 10, 90, and 100 years. Since all the mean ages exist within the boundaries of the model, no mathematical rule has been broken when these are substituted for the actual mean ages, which are 19.7, 34.2, 44.3, 54.2, 64.2, 75.5, and 83.9.

The equation of the cone curve was differentiated in order to obtain an equation for rate of dark adaptation. Thus,

$$R = \left(G^{(Ct)^{f_1(A)}}\right)\left(\frac{(Ct)^{f_1(A)}}{t}\right) f_1(A) \ln G \tag{5}$$

The data for rate of dark adaptation at the 30th second and the 6th minute for mean ages 10, 20..., 100 years are given in Table 6 and shown in Figures 5 and 6. When the dark adaptation rate data were plotted as a function of age the resulting distributions were curvilinear.

Individual Prediction

However, measuring dark adaptation sensitivity near the asymptote of the function requires between 30 to 40 min. In situations where it would be highly desirable to examine and screen large numbers of persons a test of this length would be impractical. Therefore, a short test of dark adaptation predictive of thresholds near the asymptote was developed as recognition of the importance of this phenomenon has grown.

Intercorrelation Between Age and Dark Adaptation Threshold at the 40th Minute.—

TABLE 6

RATE OF DARK ADAPTATION

	Log_{10} μμl Luminance/Min	
Mean Age	Time, 30 Sec	Time, 6 Min
10	-2.13237	-0.1241
20	-1.95500	-0.1208
30	-1.76747	-0.1166
40	-1.56913	-0.1114
50	-1.35980	-0.1051
60	-1.13860	-0.0973
70	-0.90500	-0.0881
80	-0.65833	-0.0769
90	-0.39790	-0.0636
100	-0.12346	-0.0480

Age was correlated with the dark adaptation threshold at each of 20 time intervals. To illustrate: age was correlated 0.71 with threshold sensitivity at the second minute of adaptation, 0.82 with the third, 0.80 with the fourth, etc. The greatest degree of correlation of threshold with age was 0.84 at the 37th and 40th min (Table 2). However, a correlation of 0.84, though indicating an extremely close relationship between age and dark adaptation threshold, was not considered to be adequate for predicting sensitivity thresholds for individuals.

Intercorrelations Among Dark Adaptation Thresholds.—Each dark adaptation threshold at each of 20 time intervals was correlated with all other thresholds. Since age was included as an independent variable the result was a 20 x 21 correlation matrix shown in Table 2. All correlations were highly significant. Table 2 shows that the range of intercorrelations of thresholds

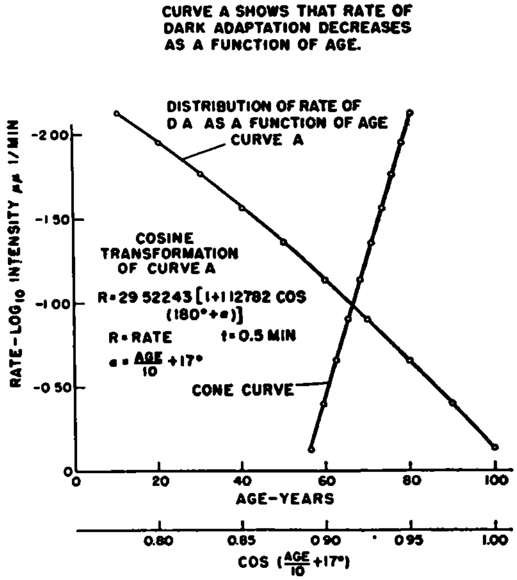

Figure 5. Rate of dark adaptation is shown to be inversely related to age at time 30 sec (cones). See extrapolation to age 5 and 100 years. The cosine transformation results in a straight line.

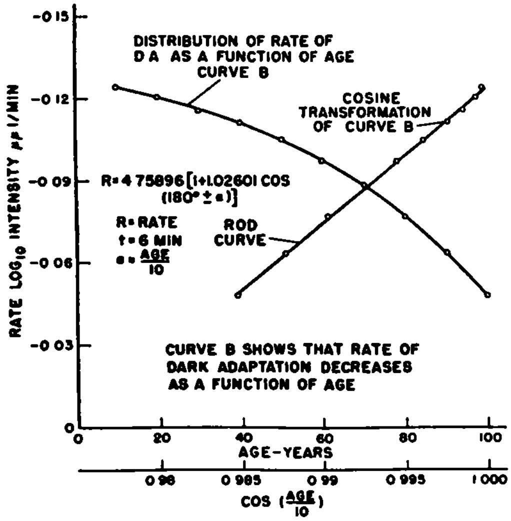

Figure 6. Rate of dark adaptation is shown to be inversely related to age at time 6 min (rods). See extrapolation to age 5 and 100 years. The cosine transformation results in a straight line.

was 0.69 to 0.99. The extremely high intercorrelation among thresholds, for example, at the 0.99 level, often was dependent upon the time relationships among thresholds. For instance, it would be expected that the thresholds obtained during the 14th minute would be highly correlated with thresholds taken at the 16th minute, and they were, merely because during that 2-min interval the dark adaptation thresholds changed very little. Nonetheless, the correlation between the 12th and the 40th minute threshold, far more remote in time, was also 0.90. This was large enough to permit individual predictions of the 40th minute threshold from knowledge of the 12th minute threshold alone, regardless of age. On the other hand, when the age variable was correlated with dark adaptation thresholds, the maximum amount of correlation was not high enough to permit predicting final thresholds for individuals.

The intercorrelation matrix shows the relationships among threshold or between age and thresholds at a given time. It does not show what the relationship would be were the intercorrelation of thresholds and the intercorrelation of thresholds and age statistically combined and handled simultaneously as conjugate variables. Theoretically, combining both variables should have resulted in increasing the predictive power of the data by a substantial margin. This was shown to be correct.

Multiple Correlations Among Age and Dark Adaptation Thresholds.—The development of a short test of dark adaptation depended on the degree to which age combined with several thresholds obtained during the first few minutes predicted thresholds remote in time. Since the dark adaptation process is nearly complete after 40 min, the thresholds at the 40th minute were arbitrarily selected as those remote in time to be predicted. Thus, threshold sensitivity at the 40th minute became the criterion.

Since the $S.D._{(est.)}$ as well as k, the coefficient of alienation (k equal to the square root of $1-r^2$ or R^2), increases rapidly as r or R decreases, the error of prediction for individual scores increases rapidly when r or R drops below 0.90. Therefore, the identification of the time interval conjoined with the age variable at which R reached at least 0.90 became the statistical objective.

In cumulative succession the thresholds obtained at time intervals 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 19, 22, 25, 28, and 31 min were combined with the age variable. Then the multiple correlations were calculated from the regression equations for each of the age-time combinations. The results are given in Table 7 which also contains the coefficient of determination, r and R^2, the beta coefficient for the age variable, and the standard errors of estimate, $S.D._{(est.)}$.

Combining the threshold variables with age in cumulative succession resulted in a steady increase in the correlation with the criterion until at the 10th minute of dark adaptation r equal to 0.9074, the minimum value making individual predictions tenable, was reached. Thus, at the 10th minute age plus all the intervening thresholds correlated 0.91 with the criterion, that is, the threshold values at the 40th minute. Therefore, it is evident that a short test of dark adaptation could be administered in 13 min including 3 min of pre-exposure to the bleaching light plus 10 min of testing thresholds every minute from 2 through 10 min. The 3-min pre-exposure could be reduced somewhat if the intensity of the pre-exposure light was increased. However, the effect of changing the intensity of the bleaching light on the statistical relationships characteristic of the present data would have to be experimentally determined.

Application

The following illustrations will show in detail how the statistical procedure can be used advantageously.

The Prediction of Mean Threshold at the 40th Minute.—The general regression equation is as follows:

$$T40 = Bo + b1(A) + b2(t1) + b3(t2) \ldots bn(tn) \qquad (6)$$

in which

T40 = the criterion; the thresholds at the 40th minute—the predicted threshold value;

Bo = the unstandardized regression coefficient for the multiple R;

b1 = the unstandardized regression coefficient for age;
b2 = the unstandardized regression coefficient for threshold at time equal to 2 min;
b3 = the unstandardized regression coefficient for threshold at time equal to 3 min;
A = age; and
t = mean threshold at time x (Table 1).

TABLE 7

MULTIPLE CORRELATION OF AGE PLUS DARK ADAPTATION THRESHOLD FOR 17 SUCCESSIVE TIME INCREMENTS WITH 40th MINUTE THRESHOLDS, THE CRITERION

Variable Order	Variables Contained in the Multiple R	r	R	R^2	Beta	S.D. (est.)
1.	Age	0.8378		0.7020	0.84	0.48
2.	Age plus threshold at 2nd min		0.8498	0.7222		0.46
3.	and plus 3rd min		0.8577	0.7356		0.45
4.	and plus 4th min		0.8604	0.7403		0.45
5.	and plus 5th min		0.8612	0.7418		0.45
6.	and plus 6th min		0.8741	0.7641		0.43
7.	and plus 7th min		0.8797	0.7742		0.42
8.	and plus 8th min		0.8862	0.7854		0.41
9.	and plus 9th min		0.8960	0.8028		0.39
10.	and plus 10th min		0.9074	0.8234		0.37
11.	and plus 12th min		0.9173	0.8416		0.35
12.	and plus 14th min		0.9267	0.8589		0.33
13.	and plus 16th min		0.9412	0.8858		0.30
14.	and plus 19th min		0.9559	0.9138		0.26
15.	and plus 22nd min		0.9715	0.9439		0.21
16.	and plus 25th min		0.9811	0.9628		0.17
17.	and plus 28th min		0.9892	0.9787		0.12
18.	and plus 31st min		0.9946	0.9893		0.09

Note: Thresholds at each successive time level are added to the multiple correlation, R. Thus, by the 31st time interval, age has been combined with all intervening thresholds. All correlation values are significant beyond the 0.001 level.

It is well known that the regression equation predicts the mean exactly. Therefore, no specific calculations of mean thresholds will be made. The regression equation would predict that the mean threshold was 2.43 log µµl which was exactly the value obtained for the mean age of the group between 16 and 29 years, that is for mean age 19.7 years. For the subjects in the 50-59 age group, mean age 54.2, the predicted and obtained mean was 3.32 log µµl (Table 1).

However, the thresholds of individual subjects were distributed around the means of their respective age groups, as well as being distributed around the mean of the entire sample. Since the S.D.$_{(est.)}$ and k are not zero, then prediction of individual scores would be less accurate than the prediction of mean thresholds. However, holding to the criterion that R must be at least 0.90 before individual scores were predicted guaranteed that prediction of thresholds would be highly accurate. Of course, higher criteria increase accuracy still further. The second illustration will demonstrate the effectiveness of selecting a stringent criterion before attempting to predict individual scores.

The Prediction of Individual Thresholds at the 40th Minute. —In the second illustration the performance of an individual subject will be predicted. Each of the first 10 equations was solved independently to show the improvement in the predictions as the first 10 thresholds are successively added to the predictive equations. A naive subject, No. 241, who was not included in the sample, and therefore who was statistically independent from it, reported the thresholds shown in Table 8. The threshold obtained for each minute where the threshold to be predicted was 3.76 log μμl at the 40th minute is given, together with the predicted thresholds for the first 10 equations. Table 8 is read as follows: When age and the first threshold at the second minute were used in the regression equation, the threshold predicted for the 40th minute was 4.54 log μμl. When age plus the first 9 thresholds were utilized the equation predicted that the threshold at the 40th minute would be 4.08 log μμl. Since the obtained threshold was 3.76 log μμl the error was reduced to a negligible quantity. Thus, in this illustrative random case the regression equation was highly predictive. The error was less than ½ log μμl, or about the usual error expected between two tests on the same subject. The values for the final equation were T40 = 0.263568 + 0.0164337(82) + 0.0498(7.395) + 0.0127(7.263) + 0.0093(7.203) - 0.2727(7.167) + 0.1781(7.143) - 0.1245(6.999) - 0.1166(6.903) + 0.1808(6.303) + 0.5957(5.281) = 4.0798 μμl.

TABLE 8

PREDICTION OF DARK ADAPTATION THRESHOLDS AT THE 40th MINUTE FOR AN INDIVIDUAL SUBJECT NO. 241, AGE 82

Threshold	2 (min)	3 (min)	4 (min)	5 (min)	6 (min)	7 (min)	8 (min)	9 (min)	10 (min)	12 (min)	40 (min)
Obtained	7.395	7.263	7.203	7.167	7.143	6.999	6.903	6.303	5.281	4.075	3.76
Predicted for time 40	4.54	4.52	4.54	4.55	4.71	4.72	4.82	4.64	4.08	3.42	-

DISCUSSION

Those who have studied the relationship between age and dark adaptation or efficiency of night vision are not all in agreement with respect to the degree of the correlation (30), nor are all in accord concerning the significance of the association of aging and the process of dark adaptation. Negative correlations which ranged -0.25 and -0.31 have been reported (2). Other results have been reported by Birren, Bick, and Fox (3), McFarland and Fisher (21), Liljencrantz (19), Birren and Shock (4), Ives, Shilling, and Curley (11), Robertson (30), and Pinson (27). Pinson, however, stated that the relationship, although positive, was less than the range of individual differences and of minor significance. On the other hand, McFarland and Fisher (21), having obtained one of the highest correlations among physiological phenomena, state that the linear correlation is so high that it may be used to predict level of dark adaptation within the narrow limits of error.

Systematic data describing the decline of dark adaptation with age should provide one kind of index representing the aging process. For instance, it has been shown that the efficiency of dark adaptation varies as a function of anoxia (23), CO concentration (25), hypoglycemia (24), and vitamin A deficiency (14, 15). This evidence suggests that metabolism in the retina may resemble metabolism in the central nervous system. Thus, because the central nervous system depends on the oxidation of blood sugar, any reduction of this substance would decrease the rate of oxidation. In a parallel manner the aging process is thought to be associated with a progressive decrease in rate, amount, or other aspects of cerebral circulation and, therefore, interference with the transport or utilization of oxygen (16). It would follow, all else being equal, that as age increases there would be a progressive increase in the demand for light. Therefore, since aging is universal, considerable variation of dark adaptation efficiency is to be expected in the general population.

For instance, Boothby, Berkson, and Dunn (5), and Lewis, Duval, and Iliff (18) have all shown that oxygen comsumption per unit of surface area declines with age. It has been indicated by Shock (32) that age and metabolic rate are inversely related. Also, the dark adaptation threshold is directly influenced by oxygen deprivation.

Since it has been shown that dark adaptation threshold and age are directly related and that physiological processes of which dark adaptation is a function in turn are related to age, then it would be expected that rate of dark adaptation would also vary, that is, decrease as chronological age increases. However, experimental evidence for a change in rate of dark adaptation relative to age is insufficient. Thus, Friedenwald (11) stated that there was a positive correlation between age and rate of dark adaptation, but the evidence in the source he cited (10) was inadequate. In this presentation the data were given in table and graphic form but no statistical evidence showing that age and rate were correlated was included. Hammond and Lee (12) calculated that the correlation between age and an indirect measure of dark adaptation, that is, drop time, was correlated -0.06 with age. McFarland and Fisher (21) obtained a correlation of -0.13 with drop time and age. There values are no greater than chance would allow. Pinson's (27) findings are in the opposite direction, since he discovered that the area subtended by the dark adaptation curve for younger subjects was greater than the area subtended by the dark adaptation curve for older subjects.

Since the original individual scores obtained by Pinson were not included in the study, no independent statistical analysis could be devised to test his conclusion. Birren and Shock (4) have asserted that there is no correlation between age and rate of either cone or rod adaptation.

The review of the literature strongly suggested that evidence regarding the relationship of rate of dark adaptation and age is unclear. Therefore, the present study has tended to clarify the uncertainty in the literature and has added quantitative data toward the solution of the relationship between the thresholds and the rate of dark adaptation as a function of age.

Turning from theoretical consideration to the matter of interpreting these data the question of significance presents itself. The group was heterogeneous, and the results obtained suggest that the aging process introduced a very large decrement into these data. The mean value at the 40th minute of adaptation for the 80- to 89-yr group was $\log_{10}$ μμ1 I 4.805 (antilog = approx. 63,830), and the level of dark adaptation at the same time for teenagers between 16 to 19 years of age was 2.427 (antilog approximately equal to 267). This means that on the average the just noticeable light stimulus for the elderly group was 68,830/427, or approximately 239 times greater than the least stimulus noticed by teenagers after each group had nearly reached the 40th minute of adaptation. It would be expected that the difference between the first values obtained at 0 to 59 seconds would not be as great. This proved to be correct. For the youngest group the $\log_{10}$ μμl value for the first score was 6.929 (antilog = approx. 8,490,000) and the value for the elderly group was 7.617 (antilog = approx. 41,000). Thus, 41,400,000/8,490,000 is equal to a factor of about 4.88. Even at that moment immediately following the pre-exposure period teenagers, on the average, were able to perceive a just noticeable stimulus about 5 times less bright than were the average persons in the elderly group. Since these values were obtained from the means of the dark adaptation curves there were subjects in the younger group who fell below their mean, and subjects in the oldest group who fell above their mean. Therefore, the absolute differences between the most and the least efficient persons in the entire sample would be larger than the values indicated above.

It can be seen in Figure 1 that although the intersections of the cone and rod curves are independent of age because they all appear at approximately the same time they are not identical with respect to level of luminance present at the time the curves separate. It should be pointed out that the concept of a certain level of luminance above which cones function and below which rods function is valid only with respect to an individual dark adaptation curve. For instance, it is generally accepted that 0.01 millilamberts is the approximate degree of luminance at which cone and rod vision separate. But this does not represent the population at all. As a matter of fact in this study the approximate mean time at which the two curves separated was the 5th-6th minute of adaptation. But the mean level of luminance varied from 5.26 $\log_{10}$ μμl I for the 20-29 age group, to 7.075 $\log_{10}$ μμl I for the 80-89 age group at the intersection of the cone and rod curves for those two groups as shown in Table 1.

Another way of interpreting these data would be to compare the relative dark adaptation thresholds of the various age groups at different times. For instance, it requires 40 minutes for the most elderly group to develop the equivalent sensitivity characteristic of the youngest group at the 6-7th minute of adaptation. And dark adaptation at the 6-7th minute of adaptation is very limited regardless of the age of the viewer. In other words, youths achieve in 6 to 7 minutes of dark adaptation a level of sensitivity that is not reached by elderly persons in more than 6 times that amount of time. Even at the average age of 55 at the 40th minute of adaptation the viewer has no greater dark adaptation threshold than youths 16 to 29 years of age at the 15th minute of adaptation, some time before the final level of adaptation is approximated.

It is unlikely that either youths or elderly persons enter on tasks demanding the degree of sensitivity characteristic of their ultimate level of dark adaptation. There is little to be seen under the levels of luminance as low as between 2 and 5 $\log_{10}$ μμl I, except, of course, the perception of some light source itself. In some military operations (2, 12, 17, 19, 27) such as night watch, dark adaptation is important for exactly this reason. Otherwise the viewer could function as well in total darkness for which no adaptation is necessary.

There are, however, other kinds of situations which may, by and large, be just as important and perhaps more so because of their ubiquity. Thus, old and young alike undertake tasks that require partial adaptation, for instance, the operation of transport equipment at night (1, 22, 20) under the conditions of intermittent, unpredictable changes of luminance. The range of luminance is quite great, and high enough to involve both the rod and cone cells of the retina (29). Therefore, the continuous process of bleaching and adaptation of the retina means that crossing over from rod to cone vision and vice versa is a common event. Rate of adaptation now becomes exceedingly important. But it is precisely in this region that certain types of inefficiency arise. The terminal level of adaptation of the cone cells almost defines the moment when 3-dimensional vision, acuity, and color vision become greatly limited, and the moment before the rod cells have generated any useful degree of sensitivity.

If these data are interpreted as baseline values for the age group and the experimental conditions under which they were obtained, then estimates of probable dark adaptation thresholds may be calculated directly from Tables 1 and 2.

For example, the probable 40th minute threshold of dark adaptation for an individual 85 years of age is shown in Table 1 to be 4.81 $\log_{10}$ μμl plus or minus 0.72. For a youth age 19.7 years a comparable level of dark adaptation sensitivity at the 40th minute is shown to be 2.43 $\log_{10}$ μμl plus or minus 0.17. The difference between the two individuals is statistically significant beyond the 0.001 level of confidence.

It is suggested that these data have practical applications. To illustrate: since age is so highly correlated with all dark adaptation thresholds, and since all dark adaptation thresholds are highly intercorrelated, the development of a short clinical test of dark adaptation is entirely feasible. Thus, the first few thresholds of dark adaptation as a function of age were shown to predict remote dark adaptation thresholds for individuals with great accuracy.

SUMMARY

In order to describe one family of dark adaptation curves obtained from an age sample of 240 men, ranging from 16 through 89 years, a mathematical model, Model A (Eq. 4), was derived.

Variation in rate of adaptation was determined by differentiating Eq. 5 at 30 seconds and 6 minutes.

It was determined that age is highly correlated with all dark adaptation thresholds which in turn are highly intercorrelated; the correlation between age and dark adaptation thresholds tends to increase as time in the dark increases; cone and rod thresholds are highly correlated; and the reduction in threshold and rate of dark adaptation in relation to age is very marked.

It was also demonstrated that a short clinical test of dark adaptation was entirely possible because thresholds obtained during the first few minutes of adaptation predicted dark adaptation sensitivity remote in time.

REFERENCES

1. "Age and the Ability to See at Night." Res. Rep. No. 43, 1953, Traffic Engineering and Safety Dept., Amer. Auto. Assoc., Washington, D.C.
2. "Reliability of Ft. Belvoir Night Vision Tests." U.S.A.F., Adjutant General's Office, Personnel Research Section, Washington, D.C. (June 1942).
3. Birren, J.E., Bick, M.W., and Fox, C., "Age Change in the Light Threshold of the Dark Adapted Eye." Jour. Gerontol., 3:267-271 (1948).
4. Birren, J.E., and Shock, N.W., "Age Change in Rate and Level of Visual Dark Adaptation." Jour. Applied Physiol., 2:407-411 (1950).
5. Boothby, W.M., Berkson, J., and Dunn, H.L., "Studies of the Energy of Metabolism of Normal Individuals." Am. Jour. Physiol., 116:468-484 (1936).
6. Clark, B., Johnson, M.L., and Droher, R.E., "The Effect of Sunlight on Dark Adaptation." Am. Jour. Ophth., 29:828-836 (1946).
7. Dartnall, H.J.A., "Visual Pigments." John Wiley and Sons (1957).
8. Davis, D.S., "Nomography and Empirical Equations." Reinhold Publ. Co., New York (1955).
9. Domey, R.G., McFarland, R.A., and Chadwick, E., "Dark Adaptation as a Function of Age and Time: II. A Derivation." Jour. Gerontol., 15:3, 267-279 (1960).
10. Ferree, C.E., Rand, G., and Stoll, M.R., "Critical Values for the Light Minimum and for the Amount and Rapidity of Dark Adaptation." Brit. Jour. Ophth., 18:673-687 (1934).
11. Friedenwald, J.S., "The Eye." In: Problems of Aging, E.V. Cowdry, ed., Williams and Wilkins Co., Baltimore (1939).
12. Hammond, C.E., and Lee, R.H., "Criteria for Scoring Dark Adaptation Tests." Report No. 3 on Studies in Aviation Medicine, Res. Section, U.S. Public Health Service, Bethesda, Md. (July 1941).
13. Hanes, R.M., and Williams, S.B., "Visibility of Cathode Ray Tube Screens." Jour. Opt. Soc. Amer. 38:363-377 (1948).
14. Hecht, S., and Hsia, Y., "Dark Adaptation Following Light Adaptation to Red and White Lights." Jour. Opt. Soc. Am., 35:261-267 (1945).
15. Hecht, S., and Mandelbaum, J., "The Relation Between Vitamin A and Dark Adaptation." J.A.M.A., 112:1910-1916 (1939).
16. Hecht, S., and Schlaer, S., "An Adaptometer for Measuring Human Dark Adaptation." Jour. Opt. Soc. Am., 28:269-275 (1938).
17. Ives, W.C., Shilling, C.W., and Curley, W.H., "Final Statistical Report on the Use of the Wald Adaptometer." U.S. Navy Submarine Base, New London, Conn., Med. Res. Lab. (Oct. 1941).
18. Lewis, R.C., Duval, A.M., and Iliff, A., "Basal Metabolism of Normal Boys and Girls from Two to Twelve Years Old, Inclusive." Am. Jour. Dis. Child., 65:834-844 (1943).
19. Liljencrantz, E., "Dark Adaptation Study." U.S.S. Enterprise, U.S. Navy Bureau of Aeronautics (May 1951).
20. McFarland, R.A., Domey, R.G., Warren A.B., and Ward, D.C., "Dark Adaptation as a Function of Age: I. A Statistical Analysis." Jour. Gerontol., 15:149-154 (1960).
21. McFarland, R.A., and Fisher, M.B., "Alterations in Dark Adaptation as a Function of Age." Jour. Gerontol., 10:424-428 (1955).
22. McFarland, R.A., Graybiel, A., Liljencrantz, E., and Tuttle, A.D., "An Analysis of the Physiological and Psychological Characteristics of Two Hundred Civil Airline Pilots." Jour. Aviat. Med., 10:2-52 (1939).
23. McFarland, R.A., Halperin, M.H., and Niven, J.I., "Visual Thresholds as an Index of Physiological Imbalance During Anoxia." Am. J. Physiol., 142:328-349 (1944).

24. McFarland, R.A., Halperin, M.H., and Niven, J.I., "Visual Thresholds as an Index of Physiological Imbalance During Insulin Hypoglycemia." Am. Jour. Physiol., 145:299-313 (1946).
25. McFarland, R.A., Roughton, F.J.W., Halperin, M.H., and Niven, J.I., "The Effects of Carbon Monoxide and Altitude on Visual Thresholds." Jour. Aviat. Med., 16:381-394 (1944).
26. Peckham, R.H., "Effect of Exposure to Sunlight on Night-driving Visibility." HRB Bul. 56, p. 17-24 (1952).
27. Pinson, E.A., "Dark Adaptation in Army Air Corps Personnel." War Dept., Air Corps, Materiel Division, Experimental Engineering Section, Memorandum Rept. No. EXP-M-54-653-51 (Aug. 1941).
28. Plant, W.H., "Night Vision and Dark Adaptation, 1946-1951: A Selected Reading List." Research and Development Board (Jan. 1952).
29. Richards, Oscar W., "Vision at Levels of Night Road Illumination, III. Literature, 1956-1957." HRB Bul. 191, p. 57-61 (1958).
30. Robertson, G.W., and Yudkin, J., "Effect of Age upon Dark Adaptation." Jour. Physiol. 103:1-8 (1944).
31. Scarsborough, J.B., "Numerical Mathematical Analysis." Baltimore, The Johns Hopkins Press, p. 374 (1930).
32. Shock, N.W., "Physiological Changes in Adolescence." In: Nat. Soc. for Study of Ed. 34th yearbook. Part I. Bloomington, Ill. (1944).
33. Wolf, E., "Effects of Exposure to Ultra-violet Light on Human Dark Adaptation." Proc. Nat. Acad. Sci., Washington, D.C. 32:219-226 (1946).

Glare Sensitivity in Relation to Age

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● THE visual sensation called glare is produced by light entering the eye in such a fashion that distinct vision is inhibited. If the glare-producing light is superimposed on a visual image so that contrasts are reduced, it is called veiling glare. When the luminances involved become exceedingly high, producing a dazzling effect, it is called dazzling glare; and when intense directed light interferes with normal retinal function, blinding or scotomatic glare is experienced. All types of glare reduce vision and make the performance of visual tasks harder, if not impossible (1).

In night driving, for instance, blinding or scotomatic glare produced by oncoming headlights seriously interferes with the visibility of objects on the road and thus jeopardizes the safety of drivers and pedestrians. Headlight glare has therefore been regarded as one of the most serious obstacles in the safety of night driving, and many efforts have been made to cope with it.

Means such as night driving goggles and tinted windshields are only illusionary remedies because they reduce road visibility to the same extent that they reduce glare, and have, therefore, no advantages but rather serious disadvantages (2, 3). Many attempts have also been made to reduce glare by avoiding specular reflections from the trim of vehicles, road surfaces, and objects on the side of the highway. Furthermore, illuminating engineering has shown that glare depends to a major extent on the brightness of an object in relation to its surround. The headlights which appear obnoxiously bright as seen against a dark background have no ill effects when seen against a bright background or the sun-lit sky. Scotomatic glare from headlights, therefore, does not seem too objectionable when experienced on a well-lighted city street, even when the four lights of a negligent driver are directed against the oncoming driver. The ill effects could therefore very well be eliminated by raising the over-all illumination prevailing on highways to such levels that the contrast between oncoming headlights and the brightness of the surround would be sufficiently reduced. However, this would require exorbitant expenses, and therefore the problem of glare cannot be easily solved in this fashion.

In the past, glare has often been regarded as a problem hard to deal with because one did not know how much of it had to be attributed to the physical nature of the light source, or sources, producing it, or the eyes of the individuals experiencing it. Only recently the properties of absorption and transmission of the various media of the eye have been studied sufficiently to understand the importance of absorption and scatter of light in the media as a factor eliciting the sensation of glare (4, 5, 6).

In studies on retinal sensitivity, and particularly through contact with photophobic patients it seemed desirable to obtain a quantitative measure of glare sensitivity. This appears useful in advising patients in the use of tinted lenses or sunglasses. In studies on tinted windshields (3), first quantitative measurements were made on glare sensitivity (2). Continuation of this work yielded a clear-cut relationship between glare sensitivity and the physiological state (age) of the individuals tested (7, 8). Thus, glare seemed to be an entoptic phenomenon, and in attempting to deal with it, the physiological conditions of the human eye at various age levels must be taken into consideration (9).

To study the effect of scotomatic glare an instrument was developed (3, 8) providing a glare source of 2-deg angular subtense at the center of a circular test field. On this test field are exhibited for identification visual targets at various distances and in different radial directions from the glare source (Fig. 1(a)). The glare source consists of a concentrated filament lamp, S_1, the light of which is collumated by a lens system, L_1, and sent through a plastic rod of 1-in. diameter. The rod is curved in a quarter circle and its end fits into a 1-in. center hole of a translucent plastic plate serving as target screen. The full luminance of the glare source is in excess of 15,000 millilamberts; by inserting filters in front of the source, F_1, the luminance can be reduced to $^1/_{10}$, $^1/_{100}$, $^1/_{1,000}$ and $^1/_{10,000}$.

The target screen is evenly illuminated by a second light source, S_2, variable in luminance in 10 percent steps between 0.00025 and 27.5 millilamberts. The luminance is varied by inserting neutral filters, F_2 and F_3, in the light path. On the target screen are exhibited Landolt rings (split rings) with an outer diameter of 0.3 in., and a gap width of 0.06 in. They are arranged in three concentric circles so that when the eyes of the observer are positioned 28 in. from the center of the target screen, the symbols of the outer circle are approximately 10 deg removed from the center of the glare source, those of the middle circle 7 deg, and those of the inner circle 4 deg (Fig. 1(b)).

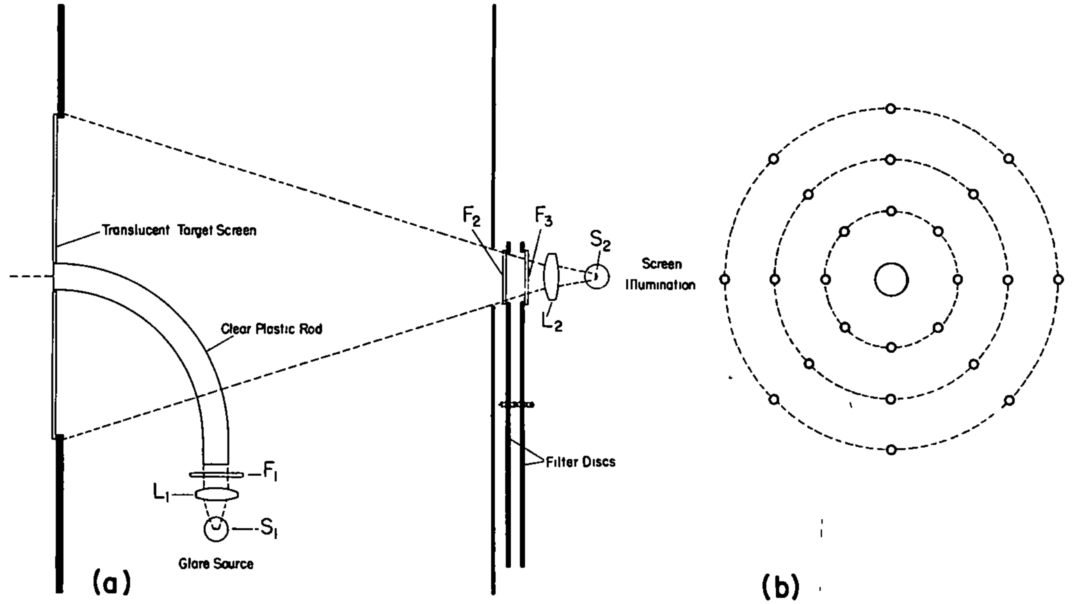

Figure 1. Diagram of (a) apparatus for testing visibility of visual targets at various distances from a glare source; and (b) target screen with circles indicating positions of targets in relation to glare source.

The observer is seated in front of the test instrument and his head held in position with the aid of a chin rest so that the eyes are at the same level as the glare source. During the test, however, he is permitted to move his eyes at will and to fixate and examine each symbol on the screen.

The tests are performed in a darkroom. When the glare source is turned on and the target screen is only weakly illuminated, all targets are invisible. The luminance of the target screen then is gradually increased until the details (the gaps in the Landolt rings) in the targets of the outer circle become visible. Then the illumination is further increased until the details of the targets of the middle circle become perceptible; finally, the luminance is increased until the details of the targets of the inner circle can be recognized. The measurements thus obtained represent luminance values for perceiving targets of fixed size at various distances from the glare source while, in addition, the luminance of the glare source may be varied between 1 and 15,000 millilamberts.

The first tests were carried out on a group of 19 college girls age 18 to 22 yr and not selected for high visual acuity. Several of the group wore glasses for correction of myopia and/or astigmatism. A second group consisted of 10 college men ranging in age between 19 and 26 yr and selected for 20/20 vision uncorrected. The results obtained with the two groups were surprisingly uniform, except that for the non-selected group the deviation from the mean was greater. When, however, individuals of advanced age were studied, it was found that the luminances required to see the gaps in the split rings were about ten times those needed by the individuals of college age.

For further studies, glare tests were carried out on more than 200 individuals ranging in age between 5 and 85 yr. The subjects were picked from the out patient depart-

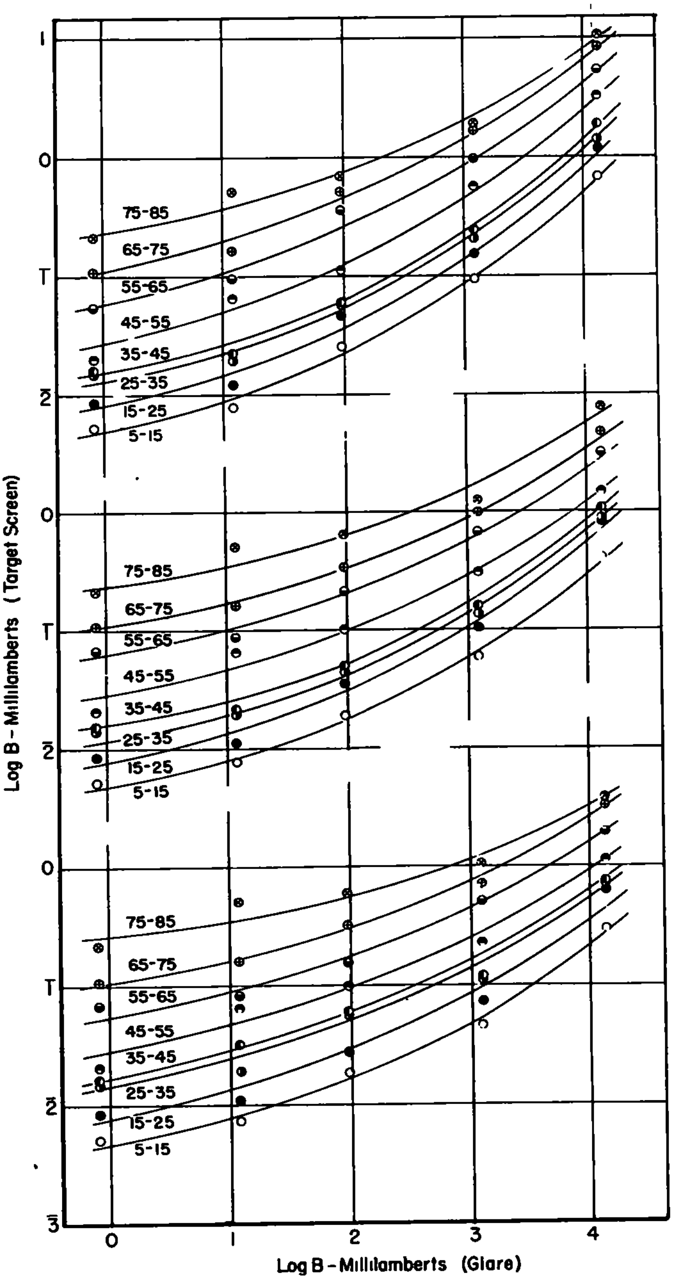

Figure 2. Relations of log. threshold luminances of target screen and log. glare luminances for nine groups of individuals in the age range between 5 and 85 yr. Top: thresholds for target recognition in the inner circle; middle: for target recognition in the middle circles; bottom: for target recognition in the outer circle of the target screen.

ment of the Mass. Eye and Ear Infirmary. With their clinical records available it was possible to use the information concerning their eye conditions and their corrective requirements. Cases in which pathological conditions prevailed were not included in this study.

In Figure 2 the results obtained in these tests are plotted on a coordinate grid, the abscissae representing the logarithms of glare luminance and the ordinates representing the logarithms of target screen luminances required for seeing the splits in the rings at angular distances of 10 deg (bottom), 7 deg (middle) and 4 deg (top) from the glare source. At low glare luminances the critical details are seen equally well at the three distances from the glare source, but when glare luminance is increased to 100 millilamberts and above, the luminance of the target screen must be made much brighter to see the targets 7 deg and 4 deg from the glare source than 10 deg from the glare source.

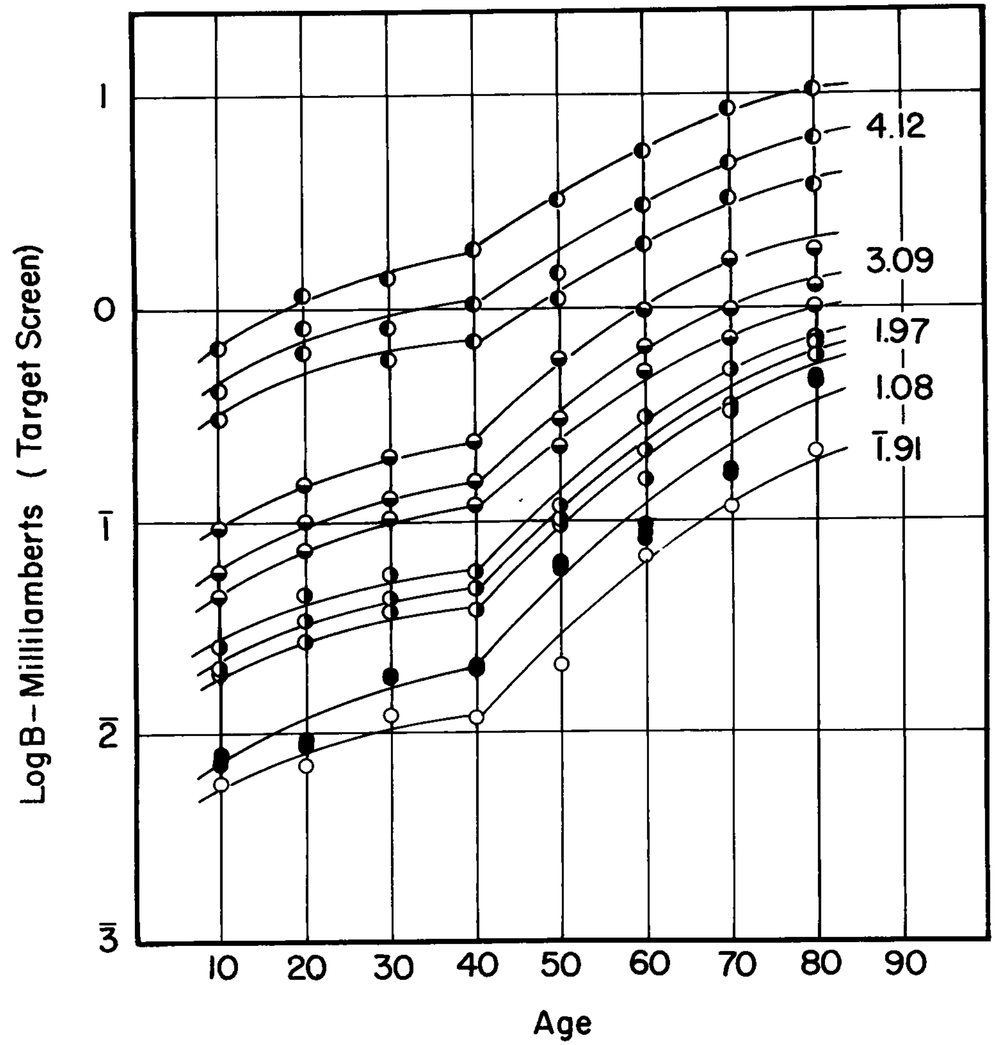

Figure 3. Log. threshold luminances for target recognition in relation to log. glare luminance plotted against mean age levels. The rise in log. target screen luminance shows a discontinuity at age 40.

Each curve represents the mean luminances for an age range of 10 yr; that is, 5 to 15 yr, 16 to 25 yr, 26 to 36 yr, etc., up to 76 to 85 yr. As age increases, the curves shift progressively to higher target screen luminance levels. The shift, however, is not the same for each 10-yr period, indicating that the increase in luminance required for seeing under glare conditions is not directly proportional to age.

This is shown more clearly in Figure 3, when plotting the logarithms of target screen luminance at various glare levels against age. The resulting curves rise slowly up to 40 yr, then suddenly change their slope and rise much more steeply in the range between 40 and 85 yr. The eye must therefore undergo some changes which make it progressively more difficult to cope with glare.

For a better understanding of the increase in glare sensitivity, especially above the age of 40 yr, the study of patients who have developed cataracts is extremely helpful. When in advanced age vision has been severely affected due to the fact that the lens has become opaque, this condition can be corrected by surgical removal of the lens. Tests on such patients before surgery yield glare curves which lie at excessively high levels of target screen luminance. After lens extraction, however, their glare curves fall back to, or below, the level characteristic for their age. This suggests that the opacities of the lens are responsible for producing the sensation of glare. To support this notion it should be mentioned that in eye examinations with an ophthalmoscope and slit lamp microscopy a noticeable increase in opacity of the ocular media is found as age advances.

Changes in visual function in relation to age have also been found in studies on dark adaptation (10, 11), and in determinations of critical flicker frequencies (12, 13). In both types of visual responses, a marked change in sensitivity above the age of 40 yr is indicated. These findings support the assumption that in the normal process of aging, the pace of change is accelerated above age 40. Measurements on the opacity of the lens and other ocular media which produce scatter of light resulting in the sensation of glare are now in progress and promise to yield a direct relationship between glare sensitivity and light scatter in the media of the eye. All evidence available at present justifies the assumption that glare is an entoptic phenomenon which must be regarded as a physiological problem for whose solution all the complex phenomena of the living human organism must be taken into consideration.

ACKNOWLEDGMENT

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REFERENCES

1. Duke-Elder, W.S., "Textbook of Ophthalmology." Vol 2, The C.V. Mosby Co., St. Louis (1938).
2. Anon., "Tinted Lenses and Night Driving." Opt. J., Rev, 96:54 (1959).
3. Wolf, E., McFarland, R.A., and Zigler, M.J., "The Influence of Tinted Windshield Glass upon Five Visual Functions." HRB Bull. 255, 30 (1960).
4. Ludvigh, E., and McCarthy, E.F., "Absorption of Visible Light by the Refractive Media of the Human Eye." Arch. Ophthalm., 20:37 (1938).
5. Pitts, D.G., "Transmission of Visible Spectrum Through the Ocular Media of the Bovine Eye." Amer. J. Optom., 36:289 (1959).
6. Fry, G.A., "A Re-Evaluation of the Scattering Theory of Glare." J. Illum. Eng. Soc., 49:89 (1954).
7. Allgaier, E., "Age and the Ability to See at Night." Traffic Engineering and Safety Dept., Am. Autom. Assoc., Washinton, D.C., Research Report 43 (March 1953).
8. Wolf, E., and Zigler, M.J., "Some Relationships of Glare and Target Perception." Aero-Med. Lab., Wright-Patterson Air Force Base, WADC Technical Report 59-394 (1959).
9. Wolf, E., "Glare and Age." A.M.A. Arch. Ophthalm., 64:502 (1960).
10. McFarland, R.A., and Fisher, M.B., "Alteration in Dark Adaptation as a Function of Age." J. Gerontol., 10:424 (1955).

11. McFarland, R.A., Domey, R.G., Warren, A.B., and Ward, D.C., "Dark Adaptation as a Function of Age. I. A Statistical Analysis." J. Gerontol., 15:149 (1960).
12. McFarland, R.A., Domey, R.G., Warren, A.B., and Ward, D.C., "Dark Adaptation as a Function of Age and Tinted Windshield Glass." HRB Bull. 255, 47 (1960).
13. McFarland, R.A., Warren, A.B., and Karis, C., "Alterations in Critical Flicker Frequency as a Function of Age and Light-Dark Ration." J. Exp. Psychol., 56:529 (1958).
14. Copinger, N.W., "Relationship Between Critical Flicker Frequency and Chronological Age for Varying Levels of Stimulus Brightness." J. Gerontology, 10:48 (1955).

Surface-Mounted Lights On Roadways—Fog Studies

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● THIS DISCUSSION of surface-mounted lights on roadways is a continuation of the subject previously presented (1). In the previous paper the development of the concept of lines of lights for contour perception was presented. The idea started at the University of California with work on airports which was later continued under the sponsorship of the Federal Aviation Agency to improve the visual aids for pilots in landing and takeoff operations. The roll-out and taxiing maneuvers on the airport surfaces were also found to be in need of improved visual aids. Even under the best of weather conditions, there was still a gap between the visual information required by pilots and that provided by conventional lighting systems.

The visual problems of motorists on the roadway are very similar to those of pilots on the runway after touchdown, or on a taxiway. There is great need for directional guidance information which will enable them to maneuver their vehicles in the desired direction and to avoid conflict with other fixed or moving obstacles on the runway or the roadway. The development of a visual-aid lighting system for both good and bad weather was reviewed in the previous report (1) and is not repeated here.

Since the last report there have been additional developments. First, two additional reports have been presented to the Federal Aviation Agency on the subject of the surface-mounted lights for runway guidance (2, 3). Second, a general discussion of the visibility of a pattern of lights on the runway was presented in an article in "Business and Commercial Aviation," Dec. 1960. The article discusses the general requirements and performance under adverse weather conditions. Also, a report has been prepared on the installation of a centerline taxiway lighting system at the San Francisco International Airport (4). Another report on Airport Lighting Studies has been prepared for the Chief Engineer of the Port of Oakland, who has under development a completely new runway for the Metropolitan Oakland International Airport (5). This report includes a discussion of multiple-line lighting patterns using surface-mounted lights in models studied in the University of California's fog chamber.

THE CONCEPT OF LINEAL PERCEPTION

The visual principle employed in the use of small lights for guidance on the surface of the roadway involves the concept of lineal perception. The application of this principle to the present problem consists of developing contours and borders of the scene to give the driver most of the orientation that he needs regarding his vehicle's position, heading and rate of closure with objects and other areas of the roadway. The logic for such a system is as follows: the visual world of the driver, external to the vehicle, is made up of edges, slopes, surfaces, shapes and interspaces, plus textures and colors. The driver's principal visual problem is one of orientation in such a world, rather than identification of specific objects, places, people, signs or signals. The primary visual elements that furnish most of the information are the edges of the roadway, the lane markers on the roadway, the horizon ahead, and the brightness gradients in the central field. These basic visual elements can be noted in any roadway scene and are included in the various figures of this report. One can note that, even without texture, color, or detail of specific objects, most of the required guidance information is available from the contours. The driver's scene is, of course, dynamic, and the perspective is constantly changing. The flow of information in the peripheral visual field and the rate of change of apparent position of parts of the field with respect to things ahead are extremely important. The peripheral region will be streaming by at a rather fast rate and can never be concentrated on. The driver is therefore forced to look toward an area from 150 to 500 feet ahead, where the rate of change is not too drastic. The axis of his line of sight will depend on his speed and the type of roadway and terrain that he is in at the time.

During the daytime and in clear weather at night, with headlights and/or street lighting on, a steady stream of uninterrupted visual information is available to the driver and is usually interpreted clearly. In areas without proper lighting at night, and in periods of adverse weather, the conditions are vastly different. Only the most meager visual aids are then present. It is therefore desirable to provide a visual environment for these adverse conditions that will resemble the more familiar daytime scene.

Satisfactory lighting patterns for clear weather night conditions may be created quite easily by providing an array of lighting in the general area which will establish reference surfaces in the immediately surrounding terrain, plus a continuously developed pattern for several hundred feet ahead. Many miles of such roadway are used at present, and for the most part, these are negotiated without incident, even though they may not be too pleasant. But there are many points of conflict in such systems that should be more critically analyzed and treated more carefully. The points of conflict are generally known to traffic engineers. Such areas include "on- and off-ramps" at expressways, regions of transition from two to four lanes, or from four lanes to a divided roadway, or at intersections. Even in good weather, such situations need more critical attention from the visual point of view. In periods of very poor visibility, the operating conditions become quite hazardous in these particular zones.

Experience to date with the surface-mounted lineal lighting system at airports indicates that very precise directional information can be achieved. It has been found that a single centerline is a great help to a pilot in taxiing. A centerline plus rows of edge lights along the border has been found to be considerably superior to edge lights alone in the landing operation. It has been observed in other tests (6) that a two-line pattern on the runway, called a "narrow-gage system," provides more information than a single centerline. Tentative data show that a multiple-line pattern of lights on the runway in the threshold region is considerably superior to a two-line pattern plus edge lights. Therefore the principle of multiple lines of lights on a runway for guidance has been reasonably well demonstrated and accepted. A photograph of the five-line multiple-lane system proposed for use on airports is shown in Figure 1. The photograph shows the visibility achieved on a model in a very dense fog in the fog chamber at the University of California's Richmond Field Station. This could be a roadway just as readily as an airport runway.

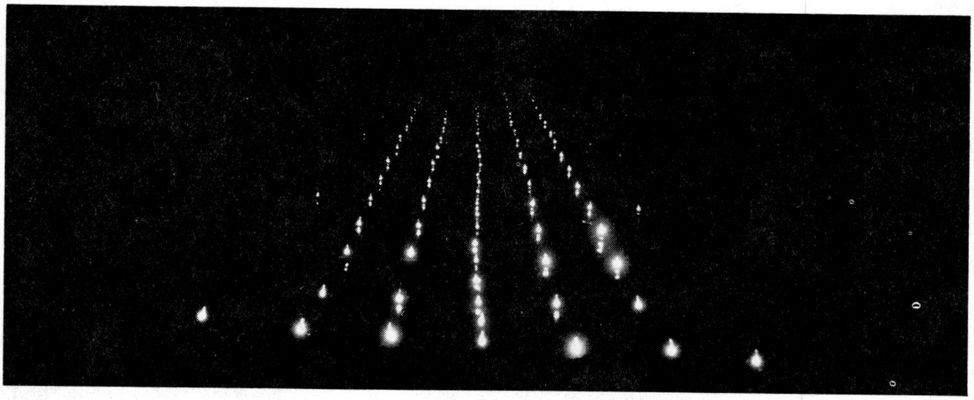


Figure 1. Multi-lane system of lights mounted in the surface of a runway—5-watt lights in a heavy fog. Centerline on 10-ft centers, parallel lines on 25-ft centers, edge lights on 100-ft centers.

NEW HARDWARE DEVELOPED SINCE THE 1959 REPORT

There has been considerable activity in the field of hardware development since the last report was presented. The Federal Aviation Agency (7) and the U.S. Air Force (8) have both issued specifications for lighting devices to be used in connection with patterns on the runways and taxiways. These specifications have been drawn up around a small, high-brightness, relatively high-wattage light source known as a 45-watt quartz, iodine cycle, tungsten bulb. This lighting unit can be operated in the open without damage by moisture, rain, snow or other weather conditions. The quartz bulb insures freedom from thermal shock, and the general construction of the unit is reported to be rugged. This light bulb is incorporated in several designs manufactured by different commercial organizations. The FAA and USAF specifications call for a flat, circular casting of suitable material, such as steel or ductile iron, approximately 6 to 8 in. in diameter and ½- to 1-in. thick. The disc-type units are known as "button lights" or "pancake" lights. These units are installed by cutting recesses in the surface of the runway or roadway and embedding the housing in an epoxy resin adhesive in a semi-flush position so that only ⅛ to ½ in. of the housing projects above the runway's surface. The bulb is protected by a cover strap which is removable to permit both replacement and servicing. The electrical conductors are placed in slots cut in the surface of the pavement and resealed with a suitable epoxy resin or pavement joint compound. The electrical service is provided by wires in direct burial trenches along the side of the pavement. Transformers supply the low voltage required by the lamps from a high voltage primary. Details of the lighting units and specifications for their installation are available elsewhere (9). The Government services have not investigated units with less than 45-watt sources so far, but they do have under consideration two other designs calling for 100- and 200-watt quartz lamps (10).

Further work on hardware has been proceeding at the University of California on a limited scale. A 1,000-ft long roadway has been provided with a centerline using units removed from the San Francisco Airport installation and modified for insetting in the roadway surface so that only ⅜ in. of the fixture extends above the roadway. The light bulbs used in these units are 5-watt, tubular shape, of the same general construction as described for the San Francisco Airport installation (2).

NEW INSTALLATION SINCE THE 1959 REPORT

A new taxiway centerline has been installed at San Francisco International Airport, in which 1,880 ft of taxiway are lighted with a centerline using button lights on 25-ft centers (4). The lights are a new design developed at the University of California and manufactured locally in California for the San Francisco Airport installation. Details of the lighting units and the electrical installation are shown in Figures 2a, 2b and 2c.

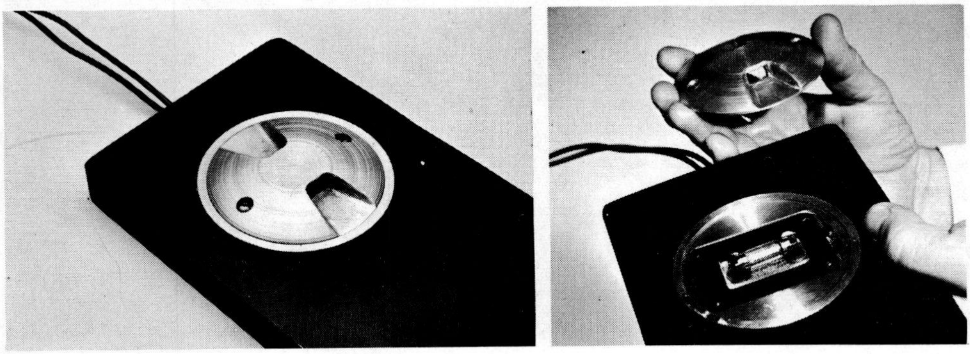


Figure 2a and 2b. Five-watt surface-mounted lighting unit as used at San Francisco International Airport.

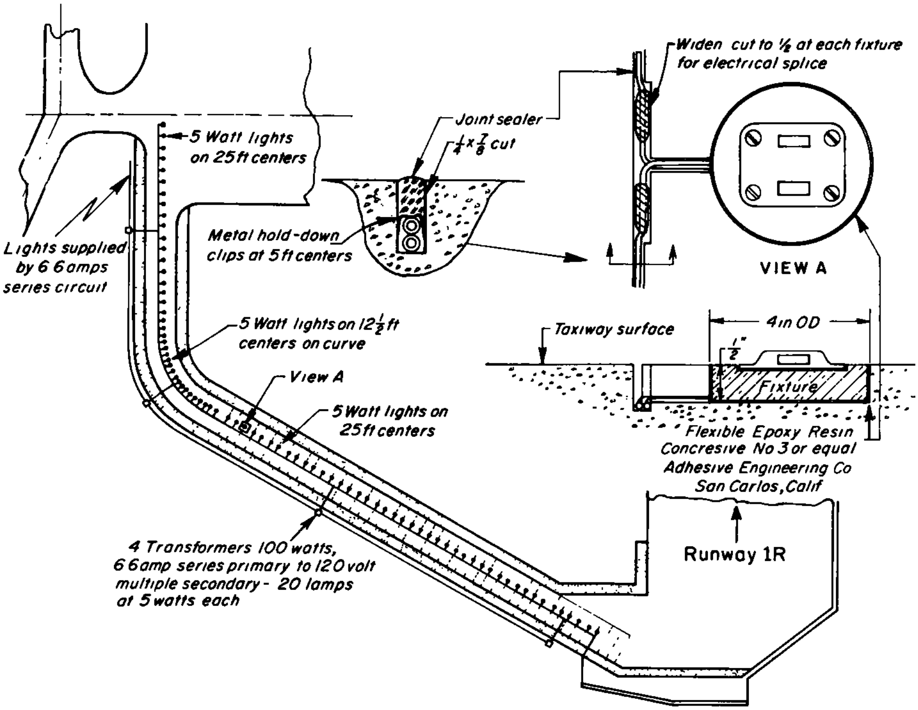


Figure 2c. Details of installation, San Francisco International Airport.

This installation uses 5-watt bulbs operated at lower than rated voltage to yield long life. The approximate power to each bulb is about 3 watts.

There has been an installation of FAA "pancake lights" at the Idlewild Airport in New York on Runway 4R-22L in which 45-watt units have been installed on 20-ft centers on the centerline of the high-speed exits. After being used in service experimentally, the lights were reconnected electrically so that the power input to the bulb was reduced to approximately 6 to 8 watts. This was done after observations and pilot comments indicated that the 45-watt light output was too high.

The Federal Aviation Agency has installed a number of its "pancake" lights using 45-watt sources at the National Aviation Facilities Experimental Center in Atlantic City, New Jersey. These have been placed on the centerline of the runway and an exit taxiway and in various other configurations on the runway for study of the pattern of lights. There has been no official report on the studies at NAFEC at the present time, but a number of unofficial comments have been made by people participating in the tests. These indicate that the centerline system is performing very well. The New York installation at Idlewild is being used continuously and shows that the centerline lights on the exit taxiway are providing adequate guidance for pilots during all of the weather that has been experienced so far, including some landings in poor visibility weather.

The U.S. Air Force has completed one full installation at the Lockbourne Air Force Base in Ohio and has another installation under construction at Andrews Air Force Base near Washington, D.C.

The taxiway centerline to Runway 1R at the San Francisco Airport has been installed for several months. The contract for the installation of the lights was completed on August 23, 1960. Runway 1R was closed for resurfacing and repair until November 15, 1960. Since that date, the runway has been in constant service, and the centerline lights on the taxiway leading to the runway have been in continuous operation. These lights are shown in Figures 3, 4, and 5. Figure 3 shows the centerline lights without the conventional side lights as viewed in a southerly direction. Figure 4 shows the centerline lights, together with the conventional side lights, and Figure 5 shows the conventional side lights, without the centerline lights. It is evident from Figure 5 that a pattern of lights that is not close enough together and not in the central field of vision is not particularly informative, even though all the individual sources may be seen. If, however, the lights are close together and tie the foreground in with the more distant spaces, the guidance is much improved. In poor visibility the situation is basically the same, except that almost all of the background visual clues are eliminated by the attenuation of the atmosphere. The only remaining source of information is that derived from the immediate foreground, using whatever pattern there is left.

Since the reopening of Runway 1R at the San Francisco Airport, comments of a number of pilots on the taxiway centerline lights have been received, and they are generally favorable. From these comments it appears that the centerline lights provide better guidance than do conventional side lights. These fixtures have required no maintenance to date. The cost of installing the fixtures, exclusive of providing the source of power, was $3,600, or approximately $2.00 per lineal foot of taxiway. The cost of the 80 fixtures, which were furnished free of charge, is estimated to be about $800, or approximately $0.44 per lineal foot of taxiway.

The Richmond Field Station installation is on a straight, asphalt roadway (Fig. 6). The work was done by a crew of the University of California's Institute of Transportation and Traffic Engineering. The fixtures are 5 in. in diameter and are inset 3/8 in. into the surface of the pavement, using an epoxy resin. The cost of installation is estimated at approximately $1,500 for 1,000 ft or $1.50 per lineal foot.

FOG STUDIES ON TYPICAL ROADWAY SITUATIONS

The visual needs of the vehicle operator in fog are greater than in the clear weather, but the amount of visual information available is many hundreds of times less. What is necessary is to have the visual information in the immediate foreground tie directly to the limit of the visual range and provide guidance and lead lines in the direction that the vehicle operator wishes to go. This situation is one in which the lighted lineal lines are particularly significant.

To provide further information on the concept of lineal perception as applied to roadway problems, several typical situations have been set up on a model basis for study. The patterns have been examined in the fog chamber at the University's Richmond Field Station. The typical installations are four basic patterns taken directly from the Planning Manual of Instructions, Department of Public Works, Division of Highways, State of California, May 1952: (a) a two-lane to four-lane transition section, (b) a four-lane multiple roadway changing from undivided to a two-lane divided roadway (derived from a three- to four-lane design in the Manual), (c) the typical turn-off from an expressway, and (d) an inlet or on-ramp to an expressway. The layouts for the models are shown in Figures 7, 8, 9, and 10, which were copied directly from the Planning Manual.

The models were set up on a 100 to 1 scale. The light sources are approximately to the same scale, although the exactly correct-size light sources were unobtainable. The light bulbs are actually made for toy headlights. They have a filament length of about 1/16 in. and operate on 16 volts at 0.1 amperes. All of the lights shown in the models are on 10-ft centers. The patterns for the roadways were laid out on strips of masonite, and the bulbs were placed in holes drilled in the masonite. The roadways were made by using various colors of cloth tape placed on the surface of the masonite to simulate typical road surfaces.

Previous data taken on brightnesses of the lights in a fog chamber indicate that for a very low transmission of fog, in the order of 2 percent, the lights would have a contrast of 1.0 in the daytime and 64 at night at the same distance used to measure the transmission. When one considers that the threshold of contrast is much less than either of these values, it is obvious that the visual range extends beyond the baseline used to measure the transmission. Thus the calculations show (2) that the lights should be visible up to about 450 ft in the daytime and approximately 1,000 ft at night in a fog

Figure 3. Centerline lights on taxiway, San Francisco International Airport, without edge lights.

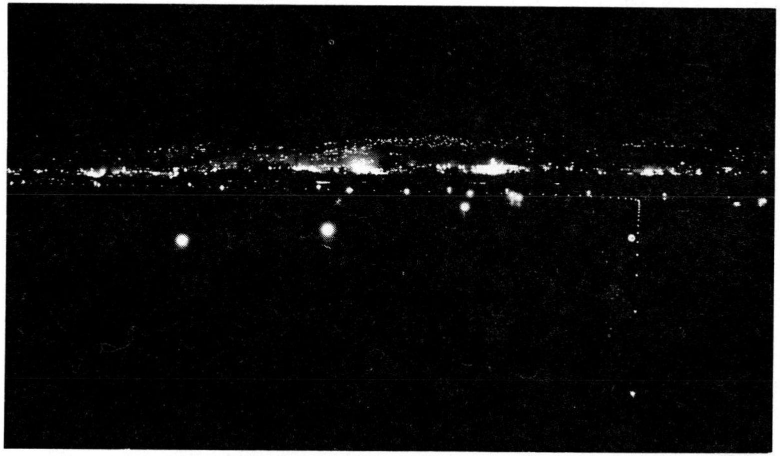


Figure 4. Centerline lights on taxiway, San Francisco International Airport, with conventional edge lights.

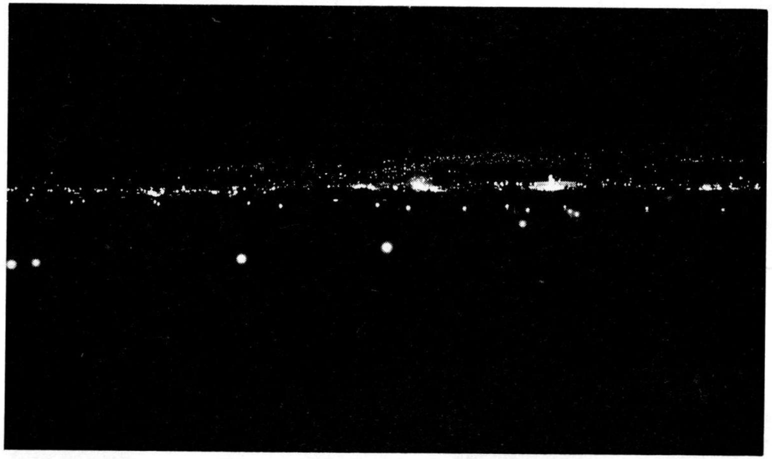


Figure 5. Same taxiway as Figures 3 and 4, conventional edge lights only.

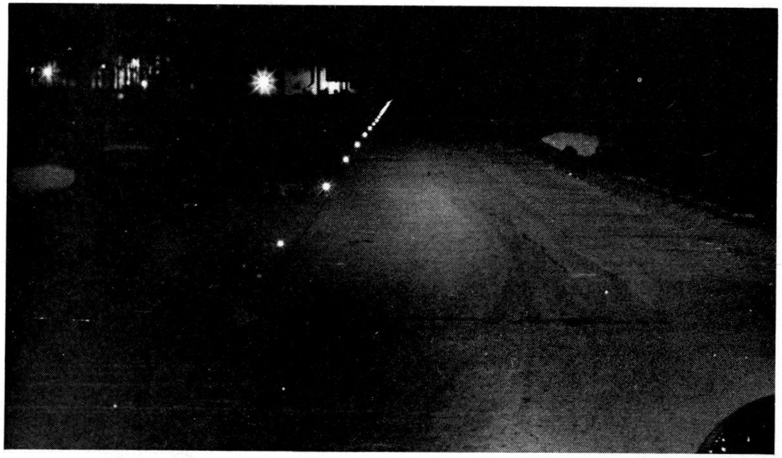


Figure 6. Surface-mounted lights on centerline of roadway at Richmond Field Station, University of California.

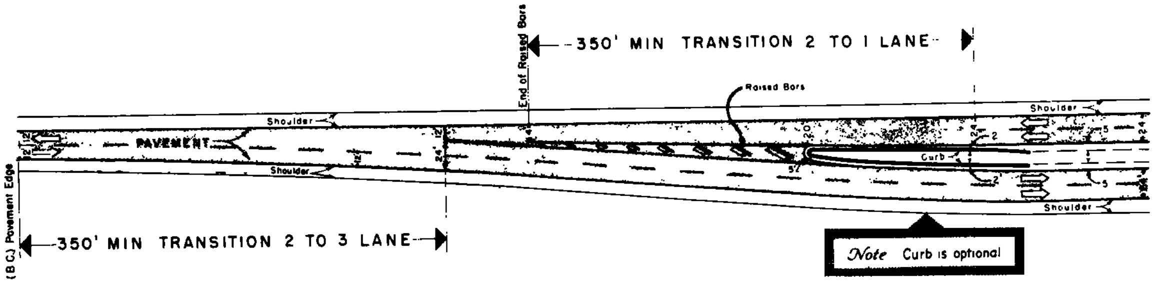


Figure 7. Two-lane to 4-lane transition.

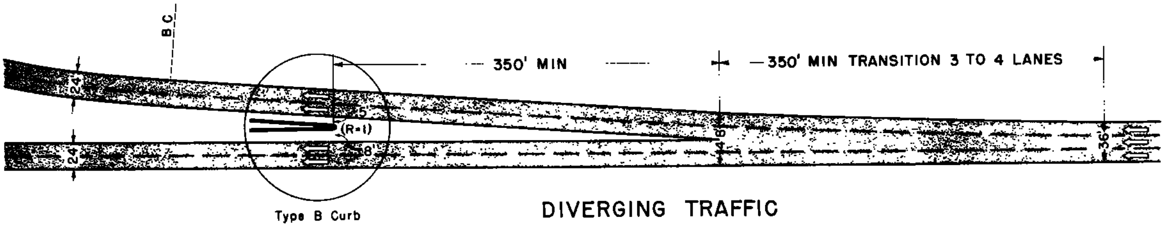


Figure 8. Three lanes diverging to 4 lanes (basis for 4-lane-undivided to 4-lane-divided model).

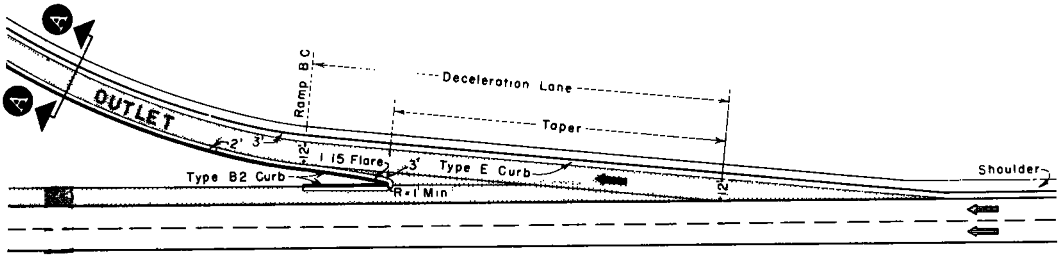


Figure 9. Typical turn-off from an expressway.

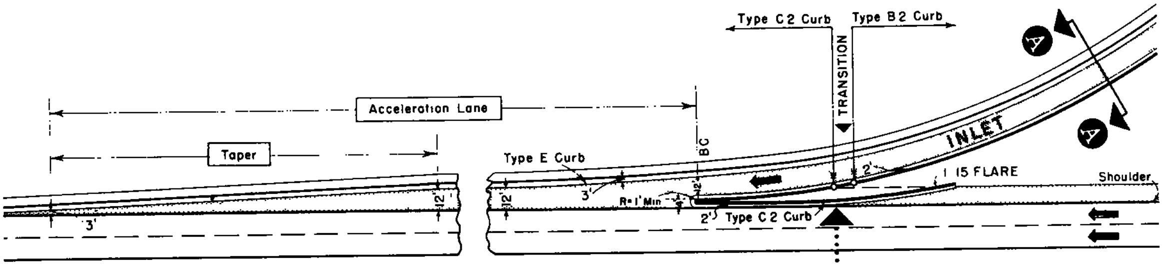


Figure 10. An inlet or on-ramp to expressway.

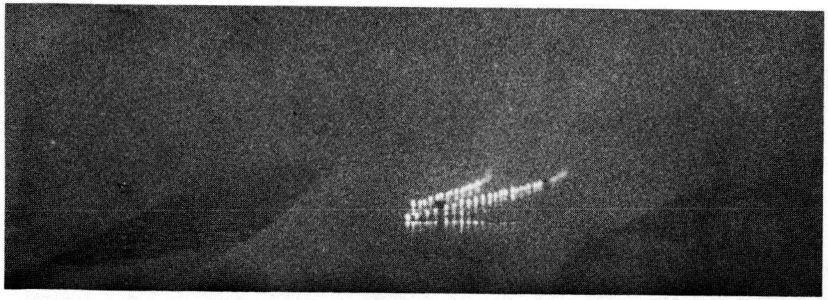


Figure 11. Daytime fog, 2- to 4-lane transition.

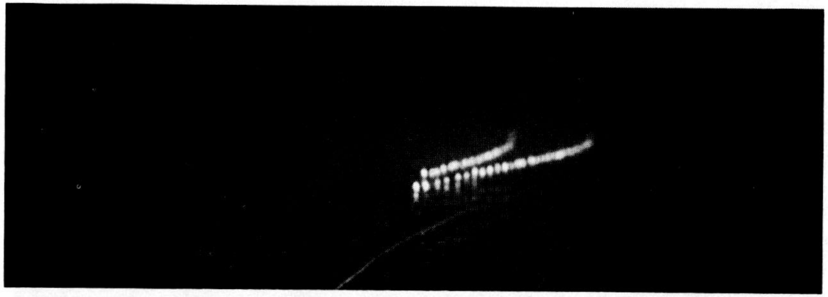


Figure 12. Nighttime fog, 2- to 4-lane transition.

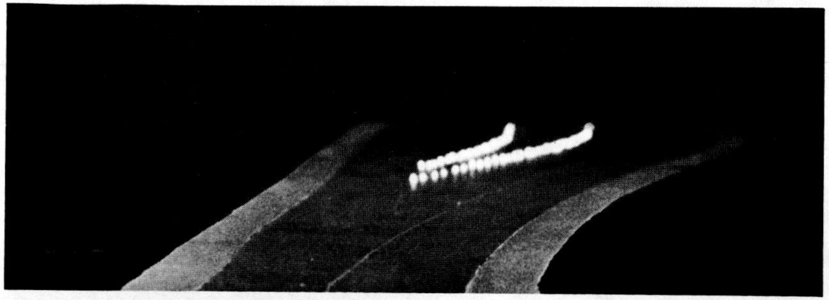


Figure 13. Nighttime, clear weather, 2- to 4-lane transition.

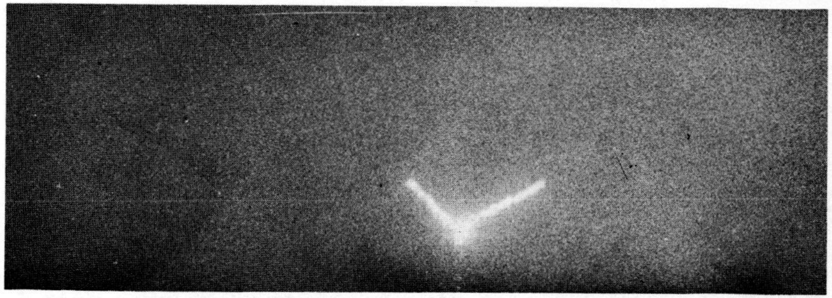


Figure 14. Daytime fog, 4 lanes to 2 lanes divided.

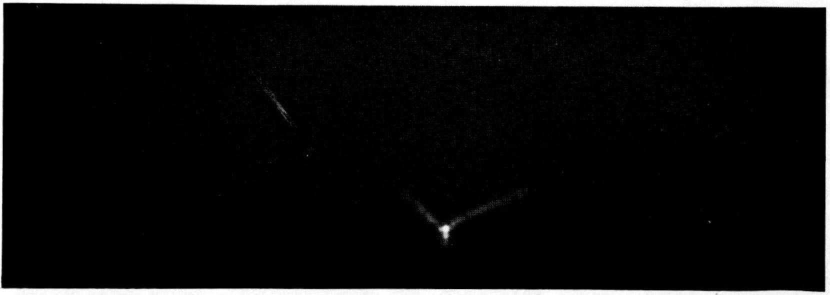


Figure 15. Nighttime fog, 4 lanes to 2 lanes divided.

Figure 16. Nighttime, clear weather, 4 lanes to 2 lanes divided.

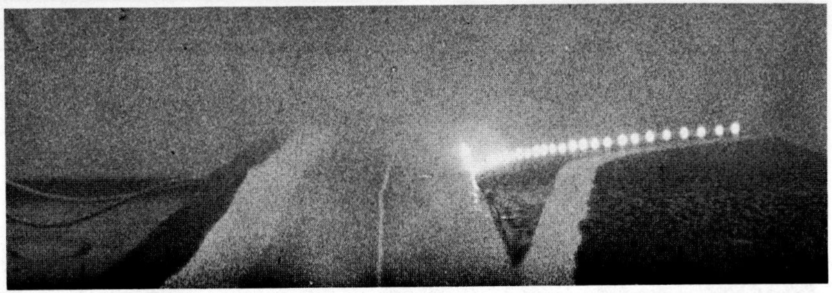


Figure 17. Daytime fog, typical turn-off from an expressway.

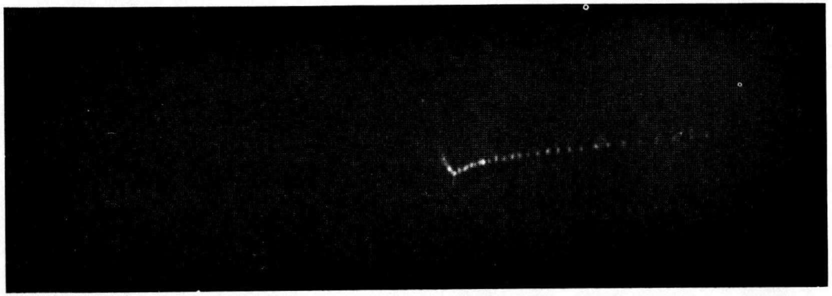


Figure 18. Nighttime fog, typical turn-off from an expressway.

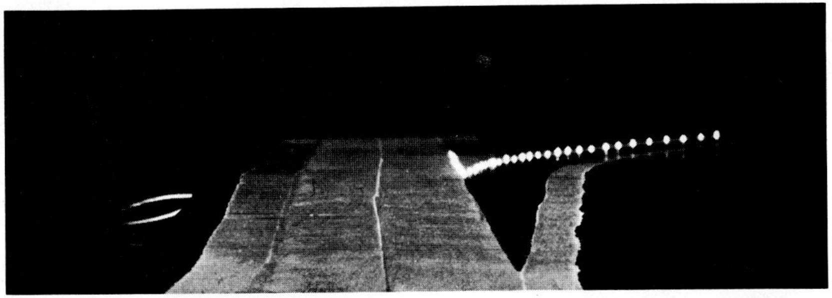


Figure 19. Nighttime, clear weather, typical turn-off from an expressway.

Figure 20. Daytime fog, on-ramp to expressway.

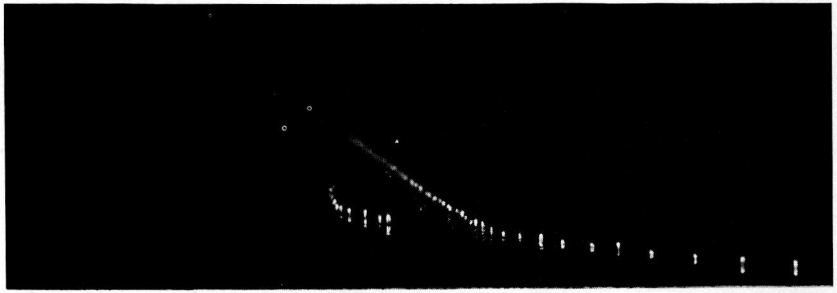


Figure 21. Nighttime fog, on-ramp to expressway.

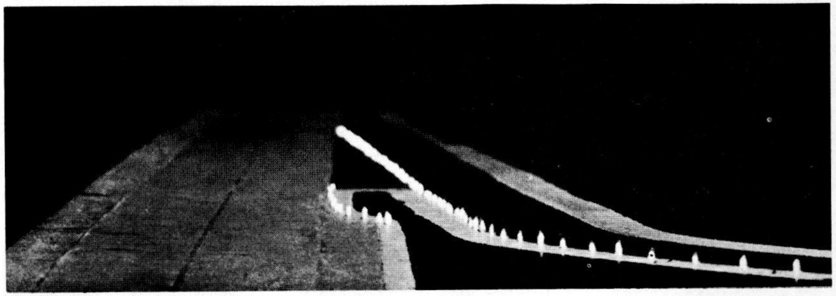


Figure 22. Nighttime, clear weather, on-ramp to expressway.

having a transmission as low as $\frac{1}{2}$ of 1 percent in an 800-ft baseline. Such a fog would be very dense and would be approximately the same as the conditions shown in Figures 11 to 22. There are a few situations in which fog densities greater than those shown would be encountered. Such situations do occur occasionally, but even under the most severe fog conditions the lights on close centers would be seen from 4 to 10 lights away. This would provide some guidance which would be most welcome under these critical conditions. The photographs of the four typical installations (Figs. 11 to 22) show a daytime fog situation, a nighttime fog condition, and a clear-weather nighttime situation in which the roadway is illuminated by fixed lights. In the case shown, a small projector was used to simulate street lights. The pictures are self explanatory and show the remarkable guidance provided around points of conflict at typical roadway situations. The models were set up to demonstrate the principle and are not to be used as a design guide. It is possible that other spacings would be more suitable and that somewhat different lighting configurations might be better than those used. The lights were layed out using the premise that the lines of light should be the same as the painted lines that are used for marking the points of conflict on the roadway.

CONCLUSIONS

The work done to date on airport runways, taxiways and high-speed turn-offs, plus the preliminary work on roadways and on model studies in the fog chamber, demonstrates the versatility and utility of the principle of lineal guidance obtained by light sources inset into pavement surfaces.

The principle of guidance as now proposed is generally accepted for airport use. It is hoped that the next step will be to apply the principle to some of the more critical areas on roadways. This is being considered, and some tests have been made by the Connecticut Department of Highways in conjunction with one of the leading lighting equipment manufacturing companies. Another trial installation has been proposed for the Golden Gate Bridge at San Francisco. This installation would be a combination lane-marking system and center-lane reversal system. The operation would be accomplished by shifting the double line from the center to one lane each side of center, using lighted lights on suitable switching circuits.

The extra-visual information provided by lighted lane-lines under good visibility conditions is a desirable feature. This means of providing added visual information under poor visibility conditions is highly desirable.

Under poor visibility conditions the range of visibility of lighted lane-lines is far greater than with any of the present paint markings or border materials. In general, the visual range can be approximately doubled, using lighted lights, over that which is available using reflective-type marking materials.

The low-wattage units placed on close spacings have been found to be preferable to higher-wattage units placed on wider spacings. One reason for this is that the continuity of the lineal pattern is improved and the glare per individual unit is greatly reduced.

It is hoped that several trial installations of lighted lane markers can be made on actual roadway locations in the near future, so that the usefulness and versatility of the system can be proved in actual field trials.

REFERENCES

1. Finch, D.M., "Surface Mounted Lights on Roadways, For Guidance." HRB Bul. 226 (1959).
2. Finch, D.M. et al., "An Evaluation of Surface Mounted Lights for Runway Guidance—Interim Report." FAA, BRD-4, Univ. of Calif., ITTE (April 1959).
3. Finch, D.M., and Horonjeff, R., "An Evaluation of Surface Mounted Lights for Runway Guidance—Final Report." FAA-BRD-4, Univ. of Calif., ITTE (June 1960).
4. Report to Julian Bardoff, Senior Civil Engr., Utilities Engr. Bureau, San Francisco, Calif., by Robert Horonjeff and D.M. Finch (Dec. 22, 1960).

5. Finch, D.M., "Airport Lighting Studies." Project UCB-ENG 6439, U.C. Inst. of Engr. Research, Dec. 27, 1960 for Port of Oakland, Oakland, Calif.
6. Strong, R.L., "Category III Test of an Integrated Approach and Landing Aid System." Westover AFB, Mass., Eighth Air Force (June 1959).
7. "Required Equipment Characteristics for Unidirectional and Bidirectional, Cylindrical, Flush 'Pancake' Type Runway-Taxiway Light, Development Directorate." FAA, (Jan. 1959).
8. MIL-L-27237(SUAF), Military Specification, Light, Marker, Runway and Taxiway, Flush, Inset (Sept. 1959).
9. Corps of Engineers drawings for Lockbourne Air Force Base, Ohio River Division Laboratories, Mariemont, Ohio. Installation Details Pancake Centerline Lighting in Rigid Pavement Runway. Dwg. No. V2-17-59-1. Developments of Pancake Lighting, FAA, Bur. of Research and Development, GPO 889720.
10. MIL-L-27476(USAF), Military Specification, Light, Marker, Airport Runway, 200 Watt, Inset (August 1960).

Comparison of Effectiveness Ratings–Roadway Lighting

CHARLES H. REX, Roadway Lighting Advance Development Engineer, Outdoor Lighting Department, General Electric Company, Hendersonville, N.C.

● THE seeing factor effectiveness of roadway lighting systems is now being measured using new instrumentation which facilitates proper evaluation of outdoor full-scale installations.

For comparison, computed ratings for the seeing effectiveness of roadway lighting systems are also presented. There is a substantially good correlation between measured and computed seeing factor ratings for roadway lighting.

During 1961 high-speed digital computers will be used for the prediction of seeing effectiveness ratings for representative roadway lighting systems. The method and data for computation have been developed and are described in previous papers including several presented to the Highway Research Board.

The measured data include comparison of systems of luminaires producing a cutoff-type candlepower distribution similar to that recommended by Christie (1), Rex (7), and de Boer (4).

The intense international, and cooperative, activity to produce visual seeing effectiveness ratings for roadway lighting is motivated by a general recognition of necessity. It is essential to provide all who represent the public, and those who desire to improve night-as-well-as-day-business activities with a basis for the proper evaluation of the humanitarian, traffic, and economic gains which good roadway lighting produces.

Knowledgeable estimates, appraisals, figures-of-merit, measurements, and ratings for the broad benefits of roadway lighting are essential. The extent by which these benefits are provided is contingent on how much seeing effectiveness is produced by the roadway lighting. Evaluation of the broad benefits will determine the extent of roadway lighting installed and the quantity and quality of seeing provided.

Hence, the evaluation of roadway lighting benefit may be expressed:

$$\frac{\text{BENEFIT RATINGS}}{\text{Humanitarian, Traffic, Economic}} \quad \text{Requires} \quad \frac{\text{SEEING RATING}}{\text{Visibility, Visual Comfort}}$$

Variations in the seeing factor effectiveness of different roadway lighting systems should be considered and factored into each evaluation of the broad benefits.

Ratings for the seeing effectiveness of roadway lighting are now being provided in terms of (a) relative visibility, and (b) relative visual comfort.

Availability of relative visibility and relative visual comfort ratings for the seeing effectiveness of roadway lighting presents a substantial simplification for all concerned.

In many countries, including the United States, evaluation of traffic and other broad benefits, as well as substantial installations of good roadway lighting, has been the direct result of engineering studies and technology applied to ratings for the visual seeing benefits of roadway lighting.

Rex (7) pointed up only a few of many economic evaluations for the aid which roadway lighting may provide for the benefit of the public and the night automotive industry:

1. Nighttime prosperity for the country and the community,
2. Aid to motor vehicle transportation industry,
3. Enhancement of social, recreational, and business activities,
4. Development of useful land areas,

5. Discouragement of criminal activities, and
6. Facilitating pleasant driving with less fear of accidents.

These humanitarian, traffic, and economic gains should be evaluated or rated.

If it is assumed that a benefit of $10,000 per mile per year is derived by the installation of lighting having seeing factor ratings of: relative visibility 9.5 (Appendix A), and relative visual comfort 0.3, the relation may be expressed as follows:

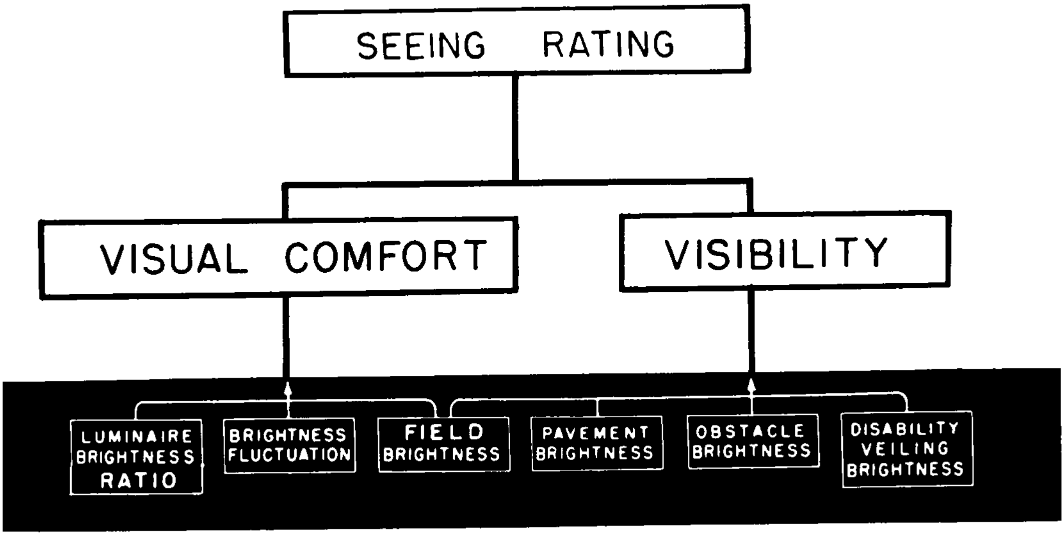


Figure 1.

$10,000		VISIBILITY = 9.5
PER MILE PER YEAR	Requires	VISUAL COMFORT = 0.3
(Benefit Rating)		(Seeing Rating)

Further simplification to a single rating in terms of relative seeing will develop from evaluation of the comparative general benefit produced by each of the major factors: (a) relative visual comfort, and (b) relative visibility.

SEEING TECHNOLOGY SPARKS NEW SURGE OF ENGINEERING INTEREST IN ROADWAY LIGHTING

A $1 million research evaluation of benefits of roadway lighting termed, "Warrants for Lighting Freeways," was recommended during 1959 (3). Progress on this project will be retarded if seeing factor effectiveness ratings for the lighting are not made available, rapidly.

The Highway Safety Study (3), prepared under the direction of Charles W. Prisk, presents an outline of numerous night driving problems, including vision, which will be substantially aided by roadway lighting providing high seeing factor effectiveness.

Everything possible must be done to facilitate evaluation of the benefits of roadway lighting. This endeavor should have the attention of all who represent the public and night-as-well-as-day-business and welfare activities. Included are economists, engineers, and scientists for whom the improvement of the public welfare is an underlying thought and impelling force.

Progress depends on cooperative efforts, which are being extended to an international activity, directed toward understanding and appreciation of the efficiency of roadway lighting in producing good seeing conditions. Accomplishment of the six objectives previously listed is contingent on the seeing provided. Hence knowledgeable estimates, appraisals, measurements, figures-of-merit, or ratings are essential for both: the degree by which one or more of the broad objectives are accomplished; and, how much seeing effectiveness is produced by the roadway lighting being evaluated. This is a simple, straightforward approach to the problem which can only be answered by engineering evaluation based on known technologies.

The rapidly increasing worldwide engineering interest in, and attention to, roadway lighting may in large part be attributed to the technology which has provided seeing factor ratings as a base for rating the other benefits.

The two seeing factor ratings, relative visual comfort and relative visibility, combine to replace the six sub-factors in seeing, shown in Figure 1.

1. Luminaire brightness ratios are being computed. The computations are backed up by measurements. Luminaire brightness is mitigated by luminaire cutoff which is explained later in this paper.
2. The important dynamic effect of brightness fluctuation, was discussed by Forbes (2). Evaluation of the effect of fluctuation on visual comfort will develop along with methods of improving this sub-factor.
3. The brightness of the driver's visual field is subject to evaluation using the Fry-Pritchard instrumentation.
4. The predominate pavement brightness factor is readily being measured. Computations are available based on previous measurements.
5. Obstacle brightness and size vary over a wide range. An abstract target of 1-ft diameter and 8 percent reflectance is generally accepted as suitable criteria for relative visibility measurements.
6. The highly significant disability veiling brightness sub-factor is now being measured as well as computed. The loss of visibility now includes compensation for the effect of dynamic fluctuation.

Relative rating scales or numbers for these seeing factors are obviously much better than word descriptions. Opinion appraisals may range from excellent to poor for the same roadway lighting system when installed in different communities or viewed by different observers. Interchangeability and communication from one portion of the world to another are also highly advantageous.

Now that ratings for roadway lighting systems can be readily provided in terms of relative visibility and relative visual comfort, the engineer can transmit to others the seeing effectiveness which he has in mind; thus avoiding the confusion and complex mental interpolations with respect to seeing factor benefit when only sub-factors—or worse yet—when only foot-candle data are used as criteria. Sufficient foot-candles of light are necessary to obtain the seeing on which benefit depends; the requirement varies over a wide range. This is well known among highway as well as illuminating engineers.

Fowle and Kaercher (6) include data showing that the ratio of average foot-candles required per foot-lambert average pavement brightness varies over a range of 2:1 for 17 different roadway lighting systems. Therefore, to obtain the predominant visibility factor, such as an average pavement brightness of 0.6 foot-lambert, may require average foot-candles ranging from less than 1.8 to more than 3.0. The system brightness computations providing the ratios shown in Figure 2 were all based on the same pavement reflection data.

Comparison or rating roadway lighting systems on the basis of foot-candles should be limited to the rare instances in which circumstances and conditions are identical, as follows:

1. Control and proportioning of the luminaire candlepower distribution extending along, across, and above the roadway;
2. System geometry including luminaire spacing, mounting height, and overhang; and
3. Pavement surface characteristics in reflecting all angles of incident light from the luminaire toward an approaching driver.

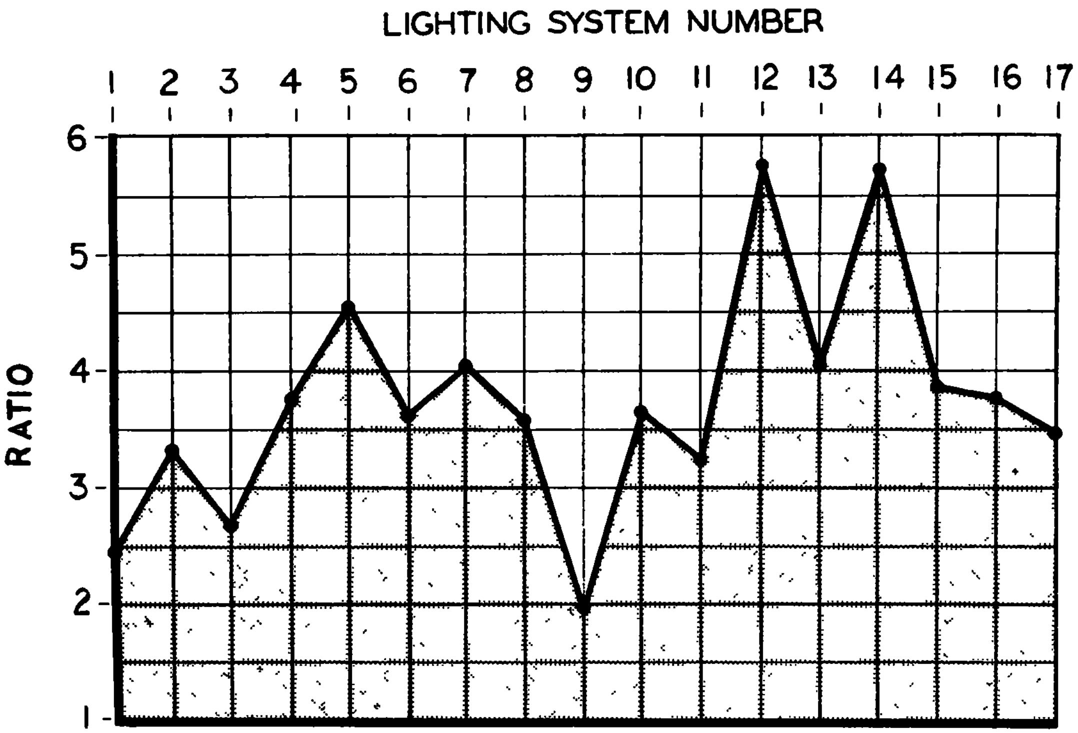


Figure 2. Average foot-candles per average foot-lambert. Pavement brightness computed for medium reflective pavement by A.W. Fowle and R.L. Kaercher.

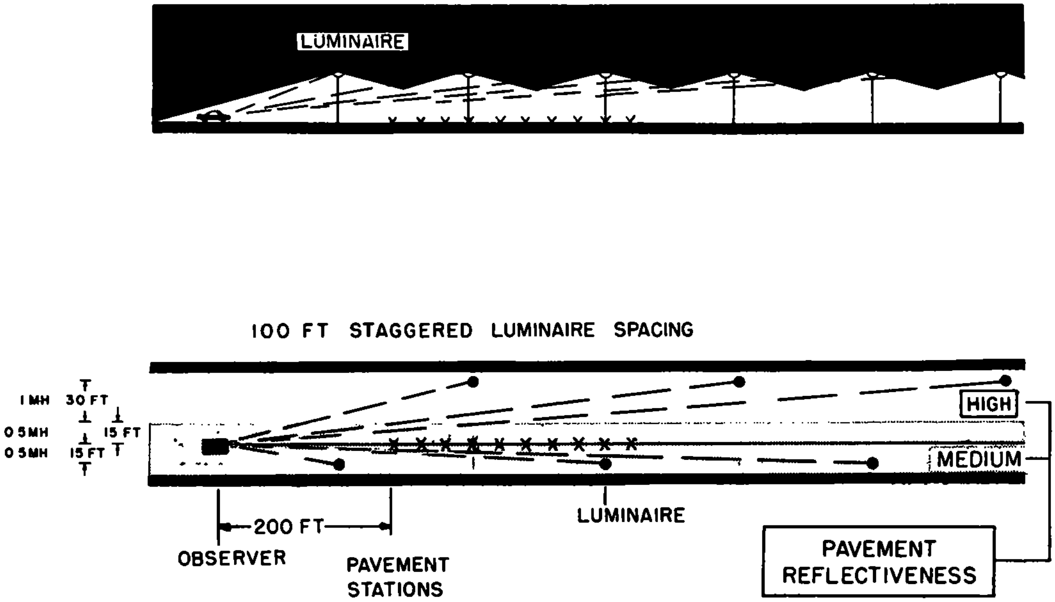


Figure 3.

Figure 4.

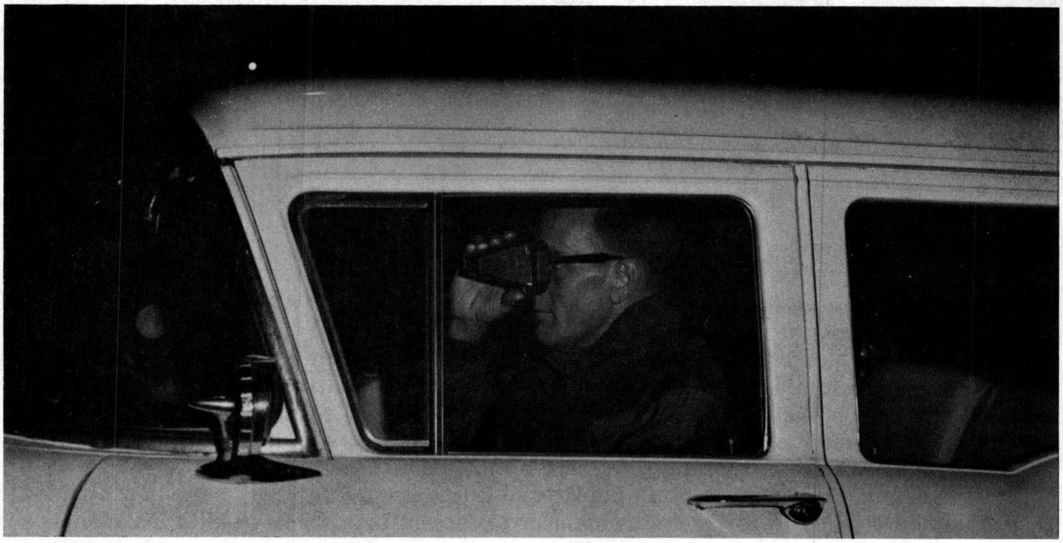


Figure 5.

STAGGERED LUMINAIRE SYSTEM RATINGS

Blackwell (9) described the staggered roadway lighting system on which his outdoor full-scale measurements were made along the 0.5 MH LRL (longitudinal roadway line) at 15-ft transverse distance from the luminaires (Fig. 3). Instead of designating the pavement surface as concrete and asphalt, the author prefers to designate the pavement surface as having high or medium reflectiveness. It is well known that the reflection characteristics of asphalt pavement can be made favorable by top surface treatment such as rolling-on a white or light gray aggregate. Also aging and traffic use may favorably affect the specular pavement reflection characteristics for roadway lighting.

The 5-yr-old asphalt pavement surface shown in Figures 3 and 4 is of medium reflectiveness.

In Figure 4 the 1-ft diameter, 8 percent diffuse reflectance disc is at 180-ft distance. This abstract target has been widely used as visibility criteria. It is similar to the black dog used in the studies by Blackwell et al. (9). The Blackwell data will soon be published in an I.E.S. paper in terms of his supra-threshold-visibility as well as pavement brightness factors. This photo was made through the windshield of the test car from the driver's eye position.

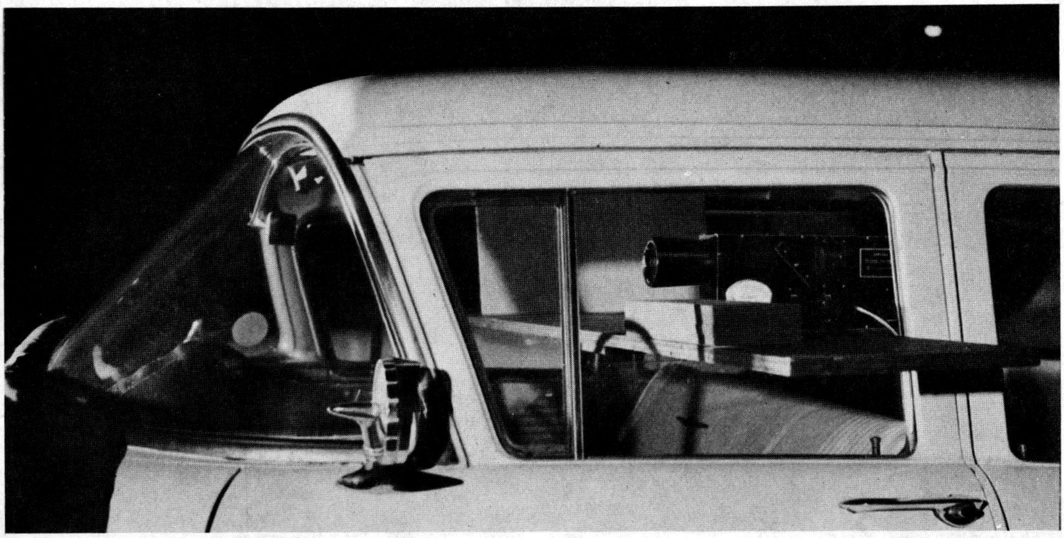


Figure 6.

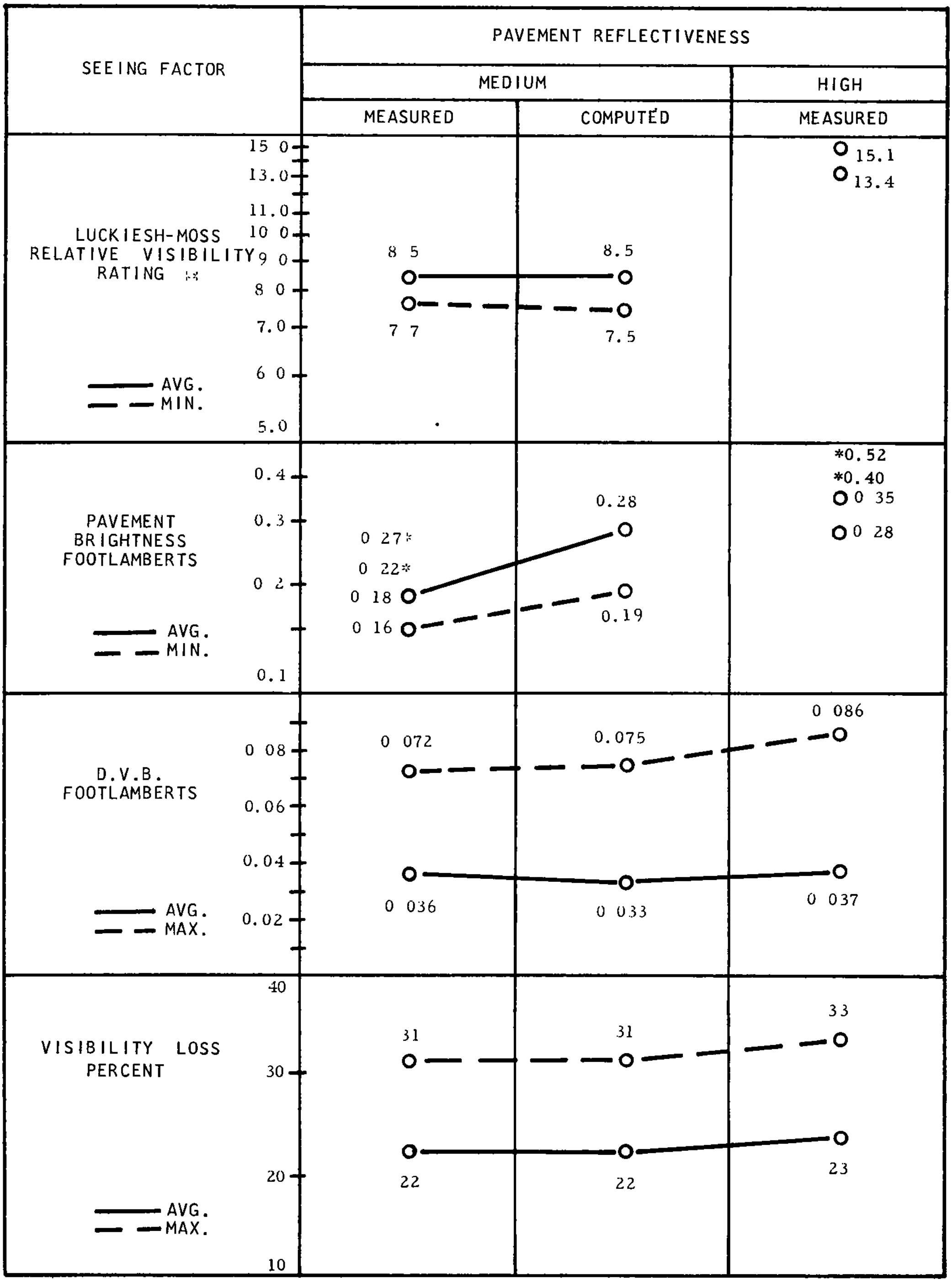
The eye-level position of an average, typical observer is used for the instrument as shown in Figure 5. In present-day autos the eye-level is 4 ft above the pavement. The average seat position is also used.

The Luckiesh-Moss Visibility Meter, shielded as shown in Figure 5 to eliminate the light from the luminaires, is being used to measure relative visibility. The Luckiesh-Moss relative Visibility Meter ratings, measured and computed, for medium reflectiveness pavement are lower than when the pavement has high reflectiveness. The new numerical scale for this meter is shown in Appendix A.

The observer's eye position was duplicated in mounting the lens of the new Pritchard Telephotometer (Fig. 6) for measurement of pavement brightness. This instrument has the additional advantage of physical scale meter readings rather than photometric balance which requires skill and experience.

The measured pavement brightness data (Fig. 7) are based on 6-min angle aperture. Thus, the pavement background at 200 ft may be contrasted with the mid-portion of the 1-ft diameter target as measured in the visibility meter tests. The Pritchard meter lens aperture is particularly desirable when there are large variations in the brightness of the pavement. The system pavement brightness is appreciably higher on the high reflectiveness pavement surface.

Figure 8 shows the instrument supplemented by a new lens developed by Fry and Pritchard (7). This now makes possible measurement of DVB (disability veiling brightness) of roadway lighting system luminaires. The brightness of the pavement is shielded from lens view. Incidentally, this is another example of new instrumentation developed by research sponsored by the Illuminating Engineering Research Institute.



* Meter Scale Reading
**Contrast Rating Per Appendix A

Figure 7. 100-ft staggered spacing—filament 15,000 lumen semi-cutoff.

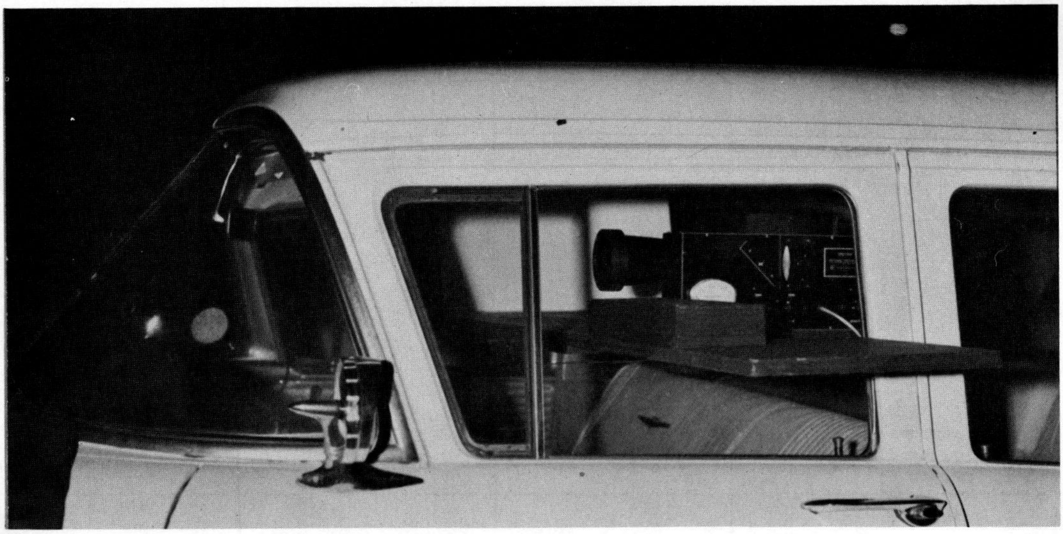


Figure 8.

Obviously, this Pritchard meter may be supplemented by an electrical recorder mounted in an automobile which may be driven along the road to obtain a graphical record of the DVB, pavement brightness, and variations or fluctuations thereof under roadway lighting.

As shown in Figure 7, the measured and computed DVB is fairly consistent for the staggered roadway lighting system. Under the dynamics of actual driving conditions, the maximum DVB may be highly important because it is indicative of the range of fluctuation to which the driver's eyes are subjected. As explained in previous papers, (12, 13, 14, 15) there are correlations showing the percent loss of visibility resulting from disability veiling brightness. This percent loss has been applied to the Luckiesh-Moss Visibility Meter ratings.

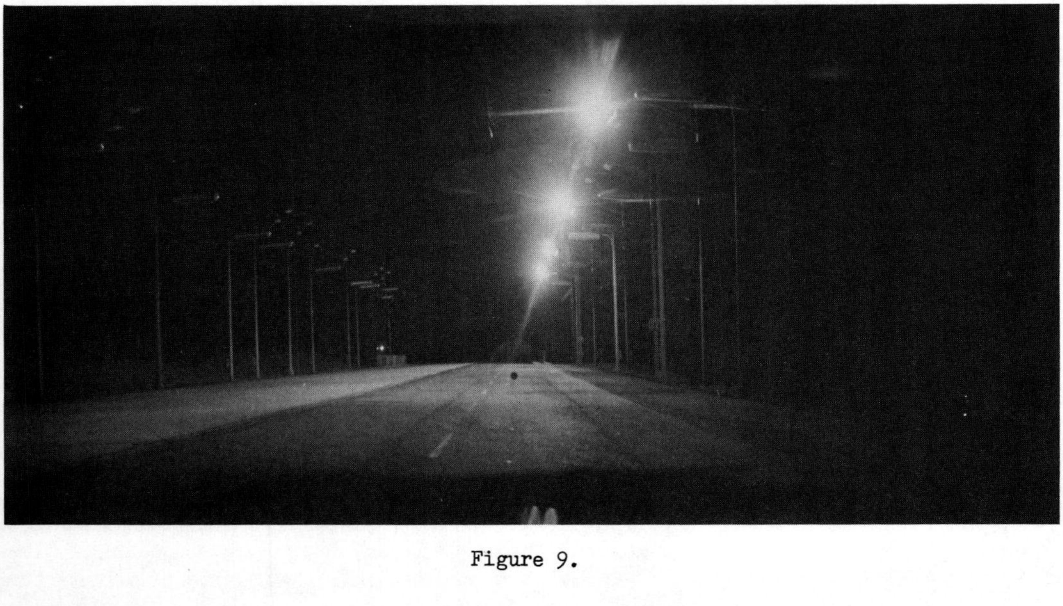


Figure 9.

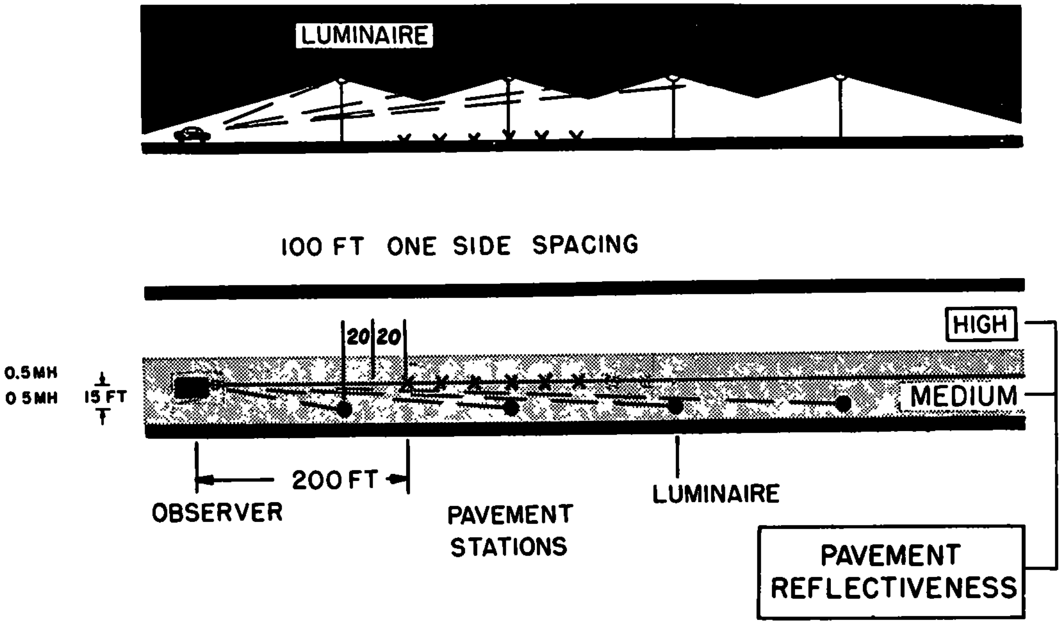


Figure 10.

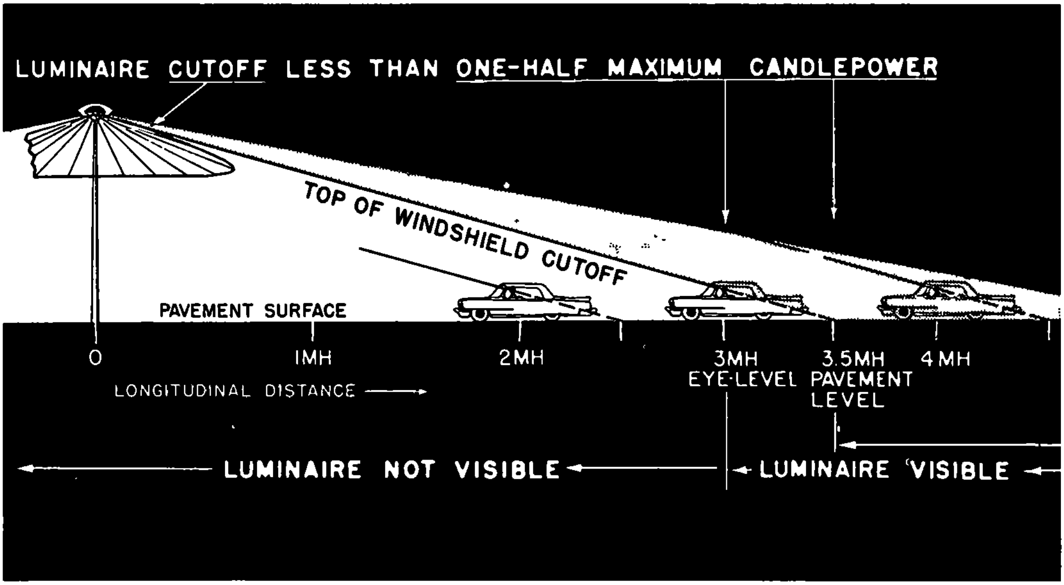
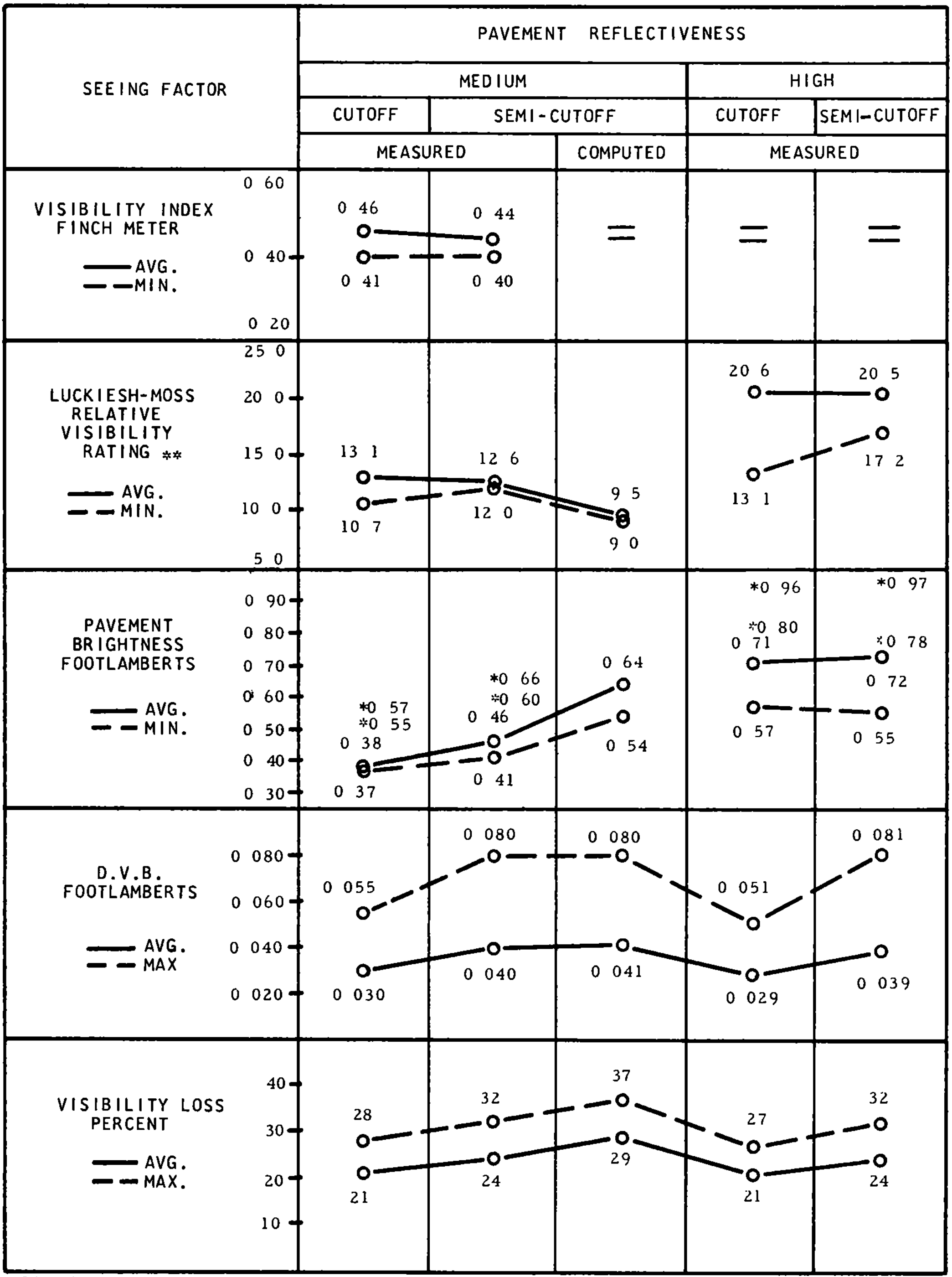


Figure 11.

ONE-SIDE LUMINAIRE SYSTEM RATINGS

Comparison of measured data for systems having 100-ft, one-side luminaire spacing is also of interest. For both high and medium reflectiveness pavement, the measurements are along the 0.5 MH longitudinal roadway line and driver path (Figs. 9 and 10).

In this system arrangement and driver path an additional comparison is provided in



*PRITCHARD METER READING

** CONTRAST SCALE AS PER APPENDIX A

Figure 12. 100-ft one side spacing—mercury 20,000 lumen.

the measurements of systems comprising cutoff luminaire candlepower distributions versus semi-cutoff candlepower distribution.

Cutoff of Luminaire Candlepower Distribution

The seeing effectiveness of most roadway lighting systems may be significantly improved by cutoff of the luminaire candlepower distribution (Fig. 11). The benefits of cutoff of candlepower distributions are most significant when the angle of cutoff is coordinated with the average top-of-auto windshield cutoff as shown on the right-hand side of Figure 11.

Under average automobile and driver conditions, the luminaire is cut off from view by the top of auto windshield at a longitudinal eye-level distance of 3 MH, three times the mounting height of the luminaire. This windshield cutoff intercepts the pavement at a longitudinal distance of 3.5 MH. It is expedient to use the 3.5 MH or pavement level expression of longitudinal distance. The pavement distance of 3.5 MH corresponds to the average demarcation or cutoff distance at which a luminaire is no longer visible to an approaching driver because of the protection provided by the automobile.

Coordinate cutoff control of the luminaire candlepower proportioning is shown at the left-hand side of Figure 11. The candlepower extending to the 3.5 MH distance is restricted to less than one-half the maximum candlepower. This means that the adverse effect of candlepower impinging on the driver's eyes is considerably less than that which would result if the maximum candlepower were elevated to coincide with, or extend above the 3.5 MH cutoff line. Obviously the sharp control of candlepower above the cutoff which extends to distances beyond 3.5 MH is also highly desirable.

The 3.5 MH one-half maximum candlepower cutoff is quite similar to that shown by Christie (1). It is also similar to that shown by de Boer (4).

Figure 13.

However, current U.S. semi-cutoff candlepower luminaire distribution has maximum candlepower of the order of 3.0 MH or 72½ degrees instead of the 75 degrees or 3.5 MH distribution shown by Christie.

Figure 12 shows the improvement in relative visibility and variations in relative visibility and variations in sub-factors due to cutoff of luminaire candlepower distributions.

Note that the average pavement brightness in Figure 12 approximates the 0.6 footlambert recommended by Blackwell, de Boer, and Guth.

The Finch Visibility Meter (22) ratings for the relative visibility effectiveness of the roadway lighting system, also shown in Figure 12 are based on measurements made with a preproduction model of the meter developed by D. M. Finch of the University of California, Institute of Traffic and Transportation. Figure 13 shows this meter being used by Mr. Karl Freund who will have six meters in production during 1961. Since luminaires are visible in the 30-deg field of this visibility meter the percent visibility loss is not applied to visibility index ratings.

Typical of his interest in night motor vehicle transportation, de Boer has donated a set of the Landolt C rings for use in comparing the effectiveness of roadway lighting systems. These rings definitely aid comparative appraisals of the visual effectiveness of roadway lighting systems. They are especially useful, a step forward in appraisals by large groups of observers.

A portable version of Blackwell's Visual Task Evaluator (9, 7, 10) is also expected to be available during 1961 for use in evaluating the relative visibility effectiveness of roadway lighting systems.

SUMMARY

High priority by highway engineers is now being assigned to the evaluation of the broad benefits of roadway lighting. This stimulus of interest is directly attributable to the international engineering emphasis on seeing factor ratings. An even more important fact is that seeing ratings also provide a base which encourages evaluation of the humanitarian, traffic, and economic benefits by the many interested agencies. The night transportation benefits of roadway lighting are also susceptible to numerical evaluation. This progress will be aided by numerical ratings for the lighting provided in such simple terms as visual comfort and visibility.

In many countries throughout the world, action with respect to figures-of-merit for both the seeing and traffic benefits of roadway lighting is interrelated and gaining new impetus. Seeing ratings are internationally interchangeable and may be communicated from one portion of the world to another. Interchange of information and ratings aids human progress throughout the world.

Improvement of the public welfare is an underlying thought and impelling force for economists, engineers and scientists. Everyone gains by attention to, and more extensive use of, roadway lighting.

ACKNOWLEDGMENTS

The author gratefully acknowledges the counsel and assistance of his associates including HRB, ITE, and IES. In particular, appreciation is extended to the staff members of the Photometric Laboratory, Outdoor Lighting Department, General Electric Company, who made the night field measurements and laboratory calibrations. The author is grateful to Mr. J. B. de Boer, Mr. J. F. T. Heemskerck Veeckens, and Mr. F. Burghout for the international comparison of pavement brightness data shown in Appendix B. It is significant that in the interest of progress toward seeing factor ratings in the United States, Mr. Harold Wall, Superintendent, and Mr. P. L. Young of the City of Detroit Public Lighting Commission, compiled the computed and measured pavement brightness data shown in Appendix C.

Measurements reported for DVB include the author's calibration factor for the Fry-Pritchard lens-meter based on computed versus measured data.

Computed combined system DVB (13) is based on IES Handbook formula $\frac{31.4E}{\theta^2}$. Future computations will use the formula $\frac{31.4\ E}{\theta\ (\theta + 1.5)}$.

REFERENCES

1. Christie, A.W., "An Experimental Low-Cost Lighting System for Important Highways in Rural Areas." HRB Bull. 255 (1960).

2. Forbes, T.W., "Some Factors Affecting Driver Efficiency at Night." HRB Bull. 255 (1960).
3. HRB Special Report 55, P. 10 (1959); also "The Federal Role in Highway Safety." Report submitted to 86th Congress, February 27, 1959, Director Charles W. Prisk, House Document No. 93.
4. de Boer, J.B., "Road Surface Luminance and Glare Limitation in Lighting for Safe and Comfortable Road Traffic." HRB Bull. 298 (1961).
5. de Boer, J.B., "The Application of Sodium Lamps to Public Lighting." 1960 I.E.S. Technical Conference Paper, I.E. (April 1961).
6. Fowle, A.W., and Kaercher, R., "Roadway Brightness and Illumination as Related to Luminaire Distributions." 1960 I.E.S. Technical Conference Paper, I.E. (April 1961).
7. Rex, C.H., "Advancement in Roadway Lighting." HRB Bull. 255 (1960); also, "Ratings for the Visual Benefits of Roadway Lighting." HRB Bull. 226 (1959).
8. Rex, C.H., and Franklin, J.S., "Visual Comfort Evaluations of Roadway Lighting." HRB Bull. 255 (1960).
9. Blackwell, H.R., Pritchard, B.S., and Schwab, R.N., "Illumination Requirements for Roadway Visual Tasks." HRB Bull. 255 (1960).
10. Rex, C.H., "New Developments in the Field of Roadway Lighting." 1959 I.T.E. Annual Meeting Paper; I.T.E. Transactions; also T.E. (March 1960).
11. Rex, C.H., "Roadway Safety Lighting." A paper and report on behalf of the I.T.E. Committee on Roadway Lighting, Annual Meeting Institute of Traffic Engineers (Nov. 13, 1958).
12. Rex, C.H., and Franklin, J.S., "Relative Visual Comfort Evaluations of Roadway Lighting." 1959 I.E.S. Technical Conference Paper, I.E. (March 1960).
13. Rex, C.H., "Computation of Relative Comfort and Relative Visibility Factor Ratings for Roadway Lighting." I.E.S. 1958 Technical Conference Paper, I.E. (May 1959).
14. Rex, C.H., "Improving Seeing Efficiency with Roadway Lighting." Traffic Engineering (Aug. 1956).
15. Rex, C.H., "Principles and Figures of Merit for Roadway Lighting as an Aid to Night Motor Vehicle Transportation." HRB Bull. 146 (1957).
16. Rex, C.H., "Luminaire Light Distribution Principles." I.E. (Dec. 1955).
17. Rex, C.H., "Report on American Standard Practice for Street and Highway Lighting." Presented Illuminating Engineering Society National Technical Conference, Sept. 1952; information with regard to roadway lines, distance, and light distribution.
18. American Standard Practice for Street and Highway Lighting approved February 27, 1953, A.S.A.
19. Rex, C.H., "Technical and Practical Aspects of Highway Lighting." Proc., Institute of Traffic Engineers, 8:41 (1937).
20. Rex, C.H., "Roadway Lighting for Efficiency." Paper presented Annual Meeting Institute of Traffic Engineers, Sept. 11, 1952, Chicago, Ill.
21. "Traffic Engineering Handbook." Institute of Traffic Engineers 1940 and 1950, Section on Street and Highway Lighting.
22. Finch, D.M., and Palmer, J.D., "Assessment of Nighttime Roadway Visibility." HRB Bull. 163 (1957).
23. Rex, C.H., "The Public Benefit Objectives—Part I." First of the series of the Export articles published during 1960 in both Modern Government (Asia, Africa, and Middle East—55 countries); and Servicios Publicos, South America.
24. Rex, C.H., "Traffic and Visual Benefit Ratings—Part II." Second of the series of the Export articles published during 1961 in both Modern Government (Asia, Africa, and Middle East—55 countries); and Servicios Publicos, South America.
25. Rex, C.H., "New Design Trends in Roadway Lighting—Part III." Third of the series of the Export articles published during 1961 in both Modern Government (Asia, Africa, and Middle East—55 countries); and Servicios Publicos, South America.

Appendix A

TABLE FOR CONVERTING L-M METER RELATIVE VISIBILITY READINGS TO RELATIVE CONTRAST[a]

Relative Visibility	Relative Contrast	Relative Visibility	Relative Contrast	Relative Visibility	Relative Contrast
1.0	2.0	3.6	29	7.2	61
1.05	2.4	3.7	30	7.4	62
1.1	2.8	3.8	31	7.6	64
1.15	3.2	3.9	32	7.8	65
1.2	3.6	4.0	33	8.0	66
1.25	4.0	4.1	34	8.2	67
1.3	4.5	4.2	35	8.4	68
1.35	5.0	4.3	36	8.6	69
1.4	5.5	4.4	37	8.8	71
1.45	6.0	4.5	38	9.0	72
1.5	6.5	4.6	39	9.2	73
1.55	7.0	4.7	40	9.4	74
1.6	7.5	4.8	41	9.6	75
1.65	8.0	4.9	42	9.8	76
1.7	8.5	5.0	43	10.0	77
1.75	9.0	5.1	44	10.5	79
1.8	9.5	5.2	45	11	82
1.85	10.0	5.3	46	11.5	84
1.9	10.5	5.4	47	12	87
1.95	11.0	5.5	48	12.5	89
2.0	12.0	5.6	48	13	90
2.1	13.0	5.7	49	13.5	92
2.2	14.0	5.8	50	14	94
2.3	15.0	5.9	51	14.5	96
2.4	16.3	6.0	52	15	98
2.5	17.5	6.1	52	15.5	99
2.6	18.5	6.2	53	16	101
2.7	20	6.3	54	16.5	103
2.8	21	6.4	54	17	104
2.9	22	6.5	55	17.5	106
3.0	23	6.6	56	18	107
3.1	24	6.7	57	18.5	108
3.2	25	6.8	58	19	109
3.3	26	6.9	59	19.5	111
3.4	27	7.0	60	20	112
3.5	28	-	-	-	-

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[a] The relative contrast scale is based on the absolute threshold contrast of a standard 4-min disc target under specific laboratory conditions. The actual threshold contrast is assigned a value of unity. The Relative Contrast Scale reading for a task at a given illumination level relates the visibility of that task to the supra-threshold contrast of the standard disc at the same illumination level.

For example, a reading of 4 on the Relative Contrast Scale for a given task means that, under the conditions of measurement, the task is equivalent in visibility to the standard disc target which is four times its threshold contrast. A reading of 10 means that the task is just as visible as the standard disc when it is ten times its threshold contrast.

This table is derived from the basic data of Figure 1, "Comparison of Visibility Measurement Systems," A.A. Eastman and S.K. Guth, Illuminating Engineering, Vol. LV, No. 3, March 1960, p. 176, and the threshold curves for a 4-min disc, from "Specification of Interior Illumination Levels," by H. Richard Blackwell, Illuminating Engineering, Vol. LIV, No. 6, June 1959, p. 317.

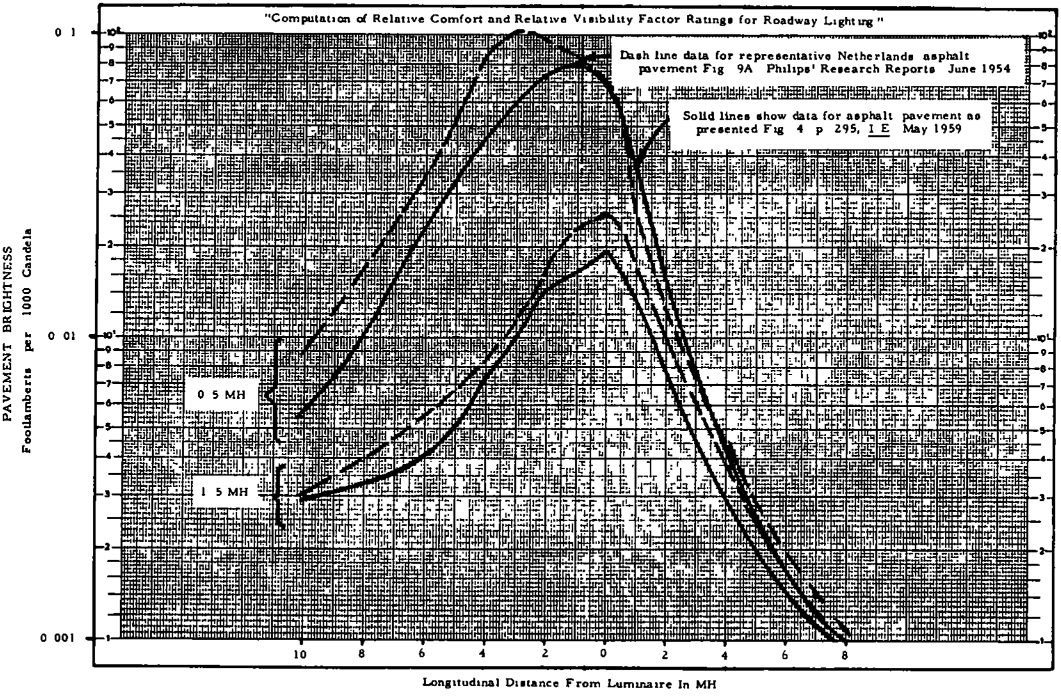
A.A. Eastman, April 3, 1961

Appendix B

COMPARISON OF PAVEMENT BRIGHTNESS PRODUCED PER 1000 CANDLEPOWER FROM SINGLE LUMINAIRE WHICH IS AT THE DRIVER'S LEFT

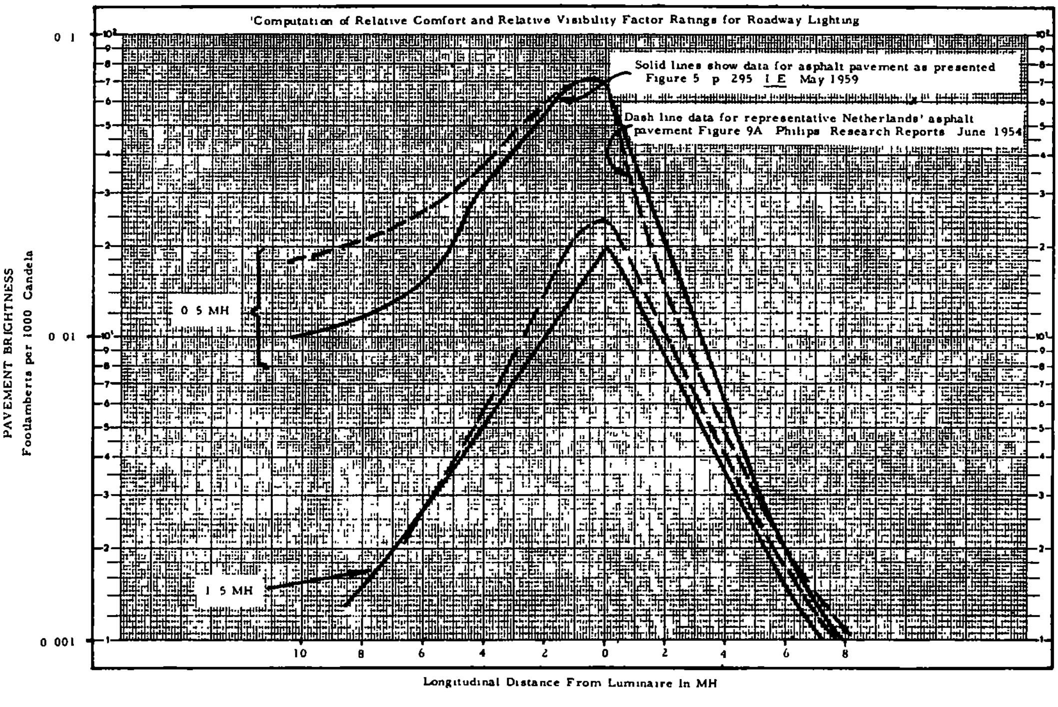
Prepared by J B deBoer F Burghout, and J F T Heemskerck Veeckens of the N V Philips Lighting Laboratory - May 3 1960 - for Charles Rex

I E May 1959 p 295



COMPARISON OF PAVEMENT BRIGHTNESS PRODUCED PER 1000 CANDLEPOWER FROM SINGLE LUMINAIRE WHICH IS AT THE DRIVER'S RIGHT

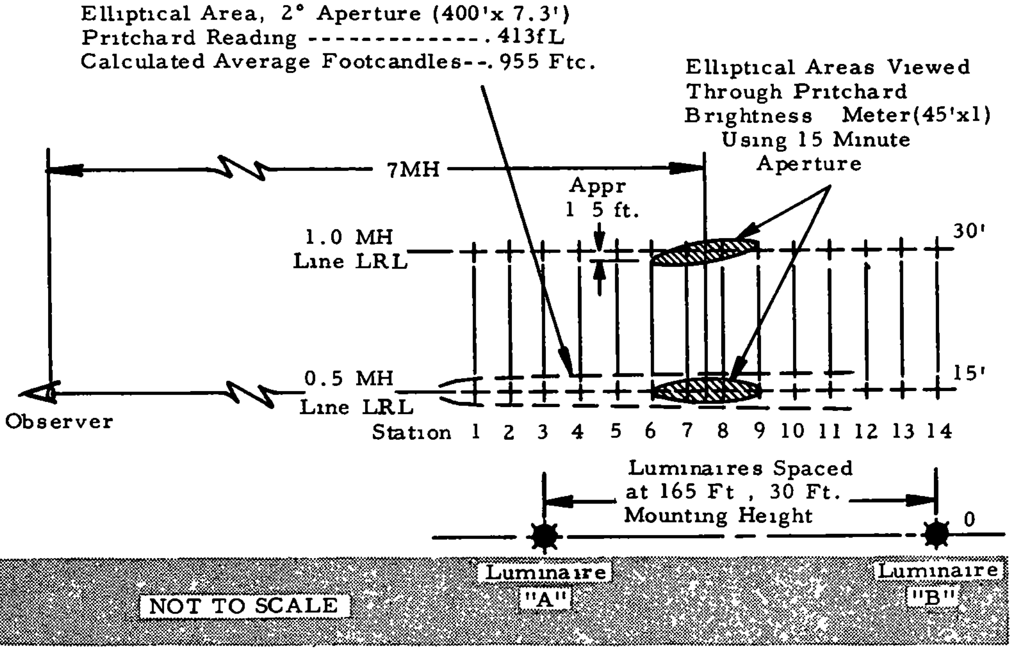
I E May 1959 p 295



Appendix C

Excerpts from Report to I. E. S. Roadway Lighting Committee
by H. F. Wall and P. L. Young, City of Detroit, Public Lighting Commission
May 23, 1961

Stations Along	Candlepower from Luminaire		PAVEMENT BRIGHTNESS		
			COMPUTED		MEASURED
.5 MH LRL	'A'	'B'	Reid-Chanon Bock-Rex Coefficients	J. B. deBoer Pavement 9A Coefficients	Pritchard Telephotometer 15 Minute Aperture
6	5520	4060	0.27 fL.	0.26 fL.	
7	7080	5334	0.33	0.33	
8	8330	6203	0.40	0.40	
9	7830	7289	0.44	0.47	
Avg			0.36	0.37 fL.	.39 fL.
1.0 MH LRL					
6	5610	5501	0.15 fL.	0.18 fL.	
7	8330	6526	0.19	0.22	
8	10374	7486	0.22	0.25	
9	9194	9522	0.24	0.28	
Avg			0.29 fL.	0.23 fL.	0.27 fL.



Headlight Glare vs Median Width

JOHN R. FRIES and L.J. ROSS, Idaho Department of Highways, Boise

● THE GLARE of approaching headlights reduces a driver's ability to see. When the lights of an approaching automobile remain on high beam during the passing maneuver, most drivers are blinded by the dazzling light and are unable to observe clearly an obstacle on the highway within the limits of the driver's headlight illumination.

The object of this study is to determine the median width that will best avoid this blinding glare from high-beam headlights of oncoming automobiles, and therefore, allow a driver to see an obstacle on the highway at a safe stopping sight distance.

EQUIPMENT

The equipment used in this study included two state vehicles—No. 2687 (1957 Chevrolet Station wagon), No. 2719 (1957 Chevrolet pickup), and a G.E. illumination meter (range—0.2 to 500 foot-candles).

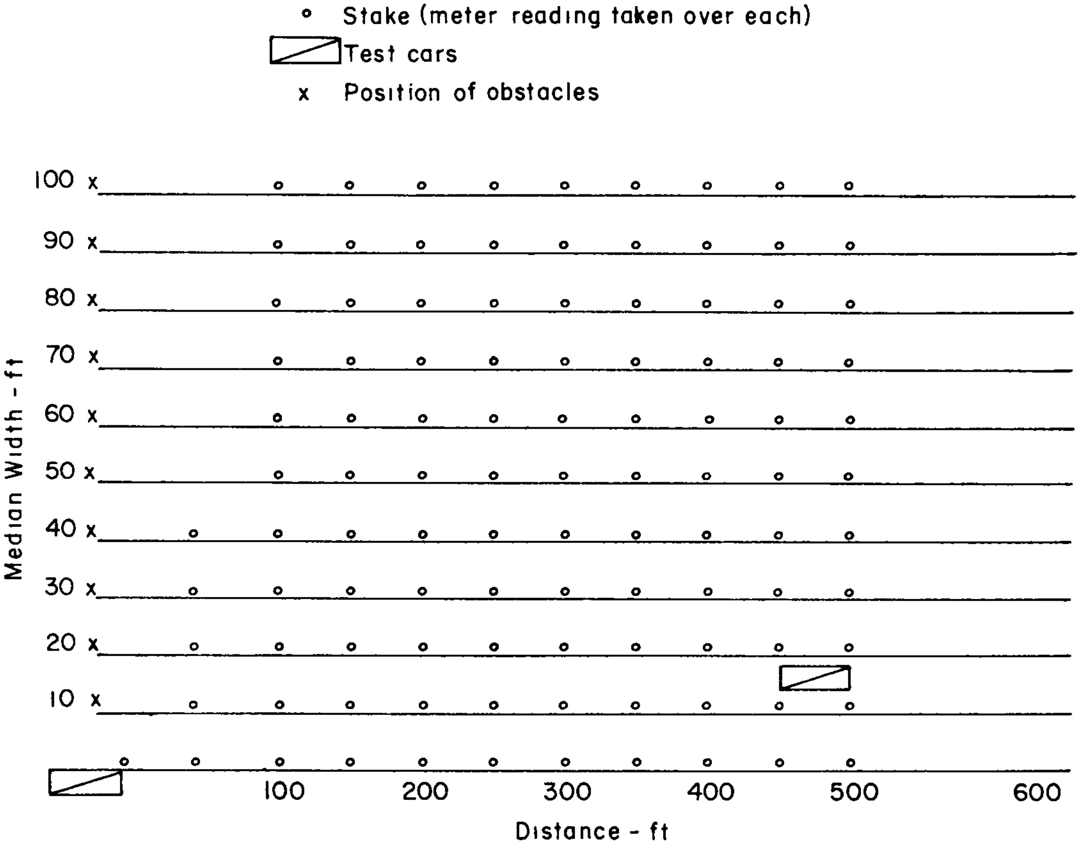


Figure 1. Plan of track used for tests.

PROCEDURE

Test A

This test was carried out on a graveled airplane runway with small vegetation growing thereon. This vegetation was, in general, small shrubs, weeds, and grass which is more or less representative of anticipated median texture. The runway was chosen because it provided a reasonable length of straight track without curves. Ten lengths of track were used to run the tests, the dimensions and layout of which are shown in Figure 1.

A baseline was stationed in 50-ft intervals for 600 ft. From the baseline, six 10-ft lanes were laid out. A test driver would then drive down each lane at an average speed of 45 mph toward a stationary vehicle parked on the baseline at Station 0/00. Both automobiles had their headlights on high beam. An obstacle was placed in the lane down which the moving auto would travel. This obstacle was opposite the stationary automobile, but far enough back so that the vehicles' lights would not reflect on the obstacle.

There were two men in the test auto. The driver stated when he could see the obstacle, while the other man dropped a marker at that point. The driver made several test runs, starting with the 10-ft median, then the 20-ft median, and so on, until there was no glare, or until he could clearly observe the obstacle with his headlights alone. A total of seven drivers performed the test.

Test B

To check the results obtained in Test A, a source intensity curve with candlepower as a function of median width and distance from source was prepared.

To determine these curves, meter readings of illumination at 50-ft intervals were taken on each 10-ft median increment, and were then converted to a measure of source intensity expressed in candlepower by the relation $I = ER^2$, in which I = source intensity in candlepower, E = illumination in foot-candles, and R = distance from source in feet.

During the test the stationary vehicle remained at station 0 + 00 on the baseline with headlights on high beam, while another auto was driven over each 50-ft station on each lane. An illumination reading was taken through the windshield at the same height as the driver's eyes.

RESULTS AND CONCLUSIONS

The results obtained during Test A are summarized in Table 1. This table was prepared from the observations of the seven drivers tested, and shows the minimum safe median widths with high-beam headlights for design speeds from 30-70 mph. The individual distance curves plotted for each driver and a sight distance curve, which is a calculated statistical average for the seven drivers tested, are shown in Figure 2.

The results obtained during Test B are shown in Figure 3. This figure was prepared from the data given in Tables 3 and 4 (Appendix). The light intensity curves show a definite relation with the observations of the seven drivers run through the test. The average curve has been plotted with these curves to show this relation. The light intensity curves indicate that the 25,000 contour of illumination is the safe maximum candlepower allowable for desirable minimum glare.

TABLE 1

Design Speed (mph)	Safe Stopping Sight Distance (ft)	Median Width[a] (ft)
30	200	10-20
40	275	20-30
50	350	30-40
60	475	50-60
70	600	60-80

[a] Minimum safe median widths with high-beam headlights. Two cars passing on 4-lane divided highway.

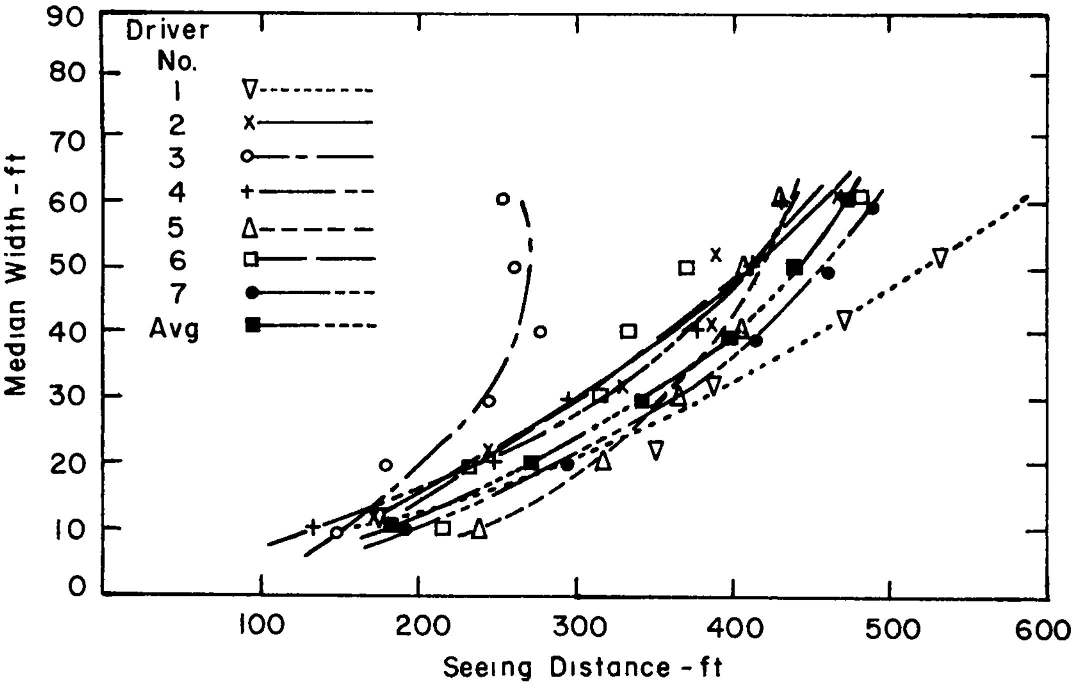


Figure 2. Seeing distance as function of median width.

Both tests have the following conditions in common:

1. Tests were run on clear, moonless nights.
2. The median widths were made of small shrubs, weeds, and grass; reflection was very low.

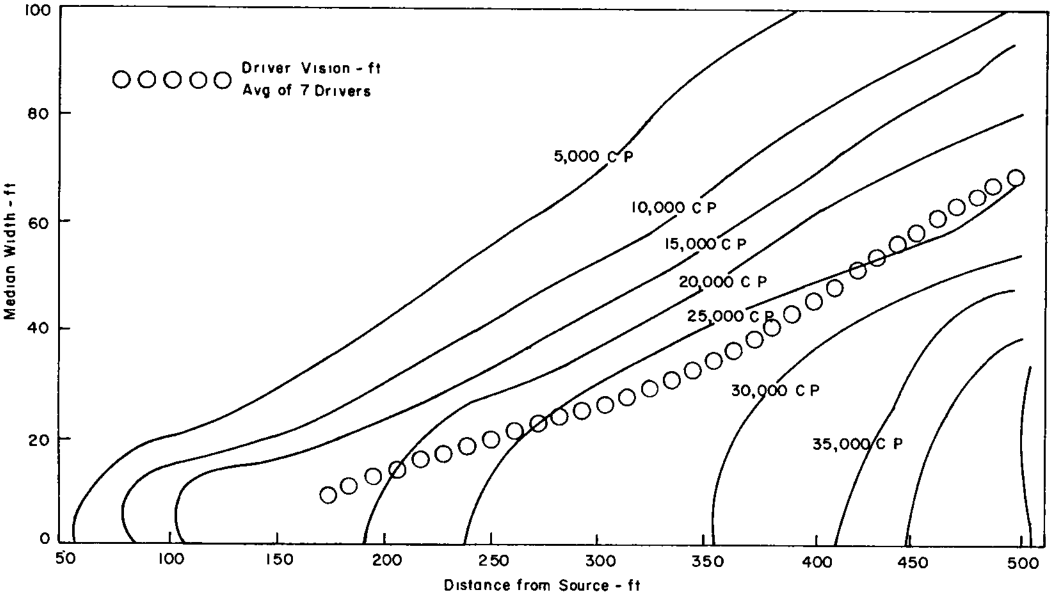


Figure 3. Source intensity as a function of median width and distance from source.

3. The obstacle was made of wood in an "A" shape about 2 ft high.
4. The target was placed in a different position on each lane so that the driver would not know where to look for the obstacle.

A review of the test as a whole suggests that more complete and varied investigations should be made to definitely establish the relation of median widths to sight distance against opposing high-beam headlights. These tests were run under one condition, considered to be average. Variable conditions, such as glare on wet surfaces, light-and dark-textured surfaces, driver characteristics, vehicle speed, and type of headlights, would create considerable differences in the degree of discomfort and/or safety introduced in the operation of vehicles on four-lane divided highways.

RECOMMENDATIONS FOR FURTHER STUDY

The conclusions expressed in this report are based on a minimum number of observations using equipment and personnel assumed to be average. It is hoped that further studies will be initiated to substantiate and expand the results obtained.

Additional studies of the following subjects would be considered especially valuable in median design.

1. The relation of safe stopping sight distance to median width against opposing low-beam headlights.
2. A comparison of light intensity curves obtained from standard headlights as opposed to those obtained from the latest quadra-beam headlight designs.
3. The effect of horizontal roadway curvature with various median widths on sight distance against opposing low- and high-beam headlights.
4. The effect of differences in roadway elevation with various median widths on sight distance against opposing low- and high-beam headlights.

Appendix

TABLE 2

NIGHT VISION DATA

Driver No.	Distance from Object (ft)[a] 10-ft Median	20-ft Median	30-ft Median	40-ft Median	50-ft Median	60-ft Median
1	180	325	365	470	500	560
2	165	225	305	375	375	450
3	150	180	240	285	260	250
4	140	240	290	360	390	400
5	230	300	350	390	390	400
6	200	210	300	310	350	460
7	190	290	350	400	440	455
Average	184	262	335	389	416	457

[a] No glare with medians wider than 60 ft.

TABLE 3

INTENSITY OF ILLUMINATION

Distance From Light (ft)	Illumination Intensity (ft-cd)										
	0-Ft Median	10-Ft Median	20-Ft Median	30-Ft Median	40-Ft Median	50-Ft Median	60-Ft Median	70-Ft Median	80-Ft Median	90-Ft Median	100-Ft Median
50	1.85	0.81	0.20	0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100	1.20	1.40	0.30	0.10	0.05	0.01	0.01	0.01	0.0	0.0	0.0
150	0.80	0.95	0.38	0.18	0.07	0.05	0.02	0.01	0.01	0.0	0.0
200	0.51	0.50	0.42	0.20	0.10	0.07	0.04	0.03	0.02	0.0	0.0
250	0.42	0.40	0.39	0.21	0.11	0.08	0.06	0.04	0.03	0.01	0.01
300	0.30	0.28	0.23	0.22	0.15	0.10	0.08	0.05	0.04	0.02	0.01
350	0.22	0.21	0.20	0.22	0.19	0.16	0.09	0.06	0.05	0.04	0.02
400	0.21	0.20	0.18	0.20	0.18	0.14	0.13	0.07	0.06	0.05	0.03
450	0.20	0.19	0.19	0.17	0.17	0.14	0.12	0.08	0.07	0.05	0.03
500	0.18	0.18	0.18	0.17	0.15	0.15	0.10	0.09	0.08	0.07	0.04
600	0.15	-	-	-	-	-	-	-	-	-	-

TABLE 4

LIGHT INTENSITY[1]

Distance From Light (ft)	Intensity, $I = ER^2$ (cd)										
	0-Ft Distance	10-Ft Distance	20-Ft Distance	30-Ft Distance	40-Ft Distance	50-Ft Distance	60-Ft Distance	70-Ft Distance	80-Ft Distance	90-Ft Distance	100-Ft Distance
50	4,625	2,106	579	170	0	0	0	0	0	0	0
100	12,000	14,140	3,120	1,090	581	125	136	149	0	0	0
150	18,000	21,470	8,700	4,212	1,687	1,250	522	274	289	0	0
200	20,400	20,050	16,968	8,180	4,160	2,975	1,774	1,347	928	0	0
250	26,250	25,040	24,570	13,314	7,040	5,160	3,960	2,696	2,067	706	726
300	27,000	25,228	20,792	19,998	13,740	9,250	7,488	4,745	3,856	1,962	1,000
350	26,950	25,746	24,580	27,148	23,579	20,000	11,349	7,644	6,445	5,224	2,650
400	33,600	32,020	28,872	32,180	29,088	22,750	21,268	11,543	9,984	8,405	5,100
450	40,500	38,494	38,551	34,578	34,697	28,700	24,732	16,592	14,623	10,530	6,375
500	45,000	45,018	45,072	42,653	37,740	37,875	25,360	22,941	20,512	18,067	10,400
600	54,000	-	-	-	-	-	-	-	-	-	-

[1] At given distance from baseline.

Road Surface Luminance and Glare Limitation In Highway Lighting

J.B. de BOER, Chief, Lighting Laboratory, N.V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands

A survey is given of the results of (a) stationary (indoor and outdoor) and dynamic (outdoor) visibility tests, (b) subjective appraisals of road surface luminance in lighted streets, and (c) recordings on the use of headlights under several lighting conditions. From these results it can be concluded that the road surface luminance should be at least 0.6 foot-Lambert, fL, (2 cd/m^2) in order to make dense road traffic safe and comfortable.

Investigations on glare in lighting for road traffic show that visual comfort of drivers, is a graver criterion for glare limitation than the impedance of seeing ability. This means that in installations where glare stays within the borders of visual comfort, disability glare will be negligible. The paper gives a survey of results on this matter providing basic data for the necessary limitation of glare in lighting installations for road traffic.

The luminance of the road surface and its distribution determines to a large extent the quality of the installation from a viewpoint of safety and comfort of traffic. The possibility of practical application of the luminance concept in public lighting is, therefore, a matter of high importance. This possibility depends on the availability of convenient methods for computing and measuring road surface luminances. A brief description is given of a simple method of calculation as well as of a photoelectric luminance meter for street lighting purposes both intended for use in everyday practice.

● THE LIGHTING of public highways is insufficient and incorrect for present traffic comfort. This statement applies to roads in all countries, apart from a few progressively lighted highways. It is apparent that practically all lighting installations in existence are inadequate, if one is put in a position to learn the conditions of traffic under artificial lighting at the peak hour on several differently-lighted highways.

In the first place, there is a category of non-permanently lit highways, the usual situation at present even on those sections where the traffic flow amounts to thousands of vehicles an hour in the peak traffic hour. Driving in traffic on such highways in bad weather (rain, sleet, snow) requires an effort which, if prolonged for one hour, far exceeds what may be demanded of the average driver in safe traffic. For example, such conditions are found on the German autobahn between Frankfurt and Cologne. This category shows that lighting by the vehicle, even for dual highways where opposing traffic is visible, is wholly unsatisfactory at high traffic densities, particularly if the road is wet and visibility is hampered by a wet windshield and damp atmosphere.

Another category comprises highway sections which have been lighted in accordance with present standards but actually offer no solution to the problem of promoting the safety and comfort of traffic by means of lighting. A typical instance is the lighting of the Connecticut Turnpike between New York and New Haven. The level (below 0.3

fL, as estimated from the illumination data available) is too low; lighting is not uniform in rainy weather; and there is too much glare for visual comfort. Therefore, on this road the quality of lighting fully "justifies" the American practice of using the passing beam of headlights on lighted highways. This does not, however, achieve the presumed object of this lighting—safety and visual comfort in traffic.

Finally, there are, sporadic examples of lighted highway sections that come into a third category in which the desired aim has been approached more or less satisfactorily. They include some sections of highway near Glasgow and Leicester in Great Britain, near Eindhoven in Holland, and the Autoroute du Sud near Paris. The lighting level in these installations is considerably higher than has been customary for public lighting, and uniformity is not unsatisfactory even if the road is wet. It is common practice in France to use "side" (parking) lights on publicly lit roads. Consequently, driving on the Autoroute du Sud gives an idea of how efficient road lighting contributes to visual comfort. Owing to the absence of the continual glare from opposing traffic and, in dry weather at least, a satisfactory luminance pattern on the road, the glare by the road luminaires being acceptable, the driver can visually relax completely while observing traffic.

Similar conditions prevail on two-way traffic roads, though here the problems involved differ because of the different nature of the traffic. A careful stock-taking of all these traffic situations leads to the conclusion that, except for a few sporadic cases, there are no traffic lighting installations in existence that are suitable for today's traffic.

If artificial road lighting is considered to be a continuation during the night of visual daylight conditions, then lighting techniques in this important field have progressed far less than lighting techniques for offices and factories, where many lighting installations approach what daylight can offer under ideal conditions.

QUALITY CRITERIA

The luminance pattern in the driver's visual field determines the details that he can perceive. It also determines the degree of comfort experienced in the observations. Ultimately this luminance pattern determines whether the object of road lighting is achieved—the promotion of safety and comfort in traffic. The following basic factors are criteria for the quality of any road lighting installation:

1. Lighting level as determined by the average road luminance; and
2. Glare as defined by luminance, apparent size, and orientation of the luminaires.

In this connection several other factors are important: the luminance pattern on the road surface, the luminance contrast of any object on the road with the road, and the color of the light.

General Level of Lighting

It has been shown that the level of lighting has a large effect on visual performance (1, 2, 3). A typical example has been derived from previous results (Fig. 1). On the right, the visibility distance S, calculated from results of stationary observations of Landolt rings, is represented as a function of the luminance of the background, L. Because only the relative effect of the lighting level on vision was to be shown, a single case was taken; namely, that of a Landolt ring with a diameter of 50 cm (20 in.) presented to the observers at 100 m (330 ft) for 0.1 sec at a mean background luminance of 1 cd/m^2 (0.3 fL). The luminance of the ring was two-thirds of the background luminance. The observers' age A was 40 years. This case, which is applicable as a relative criterion for visual performance on a lighted road, shows that a 10 percent increase in visibility distance is attained when L is increased by a factor of about 1.5.

The right-hand curve of Figure 1 is for an age of 40 years; that is, for an approximately average age of drivers, as in relevant tests an important effect of age on visual performance could be stated. Figure 1 (left) shows the visibility distance S of the slit in the ring as a function of A. This distance decreases by about 10 percent for a 10-yr increase in age. This effect of age may also be expressed as follows: the decrease of visual performance with increasing age of the driver can be compensated by increasing the background luminance; in particular, the decrease of visual performance due to a 10-yr increase in age may be canceled out by an increase in the illumination level by a factor of 1.5.

Although such tests give valuable information about the effects of certain lighting characteristics, visual tasks that resemble more closely those of importance to road safety must be considered to find indications about the absolute values of the desirable lighting level.

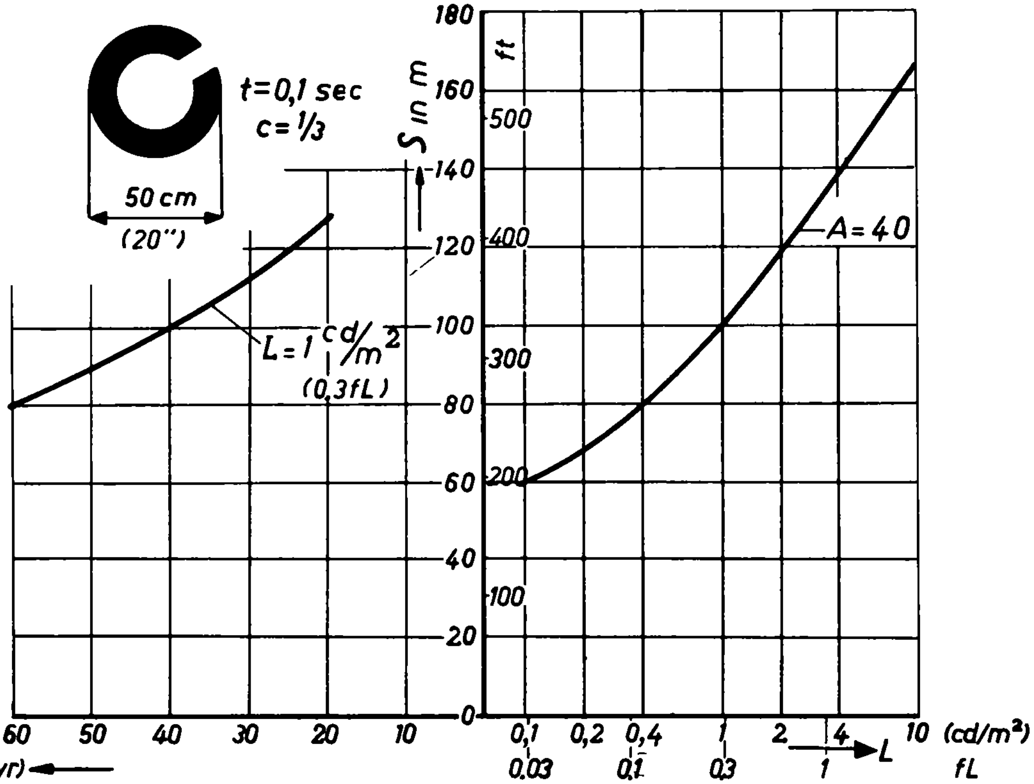


Figure 1. Effect of lighting level (luminance L of background) and of age A on visibility distance S for recognizability of Landolt ring.

A number of tests have been carried out whose results give information about the lighting level required to guarantee a minimum perceptibility from the standpoint of road safety (4, 5, 6). The following gives a survey of the most important results.

Several people observed objects in a lighted street where the correlation of object luminance to background luminance (in this case a part of the road surface) could be modified and was known. Dunbar (4) referred to observers who had perceived the objects while seated in a moving car, whereas other tests (5) referred to stationary observers who did not know where the objects would appear. The objects used in the latter tests were 28 x 28 cm (11 x 11 in.) placed at distances ranging from 50 to 200 m (150 to 600 ft). The apparent size of Dunbar's objects was about 1.5 times bigger.

The most interesting result is the correlation between road surface luminance and the contrast necessary to observation. The contrast is defined here as the ratio R_L of the road surface luminance and the object luminance. Figure 2 offers a basis for setting a minimum road luminance limit for proper road lighting. If the criterion is that a 20- x 20-cm (8- x 8-in.) object must be clearly visible to a road user from 100-m

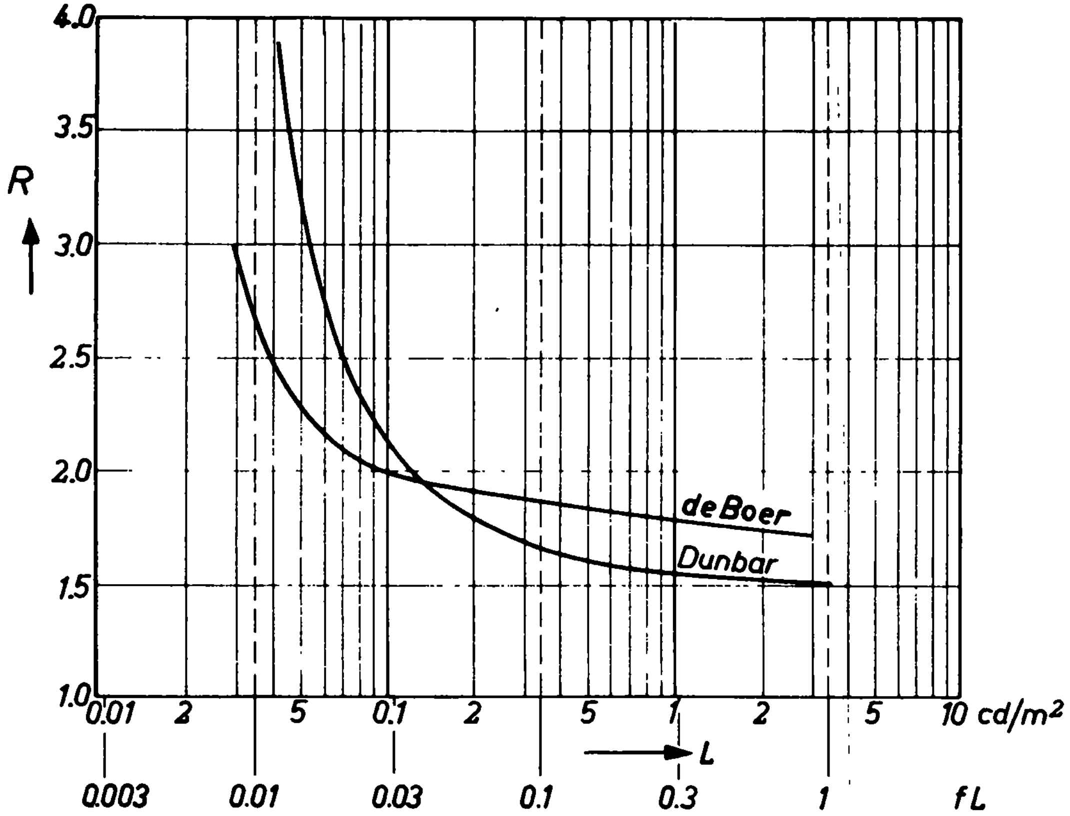


Figure 2. Minimum ratio R_L of road and object luminances needed to make 28- x 28-cm (11- x 11-in.) objects visible at from 50- to 200-m (150- to 600-ft) distances to observer under normal traffic conditions, as a function of road luminance L.

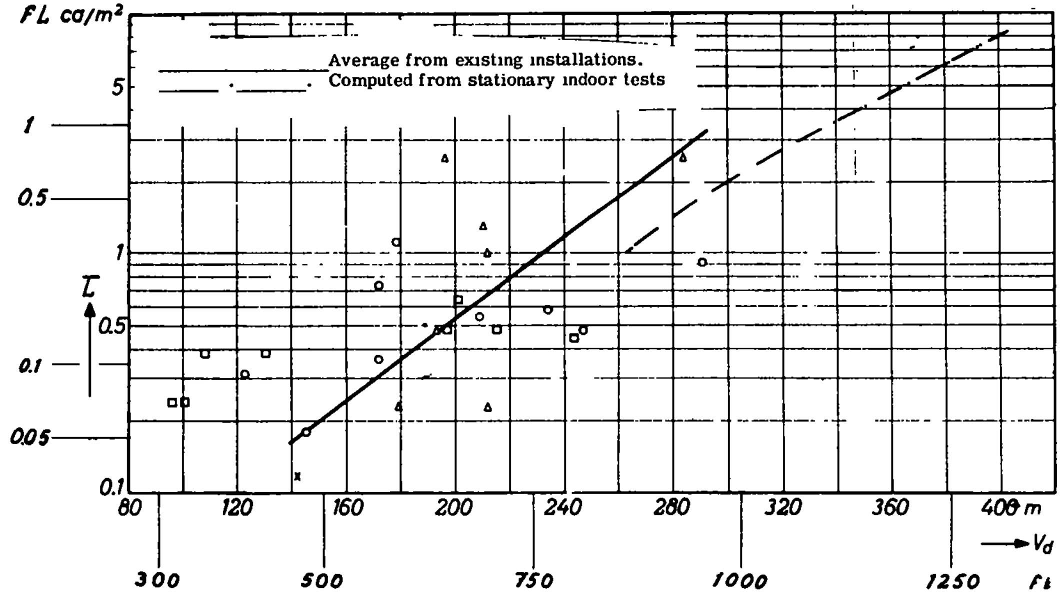


Figure 3. Dynamic visibility tests.

(330-ft) distance, even if the luminance of that object is two-thirds of the background luminance, Figure 2 proves that the mean road luminance must be at least 2 cd/m^2 (0.6 fL).

This criterion implies the adoption of two magnitudes (the size of the object and its luminance relative to its background) both magnitudes affecting the conclusion about road luminance. Obviously a higher road luminance is needed if smaller objects are to be clearly visible, or if objects are considred whose contrast with the road surface is less than the 2:3 ratio cited. From the viewpoint of road safety, objects of such a size cannot be neglected, and street lighting practice has shown that it is often difficult to keep the contrast between object luminance and road luminance above the 2:3 ratio. Therefore, these conclusions will certainly not entail overstrict requirements.

Under the dynamic conditions (6) observers seated in a car going 50 km an hour (30 mph) determined the distance at which a 20 x 20 cm (8 x 8 in.) dull screen (9% reflection factor) could be seen under existing lighting conditions. Two objects had been installed in each street. The ratio R_L of road luminance and object luminance varied from 3 to 7.5. Each point in Figure 3 represents the mean visibility distance, l, as measured in a single street by four observers (aged 24, 29, 30 and 40).

Figure 3 also includes a curve calculated from unpublished data by Balder and Fortuin regarding the measurement of threshold values for incandescent light at a ratio of 5 with 0.1-sec observation time and the observers ranging from 15 to 64 years of age. The results of the dynamic tests are shown by a full line through the center of gravity and parallel to the slope of the curve calculated at 1 cd/m^2 (0.3 fL).

The conclusions thus obtained may again be based on the requirement that a 20- x 20- cm (8- x 8-in.) test object whose luminance is two-thirds of the background luminance ($R_L = 1.5$) must be visible from at least 100 m (330 ft). According to unpublished results with incandescent lamps found by Balder and Fortuin, it appears that the observation of an object whose contrast is equivalent to $R_L = 1.5$, requires a luminance more than four times higher than the luminance required for a contrast equivalent to $R_L = 5$. This is true for an approximate luminance of 1 cd/m^2 (0.3 fL) and an 0.1-sec observation time and it constitutes an average for a group ranging regularly from 15 to 64 years of age.

It should also be considered that in the dynamic tests the observers expect to see some object. Roper (7) has found for automobile lighting that observers expecting to see an object in their field of vision will perceive the object from twice as far away as those who do not expect them. Assuming that this factor may also be applied to street lighting, a value must be recommended for the mean road luminance which is four times the luminance found in Figure 3 for l = 200 m (660 ft), in other words, a mean value of 2.2 cd/m^2 (0.64 fL).

A different way of forming an idea about the level required for a proper street lighting consists in trying to find the level at which the average driver feels comfortable without using headlights. It may be wondered if such a test will yield results that are genuinely relevant to safe traffic. Experience on the Autoroute du Sud led to the belief that such is the case, because no road traffic is possible in which safety is a condition sine qua non, if the drivers are continually placed in situations in which they are mentally overloaded. If the visual tasks demanded of the drivers can be accomplished in a comfortable and easy way, one can be sure that they will not have to resort to emergency maneuvers that, in the most favorable cases, allow only narrow escapes from accidents.

Two methods of finding quantitative information about the lighting level at which this state of comfort can be obtained have been used: (a) simply questioning a number of qualified observers concerning present levels in various lighting systems, and (b) recording the behavior of the drivers as to their use of various driving lights under different lighting conditions.

In the first series of tests (6) the observers were asked if the lighting level of the installations of a route should be rated bad, inadequate, fair, good, or excellent, or in between any two ratings (scaled 1 to 9). A total of 70 streets and roads, 46 in dry weather, were so appraised by a group of 6 observers from the laboratory and, in part, by a group of 10 engineers responsible for public lighting in some Dutch towns. The appraisals of both groups agreed to a satisfactory degree.

Figure 4, showing the more important results of these appraisals, gives the average of the 16 observers' opinions as a function of lighting level expressed in mean road luminance. The correlation (Fig. 4) shows that the lighting level is "good" if the road luminance is 1.5 cd/m^2 (0.44 fL) (between 1.3 and 1.8 cd/m^2 (0.38 and 0.52 fL) to a confidence level of 95 percent). However, the observers' opinions are inevitably linked with the characteristics of the roads in question. A road of average importance as a traffic artery will be judged differently from a road with high-intensity traffic, of the 70 installations, 28 installations were of little importance from a traffic point of view. These 28 were probably called "good" at a relatively low level of luminance.

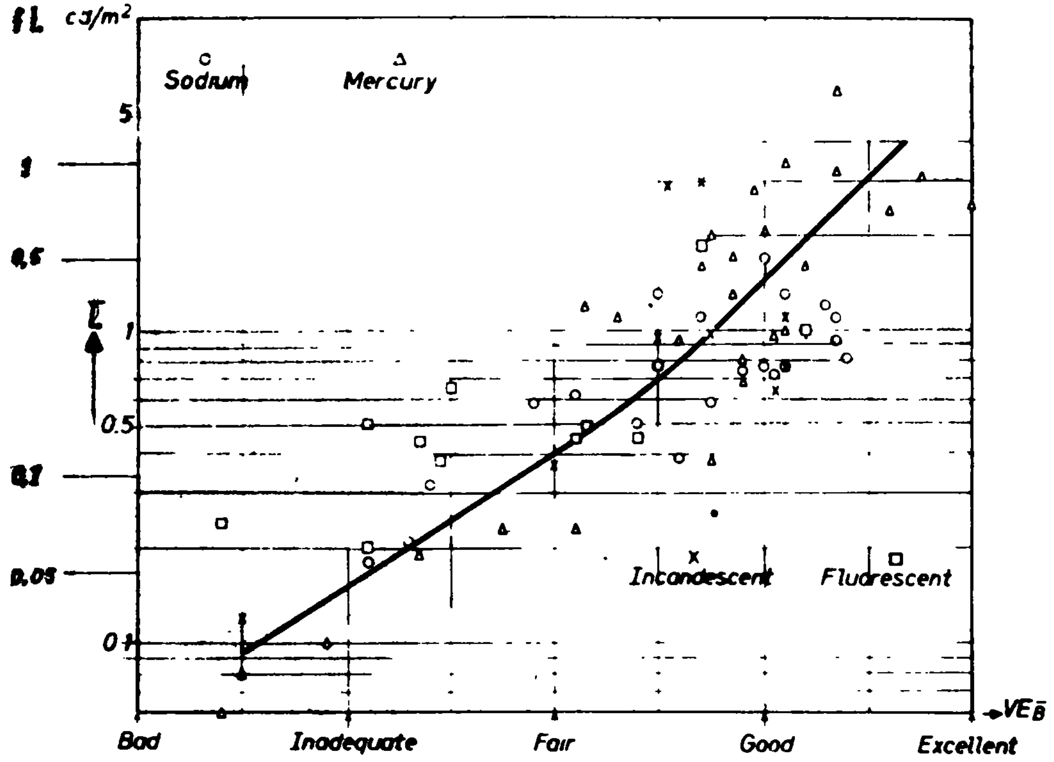


Figure 4. Appraisals of road luminance levels.

In the second test series the behavior of drivers at different lighting levels was recorded. The recordings were made largely at dusk, and during the night on a number of artificially lit roads. It was noted at which lighting levels, either by daylight or by artificial lighting, the drivers used driving lights, passing lights, or "side" lights. In measuring daylight, the decrease of daylight as a function of time was recorded to plot the number of motorists scored in each category as a function of lighting level. These recordings were always made on roads with low traffic intensities to avoid mutual influencing as much as possible. It has been observed that if one driver on high traffic intensity roads lights his headlights, a good many others immediately follow the example. In that case, the results would not be valid for the average driver. A total of 900 cars were recorded during dusk.

Figure 5 shows the number of motorists driving with lights off or with certain lights on, expressed in percent of the total of cars recorded for each luminance, as a function of road luminance level. The road luminance is shown on a decreasing scale in conformity with the decrease of luminance during dusk. Curve O gives the number of motorists who drive without lights on; at a lighting level of 50 cd/m^2 (15 fL) and higher; practically everyone drives without lights. When the lighting level falls to approximately 5 cd/m^2 (1.5 fL), 80 percent of the drivers consider the daylight insufficient for their needs; therefore, they switch on parking lights but not headlights, considering the visibility still sufficient. Curve P shows that at a lighting level between 5 and 1 cd/m^2 (1.5 and 0.3 fL), more than 80 percent of drivers are driving with "side" lights. Curve C gives the number of drivers who use their headlights on the passing beam. When the road luminance falls to 1 cd/m^2 (0.3 fL), 20 percent of the drivers find the lighting level so low as to prevent them from seeing properly and switch on their headlights. This number increases gradually as the luminance falls below 1 cd/m^2 (0.3 fL).

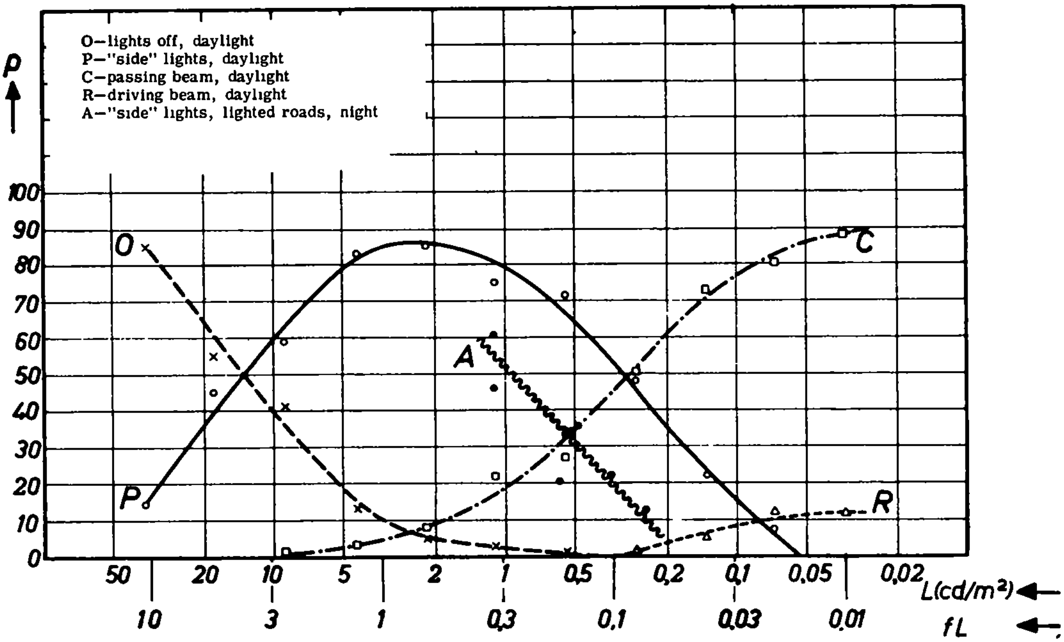


Figure 5. Numbers of cars (p) in percent driving with various lighting possibilities as a function of road luminance L.

Street lighting creates different situations from those caused by dusk because (a) there is glare, (b) road luminance is not perfectly uniform, and (c) only the road and a few meters' width on each side is visible.

The results of recordings made on 7 lighted roads (solid dots, Fig. 5) give what the average driver affected by the three factors impairing lighting quality considers to be inadequate lighting. These results are represented approximately by line A. In each case the lighted roads were at least several miles long and there were no signs requiring that parking lights be used. In Holland and Germany, where the recordings were made, it is not customary to drive with parking lights only through lighted streets as it is in Belgium and France.

The results prove that 80 percent of drivers feel that they can drive safely with only parking lights at an artificial lighting level exceeding 2 cd/m^2 (0.6 fL). A prohibition of headlights in high-intensity traffic, as demanded by safety, is justified if the lighting level exceeds 2 cd/m^2 (0.6 fL).

Glare

Glare from street lighting systems manifests itself in two ways: by a reduction of visual performance (disability glare) and by a feeling of discomfort which eventually develops into fatigue and leads to decreasing capacity of perception (discomfort glare). Disability glare can be clearly distinguished from discomfort glare by means of experiment. In cases where glare is so weak as to make it difficult to establish a reduction of visual performances, which may be found by measuring the contrast sensitivity, visual acuity or the reaction speed, this feeling of discomfort can still be clearly established. If the glare does not affect seeing comfort, a reduction of the capacity of perception is certainly not to be feared.

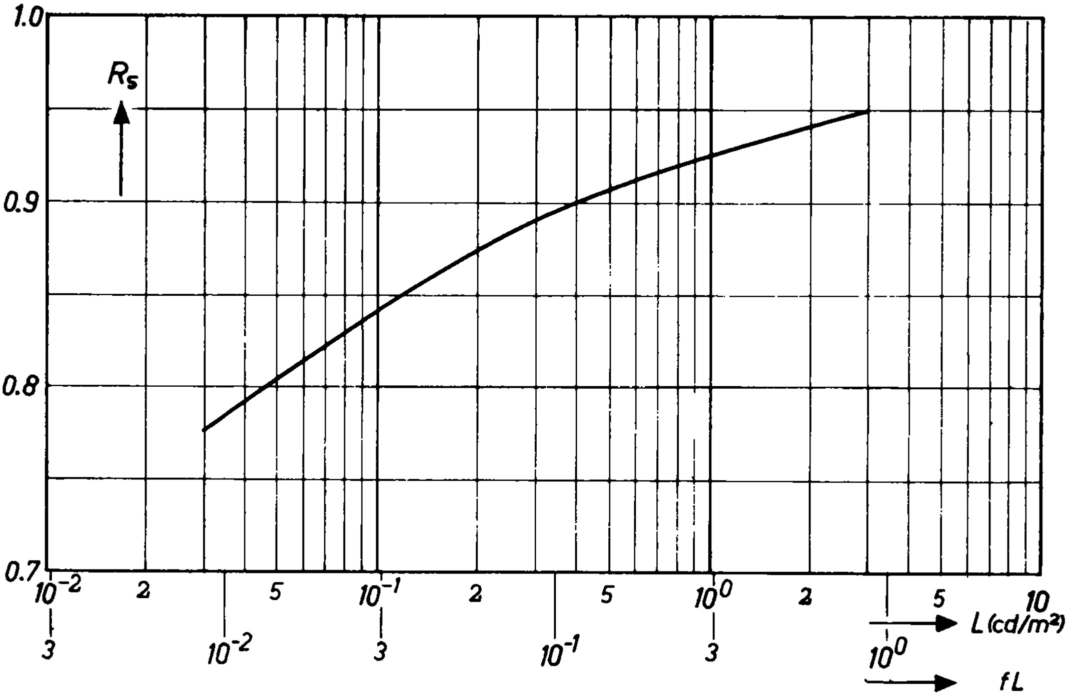


Figure 6. Ratio R_S of contrast sensitivities (with and without glare) as a function of road luminance L.

The importance of this conclusion warrants more detailed discussion of some results found in measurements of visual performance and glare on a test road (5). Contrast sensitivity, visual acuity, and reaction speed were determined for different road luminances and sources of glare. Observations were also made by many persons regarding admissible glare, taking visual comfort into account.

Since contrast plays an important part in perception in road traffic, the measurements concerning contrast sensitivity can be regarded as a specific example. They were effected for different road luminances both with fairly strong glare and without glare. The illumination of the observer's eye was about three times the "satisfactory" value. (This "satisfactory" value is the mean glare found admissible by the observers; a more detailed discussion appears hereinafter.)

Figure 6 shows the correlation for the two contrast sensitivities as a function of mean road luminance. In case of glare the contrast sensitivity for a road luminance of 2 cd/m^2 (0.6 fL) is only 6 percent below the value without glare. This even applies to the case where the illumination of the observer's eye is three times the permissible limit for visual comfort. Under these conditions and even for a road luminance as low as 0.4 cd/m² (0.12 fL), the contrast sensitivity reduction still does not exceed 10 percent.

It was previously stated that the decrease of visual performance was not to be feared provided glare is kept within the limits of the "satisfactory" value. Tests required to determine such limits may be made chiefly in the laboratory, although the results must be verified under conditions which closely resemble those prevailing on a normally lighted road (5, 8, 9, 10). The test procedure alternatives are: (a) the observers are shown a type of lighting and are asked for their opinion as to the glare experienced; or (b) the observers are given a means to modify one of the factors affecting the glare (for example, the illumination on the observer's eyes produced by the glare sources).

Where the observers' opinions are asked, a maximum permissible limit of glare must be clearly defined. Thus, the limit at which the glare experienced can be considered "satisfactory" is defined as the amount of glare beyond which, after some length of time, annoyance results, leading to fatigue.

It is evident that, in spite of all precautions, individual opinions will vary widely and the opinion of one observer about the same situation will be subject to marked variations. Therefore to obtain a worthwhile result, it is necessary to have many observations made by many observers.

Figure 7, test results of permissible glare from a single source of light, shows the maximum illumination E_b that can be produced on an observer's eye at which he still considers the glare experienced "satisfactory." Illumination E_b is shown as a function of mean road luminance L and angle δ between the line from eye to source and the horizontal plane. Solid angle ω at which the observer perceives the light source is the parameter. Illumination E_b permissible for three values of ω is shown. It is evident that discomfort will increase as illumination of the eye is increased. Each of the three curved surfaces shows a combination of situations where glare experienced corresponds to the permissible limit in view of discomfort glare. If glare should be increased by an amount of illumination E_b, this increased glare could again be neutralized by modifying the three other factors, as follows: (a) an increase of mean road luminance L; (b) an increase of angle δ (by shifting the light source away from the central part of the field of vision); or (c) an increase of the surface producing solid angle ω.

This also means that glare provoked by a light source, for a specific value of illumination, will be weaker as road luminance is increased, as the light source is moved farther from the central part of the field of vision, and as the light source size is increased.

In the case of street lighting, glare is nearly always produced by many light sources. If one of these sources should produce an illumination which (Fig. 7) corresponds to the "satisfactory" limit, the degree of glare corresponding to this limit would consequently be exceeded if other light sources should also contribute to the illumination of the eye.

If $E_{b,n}$ is the highest eye illumination that can be produced by the n^{th} light source, of which the limit corresponds to the "satisfactory" impression according to Figure 7, and if $E_{w,n}$ is the real eye illumination from the n^{th} source, the "satisfactory" limit of glare is not exceeded if the sum of correlates $E_{w,n}$ to $E_{b,n}$ remains below 1. Thus,

$$\sum_{n=1}^{n=N} \frac{E_{w,n}}{E_{b,n}} \leq 1 \qquad (1)$$

After establishing the mean road luminance, the maximum illumination not exceeding the permissible discomfort limit can be calculated. Although feasible, these calculations are time consuming and are inconvenient for daily practices. A simpler method consists in computing curves that show the mean road luminance required to reduce discomfort glare to the "satisfactory" degree as a function of mounting height

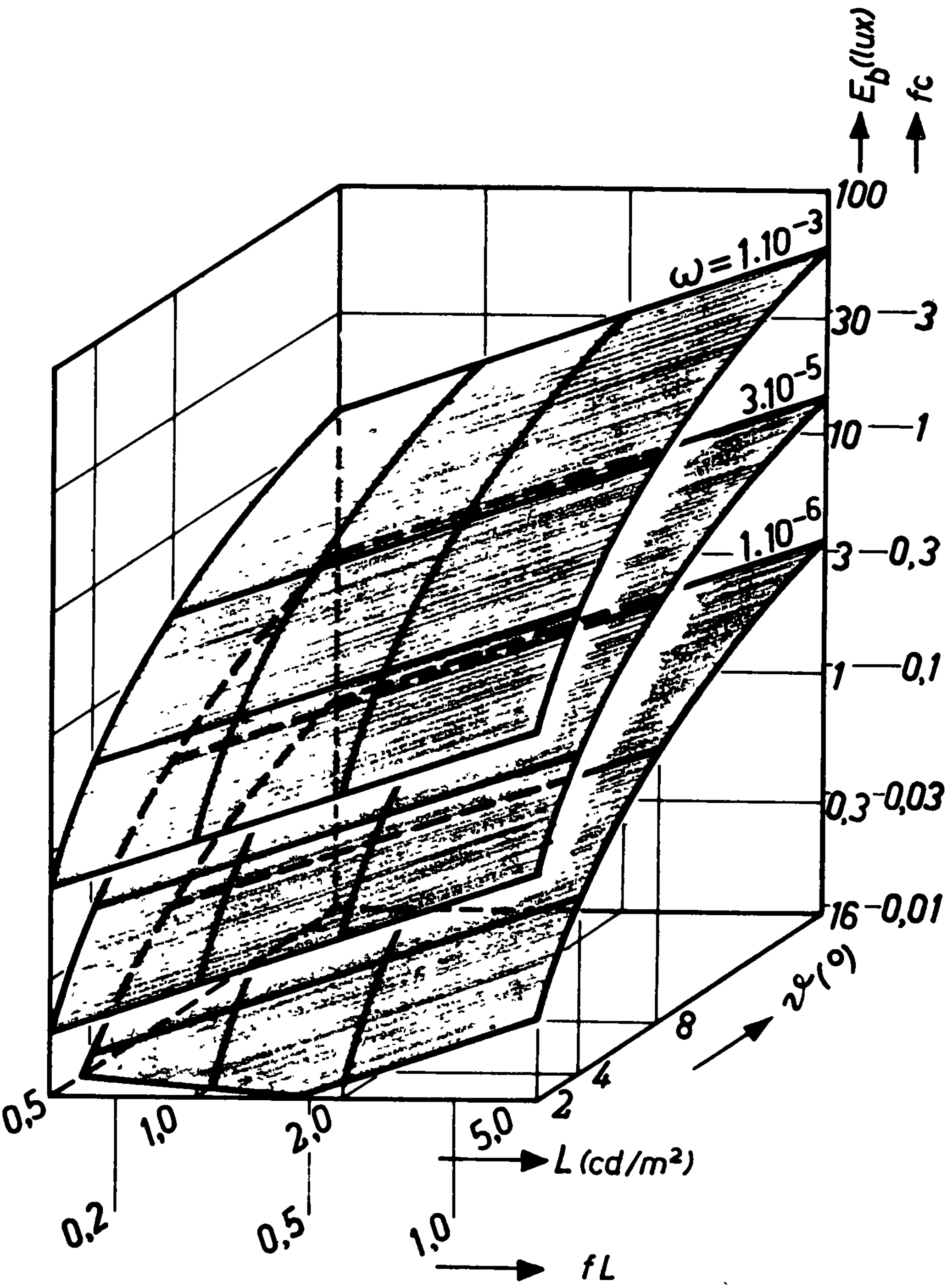


Figure 7. Eye illumination E_b as produced by single light source corresponding to criterion of "satisfactory" glare as a function of mean road luminance L and angle δ between line from eye to light source and horizontal plane for various values of solid angle ω at which light source is seen.

and light standard spacing. Such a group of curves can be computed for any combination of standards and road surfaces.

Another group of curves computed for the same combinations shows the real mean luminance as a function of the same parameters. If, for a given installation, the real luminance derived from the second group of curves exceeds the luminance required to allow for glare according to the first group of curves, the installation may be considered satisfactory (10).

The results given here are confirmed to a certain extent by experience that, with an adequate level of illumination, the glare remains within acceptable limits when lamps are used whose light emission is limited to within 80° from the vertical and whose maximum luminous intensity is at less than 60° from the vertical. This simple rule, which can be applied without any complicated measurements or calculations, constitutes the basis of design for most public lighting installations in the Netherlands. It is thought that this rule should be applied in all cases of public lighting for traffic to insure that glare remains within acceptable limits, unless a check on the degree of glare to be experienced is carried out by other means.

Conclusions on Lighting Level and Glare

For a street lighting installation to qualify as "good," it must have (a) a sufficiently high lighting level; and (b) a sufficient reduction of glare.

The test results on visibility and comfort of seeing indicate that an average luminance of 2 cd/m^2 (0.6 fL) on the road is a desirable level for roads with high-intensity traffic. This level corresponds to an average illumination of approximately 30 lux (3 ftcd) for lamps that do not emit light at more than 80° from the vertical and for road surfaces normally used in the Netherlands.

CALCULATION AND MEASUREMENT OF ROAD SURFACE LUMINANCE

The importance of the general level of lighting has been stressed as a criterion for quality of lighting for traffic. This lighting level is characterized by the luminance of the road surface and not by its illumination which does not give any information on luminance as observed by the driver. There is no simple relationship between illumination and luminance because road surface reflection characteristics depend largely on the directions of light incidence and observation. These characteristics are different for different road surfaces and vary considerably for one surface from dry to wet. Road surface luminance is a complicated function of light distribution of the luminaires and of their placement as well as of the reflection properties of the road surface.

Without going into the details of calculation and measurement (11, 12, 13, 14) a method of presentation of luminaire characteristics is described which allows computation of road surface luminance. A recently developed luminance meter, especially designed for use in every-day practice is also described.

Practical Computation of Road Surface Luminance

In public lighting practice, a satisfactory result can often be obtained if the investigation is limited to viewing directions important to traffic. A number of simplifications are permissible, particularly in determining the average road surface luminance. Only the luminance of the road surface rather far in front of the observer is important to traffic, because it is only against such a background that important details can be observed. It is assumed that only that portion of the road lying between 50 and 150 m (150 and 500 ft) in front of the observer need be considered. The average luminance, $\overline{L}$, of this part of the road surface is only slightly dependent on the location of the driver so that the influence of the placement of luminaires may easily be considered.

In fact the relationship between $\overline{L}$ and the road-width, measured from the luminaires (w - ov, Fig. 8) needs only be calculated for one case, so that the average value of $\overline{L}$ can be taken for a number of typical observer positions. This relationship for a given situation (for example with luminaires on only one side of the road), applies equally for other arrangements (luminaires opposite each other, staggered, centrally mounted) provided that the number of luminaires for a given length of the road is the same. If this relationship is determined for a mounting height h, a change in the mounting height to h' and changes in all other dimensions in the ratio h'/h, $\bar{L}$ will change in the ratio $(h/h')^2$. A simple calculation of the relationship between $\bar{L}$ and w - ov for one mounting height and arrangement, makes it possible to derive all data determining the values of $\bar{L}$ for all usual arrangements on a straight road in which the lights are mounted at regular distances. As an example, Figure 9 shows the product $\bar{L}sw$ as a function of (w - ov) and ov for a dry asphalt surface, whose reflection characteristics have been described previously (14), and for a luminaire whose light distribution is shown in Figure 10. The significance of s, w and ov is shown in Figure 8; Figure 11 shows various luminaire arrangements, together with an indication of dimensions s, w and ov. For a given arrangement, $\bar{L}$ is determined by reading the product $\bar{L}sw$ once for the value of (w - ov) and once for the value of ov and dividing the sum of these two products by sw. It is apparent that if different values of (w - ov) and ov apply for the luminaires on both sides of the road, this determination must be carried out for each row independently. $\bar{L}$ represents the average luminance of the road surface at a distance of 50 to 150 m (150 to 500 ft) in front of the observer as seen by his eye located 1.5 m (5 ft) above the surface. This implies that the luminance in the perspective road image is averaged (the luminance of each element in the road surface is weighted according to the area of this element in the perspective road image).

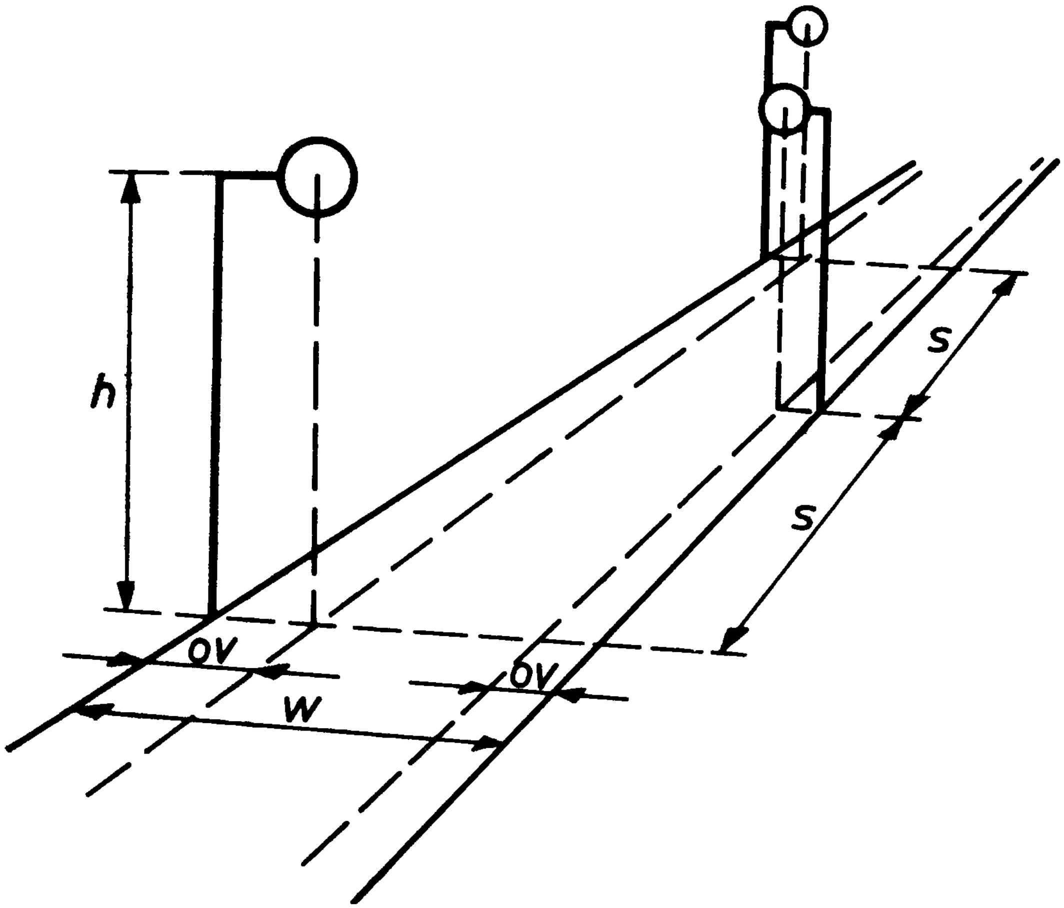


Figure 8. Significance of s, w, ov and h.

In addition, the local luminance is of importance in judging the unevenness to be expected. It has been shown (14) that for each combination of luminaires, road surface and arrangement, graphs can be determined giving certain characteristic ratios of local luminance values as a function of spacing, mounting height, and road width.

The importance of these curves and of Figure 9 is that manufacturers of luminaires can prepare graphs for typical road surfaces. The street lighting engineer is then able in everyday practice to base his design on the concept of road luminance.

Measurement of Road Surface Luminance

A luminance meter which, as far as simplicity of operation and construction is concerned, can be recommended for use in normal public lighting practice has been developed in the Philips Lighting Laboratory.

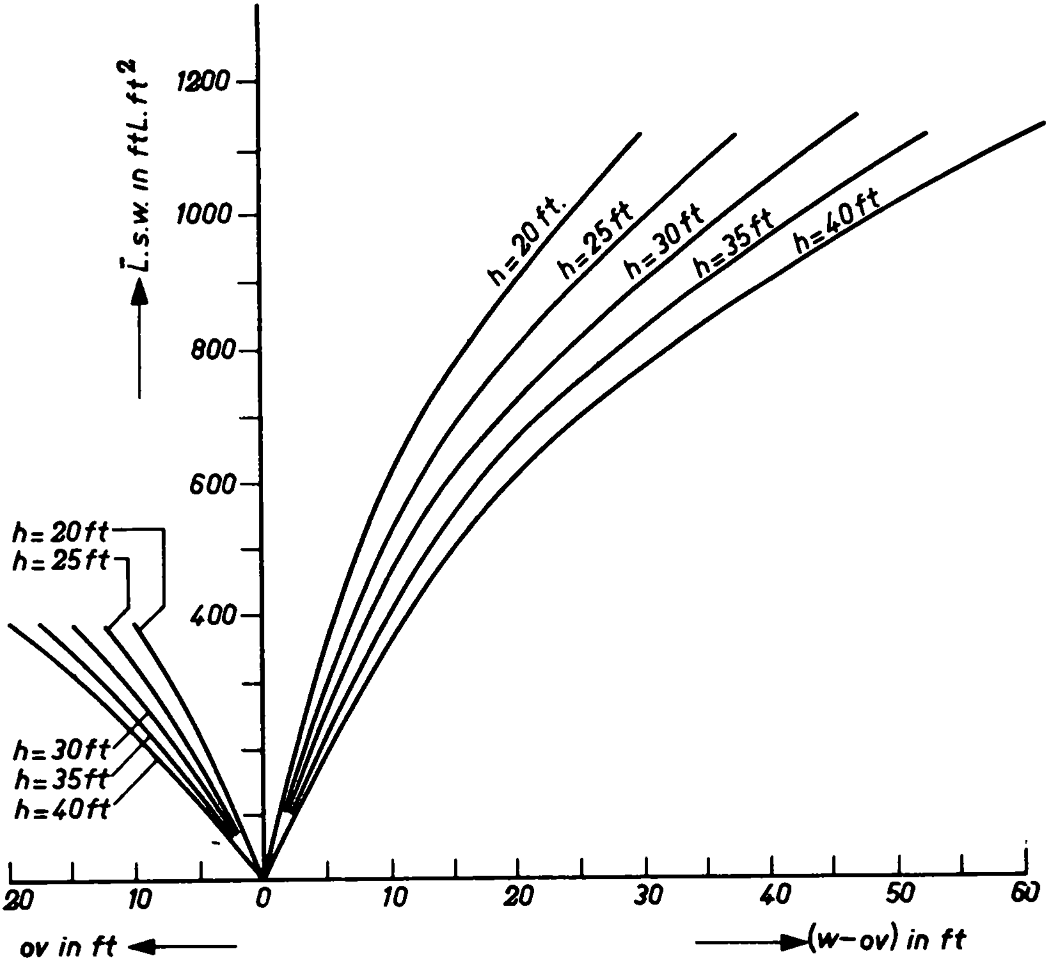


Figure 9. Product of average luminance of road surface $\bar{L}$, lantern spacing s, and width of road w as a function of road width less overhang ov and as a function of overhang ov for various values of mounting height h.

Construction of the luminance meter is shown diagramatically in Figure 12. Its use is shown in Figure 13. The objective, O_1 produces an image of the portion of the road to be photometered on the plane of slide S, which contains diaphragm D. This diaphragm

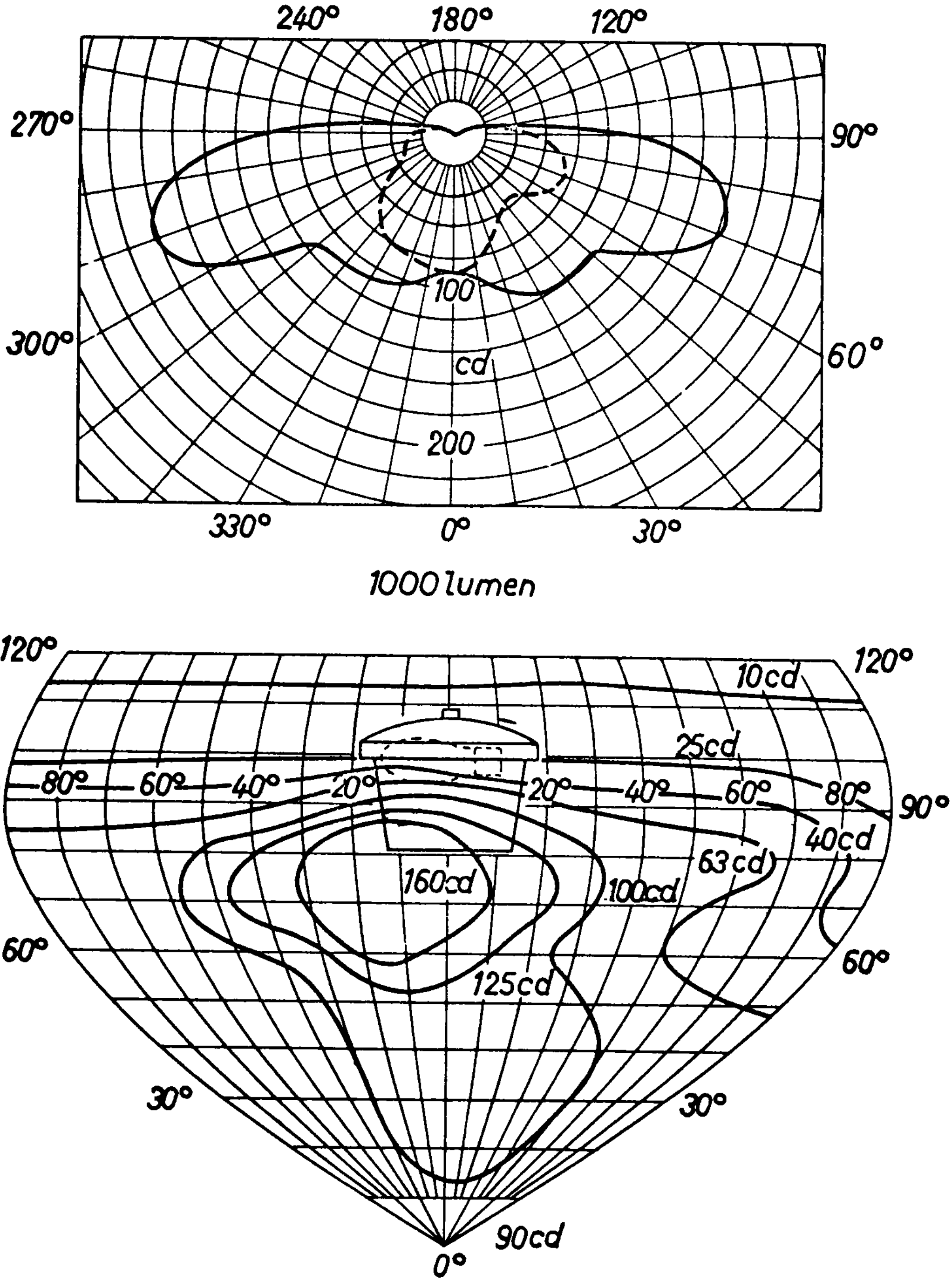


Figure 10. Light distribution of high-angle beam distribution source reduced to 1,000-lumen basis; (top) the polar light distribution curves, measured in a meridian plane for the maximum luminous intensity (full lines), and in the meridian plane perpendicular to the road axis (dotted); (bottom) isocandela curves.

has the shape and dimensions of the image on slide S. The light passes through the diaphragm via mirror M, to the cathode of photomultiplier P. Hood H prevents to much stray light from penetrating to the photocell.

The luminance meter is aimed by means of a second objective, O_2, which also pro-

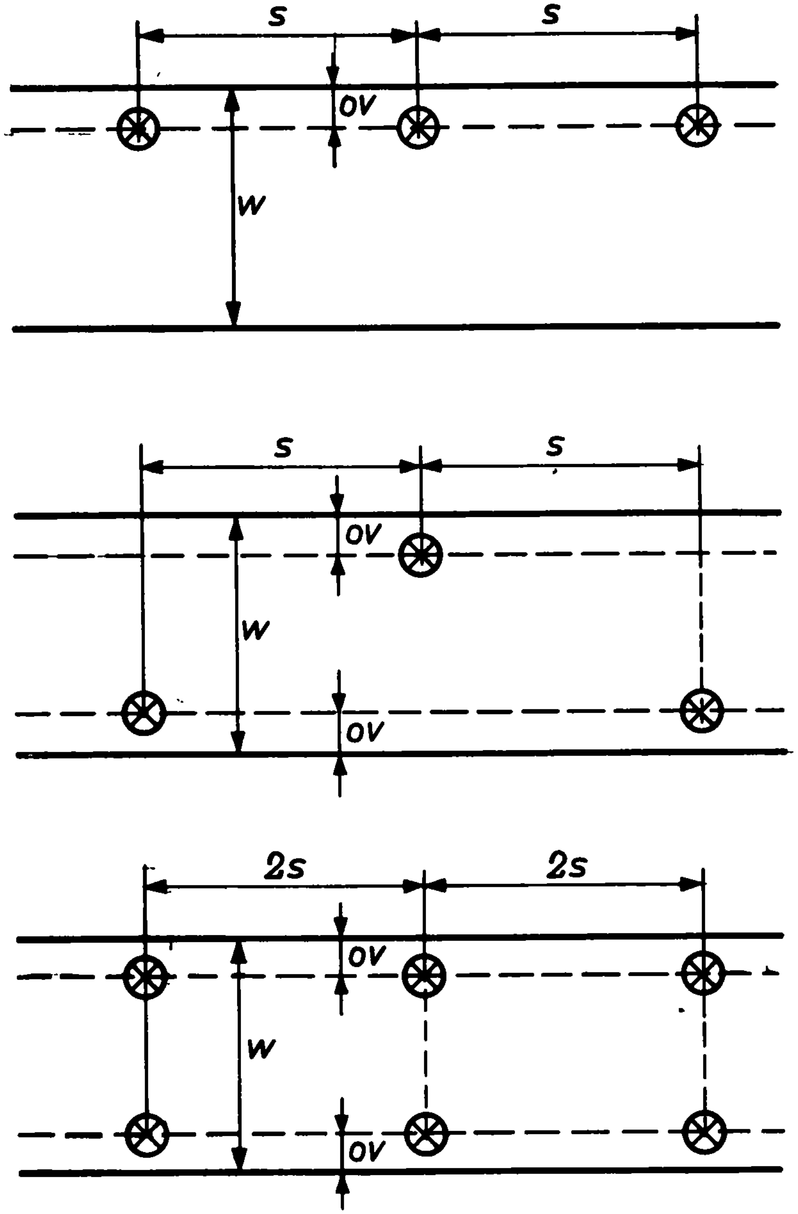


Figure 11. Indication of s, w, and ov in a number of arrangements.

duces an image of the part of the road surface to be photometered at "aiming sight" A, also located on slide S. This aiming sight is fully transparent and shows only the edges of the road surface being photometered.

A set of slides S is provided with the instrument, making it suitable for a series of roads, the width of which increases in steps of about 2 ft.

The observer points the instrument toward the portion of the road to be measured, by looking through eye piece E. As soon as the contours of the road coincide with aiming sight A, the image of that portion of the road between 50 and 150 m (150 and 500 ft) in front of the user also coincides with diaphragm D. At this moment the observer

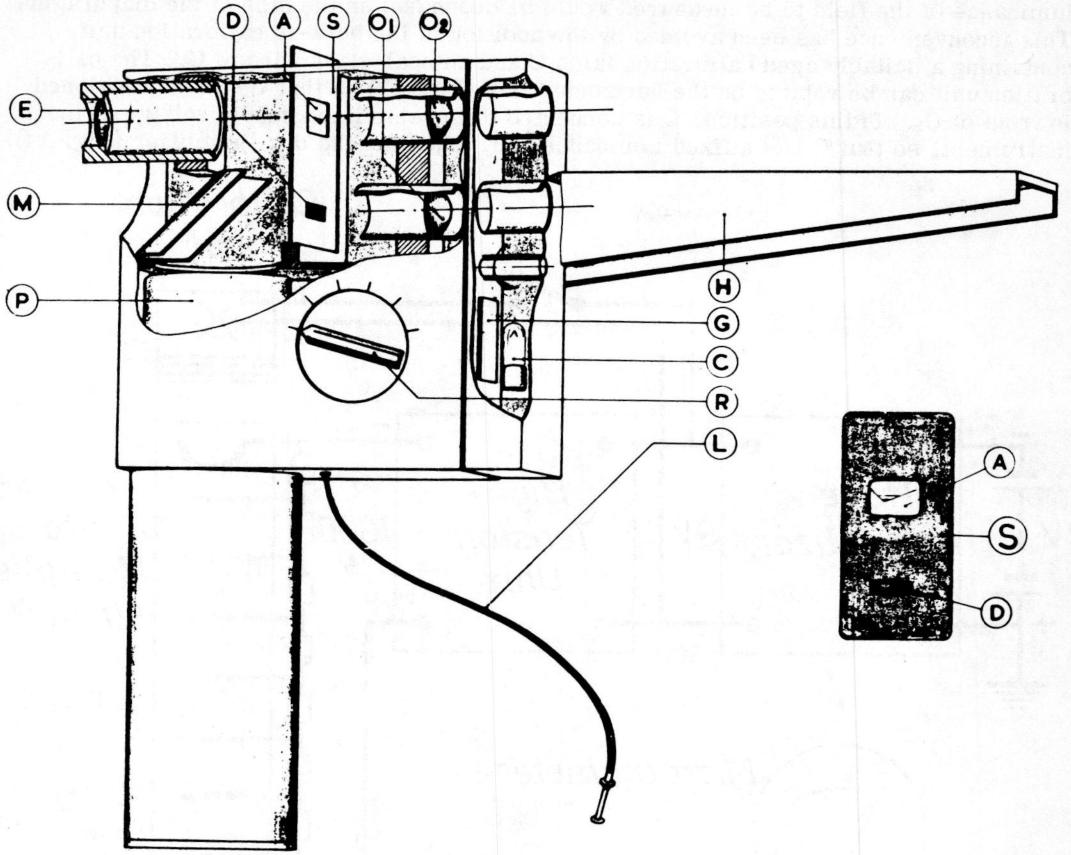


Figure 12. Diagram of the luminance meter; detail of slide inset in insert. For component descriptions see text.

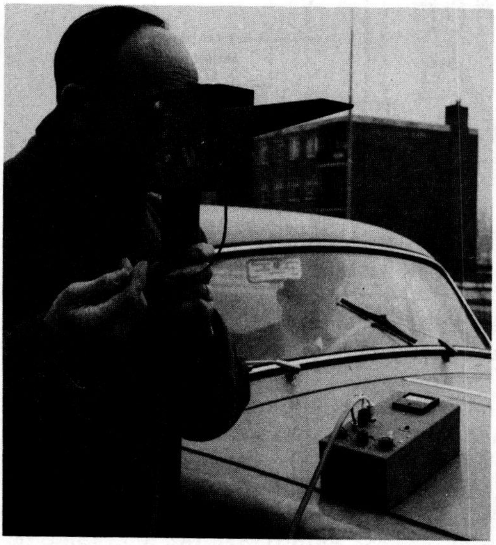


Figure 13. Operation of luminance meter.

presses cable-operated locking switch L, whereby the charging circuit of a capacitor is broken. Before the contact is broken, the voltage across the capacitor follows the average luminance of the image produced in D, with an extremely small delay. The reading of a microammeter connected to the capacitor via a d.c. amplifier is proportional to the voltage across the capacitor. When the connection is broken, the capacitor begins to discharge slowly and the observer has ample time to note the microammeter reading at the moment that the circuit was broken. Accurate aiming of the instrument is simplified by use of a supporting leg, which can be attached to the underside of the instrument.

The way in which the instrument can be calibrated is important because a number of different diaphragms D are used in the instrument. Unless precautions are taken, reading the instrument for a given average luminance of the field to be measured would be dependent on the size of the diaphragms. This inconvenience has been avoided by the addition of the built-in calibration unit, containing a suitably aged calibration lamp C and an opal-glass window G. The calibration unit can be rotated on the horizontal axis (Fig. 12) so that G can be positioned in front of O_1. In this position, C is connected to the stabilized supply voltage of the instrument, so that G has a fixed luminance. By adjusting the d.c. amplifier (Fig. 14), the same microammeter reading can be obtained on a convenient range of the instrument for each diaphragm D. Any drift in the sensitivity of the instrument can be corrected whenever desired.

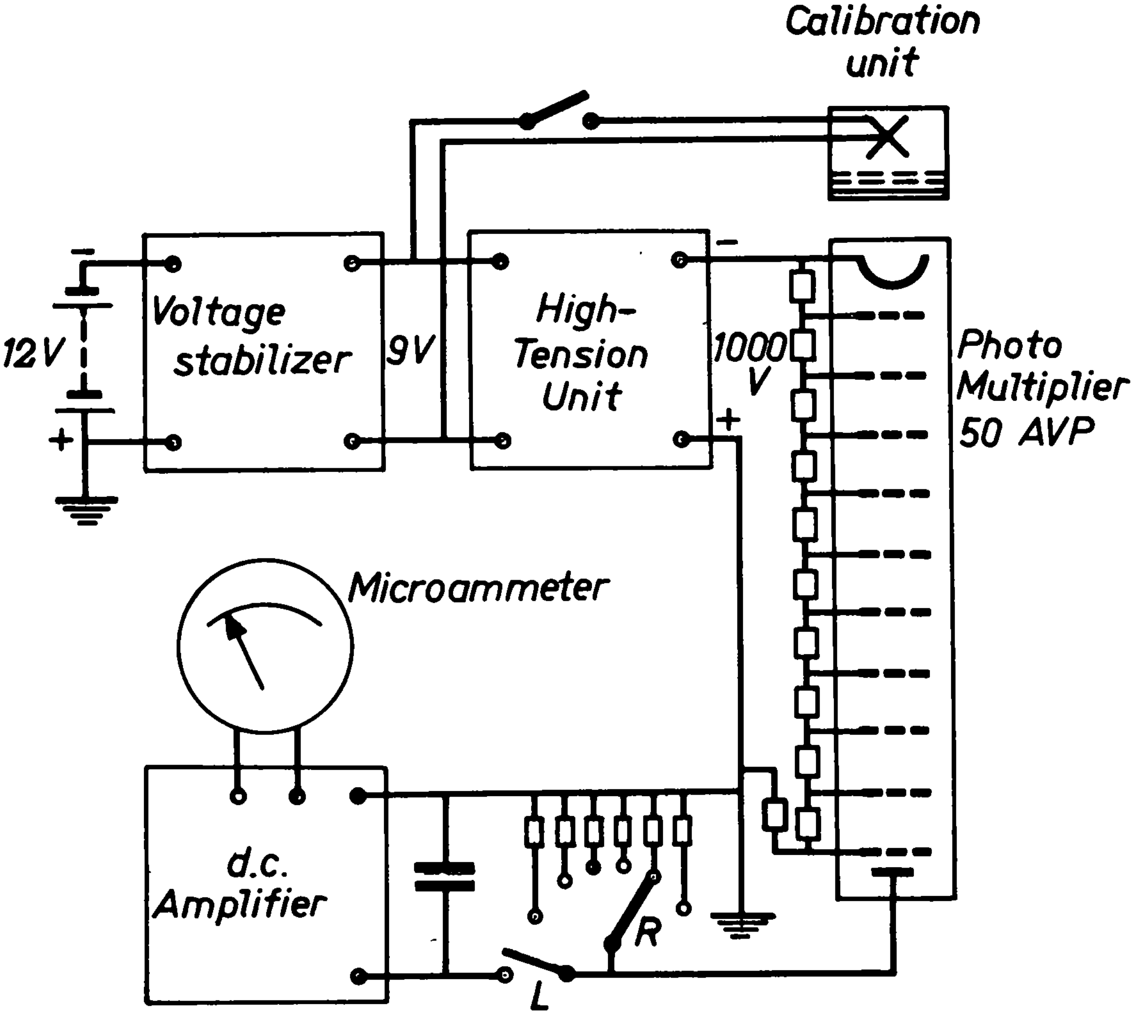


Figure 14. Block diagram of luminance meter.

Figure 14 shows the principle on which the instrument circuit is based. One of the resistances chosen by range switch R for the selection of the measuring range is connected in series with the photomultiplier. The voltage across the capacitor is then the product of the photoelectric current and the value of the selected resistance. When switch L is opened, the microammeter gives a slowly decreasing reading proportional to the capacitor voltage. The battery of accumulators, the stabilizer, the high tension unit, and the d.c. amplifier are mounted in a small box. The measuring ranges of the instrument, for full-scale deflection of the microammeter, are 0.3, 1, 3, 10, 30 and 100 cd/m^2 (1 cd/m^2 = about 0.29 fL).

This luminance meter is now suitable only for measuring the average luminance of a large part of the road. To measure local values of luminance as seen by a normal driver, far higher sensitivities are required, because portions of the road subtending very small solid angles at the observer's eye have to be considered. This difficulty can be avoided by putting the instrument at a short constant distance from every point on the road to be measured, instead of carrying out all measurements from a fixed position. A special tripod has been added to the instrument to facilitate measurement of local luminance values.

Another accessory is a grey reflection plate with a reflection factor of $\pi/10$. The instrument can also be employed as footcandle-meter, by placing the reflection plate on the road surface at the point where illumination measurements are to be made and measuring the luminance of this plate, at an angle of about 45°. The reading of the instrument in cd/m^2 gives the illumination in lux x $1/10$. The lowest measuring range then corresponds, for full scale deflection, to 3 lux (about 0.3 footcandle).

The experience with prototypes of the instrument has shown that an instrument of such simplicity, but with a satisfactory reliability for street lighting purposes, is a real need for introducing the concept of luminance in the practice of public lighting.

REFERENCES

1. Balder, J.J., and Fortuin, G.J., "The Influence of Time of Observation on the Visibility of Stationary Objects." C.I.E., Zürich (1955).
2. de Boer, J.B., "Strassenleuchtdichte und Blendungsfreiheit als Praktische Massstäbe für die Güte Öffentlicher Beleuchtung." Lichttechnik 10:7, p. 359-363 (1958).
3. de Boer, J.B., "Eclairage et Sécurité de Circulation sur les Autoroutes." Bulletin SEV 12 (1959).
4. Dunbar, C., "Necessary Values of Brightness Contrast in Artificially Lighted Streets." Trans. Ill. Eng. Soc., London, 3:187 (1938).
5. de Boer, J.B., "Fundamental Experiments on Visibility and Admissible Glare in Road Lighting." C.I.E., Stockholm (1951).
6. de Boer, J.B., Burghout, F., and van Heemskerck Veeckens, J.F.T., "Appraisal of the Quality of Public Lighting Based on Road Surface Luminance and Glare." C.I.E., Brussels (1959).
7. Roper, V.J., and Howard, E.A., "Seeing with Motorcar Headlamps." Trans. Amer. Ill. Eng. Soc. 33:417-438 (1938).
8. Hopkinson, R.G., "Discomfort Glare in Lighted Streets." Trans. Ill. Eng. Soc., London, 5:1 (1940).
9. de Boer, J.B., and van Heemskerck Veeckens, J.F.T., "Observations on Discomfort Glare in Street Lighting. Influence of the Colour of the Lights." C.I.E., Zürich (1955).
10. de Boer, J.B., "Blendung beim Nächtlichen Strassenverkehr." Zentralblatt für Verkehrs-Medizin 3:185 (1957).
11. de Boer, J.B., Onate, V., and Oostrijck, A., "Practical Methods for Measuring and Calculating the Luminance of Road Surfaces." Philips Research Reports, 7:1, p. 54-67 (1952).
12. de Boer, J.B., and Oostrijck, A., "Reflection Properties of Dry and Wet Road Surfaces and a Simple Method for Their Measurement." Philips Research Reports, 9:3, p. 209-224 (1954).
13. de Boer, J.B., "Ein Leuchtdichtemesser für Strassenbeleuchtung." Lichttechnik, 7:8 (1955). "Un Luminancemètre pour l'Éclairage Public." Rev. Gén. Routes et Aérodromes, No. 280 (1955).
14. de Boer, J.B., "Die Anwendung des Begriffes 'Leuchtdichte der Strassendecke' in der Praxis der Öffentlichen Beleuchtung." Bull. Sev, No. 12 (1960). "The Application of the Concept 'Road Surface Luminance' in the Practice of Public Lighting." Public Lighting (March 1961).

An Instrument for Precision Photometry Of Reflex Reflective Materials

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● IN RECOGNITION of the growing need for scientific reflector evaluation, a few state highway agencies have installed extensive laboratory test facilities for this purpose. While these laboratories constitute the only accurate means presently available for testing reflector performance, the procedures employed require unusual space, delicate equipment, and skilled personnel.

Previous attempts have been made to reduce the size and complexity of this apparatus. The ESNA Photometer, however, represents the first portable testing instrument whose measurements correlate completely with full-scale laboratory data and actual highway conditions. Unlike its predecessors, it provides accurate measurement of performance at discrete viewing angles throughout the range of modern reflector usage. The simplicity of its operation makes it suitable for production quality control as well as for laboratory evaluation. It fills the long-felt need for a practical, reliable device capable of testing a wide variety of reflex reflector materials for conformance to specifications.

Reflex reflectors are optical devices having the ability to accept light from a near or distant source and reflect this light back to the source in a confined beam, regardless of the angle at which the light becomes incident on the reflector. For most commercial reflectors the return beam is concentrated within a cone of 2-deg half angle, the axis of the cone being the line between the light source and the reflector. The manner in which the light is distributed within the returned light cone directly affects the visibility characteristics of the reflector under actual highway viewing conditions. As a vehicle approaches a reflector mounted on a sign, delineator, or disabled vehicle, a constantly changing angle is formed between the line from the headlights and the reflector and the line between the reflector and the driver's eyes. This angle, termed "observation angle," is inversely proportional to the distance between the vehicle and reflector. For the average passenger automobile the observation angle is equal to the angle whose tangent is 1.746 divided by the distance, in feet, between the automobile and the reflector. The value 1.746 is the average vertical distance, in feet, between the headlights and the driver's eyes. For example, at 1,000-ft distance the observation angle is $\frac{1}{10}$ deg; at 600 ft the observation angle is $\frac{1}{6}$ deg; and at 300 ft the observation angle is $\frac{1}{3}$ deg. The visibility of the reflector when viewed at any distance depends on the candlepower intensity of the reflector at the observation angle formed at that distance.

Because the candlepower intensity of the reflector at any observation angle is dependent on the quantity of light incident on the reflector, performance is measured in terms of candlepower output per foot-candle illumination. The term for this efficiency value is "specific intensity." To illustrate the importance of measuring specific intensity at discrete observation angles, certain fundamental laws of light must be introduced.

A source of light emits luminous intensity in terms of candlepower. Any surface in the path of this light is illuminated by the source in terms of foot-candles of illumination, the foot-candle level being inversely proportional to the square of the distance between the source and the illuminated surface. A source emitting one candlepower will produce one foot-candle of illumination on a surface at 1-ft distance; $\frac{1}{4}$ foot-candle at 2 ft; $\frac{1}{9}$ foot-candle at 3 ft, etc.

A reflector at distance D feet from headlights of candlepower, CP_H, is therefore illuminated by $\frac{CP_H}{D^2}$ foot-candles. The driver's eyes at distance D feet from a reflector of candlepower, CP_R, are illuminated by $\frac{CP_R}{D^2}$ foot-candles.

$$\text{Illumination at reflector} = \frac{CP_H}{D^2}$$

$$\text{Illumination (signal) at eye} = \frac{CP_R}{D^2}$$

$$\text{Specific intensity of reflector} = \text{S.I.} = \frac{\text{Candlepower of reflector } (CP_R)}{\text{Illumination at reflector } \left(\frac{CP_H}{D^2}\right)}$$

$$CP_R = \text{S.I.} \times \frac{CP_H}{D^2}$$

then

$$\text{Signal at eye} = \frac{\text{S.I.} \times CP_H}{D^2 \times D^2} = \frac{\text{S.I.} \times CP_H}{D^4}$$

Assuming the candlepower of the headlights to be a constant, it is obvious that the specific intensity of a reflector must increase proportionally to the fourth power of the distance for a constant signal at the eye. In other words, the specific intensity of a reflector at 1/10-deg observation angle (1,000 ft) must be 123 times greater than the specific intensity at 1/3 deg (300 ft) so that the driver receives the same signal at both distances.

Although no commercially manufactured reflector approaches this ideal, the discussion makes clear that in testing reflex reflectors the photometer must be capable of measuring extremely small portions of the reflected cone of light at discrete observation angles and converting measurements into values of specific intensity. The ESNA Reflex Photometer was designed and constructed to accomplish these goals accurately and efficiently.

INSTRUMENT COMPONENTS

The basic components of the photometer are: (a) a light source which illuminates the reflector, (b) a photoelectric receiver which measures the intensity of the reflected beam at discrete observation angles and converts these measurements to specific intensity values which are indicated on a galvanometer, and (c) a goniometer on which the test reflector is mounted.

Light Source

The light source consists of an optical system coaxial with the photometer tube. The heart of the system is a 10-watt Zirconium arc lamp with an intrinsic brightness of approximately 29,000 candles per square inch. The light output of the arc is amplified by a system of lenses, and finally passes through an 0.200-in. diameter aperture which simulates the headlights of a vehicle.

Receiver

Surrounding the aperture at a nominal radius of 0.208 in. is a ring of photosensitive material 0.050 in. in width. The receiver ring simulates the eyes of the driver. Light falling on this ring produces a photocurrent proportional to the quantity of light, which is indicated on the galvanometer. An Aryton shunt in the receiver-galvanometer circuit extends the range of the photometer by decade factors of 1 to 1,000, making possible the testing of all reflective materials from lowest to highest brightness.

Goniometer

The test reflector is mounted on an adjustable holder designed to accommodate a variety of reflective materials. The sample holder pivots to permit varying the entrance angle, and rotates at 300 rpm about the reflector axis to obtain an average value. The entire unit may be removed from the photometer tube and placed at various stations in the tube to change the observation angle.

INSTRUMENT CAPABILITY

The photometer is capable of measuring the specific intensity of reflex reflectors from $1/10$-deg observation angle to $1/3$-deg observation angle. Simulating actual highway viewing, the observation angle is changed by changing the distance between the source-receiver plane and the reflector. At $1/10$-deg observation angle the reflector is positioned 10 ft from the source-receiver plane and the 0.05-in.-wide receiver ring in the photometer corresponds to a 5-in.-wide observation zone on the windshield of a car at 1,000-ft distance from the reflector. The 5-in. width takes into account variations in drivers' height from average. As the reflector is moved closer to the source-receiver plane for measurements at larger observation angles, the source and receiver dimensions remain constant—as do the observation zone and headlights under actual conditions.

The relation of source and receiver dimensions in the photometer duplicate those recommended by the Society of Automotive Engineers for testing of reflex reflectors, where a light source of 2.00-in. diameter, receiver of 0.50-in. diameter and test distance of 100 ft is described.

CALIBRATION OF PHOTOMETER

Included with the photometer is a calibrating mirror which is used to calibrate the device for absolute specific intensity. Also included are color filters to be used in conjunction with the calibrating mirror for the testing of colored reflex reflectors. Before starting a test, mount the mirror on the goniometer and switch the Aryton shunt to the least sensitive range. Turn on the light source and allow the unit a warm-up period of 10 min. After warm-up switch the shunt to higher sensitivity ranges until a galvanometer deflection of over 10.0 divisions is obtained. Mask the mirror with the black zeroing mask and adjust the galvanometer to zero. Unmask the mirror and record the galvanometer deflection. Multiply by the shunt factor for a final reading of R_a. Repeat at all observation angles to be tested, and record R_a for each observation angle.

For conversion of galvanometer readings to specific intensity multiply by

$$\frac{D^2KT}{4R_a}$$

in which

D = test distance;

R_a = mirror value previously recorded for each observation angle;

K = reflection factor marked on back of calibrating mirror; and

T = 1.00 when testing crystal reflectors, or transmission factor marked on color filter used in calibrating for colored reflector testing.

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