# Road Surface Luminance and Glare Limitation In Highway Lighting 

J.B. de BOER, Chief, Lightıng 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/ ${ }^{2}$ ) 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 lightıng. 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 lumınance 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 . $\mathrm{Be}-$ cause 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 duameter of $50 \mathrm{~cm}(20 \mathrm{in}$.$) pre-$ sented to the observers at $100 \mathrm{~m}(330 \mathrm{ft})$ for 0.1 sec at a mean background luminance of $1 \mathrm{~cd} / \mathrm{m}^{2}(0.3 \mathrm{fL})$. 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 $10-\mathrm{yr}$ 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 $10-\mathrm{yr}$ 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 $28 \times 28 \mathrm{~cm}$ ( $11 \times 11 \mathrm{in}$.) 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 $20-\times 20-\mathrm{cm}$ (8-x8-in.) object must be clearly visible to a road user from $100-\mathrm{m}$


Figure 2. Minimum ratio $\mathrm{R}_{\mathrm{L}}$ of road and object luminances needed to make $28-\mathrm{x} \quad 28-\mathrm{cm}$ (ll- x ll-in.) objects visible at from 50- to $200-\mathrm{m}$ (150- to 600-ft) distances to observer under normal traffic conditions, as a function of road luminance $L$.


Figure 3. Dynamic visibility tests.
( $330-\mathrm{ft}$ ) 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 $2 \mathrm{~cd} / \mathrm{m}^{2}$ ( 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 $20 \times 20 \mathrm{~cm}(8 \times 8 \mathrm{in}$.) dull screen ( $9 \% \mathrm{re}-$ flection 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, 1, 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 $0.1-\mathrm{sec}$ 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 $1 \mathrm{~cd} / \mathrm{m}^{2}(0.3 \mathrm{fL})$.

The conclusions thus obtained may again be based on the requirement that a 20- $x$ $20-\mathrm{cm}(8-\mathrm{x} 8-\mathrm{in}$.$) test object whose luminance is two-thirds of the background lumin-$ ance ( $\mathrm{R}_{\mathrm{L}}=1.5$ ) must be visible from at least $100 \mathrm{~m}(330 \mathrm{ft})$. 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 $1 \mathrm{~cd} / \mathrm{m}^{2}(0.3 \mathrm{fL})$ and an $0.1-\mathrm{sec}$ 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 $1=200 \mathrm{~m}$ ( 660 ft ), in other words, a mean value of $2.2 \mathrm{~cd} / \mathrm{m}^{2}(0.64 \mathrm{fL})$.

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 $1.5 \mathrm{~cd} / \mathrm{m}^{2}(0.44 \mathrm{fL})$ (between 1.3 and $1.8 \mathrm{~cd} / \mathrm{m}^{2}(0.38$ 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 daylught 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 $\mathbf{O}$ gives the number of motorists who drive without lights on; at a lighting level of $50 \mathrm{~cd} / \mathrm{m}^{2}$ ( 15 fL ) and higher; practically everyone drives without lights. When the lighting level falls to approximately $5 \mathrm{~cd} / \mathrm{m}^{2}(1.5 \mathrm{fL}), 80$ 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 $1 \mathrm{~cd} / \mathrm{m}^{2}$ ( 1.5 and 0.3 fL ), more than 80 percent of drivers are driving with "side"


Figure 5. Numbers of cars ( $p$ ) in percent driving whth various lighting possibilities as a function of road luminance $L$.
lights. Curve $C$ gives the number of drivers who use their headlights on the passing beam. When the road luminance falls to $1 \mathrm{~cd} / \mathrm{m}^{2}(0.3 \mathrm{fL}), 20$ 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 $1 \mathrm{~cd} / \mathrm{m}^{2}$ ( 0.3 fL ).

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 artuficial lighting level exceedıng $2 \mathrm{~cd} / \mathrm{m}^{2}(0.6 \mathrm{fL})$. A prohibition of headlights in high-intensity traffic, as demanded by safety, is justified if the lighting level exceeds $2 \mathrm{~cd} / \mathrm{m}^{2}$ ( 0.6 fL ).

## Glare

Glare from street lighting systems manifests itself in two ways: by a reduction of visual performance (disabllity 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 per-


Figure 6. Ratio $R_{S}$ of contrast sensitivities (with and without glare) as a function of road luminance L.
ception is certainly not to be feared.
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 admıssible 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 $2 \mathrm{~cd} / \mathrm{m}^{2}(0.6 \mathrm{fL})$ 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 $0.4 \mathrm{~cd} / \mathrm{m}^{2}(0.12 \mathrm{fL})$, the contrast sensitivity reduction stıll 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 ( $5, \underline{8}, \underline{9}, 10$ ). 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' opimons 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 $\mathrm{E}_{\mathrm{b}}$ is shown as a function of mean road luminance $L$ and angle $\delta$ between the line from eye to source and the horizontal plane. Solid angle $\omega$ at which the observer perceives the light source is the parameter. Illumination $E_{b}$ permissible for three values of $\omega$ 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 $\delta$ (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 $\omega$.

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 $\mathrm{E}_{\mathrm{b}, \mathrm{n}}$ is the highest eye illumination that can be produced by the $\mathrm{n}^{\text {th }}$ 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 $n^{\text {th }}$ source, the "satisfactory" limit of glare is not exceeded if the sum of correlates $\mathrm{E}_{\mathrm{w}, \mathrm{n}}$ to $\mathrm{E}_{\mathrm{b}, \mathrm{n}}$ remains below 1. Thus,

$$
\begin{equation*}
\sum_{n=1}^{n=N} \frac{E_{w, n}}{E_{b, n}} \leqq 1 \tag{1}
\end{equation*}
$$

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 $\mathrm{E}_{\mathrm{b}}$ as produced by single light source corresponding to criterion of "satisfactory" glare as a function of mean road luminance $L$ and angle $\delta$ between line from eye to light source and horizontal plane for various values of solid angle $\omega$ 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 $80^{\circ}$ from the vertical and whose maximum luminous intensity is at less than $60^{\circ}$ 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 visibulity and comfort of seeing indicate that an average luminance of $2 \mathrm{~cd} / \mathrm{m}^{2}(0.6 \mathrm{fL})$ 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 $80^{\circ}$ 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 characterıstics 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, $\bar{L}$, 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 $\overline{\mathrm{L}}$ 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 $\overline{\mathbf{L}}$ 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 $h^{\prime}$ and changes in all other dimensions in the ratio $h^{\prime} / \mathrm{h}, \overline{\mathrm{L}}$ will change in the ratio $\left(h / h^{\prime}\right)^{2}$. 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 $\overline{\mathrm{L}}$ 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 $\overrightarrow{\text { Lsw }}$ as a function of


Figure 8. Signıficance of $s$, w, ov and $h$.
( $w-o v$ ) 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 luminairearrangements, together with an indication of dimensions s , w and ov. For a given arrangement, $\overline{\mathrm{L}}$ is determined by reading the product $\overline{\mathrm{L}}$ sw once for the value of ( $\mathrm{w}-\mathrm{ov}$ ) 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 ( $\mathbf{w}-\mathrm{ov}$ ) 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 $(5 \mathrm{ft})$ 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).

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 devel-


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 of for various values of mounting height $h$.
oped in the Philips Lighting Laboratory.
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 merldian 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 almed by means of a second objective, $\mathrm{O}_{2}$, 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 $\mathrm{O}_{1}$. 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),

Calibration unit


Figure 14. Block diagram of luminance meter.
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 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 $100 \mathrm{~cd} / \mathrm{m}^{2}\left(1 \mathrm{~cd} / \mathrm{m}^{2}=\right.$ 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 $45^{\circ}$. The reading of the instrument in $\mathrm{cd} / \mathrm{m}^{2}$ gives the illumination in lux $\mathrm{x} 1 / 10$. 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.

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