Assessment of Nighttime Roadway Visibility

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Approximately seven visibility meters have been described in the literature during the last 20 years. The salient features of each of these instruments along with their limitations and applications are briefly discussed. The U. C. Visibility Meter is discussed in detail.

The design equations of the U. C. Visibility Meter are given together with the criteria for a suitable visibility meter. Details of optical parts and calibration are included to show compliance with the design criteria.

The U. C. instrument has been used to evaluate the visibility conditions of two extremes of street lighting, that is, a uniform and an extremely non-uniform roadway brightness pattern. Under each condition a two-dimensional and a three dimensional target was used to gather information. Results of these roadway studies are presented.

These results show a great variation in visibility under the non-uniform roadway brightness pattern and less variation in visibility under the uniform roadway brightness pattern. The peak visibility of the non-uniform condition is only slightly greater than the average visibility level of the uniform condition.

● IT is a well known fact that the curtain of darkness which descends upon the roadway after dusk is responsible for many of the accidents and other hazardous and uncomfortable operating conditions that exist upon our roadways at night. The evaluation of this situation is not simple. This problem has been studied on a continuing basis at the University of California for many years and only recently have we evolved a technique which is believed to assist in answering many of the questions regarding how to make an appraisal of visibility as it actually exists.

It is the purpose of this paper to discuss the various techniques that have been used by others for making visibility measurements and to describe the visibility meter that has been developed under the auspices of the Institute of Transportation and Traffic Engineering at the University of California. Some of the preliminary results obtained in field studies will be presented together with a discussion of these results and a review of their significance.

Review of the Techniques for Visibility Measurement

A review of the literature on the subject of visibility measurement takes us back several years to 1920 when Lloyd A. Jones described a visibility meter which was used primarily to evaluate the visibility of ships at sea and to check on the adequateness of their camouflage as a protective measure from German submarines during World War I (1). Mr. Jones appreciated the problems involved in that visibility is a subjective quantity and as such is difficult, if not impossible, to measure directly. He used an established technique of experimental psychology wherein one applies various physical controls to a device which will make it possible to reduce a subjective quantity to some threshold condition wherein one can make an evaluation that the quantity does or does not exist in the perceptive field. In our case this amounts to whether the object is visible or is not visible.

Such a subjective evaluation can be made by one of four threshold measurements. (1) The object can be reduced in size until it is no longer visible. (2) The object can be exposed for a very short period of time such that it is not visible. (3) The object can be reduced in brightness along with its background until there is not an adequate brightness difference between the object and its background to allow the object to be visible. (4) The ratio of object brightness to background brightness can be reduced without changing either the total brightness of the target area or the brightness of the surround. In this case the contrast between the object and its background is changed to a threshold condition.

In the Jones meter a combination of brightness difference threshold and contrast threshold conditions are applied. The meter itself (see Figure 1) consisted of a veiling brightness source which could be moved either nearer to or farther away from the optical axis thereby increasing or decreasing the brightness of a diffusing glass. A partial mirror is placed in the principal optical path and transmits part of the incident

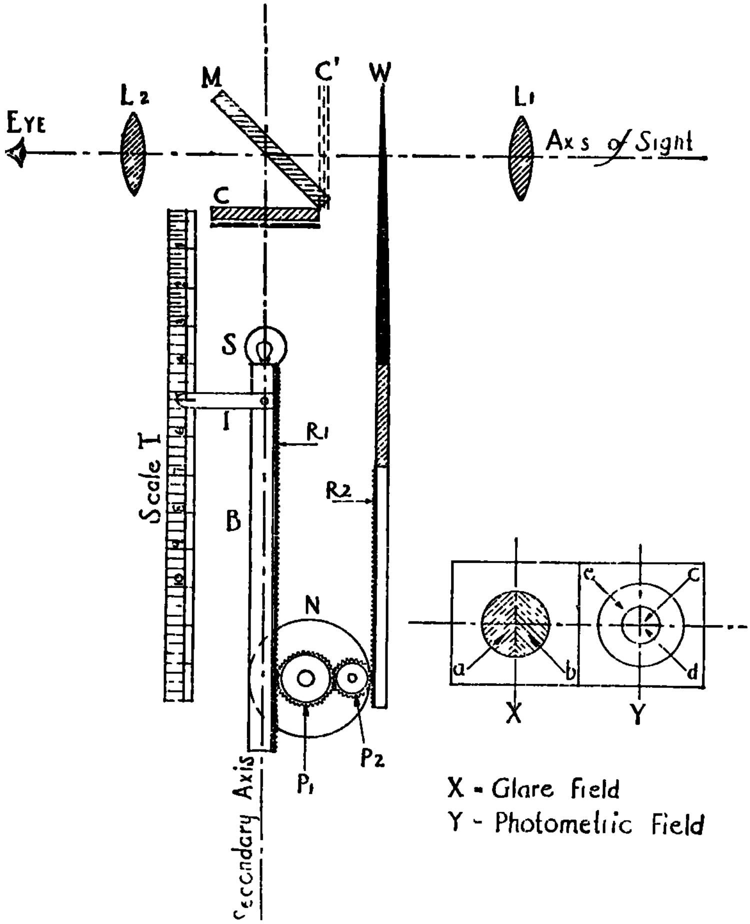
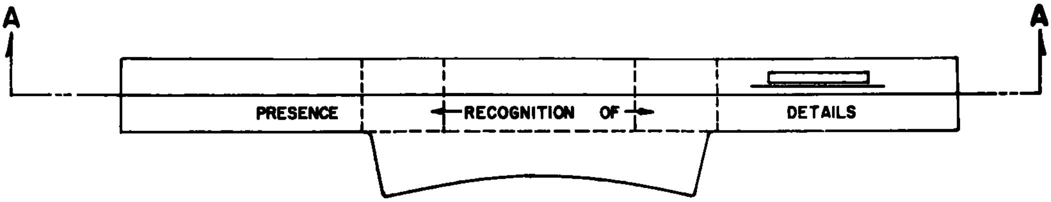
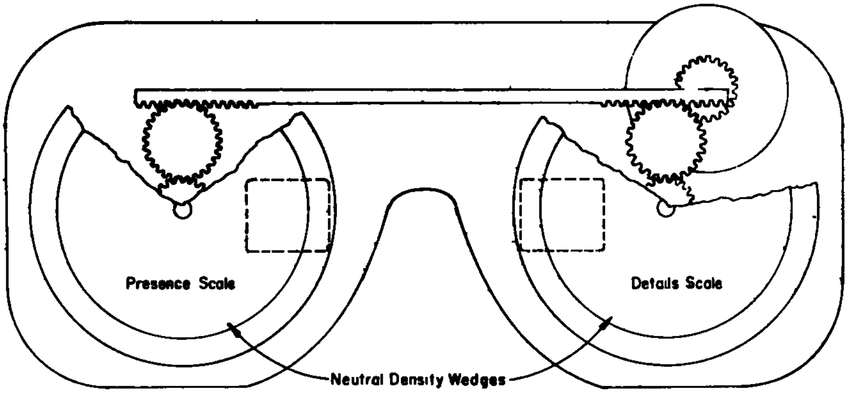


Figure 1. Jones visibility meter.

flux from the object to be viewed and reflects part of the flux from the diffusing glass which acts as a veiling brightness source. A neutral non-diffusing optical wedge was arranged to move across the path of the light from the object. The moving wedge was coupled to the moving light behind the diffusing glass which acts as a veiling brightness source as shown in Figure 1. In this manner the veiling brightness is increased as the brightness of the object and the principal field of view is reduced. This principle as will be shown later under the heading, Design Equations of the Visibility Meter, will accomplish a change in contrast in the field of view such that the object can be reduced to threshold contrast. While the instrument is based on a sound principle it has never received wide-spread use. The reason for this is not known but it would appear that mechanical problems of construction might limit its use and the fact that the overall adaptation level of the eye is changed when the variable transmittance wedge is in-



PLAN VIEW



SECTION A-A

Figure 2. Luckiesh-Moss visibility meter.

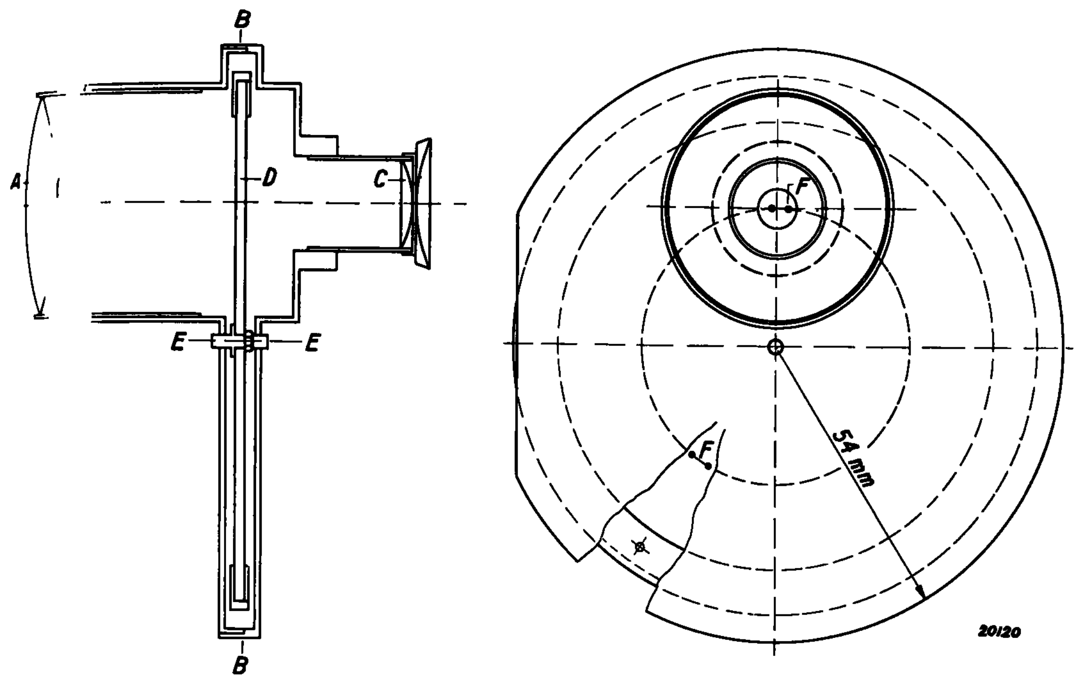
serted in the main optical axis. This would limit its application to high brightness conditions such as the viewing of ships at sea against a daytime sky.

The Luckiesh-Moss Visibility Meter was next in the evaluation of visibility measurements and appeared in about 1935 (2) (see Figure 2). This meter has been described many times and there have been numerous discussions of its application and use as indicated in the reference material (3). The meter consists of two identical circular gradients of varying density, a synchronous driving mechanism and a suitable case. The circular gradients are photographic films prepared as varying density circular wedges. The optical path of the scene viewed by the observer is through the wedges and therefore the light on the observer's side is partly diffused, scattered and absorbed by the wedge. Thus the scattering has the same effect as a veiling brightness source in front of the observer. Rotation of the discs reduces the brightness of the object and its background to threshold conditions by scattering the light from the brighter areas to the less bright areas in the field of view. A calibration scale is arranged around the edge of one of the wedges and is in terms of the relative visibility of a pair of black parallel bars viewed against a uniformly bright white background. The reduction of visibility to threshold conditions by this meter employs the use of a reduction in the brightness difference, the contrast and the visual acuity of the object. The whole field of view is reduced in brightness level and fogged until the predetermined degree of difficulty in seeing is achieved. The setting of the wedge is then read and is used as a measure of a relative visibility.

There are a number of problems in the use of this meter particularly for outdoor viewing at low brightness levels. It has not proven to be an adequate instrument for general use under nighttime roadway conditions.

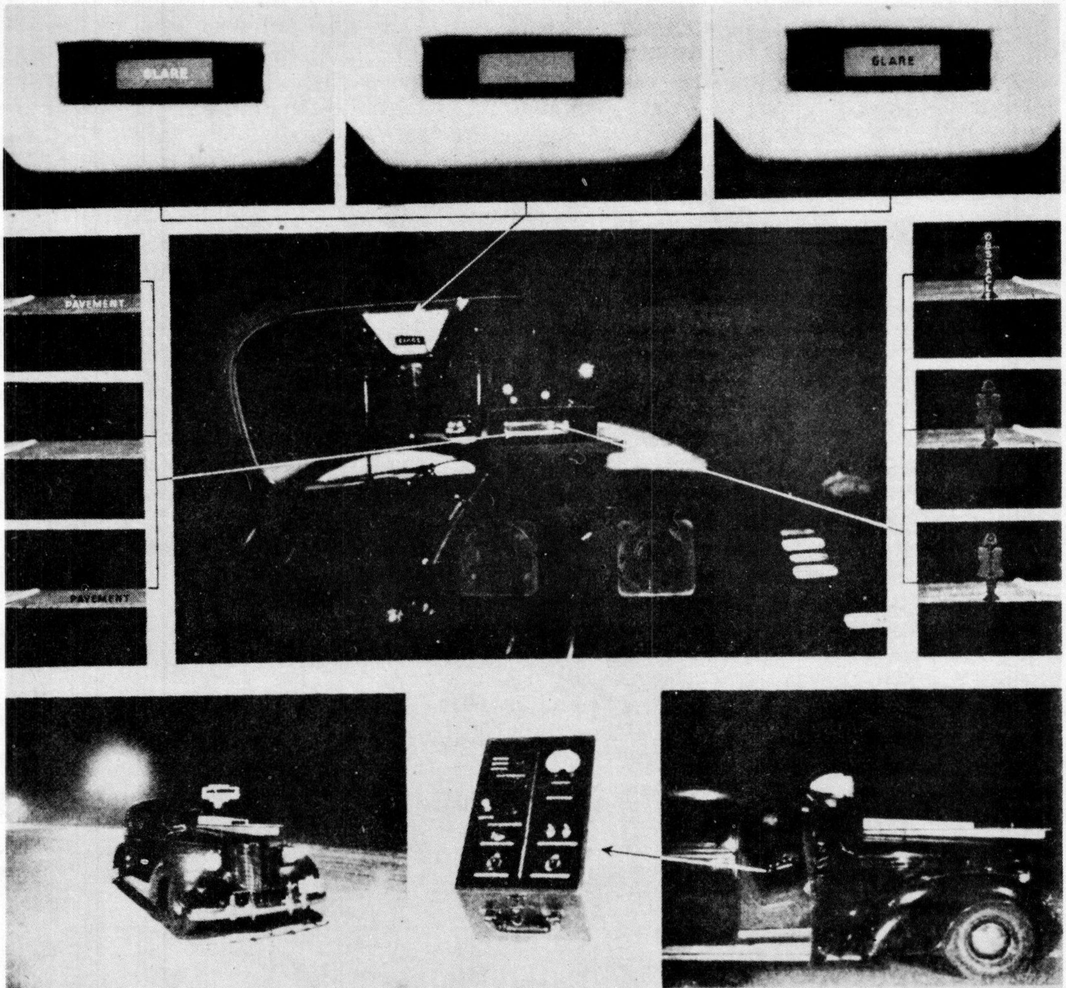
The next reference to visibility measurement is by two men from the Phillips Company in Holland, P. J. Bouma and G. Host, in 1936 (4). The instrument will be referred to as the Phillips Visibility Meter. This meter employs the principle of reduction to the brightness difference threshold. This appears to be the first meter that was specifically designed for street and highway use. Refer to Figure 3 for a line diagram of the instrument. It consists of a 1: 1 magnification system and a large disc upon which a series of 50 dots is placed on a circle. The dots are rotated so that they are seen successively in the same position in the center of the optical path and projected upon the roadway, but with varying transmittance. The instrument is aimed at the portion of the roadway to be evaluated and the disc is rotated and a spot is selected which permits the target to be just perceptible against its background. The transmission of the particular spot is then recorded and used as a measure of the relative visibility. The system is ingenious and quite well suited for field measurements in that no external power supply is required. Also the eye remains at a constant adaptation level and the field of view is large enough so that all the principal glare sources are included. Only a small central field of view is varied (approximately ½ minute of arc) and the scene is viewed as it actually appears except for the step-wise variation in the dots which makes the system somewhat indeterminate and difficult to use. This meter would seem to have considerable merit for many field applications, particularly in the daytime where the field brightnesses are high. At night at low brightness levels the application of the brightness difference threshold is not satisfactory.

Following through with the historical development of visibility meters we have noted that in March, 1939, a visibility meter was described in the French periodical, Revue Generale des Routes, and is known as the Duckler Visibility Meter (5). This meter appears to be similar to the Luckiesh-Moss instrument with the exception that a series of variable density glass discs are used in place of the continually varying neutral photographic wedges. Threshold is determined when the object can no longer be seen through a glass of stated absorptive power. The instrument is primarily a brightness



A objective and *C* lens, with which the spots *F* with progressively increasing transmission coefficients are observed against the road surface as background.

Figure 3. Phillips visibility meter.



Operator's view of pavement sample on car hood and of glare integrator above windshield. Top: Photometric field of the glare integrator. Left: Photometric field of the pavement. Right: Photometric field of the obstacle. In each case, the brightness reading in footlamberts is recorded, when the word fades out, by pressing a button which punches the record card in its holder in the control box. Lower Center: Control box for photometer circuits. Lower Left and Right: Evaluator elements mounted on car.

Figure 4. Reid-Channon street lighting evaluator.

difference threshold meter and does not take into account the degree of contrast between the object and the background against which it is seen. Also, the field of view is small so that the glare effect of street lights is not included. As far as can be determined this instrument has not received popular acceptance.

At about the same time in 1940 a composite instrument known as a Street Lighting Evaluator was developed by Kirk Reid and H. J. Channon (6). This instrument received considerable attention at the time and there have been numerous references to its use in literature (7). Basically the equipment measures three brightnesses and combines these into a single over-all reading. The quantities evaluated are (1) the brightness of the pavement, (2) the brightness of representative obstacles on or near the pavement in question, and (3) the glare effect from sources in the field of view. The equipment consists of three parts as shown in the photograph of Figure 4: (a) a miniature pavement bed is mounted over the hood of the car, (b) a glare integrator is mounted above the operator's eye on the outside of the car, (c) miniature pedestrians or obstacles are placed on the simulated pavement which is on the hood of the car. The texture of the miniature pavement is selected from available materials as being representative of the actual pavement in question and the miniature obstacles are selected as typical of those that might be seen on the roadway. The measurements of brightness are entered on a nomograph supplied with the instrument and, from the three numbers, the relative visibility is determined. The visibility scale is based upon a black obstacle of zero brightness viewed against a uniformly bright background of 0.01 foot-lambert. A number of these instruments were assembled and used throughout the country in the decade from 1940 to 1950. Several technical difficulties occurred in making the evaluation so that at the present time the equipment is not in wide-spread use.

The next visibility meter to make its appearance was one designed by Professor C. L. Cottrell, at Cornell University, based upon the contrast threshold principle. It was first discussed in literature in February, 1951 (8). This instrument was made out of a modified projection gun sight which uses a super-imposed luminous field over a visual target. The super-imposed field is used as a veiling brightness source and covers an area approximately 7 deg in diameter. A sketch of the optics of the instrument is shown in Figure 5. A constant brightness is maintained for the veiling source and varies the brightness of both the object and its background by means of a circular neutral gradient. When the transmission of the gradient is maximum (1.0) the brightness of the total field is the brightness of the veiling glare plus the brightness of the actual field

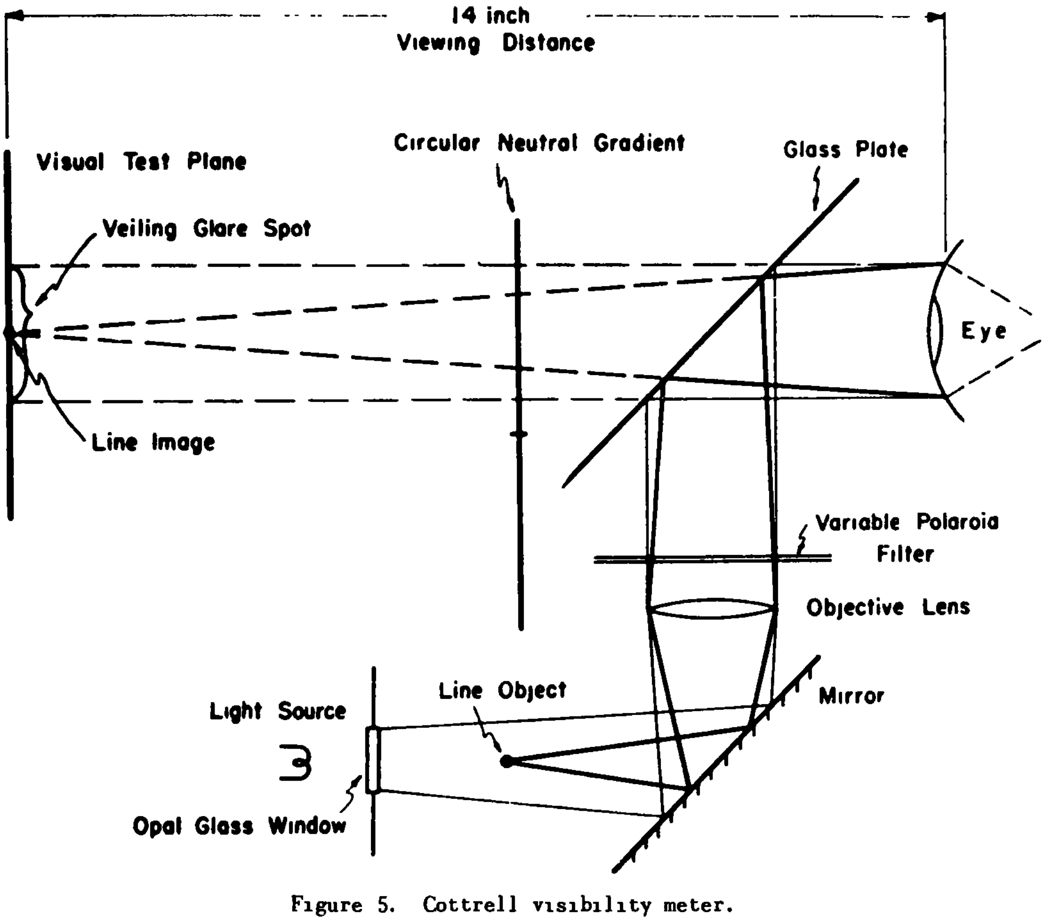


Figure 5. Cottrell visibility meter.

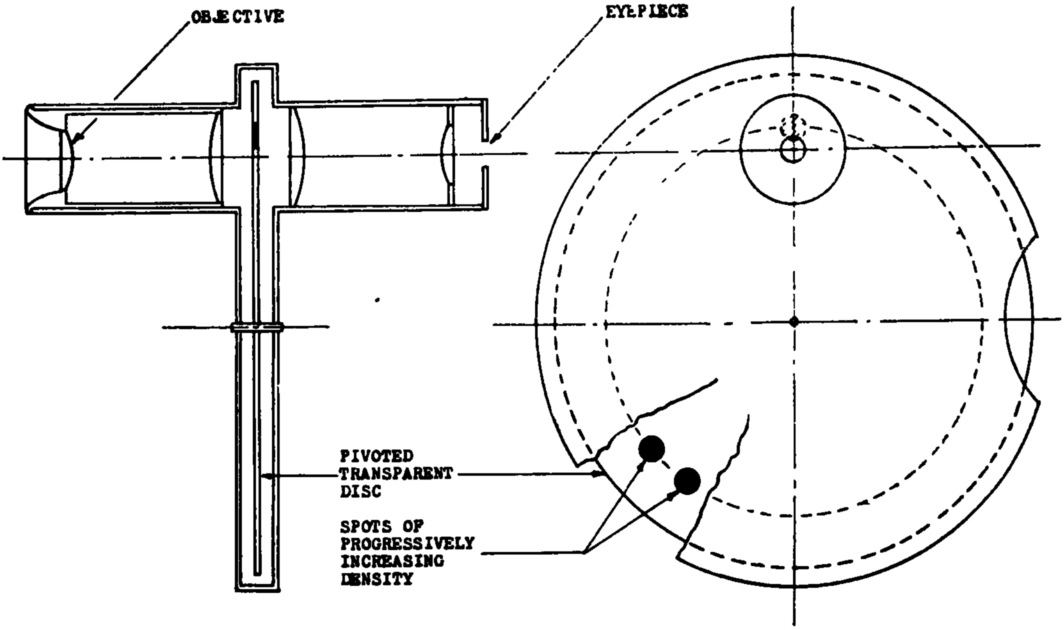
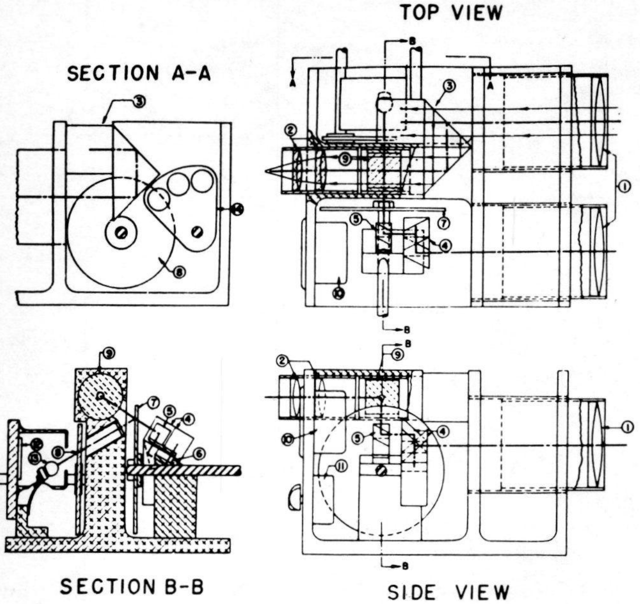


Figure 6. Horton visibility meter.

The equipment is adjusted so that the veiling glare source is equal to the brightness of the field, therefore, under the above conditions the total brightness is twice the brightness of the background. When the gradient is rotated so that the transmission is minimum (0. 0), the brightness of the veiling glare source is then equal to the brightness of the background. For any particular visibility measurement, the circular neutral gradient is rotated until the object in question is just perceived at threshold, thus the instrument does measure the contrast threshold under the particular conditions of viewing above described. There are certain limitations, however, which are recognized by the author and those who have used the instrument. The principal limitation being that the adaptation brightness is changed as the neutral density gradient is rotated. Another is that the brightness of the veiling glare source remains constant and therefore the total brightness of the object and its background is continually changing during measurements. At relatively high levels of brightness these changes are not too important and therefore the instrument has proven to be satisfactory under normal daylight and interior lighting conditions. Its use under low-level roadway brightness conditions however may be questioned. To date it has not been used for nighttime roadway work but it may have some application in this field.

A meter very similar to the Phillips Visibility Meter was described by G. A. Horton in 1951 (9). The meter is based upon the brightness-diference threshold principle and consists of a lens system with a 1: 1 magnification and a transparent disc in the focal plane of the eyepiece (see Figure 6). A series of transparent circular dots of varying transmittance are arranged around the periphery of the disc and are proportioned to obscure an object at approximately 200 ft ahead of the observer. The disc is rotated until the difference between the object brightness and its background brightness is below the brightness difference threshold. The same comments apply as for the Phillips meter.

After a complete review of the literature in which all of the above instruments were critically examined it became apparent that certain modifications to these instruments and techniques were desirable. Therefore a set of ground rules was developed and an instrument was designed around these specifications. The work was first reported in the literature in September, 1953 (10). Since that time there have been several modifications to the original design and improvements made in the optics so that the equip-



1. **Objective Lens—coated achromat 180 mm focal length.**
2. **Eyepiece Lens—coated achromat 122 mm focal length.**
3. **Binocular Prism 7 x 50.**
4-6. **Right Angle Prism.**
7. **Variable Transmittance Mirror (partial aluminum coating) — visibility index control.**
8. **Variable Density Wedge — background brightness control.**
9. **Object Mirror.**
10. **Ammeter — 100 milliamps.**
11. **Background Brightness Potentiometer.**
12. **Photocell-Round 1-inch dia., A-5.**
13. **Veiling Glare Source — 2.2-volt bulb.**
14. **Color Selector.**

Figure 7. U.C. visibility meter.

ment now approximately complies with all of the ground rules for the design which are listed as follows:

1. The eye adaptation should remain constant at the level of the particular seeing situation.
2. Only a small central portion of the total field should be varied to make the visibility measurement.
3. A change in the contrast of the small central portion of the field should cause no change in the brightness of the remainder of the field while a visual measurement is being made.
4. The total field of view should be large enough so as to include any glare source or sources that may be present.
5. A background brightness measurement should be included as a separate function.
6. Color correction filters should be available so that the reference source within the instrument can be matched in color against the field of view being evaluated.

The instrument to be described in the following paragraphs meets the above requirements and does measure the visibility with a reasonable degree of accuracy. The actual design of the instrument and its machined parts are shown in the working drawings of Figure 7. A list of the optical parts will be found in Figure 7. A plan view of the optical paths of the meter is shown in Figure 7 while the actual instrument is shown in Figure 8. The design equations follow.

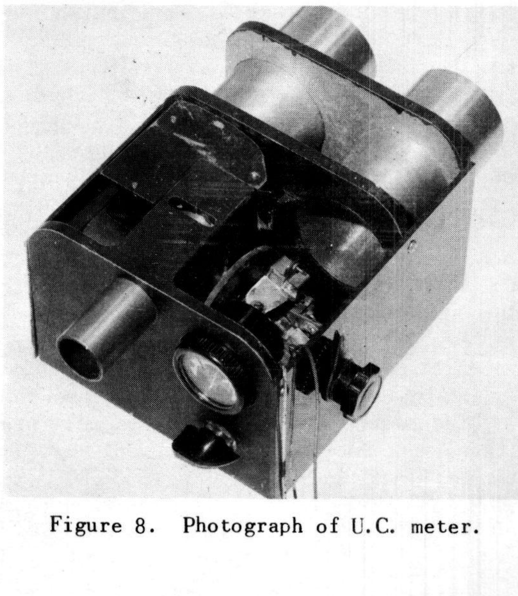


Figure 8. Photograph of U.C. meter.

<u>Design Equations of the Visibility Meter</u>

Definitions:

B_o = object brightness
B_b = background brightness (central portion of field around the object)
B_s = surround brightness (remainder of field)
B_v = veiling brightness
t_m = transmittance of variable density mirror
r_m = reflectance of variable density mirror
C = actual contrast
K = threshold contrast
$t_m + r_m = A$ (a constant - required condition in the design)

At the eye piece of the instrument: The eye sees the apparent brightness of the object, B'_o, the apparent brightness of the background, B'_b, and the brightness of the surround, B_s

$$B_o' = B_o - (1 - t_m) B_o + r_m B_v$$

$$B_b' = B_b - (1 - t_m) B_b + r_m B_v$$

Threshold conditions will occur when:

$$\frac{B_o' - B_b'}{B_b'} = K$$

So that: $$\frac{(B_o - (1 - t_m) B_o + r_m B_v) - (B_b - (1 - t_m) B_b + r_m B_v)}{(B_b - (1 - t_m) B_b + r_m B_v)} = K$$

If $B_b = B_v$: $$\frac{t_m (B_o - B_b)}{(t_m + r_m) B_b} = K = \frac{t_m C}{A}$$

Therefore: Threshold contrast = (t_m) x (a constant) x (actual contrast) which shows "t_m" to be a measure of the threshold contrast for the actual conditions that exist in the field of view. So t_m is a measure of the level of visibility above threshold contrast.

Calibration

The calibration procedure for background brightness measurements was as follows:

1. The reflectance of a piece of matte white blotter paper was measured. The paper was large enough to fill the entire field of the instrument.
2. The blotter paper was illuminated with a standard lamp.
3. The brightness of the blotter paper was then calculated and again checked with a calibrated Luckiesh-Taylor Brightness Meter. Brightness values from 0.01 to 5.0 ft-lamberts were used.
4. The variable density mirror (visibility index dial) was set to the position of maximum reflectance (97 on the dial). The current in the reference source for veiling brightness was then set at a selected value for a color temperature between 2100 deg and 3000 deg K. With these adjustments made the background brightness dial was rotated until a visual match was made between the central portion of the field and the total field.
5. The above was repeated for several values of background brightness (0.01 to 5.0 ft-l) and various currents in the veiling brightness source. The background brightness dial calibration is shown in Figure 9.

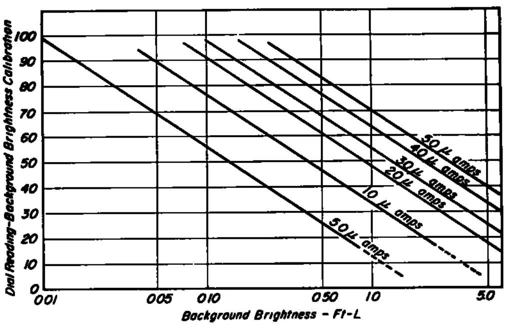


Figure 9. Background brightness dial calibration for visibility meter.

The calibration of the instrument as a threshold contrast meter was as follows on the next page.

1. A series of gray discs 3¼ in. in diameter with diffuse reflectances ranging from 11 percent to 80 percent were made in the laboratory.

2. The discs were placed in the center of a piece of matte white blotter paper which was large enough to fill the total field of the instrument. The field was illuminated with a standard lamp to develop several values of background brightnesses. Observations were made from a distance of approximately 10 ft.

3. The brightnesses of the blotter paper and the discs were calculated and then measured with a Luckiesh-Taylor Brightness Meter.

4. The visibility index dial was set to the position of maximum reflectance of the variable density mirror (97 on the V.I. dial). At this setting the background brightness dial was rotated until a visual match was made with the background brightness.

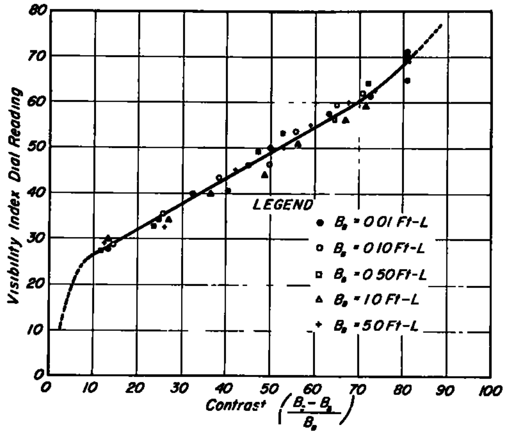


Figure 10. Visibility index dial calibration for visibility meter.

5. The visibility index dial was then rotated until threshold conditions were reached. This is the point at which the gray disc just becomes invisible (or visible). This reading represents the threshold for the particular gray disc and background in use at the time.

6. The above procedure was repeated for several values of contrast using different discs and for several values of background brightness (0.01 to 5.0 ft-l).

7. The actual contrast, $C = \frac{B_o - B_b}{B_b}$, was calculated from the brightness values

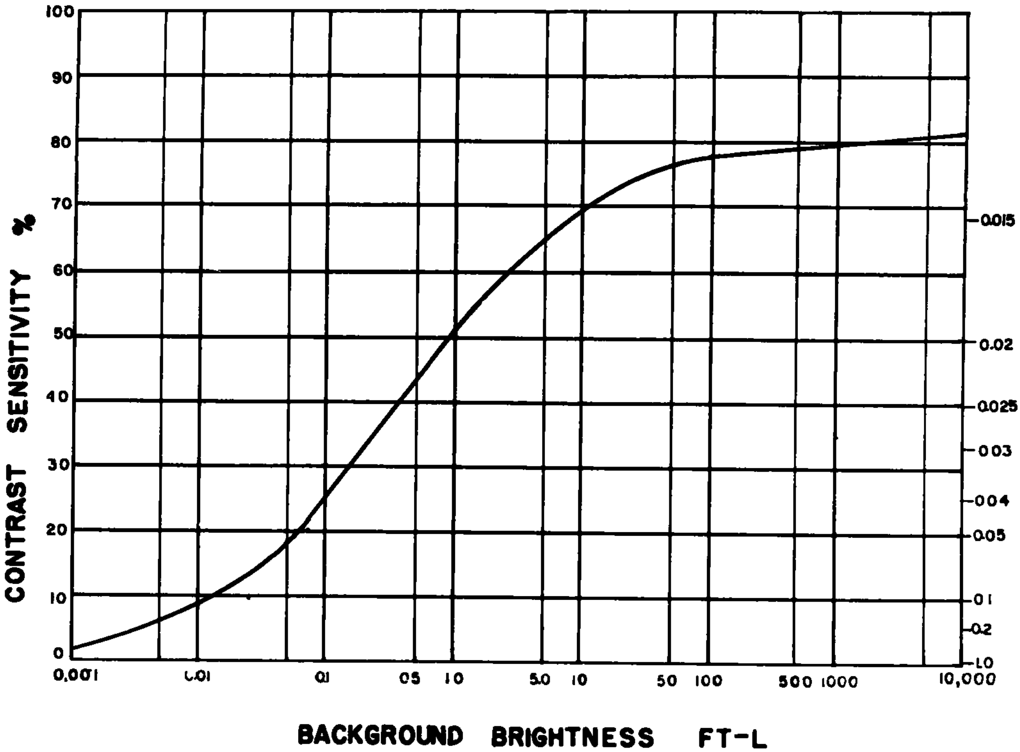


Figure 11. Contrast sensitivity variation.

Figure 12. Outdoor street lighting laboratory-daytime scene.

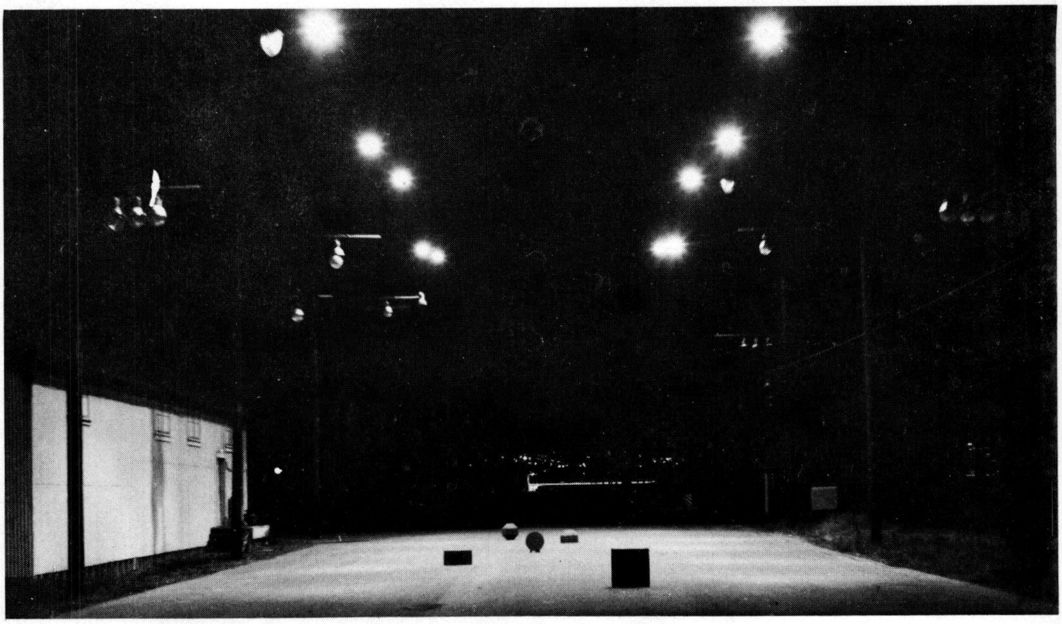


Figure 13. Uniform pattern.

obtained in No. 3. The meter readings for threshold contrast versus the actual contrast were plotted for each background brightness. These data constitute the calibration of the visibility index dial as shown in Figure 10.

It may be observed in the calibration data that the visibility index readings are approximately independent of the background brightness. This fact makes it possible to use a single curve rather than what might have been expected to be a family of curves each having as a parameter the background brightness for the various values of contrast used. From a normal curve of minimum perceptible contrast versus background brightness (Fig. 11) it would be expected that near the lower limit of the calibration curve, viz., 0.01 ft-1, the visibility index would be directly a function of the background brightness. Subsequent calibrations may verify or disprove our present findings which suggest that background brightness is not important in the range of values that we have used.

The Visibility Index

A meter reading on the visibility dial is converted to the visibility index using the calibration curve of Figure 10. The physical significance of the visibility index is this: The object in question has the same visibility as a gray disc with a contrast equal to the visibility index as given by the calibration curve. The disc is assumed to be seen against a uniform background which is at the same average brightness as the scene.

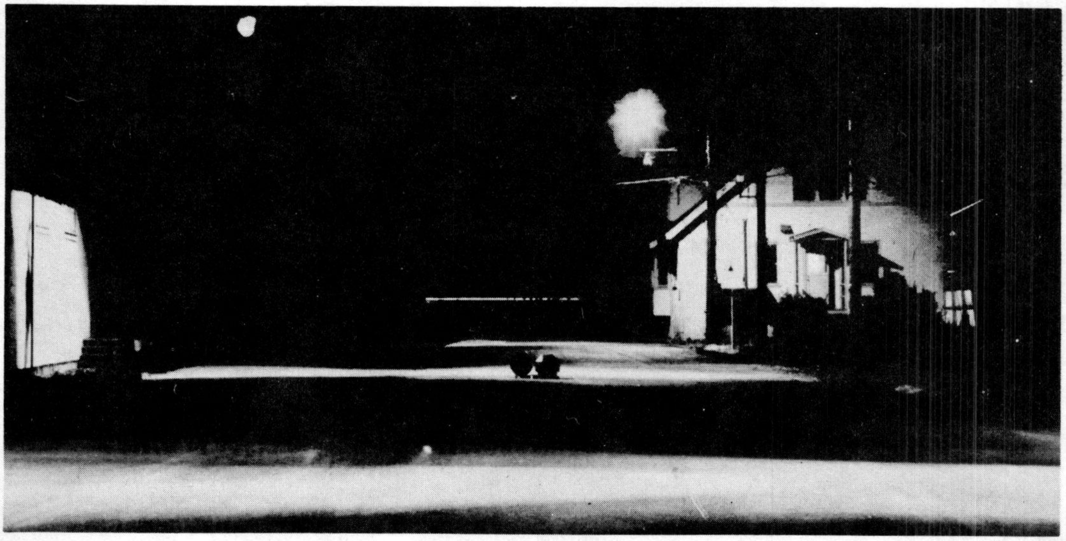


Figure 14a. Non-uniform pattern-targets at 80 feet.

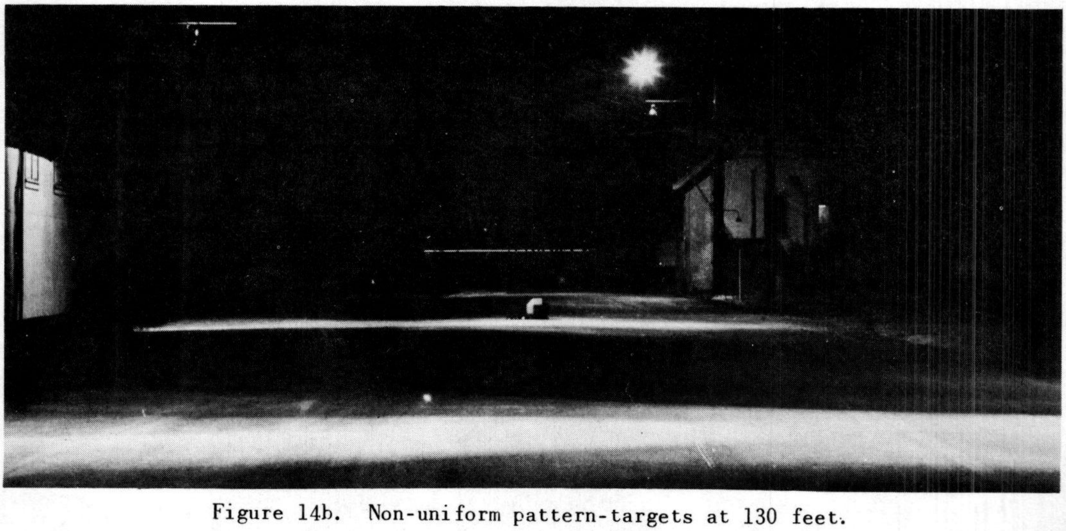


Figure 14b. Non-uniform pattern-targets at 130 feet.

TABLE 1

VISIBILITY MEASUREMENTS USING UNIFORM AND NON-UNIFORM PAVEMENT BRIGHTNESS

(Glare effect of luminaires is excluded—
field of instrument did not include the light sources)

	Uniform Pavement Illumination (1. 3: 1 variation)		Non-Uniform Pavement Illumination (19: 1 variation)		
Object Position	Pavement Brightness = 0. 20 ft-l Br. Ratio = 4:1 in test area		Pavement Brightness = 0. 35 ft-l max. 0. 03 ft-l min. Br. Ratio = 12: 1 in test area		Direct or Silhouette Seeing
	Type of Object		Type of Object		
	Circular Disc	Octagonal Sec.	Circular Disc	Octagonal Sec.	
	Vis. Index	Vis. Index	Vis. Index	Vis. Index	
At 70 ft	39				Silhouette
		28. 5			Silhouette
			0		—
				0	
At 80 ft	39				Silhouette
		31			Silhouette
			10		¼ Silhouette
				15	¼ Silhouette
At 90 ft	39				Silhouette
		34			Silhouette
			30		¾ Silhouette
				32. 5	¾ Silhouette
At 100 ft	39				Silhouette
		42. 5			Silhouette
			45		Silhouette
				51	Silhouette
At 110 ft	40				Silhouette
		48			Silhouette
			45		Silhouette
				51	Silhouette
At 120 ft	43. 5				Silhouette
		43. 5			Silhouette
			41		½ Silhouette
				51	½ Silhouette
At 130 ft	39				Silhouette
		40			Silhouette
			0		—
				44	Direct

The magnitude of the meter reading indicates the visibility above threshold contrast and is called the visibility index. A high visibility index represents good visibility and vice versa.

Preliminary Results

The instrument thus far has been used only for nighttime or low level visibility evaluation. The conditions under which the meter was used have been two different roadway illumination systems. The first system was an experimental uniform illumination (1.3 : 1) system, while the second was an extremely non-uniform illumination distribution system (19 : 1).

A number of visibility measurements were made on several different targets under both systems of illumination. Some of the first reqults of such measurements are shown in Table 1. Photographs of the outdoor street lighting laboratory in the daytime are shown in Figure 12 while the night scenes are shown in Figures 13 and 14.

The results show that the visibility of the circular disc targets remains approximately constant while they are seen against a uniformly bright background developed by closely spaced high mounted luminaires. The visibility index (equivalent contrast) for circular disc targets of 11 percent reflectance is comparatively high. The octagonal section targets showed more variation under the same conditions of illumination due to the directional properties of the lights. This is an important point which needs more attention but will not be discussed here.

While these results are significant, the results of the non-uniform brightness distribution are more spectacular. It can be seen from the results in Table 1 that the circular disc objects completely disappear from view in two positions. Also the visibility index for both objects swing through wide variations. Let us then consider what happens to objects seen on a highway at night. It is subject to the following seeing conditions:

1. The object may be located so as to have sufficient direct illumination to make the object brightness greater than that of its background (positive contrast).
2. The object may be located so as to appear dark against a lighter background (silhouette or negative contrast).
3. The object may be located so that its brightness due to direct illumination is just balanced by the background brightness thereby causing the object to be invisible (at or below threshold contrast).
4. The object may be located so that the direct illumination is very low and its background is dark. Thus, both the object and background brightness are too low to give a contrast above threshold (below threshold contrast).

When the circular disc objects are at 70 or 130 ft on the non-uniform system it can be seen that condition 4 above applies, that is, the brightness of the object is very low and the background is dark causing the object to disappear. When the circular object is in a certain position below the luminaire it can be observed that condition 3 above applies, that is, the object and its background brightness are approximately the same, causing the contrast to go below threshold and the object to disappear. This phenomenon was found to hold true only for the smaller targets having a single plane. The larger objects were usually of sufficient height so as to be in partial negative or positive contrast across alternate dark and light brightness patches at all times.

The results further show that at target locations where the objects have maximum visibility under the non-uniform system, the visibility index is approximately the same as that under the uniform system. In other words, the visibility index does not seem to rise to a significantly higher peak value under the non-uniform system. This would seem to verify many prior suggestions by others that the use of a uniform pavement brightness system has considerable merit. It should be pointed out that the uniform brightness distribution used was approximately constant over the roadway as well as uniform along a longitudinal line so that the visibility of the objects would be approximately the same regardless of position on the roadway.

SUMMARY AND CONCLUSIONS

The principles of operation of a number of designs of visibility meters have been discussed and the limitations of the meters pointed out. A new design for a visibility meter has also been reported which seems to overcome most of the limitations of the previous meters. The details of construction, calibration and use of the instrument are included. It is believed that within the design limitations that are given the meter can be used to obtain reliable visibility evaluations. The meter readings are given in terms of the "visibility index," which is related to the visibility of a circular disc of known contrast.

The results of several field studies using the instrument are reported for two dimensional (circular disc) and three dimensional (octagonal-section) targets when viewed against roadway lighting systems that develop approximately uniform and extremely non-uniform pavement brightnesses. The effect of directional lighting is evident when a three dimensional target is used under either the uniform or the non-uniform system. Much greater variations in visibility were observed under the non-uniform brightness pattern than with the uniform brightness pattern.

In extremes of pavement brightness variation, small targets are much more easily lost in the pattern than larger targets. This is particularly true with two dimensional targets having a single plane. In such cases the target brightness is uniform and it is possible to develop a situation wherein the contrast is below threshold at several positions on a roadway. Some data has been obtained for tall thin targets simulating pedestrians. These preliminary data indicate that for practically all positions on the roadway the target is above the contrast threshold at some point on the target and therefore extremes of visibility do not occur but the average level of visibility is less than that obtained for a smaller target. Also information concerning the variation in visibility over the test area of the roadway is not as evident when such targets are used. Therefore it is believed that for evaluation purposes smaller targets in the order of 12 to 18 in. in principal dimension are more suitable for appraisal purposes than targets simulating pedestrians.

The importance of the roadway brightness pattern in developing nighttime roadway visibility is evident from the preliminary data presented herein. It is apparent that more attention will have to be placed on this aspect of lighting by the engineers who are designing roadway illumination systems.

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