Luminaire Light Distribution Principles

By CHARLES REX

MODERN ROADWAY lighting practice involves luminaire light distributions which are controlled and proportioned to provide efficient seeing and to aid the rapidly increasing night use of our multibillion dollar investment in motor vehicle transportation. Streets, highways, autos, trucks and busses represent a business which must be kept open after dark.

The comfort, convenience, and safety objectives of luminaire development and application are of significance to the public. Hence there is an impelling obligation to investigate and evaluate prospects for the improvement of the seeing effectiveness of roadway lighting. This engineering work is currently underway. It includes several of the Society's Committee and Research activities.

Correlation of objective data with laboratory, field, calculated, and in-practice studies will have a common basis comprising the roadway, the vehicle and the driver. This obviously should be the basis for the presentation of luminaire light distribution data.

This paper includes suggested methods for presentation of the current light distribution principles for better understanding and appreciation of the considerable effect which directional control and proportioning of luminaire candlepower has on the factors involved in seeing.

Light Distribution from Longitudinal Roadway Lines

Candlepower distribution curves should be consistent with seeing data and the dynamics of typical motor vehicle movement along the roadway. These movements are generally linear. The eyes of the proceeding driver or observer view a succession of brightness areas which may be represented by the brightness along longitudinal roadway lines. This viewing is constantly subject to fluctuating adverse brightness effects from luminaire brightness and light entering the vehicle windshield.

Inclined Plane Candlepower Curves

For example, the candlepower distribution curves shown in perspective diagrams Figs. 1 and 2 are directly related to the well-known pavement brightness factor in roadway lighting. The shape of the luminaire candlepower curve is proportioned to obtain the desired pavement brightness at typical locations when observed from a typical series of specific driver viewing positions. Assuming constant conditions of pavement reflection and viewing, an increase or decrease in pavement brightness on the roadway is directly proportional to differences in the candlepower light distribution curves. Hence the effectiveness of different candlepower distributions, in providing pavement brightness, may be compared without the necessity of the customary intermediate brightness computations.

Representative Roadway Lines

The number of longitudinal roadway lines along which the luminaire light distribution data should be provided, obviously depends upon the variables involved and the detail desired. The 0.5 MH (mounting height) and 1.5 MH longitudinal lines[1,2] might be representative of the most important pavement areas of a typical roadway layout such as that shown in Fig. 3. Similarly, longitudinal lines at *H* ("House Side") 0.5 MH and 2.5 MH street side may be representative of the areas adjacent to the pavement.

Brightness stations are spaced at uniform longitudinal distances along the roadway in multiples of the mounting height. The accompanying transverse lines form unit areas. Road brightness stations designated X might be typical of those used for field investigations or check of calculated data. For the purpose of this paper, data have been calculated at longitudinal intervals of 0.5 MH up to distances of 10.5 MH from each luminaire.

As shown in Fig. 3, the observer view and direction of travel is toward luminaires No. 3, No. 4, No. 5 and No. 6. The suggested observer-eye position is 4.3 feet[3] above the pavement with a longitudinal road brightness viewing distance of 7 MH, which with 30 feet MH is 210 feet. All subsequent illustrations are based upon observer positions along the longitudinal roadway line at transverse distance of 1.5 MH with respect to luminaires No. 1 or No. 3 (which is at 0.5 MH with reference to luminaires such as No. 2 or No. 4).

The inclined-plane candlepower distributions

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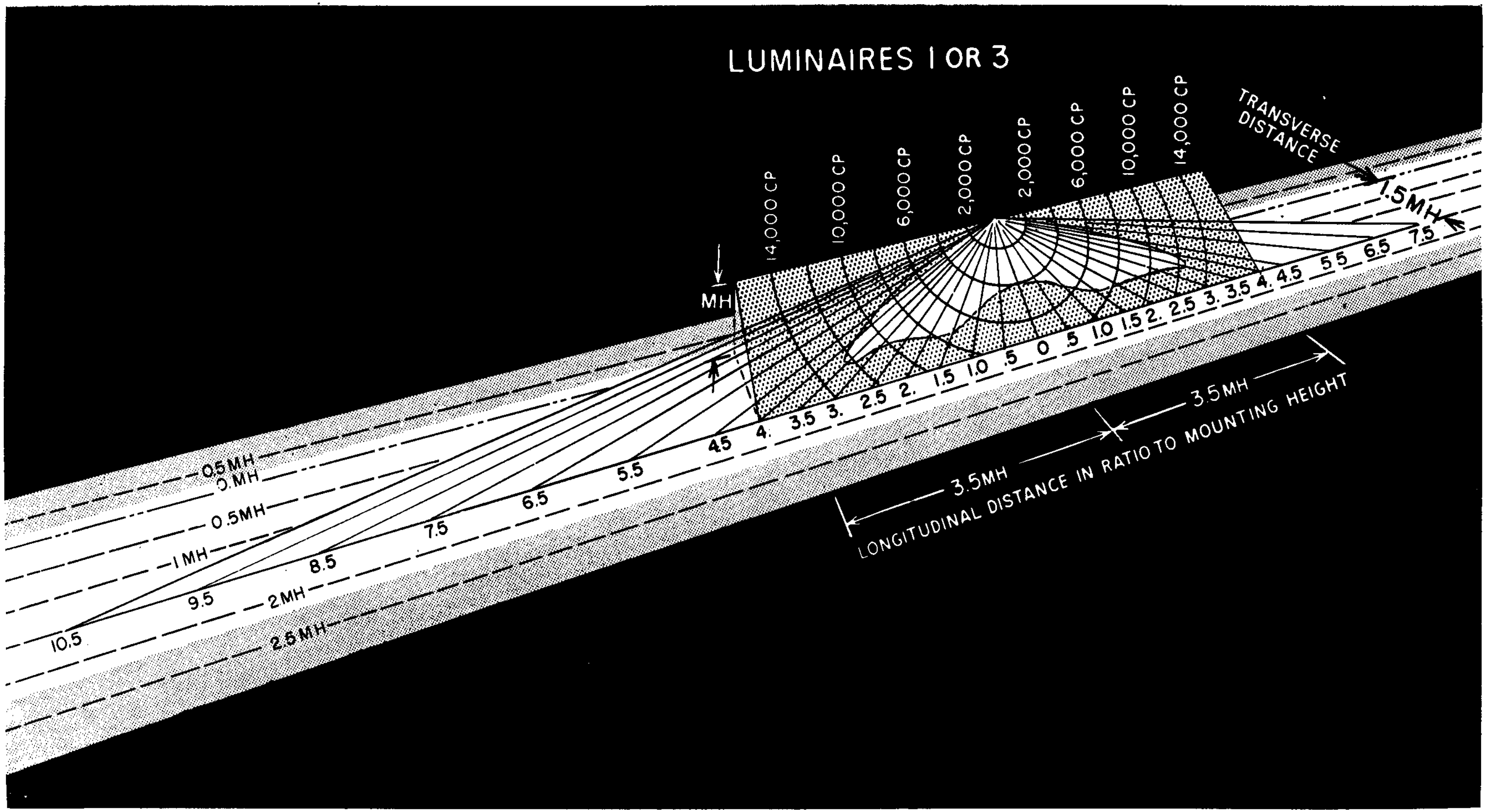

Figure 1. Buildup and proportioning of luminaire candlepower along 1.5 MH longitudinal roadway line shown in an inclined plane light distribution curve. From specified driver-observer and viewing distances, variations in pavement brightness are in proportion to variations in candlepower. This light distribution curve is hypothetical from Figure 15.

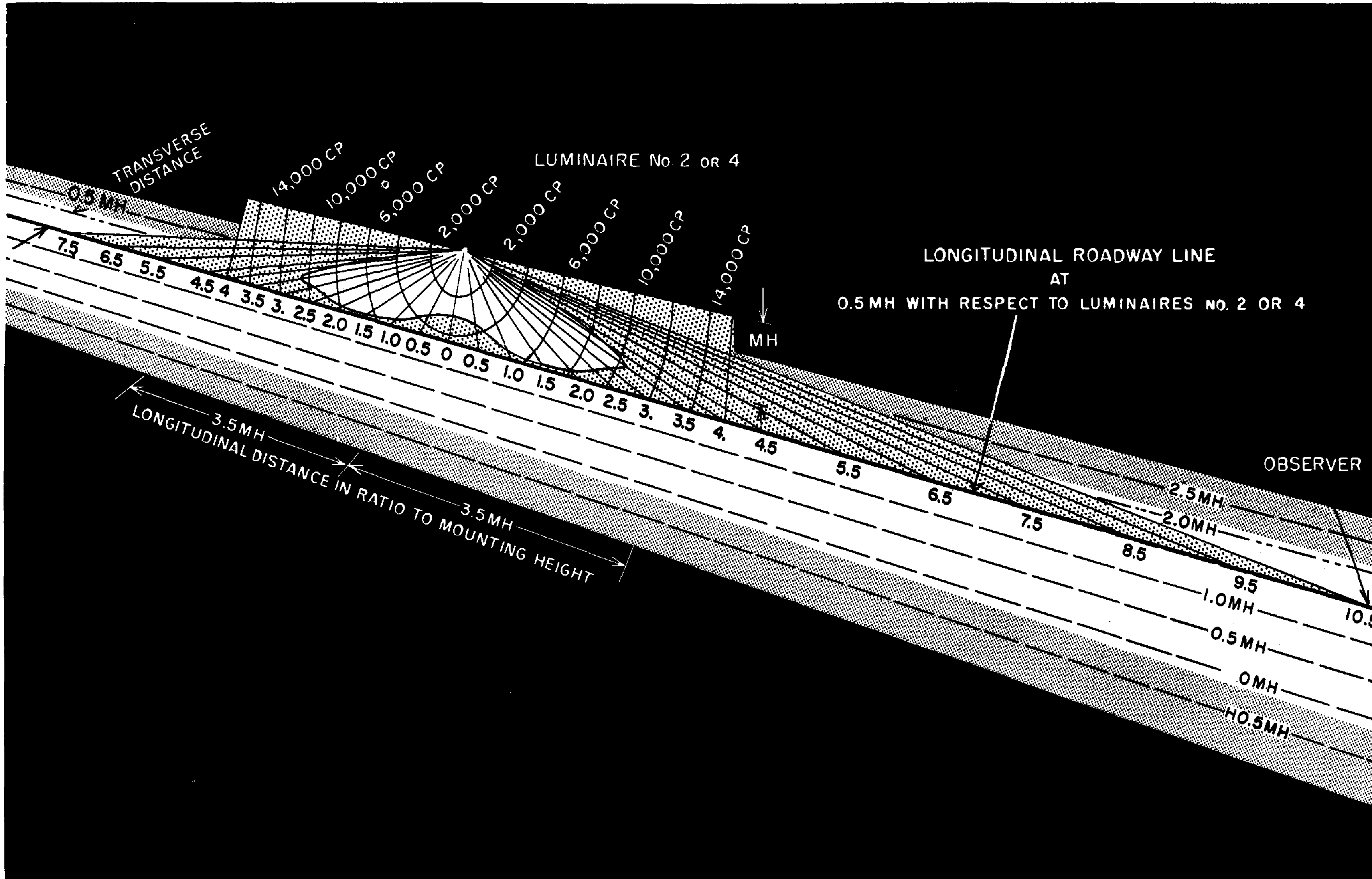

Figure 2. Directional control of luminaire candlepower along a longitudinal roadway line at transverse distance of 0.5 MH with respect to luminaires such as 2 or 4 and at transverse distance of 1.5 MH with respect to luminaires such as 1 or 3.

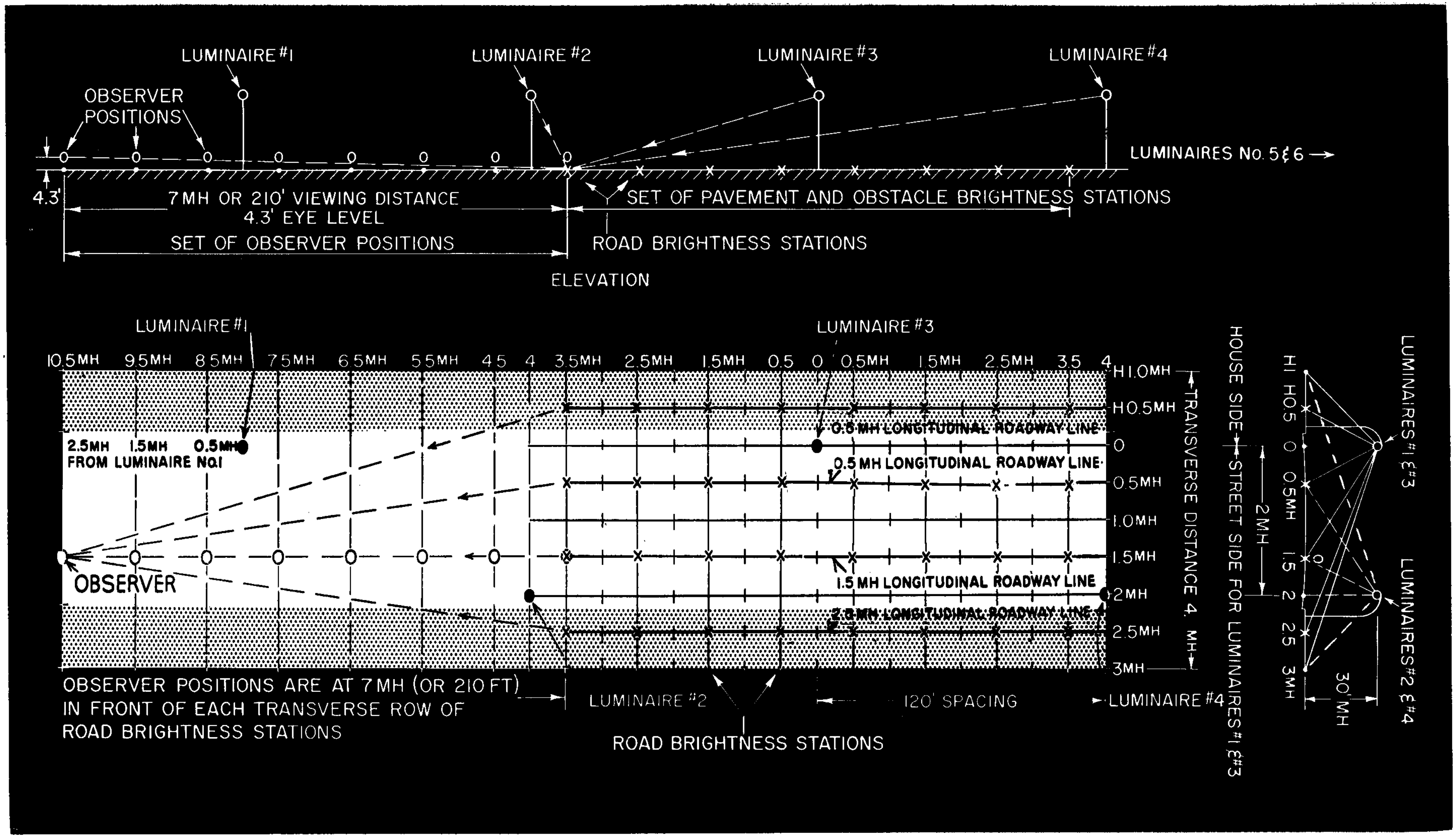

Figure 3. Representative layout of longitudinal and transverse roadway lines, driver-observer positions, and luminaire locations assumed for purpose of explanation and calculation of pavement brightness. Note in transverse section at right that 1.5 MH line with respect to luminaires No. 3 and No. 5 is the same as 0.5 MH line with respect to luminaires No. 2 and No. 4.

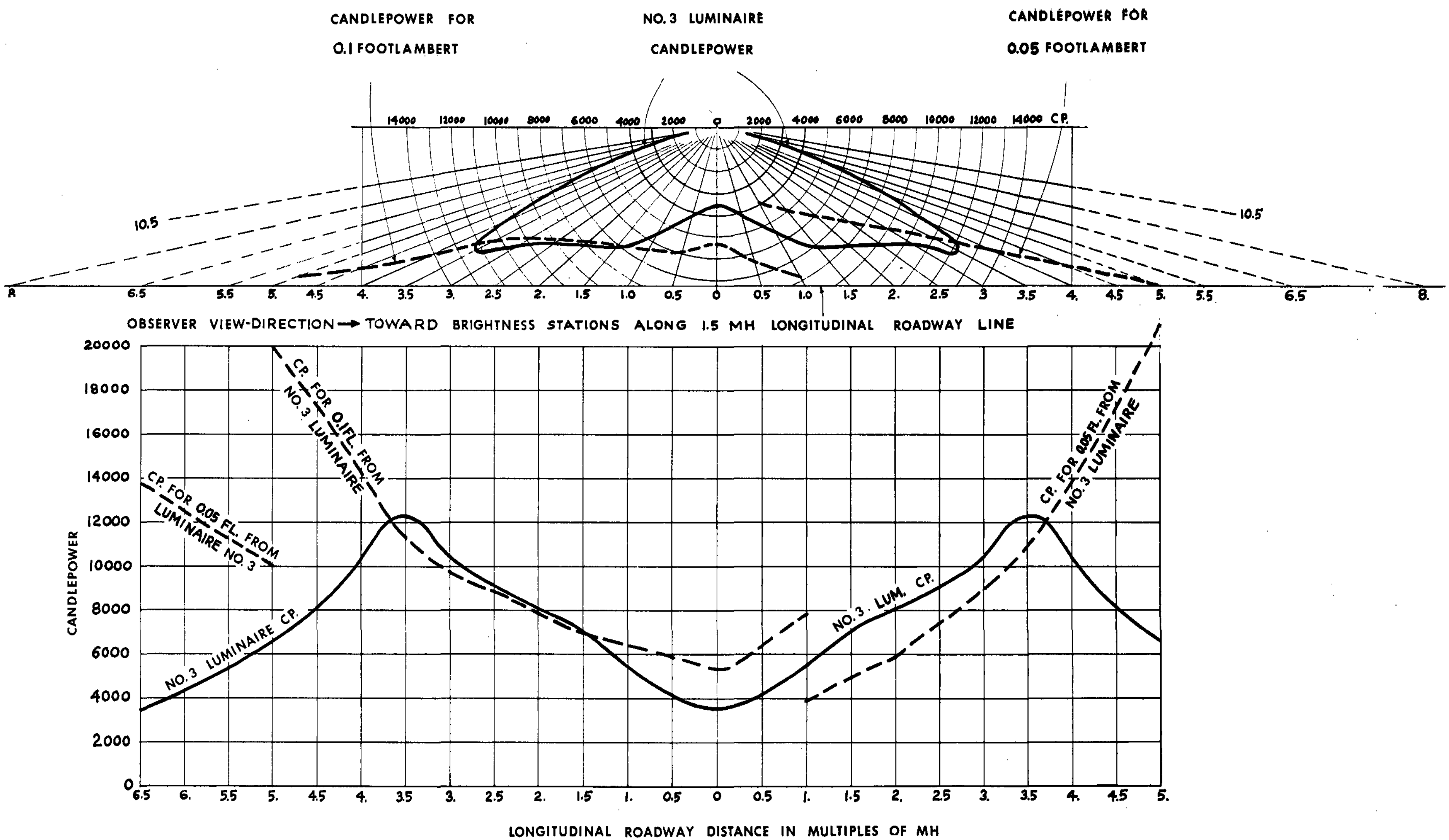

Figure 4. Candlepower required to produce uniform 0.1 and 0.05 footlambert levels of linear pavement brightness along the 1.5 MH longitudinal roadway line and diver-observer viewing path. Upper diagram shows plane-of-paper projection of 1.5 MH inclined plane light distribution from luminaire comparative interpolation gives pavement brightness produced by luminaire, based upon Reid-Chanon data for asphalt pavement.

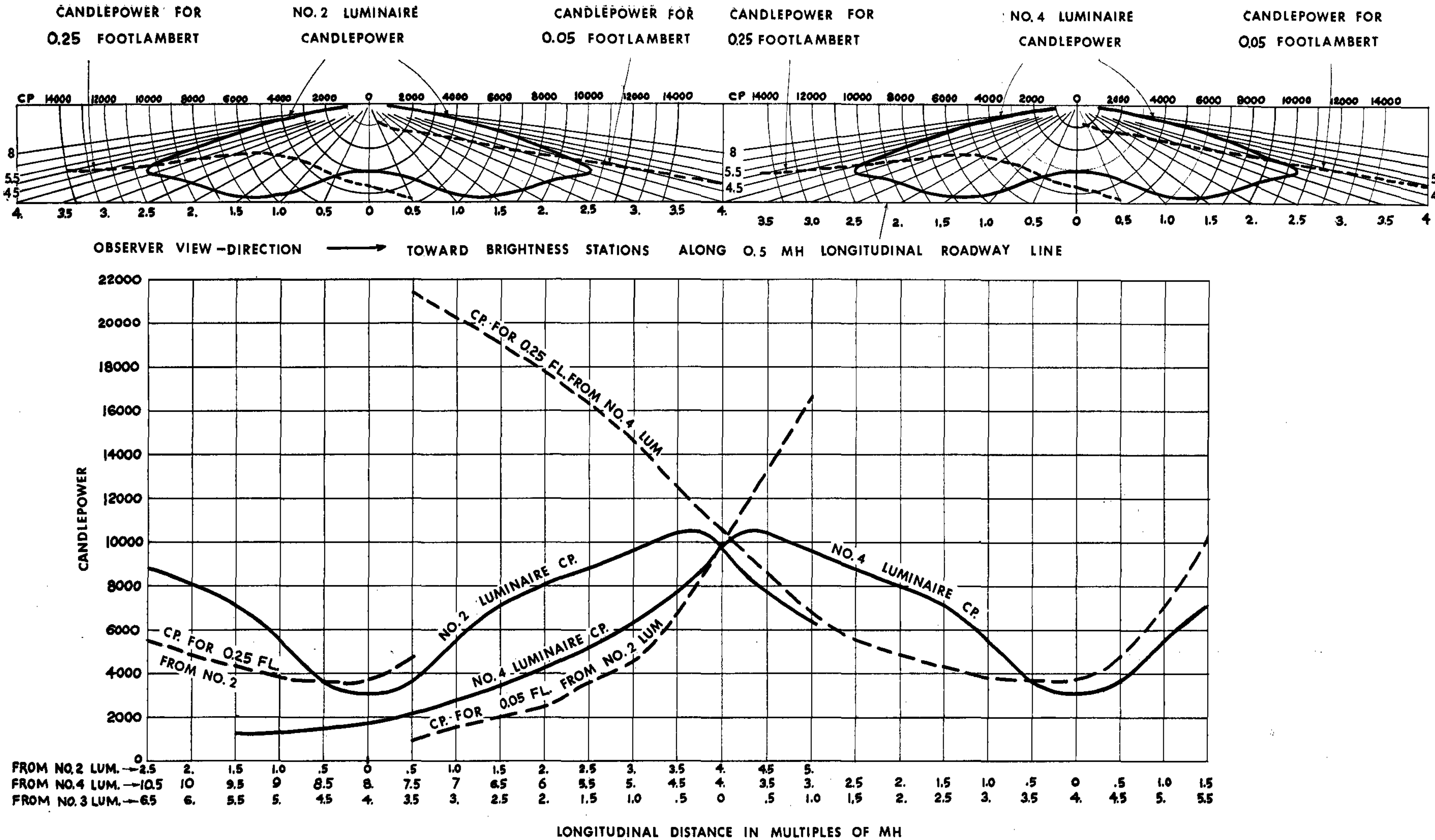

Figure 5. Candlepower from No. 2 and No. 4 luminaire locations required to produce uniform 0.25 and 0.05 footlambert levels of linear pavement brightness along longitudinal roadway line and driver-observer viewing path at transverse distance of 0.5 MH with respect to luminaires No. 2 and No. 4 or at 1.5 MH with respect to luminaire No. 3. Upper diagram shows plane of paper projection of 0.5 MH inclined plane light distribution from luminaire. Comparative interpolation gives pavement brightness produced by each luminaire based upon Reid-Chanon data for asphalt pavement.

shown in the upper portion of Figs. 4 and 5 are normal-to-plane projections of curves shown in Figs. 1 and 2. Dimensions will be to scale including the length of radial lines from the luminaire light center to the points marked off along the roadway line.

The candlepower curves shown in all illustrations are hypothetical having been estimated from the luminaire light distribution isocandle diagram, Fig. 15. This distribution, except for the increase of each candlepower value by 2.5, is the same as the isocandle diagram Fig. 15, Appendix, American Standard Practice for Street and Highway Lighting.[1]

Pavement Brightness Effectiveness

The effectiveness of the luminaire candlepower distribution in providing specific levels of pavement brightness may be judged by comparison with the dash line curves on Figs. 4 and 5 showing the amount of candlepower from the location of the luminaire that is required to produce designated levels of uniform pavement brightness.

The pavement brightness has been calculated from a new iso-pavement brightness diagram based upon longitudinal and transverse roadway distances in multiples of 30-foot mounting height. This new diagram is based on the original Reid-Chanon[4] data on traffic-used asphalt pavement as compiled by J. E. Bock.[5]

It is readily apparent that other candlepower curves similarly plotted in 1.5 MH and 0.5 MH inclined planes may be compared with respective light distributions for desired levels of pavement brightness. Such data, to be made available along representative longitudinal lines, will by interpolation indicate the pavement brightness effectiveness of a specific luminaire light distribution (vice versa for effectiveness of different types of pavement surface).

Linear Pavement Brightness for System

Fig. 6 combines the pavement brightness produced by the light distribution from each of six luminaires along the representative longitudinal roadway line for a distance of 8 MH or 240 feet. With the spacing assumed, the pattern for additional luminaires would be substantially repetitive.

The comparative extent by which each light distribution contributes to the pavement brightness and relative visibility is shown as well as the importance of luminaire placement with respect to the roadway brightness line, the driver-observer path and viewing direction.

The extent by which the light distribution from luminaires No. 4, No. 3 and No. 2 predominate is to be expected and would be increased with sharper cutoff of light at longitudinal distances of 4 to 5 MH from the luminaire. The desirability of proportionately higher candlepower along the 1.5 MH line from No. 3 luminaires is also apparent.

Visibility and Linear Brightness

The effectiveness of the light distribution in providing visibility by pavement brightness is obvious. The arithmetical average of relative visibility is 2.12. This visibility is correlated with the Luckiesh-Moss Visibility Meter.[6] It pertains to discernment of an obstacle having 100 per cent contrast per Reid-Chanon data.[4] The average combined pavement brightness is 0.38 footlamberts with about 0.8 ratio minimum to average.

The same inclined plane method will yield luminaire candlepower distribution and pavement brightness data along other representative longitudinal roadway lines. These may be combined with the above data for an average pavement brightness over the desired roadway width. For example, the 0.5 MH line with respect to luminaires such as No. 3 as viewed from the same 1.5 MH driver-observer path involves different pavement brightness curves, but could use the same 1.5 MH and 0.5 MH luminaire light distribution curves. The pavement brightness along the adjacent-to-pavement longitudinal roadway lines, *i.e.*, 0.5 MH and 2.5 MH requires different inclined-plane candlepower distribution curves as well as pavement brightness curves. Also an assumption is required as to the reflection characteristics of the ground level surface along the adjacent-to-pavement longitudinal lines.

The brightness calculation of obstacles or targets Fig. 17 at locations along the roadway lines involves agreement with respect to reflectance which may be considered typical or representative. This and standardization of target size has already been brought to the attention of several of the I.E.S Committees in progress reports by Professor D. M. Finch.[7] Generally, light distributions which are effective in producing pavement brightness are also desirable in producing obstacles brightness for discernment by surface detail and reverse silhouette. Similarly the linear brightness of portions of the "surround" such as building facades are subject to calculation after assumptions are made with respect to transverse location and reflection. This may be important for visual comfort as well as visibility.

Future comparative evaluations will determine the extent by which the effect of indirect light should be considered as reflected from surfaces such as pavement, sidewalks and buildings.

Seeing Objectives and Eye Level Candlepower

Important additional factors pertaining to the seeing effectiveness of roadway lighting are shown in Fig. 7. This has been prepared[8,9,10] to facilitate understanding of text Appendix Section A, American Standard Practice for Street and Highway Lighting.[1]

Factors such as Luminaire Brightness, Brightness Fluctuation, and Disability Veiling Brightness involve the luminaire light distribution effect on the eyes of the driver-observer. To include vehicle movement, this effect may be depicted by an eye-level longitudinal line parallel with but 4.3 feet[3] above a longitudinal roadway line such as that designated 1.5 MH.

Inclined Plane Distribution to Eye Level Line

There are several evaluation studies[7,11,12] now underway which include appraisal of visual comfort factors and for increased recognition of the advantageous control of luminaire candlepower distributions for restriction of luminaire brightness and disability veiling brightness. To aid these studies, it is recommended that use be made of the inclined-plane-to-eye-level-line presentations of luminaire light distributions. As shown in Figs. 8 and 9 these inclined planes are based upon the longitudinal driver-observer eye-level line. Except for this, these inclined planes are similar to those previously shown and described.

As illustrated in Fig. 10, the longitudinal and

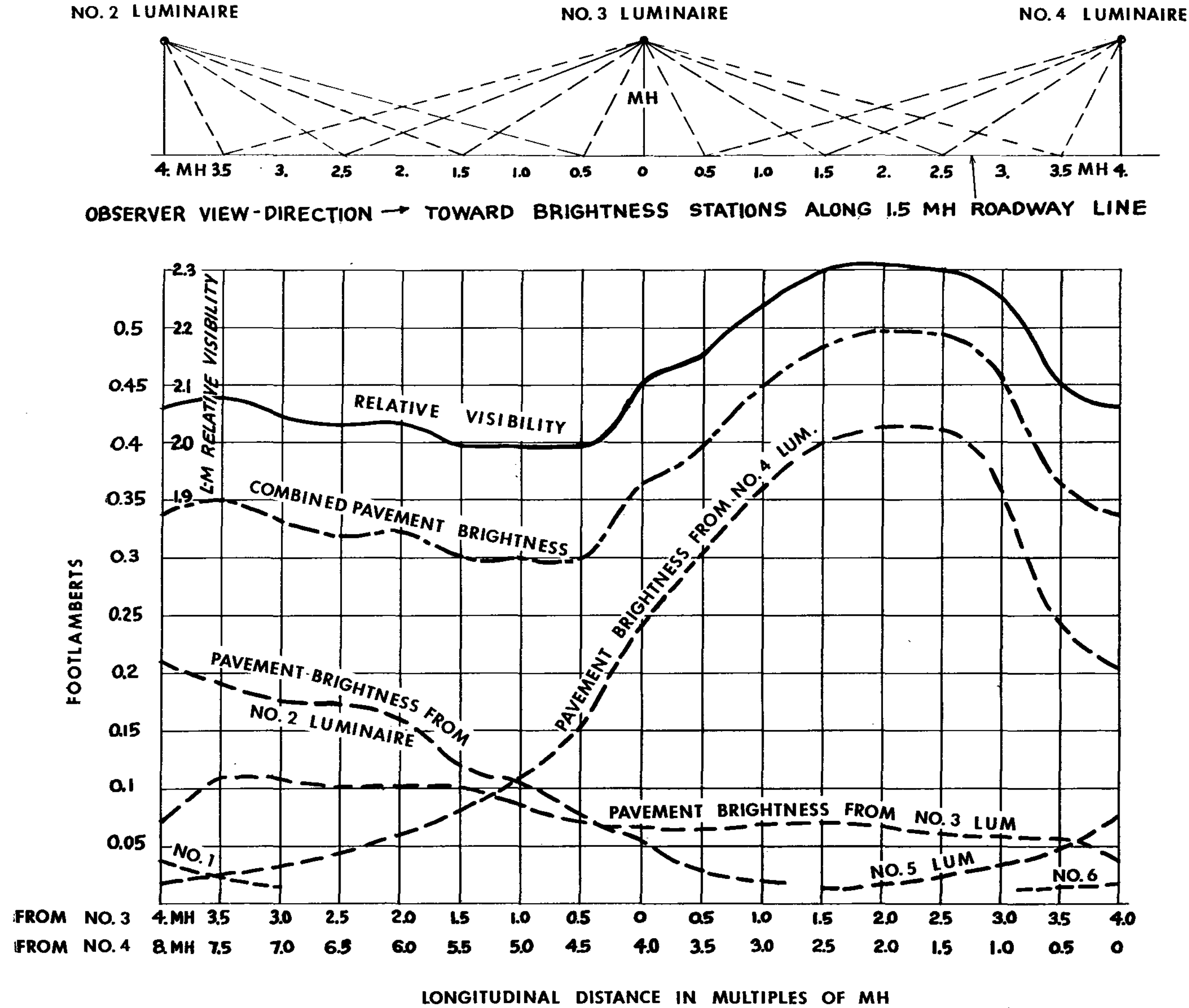

Figure 6. Combined system versus component linear pavement brightness along longitudinal roadway line and observer viewing path at 1.5 MH with respect to luminaires such as No. 3 and 0.5 MH with respect to luminaires such as No. 4. Combined relative visibility derived from Reid-Chanon data based upon Luckiesh-Moss Visibility Meter, asphalt pavement and 100 per cent contrast obstacle, luminaires are spaced 4 MH, or 120 feet, staggered.

transverse distances and spacings are similar to and coordinated with the foregoing based upon Fig. 3. The 1.5 MH driver-observer eye-level line for luminaires such as No. 1 and No. 3 is the same as the 0.5 MH eye-level line for luminaires on the observer's right such as No. 2 and No. 4.

If this one line is considered representative of a typical driver's eye-level path, along a roadway layout such as Fig. 10, only the two 0.5 MH and 1.5 MH inclined planes to eye-level will be required for check of candlepower pertaining to luminaire brightness, disability veiling brightness, and fluctuations thereof.

Luminaire Brightness and Disability Veiling Brightness

The single luminaire perspective diagram Fig. 11 may be used to illustrate luminaire brightness and disability veiling brightness calculations as listed in Table I. At the left of the diagram, observer positions A and B are at longitudinal distances of 6.5 MH and 3.5 MH respectively along the 1.5 MH eye-level line. At the right of Fig. 11, observer positions H and G are at the same longitudinal distances, 6.5 MH and 3.5 MH respectively, but on the 0.5 MH line.

The luminaire brightness viewed from H and G is less than that toward A and B in proportion to the difference in candlepower. This assumes a constant projected illuminated area of the luminaire. Otherwise the brightness would decrease in proportion to an increase in projected area.

The effect of the angles on visual comfort has not

TABLE I — Examples of Luminaire and Disability Brightness Calculations Referring to Figure 11.

Observer Position	A	B	G	H
Longitudinal distance				
along 1.5 MH line	6.5 MH	3.5 MH		
along 0.5 MH line			3.5 MH	6.5 MH
Luminaire Candlepower	2000	9700	3750	1200
Luminaire brightness cd./sq. in. assuming 100 sq. in. proj. area	20	97	37.5	12
D,—Distance from source (MH)	6.7	3.9	3.64	6.57
D,—Distance in ft. (30 × MH)	116.8	201	109.3	197.2
D^2,—Distance squared	13642	40441	11946	38888
E,—Footcandles at eye	.049	.711	.314	.0463
θ,—Angle, source & sight line (deg.)	14	26	16	8.5
Angle θ to 2.5 power	733	3420	1039	211
Angle θ to 1.8 power	116	350	149	47
Disability veiling brightness foot (lamberts)				
Fry Alpern $\frac{22.4\,E}{\theta^{2.5}}$	.0015	.00466	.018	.00492
Holladay $\frac{23\,E}{\theta^{1.8}}$	.0098	.0467	.130	.023
Reduction in Visibility per Holladay and Reid-Chanon data	12	26.5	38.5	19

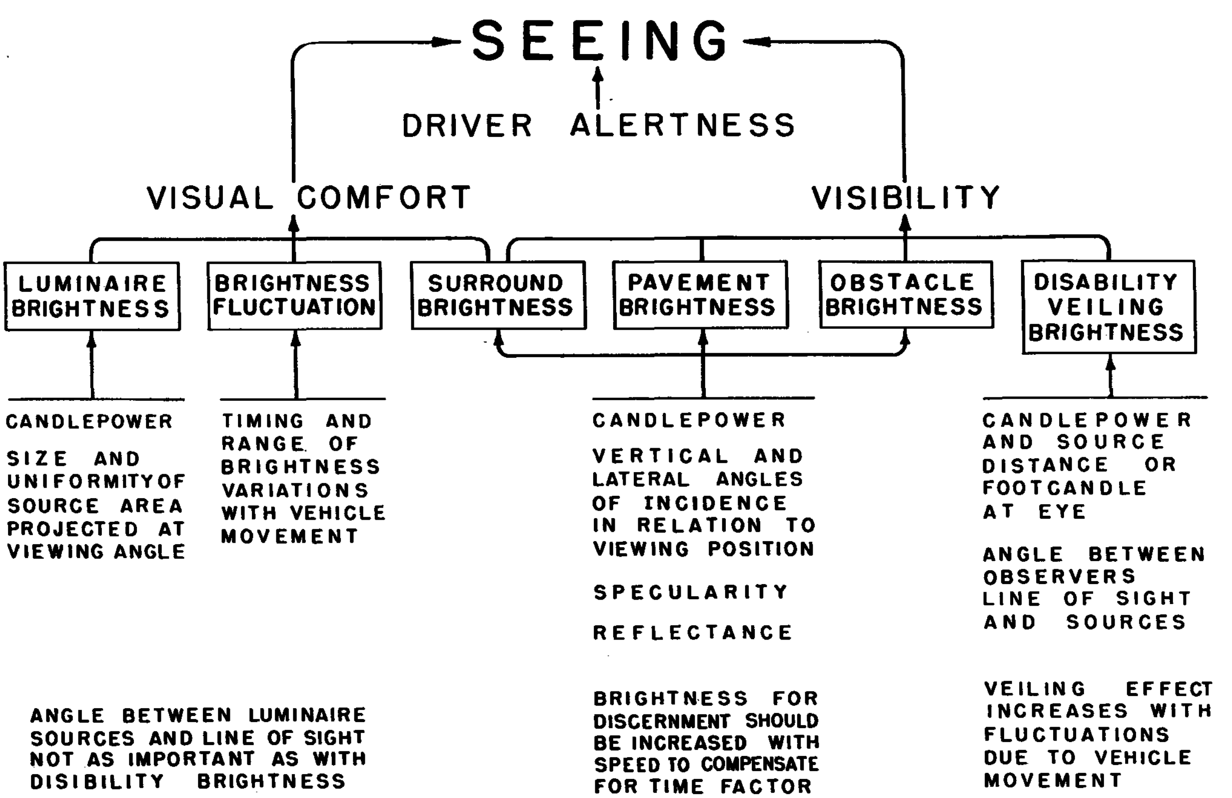

Figure 7. Seeing factors in roadway lighting. Objectives such as relatively nominal luminaire brightness, disability veiling brightness and fluctuations with vehicle movement involve control of luminaire candlepower along longitudinal line at driver-observer eye level. Top of automobile windshield cutoff and vehicle speed are also involved. It is assumed that objects to be discerned are of typical size such as a brick, person, or vehicle.

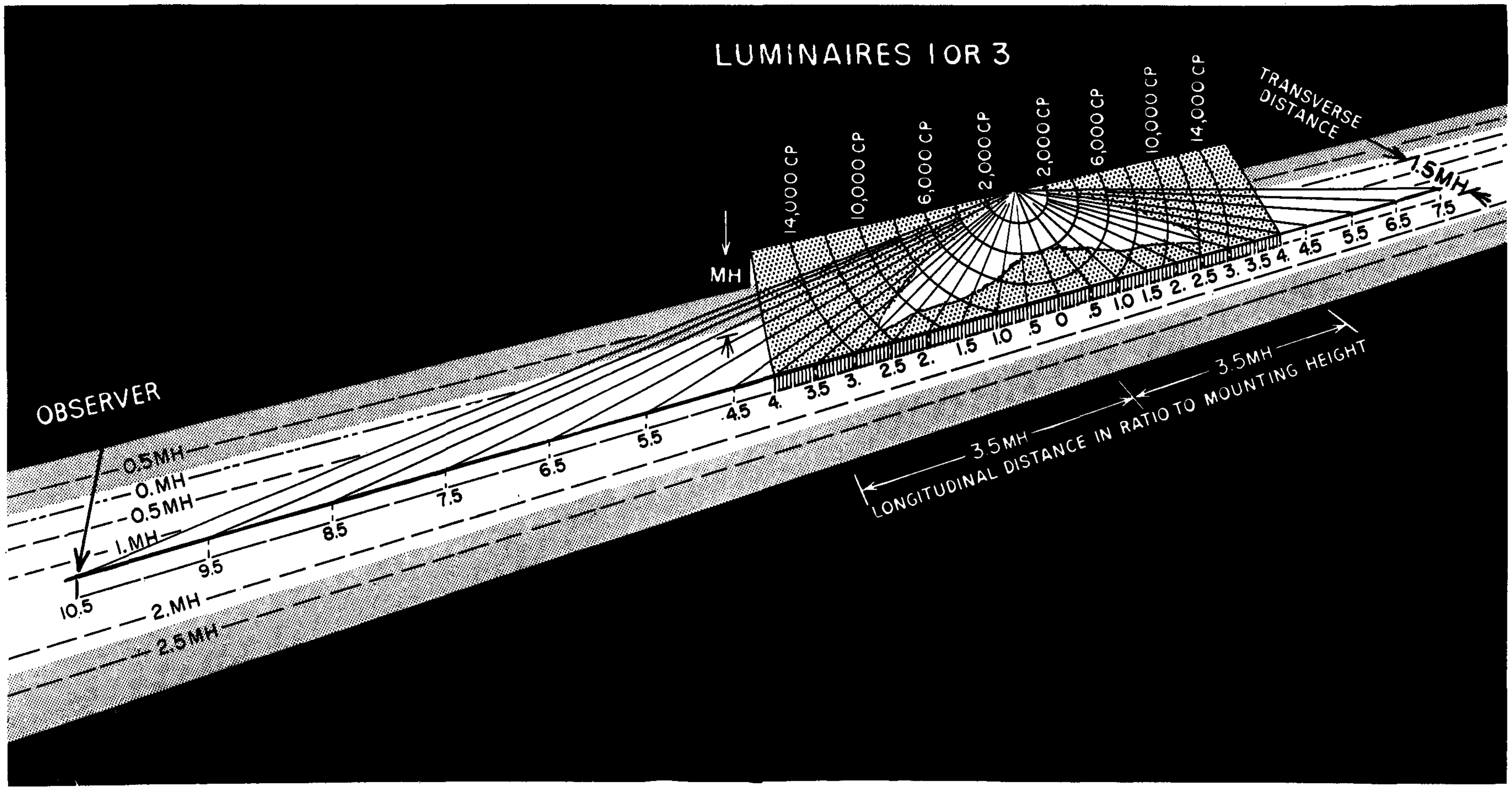

Figure 8. Control of luminaire candlepower along driver-observer eye level longitudinal line 4.3 feet above 1.5 MH line shown in an inclined plane light distribution curve on perspective diagram. Luminaire brightness is proportional to candlepower if projected area is constant. Light distribution curve is from Figure 15.

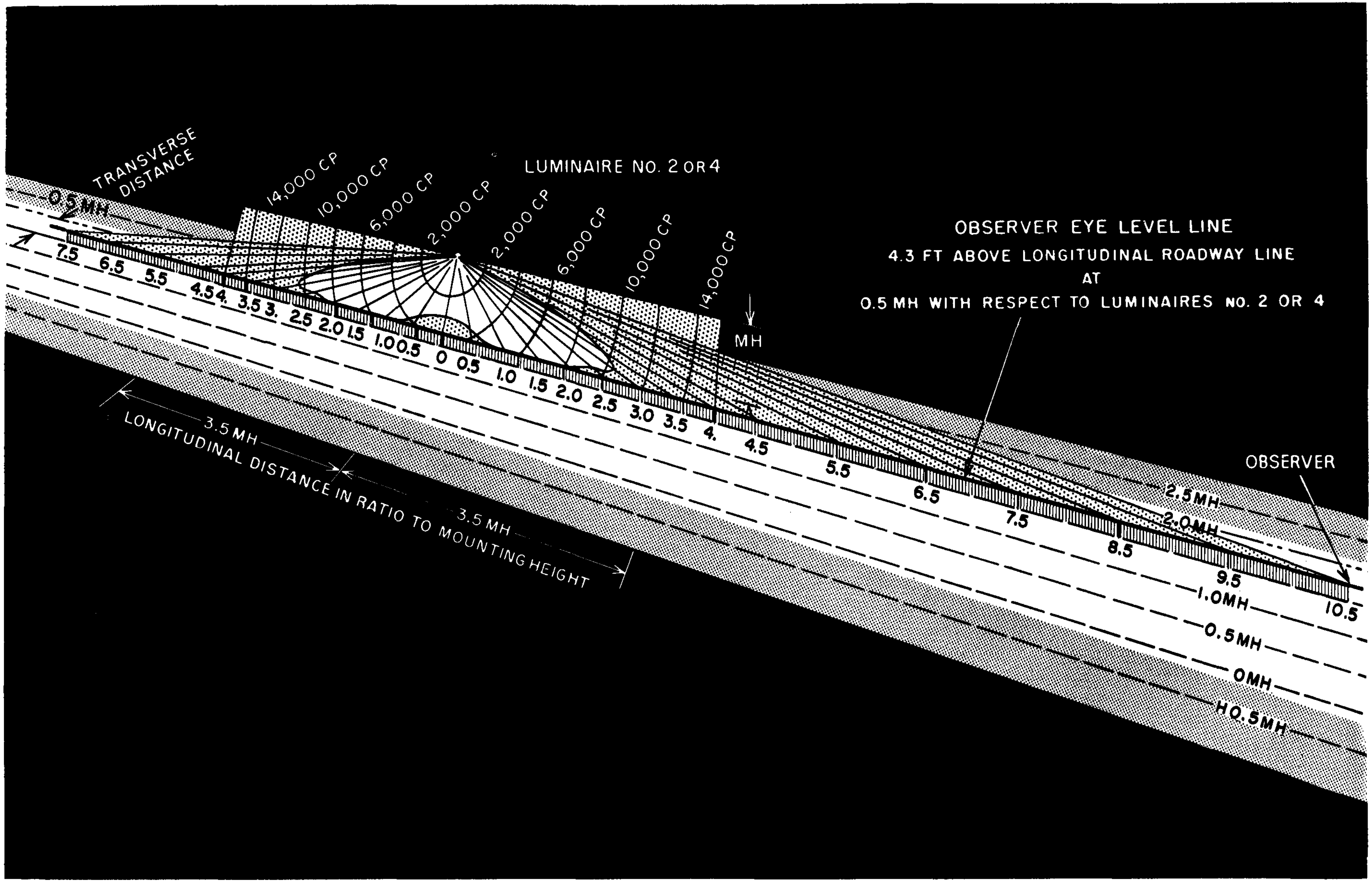

Figure 9. Directional control of luminaire candlepower along driver-observer eye level line which is 4.3 feet above roadway line at 0.5 MH with respect to luminaires such as 2 or 4 and at transverse distance of 1.5 MH with respect to luminaires 1 or 3.

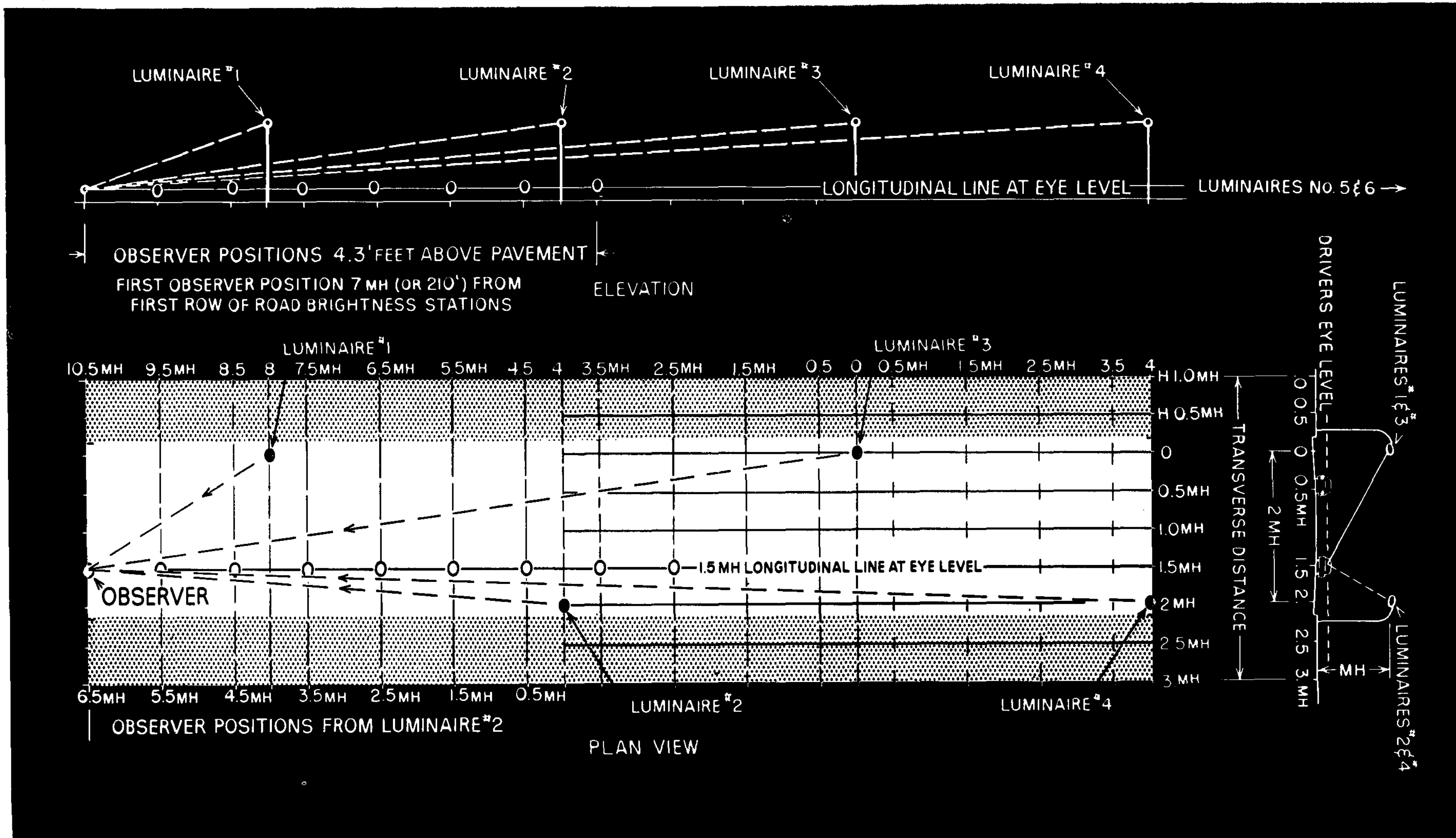

Figure 10. Representative roadway layout showing longitudinal eye level line, driver-observer, positions and luminaire locations assumed for purpose of explanation and calculation of luminaire brightness and disability veiling brightness. Note in transverse section at right that the 1.5 MH eye level line with respect to luminaires such as No. 3 is the same as 0.5 MH line with respect to luminaires such as No. 4.

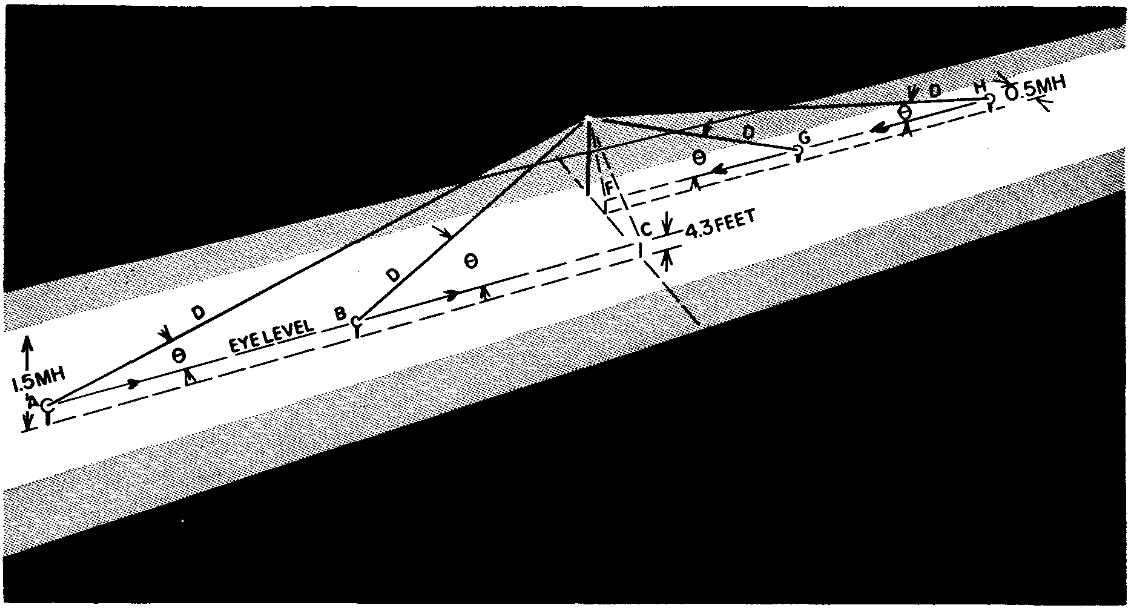

Figure 11. Distances between luminaire and driver-observer eye positions and angles θ with respect to line of sight along longitudinal eye level line at 0.5 MH and 1.5 MH. For data refer to Table I.

been calculated because of lack of data which is known to be applicable to roadway lighting conditions. The best estimates indicate that the threshold of discomfort does not increase uniformly or in proportion to an increase in angle with the line of sight.[13]

In contrast, the disability veiling brightness decreases quite appreciably in proportion to the degree increase in angle raised to the 1.8 or 2.5 power. The difference in exponent depends on whether the Holladay[14] or Fry-Alpern[15] formula is used. In Fig. 11 and subsequent illustrative calculations, the driver-observer line of sight is assumed to be along the eye-level line. As indicated the angles in degrees between this line of sight and the line *D* from the observer's eyes to the luminaire are in the inclined planes.

At comparable longitudinal distances, the disability veiling brightness and loss of visibility along the 0.5 MH eye level line is appreciably higher than that along the 1.5 MH eye level line because of the large difference in angles θ. The per cent loss in visibility is from Reid-Chanon data[4] correlated with Holladay[14] calculations, and the Luckiesh-Moss Visibility Meter.[6] The Reid-Chanon data include the 20 per cent increase found to be caused by the fluctuation with vehicle movement at 25 to 40 miles per hour under representative roadway lighting. It also includes losses due to reflected glare.

Candlepower for Levels of Disability Veiling Brightness

In the upper portion of Figs. 12 and 13 the candlepower curves are shown in projections normal to the inclined plane. In such a plane of paper projection, the angles between the eye-level line and the radial lines to the luminaire light-center are the angles θ mentioned in reference to Fig. 11. The distances along these radial lines will be to scale with respect to the mounting height and longitudinal roadway distances along the eye-level base line.

The candlepower from the luminaire location which will produce the designated uniform levels of disability veiling brightness is shown on the dash-line candlepower curves. This is also shown on the rectangular plot in the lower portion of the diagram.

The approximate 3 to 1 difference in disability veiling brightness along the 0.5 MH eye level line at longitudinal distance such as 9.5 MH and 10.5 MH are to be expected from the difference in the formulas.[14, 15] The angles at these longitudinal distances are about 6 degrees and 5 degrees respectively, exceeding the 4.5-degree limit mentioned with respect to the Fry-Alpern formula. The latter formula has been used advisedly so that its applicability to roadway lighting may be appraised.

Automobile Windshield Cutoff Helps

The large shaded portion of the candlepower distribution shown in Figs. 12 and 13 is assumed to be shielded from the observer-driver view by the top of his automobile windshield. The longitudinal distance of 3.3 MH to a point along the eye-level line has been adopted as a reasonable average approximation representative of 1955 automobiles.[9,16]

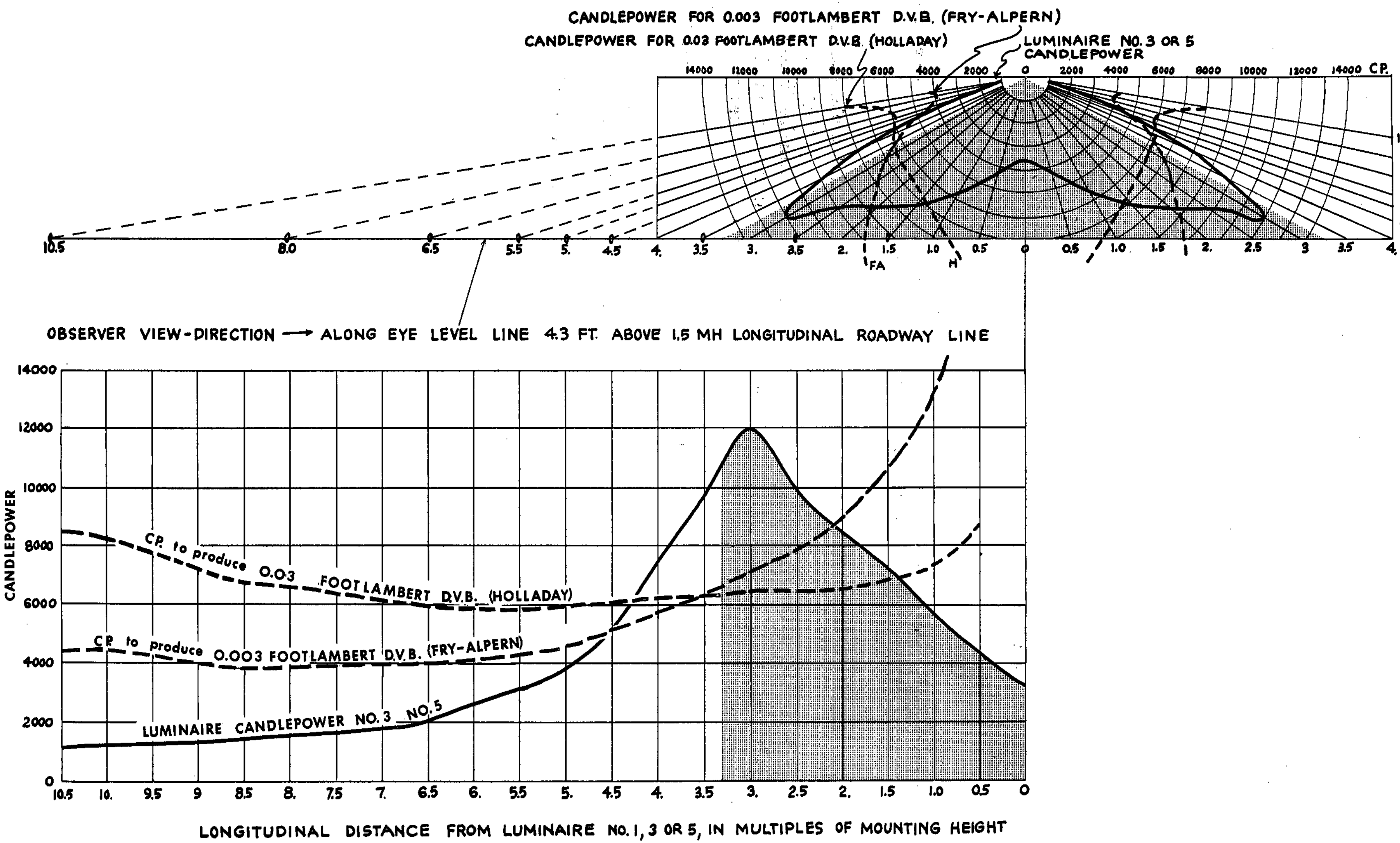

Figure 12. Candlepower from location of luminaire such as No. 3 which produced designated uniform disability, veiling brightness along longitudinal eye level line at 1.5 MH as calculated from Holladay and Fry-Alpern formulas compared with luminaire candepower which in upper diagram is shown in plane of paper projection of 1.5 MH inclined plane to eye level. Comparative interpolation gives D.V.B. produced by luminaire. The large shaded portion of the candlepower distributions may be assumed shielded from view by top of automobile windshield.

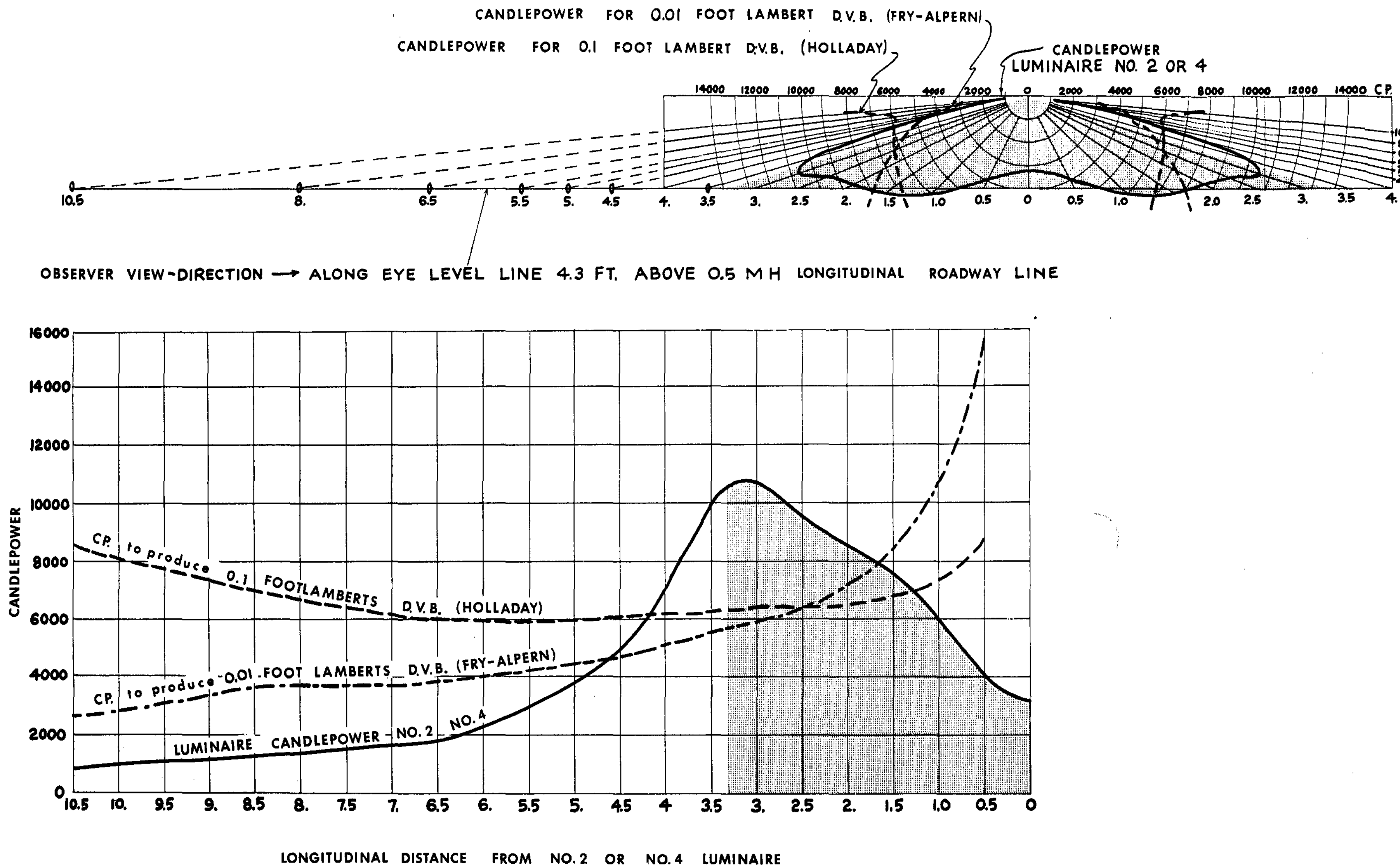

Figure 13. Candlepower from location of luminaire such as No. 4 which produced designated uniform disability veiling brightness along longitudinal eye level line at 0.5 MH with respect to luminaire such as No. 4, or at 1.5 MH with respect to luminaire such as No. 3. D.V.B. calculated from Holladay and Fry-Alpern formulas compared with luminaire candlepower which in upper diagram is shown in plane of paper projection of 0.5 MH inclined plane to eye level. Comparative interpolation gives D.V.B. produced by luminaire. The large shaded portion of the candlepower distributions may be assumed shielded from view by top of automobile windshield.

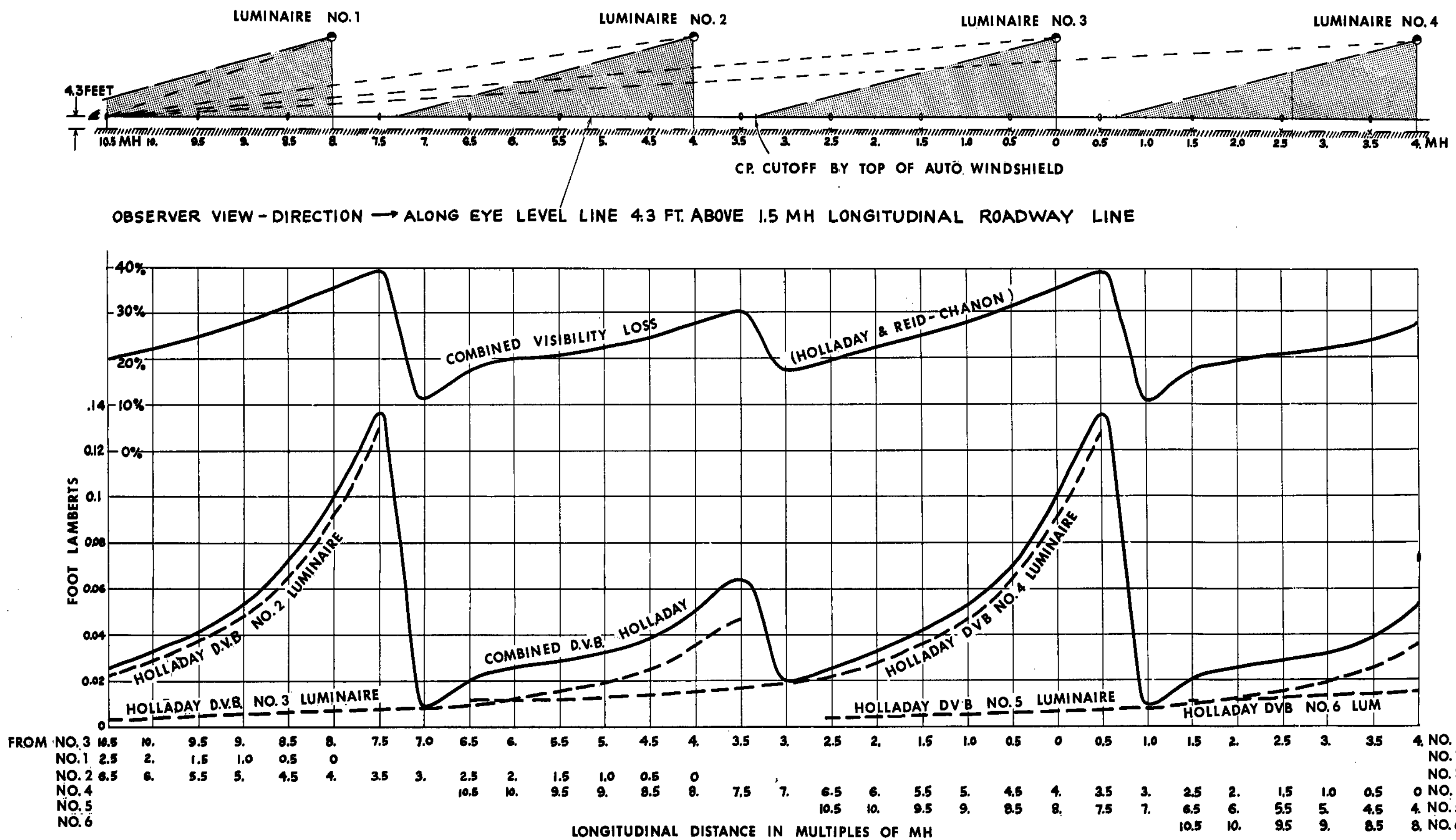

Figure 14. Combined and component disability veiling brightness from light distributions of a system of luminaires spaced 4 MH staggered. Combined visibility loss averaging 26 per cent is from Reid-Chanon data. Veiling brightness from Holladay formula combined along longitudinal eye-level line at 1.5 MH with respect to luminaires such as No. 3 or at 0.5 MH with respect to luminaires such as No. 4. This is correlated with Figures No. 6, No. 3 and No. 10.

Comparison of candlepower to produce certain uniform levels of disability veiling brightness, Figs. 12 and 13 again shows that the problem of control of luminaire candlepower along the 0.5 MH eye level line is about three times as important as along the 1.5 MH eye level line. Comparison with the luminaire candlepower distribution shows the control for restriction of disability brightness which is provided.

According to the Holladay curves, there are only small changes in candlepower for uniform levels of disability veiling brightness over the range of longitudinal distance from 3 MH to 7.5 MH. The angular differences tend to compensate for the long variations in distance. Hence without control, assuming for example a circular candlepower distribution from the luminaire, with the same candlepower at 8 MH as at 3 MH, would mean that the disability veiling brightness and per cent loss of visibility would be the same over this extensive 8 to 3 range of longitudinal distance from the luminaire.

D.V.B. and Visibility Loss from System

The manner in which the disability veiling brightness from each of several luminaires combine in a system is shown in Fig. 14. The spacing is 4 MH staggered[1] as shown in Fig. 10.

The 3.3 MH top-of-auto-windshield-cutoff aids the luminaire light distribution control of candlepower. This results in an appreciably lower average combined disability veiling brightness and per cent loss in visibility from that which the driver-observer would otherwise experience. The Holladay[15] combined average is 0.47 which, according to Reid-Chanon,[4] would account for a 26 per cent loss in visibility.[17]

The predominant disability effect of candlepower from luminaires No. 2 and No. 4 is obvious.

The correlation of data shown in Figs. 6, 14 and 17 with observer and pavement brightness locations shown in Figs. 3 and 10 is of interest. For example, an observer-driver at 7.5 MH, with respect to luminaire No. 3, experiences maximum combined disability veiling brightness while viewing brightness location at 0.5 MH where the combined pavement brightness, Fig. 6, and obstacle brightness, Fig. 17, are low. The pavement or obstacle brightness location is 7 MH (210 feet) ahead of the observer.

Fig. 18 shows the combined net relative visibility for the system using Reid-Chanon data.[4] The visibility is calculated for pavement and obstacle brightness correlated with the disability veiling brightness incurred by the driver-observer. It also shows how the combined pavement and obstacle field brightness weighted 70 per cent - 30 per cent respectively[4] varies with roadway location.

The distance or time cycle between peaks in disability veiling brightness, Fig. 14, is 8 MH (240 feet) or 4 seconds. The effect of such fluctuations on the typical driver-observer, will doubtless be evaluated numerically as well as in terms of overshooting, residual distraction and lag in adaptation for representative roadway lighting systems.

Visual Comfort

Visual comfort evaluations will also doubtless include the effect of flicker or any rapid and large variations in brightness. The luminaire brightness, assuming constant projected area, varies in proportion to the luminaire candlepower shown in Fig. 12 and 13. If the projected area is assumed to be constant at 100 square inches, there is a 7 to 1 range of luminaire brightness. As shown in Fig. 19, the peak distance intervals are 4 MH (120 feet) apart corresponding to time interval of 2 seconds.[1,18] There is some similarity with Fig. 14, disability brightness from luminaires No. 2 and No. 4. The effect upon threshold of discomfort when luminaire brightness is compensated by the larger viewing angles with respect to luminaires such as No. 3 will be interesting. In this connection it is well known that luminaires appear much brighter when driving toward them along the roadway than after a few seconds of steady viewing from a fixed position.

The foregoing involving the dynamics of motor vehicle movement points up the need for an assumption with respect to vehicle speed so that distance may be interpreted in terms of time. The author suggests 2 MH, or 60 feet, per second corresponding to an assumed speed of about 41 miles per hour.[18]

It should be apparent that the suggestions made in this paper will aid in predicting the efficiency of roadway lighting in terms of seeing objectives thus hastening the time at which recommended practice will be based upon seeing factor criteria.

Conclusion

Advantageous principles, proportioning and control of light distributions, the engineering inherent in roadway lighting, and the data for the evaluation of factors in seeing, are of value only to the extent that they are used. Improved presentations will contribute to understanding and more general use of the data which is already available. Agreement on conditions and assumptions which are representative of at least an important segment of streets and highways, will encourage and accelerate future data and developments. Any extra effort that may be involved is small in comparison with the objectives which will be gained. Progress in increasing the use and seeing efficiency of roadway lighting at a more rapid future pace is essential to the public welfare.

Acknowledgments

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Appendix

The Fig. 15 isocandle diagram has been previously identified. The customary web as described, Appendix B6, page 24 of 1953 American Standard Practice for Street and Highway Lighting, does not include the overlay of longitudinal roadway lines (1) (2) shown in Fig. 15 and Fig. 3. The shaded area Fig. 15 is beyond the roadway area shown in Fig. 3. The unshaded area and the longitudinal lines indicate the portions of the luminaire light distribution which may be most significant.

In order to estimate the candlepower at longitudinal distance points or intervals along the roadway lines shown in Fig. 15, the vertical and lateral angles pertaining thereto can be supplied. Table II provides such information for the H0.5 MH, 0.5 MH, 1.5 MH and 2.5 MH roadway lines.

For the longitudinal distance points along the 0.5 MH and 1.5 MH eye level longitudinal lines which are not shown in Figs. 15 or 16 a similar tabulation of vertical and lateral angles can be supplied. Table II provides such information for eye-level lines at 0.5 MH and 1.5 MH. The angles θ and distances D are also supplied.

Fig. 16 shows longitudinal and transverse roadway lines at pavement level corresponding to the roadway lines in Fig. 3 at intervals of 0.5 MH (2). If the isocandle roadway lines are in color or reproduced on a transparency, they may be applied directly over the conventional isocandle diagram of light distribution lines of equal candlepower. Another better alternative is to provide a web omitting the vertical and lateral angles, comprising only the roadway lines shown in Fig. 16 and plotting the isocandle or lines of equal candlepower thereon to show the light distribution to be presented.

For more accuracy in estimating luminaire candlepower from isocandle diagrams enlargements have been provided allowing closer spacing between lines of equal candlepower.

Also, on the photometer, the candlepower at lateral and vertical angles corresponding to the roadway lines may be read directly. Future photometers may provide automatic recorder curves of the luminaire candlepower along representative longitudinal roadway lines and eye-level lines.

As is doubtless apparent, the isocandle diagrams are not well adapted to showing comparisons such as presented in the foregoing paper.

TABLE II—Angle and Distance Information pertaining to points along pavement-surface and eye-level longitudinal lines.

θ is angle between driver-observer line of sight and the line D from the eye point to the luminaire. Refer to Fig. No. 11.

Longitudinal Distance (MH)	Lateral Angle	Vertical Angles Pavement Level	Vertical Angles Eye Level	Angle θ	D (MH)	D in Terms of M.H.
0.5 MH Line ("Street Side" or "House Side") Longitudinal Line at Transverse Distance 0.5 MH						
0	0°	26.5°	30.3°	90.0°	29.7	.99
0.5	45	35.3	39.5	63.2	33.3	1.11
1.0	63.5	48.2	52.5	44.8	42.3	1.41
1.5	71.6	57.6	61.5	33.5	54.0	1.79
2.0	75.9	64.1	67.4	26.4	67.0	2.23
2.5	78.7	68.5	71.4	21.7	80.7	2.69
3.0	80.5	71.8	74.3	18.3	94.8	3.16
3.5	81.9	74.2	76.4	16.1	109.3	3.64
4.0	82.8	76.1	78.0	13.9	123.6	4.12
4.5	83.6	77.5	79.3	12.4	138.2	4.61
5.0	84.3	78.7	80.3	11.3	153.1	5.10
5.5	84.8	79.7	81.2	10.3	167.7	5.59
6.0	85.3	80.5	81.9	9.3	182.4	6.08
6.5	85.5	81.3	82.5	8.5	197.2	6.57
7.0	85.9	81.9	83.0	8.1	212.1	7.07
7.5	86.1	82.4	83.5	7.7	227.0	7.57
8.0	86.4	82.9	83.9	7.3	242.0	8.07
8.5	86.6	83.3	84.3	6.9	256.9	8.56
9.0	86.8	83.7	84.6	6.4	271.7	9.06
9.5	87.0	84.0	84.8	5.9	286.5	9.55
10.	87.1	84.3	85.1	5.5	301.4	10.05
10.5	87.3	84.5	85.3	4.3	315.9	10.53

Longitudinal Distance (MH)	Lateral Angle	Vertical Angles Pavement Level	Vertical Angles Eye Level	Angle θ Fig. 11	Distance D (Feet) Fig. 11	D in Terms of M.H.
1.5 MH Line						
0	0°	56.3°	60.3°	90°	51.8	1.73
.5	18.4	57.7	61.5	73.8	53.8	1.80
1.0	33.6	60.9	64.5	59.8	59.7	1.99
1.5	45.0	64.8	68.0	49.0	68.6	2.29
2.0	53.1	68.1	71.1	40.8	79.4	2.65
2.5	59.0	71.1	73.6	34.6	91.1	3.04
3.0	63.4	73.3	75.7	30.1	104.1	3.47
3.5	66.8	75.3	77.3	25.9	116.8	3.89
4.0	69.4	76.8	78.6	22.9	130.2	4.34
4.5	71.5	78.1	79.7	20.3	144.0	4.80
5.0	73.3	79.1	80.6	18.0	157.7	5.26
5.5	74.8	80.0	81.4	16.3	171.9	5.73
6.0	75.9	80.8	82.0	15.0	186.4	6.21
6.5	77.0	81.4	82.7	14.0	201.1	6.70
7.0	77.9	82.0	83.2	12.8	215.5	7.18
7.5	78.7	82.5	83.6	12.6	230.6	7.69
8.0	79.3	82.9	83.9	11.8	245.2	8.17
8.5	80.0	83.4	84.3	11.2	259.9	8.67
9.0	80.5	83.8	84.6	10.8	274.8	9.16
9.5	81.0	84.1	84.8	10.7	290.1	9.67
10.0	81.5	84.3	85.2	10.4	305.0	10.17
10.5	81.9	84.6	85.4	9.4	319.3	10.64
2.5 MH Line						
0	0	68.2				
0.5	11.3	68.6				
1.0	21.8	69.6				
1.5	30.9	71.1				
2.0	38.7	72.7				
2.5	45.0	74.2				
3.0	50.2	75.6				
3.5	54.5	76.9				
4.0	58.0	78.0				
4.5	60.9	79.0				
5.0	63.4	79.9				
5.5	65.5	80.6				
6.0	67.4	81.3				
6.5	68.9	81.8				
7.0	70.3	82.3				
7.5	71.5	82.7				
8.0	72.7	83.2				
8.5	73.6	83.5				
9.0	74.5	83.9				
9.5	75.3	84.2				
10.0	75.9	84.4				
10.5	76.6	84.7				

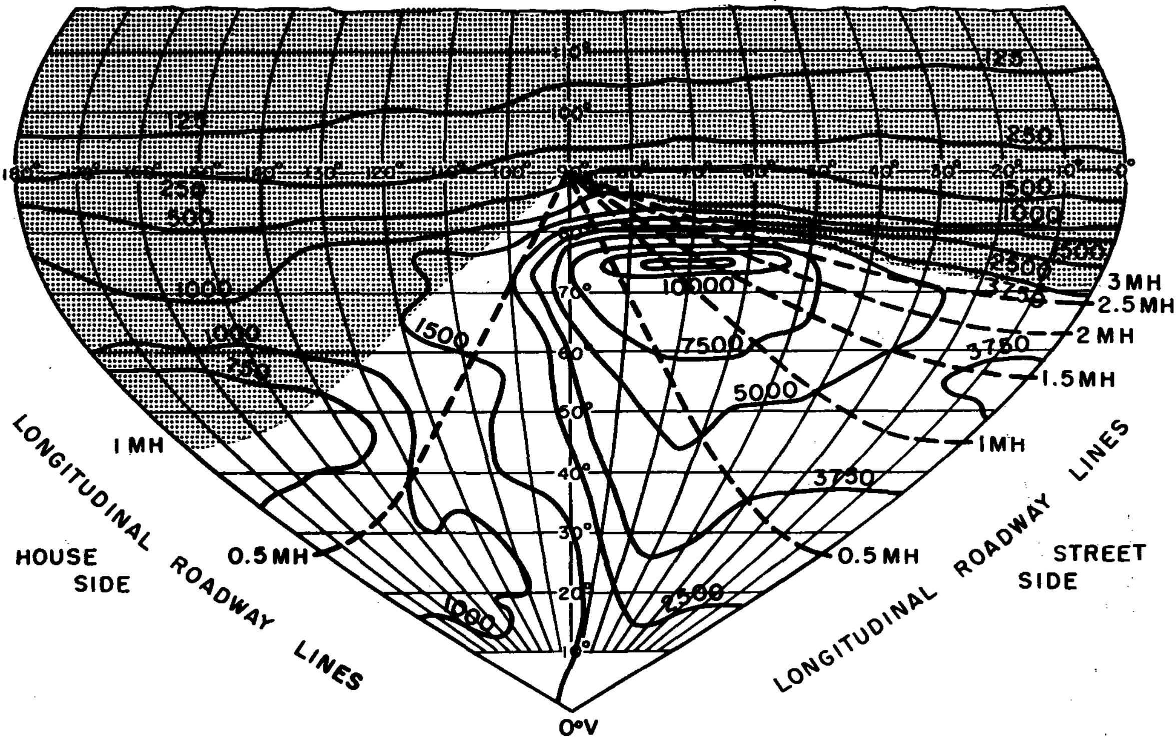

Figure 15. (Appendix) Isocandle diagram of luminaire light distribution used in calculations and illustrations in this paper. This is based upon Figure 15 Appendix American Standard Practice for Street and Highway Lighting except all candlepower values increased in ratio 2.5 to 1. Note longitudinal roadway lines corresponding to Figure 3. Longitudinal eye level lines are not shown.

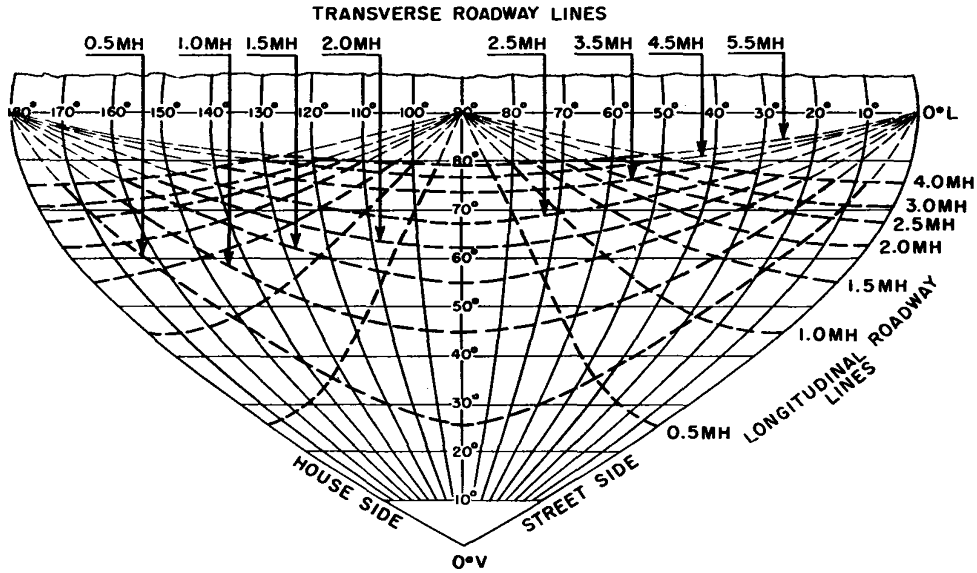

Figure 16. Longitudinal roadway lines and distances in multiples of 0.5 MH as designated by points of interception by transverse roadway lines, superimposed upon vertical and lateral web lines similar to those used for isocandle diagram.

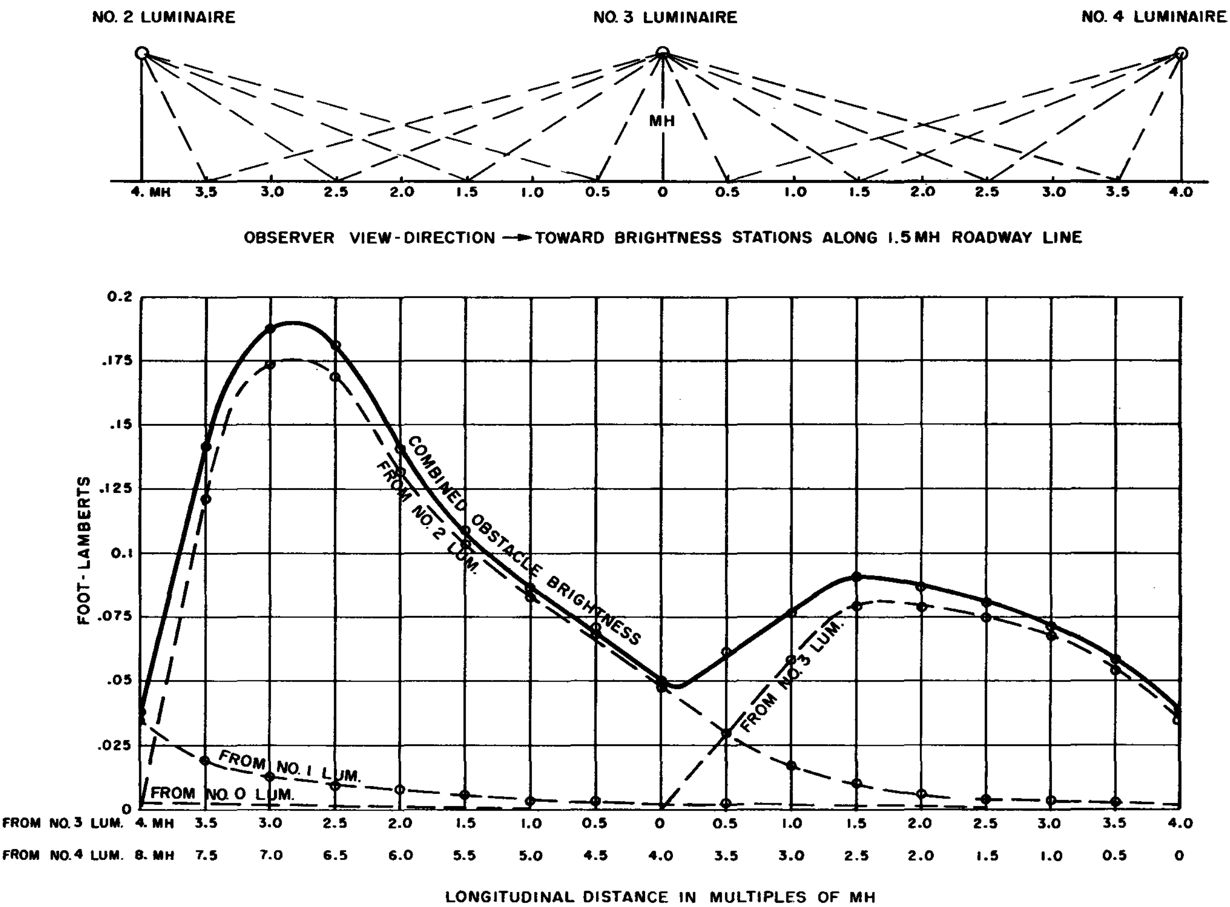

Figure 17. Combined system versus component obstacle brightness at locations along longitudinal roadway line and observer viewing path at 1.5 MH with respect to luminaires such as No. 1 and No. 3 and at 0.5 MH with respect to luminaires such as No. 4. The obstacle reflectance is assumed to be 8 per cent.[4] Luminaires are spaced 4 MH or 120 feet staggered per Fig. 3.

References and Footnotes

1. American Standard Practice for Street and Highway Lighting approved February 27, 1953, A.S.A.

2. Footnote: For information with regard to roadway lines and distances in relation to light distributions refer to reprint "Report on American Standard Practice for Street and Highway Lighting" presented at Illuminationing Engineering Society National Technical Conference September 1952, by Charles H. Rex.

3. Footnote: The 4.3 feet above the pavement is based upon 51.7-inch average driver eye height in 25 makes and models of American cars, as of June 1955, according to information kindly supplied by T. J. Carmichael, Engineering Staff, General Motors Corporation Technical Center, Detroit, Michigan.

4. Reid, Kirk M., and Chanon, H. J.: "Evaluation of Street Lighting," ILLUMINATING ENGINEERING, 34, 1939, 1209.

5. Bock, J. E., Report M25449S, T6670, Outdoor Lighting Department, General Electric Company.

6. Luckiesh, Matthew, and Moss, F. K.: "Visibility — Its Measurement and Significance in Seeing," *Journal of the Franklin Institute*, 220, 431, 1935.

7. Finch, D. M.: Progress reports on "Investigation of Factors Influencing the Night Visibility of Roadway Obstacles," I. E. Research Project No. 37

8. Rex, Charles H.: "Technical and Practical Aspects of Highway Lighting," *Proceedings of the Institute of Traffic Engineers*, Vol. 8, p. 41, 1937.

9. Traffic Engineering Handbook, Institute of Traffic Engineers, 1941, Section on Street and Highway Lighting.

10. Rex, Charles H.: "Roadway Lighting for Efficiency," paper Annual Meeting Institute of Traffic Engineers, September 11, 1952, Chicago, Illinois.

11. I.E.S. Technical Advisory Committee on iLght and Vision consideration of questions by Research Subcommittee, Fluorescent Subcommittee, and the author, on behalf of I.E.S. Committee, Street and Highway Lighting.

12. Putnam, R. C., and Gilmore, W. F.: Study of Discomfort Glare in Street Lighting.

13. Dr. Glenn A. Fry, June 21, 1955, August 19, 1955.

14. Holladay, L. L.: "Fundamentals of Glare and Visibility," *J.O.S.A.*, 12, 271, 1926 — formula $B = 23E/\theta^{1.8}$
The formulas for candlepower to produce disability veiling brightness, B, are:

Fry-Alpern — $CP = \dfrac{B\,D^2\,\theta^{2.5}}{22.4}$ Holladay — $CP = \dfrac{B\,D^2\,\theta^{1.8}}{23}$

15. Footnote: Report sponsored I.E.S Research Fund Project No. 17 by Dr. Glenn A. Fry and Matthew Alpern, ILLUMINATING ENGINEERING, p. 31, January 1955, formula $B = \dfrac{22.4E}{\theta^{2.5}}$ is qualified in the appendix: "It should also be noted that the data presented by the authors are limited to glare angles from 3/4 to 4.5 degrees, and the data presented by Stiles and Holladay and Stiles and Dunbar cover much larger glare angles."

16. Footnote: Data available at present on 1955 cars indicates that the following quote from 1941 edition of the "Traffic Engineering Handbook" is approximately correct according to K. A. Stonex, General Motors Proving Ground: "The angle from the vertical at which the top of automobile windshield cuts off light which would otherwise strike the driver's eyes is about 76 degrees." It should be noted that the longitudinal distanc is to the point at which this angle intercepts the eye level line 4.3 feet above the roadway.

17. Footnote: Recent field tests have been made involving Dr. S. K. Guth, A. A. Eastman, D. A. Toenjes, H. A. Breeding, J. S. Franklin, and the author, using the Luckiesh-Moss Visibility Meter equipped with removable shield for excluding all luminaire light from the meter Relative visibility measurements on representative lighting systems using this meter with and without the shield indicate average per cent losses due to luminaire candlepower in the range of 20 to 30 per cent.

18. The 2MH, or 60 feet, per second assumption based upon 41 miles per hour is a compromise between urban and rural driving speeds. "Reports by 26 states summarized by the U. S. Bureau of Public Roads indicate that drivers traveled on main rural highways in 1954 an average speed of 49.7 miles per hour."

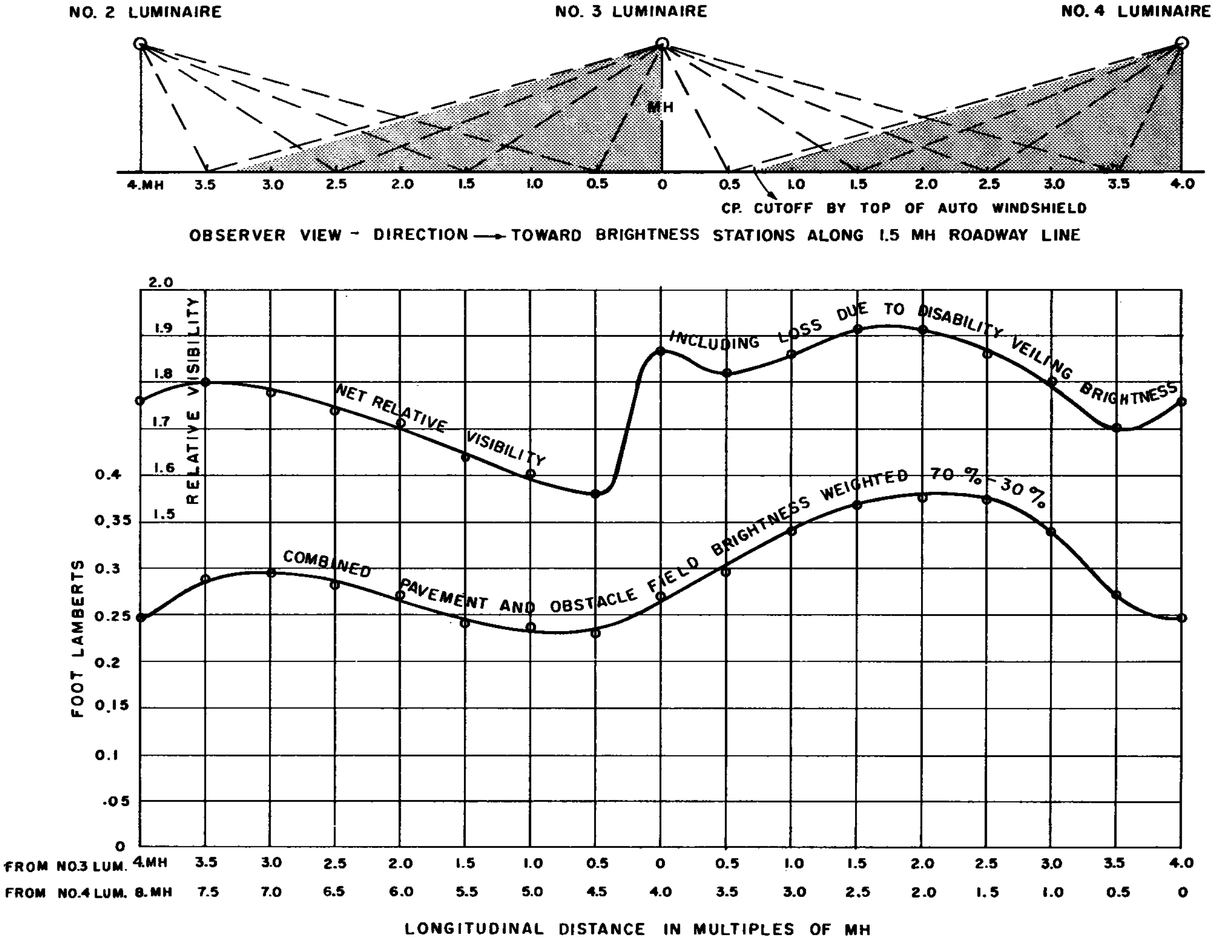

Figure 18. Combined system weighted field brightness combining pavement brightness Fig. 6 with obstacle brightness Fig. 17 in accordance with 70-30 percentage ratio Reid-Chanon data. The net relative visibility including loss due to disability veiling brightness, Fig. 14, is derived from Reid-Chanon[4] data based upon Luckiesh-Moss Visibility Meter. Luminaires are spaced 4 MH, or 120 feet, staggered per Fig. 3.

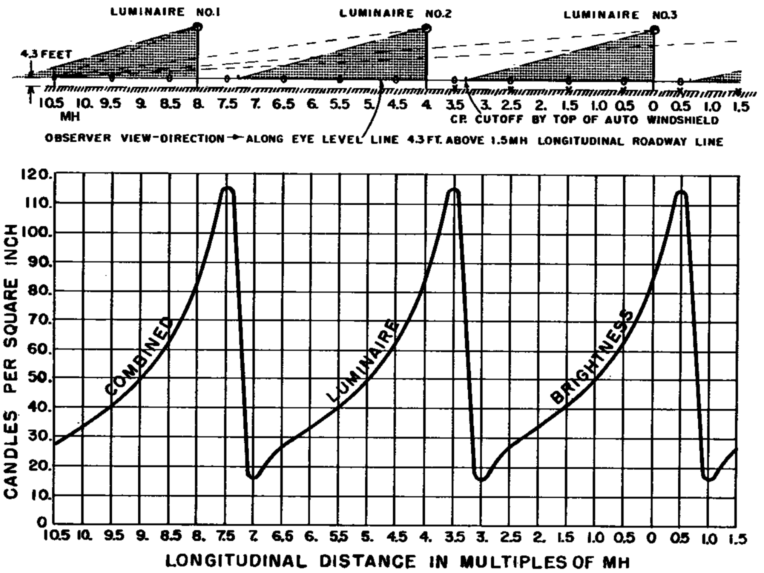

Figure 19. The fluctuation in combined luminaire brightness from a system as the driver-observer proceeds along eye-level line above roadway line at transverse distance of 1.5 MH with respect to luminaires such as No. 3 and at 0.5 MH with respect to luminaires such as No. 2. Candlepower distribution shown in Figs. 12 and 13. Luminaire source area assumed constant at 100 square inches. At some locations as indicated brightness is shielded from view by top of automobile windshield. Luminaires are spaced 4 MH or 120 feet staggered per Fig. 10.