

Highway Lighting Without Glare— A New Lighting Technique

By W. M. WALDBAUER

Introduction

The last several years have seen a tremendous growth in the number of vehicles utilizing highways in this country. Traffic-conscious city, state and federal governments have realized that they must expand their roadways both in capacity and in mileage in order to handle the ever increasing traffic flow. The increase in long distance pleasure travel by the American public has substantially promoted the growth of freeways, limited access highways and turnpikes of the multi-lane, dual-roadway type. There is general agreement that eventually these highways should be lighted for maximum safety.

With wider and wider medial strips, these roadways must be considered separately, from a lighting standpoint. For example, all new roadways built in cooperation with the Federal Highway Program must have medial strips at least 32 feet wide. Heretofore, it has been the practice to provide standard type street lighting systems only in interchanges and service areas and the deceleration and the acceleration lanes leading to and from these areas on the modern turnpike type roadways. This practice has generally been satisfactory in guiding the motorist to and from these areas and providing advance warning of traffic merging areas. However, such systems are of no value in assisting the motorist to discern traffic and obstacle hazards along the highway between these areas. As a result, it has been necessary for the motorist to depend entirely on the automotive headlights with which his vehicle is equipped to provide the necessary illumination. Present day vehicle speeds and recognition distances provided by commercially available automotive headlight systems do not always allow the average motorist sufficient time to execute the necessary safety or precautionary maneuvers. Assuming that a vehicle is equipped with good brakes, and allowing a $\frac{3}{4}$ -second driver reaction time (fairly alert driver), a vehicle speed of 60 miles an hour

would require a minimum of 260 feet to stop on dry concrete. However, if we assume a two-second reaction time and a 0.4 coefficient of friction, driver stopping distances for 60 miles per hour would be 480 feet and for 70 miles per hour, 610 feet. Actual tests showed that the values of stopping distances given above may be substantially lower than those found in actual practice, due to the many variations of different vehicles, drivers, and pavement conditions.² When we realize that present day automotive systems provide 0.1 to 0.2 footcandle on a vertical surface 750 feet in front of the car, it is easily understood how a motorist can fail to recognize an obstacle in time to take the necessary corrective action.

For the purpose of this paper, we shall define a highway as a multi-lane, dual-roadway type. Specifically, we have chosen roadways 36 feet wide with a 32-foot medial strip separating the two roadways. A 36-foot width, therefore, provides for two high-speed traffic lanes plus an emergency lane located on the right hand side of paved traffic lanes.

Major Types of Systems

GENERAL

Whenever the lighting industry has been faced with a new application for street lighting, the natural tendency has been to extend the use of presently available luminaires, with little or no modifications, to the optical principles involved. It is not surprising, therefore, that until recently, intra-city expressways, turnpike interchanges, and access roads, and now even the Connecticut Turnpike have utilized standard bi-directional street lighting luminaires to provide the necessary illumination. The use of such luminaires is based largely on the facts that they are commercially available, and a great deal of application experience is available.

The Federal Bureau of Roads suggests that lighting arrangements and illumination values shall be in accordance with current provisions of the *American Standard Practice for Street and Highway Lighting*. In general, this would require a minimum average maintained illumination level of 0.8

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footcandle, while maintaining a 4:1 average to minimum ratio. Using modern day, high efficiency, mercury luminaires, this would allow spacings in the order of 200 feet maximum.

For the most part, application experience using these bi-directional luminaires has been limited to urban areas. Under these conditions, the motorist is driving at relatively low speeds for short periods of time. Even in the more recent application of these luminaires to intra-city expressways, the amount of time that a motorist spends driving under such a system is relatively short. If we then further extend the application of these luminaires to lighting many miles of turnpike or limited access roadways, we are faced with an entirely different situation. As the car travels along a roadway so illuminated, there is a pronounced blink each time the windshield cuts off the light from the approaching luminaire. At normal turnpike speeds, this blinking, or so-called shutter effect, would occur at the rate of 24 to 30 times per minute. Where there is no specific data covering this situation, many people have expressed concern that this pronounced blinking effect, rapidly repeated, will produce a state of mild hypnosis in the driver which, in turn, would decrease his alertness and most probably increase his reaction time. Such opinions are, of course, highly speculative, since no systems are presently available under which this effect could be evaluated. The continuous lighting of the Connecticut Turnpike may provide some of the answers regarding this particular point.

More recently, it has been proposed that a uni-directional lighting system be used on the dual type highway. For many years, there has been considerable discussion regarding just how the human eye actually sees. Certainly, under a standard bi-directional system, this seeing is provided by illumination which allows both direct discernment and silhouette discernment of the obstacle ahead. A uni-directional system, which would aim its lights against traffic, has been proposed on the basis that normal seeing at low illumination levels is primarily by silhouette. Certainly small dark objects are seen primarily by their silhouette against a brighter background, which in this case would be the brightness of the pavement itself. However, it is felt that the eye discerns most larger objects by direct discernment and certainly cars along the roadways are seen as cars, not just as silhouettes.

It is felt that one of the major limitations of these systems would be the fact that they could not be spaced over long distances. In order to maintain an adequate footcandle level on the roadway and the resultant pavement brightness, high candlepowers would be necessary if these lumi-

naires were extended beyond 150 to 200 feet apart. It is obvious that such an "up stream" lighting system cannot eliminate the luminaire as a potential glare source.

A third system, and the one with which this paper deals directly, is a highway lighting system, uni-directional in nature, aimed so that the light is in the direction of traffic flow. This system, together with the associated photometric requirements, luminaire requirements and application requirements will be discussed more fully in this paper. For now, it suffices to say that these luminaires would be installed on the left hand side of the roadway, that is, in the medial strip, aimed in the direction of traffic flow, with little or no light coming back toward the driver.

A fourth possible system for highway lighting would be the use of continuous fluorescent strip mounted off to one side of the roadway. This would, in essence, provide the greatest amount of light directly across the highway and, if the mounting heights were properly chosen, could provide good illumination. Based on the recent fog study at the Pennsylvania State University, such a lighting system may provide improved visibility under fog conditions. However, it is felt that the cost, at least at this time, would be such that it could not be considered for lighting the many thousands of miles of open highway.

DISABILITY VEILING BRIGHTNESS COMPARISON

Disability veiling brightness of disability glare is related to the total amount of light flux that enters the eye and the angular displacement of the glare sources from the normal line of sight. In this paper, the expressions developed by Holladay and Stiles,³ as modified by Moon and Spencer,⁴ have been utilized to calculate the disability veiling brightness for various systems. The standard formula for calculating DVB is as follows:

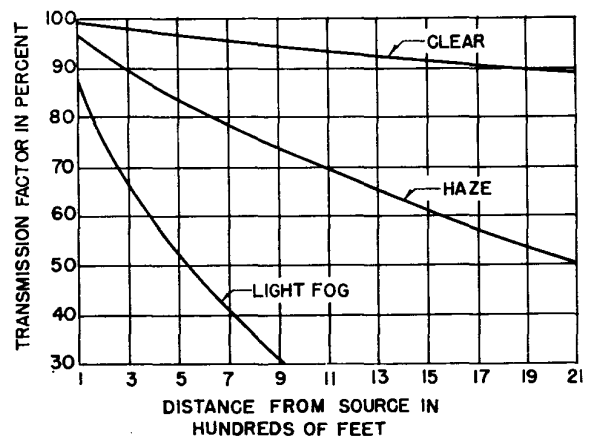


Figure 1. Atmospheric transmission factor.

$$DVB = \frac{10 \pi E v}{\theta^2}$$

where $E v$ = The vertical footcandle at the eye, on a plane perpendicular to the normal line of sight, and

θ = The angle between the normal line of sight and the glare source measured in degrees.

This expression has been further modified to take into account the atmospheric absorption. The resultant expression then may be expressed as follows:

$$DVB = \frac{10 \pi E v}{\theta^2} \cdot T^x$$

where T = The transmission factor for various atmospheric conditions per 100 feet, and
 x = Distance from the glare source to the eye in hundreds of feet.

Fig. 1 shows the effect of atmospheric transmission under various conditions.

Referring now to Fig. 2, System 1 represents a typical bi-directional installation on a divided highway with 36-foot roadways and a 32-foot medial strip based on the luminaires being spaced 200 feet apart. The observer is located 10 feet in from the edge of the roadway and 100 feet from the first luminaire.

In calculating the disability brightness for a conventional bi-directional system, two types of systems have been utilized. The first is in idealized system which is represented by a luminaire having positive cut-off above 79 degrees vertical in the

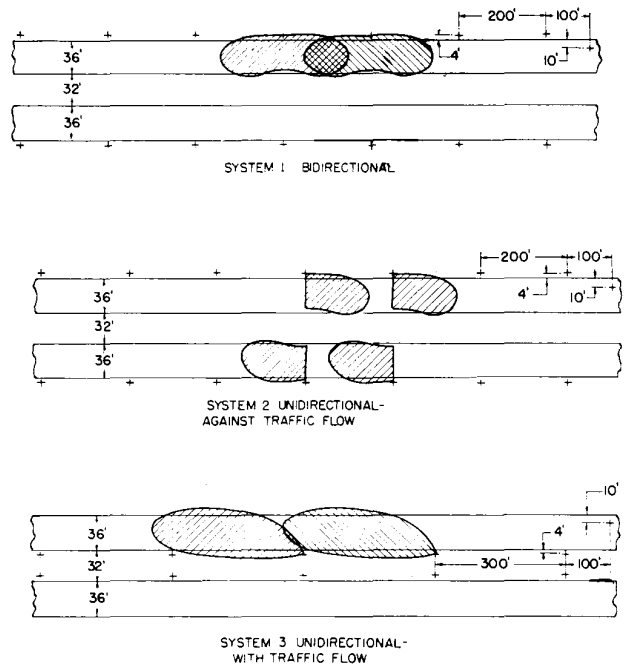


Figure 2. Luminaire arrangement for glare calculations.

main beam area and cut-off across the street such that the observer does not receive any flux from luminaires located on the opposite roadways. The results of this calculation are shown on Table I. For the second series of calculations a standard, commercially available luminaire was used. In the design of this standard street lighting luminaire, many factors combined which did not permit the absolute cut-off specified above for the ideal system.

TABLE I — Disability Veiling Glare from Idealized Design, Comparison of System DVB.

	System 1		System 2		System 3
	Mercury	1500 ma Fluorescent	Mercury	1500 ma Fluorescent	Mercury
Totals .....	.0718	.0422	.0718	.0422	0
Loss in Visibility ⁶	30.6%	24.7%	30.6%	24.7%	

TABLE II — Disability Veiling Glare from Practical Design, Comparison of System DVB.

Pole No.	System 1		System 2		System 3	
	Mercury	1500 ma Fluorescent	Mercury	1500 ma Fluorescent	Mercury	Mercury
1 .....	.07180	.0422	.07180	.0422	1	—
3 .....	.00890	.0256	.00890	.0256	3	—
5 .....	.00800	.0229	.00800	.0229	5	—
7 .....	.00620	.0226	.00620	.0226	7	—
9 .....	.00628	.0228	.00628	.0228	9	—
11 .....	.00570	.0228	.00570	.0228	11	—
13 .....	.00564	.0214	.00564	.0214	13	—
2 .....	.014000	.0134	—	—	2	.04010
4 .....	.000845	.0020	—	—	4	.00219
6 .....	.000760	.0018	—	—	6	.00511
8 .....	.000595	.00183	—	—	8	.00995
10 .....	.00078	.0024	—	—	10	.01220
12 .....	.000510	.00185	—	—		
14 .....	.000460	.00175	—	—		
Totals .....	.13047	.20533	.11252	.13030		.02955
Loss in Visibility ⁶	88%	44%	36%	42.5%		21.2%

As a result, each luminaire shown in System 1 contributes to the total disability veiling brightness at the observer. The amount of glare produced by each luminaire is shown in Table II. It is interesting to note that while the mercury type of System 1 produces more glare from the closest luminaires than does the fluorescent type, total DVB is less for mercury. This, of course, is primarily due to the fact greater control of light is obtainable from mercury systems with their smaller light sources, and the upper cut-off is much sharper. A typical fluorescent system starts out with less brightness produced by the closest luminaire, but does not decrease at nearly so rapid a rate, with the result that more glare is actually produced by this fluorescent system than by the mercury system.

System 2 represents a uni-directional system aimed towards the driver. It should be noted that the luminaire in this case represents only one-half of a luminaire used under System 1, the side facing away from the driver being blacked out. No attempt has been made to take into account that a greater amount of light flux, and consequently more glare, would be directed towards the driver if the luminaire were designed expressly for this purpose. It is seen that in this system the idealized luminaire (Table I) provides exactly the same amount of glare as did the luminaire in the bi-directional system.

In Table II, a more practical system is calculated on the basis of glare, and it, too, provides essentially the same amount of disability veiling brightness as did System 1, with the exception that the luminaires on the opposite roadway produced no glare component.

System 3 represents a uni-directional system which is aimed in the direction of traffic flow. Here the idealized luminaire (Table I) would be one which would produce a cut-off such that the light from the opposing luminaires would not reach the observer's eyes. Under such an idealized system, no disability glare would be encountered. From a more practical standpoint, luminaires which are lighting the opposite roadway would be visible to the observer and, therefore, would produce a certain amount of disability veiling brightness (Table II). It should be noted that these calculations are based on a distribution having the minimum performance which the author considers acceptable. It is hoped that through further study and greater refinement in design these values will be further decreased.

Here then is a system which, even in its practical state, provides less disability veiling brightness than the idealized version of either the bi-directional system or the uni-directional aimed towards

the traffic system. Up until now, the street lighting designers have paid more attention to the illumination which the system would produce than to the comfort of the motorist. Certainly, no one will deny that the most important task of street lighting is to provide visibility. However, when we consider that a motorist may be subjected to long hours of driving under the visibility conditions produced by a lighting system, his comfort becomes a major factor. The author feels that both visibility and comfort must be equally evaluated when considering highway lighting systems.

Possible Criteria for Evaluating A Highway Lighting System

In general, the street lighting industry has long recognized that horizontal footcandles, as a means of evaluating a particular installation, are applicable only when the mounting height and type of distribution are predetermined. For urban areas, this has represented the most convenient way of evaluating a given system. The method has, however, depended largely on prior experience and visual observation of qualified observers for correlating all the factors concerning visibility, glare, uniformity and comfort. If the distribution of the luminaire in question is substantially changed from that on which we have prior experience, it is felt that horizontal footcandles alone will not give the complete story.

It is hoped that the work of Messrs. Blackwell, Fry and Finch will result in a visibility meter which will correlate all of these aforementioned factors, and whose size and manner of operation will be such as to make it practical for use in evaluating street and highway installations.

Development of a Highway Luminaire

GENERAL CONSIDERATIONS

In the choice of an actual design approach for a highway luminaire, many factors must be taken into consideration and many compromises made. The theoretical considerations of the way we see and the effects of disability and discomfort glare must, of course, be the basic motivating force behind a good decision. Other factors which must be considered are: cost, accessibility of the luminaire for maintenance, pole spacing, and pole location as a contributing factor in accidents. Due to the fact that highway driving is a continuous process without appreciable environmental change, it is felt that a design which achieves freedom from glare is of major importance. With poles at a uniform spacing and the car traveling at a constant speed, the consistent flashing of a glare source at regular

intervals into the eyes of the driver is believed to be one of the most serious problems in highway lighting.

This premise precludes the choice of a uni-directional system with the light source pointed towards traffic or a standard bi-directional type of luminaire. It also means that the utmost design consideration must be given to making sure the luminaire is not an offending glare source.

Visibility is the second most important factor. Automobiles are equipped with headlights which produce a certain type of visibility. This visibility is the result of vertical footcandles which serve to reveal an obstacle or object to the driver by means of reflected glint and direct discernment. It is strongly believed that a lighting system which depends on another type of visibility for revealing the object, *i.e.*, silhouette discernment, when used in combination with high beam headlights, would produce a lower over-all visibility rating for the combination and would tend to confuse a driver, since his basis of judgment would not be constant. With this as an added factor, the choice of a luminaire which is uni-directional in nature with the maximum candlepower directed in the direction of traffic flow is clearly indicated.

Luminaire Distribution

The factors of physical size, lumens per watt and lamp life led to the selection of the 400-watt E-H1 mercury lamp as the most suitable light source to produce the required vertical footcandle level. It was felt that to facilitate maintenance operations the luminaire should be located off the actual roadway area so that it could be serviced with a truck which would not have to be stopped in an active traffic lane. This indicated that the light distribution should be such that no light would be directed directly downward from the luminaire. The tentative specification of the luminaire mounting location from five to six feet outside the traffic lane was selected.

Working backwards from the criteria of one vertical footcandle, it was possible to construct an idealized candle distribution for the luminaire. This is shown in Fig. 3, and is further discussed as related to the beam requirements.

If such a highly idealized type of distribution could be obtained, we would have a roadway which would be uniformly lighted to the level of one footcandle vertically and with no light into the opposite roadway. However, all will recognize that one cannot design a luminaire which will provide a main beam candlepower in the order of 100,000 and so cut off the beam as to have zero candlepower immediately adjacent to this peak. It is, therefore,

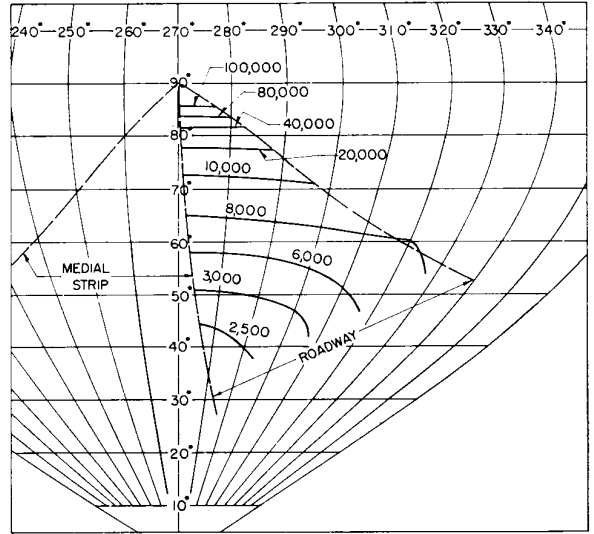


Figure 3. Ideal distribution.

necessary to modify this idealized distribution to one which is more practical, considering the inherent spread of any optical system. Such a distribution is shown in Fig. 4. This distribution still provides essentially uniform vertical footcandles in the order of one footcandle, and the asymmetric distribution requires a very sharp cut-off in the direction of the opposite roadway.

The initial considerations were based on luminaires being spaced approximately 300 feet on the left hand side of the roadway with the poles located in the medial strip. The luminaire would be located four feet to the left of the edge of the high speed lane with the pole located a minimum of ten feet from the edge of this lane. Luminaire mounting

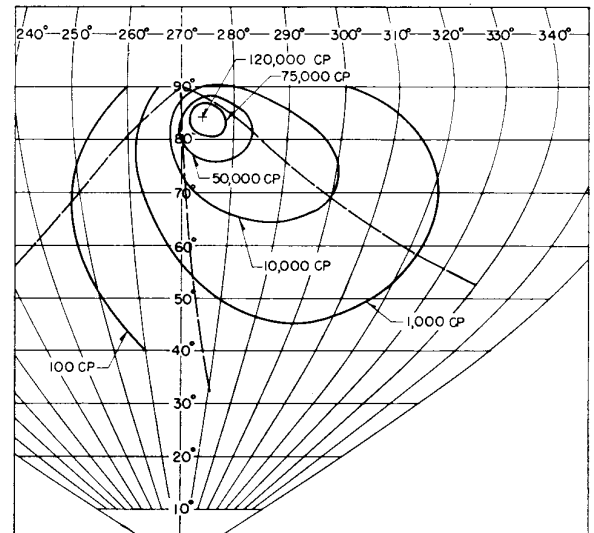


Figure 4. Proposed distribution.

height would be 30 feet. The luminaire would be aimed so that the axis of the parabolic section would intersect the pavement at the middle of the roadway directly opposite the next pole. This would result in an aiming angle of approximately 84 degrees vertical and 274 degrees lateral. Even with a medial strip 32 feet in width, the adjacent curb of the opposite roadway is only 10 degrees laterally from the peak of the main beam. As the highway extends further and further away, both roadways tend to be asymptotic and will converge at 90 degrees vertical and 270 degrees lateral. Such a condition makes the cut-off requirements extremely critical. As can be seen from the proposed distribution, the peak candlepower of 120,000 must be reduced to 10,000 in 7 degrees, to 1,000 candlepower in 10 degrees, and to 100 candlepower in approximately 20 degrees. These distribution requirements are tied in very closely to the DVB calculations made previously. It is only with good lateral control that such low values of disability veiling glare can be achieved.

Optical System

Since lateral control is of the greatest importance, the optical system design was based on achieving minimum lateral spread with all possible accent on sharp cut-off to the left of the main beam peak.

As was mentioned before, the light source used in this luminaire would be a 400-watt E-H1 mercury lamp. The lamp would be mounted in a vertical position with the base up. The main body of the reflector would be a parabolic section of revolution whose major diameter is 20 inches. The rear section of the reflector essentially by-passes light around the arc stream in such a manner as to minimize

spread. A prismatic lens would be utilized to further control this light. This prismatic lens would be divided to two major areas, one to deal with the light coming off the parabolic reflector, and the other to deal with direct light from the lamp (see Fig. 5). The center concave section is essentially a bull's-eye segment which will take the divergent direct light and transmit it as a parallel beam. The outer annular convex section of the refractor will modify the essentially parallel light coming off the parabolic section in such a manner as to provide an asymmetric beam of high candlepower whose lateral spread towards the opposite roadway is the bare minimum. Every precaution was taken so that both the main beam rays and the prism riser rays would not provide an offending component into the opposite roadway.

Preliminary Evaluation

To prove that good visibility could be obtained from a highway lighting system which depended essentially on vertical footcandles to provide discernment, an experimental installation of three luminaires was made on a test street. The test installation was made utilizing a general purpose floodlight with an E-H1 mercury lamp and a horizontal spread lens. The luminaires were mounted approximately 30 feet above the pavement with a spacing of 250 feet between units. In addition, an open suburban unit with a L-H4 100-watt mercury lamp was mounted adjacent to the general purpose floodlight. The purpose of the low wattage open unit was to evaluate the desirability of a small component of light down and towards the driver. Units were mounted and wired in such a way that they could be operated independently of each other or together, as desired. Since the primary object of this test installation was to test the visibility, no attempt was made to achieve the adjacent lane cut-off.

Figs. 6, 7 and 8 show the results obtained from this test installation. The target shown in the photographs is of the type recommended by Finch⁴ in his studies on visibility. The target shape is a three-sided section of a right rectangular prism with one normal and two 45-degree vertical planes, each one foot wide. Two target heights were selected, the first five feet high and the second, one foot high. Targets were painted with an extremely flat paint. The white target had an average reflection of 87 per cent while the black target had an average reflectance of 7½ per cent as measured with a Taylor reflectometer.

Fig. 6 shows the installation with both the general purpose floodlights and the open suburban units on. The white targets are located 200 feet

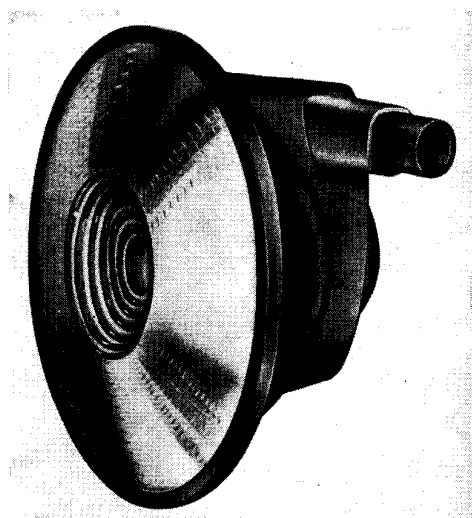


Figure 5. Specially designed luminaire.



Figure 6. Test installation with general purpose floodlights and open suburban units turned on.



Figure 7. Test installation with open suburban units turned off.

from the camera while the black targets are located 450 feet from the camera. Fig. 7 shows the same target location but with the open suburban units turned off. Fig. 8 is again with the open suburban units turned off, *i.e.*, no light coming back towards the driver, with cars placed as they would be on the emergency lane of a 36-foot roadway. The cars are located 150 feet, 250 feet, 375 feet and 650 feet, respectively, from the camera.

Fig. 9 shows both horizontal and vertical footcandle readings taken of this test installation. These readings were taken with both the general purpose floodlights and the open suburban units on. Since this installation requires cooperative action between the various luminaires, it is felt that the readings taken from the second luminaire on out represent those which would be representative of a continuous installation. It should be noted that in

this area the maximum to minimum ratio of vertical footcandles was 1:9. A similar set of readings was taken with the open suburban units off. Little effect on the vertical footcandle level was noted.

It is felt that the above photographs and readings taken on the test installation conclusively prove that the uni-directional lighting system aimed in the direction of traffic flow provides a satisfactory level of illumination with good obstacle discernment and no offending glare. Since this installation was made prior to the time when a luminaire specifically designed for this purpose was available, it was not possible to evaluate the light coming from luminaires lighting the opposite roadway.

Conclusions

Throughout this paper the need for evaluating a highway lighting system based on two primary criteria has been stressed. These are that it must provide good visibility while maintaining comfort at the highest practical level. It has been shown that the system outlined in this paper can provide good visibility and obstacle discernment. In addition, it has been shown that with the proposed distribution a system which is virtually free from glare can be achieved.

While it is apparent that complete elimination of veiling glare cannot be expected in the first optical



Figure 8. Test installation with open suburban units turned off and cars placed as on the emergency lane of a 36-foot roadway.

250'														10'
25'														
HORIZONTAL FT-C	.36	.25	.25	.17	.17	.12	.19	.37	.79	.77	.58	.25		
VERTICAL FT-C	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1.26	1.37	1.62	1.50	1.30	1.18	1.07	.97	.87	1.48	1.37	1.34		
HORIZONTAL FT-C	.32	.19	.26	.17	.12	.11	.16	.29	.49	.41	.27	.20		
VERTICAL FT-C	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	1.0	1.26	1.50	1.40	1.32	1.17	1.11	1.00	.87	1.08	1.13	1.17		

Figure 9. Footcandle readings of test installation.

designs, it does exist as a goal. The minimum acceptable goals which have been set are below, in DVB, the idealized minimum possible with the other two systems. Certainly the end result, highway lighting without glare, is an objective that now appears attainable.

References

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DISCUSSION

W. H. EDMAN:* Without doubt, this paper will stir up some controversy. There will be many who believe it to be a bit bold in advocating the reversal of light flux direction and literally abandoning the popular concept of silhouette lighting. I, for one, am glad to see this development, because we have gotten a little off balance in advocating, almost exclusively, that roadway lighting should depend on pavement brightness and silhouette seeing.

Let us be truthful and admit that silhouette lighting is "poverty lighting" and is not preferable to seeing by reflected light if the latter can be economically achieved. This approach seems to have much promise. Also, let us not forget that it is much easier to judge depth perception under direct illumination than by silhouette. In fact, on observing the test installation described by the author, I found the difference in depth perception quite remarkable. Judgment of distance too, will become more important with the ever increasing high-speed traffic of the future.

This system is really a continuous or super-vehicular lighting system. It has the added advantage of high mounting. Under such a system, the need for main beam vehicular headlights literally becomes unnecessary. This would also eliminate the headlight glare from oncoming traffic.

Under the severe limitations of the increasingly lower automobile designs, it is unlikely that much greater headlight candlepower will result in any net accomplishment.

D. A. TOENJES:** It is encouraging to see, as evidenced by this paper, the continuing interest in effects of glare from roadway lighting installations. In this proposal of a uni-directional lighting system with overhead mounting, the author recognizes the necessity of modifying an idealized candlepower distribution into the form of a practicable luminaire.

One question on which the author might care to comment is this: In some earlier trials of low-mounted lighting, also aimed uni-directionally with the flow of traffic, one most disturbing glare effect was that of high candlepower into the rear-vision mirrors of each vehicle. In this new system, will the higher mounting remove such reflections of high beam candlepower sufficiently, from the driver's field of vision? We note that the maximum beam candlepower is depressed only six degrees below horizontal. Since it is

proposed that the luminaires be mounted on the left-hand side of the road, the reflections into a vehicle's side mirror might be the main cause of such glare difficulty.

G. A. NAGEL:* This paper presents an interesting yet controversial approach to the subject of expressway lighting. The system described presents certain refinements over previous installations based on similar principles, but the idea of providing "downstream" directional lighting is not new. It is to be noted that such installations as have been made have not been regarded as successful because the disadvantages have outweighed the advantages.

There is need for some reflected light from obstacles where reverse silhouette, detail and color discrimination are desired. It may be that obstacle brightness is required in locations where the traffic is dense, and to a degree, reflected light may aid judgment of speed and distance, although it could well detract from the latter if the background against which vehicles are moving is not adequately bright. Our past experience indicates that it is still necessary to provide a large amount of silhouette lighting for economical roadway illumination with sufficient contrast for safe nighttime driving. This experience also supports the generally recognized importance of comfort from roadway lighting installations.

It will be interesting to see how well the luminaire which Mr. Waldbauer proposes for expressway lighting bears up in actual installation as compared with the DVB computations presented in the paper. We noted that an installation is being made on Route 401 in Toronto, Ont. and this should help to answer some of the many questions which naturally arise.

Since we do not concur in the conclusions drawn by the author, there are several questions we would like to ask.

(1) What are the candlepower distributions assumed by the author to be representative of conventional mercury and fluorescent roadway lighting? It seems that the author's claims with regard to per cent loss due to DVB in these two systems are inordinately high. Visibility factor computations, along the lines proposed by Rex,¹ should be provided for comparison of the various lighting systems under discussion in the paper.

(2) Do the selected observer positions favor the proposed system? The author should show the relationship of the three systems, as given in Table II, when the observer is in a passing lane. DVB computations by the writer, from measurements on a highway lighting test installation,² show that the values vary considerably depending upon the driver path in a traffic passing lane under conventional mercury luminaires, as compared to the outside lane. It would seem reasonable to assume that a vehicle driver in the passing lane, being closer to the maximum candlepower beam from luminaires on his left in the proposed lighting system, might suffer DVB loss considerably higher than that shown for the outside, or emergency, lane selected. We should have the complete comparison of visibility and comfort of the author's proposed system *vs.* conventional mercury or fluorescent roadway lighting.

(3) With the vehicle driver in the passing lane, wouldn't there be a considerable "flicker effect" from the luminaires on his left, both from light coming directly toward him and from light reflected from the vehicle surfaces, rear-view mirrors, etc., when the vehicle passes under the proposed directional luminaires?

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(4) Has the author made any discomfort glare comparisons taking into consideration reflecting surfaces as well as the light sources themselves?

(5) Has the author calculated and evaluated the contrast produced by his proposed system as compared to other systems in present use? It would seem that this information should be given.

(6) Has the author given due consideration to the shadow effect ahead of the vehicle as it passes through successive high candlepower beams from luminaires in the proposed lighting system?

Unless the answers to the above questions are quite different from what we expect they will be, we are of the opinion that the proposed lighting system will be found wanting as compared to presently accepted roadway lighting for expressways. If this be the case, the author may wish to modify, considerably, the conclusions he has drawn with regard to visibility and freedom from glare (in all its forms), and his implication as to how poor conventional expressway lighting is.

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2. Nagel, George A.: "A Highway Lighting Test Installation." ILLUMINATING ENGINEERING, Vol. LII, No. 3, p. 162, Fig. 8. (March 1957).

JOHN W. YOUNG:* Lighting systems accomplished by new light distributions are always stimulating. In this paper, Mr. Waldbauer has presented a new concept for highway applications that merits examination and trial. This contribution should increase the sum total knowledge of applying illumination on dual-road, high-speed roadways in particular.

The light distribution principle calls for dealing with strong vertical candlepower beams and resulting glare effects, although such are not observed directly. One could enumerate several points that might have a bearing on the performance of the proposed illumination and which probably have been observed in experiments or considered for resolving in actual application. It would seem that annoying "traveling" shadows might be cast in front of the car (a situation noticed with low mounting of large light sources in bi-directional systems). Conceivably, there are reflections and strong glare from car surfaces, glass windows (sides), from rear-view mirrors, strong beams inside cars and various other surfaces. There is also the situation, possibly, of glare experience from areas adjacent to the highway and the necessity of modification of the light distribution at interchanges, service areas and other locations.

One item on which it is hoped the author will expand is the consideration of mounting height of luminaires. A height of 30 feet is the minimum, very probably, but what is the case for some higher mounting height from a light distribution standpoint, that is, pattern and spacing? Also, would not some greater height subject the driver and other observers to less reflected glare conditions?

It seems that lowered investment and annual operating costs might be substantial with this system. There are factors, apparently, quite favorable compared with present applications.

(a) The 300-foot spacing results in a reduction of lamp units to approximately 18 per mile of roadway as com-

pared with possibly 24-26 and 30 units in some bi-directional lighting done today on dual roadways. In many instances, a reduction of lamp units is virtually the sole opportunity to effect lower investment in highway lighting installations. With underground construction, the savings can be sizable.

(b) One way of rating energy requirements for lighting a given type of roadway is in watts-per-lineal foot of roadway. It is apparent that the wattage for 300-foot spacing results in a reduction of the electrical energy component of the per mile annual maintenance cost as compared with alternate installations frequently done today.

(c) Such a system as proposed, that is, for dual roadway and medial strip arrangement, offers an opportunity for a considerable reduction in the electrical distribution system cost per mile. This comes about by reason of the lamp units being located in the medial strip, primarily for light distribution purposes, of course. For a direct burial wire distribution system, all in the medial strip, trenching (and circuit run) for one tentative layout would be around 65 per cent less per mile of dual roadway than where lamp units are located on the outside of each roadway and served by a distribution circuit for each side.

The author and his associates have made an important contribution in lighting techniques and developments will be watched with much interest.

W. B. ELMER:* Street lighting engineers have speculated, for many years, on the merits of lighting systems other than the almost universally used bi-directional system. As long ago as the early twenties, a system very similar to that described by the author was tried out by Lamson on Boylston Street in Boston and subsequently abandoned. In the late thirties (?), a very slightly modified bi-directional system, in which slightly more light was projected upstream than downstream, was used in Detroit with presumed success. Prior to 1948, a uni-directional system was developed and installed in England, and was reported as successful by J. S. Smyth to the Association of Public Lighting Engineers. In the early 1950's, a low level uni-directional downstream system was installed on the Mystic River Bridge in Boston. This system has been thoroughly condemned because of the reflections in the rear-view mirrors of automobiles. In 1957, I developed a new "directional" lighting system using a large low-brightness mercury or incandescent luminaire. This system was installed, at first experimentally, and later commercially, by both the Connecticut State Highway Department and the Connecticut Light and Power Co., with highly satisfactory results. This system is designated as "directional" to distinguish it from the "uni-directional" system, inasmuch as the normal degree of illumination is projected upstream, whereas the downstream light is limited to about a third of the normal value. More recent experiments with strictly uni-directional fluorescent lighting directed upstream have been adjudged unsatisfactory by Harold Wall of the Detroit Public Lighting Commission.

Against this fragmentary history of directional and uni-directional lighting, we are now presented with Mr. Waldbauer's interesting re-espousal of the hitherto rejected downstream uni-directional system.

In passing, let it be noted that the author's statement on the first page, that "... and now even the Connecticut Turnpike [has] utilized standard bi-directional street lighting luminaires ..." is misleading, ignoring the fact that a substantial quantity of upstream directional low-brightness

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mercury luminaires are being installed on the uncompleted east end.

In his opening discussion, the author rejects upstream lighting for highways because of a supposed hypnotic shutter effect during prolonged driving periods. He has not considered the possibility of installing larger lights at higher elevations and on greatly extended spacing, which would also overcome the shutter effect to a considerable degree, if this effect is truly a hazard. The author admits that his fears are speculative and it should not be forgotten that a rhythmic variation in lighting might have the opposite effect from that which he fears, *i.e.*, the repeated flashing by overhead light sources may act as a stimulant to keep the driver awake. Certainly, I have never heard that an insomniac can lull himself to sleep by subjecting himself to repeated flashes of light.

I believe that the key to the present question lies in the light level used. It is well-known that discernment by direct illumination is most difficult below five footcandles. Such gloomy levels are only tolerated in churches where a "dim religious light" is required, or in warehouses, where no small objects or fine details need be discerned. Well below this level, in the usual street lighting ranges from 0.2 to 1.2 footcandles, it is traditional knowledge that vision is accomplished by silhouette. This is the first fundamental learned by every young street lighting engineer.

The illumination level at which silhouette vision leaves off and direct discernment begins has probably never been clearly defined. It seems likely that this null region lies somewhere between 5 and 10 footcandles; above 10 footcandles, direct discernment becomes effective; below 5 footcandles, silhouette vision is the medium of perception.

A consideration of contrast will provide a very good answer to this question. Visibility is provided by contrast, both brightness contrast and color contrast, and it is reduced by veiling glare. For the street lighting problem, where an object must be perceived several hundred feet ahead of the moving vehicle, the contrast is expressed by:

$$C = \pm \frac{(B_1 - B_2)}{B_1}$$

where C is always positive,

B_1 = Brightness of pavement behind obstacle,

B_2 = Brightness of obstacle.

In the case of silhouette vision, B_2 is approximately zero, hence contrast is approximately unity. In the case of direct illumination, in order to obtain contrast equal to that provided by silhouette vision (unity), B_2 must equal $2B_1$. If the illumination on the obstacle is double that on the pavement, the contrast will be equal to that obtained by silhouette, provided reflectances are equal. If, however, the obstacle reflectance is half that of the pavement (a common case), the contrast is zero. This is the well-known neutral point that occurs beyond a street light, where visibility can be completely lost unless color, texture or geometric differences exist. This is the reason why higher orders of illumination are required for downstream roadway lighting than for upstream.

For the author to claim satisfactory visibility at one foot-candle by direct discernment, therefore, is contrary to all lighting experience. A careful study of Figs. 6, 7 and 8 does not appear to support the claims of satisfactory visibility. The large white target in Fig. 7 is visible only because it extends above the pavement background and because it rises against a line of pavement darkness close behind it. The small white target is hardly visible. The black targets are not visible because of the direct illumina-

tion, but despite this, and because of silhouette against the pavement, the upstream directional system would give far superior discernment in all cases. Photographs of a variety of targets of graduated reflectances under both systems would be necessary to reveal the inadequacy of downstream lighting under recommended illumination levels.

It is, of course, highly commendable to seek the elimination of glare. The disability veiling brightness from modern, well-designed luminaires and particularly, in my opinion, from the low-brightness mercury luminaires with their excellent optical system, subtracts not more than five or ten per cent from the excellent silhouette visibility afforded by that luminaire. It would require an estimated 10 to 12 footcandles from the proposed downstream uni-directional system to equal the visibility afforded by 1-1.5 footcandles of upstream light properly distributed, glare notwithstanding. The proposed downstream system, therefore, appears to be impractical on the score of cost, if comparable visibilities are considered.

Before concluding, I would like to request that the author cite the source of data used in the interesting atmospheric absorption chart, Fig. 2.

R. E. FAUCETT:* Mr. Waldbauer is to be complimented for taking a fresh look at the relatively old idea of uni-directional street lighting. C. A. B. Halvorson reported upon similar studies conducted about 20 years ago on a 1000-foot section of the Taconic Parkway near Poughkeepsie, N. Y.¹ The object of these studies, sponsored by H. E. Dexter and M. N. Waterman, then of the Central Hudson Gas & Electric Corp., was to determine to what extent pavement brightness might be enhanced by properly coordinating the design of pavement surfaces with projector-type luminaires pointed generally in the direction of travel. A more recent installation on the Mystic River Bridge was reported by W. J. McClain, J. E. Greiner Co.²

The main difference between these earlier studies and the one reported by Mr. Waldbauer is that of mounting height and spacing. Mr. Halvorson's studies used approximately 3½-foot mounting heights and 100-foot spacings, compared to Mr. McClain's 4-foot mounting heights and 52-foot spacings. The present study reports 30-foot mounting heights and 250- to 300-foot spacings. The geometry of any of these installations is such that the angle of incidence of light at the pavement is quite large. Apparently, the Mystic Bridge installation and the present experimental installation have a very similar ratio of spacing to mounting height.

It has been reported by some observers of these earlier installations that light being projected from behind drivers causes glare in the rear-view mirrors, windshield and other specular surfaces, as well as disconcerting moving shadows within the vehicle.

Superficial thinking on the matter may lead one to the conclusion that the shutter effect would be eliminated by a uni-directional lighting system. Actually, this probably is not the case because of the reflected light received by the eye from the automobile's structural and ornamental elements, as well as from other objects along the street such as parked or moving vehicles, signs, etc. There would, therefore, still be a shutter effect. However, the shutter effect existing under a uni-directional system would be "out-of phase" with that which would exist under conventional

*General Electric Co., Outdoor Lighting Department, Hendersonville, N. C.

roadway lighting systems. The reasoning behind this is that the full brightness impact of the source is observed during the approach in a bi-directional system, whereas the full brightness impact is observed after passing the source in a uni-directional system. It is felt that this out-of-phase relationship has no significant effect upon over-all comfort or visibility. The important thing in either case, when considering comfort, is the ratio of the effective glare brightness to the adaptation brightness of the observer, assuming all other factors, such as effective source sizes, position factors, time of exposure and color of illuminant, are constant.

Observers of the earlier studies also reported that a continual impulse to slow down and let the "close-following automobiles" pass existed. A uni-directional lighting system has also been observed to produce moving shadows of the vehicle in its own path. This could, in itself, be very dangerous because the distractions to the driver could more than offset the advantages gained by the illumination.

It is believed that these presently proposed higher mounting heights will help reduce the annoyances pointed out above as being some of the undesirable results of a uni-directional lighting system. In addition to these higher mounting heights, the shutter effect can be further minimized by proper design of the light distribution pattern, including a proper choice of the angle of maximum candlepower.

Mr. Waldbauer states that "... all new roadways built in cooperation with the Federal Highway Program must have medial strips at least 32 feet wide." It should be pointed out that this is merely a recommendation, and certainly a desirable achievement. The Federal Bureau of Public Roads recognizes that this is a very difficult thing to achieve, and is in many cases impossible because of limited area or right-of-way obstacles. Therefore, as a practical result, it is more the exception than the rule, at least at the present time, to find these wide medial strips incorporated into highways.

When medial strips are less than 32 feet wide, appreciable flux is furnished from luminaires mounted over the far roadway. This additional flux can only be ignored when the medial strip appreciably exceeds 32 feet. Most existing heavily-traveled roads that will be lighted, have medial strips less than 32 feet wide.

The author points out that, in general, highway lighting systems are being installed at interchanges, service areas, and access entrances, but not along the highway between these areas. This represents a terrific challenge for the lighting industry. The highway and traffic consultants tell us that there is no existing evidence today to justify lighting areas between interchanges on controlled access highways. There appears to be general agreement that all parts of a non-controlled access highway should be lighted. Therefore, I would like to repeat that it is up to us to offer *proof* of the need of a fixed lighting system on these high-speed, controlled-access highways now being constructed. However, even in the face of this lack of evidence, many urban expressways are being lighted continuously. Atlanta reports over 30 miles of continuous lighting. Chicago, Dallas, Detroit, Fort Worth, and even relatively smaller cities such as Austin, Texas and Winston-Salem, N. C., have continuous systems on modern expressways.

The author recognizes that the Connecticut Turnpike was illuminated by employing conventional bi-directional equipment because "... a great deal of application experience is available." This should be explained a little more in detail because experience has thus far proved that bi-directional

equipment is the most economical and practical means of providing optimum visibility on our present day roadways when all factors are considered.

Previous investigations have indicated that uni-directional lighting systems have some merit as long as pavement surfaces remain diffuse in reflection characteristics. On traffic-worn, smooth surfaces or otherwise specular pavements, such as wet concrete, it has been repeatedly concluded that light aimed generally in the direction of travel is ineffective. This has been demonstrated to be the case even on a wet rough surface.

Many authorities have recognized the importance of pavement brightness throughout the years. Recently, one stated: "One quantity that seems to be a key to the entire problem is the roadway brightness as seen by a vehicle operator."⁸

The author states that "... the eye discerns most larger objects by direct discernment and certainly cars along the roadway are seen as cars and not just as silhouettes." I am in agreement with the author as long as the roadway is lighted to a relatively high vertical footcandle level. However, it is not necessary that the object be lighted to this high vertical footcandle level if it is seen by silhouette and it is not necessary to have a high brightness background to discern by silhouette. Therefore, not as much candlepower is required toward the eye to achieve threshold awareness by silhouette as is required to achieve threshold awareness by direct discernment. Therefore, despite some glare, the threshold of awareness of objects on the pavement is frequently improved when viewing the roadway in a direction opposing the incident light.

The author points out that: "A fourth possible system for highway lighting would be the use of continuous fluorescent strip mounted off to one side of the roadway." Such a system was installed in October 1956 on an experimental basis, over a 100-foot section of 70-foot wide roadway. Fig. A depicts this installation. Notice the uniformity produced as evidenced by the absence of shadows of the observers in the streets. If properly baffled, such a system could be virtually glare-free. This system has many merits, but a treatise on this installation is beyond the scope of this discussion. This type of lighting technique will become more feasible when high frequency power sources are more commonly available. By high frequency, I do not mean 400 cycles, but rather the kilocycle ranges — perhaps higher.



Figure A. Continuous fluorescent strip lighting over a 100-foot section of 70-foot wide roadway. Eight-foot fluorescent floodlighting units equipped with 96T12 cool white rapid start lamps are mounted on catenary 28 feet above the roadway.

It was stated that: "Up until now, the street lighting designers have paid more attention to the illumination which the system would produce than to the comfort of the motorist." This certainly has not been the case with my company. For years we have been preaching the importance of comfort.* Many basic research studies on comfort could be listed, such as the work of Drs. Guth and Harrison, as well as practical application papers by Reid and Toenjes⁵ and Rex.^{6,7}

On the fourth page of his paper, the author states that "... the most important task of street lighting is to provide visibility." Then on the next page, he says that "visibility is the second most important factor." I assume that the implication here is that comfort is perhaps the most important after all. I heartily disagree. It is my opinion that the most important item is safety. Then, let either visibility or comfort come in second place, whichever one is needed to achieve safety.

It would be interesting to evaluate the evidence on which the author bases his belief that a combination lighting system (one which provides both direct and silhouette discernment) would produce a lower over-all visibility rating than one which provides a direct discernment visibility only. Also, if a uni-directional system (direct discernment) were employed with the units aimed generally in the direction of traffic flow, why should headlights be used at all?

The author has expressed his full realization of the practical difficulties in designing an optical system to meet the practical requirements of the uni-directional lighting system. Therefore, until such time that these practical optical control design problems can be solved, it is recommended that we continue to improve functional performance of products used in the more conventional, experience-proven systems.

I wish to express my sincere appreciation to the author for affording me the opportunity of commenting on this fascinating approach to the problem of seeing on roadways. I also wish to acknowledge the assistance given me by W. E. Schwanhauser in preparing this discussion.

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W. M. WALDBAUER:* I wish to thank those who took the time to prepare the above thought-provoking discussions. It is encouraging to note that the discussers unanimously agreed that it is "highly commendable" to seek the elimination of glare from roadway lighting systems. It is natural that certain questions and doubts are raised in the minds of those who read this paper, since it represents an un-

conventional and virtually untried departure from the principles currently used in roadway lighting.

Several of the discussers have cited the previous experience of uni-directional systems, especially those on the Taconic Parkway and Mystic River Bridge. These discussers report that there were serious objections to the uni-directional approach based on a reflection received by the driver's car windows, interior surfaces and rear- and side-view mirrors. These installations utilize luminaires at relatively low mounting heights, *i.e.*, 3½ feet as compared with the 32-foot mounting height proposed by the author.

Two test installations of the proposed system have been made thus far. One is located in Cleveland and the other in the outskirts of Toronto. While neither of these systems represents what might be termed ideal installations, observers who have driven under the installations have reported no difficulties regarding reflected glare from various surfaces of the car. Another factor considered by several of the discussers is the probability of annoying effects from "traveling shadows" created by the car itself. Under the proposed system, such shadows do exist and can be quite long considering the relatively small angle of depression of the main beam from the horizontal. However, such shadows are annoying only when driving is done without the aid of vehicle headlights. With the headlights on, these shadows are washed out and no annoying effects are noted.

Several questions regarding the application of this system have arisen and are deserving of further comment. Regarding the modification of the distribution of this luminaire at interchanges, service areas and the like, it is my opinion that this system would find its principal use along dual-lane roadways between interchanges and service area points. At interchange and service areas themselves, either conventional bi-directional luminaires or another type of "no glare" luminaire would be required.

Regarding the question of medial strip width, the present luminaire is being developed for medial strip widths of 32 feet or more. As the optical system is further developed, and the cut-off of the luminaire improved, medial strips less than 32 feet in width will be in order. It should also be remembered that the current recommendations of medial strips 32 feet in width or greater are based on achieving a certain reduction in DVB as compared with current roadway lighting systems. Even in its current state of development, the luminaire could be installed on medial strips less than 32 feet wide but only with a resulting increase in DVB.

Regarding the source of data for Fig. 2, these were calculated using Bouguer's or Lambert's law with the value of the exponent "X" having been determined from the data given on pages 9-44 and 15-21 of the *IES Lighting Handbook*, Second Edition.

While much work remains to be done before this proposed lighting system becomes a practical reality, my company has more than a theoretical interest in "lighting without glare." The development of the high utilization fluorescent street light, mounted parallel to the curb, together with this development adequately provides proof of this statement. In addition to this, the company has continued to provide improved developments in the field of bi-directional lighting as well as in the associated field of improved light sources. While providing visibility is our most important task, we must make sure that in attempting to improve visibility with higher illumination levels, we have not sacrificed driver comfort or over-all visibility.

*Author.