AUTOMOBILE GLARE AND HIGHWAY VISIBILITY MEASUREMENTS

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SYNOPSIS

The results of the measurements indicate that headlight glare is more of a hindrance to full highway visibility than heretofore recognized. Even if the opposing headlights are dimmed to relieve completely the discomfort of glare, the meeting visibility still can be too sluggish for safe travel. Because of the changeableness of eye sensitivity this inadequacy of meeting visibility can escape detection unless there is a standard of measure.

The measurements of visibility here reported, are based on the premise that the driver needs to see as well when meeting other cars as when driving alone in the open road. For economy of electricity the open road visibility provided by present "upper" beam headlights is not more than found, by experience, to be needed. The tests seek to show how dim the opposing glare must be in order to maintain meeting visibility equivalent to the open road visibility.

Considering how the eyes function, we know that when driving in open road the eyes become adapted to the general brightness level of the roadway ahead as illuminated by the headlights and visibility may be reasonably satisfactory and safe. It is possible to maintain the same order of visibility when cars meet, provided the adaptation level from the glare of the other cars is in the same order of brightness as that from the headlighted roadway when in the clear. The procedure of the tests was to measure separately the adaptation level of the eyes when exposed to the roadway illuminated by Sealed Beam (up beam) headlights and then when exposed to the glare of various candle powers. Thus a candle power value of the glare source was found which causes the same adaptation level as does the headlighted roadway. Computations from these test data indicate that meeting visibility up to 80 percent of open road visibility can be attained if the opposing glare is not more than 20 candle power. By comparison, the glare from present headlights may reach 800 to 1,000 candle power even with the beams tilted down.

If such quantitative measure of the effect of glare on visibility is made available, there may be more encouragement for research toward safe headlighting. Then any possible development of superior merit, even if a complete departure from present conventions and concepts, could have a better chance of recognition.

Highway visibility has much to do with highway safety. If the driver can't see conditions on the road ahead he certainly can not be expected to drive safely. Studies of statistics seem to show that the worst driving hazard of all, per mile of travel, is on the rural highways at night. It appears that, on the average, if one drives over a given stretch of highway at night his chances of being involved in a fatal accident are three times greater than on the same stretch of highway in the daytime. What can make such a large difference between night travel and day travel? One sure difference is visibility and in the country we usually are dependent solely upon headlights. It seems apparent that the foremost hindrance to seeing by the use of headlights is glare from the headlights.

We read articles in the papers in behalf of safety which seem to blame accidents on habits of drivers and pedestrians; and to highway alignments and constructions; but little seems to be said as to any mechanical faults of the automobile itself. Certainly, the major cause of the preponderance of night fatalities can be due to the shortcomings of the headlights on the automobiles.

Would it not be worth-while to try some research from a different point of view? For instance, the kind of research which tries first to find what the eye actually needs for highway seeing and then try to design headlighting to suit; - not the other way around. In any basic research it is customary to make measurements Yet in headlighting there appears no direct measure of the effect of glare on highway visibility of the full field ahead. Previous data have been based on measurements of visibility distances of a single target at a particular location along the roadside. But the seeing of a single object is only one element of full field visibility. To take in the full scope of conditions ahead, in the limited time while the car speeds along, the eyes of the driver must resort to the less distinct parafoveal vision and to Gestalt conceptions. This kind of seeing is different from looking at one single object where we have the clear visual acuity of central foveal vision. In the measurements reported herein, an approach is attempted which includes visibility of the full field. When such measurements are made they seem to show the utter hopelessness of the underlying principles of projection as used in present headlighting.

CONCEPTS BASED ON PRESENT HEADLAMP PERFORMANCE NOT APPLICABLE FOR APPRAISAL OF NEW DEVELOPMENTS

If it once is demonstrated and conceded that there is little chance that present headlighting principles can ever accomplish safe night visibility, then the obvious approach would be to open our minds and turn to some other optical principle such as polarizing the light or still other scientific phenomena. But the trouble is that the introduction of any new headlighting development is different from the customary procedure of building up the use of a new product from small beginnings. Any new headlight beam may involve other users of the highways. So it must be a cooperative affair depending upon some central authority representing the interests of all the people. Central authority leads to mass thought and in the absence of a rational measure, general habits of thinking have become so reconciled to present glare and so devoted to previous headlamp performance that any complete departure from established ideas and precedents is expected to meet resistance. Experiences indicate that this situation does exist and has tended to retard research.

Of course uniform standards and rules are necessary for interpreting the State statutes for regulating present headlamp practice. Current problems must be met year by year, and it is understandable why the beam specifications have been drafted to include existing headlamp performance.

But basic research is another problem. These rules or orthodox concepts and thinking in terms of these rules are

not applicable for sizing up new developments. Certainly innovations should be gaged on measurements of what the eye is capable of doing, regardless of what previous headlamps have been doing. However, because the rules for previous headlamps have had to ignore the effect which glare has on visibility, it does seem that of the two major causes which have been considered for universal adoption - the Sealed Beam and Polaroid - the full advantages of reducing glare to a minimum were ignored. In each of these improvements better driver visibility could have been secured if consideration had been given to the quantitative effects of disability glare. What chance does any invention or new development have if the real hindrance to night visibility - glare - is not to be given full consideration in balancing the advantages against the disadvantages?

There is hope that if means for isolating and quantitatively measuring the effects of glare are made available, decisions can then be based on factual data rather than upon opinions. It is the purpose of this paper to report a method for quantitatively measuring disability glare.

MEASUREMENT OF DIFFERENTIAL BETWEEN MEETING VISIBILITY AND OPEN ROAD VISIBILITY

The measurements of visibility in the present study are based on the premise that the driver needs to see as well when meeting other cars as when driving alone in open road. The needs for headlight beam patterns for adequately viewing the full scope of the field ahead when driving alone in open road have already been worked out as now accomplished in the modern Sealed Beam "uppers". Further increase in volume of light could be secured at any time, with no change in the basic optics of projection, merely by the use of larger parts and the expenditure of more wattage. So we are concerned only with the difference between visibility against glare and open road visibility; and the starting point, or datum, from which the effects of glare are reckoned in this study is taken as the open road visibility from present headlighting. The measurements submitted herein are to show to what extent glare needs to be reduced in order to obtain meeting visibility which approaches present open road visibility.

The results of measurements to date, as reported in detail below, indicate that to get meeting visibility up to, say 80 percent of open road visibility, the opposing glare must be restricted to at least 20 c.p. with the driver's own headlights still giving him the same field brightness as do present Sealed Beam "uppers". This is a ratio of over 2500 to 1 between the candle powers of the beam for long ranges and the glare.

By way of comparison, the meeting beams of present headlamps may give 800 to 1000 c.p. glare and are so tilted that their main force strikes the foreground only some 100 or 200 ft. ahead. Visibility straight ahead for reasonable driving ranges is extinct.

DISCOMFORT GLARE AND DISABILITY GLARE

A factor which perhaps may need some clarification in this study, is the difference between discomfort glare and disability glare. As a hypothetical example let us suppose we are approaching another car with headlights shining say 10,000 c.p. glare in our eyes. We feel that this glare is uncomfortable and irritating. Then if the beams of the other car are shifted down to, say, 1,000 c.p. it seems like a welcome relief. The glare seems gone. However that reduction of 10 to 1 is a small part of the ratio of over 2,500 to 1 needed for visibility. This example may illustrate why when glare is reduced only on the basis of easing the eyes of opposing drivers it may be nothing more than a feeble gesture toward maintenance of adequate visibility.

EFFECTS OF CHANGES IN EYE SENSITIVITY - ILLUSTRATIVE EXAMPLES

In considering the results of the measurements it may be kept in mind

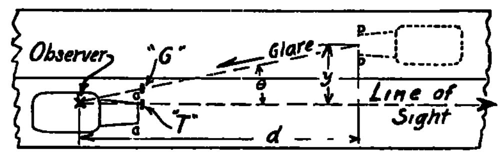
that the depletion of visibility in the presence of glare is solely a question of change in eye sensitivity. What really is measured, although objectively, is eye sensitivity. It is almost beyond our comprehension just how much eye sensitivity does change. As an example, the level of illumination in sunlight may be one billion times greater than under starlight. Yet our eyes so change that we can see to get around in both cases. At any one setting, or adaptation brightness level of the eye, within that extremely wide range, the band within which the eye normally can function - pure white against dead black - is only a contrast of 100 to 1; - quite a small fraction of a billion times. As another example, the stars in the sky are sending as much light down to us in the daytime as at night but we do not see them by day. The change is not in the stars. It is in our eyes.

NORMAL SEEING AND PRESENT AUTOMOTIVE SEEING

These are examples of a phenomenal property of the eyes. That is, the changeable sensitivity of the eye somehow maintains a fixed relationship to the surrounding brightness to which our eyes, for the moment are exposed. Let us first examine how normal seeing works and then how and why the customary combination of headlight illumination and glare fails to work.

In normal seeing when the candle power of the source of illumination is increased, the brightness of all objects within the field, and their brightness differences, increase in direct proportion. Under these increased brightnesses, the eye does not need to be as sensitive for maintenance of the needed seeing ability. So nature has provided that when the general brightness of the field increases in this manner the eye sensitivity decreases. The decrease is in almost straight line inverse proportion to the brightness. One change offsets the other and visibility remains about the same. This wonder of nature, and it is a wonder, acts in accordance with Weber's law of psychophysics which, when applied to the sense of sight, can be stated as: "the least perceptible brightness difference is a constant fraction of the surrounding brightness." The "least perceptible brightness difference" is a measure (inverse measure) of eye sensitivity.

FIG I



Test Car - Plan

Present headlighting habits are contrary to this law of nature. When driving in open road, our eyes become adapted to the brightness of the field illuminated by our headlights, most dominant of which is the pavement surface in the foreground, and visibility may be reasonably satisfactory and safe. When meeting another car having present style headlights, things drastically change. The effective brightness of the opposing glare, even with the lower beams, is so much greater than the road brightness to which our eyes have been adapted that, in accordance with Weber's law, the optical sensitivity of our eyes drops way down. Now, in normal seeing, eye sensitivity goes down only when the field brightness has gone up. In this instance, however, the brightness of objects in the field ahead, as illuminated by our own headlights, has not increased to compensate for the drop in eye sensitivity from the glare. In fact it is required that drivers tilt down their beams and take light away from the long ranges, instead of increasing it. This is not normal seeing, it is contrary to natural laws and visibility becomes extinct at the longer ranges.

The effect is that just at the critical time whenever cars meet and pass each other, both drivers must blindly enter head-on into a zone of darkness. Even

at modest speeds, both are temporarily incapacitated and many things may happen such as colliding with each other, running off the road, running down a pedestrian, or suddenly encountering an unexpected obstruction. This situation is the crux of the night highway visibility problem.

MEASUREMENTS - EQUATING GLARE BRIGHTNESS TO OPEN ROAD FIELD BRIGHTNESS

In considering the above mentioned characteristics of the eye it is obvious that it would be possible to get meeting visibility to approach open road visibility if, without changing the illumination on the road ahead, we keep the opposing glare down to the same order of brightness as the field brightness illuminated by our headlights; - that is, if we keep eye sensitivity near the same both when meeting and when alone in open road. The procedure in making the measurements is to find, in terms of candle power, what brightness of opposing glare is equal to the brightness of the headlighted field.

TEST EQUIPMENT

The simple apparatus used for making such measurements is installed on a test car as illustrated in Figure 1. This is a plan view of a portion of a highway with our test car shown in full lines and a possible glare car in the adjacent lane shown dotted. In addition to standard Sealed Beam glass reflector headlamps, the test car is equipped with two sources of brightness, "T" and "G". The brightness source "T" is in the shape of a 1-deg. square target framed by a 1/2-deg. black border. The target is in the driver's line of sight when looking toward the most distant objects on the highway directly ahead. The brightness source "G" is a small incandescent lamp, such as used in taillights and is in direct line between the driver's eyes and the position of opposing headlights in the adjacent lane at a distance where glare may be bothersome - say 100 ft. Thus, the small lamp "G" has the same effect on the driver's eyes as opposing glare, the actual candle power values being adjusted, of course, in accordance with the inverse square of the distances from the eye to the sources. The brightnesses of each of these sources "T" and "G" are independently controlled by rheostats in their respective electrical circuits. A special voltage regulator is used for obtaining brightness consistency in all tests.

The target "T" is the yard stick for the measurements. That is, a balance is found in which some setting of the brightness of target "T" is just barely visible when the driver's eyes are exposed solely to the field illuminated by his own headlights and also is just barely visible with his eyes exposed solely to some certain candle power value of glare "G". With this balance, the effective sensitivity of the eye must be the same when exposed to that particular candle power glare as when exposed to the headlighted highway. Also, the "contrast sensitivity" is the same in both cases. This gives a unit for evaluating the glare in terms of open road visibility.

TEST PROCEDURE

The observations for just barely visible brightness between target "T" and its dark background were made in two phases. In one phase the eyes of the observer were exposed to the glare lamp "G" alone, and in the other phase to a headlighted roadway alone. The observations were made in runs, each run being made with a fixed candle power value of glare lamp "G" ranging from the equivalent of 25 to 800 c.p. glare in the one phase and at a given highway location in the other phase. From 50 to 283 separate observations were taken in each run. The collected data from the respective runs were plotted and the curves for the two phases matched graphically for finding the balances between adaptation levels from exposure to glare and exposure to the headlighted roadway.

The observations with eyes exposed

to the glare "G" could be done in an undisturbed yard so that only the observations from the headlighted roadway had to be made on the public highways.

The black border of target "T" was of such low brightness during all tests, that the "minimum perceptible brightness difference" between target "T" and its background was equal to the "minimum perceptible brightness" of the target itself. Care was used to keep factors, other than brightness, constant; - such as, size of target, orientation of the line of sight and time of exposure. The 1-deg. size of target was selected as most typical of major objects to be seen on highways. The line of sight was always directed straight ahead toward the horizon during both phases of the tests. As to exposure time; - just before each run, the eyes of the observer were exposed to the specific brightness of the glare lamp "G" or to the headlighted roadway, as the case might be, for a sufficient period for long time adaptation. Starting at an unknown position of the dial which regulates the brightness of target "T", it was gradually increased at a uniform rate until just visible. This was done manually after preliminary practice. Each observation was made by ascending rather than descending brightness of the target "T" in order not to molest the adaptation level of the eye by the brightness of the target itself.

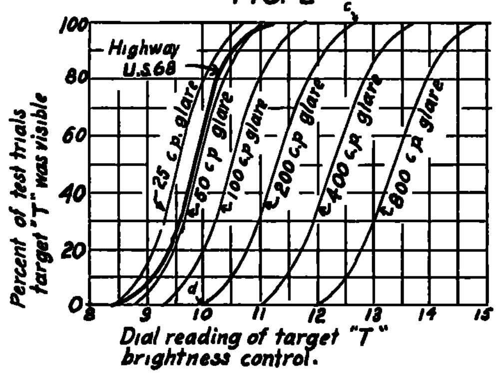
It is to be noted that the brightness of the target, as to itself, has no significance. It is only that whatever visual arrangement of the target might be selected for the tests it must be the same when exposed to the headlighted roadway as when exposed to the glare. The sole function of the target was to strike a balance for equality of the seeing capability with eyes exposed to the headlighted roadway as when exposed to the glare.

It is not intended that the particular results here reported are final. A more elaborate program could procure more refined and reliable data. However, it is believed that the present measurements give adequate data for quantitatively demonstrating the serious discrepancy in current concepts of the effect of glare on highway visibility.

TEST RESULTS

The summarized test data are shown in Figure 2. The light line curves are from tests of the visibility of target "T" against various candle power glares. The heavy line curve gives the visibility of target "T" with eyes exposed to the highway illuminated by the headlights. The readings for this particular curve were taken on highway U. S. 68, one mile north of Midland, Ohio. The horizontal scale is a function of the brightness of target "T".

FIG. 2

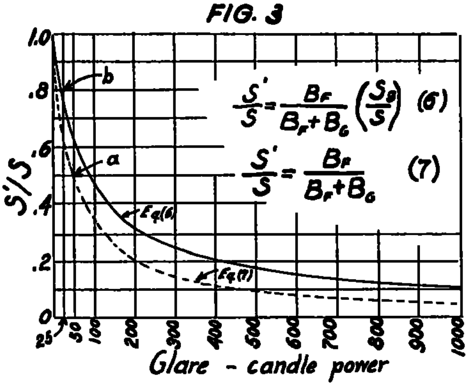


It is in terms of the dial settings of the rheostat which governs the brightness of target "T". (For the purpose of comparison it is not necessary to reduce the dial readings to units of brightness but they were in the order of 0.0003 foot lambert.) The vertical scale gives the percentile or percentage of total test trials of each run in which target "T" was visible. For example, in the test when facing 200-c.p. glare, target "T" was visible at all settings of the dial above 12.6 indicated at c, and at no settings of the dial below 10.0 indicated at d.

The plan at first was to collect visibility data for different types of highway pavement, roadside development, etc., but it did not work out that way. The deviations of the visual perceptions under identical conditions were much greater than deviations at different highway locations. For instance, the test run plotted by the heavy

line curve of Figure 2 coincided almost precisely with runs taken on other highways. There were indications, however, that some locations on sparsely used highways gave higher adaptation brightnesses but on well aged and traveled highways where rigid pavements had become darker, and flexible pavements lighter, no material difference in brightness could be detected. So these observations on highway U. S. 68 were taken as typical.

FIG. 3

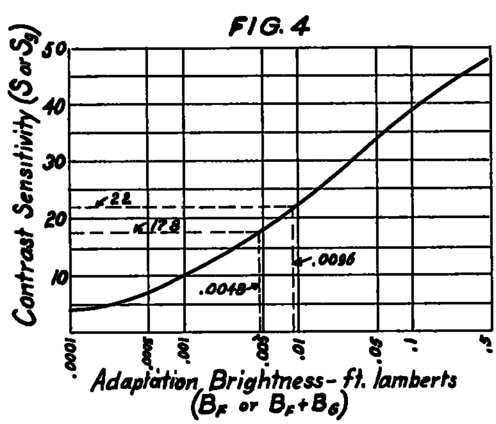


It is noted in the curves of Figure 2 that the average adaptation brightness of the eye exposed to this headlighted highway (heavy line curve) approximately matched the curve for 50 c. p. glare. Interpolation between the 25 c. p. and 50 c. p. glare curves might indicate nearer coincidence but considering other uncertainties in measurements of this kind, 50 c. p. is a sufficiently close approximation. This is the information sought from the tests. "Eye sensitivity" or "adaptation brightness level" is the same when facing 50 c. p. glare on a straight two-lane highway as when facing the headlighted field.

COMPUTATIONS OF MEETING VISIBILITY IN TERMS OF OPEN ROAD VISIBILITY - BASED ON MEASUREMENTS

The result of the measurements means that eye sensitivity is practically the same when facing 50 c. p. glare alone and when viewing the headlighted highway alone; - either one or the other. Actually in the situation of meeting another car, the driver's eyes are exposed to both the glare and the headlighted roadway. This is accounted for in the complete study of the actual meeting conditions as summarized by the curves and equations of Figure 3. The derivations of Equations (6) and (7) which are based on the Holladay (1)[1], (2) analysis of glare are given in the

FIG. 4



Appendix.

It may be recalled that the findings and analysis by L. L. Holladay of the Nela Park Laboratories of the General Electric Company were presented in a number of technical papers back in the 1920's. As now included in the recently published Illuminating Engineering Society Lighting Handbook, the analysis seems to be applied mostly to problems of interior lighting. But of all places where glare needs to be analyzed, it is automobile glare.

In Equations (6) and (7) the symbol S represents "Contrast Sensitivity" when in open road and S' is the "Effective Contrast Sensitivity" when meeting glare. The technical term "contrast sensitivity" may be considered as a general measure of visibility under any particular lighting condition, and general "visibility" as used herein is synonymous with "contrast sensitivity". The meaning of "contrast sensitivity" is, of course, different from the more

[1] See references listed at the end of this paper.

generic connotation referring to sensitivity of an instrument or human sense organ as we have been saying in respect to general eye sensitivity. In the equations, the symbol S can be considered to represent open road visibility and S' to represent meeting visibility. So the fraction S'/S gives the ratio of meeting visibility to open road visibility. The symbol B_F is the adaptation brightness level of the eye from the field as illuminated by our own headlights and B_G is the adaptation level from the opposing glare source. Equation (7) is in more general terms and assumes Weber's law to hold rigorously. Equation (6) is nearer exact in that variations in Weber's law at the relatively low illumination levels encountered in headlighting are accounted for as discussed in the Appendix.

It is noted in Equation (7) for example, that if B_G is large compared to B_F, S'/S is small and meeting visibility is low. This is the case with present headlights. To get meeting visibility which really approaches open road visibility, B_G needs to be small. The condition which was measured in our test was when $B_F = B_G$, in which case the fraction S'/S is equal to 0.5 and meeting visibility would be 50 percent of open road visibility by approximate Equation (7). For this condition the source of glare brightness was measured to be 50 c.p. Starting from this point a of ordinate 0.5 and abscissa 50 where $B_F = B_G$, Equation (7) is plotted as the broken line curve. The glare brightness B_G can be expressed in candle power as shown since the brightness B_G and the candle power I_G of the glare are directly proportioned to each other. (As derived in Appendix $B_G = .0000955\ I_G$.)

The full line curve which is a similar plot of Equation (6) gives nearer exact values of S'/S because variations from Weber's law are accounted for as explained in the Appendix.

CONCLUSION

The conclusion resulting from the tests is shown by the full line curve of Figure 3. If meeting visibility is to be anywhere near equivalent to present open road visibility, say within 80 percent, as indicated by point b on the curve, the glare must be reduced to 20 c.p. Such performance will seem fantastic if we keep thinking in terms of present headlamp performance. However, if the magnitude of the glare effect is once made known and a clearly defined ideal is set up as a goal to strive toward, there may be more incentive for the development of night driving safety measures. The diagnosis of the case might lead to a remedy.

REFERENCES

1. Luckiesh, M., and Holladay, L. L., "Glare and Visibility", *Transactions*, Illuminating Engineering Society, Vol. 20, p. 221, 1925.
2. Holladay, L. L., "Glare of Street Lamps and Its Influence on Vision", *Transactions*, Illuminating Engineering Society, Vol. 21, p. 969, 1926.
3. Illuminating Engineering Society Lighting Handbook, pp. 2-20, 1947.

APPENDIX

Equation (7), Figure 3, gives the approximate ratio between general visibility when meeting glare and when in clear road. Equation (6) gives a nearer exact ratio by consideration of variations from Weber's law. The background for the derivation of Equations (6) and (7) is given below by reference to the Holladay (1), (2) analysis of disability glare.

Sensitivity of the eye as used in the present study may be expressed as:

$$\text{Sensitivity of the eye} = \frac{1}{\Delta B} \quad ..(1)$$

where ΔB is the minimum perceptible brightness difference. It is a measurable quantity as determined by finding the borderline (threshold) between when the test target is seen and is not seen.

Contrast Sensitivity, S, is a measure of general visibility and is expressed by:

$$S = \frac{B}{\Delta B}$$

where B is the adaptation brightness corresponding to the momentary minimum perceptible brightness difference, ΔB.

In accordance with Weber's law S is practically constant at approximately 100 throughout the wide range of brightness levels within which the eye is capable of operating. At the lower brightnesses, the contrast sensitivity S, falls off to unity at the absolute threshold of vision. The change from 100 down to 1 occurs in about $\frac{1}{1000}$ th of one percent of the complete brightness range of vision. It is within this $\frac{1}{1000}$ th percent that headlighting brightnesses are encountered. To account for different values of contract sensitivity, we may designate:

$$S = \frac{B_F}{\Delta B_F} \quad ....(2)$$

and

$$S_g = \frac{B_F + B_G}{\Delta B_{(F+G)}} \quad ....(3)$$

where B_F is the adaptation brightness from the field as illuminated solely by our own headlights and B_G is the adaptation brightness from opposing glare. ΔB_F and $\Delta B_{(F+G)}$ are the minimum perceptible brightness differences for adaptation brightnesses B_F and $(B_F + B_G)$ respectively.

Equation (2) expresses the actual Contrast Sensitivity for normal seeing when driving alone in open road. Equation (3) is a fictitious condition in which the state of normal seeing is assumed when meeting glare. (This does not exist.) That is, when meeting the glare, the effective brightness to which the eyes are exposed increases from B_F to $(B_F + B_G)$. Accordingly, the minimum perceptible brightness difference increases from ΔB_F to $\Delta B_{(F+G)}$, as given in Equation (3). But the field brightness which contributes to visibility remains at B_F as in Equation (2). So the "effective contrast sensitivity", S', when meeting the glare, is fixed by the field brightness B_F, (the same as when in open

road) and by the minimum perceptible brightness difference $\Delta B_{(F+G)}$ as when the eyes are exposed to both the glare and the illuminated field, expressed by the formula,

$$S' = \frac{B_F}{\Delta B_{(F+G)}} \quad \ldots.(4)$$

The ratio between the effective contrast sensitivity when meeting glare and the contrast sensitivity when alone in clear road, is, by dividing Equation (4) by Equation (2).

$$\frac{S'}{S} = \frac{\Delta B_F}{\Delta B_{(F+G)}} \quad \ldots.(5)$$

But from Equation (2) $\Delta B_F = \frac{B_F}{S}$ (2a)

and from Equation (3)

$$\Delta B_{(F+G)} = \frac{B_F + B_G}{S_g} \quad \ldots.(3a)$$

Substituting these values of Equation (2a) and Equation (3a) in Equation (5).

$$\frac{S'}{S} = \frac{B_F}{B_F + B_G} \, \frac{S_g}{S} \quad \ldots.(6)$$

When Weber's law can be considered to hold rigorously, $S = S_g$ and

$$\frac{S'}{S} = \frac{B_F}{B_F + B_G} \quad \ldots.(7)$$

This expression gives an approximate ratio between the general visibilities when meeting glare and when in clear road. The measurements of the tests indicate that, when the opposing glare is 50 c.p., $B_F = B_G$ and from Equation (7), $S'/S = ½$. With this point fixed the broken line curve of Figure 3 is plotted for other values of glare brightness, B_G.

For a nearer exact analysis, accounting for variations in Weber's law, it is necessary to find the actual brightness values of B_F and B_G. The Holladay-Stiles formula for adaption brightness caused by glare, as given in the Illuminating Engineering Society Lighting Handbook (3) is:

$$B_G = \frac{10 \pi E}{\theta^2} \text{ foot lamberts.} \quad (8)$$

where E is the illumination in foot candles in the driver's eyes from the opposing glare and θ is the angle, in degrees, at the driver's eyes between his line of sight straight ahead and the direction toward the opposing headlights. For a straight highway, the angle θ is relatively small and can be considered to be proportional to its tangent

$$\theta = 57.3 \frac{y}{d} \text{ degrees} \quad \ldots.(9)$$

where y is the lateral distance and d the longitudinal distance between the driver's eyes and the opposing headlights, both in feet. (Fig. 1). Also,

$$E = \frac{I_G}{d^2} \quad \ldots.(10)$$

where I_G is the opposing glare in candle power. Combining Equations (9) and (10) in Equation (8) the distance, d, cancels out, and

$$B_G = \frac{.00955 \, I_G}{y^2} \quad \ldots.(11)$$

For a typical two-lane highway, y = 10 feet, whence, from Equation (11),

$$B_G = .0000955 \, I_G \quad \ldots.(12)$$

It was found from the measurements, reported herein, that when $B_G = B_F$,

$$I_G = 50 \text{ candle power}$$

Substituting this value of I_G in Equation (12)

$B_G = B_F = .0048$ foot lamberts, and

$$B_G + B_F = .0096 \text{ foot lamberts}$$

Referring to the curve of Figure 4, which is taken from Holladay's data, (Fig. 7, page 969, Illuminating Engineering Society Transactions, 1926) it is found that for B_F = .0048 foot lamberts, S = 17.8 and for $B_F + B_G = .0096$ foot lamberts, $S_g = 22.0$.

Substituting the above values for B_F, B_G, S and S_g in Equation (6)

$$\frac{S'}{S} = \frac{.0048\ (22.0)}{.0096\ (17.8)} = 0.617$$

This is the ratio between "Effective contrast sensitivity" when meeting 50 candle power glare and "Contrast sensitivity" when alone in open road. The ratios when meeting other values of glare as computed from Equation (6) and with reference to the curve of Figure 4, are plotted as the full line curve of Figure 3.

Note: It may be observed that the curve for contrast sensitivity in Figure 4 (which is taken from Holladay's data) is considerably different from the similar curve in I.E.S. Lighting Handbook. As investigated by Holladay, as encountered in automotive seeing and as measured in this study, brightness differences of larger objects (in the order of 1 degree sustended angle) are of more concern than visual acuity of fine detail.

DISCUSSION

DR. A. R. LAUER, *Iowa State College* - In the first place may I say that Mr. Bone has sensed an important problem in driving, although for most drivers it is not a crucial one. A few persons are blinded badly by light and any method which would help them in this respect would be justified and of value.

I seriously question his statement that, "it is possible to maintain the same order of visibility when cars meet." His proof of the statement is decidedly vague. He speaks of glare as being not more than 20 c.p. and again up to 800-1000 c.p. I think his terminology is confused. Candle power refers primarily to the power of the luminaire. The direct light emitted and measured at any given point is designated as foot-candles. It decreases with distance approximately according to the inverse-square law.

Our studies have indicated that the light from two cars meeting rarely exceeds 1.25 f.c. at the eye of the driver. These measurements were made by actual road tests. The candle power of the luminaire remains the same except for the decrease in each direction away from the "hot spot" of the beam. I do not understand his discussion of variable candle power.

The effect of glare is greatly reduced by general illumination of the surroundings. The adaptation of the eye, as Mr. Bone points out, is enormous. Therefore we are inclined to minimize the cogency of his argument of the ill effect of approaching lights and the possibility of neutralizing it. Our studies have shown a proportional decrease in visual acuity with any source of opposing light.

Again he seems confused in speaking of Weber's law of psychophysics and using symbols ordinarily associated

with Fechner's law. The two are not the same and it is not clear just which he means to utilize in his theory.

So far as his experiments are concerned they seem to back the precision of controls and statistical evaluation which we would like to see and it is conceivable that his rheostat with consequent changes in wavelength of light would void any conclusions made.

It would be my suggestion that Mr. Bone completely rework the paper, repeat his experiments with more rigid controls and carefully revised his terminology to suit the usage made. Unless written up in such a fashion that one might repeat his study exactly I am afraid its influence and usefulness will be quite limited. In the present form it does not do justice to the effort he has undoubtedly put into it.

R. P. TEELE, *National Bureau of Standards* - Several members of the Committee on Night Visibility do not agree with the findings reported by Mr. Bone. Two members submitted written comments and I have been asked to comment on these and the paper (one of these was withdrawn).

It is certainly conceded by those working in the field of night visibility and by motorists that the present seeing conditions on the roadways at night using existing headlights and street lighting installations are not ideal. If they were ideal we would not have a night visibility committee.

Part of the comments submitted, I believe, are brought about by nomenclature differences. In the paper the words "eye sensitivity" are used where "brightness-contrast sensitivity of the eye" is the more common term. The two expressions are not interchangeable and convey very different meanings.

There are one or two other technical points which are open to question but they would require a long and rather technical discussion and these are being passed over to bring out several things which are considered to have more bearing on the differences between the present results and other experience and tests.

A glare source of 20 candles has been found by Mr. Bone to be the maximum allowable for 80 percent "open road visibility". From experience with observer drivers engaged in headlight tests, it has been found that to obtain 80 percent of clear road visibility distance, we can allow much more than 20 beam candle power from oncoming headlamps. The present sealed-beam headlamps, when the depressed beam is used, have a beam candle power of 800 to 1000 above the horizontal and to the left, that is, toward the approaching car. What causes this factor of 40 to 50 between the test just reported and driver observer experience?

The present work was done "in an undisturbed yard" when the glare source was being used. The glare source was viewed against a comparatively dark background. It is not clear in the paper what comprised the background for the target. However, if I understood Mr. Bone correctly, the headlights were turned off when the glare source was being tested and presumedly the background for the target was also comparatively dark.

When we try to apply this laboratory experiment to actual driving conditions, what factors must be considered?

First, let us consider attention. In the yard laboratory attention is directed at one problem. In driving, a considerable amount of attention should be given to operating the motor vehicle, and the glare source viewed as a side issue with whatever part of our total awareness is not used in driving. This division of attention is not a small factor.

Then there is the time element. How long is the glare source in the field of view? The time is important; if a flashbulb were flashed here we would hardly be aware of it. Certainly our seeing ability would not be appreciably altered. However, if a source of the same candlepower as the peak intensity of the flashbulb were held in the same place, we would be temporarily blinded by it.

Next let us consider the background-to-glare-source contrast. In the yard laboratory a dark background was used.

On the road the headlights of the oncoming car are viewed adjacent to a surface lighted not only by our own headlamps but by the headlamps of the oncoming car. This field brightness influences the adaptive state of the eye. In one case it is quite low and on the road appreciably higher, the actual value depending upon the reflectance of the road surface. There is little doubt that the adaptive state in the yard laboratory was appreciably lower than would be encountered in night driving. The influence of the adaptive state is a common experience. Headlights observed in the daytime or on a well-lighted street are not nearly as glaring as the same lights observed on a rural highway at night.

A point not covered in the paper is the fixation point. If the attention is directed at the glare source and the target viewed by off the axis vision, the situation is quite different from directing the attention at the target and viewing the glare source by off the axis vision. This is easily demonstrated at night by directing the eyes at the right-hand edge of the road when a car is approaching. Approaching lights are much less glaring then than when one looks directly at them. Many motorists fail to make use of this fact when driving at night.

The points just discussed all lead to the obtaining of a higher value of allowable candle power for a glare source in observer driver tests than in the yard laboratory tests just described. The latter are such that a minimum value of the maximum candle power of the glare source is likely to be obtained.

Other experimenters find a large difference between laboratory work and field practice. P. J. Bouma, in a paper in the Philips Technical Review, Vol. 4, January, 1939, found a multiplier of 200 to be correct in applying laboratory visibility observations to practical navigation. In blackout studies during the war, described in a paper by W. S. Everett and Kirk Reid, a factor of 100 was used when observations were made from planes flying at 150 to 200 m. p. h.

It seems likely that in the present case a factor somewhere between 10 and 50 would be found if an extensive series of tests were made under both sets of conditions. The work reported here and values found in observer driver tests are in all probability not as divergent as it seems at first glance.

E. P. BONE, *Closure* - It is regrettable that one of the written comments mentioned by Mr. Teele has been withdrawn and that the other committee members who did not agree with the findings as reported in the paper have not voiced their objections. About one-half of the voting members of the Night Visibility Committee opposed the paper. In response to a number of questions and doubts which have been indicated, I shall try to answer the points raised by the discussions of Mr. Teele and Dr. Lauer in some detail.

It is gratifying to read in the closing two paragraphs of Mr. Teele's welcome discussion why the results reported in the paper and the results from other generally recognized tests "are in all probability not as divergent as it seems at first glance". It is interesting that Mr. Teele points out visibility problems of navigation and airplane flight where laboratory observations are multiplied by factors ranging up into the hundreds for use in actual practice. It has not been customary to use any such large factors for automotive seeing for which Mr. Teele now suggests a factor between 10 and 50. It appears that hereby is the principal point of controversy.

Let us examine why there may be a need for such high factors. In laboratory tests, it is customary to measure the visibility of some single target taken as a standard. However, the adequate seeing of any general field of view depends upon many objects and details and in this respect is entirely different from the seeing of a single test target. There are many reasons for this, one of which is that the complete field of view cannot be comprehended in one look. Normally the eye scans its field fixation point by fixation point. This consumes time, and time is limited when driving an automobile. These phenomena constitute a separate

study in themselves but consideration is here invited to such factors because they seem to be the reason for some of the skepticism of the results which I have reported. In observer driver headlight tests as further cited by Mr. Teele it is customary to study the visibility distance of only a single target such as the figure of a man in dark clothing.

In the paper a different approach was attempted in which it may not be necessary to speculate on these wide factors between laboratory test seeing and seeing in actual practice. It may be kept in mind in reviewing the paper that the approach here attempted rests on the simple logic that if we keep the illumination on the field of view the same when meeting cars as when alone on the road, and somehow keep the adaptation level of our eyes near the same in both cases, then our overall visibility must be near the same in both cases.

The glare analysis is based on the findings of L. L. Holladay and his contemporaries. The Holladay data are expressed in several empirical formulas, one of which is listed as Equation (8) in the Appendix. I may have put too much emphasis on my own testing because all I have done was to make a few incidental tests for reducing visibility against glare as treated by Holladay and visibility when alone on the road, to a common denominator. Then by calling visibility when alone on the road 100 percent, we can isolate and evaluate the relative effects of glare. My testing had nothing whatever to do with measuring the visual discernment of any particular objects on the highway. It was only for comparing general visibility when facing oncoming headlight glare with general visibility when alone on the road, whatever the latter may be. The reason for isolating the effects of glare is that better clear road visibility can be obtained merely by increasing the candle power of present headlamp designs. But this would increase glare in proportion. To keep the glare down, some new application of optical principles seems to be needed.

Holladay's findings for quantitatively evaluating glare have been before us for the last twenty-five years. Yet, until very recently, it seems that no use of them has been made for headlighting. When the Holladay formulas are applied to headlight glare they immediately show the hopelessness of attaining safe driving when cars meet each other on the country roads at night by devices based on the optical principles of present type headlamps. But the usefulness of the Holladay analysis goes further than that. It shows what the eye needs for obtaining safe night visibility. Some of us who have been devoted to headlighting from other than, let us say, orthodox viewpoints, have very practical reasons to be convinced that the mechanical and optical means are at hand for a complete reform of headlighting in the cause of night driving safety. The difficulty in enacting such reform is not with headlamp constructions. It seems rather that, in our wishful thinking to condone, somehow, the present lack of night visibility, we let our interests become diverted away from the primary essentials for securing that night visibility. This brings in one of the most difficult problems of all. When thinking of reducing glare we are apt to disregard the extent to which it needs to be reduced unless we are willing to get back to thinking in more fundamental terms of the phenomena of seeing.

Both Mr. Teele and Dr. Lauer refer to "nomenclature" and "terminology" and also bring up a number of questions about the method of testing. It is in the attempt to express some quantitative concept of the magnitude of the changes in the eye, that the more fundamental terms were used in the paper than are considered necessary in most conventional problems of visibility. As to the technique of the tests, the details in general were intended to follow routine practice. However, in view of the questions which have been brought up, both nomenclature and test methods will be discussed in some detail below.

For clarifying any misunderstanding of nomenclature let us consider Mr. Teele's statement, "In the paper the

words 'eye sensitivity' are used where 'brightness-contrast sensitivity of the eye' is the more common term. The two expressions are not interchangeable and convey very different meanings". Contrary to Mr. Teele's impression, the meanings of the two terms were intended to be different. The concept of eye sensitivity, expressing the state of being sensitive, was purposely used because it may give a better realization of the quantitative effect of glare. In normal seeing the eye adapts itself to the prevailing brightness and this automatically helps seeing. So an elastic unit of measure, such as contrast sensitivity, which goes up and down with the large changes in general brightness, is adequate and very useful for many problems of visibility. But in automotive night seeing the adaptation action, as dominated by oncoming glare, is a hindrance, rather than an aid, to the seeing. If we are to get anywhere near equivalent visibility when cars meet as when in clear road, the eye sensitivity must be near the same in both cases. That is, so long as the illumination on the road is kept the same in both cases. Or, we could just as well say adaptation level must be near the same in both cases. But when making comparisons with some other condition of seeing such as between the 20 c.p. glare for near ideal visibility and the 800 to 1000 c.p. glare as from present headlights, we should use the term eye sensitivity, not adaptation level. The reason for this is that at low levels of illumination, the ratio between eye sensitivity and adaptation level varies with brightness. The difference is illustrated in Figure 3, where the dotted line curve shows the approximate comparisons when assuming the relationship between adaptation level and eye sensitivity to be constant and the full line curve shows the comparisons when accounting for the actual changes which exist in their relationship.

The difference between the two terms eye sensitivity and contrast sensitivity is specifically defined in the article of the paper headed, "Computation of Meeting Visibility in Terms of Open Road Visibility - Based on Measurements", in the third paragraph. Then in the Appendix they are further defined even in the exactness of mathematical formulas. At the beginning of the Appendix "eye sensitivity" is evaluated by Equation (1). Then in the next (unnumbered) equation ten lines below, the formula for "contrast sensitivity" is given. It is observed that contrast sensitivity is equal to eye sensitivity multiplied by the adaptation brightness, B.

There seems to be another misunderstanding in wording where Mr. Teele makes a comparison between the "open road visibility" as treated in the paper and "clear road visibility distance". The studies in the paper refer to visibility; - not visibility distance. In the introduction of the paper, I endeavored to make it clear that "full field visibility" as needed for safe headlighting is not the same as "visibility distance" of a single target as generally used in headlight tests. The two are not directly comparable for the same reason that single target laboratory seeing and seeing in actual practice are not the same. The visibility distance of a single target is a logarithmic function of the beam candle power. For that reason if the beam candle power should be reduced as much as one half (50 percent), the visibility distance of a single target is shortened only about 10 percent. Yet in reducing the candle power to one half, many objects and details throughout the full field may fall below the threshold of vision and thereby decrease the driver's knowledge of the situation ahead much more than 10 percent. This concerns the present study because a proportionate increase in opposing glare has approximately the same effect as a decrease in our beam candle power. So the experience cited by Mr. Teele that "with observer drivers engaged in headlight tests, it has been found that to obtain 80 percent of clear road visibility distance we can allow much more than 20 beam c.p. from oncoming headlamps", does not apply to full field visibility.

Then Mr. Teele points out that present sealed beam headlamps project 800 to 1000 c.p. toward the eyes of the driver and later, when discussing the fixation point, he sort of chastises motorists for not directing their eyes at the right-hand edge of the road in order to help alleviate effects of oncoming glare. Here Mr. Teele strikes the very heart of the present headlighting problem. Let us consider the full meaning of this. It is desirable for safety that the driver be able to see straight ahead of his course of travel and far enough ahead for making up his mind what to do in each successive situation. The direction straight ahead is his principal line of sight in the daytime and even at night when in clear road. Yet the best that can be done with the present headlighting system, when meeting another car, is to expect the driver to take his eyes away from the direction in which his car is traveling and look down at the right-hand edge of the road. This means that the only function of modern headlighting when cars meet is to keep in the track. The driver can only gamble on what is ahead. The situation is what Dr. Land, in describing Polaroid Headlamps in Highway Research Bulletin No. 11 (1948), called the "blind driving zone". So the answer to Mr. Teele's question as to why my analysis indicates that for near ideal headlighting the glare should not be more than 20 c.p., whereas present headlamps cause 800 to 1000 c.p. (40 to 50 times as much) is that the analysis studied in the paper is based on seeing the full field, including the directions straight ahead, whereas in tests of present headlights, consideration is given to only one target and drivers must be advised to look down at only the right-hand edge of the road.

The above mention of the deficiency of the present headlighting system is, in no way, a criticism of the engineering accomplishments shown by the precision manufacturing of the modern automobile headlamp which has culminated in the development of the sealed beam. It refers, rather, to the lack of general interest in, and appreciation of, what is actually needed for real safety as to night visibility on the rural highways.

The remainder of the points raised by Mr. Teele concerns mostly the test methods. It may be kept in mind that the purpose of the tests was merely to find a value for use in Holladay's glare analysis for balancing and comparing adaptation levels with and without glare. The value can be found in other ways, for instance, it can be computed by following the work of Stiles in England, but the test method seems direct and simple. After finding that the 50 c.p. glare caused the same adaptation level as did the headlighted roadway, the Holladay data were used from then on.

For the purpose intended, it was unimportant whether the tests were made from a moving or a stationary car out on a highway, in an undisturbed yard, or in an inclosed laboratory. The thing which was important and to which I tried to adhere was that the same pertinent conditions prevailed when measuring adaptation levels with eyes exposed to the headlighted highway and when exposed to the glare.

Mr. Teele calls attention to the importance of the background and fixation point. In all tests the line of sight of the observer was toward the target "T" which was straight ahead on the horizontal. Since the immediate background of the 1 deg. square target "T", as formed by the 1/2 deg. black border, was always below the threshold, the "brightness difference" of target and background was synonymous with "brightness" of the target. Moreover, since the target was just barely perceptible, its brightness had no appreciable effect on the adaptation of the eye. In the phase of the tests when facing the headlighted roadway, the adaptation state was established by the surround brightness which comprised only the headlighted roadway and environs adjacent to the fixation point toward target "T". In the other phase of the tests in the undisturbed yard, the adaptation state was established only by the brightness of glare lamp "G" also adjacent but further to the side of the fixation point toward target "T". Then following the Holladay method of anal-

ysis, the adaptation levels of both phases were added together for computing the adaptation level simulating actual driving conditions. The Holladay summation method is shown on page 2-20 of Illuminating Engineering Society Lighting Handbook (3). It is true, as Mr. Teele suggests, that the effect on adaptation level of the road surface brightness as illuminated by the other car was neglected. This would help silhouette seeing between the two cars, but would interfere still more with the seeing of road conditions beyond the other car.

There may appear at first to be a material discrepancy in the exposure time when testing for the least perceptible brightness of target "T" with eyes exposed to the different candle power values of glare lamp "G". During each run of this phase of the test procedure, the eyes were exposed continuously to some particular candle power glare, whereas in actual driving the glare source normally remains in the field for only a relatively short period. But what we were seeking was the one candle power glare value which caused the same adaptation state of the eye as did the headlighted roadway when looking straight ahead. Since this was found to be approximately 50 c.p. we know that in all tests against glares in the neighborhood of the 50 c.p., the adaptation levels were near the same as the adaptation level with eyes exposed to the headlighted roadway. So it made no material difference whether the eyes had been exposed to the 50 c.p. glare for a long time or to the headlighted roadway for a long time.

The reason for keeping the attention of the observer and the fixation point of his eyes directed straight ahead in all tests was that this is the direction in which the driver needs most to look in order to appraise, at ample distances, the destiny of his speeding car.

In Dr. Lauer's discussion, it appears by his first paragraph that he considers the problem of glare "for most drivers is not a crucial one" and he goes on to say, "A few persons are blinded badly by light . . ." Can it be that Dr. Lauer is oblivious of the problems of night visibility and the hazards of nighttime driving as consistently disclosed by the statistics from accident records? He seems to be talking about the rare occasions when motorists are totally blinded by headlight glare and whether they are bothered by discomfort of glare. In contrast, the scope of the paper is limited to the reasons for the depletion of vision which, with present headlights, occurs every time cars, traveling at normal speeds, meet each other on typical country roads at night. So our interests seem to be in different lines and in that respect the comments of Dr. Lauer are, in the main, irrelevant to the subject matter of the paper.

Because of the above divergence of objectives and the carelessness of his reading of the text, as repeatedly displayed in the looseness of his misquotations, there is no wonder that Dr. Lauer keeps talking about "confusion". For example, he purports to make a quotation that, "it is possible to maintain the same order of visibility when cars meet", which anyone as well as Dr. Lauer, would naturally question. This misquotation is evidently taken from the Synopsis, third paragraph, where the sentence begins, "It is possible to maintain the same order of visibility when cars meet, provided . . ." Dr. Lauer stopped the sentence at the comma to exclude the modifying clause. The proviso in the statement, as carried throughout the paper, is that adaptation level be kept near the same when meeting cars as when not meeting cars. This is the essence of the analysis.

Then he mixes my statements regarding the 20 c.p. and the 800 to 1000 c.p. as though they both were intended for a measurement of the same thing. In the article of the paper titled, "Measurement of Differential between Meeting Visibility and Open Road Visibility", second paragraph, it was reported that the analysis indicates the need of keeping glare down to 20 c.p. for desirable visibility when cars meet. The next paragraph starts out, "By way of comparison . . .", merely to illustrate that headlamps now on the roads cause 800 to 1000 c.p. glare which is 40 to 50

times as much as the desirable 20 c. p.

Next Dr. Lauer recites the relationship between candle power, foot candles and distance as found in elementary text books even on general physics. Holladay (2) pointed out that, on a straight roadway the problem of glare can be simplified by considering only the candle power of the source of glare. It is simply that as an oncoming glare car comes closer, to thereby increase the glare in proportion to the foot candle illumination, at the same time the angle between the direction of the glare source and the line of sight, straight ahead, gets wider. The two opposing influences neutralize each other so we need to consider only the candle power of the glare source (Fig. 1).

Of course Weber's law and Fechner's law are not the same. I referred to Weber's fundamental law because it may give some concept of the magnitude of the changes in eye sensitivity which is the basis of the study in the paper. But this has no connection with Fechner's addition to Weber's law. It again may be noted that because Weber's law shows the product of prevailing brightness and eye sensitivity to be a near constant, it can explain the magnitude of the large changes in eye sensitivity which in conformance with this law, must occur under the large changes in the prevailing brightness. (Note: The prevailing brightness includes the opposing glare.) Although Weber's product departs from a constant at the low levels encountered in headlighting, its rate of decrease is only 1/25th of the proportionate rate of decrease in prevailing brightness. So a change in prevailing brightness continues to cause a large change in eye sensitivity. Eye sensitivity is defined (Eq. 1) as the reciprocal of minimum perceptible sensation. Weber's law refers only to the relationship of stimulus to this minimum perceptible sensation. Fechner's law states the relationship between the stimulus and intensity of sensation when above the threshold concerning which we are not involved in the present study.

If it is the symbol S to which Dr. Lauer objects, it may be noted that in Fechner's formula, stimulus is often represented by the symbol S. However, sensation and sensitivity also begin with the letter S. In the particular algebra included in the paper, the meaning of the symbol S is clearly defined at the beginning of the Appendix which seems sufficient for the problem at hand. Perhaps, however, I should have thought of another symbol. This seems like a trivial point but it would be unfortunate if the contributions which the psychologists can make toward safer headlighting should be hampered merely because of different customs in the use of symbols in simple mathematics.

Dr. Lauer brings in an instructive point in regard to the precision of the testing. My testing did not have refinements procurable where more elaborate laboratory facilities are available. But in the present study the extra effort required for more refinement does not seem warranted because measurements of visibility involve other wide variables and uncertainties. While Holladay's formulas can serve in the solving of the major problem of headlight glare they are, after all, empirical and not intended for detailed precision. More exactness would, in itself, be interesting but we are so apt to get intrigued with our own test technique as to miss seeing the forest for the trees.

No doubt the change in color of the filaments toward the red as dimmed by the rheostats contributed some error. Photometric calibrations were made with a barrier layer photo-electric cell.

Dr. Lauer further advises revision of the terminology in conformance with more conventional usage. Effort was made to avoid that very thing lest the essence of the analysis be lost. Ordinarily, as mentioned above, the capability of the eye to adapt itself to the prevailing brightness helps seeing but in automotive night seeing that adaptation action, being dominated by the opposing headlight glare depletes, rather than aids, the seeing process. So it seems necessary to get back to some fundamentals which properly can be omitted in most problems of seeing.