Headlight Glare and Median Width

Three Exploratory Studies

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Three study methods were explored for determining the effect of location of an opposing glare vehicle on visibility at night. Both lateral separation and longitudinal distance between glare vehicle and observer were varied. In Study 1, both glare car and target were stationary; the observer drove toward the target and indicated when he could detect it. In Study 2, both target and observer were stationary while the glare car moved toward the observer; locations of the glare car were found for which the target was just visible to the observer. Study 3 involved a self-luminous target, and, as in Study 2, both target and observer were stationary while the glare car moved toward the observer; the observer continuously adjusted the brightness of the target and attempted to keep it barely detectable. Some limited measurements of discomfort due to glare were made, but this line of investigation was abandoned due to high variability in the results and the lack of an adequate definition of discomfort.

The results showed that the effects of glare decreased with increasing lateral separation of the glare car, as expected. At any given lateral separation, the effects of the glare were present even when the glare car was at a considerable distance from the observer (3,000 feet or more); the rate of change of the effect with distance was small for a large part of this distance. Recommendations are made for the conduct of target detection studies of this type, remarks are made concerning the visual problems in night driving, and possible areas for future investigation are suggested.

•THIS REPORT summarizes several exploratory studies employing different methods of studying the relationship between median width of highways and the disabling effect of opposing motor vehicle headlight glare. The studies were performed with the intention of gaining insights into the factors which were operating and the methods which would best determine those relationships. Because insights were the main objective, the amount of data collected was small and little reliance is placed on the quantitative values. Each of the methods grew out of analysis of the limitations of the previous method. Although the studies were performed in the spring of 1961, because of recognized limitations in the data or, in some cases, a lack of understanding of what the results meant, the preliminary report was not published. Subsequent readings in the psychological and physiological literature have pointed the way to an interpretation of the results. The report is now presented for the information of others contemplating this type of research, and includes discussions of possible pitfalls and factors for which account may have to be taken. For this reason considerable detail is presented concerning field layouts, procedures, and qualification of results.

The results of these studies are based on small samples with few replications. They are more suggestive than conclusive and are of value primarily to show the types of results that may be expected and to illustrate certain effects of factors which may be

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operating. The quantitative values hold only for the particular targets, subjects, surroundings (pavements, backgrounds, ambient illumination) and lamps tested. The relative values (the effect of lateral separation) may also be dependent on these variables.

It had also been proposed that the discomforting aspect of headlight glare be studied. The discomforting effect, however, was elusive of definition, and more so of measurement. An attempt to measure it was made in Study 1, but the results were too variable to be of any use. It was thereafter decided to limit the objectives to what was thought to be the more critical case of disabling glare.

Data for Studies 1 and 2 were collected in one night each and for Study 3 on two successive nights. Although different ambient illumination conditions may have existed on the different nights, it is assumed that they were fairly constant for the duration of each night; furthermore, the use of balanced experimental designs and random orders of exposure to the different conditions, e.g., lateral separations, leads to the belief that the data for each study are not biased due to serial changes in conditions. Where the data are subject to question on other accounts, qualifications to the results are given.

The existence of possible differences between nights, as well as differences in some of the other variables, reduces the comparability of the results of the different studies.

GENERAL NOTES AND DEFINITIONS

Available as a test site was a new portland cement concrete runway, two miles long by 150 feet wide, at Dulles International Airport, prior to its being opened to air traffic. The site was 25 miles from downtown Washington, D.C., and about 12 miles from the nearest sizeable town. The area surrounding the runway was flat and grassy. Consequently, the ambient illumination was uniform and at a very low level. Few, if any, extraneous light sources were visible, depending on the direction in which the subjects were facing for the different studies. When present, these lights were distant and constant during the collection of data. For the conditions of the studies, the effects of cross-slope of the runway were assumed to be negligible so that, except where noted, all studies were performed on portions of the runway considered to be a plane surface.

The tests simulated only the meeting of a single vehicle with a single opposing glare vehicle on a constant-grade tangent section of highway where, at any cross-section, the pavements for both directions of travel are at the same elevation. The results do not necessarily hold for other geometries.

All vehicles employed in the studies had four headlamps. Before each study, the aim of the headlamps of both the glare car and the car with test subjects was adjusted according to Virginia State standards. All tests were conducted with the glare car headlights on high beam. The windshield of the car in which the test subjects were seated, the outsides of the headlamps of both the glare car and subject car, and the reflectors on the target car were maintained clean throughout the course of the studies.

Instead of median width, the more definitive concept of "lateral separation" has been used in this report. As employed here, "lateral separation" refers to the lateral distance between the driver and the near side of the opposing glare vehicle. Lateral separation can be used to convert to different combinations of median width, vehicle position, and lane width (Fig. 1). The conversion assumes that each of the two vehicles is 6.5 ft wide and centered in its lane; the driver's eyes are assumed to be 1.5 ft from the left side of his vehicle. Figure 1 may be used as follows: if conditions are median width of 20 ft, 4-lane divided highway, both vehicles in the right lane (two lanes intervening), and lanes are 12 ft wide, the resulting lateral separation is 51 ft.

The condition where no opposing vehicle was present can be thought of as corresponding to an infinite lateral separation. For convenience, this is also referred to as the "no-glare" condition, although technically any light in the field of view will produce some glare, e.g., the area of pavement illuminated by the driver's own headlights.

The term "threshold" will be found throughout this report. Psychophysical "absolute threshold," according to Stevens (1), is that level of a stimulus (e.g., brightness of an object) which marks the transition between response (detectability) and no response

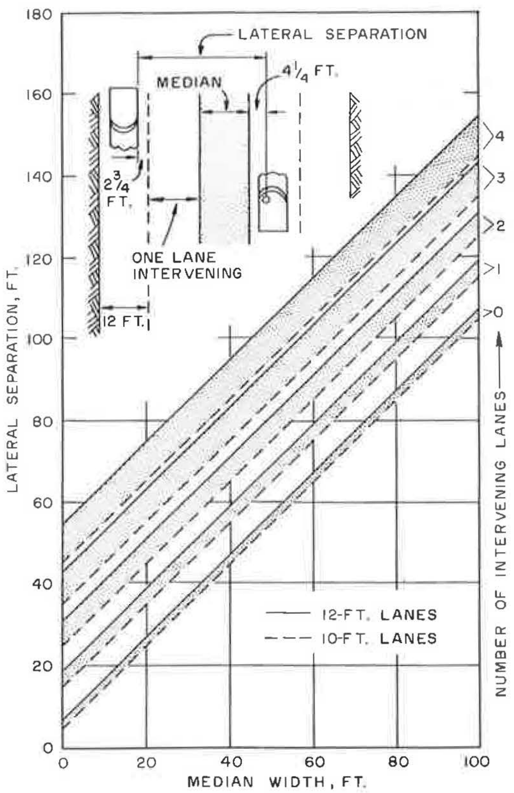

Figure 1. Relationship between lateral separation and median width for different combinations of vehicle position and lane width.

(nondetectability). This threshold level ordinarily fluctuates from moment to moment within a range separating those stimulus levels which definitely produce a response from those which definitely do not produce a response. A given stimulus value within this range will produce a response only part of the time. The probability of detection of a stimulus within this range, therefore, will vary from close to zero to almost 100 percent. Usually, the stimulus level which produces a response 50 percent of the time is called threshold (50 percent threshold). For identical conditions, the average thresholds for different subjects may be different.

The use of the term threshold in this report is much less restrictive and refers, generally, to those instances where, under the conditions present, the subject reported that he detected or lost sight of the target. Obviously, the conditions of exposure of the stimulus (e.g., time of exposure of the target, subjects' adaptation levels, and criterion for confidence of detection) could not be controlled as precisely as in a less "realistic" laboratory setup, and the individual threshold measurements reported herein could have varied considerably from the 50 percent detection level.

Although the studies were run at low speeds and for long distances (not quite long enough, it turned out), the distances (2,000 ft or more) are not as extreme as they may appear at first glance. On modern divided highways, sight distances to opposing headlights of several thousand feet are fairly common. Two opposing vehicles, each traveling at 70 mph, will have a relative velocity of approximately 200 fps. If the two vehicles are initially 2,000 ft apart, they will meet in 10 sec.

STUDY 1

The field layout for Study 1 is shown in Figure 2. (As employed in this report, "layout" refers to the plan of the site for each study; "setup" refers to the relative position of glare car and target car.) The headlights of both the glare car and the car in which the test subject drove were on high beam. The glare car and the target car were both stationary, the rear of the target car being situated 100 ft beyond the headlights of the glare car. Of the five subjects, three in their twenties and one, age 54, reported normal or corrected-to-normal visual acuity; one, age 33, reported poor acuity.

Each test subject, guiding along a pavement joint, drove toward the rear of the unlighted target car at a speed of 20 mph. His instructions were to call out to a recorder seated in the car when he felt the glare to be discomforting and again when he could discern any part of the target car (this turned out in all cases to be one or more of the six rear red reflectors). Distance markers, 40 ft apart, lined the opposite edge of the runway. The recorder would note the car's position relative to the nearest adjacent distance marker, from which the longitudinal distance could be estimated to be within

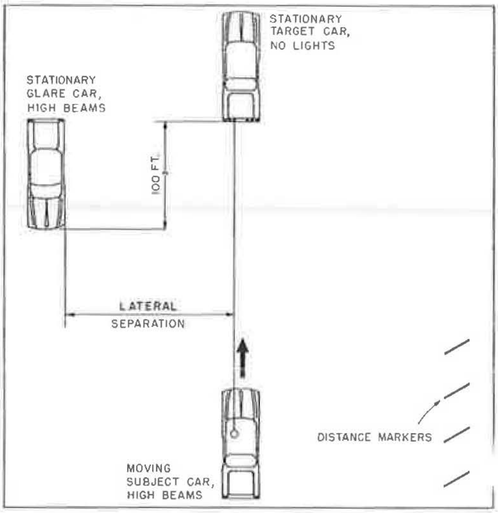

Figure 2. Field layout for Study 1.

20 ft. The course markers carried reflectorized letters and were turned away from the view of the subject. The recorder viewed them by shining a flashlight out the side of the car.

Each subject made three runs at each of four different lateral separations (7, 32, 57, and 82 ft) and also for the no-glare case (corresponding to an infinite separation). Runs were made in random order, although each subject made all his runs consecutively. For each different lateral separation the target car was positioned so that it was directly ahead of the subject car. This procedure is similar to that used by the Idaho Department of Highways in a 1957 glare test (2).

The glare car was not moved at all during the conduct of Study 1 as all data were collected in one night. Therefore, the orientation of the headlight candlepower distribution was constant for all runs. However, it is not known whether the axis of the car, and consequently of the headlights, was exactly parallel to the line of travel of the subject.

Results

Study 1 is the only study for which data relative to both disability and discomfort glare were obtained. The results of the discomfort test indicated that the discomfort measurements were highly subjective and variable.

Discomfort

Figure 3 shows, for the different lateral separations, distances from the glare vehicle at which subjects stated that they were discomforted by the opposing headlights. (Discomfort is assumed to be present for combinations of lateral and longitudinal separation from the glare car which lie under the curve.) The grid portion can be viewed as a plan of the test site. Each subject is identified by a different letter, A to E. The points are plotted at the distances for each run at which the subject reported discomfort; where the subject reported no discomfort during a run the point is shown to the left of the zero line. For two runs at each of the two narrowest separations, subject E reported discomfort at the beginning of the run but before he was adjacent to the beginning of the series of distance markers (2,520 ft). Therefore, these distances are unknown, but greater than 2,520 ft, and have been plotted arbitrarily at 2,700 ft.

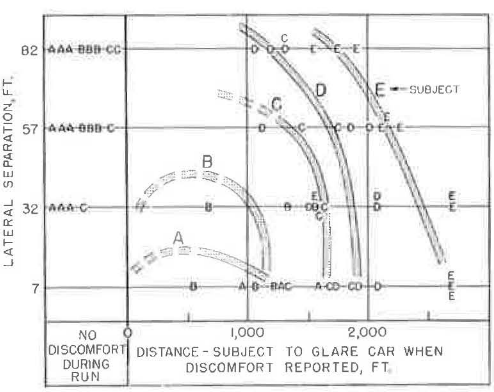

Figure 3. Effect of position of opposing high beams on reported discomfort by five subjects.

A curve has been drawn for each subject. These curves are very approximate due to the extreme range and variability of the data. Had each curve been drawn to pass through the mean discomfort distance value for each lateral separation some of them would have been S-shaped.

As expected, the distances at which the onset of discomfort was reported generally increased with decreasing lateral separation; or, to put it simply, discomfort was experienced sooner at the narrow separations. At a distance of 1, 000 ft from the glare source, for example, subject A stated that he experienced discomfort only for the 7-ft lateral separation; subject B, when the separation was 25 ft or less; subject C, at separations of 50 ft or less; subjects D and E reported discomfort even with a lateral separation of 82 ft.

For any given run, as the distance between the subject and the glare car decreased and the opposing headlights got further away from his line of sight and decreased in brightness, there obviously had to be a point where discomfort began to diminish and another point where it ended, even if one or both of these are where the subject passed the glare car and the headlights were no longer visible. Therefore, the discomfort threshold curves must bend over at small longitudinal distances. Data were not collected for this end of the discomfort curves, but for illustrative purposes these parts of the curves are shown as broken-line portions for subjects A, B, and C.

The variation among subjects is no doubt due to differences both in sensitivity to glare and individual definitions of discomfort. However, it is hard to believe that the large variation for any individual subject was due to the small sample size alone. Therefore, it became apparent that discomfort glare criteria were going to be difficult to define, and subsequent research was devoted solely to the study of disability glare. Part of the variability may have been due to the fact that the subject had two tasks to perform: to report discomfort and to report detection of the target. Because detection of the target was the more emphasized task, subjects may have failed to concentrate or report on discomfort if it would have occurred at the same time that the target became detectable.

Target Detection

Figure 4 shows the variation in target detection distance with lateral separation. The part of the target car which was detected first was always one or more of the six rear red reflectors. Each plotted point represents one run by one subject at the particular lateral separation. The data for each subject are shown with a different symbol. The data appear to fall into two distinct groups, apparently according to the nighttime visual ability of the subjects. Consequently, they have been so grouped. The solid curve is for the three subjects in their twenties, who had reported normal acuity. The lower dashed curve is for the other two subjects, the one, 33 years old who had reported poor acuity, and the one, aged 54 who had reported normal acuity. For purposes of identification, the former group, who were judged to have normal visual ability, have been given the designation N; the latter two subjects, whose performance was judged somewhat lower, have been designated L. Within each group the variation among subjects appears small and curves drawn for individual subjects would approximate the curve for the particular group. The alternate dashed and dotted curve is an average for all five subjects.

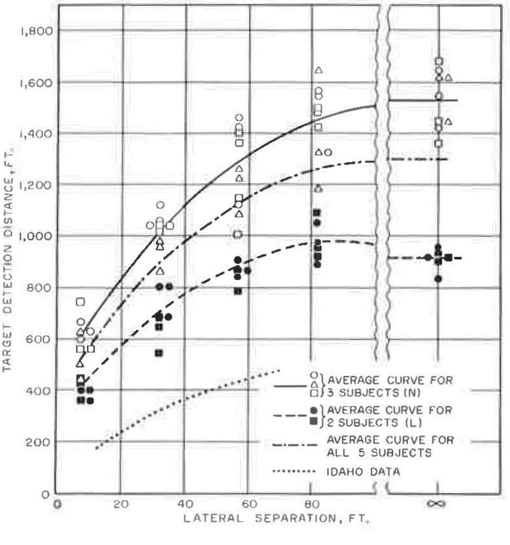

Figure 4. Variation in target detection distance with lateral separation for five subjects for conditions of Study 1 (target 100 ft beyond glare car).

The distances at which the target was detected increased with increasing lateral separation, as expected. Average detection distances appear to approach those of the no-glare condition at lateral separations of approximately 80 ft. However, the curves for the two sets of subjects are somewhat different in that the curve for the two subjects (L) approaches a maximum at a slightly narrower lateral separation compared to the curve for the three subjects (N). The apparent anomaly, for the two subjects (L), of greater detection distance at the 80-ft lateral separation than for the no-glare case can be attributed to the small sample size. Otherwise, a new theory is called for. Data from the Idaho study, which employed a different target, are also plotted. The median widths given in the Idaho report have been adjusted to the same lateral separation assumption used for Study 1. The Idaho study did not include data for wider separations or for the no-glare case, therefore, the shapes of the curves for the different targets cannot be compared.

Discussion

It might be useful to compare the performance of the subjects in the visibility test of Study 1 with the discomfort test to see whether there is any correlation between the two measures. The two subjects (L), who showed somewhat poorer visual performance, are shown as subjects B and E in Figure 3 for the discomfort test. Subject E, age 54, reported discomfort at all lateral separations, whereas subject B, age 33, who had reported poor acuity, reported discomfort for only the two narrowest separations. The other three subjects (A, C, and D), whose performances in the visibility test were nearly identical, showed different degrees of discomfort. On the basis of these limited data, therefore, there is no evidence of a correlation between visual and discomfort sensitivities to glare.

One argument which may account for the difference in the target detection distance curves for the two groups of subjects relates to the fact that automobile headlamps send out focused beams with different light intensities at different angles from the axis of the lamp. This may explain why the curve for the two subjects (L) approaches the no-glare value at smaller lateral separations than the curve for the three subjects (N). Because of poorer visual ability, even without glare, the former group had to be closer to the target to detect it under any condition. Being closer to the target, they were also closer to the glare car but were subjected to lower intensities of opposing glare. The three subjects (N) were able to detect the target at greater distances for the no-glare case. At these greater distances and the same lateral separation, they were subjected to higher levels of glare and the extent of the reduction in target detection distance, compared to the no-glare case, was greater.

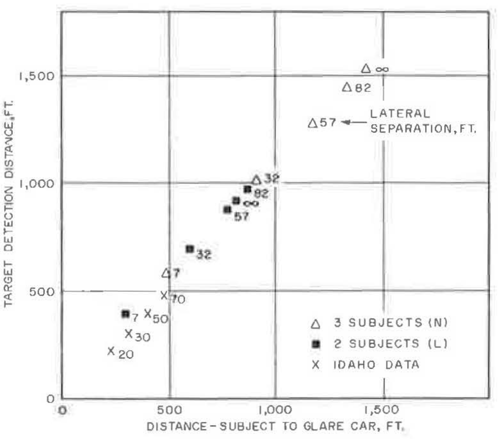

Figure 5. Target detection distance vs distance of glare car for different lateral separations, Study 1.

For the same reasons, targets of different difficulty, which will be detectable at different distances, may give different relationships between lateral separation and detection distance because the observer will be in a different orientation to the opposing beam for each target at the time when it becomes detectable.

Re-evaluation of the study procedures for Study 1 showed that there were conditions which limited the applicability of the results obtained for disability glare. Among these are the dependence of the results on the particular geometry, headlight configurations, subjects, and target used in this experiment. A major limitation of the data, however, even given the conditions of the experiment, was that the relative positions of target and glare car were fixed as shown in Figure 2. As the subject approached both the glare car and the target, his position with respect to the

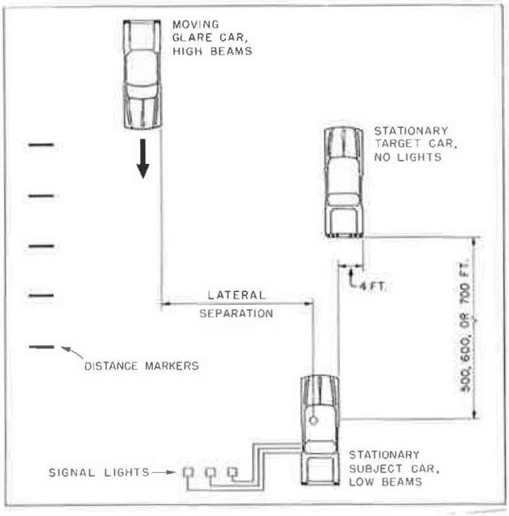

Figure 6. Field layout for Study 2.

opposing headlight beam pattern changed simultaneously with the change in apparent size of the target and the illumination on it from his own headlights. Regardless of when the subject could detect the target, the detection distance was always equal to the glare car distance plus 100 ft. This is further illustrated in Figure 5, which compares target detection distances with distance to the glare car.

All data of Study 1 fall on a line, the equation of which is $D_t = D_g + 100$, in which D_t is target detection distance and D_g is distance of subject to glare car. Similarly, the Idaho data fall on a line, $D_t = D_g$, because, in the Idaho Study, the target was adjacent to the glare car. With this study methodology, detection distances of the target cannot be determined for other relative positions of glare and target cars. For example, for a lateral separation of 7 ft, how far away could a subject have seen the target when he was 1,000 ft from the glare car? In attempting to describe the relationship between the effects of headlight glare and lateral separation, it is necessary to know whether the detection distances derived were the most critical distances. The question remains, in regard to the results of Study 1, were these the minimum detection distances for each lateral separation?

That part of the lack of applicability of the data which was due to the study method resulted from the lack of independence of the two variables, distance to target, and distance to glare car. Therefore, this study method was abandoned in favor of one in which only one distance at a time was varied. This is the method that was utilized in Study 2.

STUDY 2

The field layout for Study 2 is shown in Figure 6. In this case, the subject and target cars were stationary, and the glare car, with high beams, was moving. The subject car's headlights were on low beam. This is considered to be the worst condition for a two-car meeting situation.

The three test subjects reported visual acuities ranging from poor to good. Each was equipped with a pushbutton that operated a signal light of different color for each subject. The signal lights, consisting of 1-ft squares of red, yellow, or green translucent plexiglass illuminated from behind by incandescent bulbs, were situated out of the view of the subjects and sufficiently far apart to be distinguishable by the experimenters at distances up to 3,000 ft.

The three subjects, seated in the subject car (two in front, one in rear), viewed the rear of the target car as the glare car moved toward them. As long as the reflectors of the target car were visible to him, each subject kept his particular signal light on. Subjects were instructed not to communicate with each other during a run.

The same distance markers which had been used in Study 1 were situated at 100-ft intervals along the side of the test site, facing the glare car. The glare car contained three men: a driver, an observer, and a recorder. The driver's function was to stay on course, maintain a speed of 25 mph, and call off the distance markers as they were passed. The observer would call out the status of the signal lights (on or off) and the recorder would indicate this on the data sheet relative to the appropriate marker designation. Distances were estimated to the nearest 50 ft. The farthest distance from the subject which could be measured in this manner was 2,600 ft.

Three runs were made at each of six different lateral separations (4, 14, 24, 34, 45, and 59 ft) and for each of three different distances of the target car (500, 600, and 700 ft). The odd figures for the lateral separations resulted from the desire to arrange convenient tracking guides in relation to the pavement joints; separations of 4- and 14-feet were intended to bracket the zero median case, which, for lanes 12 ft wide, would provide a lateral separation of 7 ft. The target car was offset 4 ft laterally to the right of the subject car, primarily to provide clearance for, and prevent displacement by, the glare car during runs at the narrowest separation.

The order of presentation of the different target distances was arranged in sets, a set consisting of one each of the three target distances, 500, 600, and 700 ft. For each target distance within a set of three, one run was made at each lateral separation, in random order. The order of target distances within a set was random; three sets were run.

The distance at which each of the three subjects could see the reflectors on the target car without the presence of the glare vehicle was also recorded. However, only one such no-glare measurement was made for each subject.

Essentially, the objective of this study was to find those positions of the glare car for which the target detection distance was at certain specified values.

Results

The following detailed description and discussion of the development of the data from raw to final form will be of value in pointing out many of the factors involved in visibility testing.

Figure 7 shows the positions of the glare car at which the target was visible at 700 ft to one of the subjects. Data for three replications for each lateral separation are shown. The figure can be viewed as a plan of the test site. The glare car ran from right to left, with distance measurements beginning at a longitudinal distance of 2,600 ft from the test subject. At some point the subject could no longer see the target (visibility fell below threshold). As the glare car continued its run, a point was reached where the subject could again detect the target. An average threshold curve has been roughed in. Points below the curve represent positions of the glare car (i.e., combinations of longitudinal and lateral separation) at which the target was not visible to the subject at a distance of 700 ft; i.e., the target detection distance was less than 700 ft.

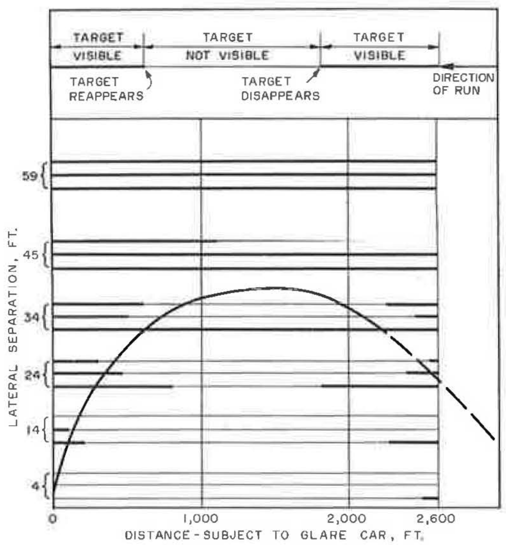

Figure 7. Target visibility data and threshold curve for one subject, Study 2.

For the narrow separations the target was often below threshold for the subject before distance measurements could be taken on the glare car. Consequently, the far end of the threshold curve has been drawn with a broken line to indicate the extreme uncertainty of its location. The curve has been extrapolated beyond 2,600 ft to illustrate the method. Had the glare car measurements begun at a greater distance there would have been some point at which the target would have been above threshold.

Again for the narrow separations, the targets did not rise above threshold until after the glare car had passed the subject. (Inasmuch as exact quantitative values have not been strived for, to simplify the illustrations, the threshold curves of Figures 7 and 8 have been drawn as though the target were always visible after the glare car had passed the subjects.) This could have been due to the time lag in readapting to the no-glare condition or reaction-time lags in actuating the signal buttons and in the observing-recording process. All of the longitudinal distance data are probably too small due to time lags in the signaling-observing-recording process.

At the wider separations, the target was sometimes above threshold during the entire run of the glare car; i.e., the target detection distance was always greater than 700 ft. This was the case for one of the runs when the separation was 34 ft, for two runs at the 45-ft separation, and for all three runs at the 59-ft separation in Figure 7. Because threshold is usually defined as a 50 percent probability of detection, the threshold curve has been drawn to level out at that lateral separation where the target was always detectable 50 percent of the time, or 1.5 out of 3 runs. Therefore, the curve has been drawn to level out in the vicinity of the 1,500-ft longitudinal distance, where a maximum point would appear to be, and midway between the 34- and 45-ft separations, where the target was detectable for the entire run, respectively, once and twice out of three runs. (This assumes that 50 percent detection threshold data were being obtained. However, it is doubtful whether the points where the target appeared or disappeared represents 50 percent detection thresholds.) Many more replications would be needed to determine the exact location of the average threshold curve.

Figure 8 shows average threshold curves for the combined data of all three subjects for each of the three target distances. The parts of the curves shown with broken lines are uncertain, as explained for Figure 7. The curves can be thought of as representing contours of equal disability due to glare, in that the target detection distance is constant for all positions of the glare car which lie along each curve. The target is not visible at the distance indicated for each curve for combinations of lateral separation and longitudinal distance of the glare car which lie under the curve. Due to the difference in the horizontal and vertical scales in Figure 8 the shapes of the curves as drawn are deceptive. Inspection of the scales shows that the curves are actually very long and flat, indicating that the effect of the opposing glare on target detection is fairly constant for a large range of distances from the glare car.

These data can be shown in another way. By noting the distances of the glare car at which a horizontal line representing a chosen value of lateral separation intersects the threshold curves of Figure 8, the relationship between target detection distance and distance of the glare car for that particular lateral separation can be obtained. Points of intersection so obtained have been plotted in Figure 9 for arbitrarily chosen lateral separations of 7, 17, 27, and 37 ft. At separations wider than 37 ft, the target detection distance was always greater than 700 ft and, because target distances greater than 700 ft were not tested, no points could be obtained for these wider separations. Curves showing the variation in target detec-

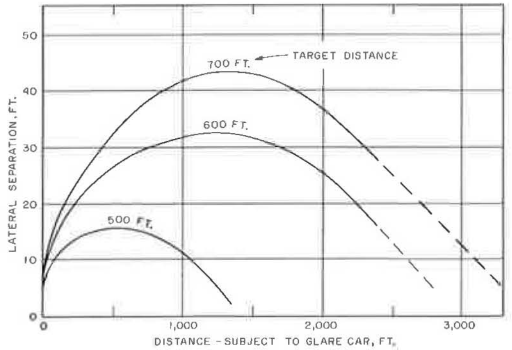

Figure 8. Combined average threshold curves for three subjects of Study 2 for each of three target distances.

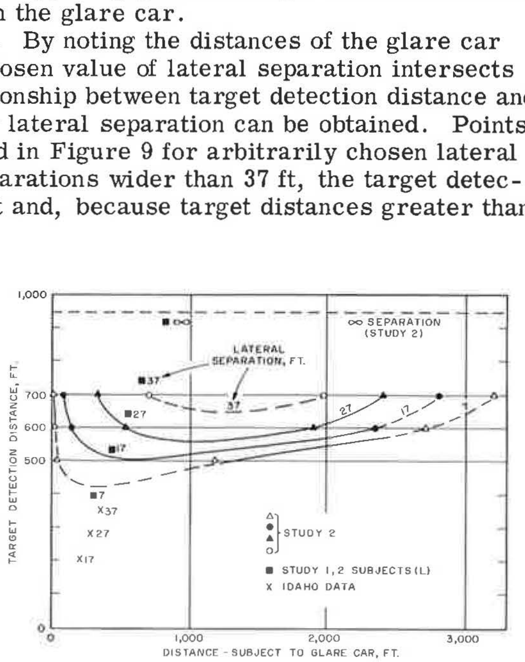

Figure 9. Variation in target detection distance with glare car distance for different lateral separations, Study 2 (partial data of Study 1 and Idaho study shown for comparison).

tion distance with position of the glare car for the chosen lateral separations have been drawn through the points. Again, the uncertain portions are shown with broken lines. The average no-glare detection distance for the three subjects was 940 ft, was derived from only one measurement per subject, and is, therefore, shown by a broken horizontal line in Figure 9.

The curves show that target detection distance is relatively high at far distances from the glare car. This is reasonable because the illumination reaching the subjects' eyes from the opposing headlamps is small. Target detection distance decreases gradually as the glare car gets closer to the subject, reaches a minimum, and then rises again as the glare car, continuing its run, moves away from the center of the visual field and the less intense portion of the opposing headlight beam is directed at the eyes of the subject. As the lateral separation increases, the minimum target detection distance that is reached is higher and appears to occur at greater distances of the glare car.

Discussion

The extent of the curves and the low rate of decline in target detection distance with glare car distance indicate that the effect of the opposing glare on target detection distance extends for considerable distances of the opposing glare car and is fairly constant for long durations. This was previously pointed out for the threshold curves of Figure 8, from which the curves of Figure 9 were derived.

It was previously pointed out that, at lateral separations greater than 37 ft, the average target detection distance is greater than 700 ft. Similarly, the curve of target detection for the 7-ft lateral separation dips below 500 ft to an unknown value. Therefore, to have obtained data from which to draw the curves for lateral separations greater than 37 ft and to have obtained the minimum target detection distance for the 7-ft lateral separation, target distances greater than 700 ft and less than 500 ft would have had to be tested. The minimum points for the curves fall at values of target detection distance where no data exist. Intermediate target distances would have had to be tested to have obtained more accurately the minimum value of target detection distance and its location for each lateral separation.

The slope of the curves for glare car distances beyond 2,000 ft is uncertain because these parts of the curves are based on extrapolations of the threshold curves. Another cause for suspicion about the shape of the curves in this area is inherent in the study method. Because the target was at a fixed distance from the subject the threshold point of detection for far distances of the glare car was determined in a situation where the target went from an initially visible condition to an invisible one. The subject was, therefore, able to fixate on the target and could maintain detection of it for a longer time, as the glare car approached, than if the target had gone from an initially invisible condition to a visible one. It is possible, therefore, that target detection distances for the far distances of the glare car should be lower than they are shown. The shapes of the curves obtained in similar studies by the Road Research Laboratory in England (3, 4, 5) did not have as great a slope as the curves of Figure 9 at the far distances of the glare car.

The British studies utilized theoretical expansions of field data. In part, they showed, for British high and low beams and for appropriately aimed American low beams, curves for "seeing distance," for straight-ahead and curb-side test objects, that fell gradually with decreasing distance of the glare car and then rose slightly at small distances. It is significant that the curve shapes and the minimum seeing distances varied with different positions of the object across the roadway and with different headlight beam configurations (high beams facing high beam or low beam facing low beam).

The roundabout method of developing the data just demonstrated, which involved drawing the threshold curves (Figure 8) and intersecting them with chosen lines of lateral separation to obtain points with which to plot the target detection distance curves (Figure 9), was resorted to in order to illustrate some important concepts, such as the variability of threshold measurements. The average distance of the glare car for threshold detection of the target could have been plotted for each target and lateral separation directly on Figure 9. It would not have been possible, however, to have interpolated for lateral separations other than those at which data were actually obtained.

Although this would have been a more direct method, there would still remain the problem of what to do where some, but not all, runs at a particular lateral separation do not result in threshold points, i.e., where the target is detectable for the entire run. This points up a fundamental disadvantage of this method. Because distances of the glare car are found at which the target detection distance is a given value, the data essentially fall on lines of constant target detection distance (because target detection distance is the ordinate in Figure 9). The curves of target detection distance by glare car distance that are to be derived from these data are long flat curves, indicating that the glare levels, or disability contours, which result in particular threshold detection distances, are long in extent and roughly parallel to the line of travel. If these disability glare levels can be visualized as long thin cigar-shaped contours emanating from the glare car, it can be seen that their intersection with the subject's line of travel is at a very small angle. This, combined with the variability inherent in threshold measurements, results in such a high degree of variability that the number of repetitions required for accuracy becomes impractical.

To compare the attributes of the two methods discussed so far, the data of the two subjects (L) who showed poor performance in Study 1 are shown in Figure 9. Although these data of Study 1 closely approximate the data of Study 2, it should be borne in mind that the data of the two studies are not exactly comparable due to differences in subjects, beam configurations, and methods of testing and, therefore, the fairly close apparent agreement may be mere coincidence. The data for the other three subjects (N) who took part in Study 1 were omitted from Figure 9 to conserve space on the illustration. For the same lateral separations, these subjects were able to detect the target at significantly longer distances, illustrating the wide differences that may exist between different groups of subjects.

Because the Study 1 method utilized a fixed relationship between the glare car and the target, all data of Study 1 fell on a straight line, as was illustrated in Figure 5. In Figure 9, this line intersects each lateral separation curve at one point only. Furthermore, these points are not necessarily the minimum detection distances for each lateral separation.

It should be pointed out that the retroreflectors which constituted the target in these studies were a relatively high-contrast task. These reflectors have a reflection factor in the order of 1,000, whereas all objects which reflect diffusely have reflection factors smaller than unity. The data of the Idaho study, for a target with a reflection factor smaller than unity, are also shown in Figure 9 to illustrate the differences in the magnitude of the detection distance that will result from the use of different targets. Because targets of different initial difficulty will be detected at different distances from the glare car, the driver will be oriented differently to the opposing headlight beam pattern (i.e., he will be exposed to different levels of glare), and the curves for other targets may have different shapes than those derived from Study 2.

INTERIM SUMMARY AND RECOMMENDATIONS

The two studies discussed so far utilized target detection distance as the measure of visibility. Because the third study did not, it would be well to summarize the results of Studies 1 and 2 at this point.

Interim Summary

One surprising result of these experiments was the extent, in terms of distances between the subject and the opposing vehicle, to which the opposing glare had an effect and the relative constancy of the effect over a large range of these distances. Just how far a substantial glare effect extends is not known, but the results of Study 2 indicate that visibility will be affected to a considerable extent by opposing headlights at distances in excess of 3,000 ft.

That human beings differ in visual ability and sensitivity to glare was known, but what was not realized was the effect this variability might have on the relationship between target detection distances and lateral separation, as indicated by the differences in the curves in Figure 4 for the three subjects (N) compared to the two subjects (L). It was surmised that the reason for this difference in the relative effect of glare was that the two groups of subjects, differing in initial visual ability, were at different distances from the glare car when the target was at threshold for them individually and they were, therefore, subjected to different levels of glare when detection occurred. It was further suggested that the use of targets of different initial (no-glare) difficulty would also result in different relationships between detection distance and lateral separation.

Evaluation of Study Methods

Assuming that the effects on target detection distance are the criteria chosen for evaluating the effects of glare, interim recommendations can be made on the basis of the two studies considered so far, both of which utilized target detection distance as the parameter.

Figure 10 illustrates the qualitative theoretical relationships between target detection distance and distance of the glare car for several different methods of study. The broken-line curves represent hypothetical typically shaped curves of target detection distance by glare-car distance for constant lateral separations. The two curves in each graph might represent data for different lateral separations for different targets, or for subjects with different sensitivities to glare. The light solid lines are intended to illustrate the manner in which the data are derived.

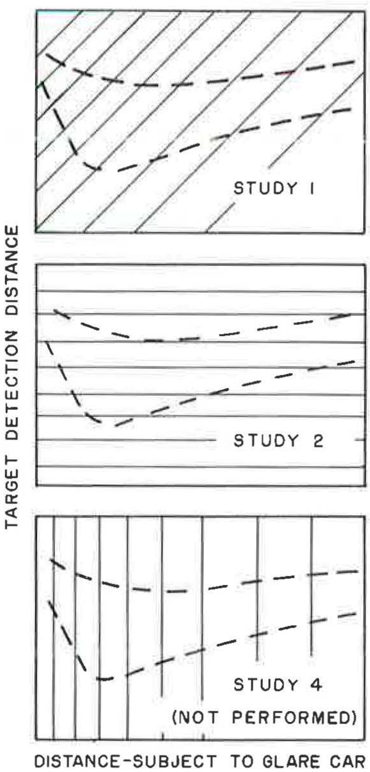

Figure 10. Theoretical relationships between target detection distance and glare car distance for different study method.

The top part of Figure 10 illustrates these relationships for Study 1, in which the opposing glare car and the target were stationary and the subject drove toward the target. This fixed relationship between glare car and target resulted in a fixed relationship between distance of the glare car and target detection distance. Figure 5 showed that the data for the different lateral separations all fell on a diagonal line which intersected the ordinate at a distance equal to the longitudinal separation between the glare car and the target, and with a slope of unity. This demonstrated that, for any one setup (i.e., relative positions of glare and target cars), there is a direct relationship between the distance of the glare car and the distance at which the target was detected. Thus, all data for Study 1 fell along one of the diagonal lines in the top part of Figure 10 and severely limited the general value of the study. However, this limitation can be overcome by collecting data for several setups, each of which would involve a different distance between glare car and target. The data for each setup would fall on one of the diagonal lines in the top graph of Figure 10. A curve can then be drawn through the appropriate values for each lateral separation.

In Study 2, subject and target were both stationary and the glare car moved. With this method, distances of the glare car were found for constant target detection distances. The data, therefore, fell along lines of constant target detection distance (indicated by the horizontal lines in the middle graph of Figure 10). The threshold points which resulted from the intersection of the subject's line of travel with the threshold curves (Fig. 8) were used to generate the curves of target detection distances by glare car distance (Fig. 9). Because the threshold curves extend for such long distances and are nearly parallel to the line of travel, the locations of these points of intersection are subject to a great deal of variability. The fact that these curves are nearly parallel to the line of travel indicates that the glare effect is apparently fairly constant for a large range of longitudinal distances between subject and glare car. The Study 2 method would be more suitable for those portions of the target detection distance curves that have considerable slope, i.e., where target detection distance changes rapidly with glare car distance. However, Figure 9 shows that these conditions apply to only a small portion of the curves.

A third possible variation of this type of study, which was not performed, would be to have the subject and the glare car stationary while the target is moved toward the subject. This method is shown as Study 4 in Figure 10 because a study which was performed and is described in the following section is known as Study 3. With the glare car and subject stationary, the glare condition would be constant and the distance at which the target could be detected at different lateral separations would be found for this condition of glare. Several different distances between the glare car and the subject would be used. The data, in this case, would fall along lines of constant distance between subject and glare car and would be represented by the vertical lines in the bottom part of Figure 10. This would probably be the best method for obtaining those parts of the target detection distance curves which have a low slope. For the large-slope portions of the curve, the points of intersection would be subject to error. The main objections to this study method are the difficulty of moving the target toward the subject and the consequent changes in the environment of the target.

Recommended Method

Although the greatest initial objections were made to the method of Study 1, the use of several relative distances between target car and glare car disposes of these very objections. Therefore, this method, with some modifications as described subsequently, is recommended for visibility tests based on target detection distance.

In addition to using several relative distances between glare car and target, a number of subjects should be used, preferably representing a cross-section of ages and degrees of visual ability. There is evidence which indicates that older drivers have poorer night vision (6) and are affected by glare to a greater degree than those with normal vision (7, 8). It should be pointed out that vision scores under daylight levels of illumination are not an assurance of the degree of night visual ability (9).

The use of one particular target for these tests will give relationships between lateral and longitudinal separations and detection distance which hold for that target only. These relationships may be different for different targets depending on the magnitudes of the distances at which the targets are detectable and at which the different subjects are able to detect them. Therefore, it is recommended that several critical targets of interest and of varying difficulty be used.

Because threshold is related to the probability of detection, target detection will be affected by the degree of attention devoted to the task and the degree of expectation associated with the target's presence and location. (According to Roper (10), objects were detectable at twice the distance when subjects were actively looking for them as when they were unexpected.) It is, therefore, important that all subjects receive the same instructions and utilize a constant criterion (e.g., "I definitely see it," "I think I see it") for all tests so that the results can be compared. To reduce guessing and anticipation, it is suggested that during the course of the experiment the target not be present at times and that the targets be changed at random between runs.

Varying the position of the target transversely across the subject's line of travel is not recommended because this will change the illumination on the target from the subject's own headlights and will change his line of sight with respect to the opposing headlights. It will be shown in the discussion of Study 3 that the background against which the target is viewed has a critical bearing on the detectability of the target. Also to be described will be a possible effect due to light from the opposing headlights which is reflected from the pavement in the vicinity of the target. Light from the opposing headlights may be reflected from the target itself. The results of a study by Schwab (11) indicate that light from opposing headlights affects the visibility of targets in ways aside from the glare effect. Changes of target position, therefore, may be equivalent to using different targets and, if done, a complete set of data should be taken for each position and analyzed separately. It may be that minor variations in position across the subject's lane may not be critical where the target is one which can be detected at great distances (500 ft or more). Still, any variation in position will tend to increase the variability of the data.

Because it is difficult to determine beforehand where the critical points in the curves will occur (e.g., breaks in the curves, minimum detection distances for each lateral separation), particularly where several targets differing in difficulty are used, preliminary estimates of the relative distances between glare car and target and the lateral separations to be studied should be based on pilot studies utilizing the targets and the subjects that will take part in the experiment.

Greater efficiency may be obtained in executing the field studies if several subjects are employed simultaneously. Allowance should be made for any differences in their lateral positions. One possibility would be to have them alternate positions. No subjects should be seated in the back seat of the subject car because this will result in the opposing headlights sometimes being blocked by those in the front or by parts of the car itself. One possible disadvantage to this procedure would be that differences in the degree of concentration of the subjects would result if one drove while the others were able to devote their full attention to looking for targets. Again the subjects could alternate driving and riding in a carefully balanced and randomized fashion.

To reduce reaction-time lags and promote greater accuracy and convenience in the distance measurements, some method of instrumenting the distance measurement and recording of responses should be utilized, e.g., a fifth wheel device for distance measurement with a pushbutton for response by the subject actuating a print-out or pen recorder. Whatever method is used, it is important that, where more than one subject is run at a time, subjects be prevented from influencing each other.

The exploratory studies reported here and studies reported elsewhere have dealt solely with the case where a single opposing vehicle is met. Although this is not an unusual situation, it is perhaps more common for a driver to be faced with several opposing vehicles at a time at frequent intervals along the highway. It is, therefore, suggested that the more critical case of a continuous line of opposing vehicles be tested. The spacing of these vehicles and the number of lanes of opposing vehicles could be varied to simulate different volume conditions and lane configurations. In this case, the variable, distance of the opposing glare car, would be replaced by the level of glare (in terms of density of opposing vehicles or veiling brightness). Inasmuch as these exploratory studies have shown that the glare effects extend for long distances of the opposing glare car, the line of opposing vehicles would have to extend for considerable distances. Should this not be feasible, shorter lines of opposing vehicles could be utilized, but another variable would be present, i.e., distance to the first (or last) opposing vehicle. It is possible that the difference in glare effect between that due to a continuous line of opposing vehicles and that due to some critical segment of the line may be negligible. To determine the critical segment, if there is one, might itself require an extensive study.

At the risk of appearing facetious, one further suggestion is made. Studies of headlight glare utilizing clean windshields do not achieve the realism typical of that of actual windshields in use. Perhaps the most critical case should include a dusty windshield. However, problems can be forseen in maintaining the windshield condition constant. Perhaps some method can be found to simulate the light-scattering properties of a dusty windshield.

Detection Distance as a Parameter

The values of target detection distance given here are the maximum possible because they represent measurements at the lowest possible limit of performance, i.e., bare detection under conditions where the subject is concentrating on detecting something, usually knows what he is looking for, and knows approximately when and where to look for it. In the actual driving situation this is not the case and, compared to the test situation, the driver will be closer to the target when he detects it. At detection, the angular dimensions of the target (visual angles subtended by the visible dimensions) will be greater and the illumination on it will be greater by the square of the ratio of the respective distances (inverse square law of illuminations). For example, if the driver needs to be half as close to detect the target in an actual driving situation as in the test situation, the angular dimensions of the target have had to be doubled while the illumination on the target has had to be increased four times. By the same token, relative detection distances do not represent the same relative degrees of visibility. It cannot be said that visibility is twice as good under one set of conditions as under another but only that the detection distance of a particular target is twice as great. Because, however, in a test situation one cannot simulate the degree of attention and expectation existing in the actual driving situation and still expect to elicit usable responses from subjects, one must make some concessions to practicality.

It should be realized that the detection distance obtained by taking the average of a number of detection distance observations represents the distance at which the target is barely detected with maximum concentration 50 percent of the time. This would be acceptable because relative values are useful if one could count on actual driving detection distances being directly proportional to those obtained in the test situation. This appears doubtful, however, in view of all the other changes that take place as distance to the target changes.

To adjust partially for realism, it is suggested that some higher probability level of detection be shown, such as those distances at which the target is detectable 95 percent of the time. Practical limitations, in terms of the amount of data that would have to be collected, would prevent the achievement of any higher probability of detection. Where it is possible to obtain approximately 100 replications for each condition (one lateral separation, one target, for one setup of glare car and target), that detection distance which is exceeded 95 percent of the time may be taken from a cumulative frequency plot. This procedure is unreliable where the sample size is much smaller; for instance, with a sample size of 20 observations, the lowest 5th percentile would have to be based on only one observation. Where the sample is smaller than 100, a normal distribution may be assumed or tested for, the mean and standard deviation calculated, and the 5th percentile computed. The higher the variability in the data, the larger the sample size needed for reliability.

These problems arise from the use of detection distance as the parameter for ascertaining the effects of opposing glare on visual performance because the only data which can be obtained are at locations where the target is at threshold. The level of visual performance at other locations cannot be measured. That is, if, under a given set of conditions, a target of interest can be seen (i.e., it is above threshold), there is no way of knowing how well it can be seen.

Discussion of some of the other controls and factors of importance in visibility tests, such as measures of glare levels and the effects of the areas against which the target is viewed, must be postponed until after the discussion of Study 3.

It was stated at the beginning of this section that the recommendations would be based on the assumption that the effects on target detection distance were to be the criteria for evaluating the effects of headlight glare. The recommendations for this type of study hold only for this assumption. This is another way of saying that studies of target detection distance should be performed only if effects on target detection distance are meaningful.

STUDY 3

The analyses and interpretation of the results of Studies 1 and 2 were plagued by the problems of the dependency of the results on a particular practical target, of possible variations due to different headlight aims and different positions of the target, and by the simultaneous changes in both the illumination on, and the angular size of, the target as the subject approached it. To obtain a general picture of the extent of the glare effect, a different approach from the previous methods was attempted in Study 3.

The aim was to have a constant-size fixed target, the visibility of which could be varied by varying its brightness. It was thought that the relative brightnesses necessary to maintain a constant level of visibility of the target would give indications of the relative effects of different lateral separations and of longitudinal distance of the opposing vehicle. The only measure of the level of constant visibility that could be obtained was the threshold level.

The field layout for Study 3 is shown in Figure 11. The target consisted of a 21- by 26-in. white translucent plexiglass screen illuminated from behind by an incandescent lamp. A variable transformer was used to vary the voltage across the lamp and thereby vary the brightness of the target. The voltage induced in a photocell mounted next to the lamp was recorded. A range of brightness readings on the target was obtained using a Spectra Brightness Spot Meter (12) reading directly in footlamberts (lumens/square foot); this calibration was used to transform the recorded photocell output into brightness values.

The subject was seated in a stationary car and viewed the self-illuminated target at a distance of 900 ft. The target was situated directly ahead of the subject with its center approximately 3 ft above the pavement. The subject's eye height was 4 ft. The subject's line of sight was, therefore, essentially parallel to both the path of the glare car and to the pavement. The 21- by 26-in. rectangular target, at 900 ft, subtended visual angles of approximately 7 by 8 min of arc. The subject car's headlights were on low beam to establish a constant brightness on the pavement and adjacent area typical of that found in the normal driving situation.

As the glare car, with high beams on, came down the track at a speed of 10 mph, the subject used the variable transformer to vary the brightness of the target so that it remained approximately at the threshold of visibility. He did this by increasing the target brightness until he could just detect the target, then decreasing the brightness until the target disappeared, etc. After some practice these oscillations were capable of being performed rapidly (approximately one cycle per second) and with low amplitude. The middle of the range was taken as threshold.

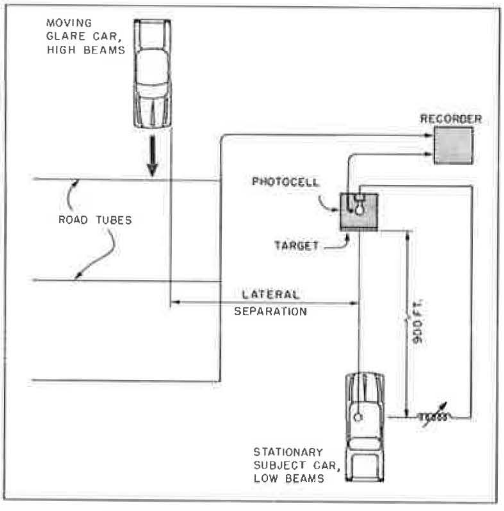

Figure 11. Field layout for Study 3.

After the glare car had passed him, the subject continued to keep the target at an approximation of threshold while his eyes readapted to the no-glare condition. This was assumed to have occurred when the record of the photocell output reached a constant level. The average of these values over all runs was taken as the no-glare threshold for the subject.

The longitudinal distance between the subject and the glare car was obtained by road tube actuations which were recorded simultaneously with the photocell output.

Runs were made in random order with the glare car at lateral separations of 7, 20, 32, 57, and 107 ft. The first road tube was situated 3,000 ft from the subject, but because it apparently took some time for the subject to find his threshold level, the data are not considered entirely reliable before 1,800 ft.

Results

It was expected that the results of Study 3 would be more clearly interpretable than those of Studies 1 and 2 because it was believed that the variables were more exactly controlled and were more exactly subject to measurement. That this was partially true, at least in a qualitative sense, can be seen from Figure 12. A set of curves is shown for each of two subjects, A and B. That part of the abscissa to the right of the zero-distance point is the longitudinal distance between the subject and the glare vehicle. That part to the left is the time after the glare car passed the subject. (The time scale is equivalent to the distance scale for the 10 mph running speed of the glare car; i.e., 10 mph is 15 fps, and the time and distance scales have been so drawn that a 1-sec interval on the former is the same length as a 15-ft interval on the latter.) The ordinate is the target brightness in footlamberts, such that the target was at the threshold of visibility for the subject. Each curve is for a different lateral separation and represents the smoothed average of at least three and sometimes four replications.

The interpretation of Figure 12 can best be visualized as follows: the subject is considered to have been situated at distance zero, facing the glare vehicle as it approached from the right of the figure. As the distance between subject and glare source decreased, the decline in the curves indicated that the brightness necessary to maintain threshold visibility also decreased; i.e., the disabling effect of the glare source was apparently decreasing. This was contrary to what had been expected.

For example, in Figure 12a, for a lateral separation of 7 ft, when the glare vehicle was 1,800 ft away the subject required a target brightness of 4 footlamberts for threshold visibility. When the glare vehicle was 600 ft away, only 2 footlamberts were required. When the glare vehicle was not present, only 0.018 footlamberts were required.

All curves do not approach the no-glare level at zero distance; this is no doubt due to the fact that the subject's eyes had not readapted to the no-glare condition. The time to readapt is shown to the left of the zero-distance point.

These readaptation times are possibly longer than would be the case in the normal driving situation because of the long duration of exposure. On the other hand, the readaptation times obtained may be shorter than those found in the normal driving situation due to the slowness of the simulated meeting. The subject must obviously be readapting during the time the glare level is dropping as the opposing vehicle is about to pass him. This time period between the exposure to the higher glare levels and the disappearance of the glare source would be much shorter at normal speeds; readaptation in the normal driving situation would begin closer in time before the zero-distance point and might, therefore, continue for a longer time after the glare car had passed the driver. The net effect on the observed adaptation times of these two compensating operations cannot be determined for the test situation.

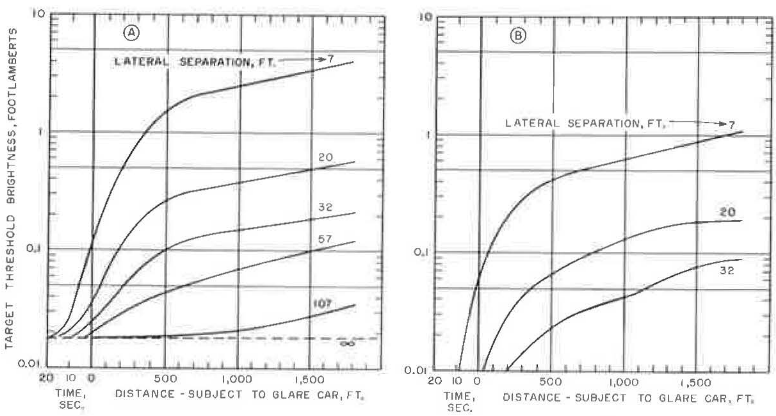

Figure 12. Threshold brightness of 8-min target—variation with distance of glare car for different lateral separations for two subjects, (Study 3), (a) subject A, and (b) subject B.

Because the curves represent the smoothed averages of a few replications, there may have been significant changes in slope at various distances of the glare car which could not have been determined because of the limited sample size. As an indication of the variability between runs, or of the range of values which approximate threshold, subject A's no-glare thresholds varied from 0.013 to 0.026 footlamberts, or one-third of a log unit. This is comparable to the variation in thresholds normally found in this type of research. Because this was a steady condition, the no-glare threshold measurements showed the least variation between runs.

Both subjects had taken part in Study 1. Subject A was one of those who showed relatively poor nighttime visual performance (L) and subject B was one of those who were classed as normal (N). It can be seen from Figure 12 that subject A required more than half a log unit more brightness to detect the target than subject B. To bring the target down to threshold when the glare car was at the wider lateral separations, subject B required brightnesses lower than those which could be obtained with the apparatus available. Furthermore, for the no-glare condition he was able to detect the target by the light from his own headlights without its being internally illuminated at all. Before a continuation of the discussion of these results can be presented, a digression is necessary.

Psychophysiology of Vision

An explanation of the results requires examination of the phenomena which are operating, based on a background of the psychophysiology of vision (13, 14).

When one looks directly at an object, light from the object forms an image at the central part of the retina, called the fovea, where the most distinct vision results. Light entering the eye from a bright source away from the line of sight should form an image on the retina away from the fovea. However, because the media of the eye (cornea, lens, etc.) are not perfectly transparent, this light is partly scattered within the eyeball and some of it falls on the fovea, raising the adaptation level. The effect is similar to the interposition of a veil of light between the object and the eye and has, therefore, been termed "veiling brightness." An equation for the veiling brightness, B_v, produced by a point source (e.g., a headlight) is given by Fry (15):

$$B_v = \frac{k E \cos\theta}{\theta(\theta + 1.5)} \quad (1)$$

$$E = \frac{I}{d^2} \quad (2)$$

in which B_v is veiling brightness (footlamberts), E is illumination at the eye (footcandles), I is intensity of the source directed at the eye (candles), d is distance of the source from the eye (feet), θ is angle between the source and the line of sight (degrees), and k is proportionality factor (28.9 when these units are used). This equation was derived from experiments involving male college subjects. Older subjects may be expected to experience greater amounts of scattering due to increased opacity of the media of the eye with age (8, 16).

An object is detectable because of the contrast of its brightness, B_o, to the brightness of the background, B_b, against which it is viewed (more correctly, to the level of brightness to which the area of the retina adjacent to the image is adapted). Contrast is expressed by Blackwell (17) as

$$C = \frac{B_o - B_b}{B_b} \quad (3)$$

Because the veiling brightness exists in the eye, its effect is to appear to add to the brightness of the target and the background. However, it decreases the effective contrast, C_e, because the brightness difference between the object and its background remains unchanged while the adaptation level (the original B_b plus the superimposed B_v) is raised.

$$C_e = \frac{(B_o + B_v) - (B_b + B_v)}{B_b + B_v} = \frac{B_o - B_b}{B_b + B_v} \tag{4}$$

Therefore, the extent to which a given magnitude of veiling brightness will reduce visual ability will depend on the magnitudes of the existing brightnesses. (To complicate matters further, lest it be thought that the contrast required to detect a given size target is constant, threshold contrast varies with adaptation brightness.)

Discussion

Utilizing Eqs. 1 and 2 and a candlepower diagram for the configuration of headlamps (four-lamp high beams) used in this experiment, values for veiling brightness due to the opposing headlights were calculated for each of the lateral separations for the geometric conditions of the experiment. Veiling brightness may be measured directly by the Fry-Pritchard glare lens used in conjunction with a Pritchard Telephotometer. This lens, attached to the photometer, measures the veiling brightness due to all light sources in the field of view by integrating them according to Eq. 1. Both this lens and the Pritchard photometer are briefly described by the American Standards Association (12). Fry (18) gives a detailed description of the lens. Figure 13 shows the variation in veiling brightness with longitudinal distance of the glare car. The calculations, for a horizontal line of sight, are based on the assumption that the glare car is traveling in a path parallel to the subject's line of sight on a horizontal plane. The magnitude of the veiling brightness and the shapes of the curves will be different if any of the following are changed: orientation of the line of sight, highway geometry (affecting the orientation of the opposing headlamps), and number of glare sources or headlight beam (high to low). In addition, the degree of opacity of the media of the eye will differ between individuals. The peculiar shapes of the curves are caused by the way in which the factors affecting veiling brightness vary with lateral and longitudinal separation.

The curves are drawn in the same format as those of Figure 12; i. e., the subject is assumed to be situated at distance zero facing the glare car as it approaches from the right of the illustration. Veiling brightness at the 7-ft lateral separation rises

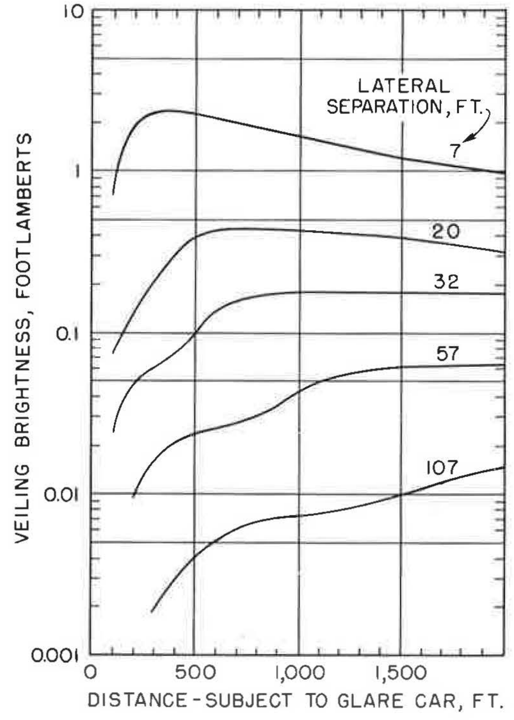

Figure 13. Veiling brightness for opposing high beams, Study 3 (Eq. 1).

gradually to a peak as the glare car approaches from 2,000 ft away to within 400 to 300 ft, and then drops sharply. Veiling brightnesses at the 20- and 32-ft lateral separations are fairly constant for long distances, beginning to drop off at about 600 and 700 ft, respectively. Veiling brightnesses for the 57- and 107-ft lateral separations are already decreasing as the glare car approaches to within 2,000 ft of the subject.

Values for veiling brightness are not shown at small longitudinal distances because the candlepower diagram does not give values for very large angles. At these distances, candlepower is very low and the glare angle (θ) is getting so large that veiling brightness becomes very small. Veiling brightness due to the headlights must obviously be zero at zero longitudinal distance from the subject; therefore, the curves must approach the zero distance line asymptotically on the log scale.

Target threshold brightness is related to veiling brightness through the brightness-contrast function (Eq. 4). Unfortunately, the equipment available at the time this experiment was performed was inadequate to measure the low levels of background brightness which were present at the site, so that target contrast could not be calculated. However, all other things being constant, target threshold brightness should vary directly with veiling brightness; e.g., where veiling brightness is high, target brightness should be correspondingly high.

Comparison of the threshold brightness curves of Figure 12 with the veiling brightness curves of Figure 13 shows this, generally, to be the case. However, there is some inconsistency. For the 7-ft lateral separation, between 1,800 and 300 ft, target brightness is falling while veiling brightness is rising. At lateral separations of 20 and 32 ft, target brightness is falling even while veiling brightness remains fairly constant. Only for the 57- and 107-ft separations do target brightness and veiling brightness decrease concurrently.

A comparison of the Study 2 target detection distance curves of Figure 9 with the veiling brightness curves of Figure 13 shows them to be generally consistent (to visualize this, imagine that Figure 9 is turned upside down). For the narrow separations, at glare car distances where veiling brightness is increasing, target detection distance is decreasing, and vice versa. Therefore, the Study 2 target detection distance curves seem to show a different relationship between the effects of headlight glare and position of the glare car than do the target threshold brightness curves of Study 3. Based on the target detection distance, the disabling effect of glare was shown in Study 2 to increase as the glare car approached from far distances, to reach a maximum and then to decline. On the other hand, the Study 3 data on target threshold brightness show the disabling effect of glare to be worst at far distances of the glare car (up to 1,800 ft) and to decline as the glare car approached. Is this difference in results due to the differences in the targets and the study methods? Perhaps a different way of looking at the data of Study 3 will be helpful.

It was postulated previously that if all other things remain constant for different locations of the glare car, then changes in veiling brightness alone should determine changes in the contrast conditions and, consequently, in target threshold brightness. It should follow, therefore, that where the same value of veiling brightness occurs for different locations of the glare car, the corresponding target threshold brightnesses should also be equal.

To check this, the data of Figures 12 and 13 have been combined in Figure 14 to show target threshold brightness for the associated veiling brightness for each subject, lateral separation, and distance of the glare car. Two sets of curves are shown, one for each subject. The small numerals on the curves are the distances, in hundreds of feet, of the glare car at which the data were derived. The boxed-in numerals are the lateral separations for each curve. If the target threshold brightness is wholly dependent only on the level of veiling brightness (and if the calculated values of veiling brightness are correct), all curves for each subject should overlap. Considering the limitations of the target threshold determinations and the fact that veiling brightness has been calculated rather than measured, the coincidence of the curves for the different lateral separations for each subject is quite good. An arbitrary trend line has been drawn for each subject. The curves for each lateral separation have been drawn as far as the veiling brightness values available would permit. Were very low veiling

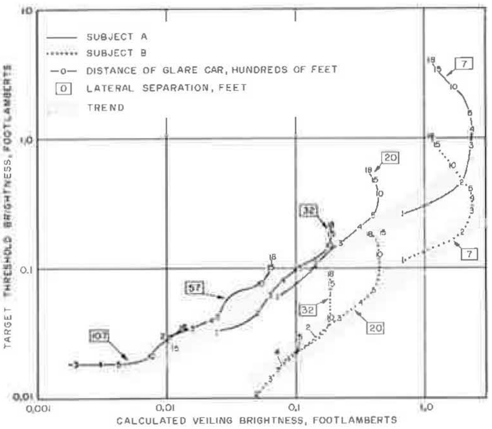

Figure 14. Target threshold brightness vs calculated veiling brightness for two subjects.

brightness values available for the small distances, all the curves theoretically would follow the trend lines to the no-glare level, were it not for the lag in adaptation. This may be why most of the curves show a decreasing slope at the small distances.

Although, for the most part, the curves show a high degree of coincidence, there are discrepancies where the curves do not follow the trend lines or the trend slopes. The inconsistencies noted when the target brightness curves of Figure 12 and the veiling brightness curves of Figure 13 were compared stand out clearly. Closer examination shows that these departures from the trend lines occur most pronouncedly at the narrow separations and at the far distances of the glare car. Here a visualization of the target and its background, as viewed by the subject, may aid the interpretation. Part of the target, being somewhat closer to the pavement than the subject's eyes, is viewed against a background of pavement. The opposing headlights not only introduced veiling brightness into the eye but also lighted up the pavement near the glare car. In addition, at long distances there is some specular reflection from the pavement between the glare car and the subject. Furthermore, for far distances and, particularly, at narrow lateral separations, the opposing vehicle is very close in angular distance to the target. Therefore, for these long distances and narrow separations, a lighted area of pavement existed close to the target. This would have decreased the contrast of the target, requiring a higher target brightness to bring it up to threshold. Furthermore, the veiling brightness calculations have been based on the assumption of a fixed unwavering line of sight. Because, presumably, the target was approximately at threshold, it should not have been visible approximately half the time, and so could not be fixated upon constantly. (Even if the threshold brightnesses derived are not for 50 percent detection, the oscillations in target brightness brought about by the subject required that the target be nondetectable approximately half the time.) Small eye movements undoubtedly brought the line of sight closer to the opposing headlights, thereby increasing the veiling brightness over that which had been calculated. It is possible that the subject may have occasionally glanced directly at the headlights. A third possibility, suggested by Schwab (11), is that forward scattering in the atmosphere of the light from the opposing headlights is appreciable at small angles. This scatter light would be similar in nature, and in effect, to the scattered light in the eye, which results in veiling brightness. It would reduce the effective contrast of the target, requiring a higher brightness to bring it to threshold. It is also possible that the extremely bright headlights, being the only prominent objects in the field of view, tended to distract the subjects' attention partially from concentrating on the target so that the target had to be brighter to overcome the competition. All of these effects would be present to some extent in the actual highway driving situation. The effect of the spillover light from the opposing headlights onto the pavement of the driver's own roadway would be mediated by the characteristics of the median and the geometries of the two roadways.

The questions raised previously as to why the Study 2 target detection distance curves showed a somewhat different relationship of the effects of headlight glare to location of the glare car than do the target threshold brightness curves of Study 3, therefore, cannot be answered exactly. It is possible that the answers may lie in some of the differences between the studies. The differences between the shapes of the curves for calculated veiling brightness and target threshold brightness of Study 3 were attributed to several possible factors. Among these were the reduction in target contrast due to the area of pavement lighted by the opposing vehicle, and the proximity of

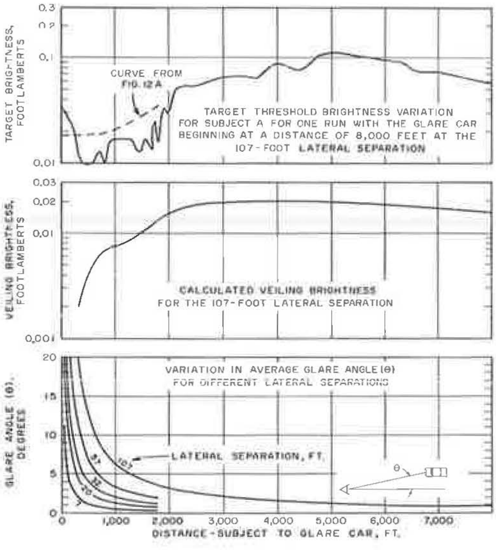

Figure 15. Variation of target threshold brightness, calculated veiling brightness and average glare angle (θ) with glare car distance.

the opposing headlights to the target. However, the background against which the reflectors which constituted the target in Study 2 were viewed, in part, consisted of the dark car body and not the pavement. In addition, the target car was offset laterally from straight ahead (the angular distance of the reflectors on the right side of the car averaged about one-half degree away from the straight-ahead position).

8,000-Foot Run

The target threshold brightness measurements discussed so far have been for glare car distances of 1,800 ft or less. The top part of Figure 15 is a plot of the target threshold brightness for subject A for one run with the glare car at a 107-ft lateral separation and beginning at a longitudinal distance of 8,000 ft. The glare car moved at 60 mph to 3,000 ft, whereupon it rapidly decelerated to reach 10 mph by 2,400 ft. A sag grade change in the runway of 0.3 percent existed at a distance of 2,650 ft from the subject. That the curve at the small longitudinal distances fluctuates around, and falls below, the average no-glare threshold value of the other runs for the 107-ft lateral separation should not cause too much concern. Target threshold brightness is varying in the no-glare range and, for this particular run, it happens to be in the low part of the range. To illustrate some of the variability in threshold, the curve has not been smoothed very much; only the oscillations around threshold have been omitted. The minor fluctuations are probably random and do not represent any significant changes in threshold.

It can be seen that the target had to be maintained at a substantial brightness while the glare car was between 1½ and ½ mi from the subject. The curve of target threshold brightness from Figure 12, for the same subject and lateral separation, is shown for comparison. Were this curve to be extended, it appears that it would meet the 8,000-ft curve at about 2,100 ft.

For much of the 8,000-ft distance, the target brightness values for subject B for this same type of run were too low to be measured and are, therefore, not shown in the figure. However, from 8,000 to 3,000 ft the measured target brightness was approximately 0.01 footlambert with a slight rise above 0.01 between 6,000 and 3,000 ft. This seems to indicate a rise and decline in threshold similar to that of subject A at these distances.

The middle part of Figure 15 shows the variation in calculated veiling brightness from the glare car headlights for the 107-ft lateral separation. Although the shapes of the veiling brightness and target brightness curves are similar, for both subjects the target brightnesses for the far distances are, again, much higher than they should be for the corresponding calculated values of veiling brightness at these distances. Therefore, it is concluded that the high values of target brightness at the far distances are not due to glare from the headlights alone, but that the effects of reflected light from the pavement, fluctuations in fixation, or forward scattering in the atmosphere are making themselves felt.

The lower part of Figure 15 shows the variation in average glare angle, θ (measured to center of glare car rather than to the individual headlights), with distance for the different lateral separations.

SUMMARY

The studies reported herein were undertaken with the intention of exploring alternative methods of studying the relationship between headlight glare and median width. Inasmuch as insight into the magnitude and extent of the glare effect and the factors involved was desired, the amounts of data collected were small; therefore, little reliance should be placed on the absolute quantitative values. Furthermore, the quantitative values hold only for the particular conditions studied, such as the geometry of the test situation, target, subjects, and surroundings. The qualitative relationships between target detection distance and position of the glare car will also be affected by the values of these variables. The tests simulated only a meeting with a single opposing vehicle with high beams on.

The results of the discomfort test in Study 1, the only study which dealt with both discomfort and visibility, showed that measurements of discomfort due to glare were too variable, and discomfort, itself, was too difficult to define, for a limited study to have much value. No apparent relationship was found between visual and discomfort sensitivities to glare.

Studies 1 and 2 utilized the rear of a black unlighted car as the target. In all cases, the rear red reflectors were the part first detected. Study 3 utilized a self-luminous target the brightness of which could be varied. The results of all three studies showed that the effects of glare on visibility (i.e., target detection) decreased with increasing lateral separation and were substantial even when the opposing glare car was at a longitudinal distance of several thousand feet from the observer. Very limited data from Study 3 indicate that effects of the opposing headlights on visibility may be present even when they are at distances of as much as 8,000 ft from the subject. For any individual lateral separation, the rate of change of visiblity with distance of the glare car was small. Large differences in night visual ability and glare sensitivity may exist between subjects; other research has correlated these differences with age.

It was concluded from an analysis of the results of Studies 1 and 2 that different relationships between position of the glare car and target detection distance may result for different targets or different subjects because of the interaction between distance at which detection occurs and level of glare existing at that distance. This comes about because of differences in orientation with respect to the opposing headlight beams at different distances from the glare car.

The method of Study 1, where the glare car and target were stationary and the subject moved toward the target, was shown to yield incomplete results if a fixed relationship between the target and glare car were maintained. This would impose an arbitrary relationship between distance of the glare car and detection distance. To overcome this disadvantage, it was suggested that several different relative distances between glare car and target be used, with the target both in advance of and beyond the glare car.

The method of Study 2, where target and subject were stationary and the glare car moved toward the subject, was shown to be inaccurate because the cigar-shaped actual glare disability contours cut the subject's theoretical line of travel at such small angles that numerous repetitions are required for any accuracy. In addition, the threshold probability levels are unknown, so that it is impossible to determine where to draw the contours in the vicinity of those lateral separations where, for some runs, the target is always detectable for the entire run.

Other recommendations were made for the performance of detection distance studies, such as the use of several different types of targets, random orders of presentation, representative observers, and a constant criterion for reporting detection (in terms of the observers' confidence of detection); it was also suggested that one of the most critical realistic conditions would be that where a driver is faced by a large number of opposing vehicles on low beam. To render the situation even more critical and realistic, a dusty windshield could be used.

The difficulty of interpreting relative detection distances for the purpose of assessing visibility was discussed, particularly in view of the probable lack of proportionality between detection distances under the conditions of attention and expectation existing

in the test situation as compared to the normal driving situation. To approach more closely values of detection distance which would be representative of detection distances in actual driving, it was recommended that the values shown be the 5th-percentile detection distances, rather than the average detection distances. The use of the 5th-percentile rather than the average would give distances at which the target was detectable 95 percent of the time rather than 50 percent.

In Study 3, subject and target were stationary and the subject attempted to keep the self-luminous target approximately at the limit of visibility while the glare car moved toward him. As expected, target visibility increased with increasing lateral separation. At the narrow separations, readaptation times to the no-glare condition were on the order of 5 to 10 sec. Surprisingly, it was found that target visibility appeared to increase as the glare car approached the subject, at least for the distances which were analyzed (1, 800 to 0 ft). This result was found to be consistent with the variation of calculated veiling brightness for the wide separations, but not for the narrow separations. Comparison of veiling brightness and target brightness indicated either that the veiling brightnesses as calculated were not the same as those present in the experiment, or that other factors were affecting the visibility of the target. It was conjectured that these other factors, which may have affected both the subject's adaptation brightness and the contrast of the target, were due to fluctuations in the line of sight, changes in brightness of the pavement against which the target was viewed due to light from the glare car headlights, or forward scatter in the atmosphere of light from the glare car headlights. Other possibilities are that the subject occasionally glanced directly at the headlights or that the headlights, being the only prominent objects in the field of view, had an attention-distracting influence.

It appears, therefore, that a report of the location of the opposing vehicle is not sufficient alone to define the visibility conditions. The independent variable should be some measure of adaptation, rather than the number or position of opposing vehicles or horizontal footcandles. In night visibility research, therefore, account should be taken of all factors which would affect the visual adaptation level so that results may be tied to a common denominator.

REMARKS

To explain some of the results of Study 3, some aspects of the physiological basis of vision were reviewed. They are repeated here to form a basis for the ensuing remarks.

Visual receptors are sensitive to a wide range of luminances. They adapt to the particular levels available, although there is a time lag, particularly when going from higher to lower levels of illumination. Objects are discriminable by contrast, defined as the difference in brightness between the object and the adjacent background against which it is viewed, divided by the latter (Eq. 3).

Because the media of the eye are not perfectly transparent, all light entering the eye is somewhat scattered or diffused. Where the field of view is dark, this scattered light from high-intensity sources can be of appreciable magnitude in comparison to the brightnesses of objects. This scattered light within the eye has the effect of a veil of light, superimposed over the field of view and varying in brightness with angular distance from the source. It is, therefore, called veiling brightness. An equation for the veiling brightness, B_V, equivalent to that due to a point source (e.g., a headlamp) situated at a distance, d, from the eye, and at an angle, θ, from the line of sight, directing an intensity, I, at the eye, is

$$B_V \propto \frac{I}{d^2 \theta (\theta + 1.5)} \tag{5}$$

I/d^2 will be recognized as the illumination, E, from a point source, in footcandles if I is in candles and d is in feet.

The disability glare effect is largely due to this veiling brightness which lowers the effective contrast by raising the adaptation brightness while leaving unchanged the difference in brightness between the object and its background (Eq. 4).

The brightness of the object itself, as viewed by the driver, will depend on the light it emits, if any, and the light it reflects from the environment, from the driver's own headlights, from other sources such as other vehicles moving in the same direction as the driver, and from opposing headlights. The brightness of the background against which the object is viewed may also derive from any of these sources.

Light on the pavement from the opposing headlights may help delineate the roadway alignment ahead of the driver by increasing the contrast between the pavement and the shoulder. This is especially true where the pavement surface has different specular reflection characteristics from the shoulder. This is usually the case because roadway shoulders ordinarily are unpaved. In addition, this effect will enhance the visibility of objects seen in silhouette but will reduce the visibility of objects seen in direct light, such as pavement markings.

The factors which determine visibility, such as veiling brightness or background brightness, will themselves be affected by various median features. One of these features is median width. At any given longitudinal distance separating an opposing vehicle from an observer, a greater horizontal separation will result in the opposing headlights being at a greater angle from the line of sight; lower intensities of light and, consequently, less illumination will be directed at the eye of the observer. Both the increased angle and the lowered intensity will result in lower veiling brightness. Background brightness will be reduced because less of the forward-scattered component of the light will be present along the line of sight and less light from the opposing headlights will fall on the driver's own roadway.

On divided highways in rolling or hilly terrain, independent roadway design frequently is employed for all or substantial portions of the highways. With this type of design, usually combined with curvilinear alignment (continuous flat curves), the two roadways are designed as separate cross-sections with variable widths of median and independent grade lines. In general, this design tends to reduce glare by providing sections of wide medians, frequently with natural growth or dense plantings between the roadways. Sections of earth or rock may be left in the median area. The independent grades also may reduce the glare from oncoming cars. However, in certain locations, where the centerlines of the two roadways tend to converge or where the difference in adjacent grades is slight, glare problems may be accentuated. In good design, these potential problems are located during design and, if possible, avoided. If they cannot be eliminated, screen planting is usually specified.

Those types of median features which mediate the effects of opposing headlights by interposition can be classed as light-obstructors. Full screenage of the opposing headlights from view can be achieved by earth mounds, solid plantings of vegetation, solid fences, or fences which block the view of opposing headlights at almost all angles at which they would be visible, such as a venetian blind-type slat fence or expanded-metal antiglare screen. Partial blockage can be achieved by means of chain link fence, which completely blocks the view of opposing headlights at small angles only. Plantings of vegetation in the median can block the view of opposing headlights, if very thick and continuous. Less dense planting may tend to result in intermittent flashes. Deciduous plantings may lose much of their effectiveness when their foliage is gone, but evergreen types eliminate this difficulty. Some limited use has been made of translucent screens which reduce the intensity of the light from opposing headlights by reflecting some, absorbing some, and diffusing the rest.

Other median features may produce undesirable shadows where light from opposing vehicles falls on the driver's own roadway. A high curb may put the left edge of the pavement in shadow. A curb may also diminish the contrast between pavement and median. A low solid barrier may accentuate the shadowing effect. Guardrail posts and vegetation in the median may introduce irregular, moving shadow patterns on the roadway ahead of the driver.

Other solutions or aids to the night visibility problem have been proposed or are in use. Foremost among these has been the increase in visibility by increasing the ambient illumination and roadway brightness by highway lighting. It should be pointed out that the luminaires, themselves, may constitute important glare sources.

Additional illumination in the driver's field of view could be provided easily by increasing the intensity and angular spread of the headlights. This would, of course, greatly intensify the glare problem. The headlight glare problem results from the need to provide light directed along the roadway while the condition exists that drivers traveling in opposite directions on the same road face each other's light sources. Polarization of headlights has been proposed as a means of drastically diminishing the apparent brightness of opposing headlights while maintaining or increasing the efficiency of the light output of the driver's own headlights (19). This solution has heretofore foundered on the problems associated with the period of transition between partial and complete conversion to polarized headlights. Changes in conditions since the time this system was last considered may yet enable this solution to be realized (20).

A partial remedy has been to increase the reflectivity or luminance of some significant objects of interest to make better use of or to overcome the limitations of existing headlight illumination. Reflectorization of signs and pavement markings and the provision of taillights and rear reflectors on vehicles are examples of this.

Perhaps it would be of value, before considering solutions, to attempt to achieve a more definitive formulation of the problem.

Opposing headlight glare is a problem because it reduces visibility at night. But visibility at night, even without glare, is not considered good. Therefore, the visibility-reducing aspects of headlight glare are a part of, and not different from, except in degree of severity, the entire night visibility problem. The night visibility problem can be defined, superficially, as a lack of sufficient light. The next step would seem to be to consider what it is for which there is a lack of sufficient light and what the results are of the lack of visibility thereof. This line of argument leads to a consideration of what needs to be seen. What needs to be seen would depend on what visual information is utilized by the driver in the performance of the driving task. Unfortunately, knowledge as to these information needs is limited, as is appropriate definition of the major aspects of the driving task itself. As additional definition of the driving task is obtained, it is envisioned that more light (figuratively) will be shed on the driver's requirements for light (literally). In the meantime one can speculate, in the hope of opening up lines of approach which may prove fruitful.

One can begin by observing that there is apparently sufficient light being presently provided for the visual task to enable the night driving task to be accomplished. This can be stated with some degree of confidence because of the fact that, for the most part, drivers do succeed in accomplishing the task. However, all this may prove is that human beings are highly adaptable. It is not to say that the task could not be accomplished with more of a margin of safety and comfort. What appears to be lacking at this point is a reliable quantitative measure of the degree of adequacy of visibility for the night driving task because of a lack of understanding of what constitutes the task.

The primary area of concentration thus far has been on detection or visibility of targets, perhaps because this is the easiest thing to measure and appears to have the most direct bearing on the visibility problem. The problem of interpreting detection distances has been discussed previously as has the limited applicability of absolute threshold data to the actual driving situation.

Several instruments have been developed which attempt to assess the visibility of objects at suprathreshold levels. Among these may be mentioned the Visual Task Evaluator (12, 21, 22) and the Finch Visibility Meter (12, 23). However, even the visibility data obtained with these instruments must be evaluated by arbitrary criteria. In addition to enabling suprathreshold measurements, these instruments offer the advantage that a wider range of types of targets, such as selected portions of a continuous target (e.g., a pavement edge), may be studied than is the case where observations are made of detection distances for test subjects, where targets are limited to discrete objects. However, the presence of objects (i. e., objects which may be struck, as differentiated from objects of interest such as pavement lines) in the roadway is rare. The following hypothetical set of conditions may be considered: (a) the driver can be confident that there are no objects in his path of travel except for other vehicles, and (b) all vehicles are sufficiently well lighted and marked as to be detectable even under severe conditions of opposing glare. Given these conditions, would there then be no night visibility problems? Hardly! The driver would still have to be able to see the roadway to obtain information for steering and lateral position control and for judging the location of other vehicles relative to his path of travel.

There are indications that drivers' judgments for steering and position in lane, as well as judgments of relative speed and position with respect to objects and vehicles, are determined by judgments of angular velocities, and that the distance ahead at which these cues are detected is proportional to speed (24). If it is therefore necessary for the driver to detect these cues at some distance ahead of him, he would be required to reduce his speed under conditions of lower visibility. Should he desire to maintain the same speed as under good visibility conditions, some compensation probably must take place and he may have to devote more concentration and attention to the task of retrieving information, resulting in increased tension and fatigue but little or no measureable effect on gross driving performance. It is also possible that the ability to determine the course of the roadway even further ahead than is necessary to detect steering cues facilitates the driving task by relieving the driver of part of the vigilance task.

On the basis of subjective experience it seems that, even where the glare effect on visibility is small, such as where a wide median exists, the presence of opposing headlights is annoying. Allied to the problem of the increased vigilance required when visibility is poor is the possibility that the awareness of a deficiency in visibility, and the ensuing uncertainty of detecting cues, may themselves induce tension. Because man is by nature a daytime animal, the mere presence of darkness may be psychologically depressing.

Because opposing headlights (or other high-intensity sources such as luminaires, advertising displays, or lights associated with roadside business establishments) tend to be by far the brightest and most prominent objects in the field of view, they may tend to distract the driver's attention from the primary visual task in addition to and because of their effect on contrast. This distraction (visual "noise") effect could result in visibility reduction from the psychological effect in addition to the physiological effects. As an additional aspect of the problem of the intensified vigilance required, it would add to tension and fatigue. In addition to the psychological stress and discomfort engendered, continued exposure to bright headlights may be physically discomforting.

It may well be that the major benefits of eliminating high-intensity glare sources from the driver's field of view will be in the area of driver comfort; perhaps increased emphasis on investigations of glare and visibility vs comfort and fatigue is warranted.

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