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IMPROVED LOW-BEAM PHOTOMETRICS

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16. Abstract
The purpose of this project was to determine what changes might be made to the automotive low-beam lighting specifications to improve driver nighttime performance.

The project was carried out in two phases. In Phase 1 the literature was reviewed and four studies of rear view mirror glare problems were conducted. Recommendations were made for modifications to the low-beam system.

In Phase 2 several laboratory and field studies were carried out. These were concerned with discomfort glare, foreground illumination, and beam color. An analysis of system performance of headlamp beams was conducted, using data from another study.

Headlamps embodying the photometrics recommended in Phase 1 were fabricated and tested in a target identification study. The experimental lamps generally outperformed the control systems. Computer modeling techniques were used to expand the analysis to include hills and curves.

The various lighting systems that had been field tested were also analyzed using the Ford CHESS model to evaluate system performance. Systems that did well on the earlier tests did no better than the control systems based on this procedure.

Based on the results of the experimental work reported here, recommendations were made for changes to the low-beam specifications in FMVSS 108.

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TECHNICAL SUMMARY

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The purpose of this project was to determine what changes should be made to headlighting specifications to improve driver nighttime performance.

The project was carried out in two phases. In Phase 1 a review of the literature was conducted, both to acquire a data base for decisions concerning possible changes, and to identify areas in which there was inadequate information. It was felt that there was insufficient information about the problem of glare in rear view mirrors, so four studies were planned and conducted in that subject area.

The two laboratory and two field studies on rear view mirror glare looked at various aspects of the problem. The findings make it clear that, if the driver takes no action to reduce glare (such as switching the interior mirror to the "night" setting), both disability and discomfort effects are significant at present-day low-beam glare levels. Further increases in illumination projected into this area can only make the problem worse. However, there are potential solutions available in the form of adjustments to mirror reflectivity levels. Research in this area is very desirable.

At the conclusion of Phase 1 recommendations were made for changes to the low-beam specifications. The headlamp pattern that would be made possible by these changes was a modified mid-beam system. It was characterized by much higher intensities along the right side of the road and somewhat higher glaring intensities.

In Phase 2 a number of studies and analyses were carried out. These addressed discomfort glare, foreground illumination, beam color, and system performance. Headlamps were fabricated to meet the revised specifications and were evaluated, together with other standard and experimental lighting systems, in terms of the visibility they provided. Lighting system performance analyses were also carried out using computer modeling techniques.

(Continue on additional pages)

HS Form 321
July 1974

Three discomfort glare studies were carried out. The first was a laboratory investigation in which the primary independent variables were the range of stimuli presented to the subjects and subject age. The results indicated that stimulus range has a significant effect on judged comfort and that there is relatively little difference between older and younger subjects. The second discomfort glare study compared ratings of glare using two scaling techniques in an effort to improve understanding of the results. The third discomfort glare study was conducted under full-scale meeting conditions and also varied the stimulus range. Once again the range of stimuli presented to the subjects affected their comfort ratings. Also, the ratings made under these conditions were generally significantly more comfortable than those made under laboratory conditions.

Two studies were carried out on the question of foreground illumination. The first of these measured the effect different levels of foreground illumination would have on driver eye fixations. It was found that drivers tended to look further from the car as foreground illumination increased. The second study assessed the effect of foreground illumination on target identification distances. No differences were found.

The effect of beam color on discomfort glare was assessed in another study. No differences were found.

Using data from another investigation, an analysis was carried out to illustrate system effects. It was shown that glare and illuminating intensities vary greatly under real world operating conditions, and that beam pattern changes designed to have a particular effect may not work as well as anticipated in actual practice.

A field evaluation was conducted to measure how well subjects could detect and identify various targets using various standard and experimental lighting systems. Included were:

a. Two variants of the modified system recommended in Phase 1.

b. A U.S. and European control.

c. An experimental single-beam system.

d. A U.S. low beam augmented in the foreground area.

The modified low beam based on Phase 1 recommendations and the single beam generally outperformed the others by a significant margin. However, none of the systems were adequate for safely revealing low-contrast objects at legal maximum speeds.

As a final step in the analysis, the test lighting systems were evaluated using computer models. One of these compared performance on hills and curves. Those systems that did best in the field test did best here as well. The second analysis was designed to provide a comprehensive systems evaluation. These results indicated that none of the lighting systems used in the field test and first computer evaluation outperformed some of the standard systems used as references in the computer files.

Based on the results of Phases 1 and 2 of this program, recommendations were made to upgrade the photometric standards for low-beam headlamps. Recommendations were also made for future research in the area.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

In September 1979, the National Highway Traffic Safety Administration (NHTSA) awarded a contract entitled "Improved Low-Beam Photometrics" to the University of Michigan Transportation Research Institute (UMTRI)[1]. The purpose of the study was to determine whether and how the current intensity distribution requirements of low-beam headlamps could be modified to improve driver nighttime visibility.

The investigation was carried out in two phases. In Phase 1, the relevant literature was reviewed, deficient areas identified, and a series of studies was conducted to provide the necessary information. Finally, recommendations were offered for modification to the low-beam lighting system. Phase 1 activities are described in the project Interim Report (Olson and Sivak, 1981).

One purpose of Phase 2 was to evaluate the lighting system proposed in Phase 1. To this end, hardware was fabricated and a field test was carried out. Two versions of the modified lighting system were evaluated, together with representative "standard" U.S. and European systems, a high-foreground U.S. system, and a "single-beam" system.

Additional work carried out in Phase 2 consisted of laboratory and field studies of discomfort glare, the effects of changes in foreground illumination, and beam color.

This is the final report of the project. It consists of three main sections. The first of these, entitled "Studies Concerning Special Issues," describes the work done during Phase 2 on discomfort glare, foreground illumination, and beam color. The second main section, entitled "Visibility," describes the field evaluation of various

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[1]At the time of the award, the Institute was named the Highway Safety Research Institute (HSRI).

lighting systems and the computer simulations of these lighting systems under various conditions of road geometry. Finally, the third main section presents the recommendations that we feel are warranted, based on the results of these studies.

2.0 STUDIES CONCERNING SPECIFIC ISSUES

2.1 Discomfort Glare

2.1.1 Introduction. Discomfort glare is one of the most difficult and controversial questions in vehicle headlighting. It is one of the principal areas of disagreement between European and American lighting engineers and a major barrier to the desirable goal of international harmonization.

Since glare cannot be entirely eliminated, the question must be asked "how much glare is acceptable?" Discomfort being a subjective phenomenon, this is not a simple question to answer. It is one matter to agree that an intense stimulus of some kind produces an unpleasant sensation. It is quite another matter to try to decide at what point along the intensity continuum the stimulus becomes unpleasant.

By and large, decisions about acceptable glare levels have been made on a consensus basis by engineering committees concerned with headlighting standards. In the 1930's the Europeans adopted a shielded filament concept that made it possible to produce a relatively low-glare unit inexpensively. The Americans took a different approach, relying on lens prisms to control both illumination and glare. As a result, glare levels associated with U.S. lamps are higher. So, the lighting systems have evolved, with different glare levels, over a period of more than forty years. It is easy to understand how a European, being used to one lighting system, would find U.S. headlamps more glaring and more uncomfortable to look at. They are.

But, relative comparisons of glare and its effect on the observer's feelings of comfort are of limited use. Rational decisions concerning the trade-offs between glare and visibility require empirical data. In the case of discomfort glare, it is desirable to know in quantitative terms the relationship between glare and the level of discomfort. If there is a point beyond which it is clearly undesirable to go, this should be identified.

In automotive headlighting the most successful approach to quantifying discomfort due to glare was pioneered by DeBoer (1973). DeBoer developed a 9-point rating scale as follows:

1. unbearable
2.
3. disturbing
4.
5. just acceptable
6.
7. satisfactory
8.
9. just noticeable

This scale has been used by a number of investigators. Perhaps the most significant work is the meticulous laboratory study of Schmidt-Clausen and Bindels (1974). Their data, for one combination of parameters, are reproduced in Figure 2.1. Based on these data, the peak glaring intensities of U.S. low beams in a meet on a straight, flat, two-lane road would be rated about "4," suggesting that they are already too glaring and that further increases are undesirable.

Schmidt-Clausen and Bindels developed a mathematical model of discomfort glare. One version of this model (as described in Bhise et al. [1977]) is as follows:

$$W = 2 \log_{10} (1 + 269.0966L_a) - 2 \log_{10} (\Sigma Ei/\theta_i^{0.46}) - 2.1097$$

where W = scale value as defined above

L_a = adaptation luminance

Ei = illumination directed toward the observer's eyes from the ith source

θi = glare angle

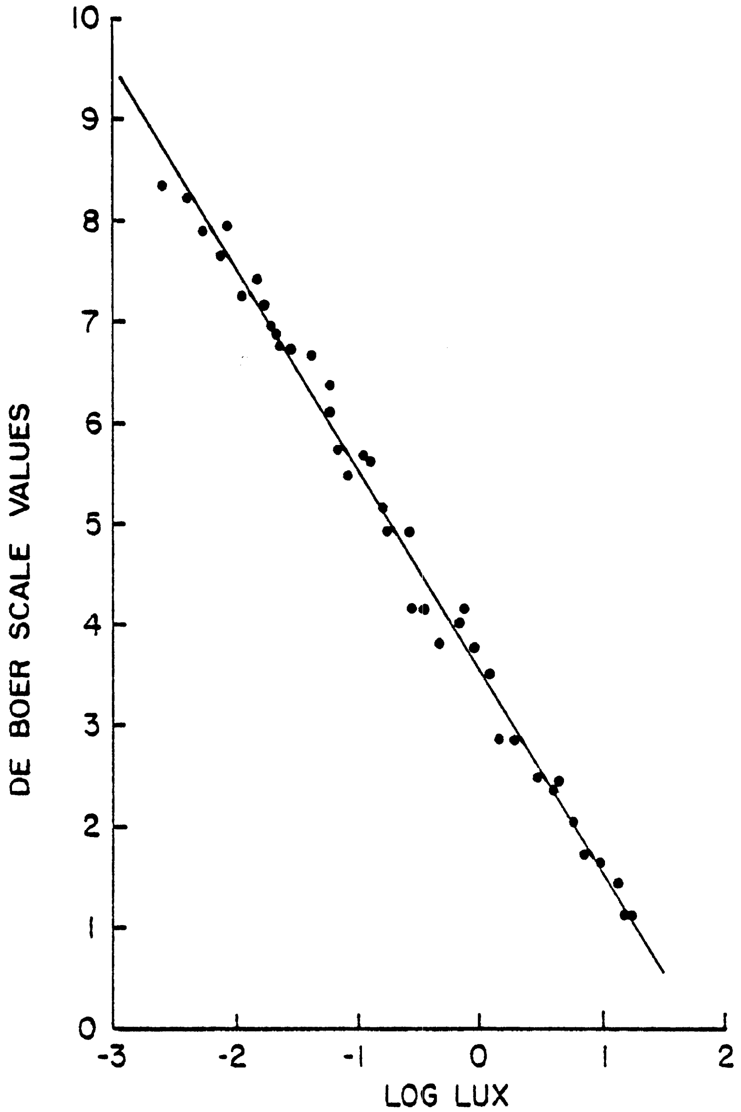


Figure 2.1. DeBoer ratings (W) as a function of glare illuminance. (From Schmidt-Clausen and Bindels, 1974.)

The Schmidt-Clausen and Bindels study was conducted using brief (two-second) exposures of fixed levels of glare. This is not the way glare is typically experienced in the real world, hence the applicability of the results may be questioned.

Bhise et al. (1977) evaluated the Schmidt-Clausen and Bindel's data in a dimming-request study. This study was run on public roads in such a way that the investigators could calculate glare at the eyes of oncoming drivers and measure the distance at which they flashed their headlamps to request dimming. They found that dimming requests began increasing rapidly when the glare experienced was such as to produce a rating of "4" or less.

However, there is a possible problem with dimming request as a criterion. It is not clear to what degree the response merely reflects a judgment on the part of the approaching driver that he/she is being glared more than necessary (i.e., that the test car is on high beam). Some indication that this may be the case can be found in instances in which four lamps on a test car received more dimming requests than two lamps, even though the glare was the same (e.g., Mortimer and Olson, 1974a).

Another approach is to take glare ratings in a full-scale meeting situation. Such data were collected by Mortimer and Olson (1974b). They report mean ratings of about 5.7 and 4.4 for U.S. low beams when the subjects were searching for targets to their right and left, respectively. Although this study lacked the precision of the others mentioned, it does provide some reason to believe the laboratory data of Schmidt-Clausen and Bindels may be conservative.

A somewhat different, but relevant, issue has been raised by Lulla and Bennett (1981). They noted that subjective ratings for a given stimulus level can be affected by the range of stimuli to which the subjects are exposed. In their work two groups of subjects made estimates of the borderline between comfort and discomfort (BCD). The lowest glare level for each group was the same, but the maximum for one group was ten times greater than for the other group. The group with the greater range set the BCD an average of seven times higher than the other group.

The "range effect" with which Lulla and Bennett were concerned indicates that judgments of discomfort in a study such as that of Schmidt-Clausen and Bindels are relative, not absolute, at least to some extent. Therefore, were a higher output lighting system introduced, the public might accept the higher glare levels with no special problems.

Based on the preceding discussion, it seems clear that the matter of discomfort glare is not yet settled. Therefore, given the importance of discomfort glare as a criterion in beam design, it was appropriate that it become a significant aspect of this research program.

As a first step, three studies were carried out to better define and understand certain questions related to discomfort associated with glare. These will be described shortly. Subsequently, other analyses were conducted to model glare exposure under real-world driving conditions. Those will be covered later in this chapter.

2.1.2 Laboratory Study of the Range Effect. The work of Lulla and Bennett (1981), cited earlier, indicated that judgments of the level of comfort-discomfort for a specific stimulus are made relative to the range of stimuli offered. However, there are differences in the methodology used by Lulla and Bennett and that used by Schmidt-Clausen and Bindels that raise questions whether the range effect would be an issue in the latter study. For example, BCD judgments are typically made using a procedure in which the subject adjusts the glare level him/herself, exploring the range available to find the BCD. On the other hand, much headlamp glare work is done using a technique in which subjects are exposed to a variety of glare levels and asked to assign a DeBoer scale value to each. Further, the DeBoer scale is identified by adjectives (e.g., Unbearable, Disturbing) at five of its nine points. Possibly, these adjectives would provide some "anchoring" and reduce or eliminate range effects.

This first study was run to determine whether judgments of discomfort glare made using a discomfort glare scale would be affected by the range of glare stimuli offered. It was designed to approximate the conditions of the Lulla and Bennett study in that the minimum glare levels remained the same and only the maximum end of the range was altered. It was also designed to conform as closely as possible to one of the Schmidt-Clausen and Bindels studies, in terms of general procedure and parameters, so that the results could be easily compared.

2.1.2.1 Independent Variables

2.1.2.1.1 Glare Illuminance. Twenty glare levels were used in the study. These are listed in Table 2.1. The subjects in the "full range" group experienced glare from 6.46 to 0.00039 lux. For the "partial range" group, the four maximum levels were not used. Thus, their range was from 1.14 to 0.00039 lux. Consequently, the difference in intensity of the maximum glare experienced by the full and partial range groups was about 5.7:1.

TABLE 2.1

GLARE LEVELS USED IN LABORATORY STUDY OF THE RANGE EFFECT

NUMBER	LUX	FT-C
1	6.46	0.60
2	5.10	0.47
3	3.23	0.30
4	1.61	0.15
5	1.14	0.106
6	0.63	0.059
7	0.40	0.037
8	0.194	0.018
9	0.165	0.0153
10	0.103	0.0096
11	0.0704	0.0065
12	0.0388	0.0036
13	0.0220	0.0020
14	0.0155	0.00144
15	0.0084	0.00078
16	0.0068	0.00063
17	0.0028	0.00026
18	0.00155	0.000144
19	0.00052	0.000048
20	0.00039	0.000036

2.1.2.1.2 Subject Age. Subjects of two age groups participated. The "younger" group consisted of 16 persons whose ages ranged from 19 to 41. The "older" group consisted of 24 persons whose ages ranged from 63 to 78. Half of each age group was assigned to each glare-range group. Thus, there were eight younger and twelve older subjects in each glare-range group.

2.1.2.2 Dependent Variable. The subjects provided a rating of each glare experience using the discomfort glare scale described earlier.

2.1.2.3 Equipment. Glare was provided by a 35-mm slide projector. Neutral density filters in the slide tray were used to adjust the glare illuminance levels.

The subject was seated at a desk, facing toward a wall which was illuminated at 0.034 cd/m^2. A small, red LED was provided as a fixation point. The lens of the glare projector was located to the left and slightly below the fixation point. At the ten-meter viewing distance, the angle from the glare source to the fixation point was 2°. The diameter of the glare source was 2.5 cm, resulting in an angular size of 0.145°.

The only significant source of illumination in the room was the lamp used to provide the adaptation luminance. A copy of the rating scale was provided on a small card located to the left of and slightly behind the subject. This was also illuminated, to a level just adequate to make it legible when the subject was fully adapted to the test conditions.

2.1.2.4 Procedure. Each subject was tested individually. After signing a consent form, the instructions were read to them (see Appendix) and any questions answered. At this point the room lights were extinguished and the dark adaptation period began.

When dark adaptation was completed, after about 10 minutes, data collection began. There were no practice trials. Each trial was preceded by a warning tone lasting one second. Two seconds after the initiation of the warning tone the shutter on the glare projector opened and stayed open for two seconds. When it closed the subject decided on a numerical rating and called it out to the experimenter, who wrote it down and adjusted the slide tray for the next trial. This cycle was generally repeated about every ten seconds, except for the most intense stimuli, where a 15-20 second recovery period was allowed.

Each scheduled glare level was presented ten times to each subject. The order of presentation was varied randomly.

2.1.2.5 Results

2.1.2.5.1 Glare Range. Figure 2.2 is a plot of the mean ratings assigned each glare value by the twenty subjects in each glare range group. The diagonal line marked S-C & B is the best fit line from the Schmidt-Clausen and Bindels plot shown in Figure 2.1.

The data demonstrate a trend that would be expected based on the range hypothesis. That is, the ratings were virtually identical at low glare levels and diverge at higher glare levels. The ratings for the six highest glare levels that both groups experienced differ on average by about one step on the discomfort glare scale. The differences are statistically significant ($p < 0.03$).

As in any study of this type, there were large between- and within-subject differences. Figure 2.3 is a probability distribution of judgments of "5" on the discomfort glare scale for both the full and partial range group.

The percentile values in Figure 2.3 are:

5%		0.01 lux
50%	(full range)	0.22 lux
	(partial range)	0.12 lux
95%	(full range)	2.0 lux
	(partial range)	1.0 lux

By comparison, the equivalent values from Schmidt-Clausen and Bindels (1974) are:

5%	0.013 lux
50%	0.14 lux
95%	1.78 lux

2.1.2.5.2 Age. Figure 2.4 is a plot of the mean ratings assigned each glare level by the subjects in each age group. Once again the diagonal line is the best fit

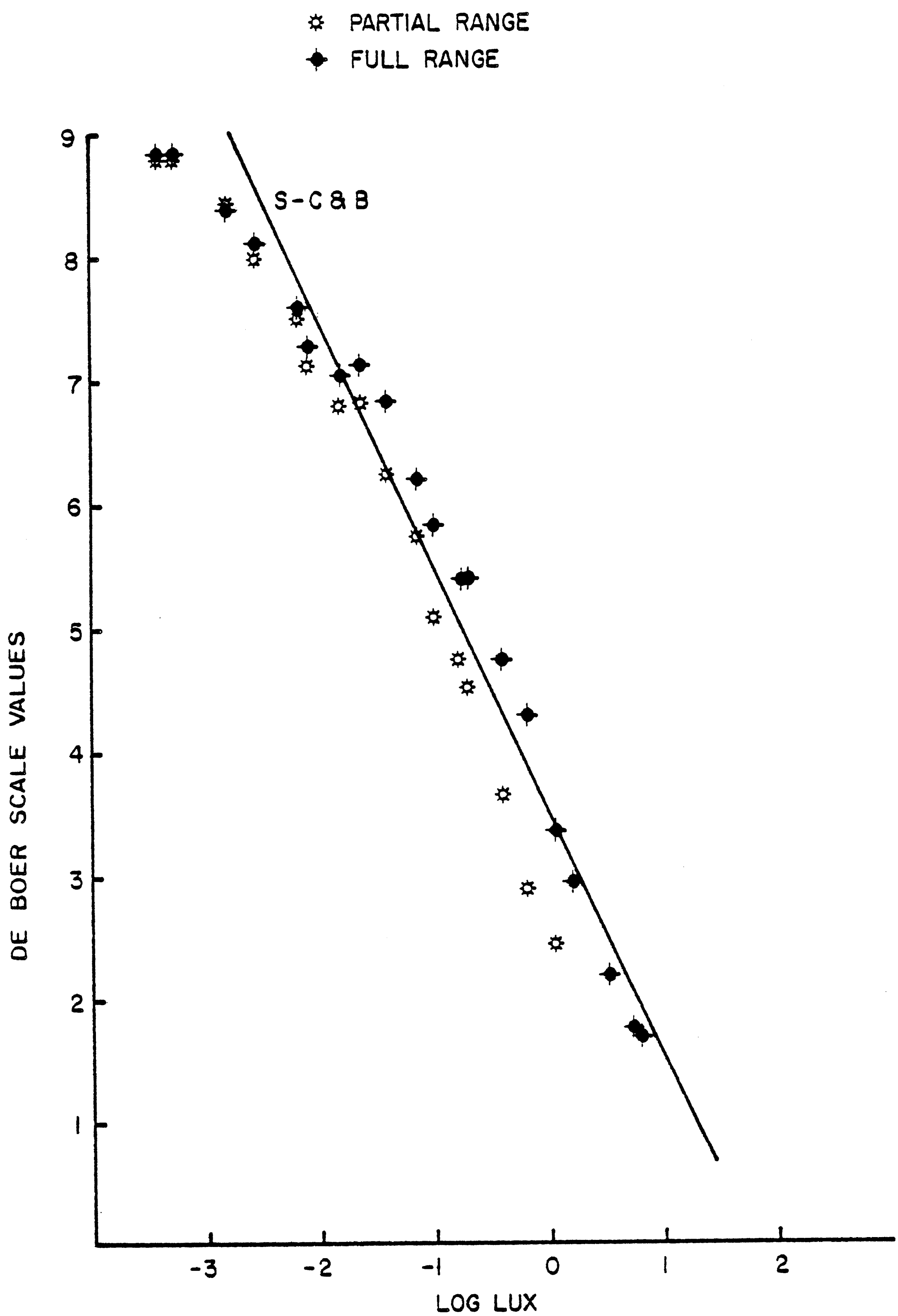


Figure 2.2. Mean DeBoer ratings assigned by subjects under two range conditions. Twenty subjects in each group, ten replications of each glare value.

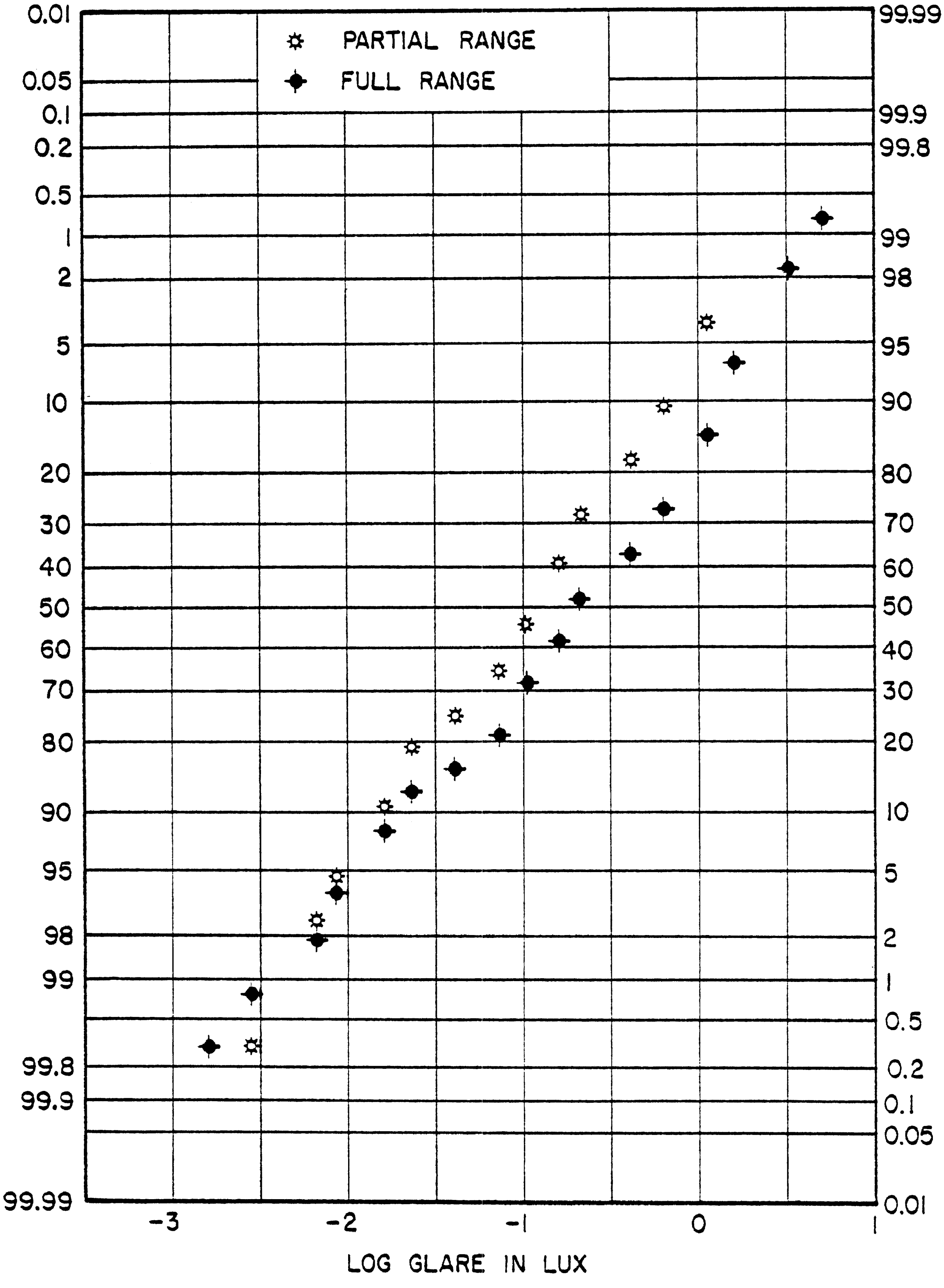


Figure 2.3. Probability distribution of glare ratings of "5" on a DeBoer scale. Twenty subjects in each range group. Ten replications of each glare value.

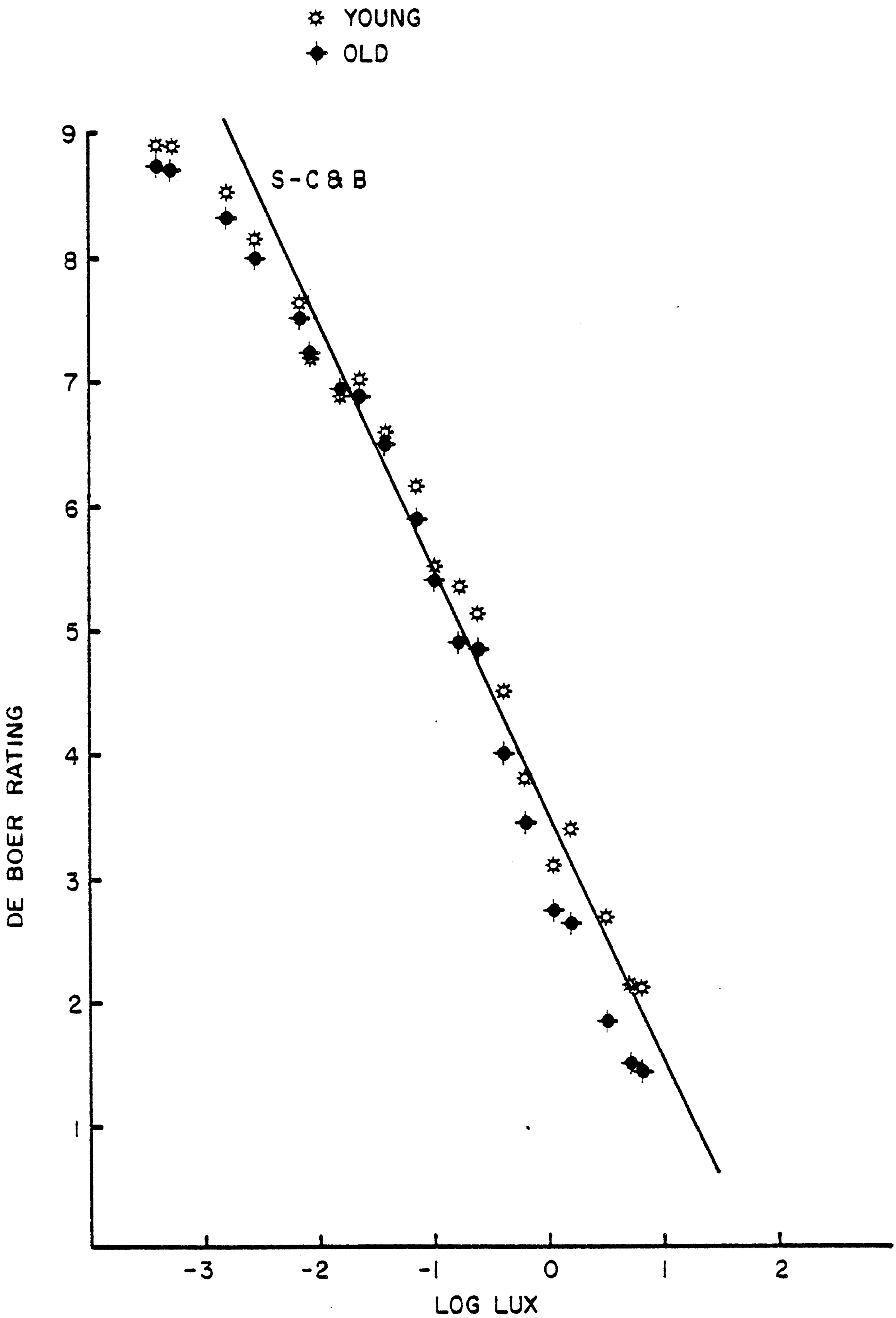


Figure 2.4. Mean DeBoer ratings assigned by subjects in two age groups. Sixteen young and 24 old subjects. Ten replications of each glare value.

line from the plot of Schmidt-Clausen and Bindels' data in Figure 2.1. The differences between the two groups are negligible at low glare levels and diverge at higher glare levels. The differences between groups are not significant at the ten lowest glare levels ($p > 0.05$), but are significant at the ten highest glare levels ($p < 0.03$).

2.1.2.6 Discussion. This study had two main purposes: First, to determine whether the range of stimuli provided in a discomfort glare study affects the subjects' judgments and, second, to investigate the effect of observer age.

The results of this study, together with the results reported by Lulla and Bennett (1981) indicate that judgments of glare discomfort are influenced, in part, by the range of glare stimuli provided by the experimenter. That being the case, inferences concerning "acceptable" glare levels based on studies like this one must be made with some caution.

If judgments of the level of comfort-discomfort are affected by the stimulus range in a laboratory situation, they may very well be affected by changes in real-world conditions too. As noted earlier, this means that the introduction of a more glaring lighting system may not lead to an appreciable increase in complaints, at least after a period of adaptation.

The effects of observer age tend in the expected direction. However, the differences are smaller than expected. Even at the highest glare level tested, the difference in glare required to produce the same rating averaged only about half a log unit. At levels that were likely to produce a "5" rating, the differences were much less. Thus, while glare is more discomforting to older drivers, these data suggest that no serious errors would result from studies that used younger drivers exclusively.

2.1.3 "Calibration" of the DeBoer Scale. The purpose of the study that will now be described was to acquire a better understanding of the meaning of discomfort glare ratings. In our opinion, none of the terms used to identify scale points have an adequately precise meaning. This is the result of trying to wring a great deal of information from a very difficult concept. It would be helpful in interpreting discomfort ratings if they were tied to concepts that were more readily defined.

The question becomes whether there are concepts in discomfort glare that have a clearer meaning. In our opinion, there are three levels of glare discomfort that are intuitively reasonable. These are:

A. Glare can be so weak as to produce no sensation of discomfort. Low-beam headlamps across a wide freeway median might be one example. Such experiences should be rated "9, just noticeable" down to perhaps as low as "7, satisfactory" on the DeBoer scale.

B. Next are glare experiences that produce noticeable discomfort, but at a level best described as tolerable. The critical DeBoer scale point "5, just acceptable" probably lies in this range.

C. Finally, glare can be so intense that it produces an avoidance response. This can take a variety of forms, e.g., squinting, looking away, or holding up one hand in an effort to block it out. Such experiences should be rated "1, unbearable" down to perhaps "3, disturbing" on the DeBoer scale.

In beam design it seems important to minimize the likelihood of exposing drivers to glare levels in category C because, discomfort and disability issues aside, the reactions described could lead to control problems. Thus, it was felt desirable to attempt to quantify this level.

A study was carried out to collect glare discomfort ratings on the three-point scale just described. The primary purpose was to add another scale to the basic discomfort ratings to aid in their interpretation.

2.1.3.1 Method. The same equipment and general procedure were used in this study as in the laboratory range study discussed above (Section 2.1.2). The full-range stimuli were employed. The subjects were drawn from the full-range group in the first study. Of that group of 20, 13 were able to participate in this study. Eleven of these were older, two were younger.

The only difference in this study and the range study was that the 3-point scale described above was employed. This required changing the subject instructions. The instructions are reproduced in the Appendix.

2.1.3.2 Results. The primary results of this study are shown in Figure 2.5. This figure shows the percent of time each glare condition was called either "A" or "C." Also shown across the top is the mean DeBoer rating provided by the same subjects during the range study.

The two distributions overlap only slightly, crossing over at an abscissa scale value of about -0.5 log lux and an ordinate value of about 10%. The DeBoer rating of particular interest (5) corresponds closely to the crossover point.

2.1.3.3 Discussion. Of special interest in this study was the relationship of glare to category "C" judgments and the relationship of DeBoer ratings to the 3-point ratings.

Category C judgments reach a level of about 10% at a glare level of about 0.3 lux under the condition of this study. This corresponds to a discomfort glare rating of about "5."

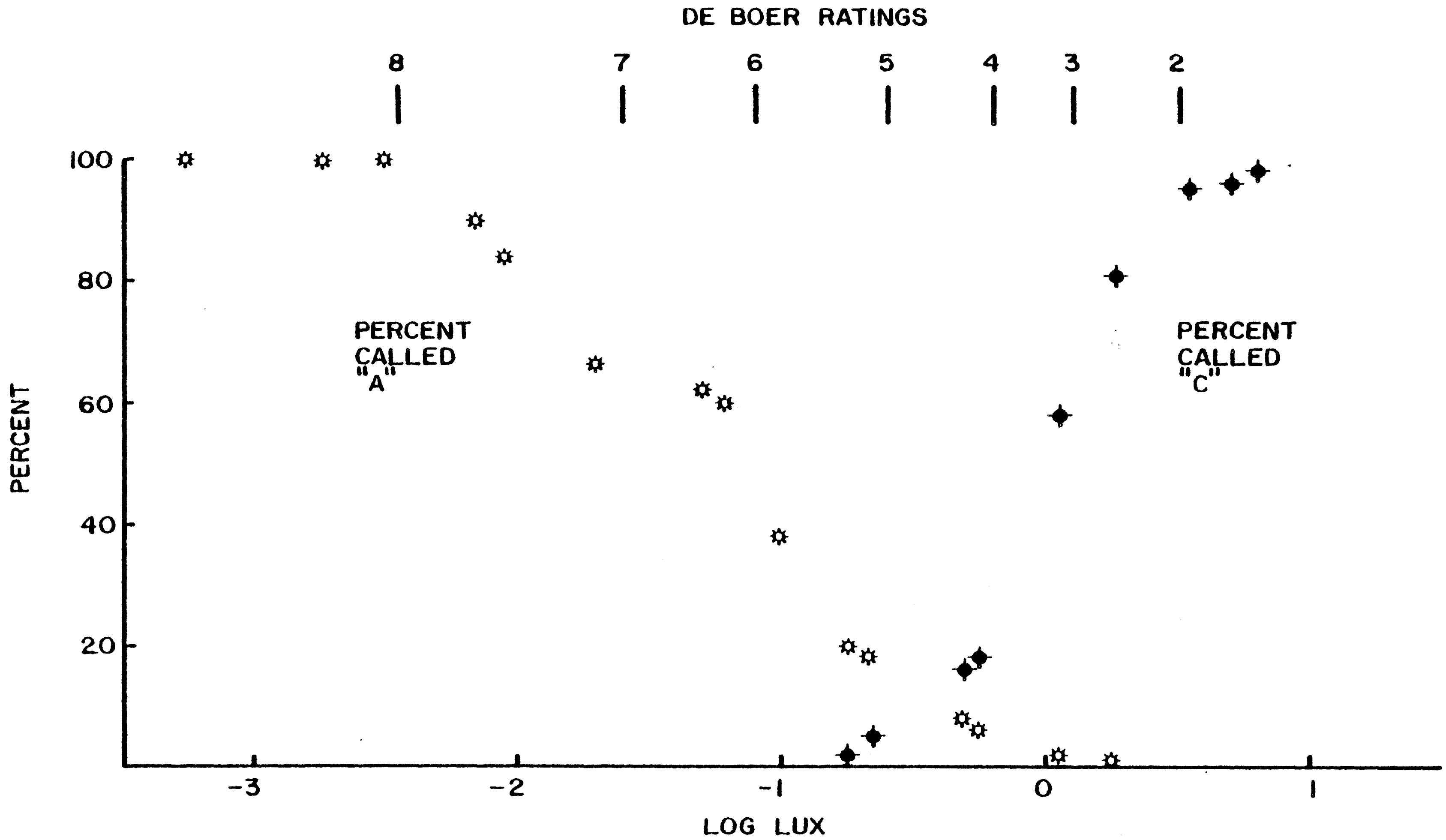


Figure 2.5. Percent of time various glare levels were rated "A" (no discomfort) or "C" (intolerable). Thirteen subjects, eleven older, two young. Ten replications for each glare level.

A rating of "4" (used as the cut-off in the Ford CHESS model [Bhise et al., 1977]) corresponds to about a 20% probability of a category C rating. Above that glare level the probability of a category C rating increases rapidly, making the choice of scale value "4" a very logical upper limit.

Scale ratings of "3" and "2" correspond to category C probabilities of about 0.60 and 0.95 respectively. Clearly, these are glare levels to be avoided.

2.1.4 Field Glare Study. It is evident from the results of the laboratory glare range study that the range effect described by Lulla and Bennett (1981) applies to data taken using the discomfort glare rating scale as well as the usual BCD approach. This has implications for the acceptability of new lighting systems. However, the introduction of a more glaring lighting system, such as that proposed in the project interim report (Olson and Sivak, 1981), would result in a glare distribution having the same upper limits as the present one, but a higher incidence of medium glare levels. It was thought desirable to simulate this effect on the range phenomenon.

In addition, there is a serious question about the applicability of laboratory studies of glare in setting limits for real-world exposure. Hence, it was also thought desirable to take glare data in a realistic simulation of a two-car meeting situation and determine whether and to what extent this changed the ratings.

Thus, this study had two main purposes:

1. To provide additional information on the range effect under more realistic conditions.
2. To obtain ratings of discomfort glare under conditions approximating normal vehicle meetings.

In addition, data were collected to provide some information on two other questions, i.e., the effect on glare ratings of:

1. Glare duration.
2. The point of onset of glare.

2.1.4.1 Independent Variables

2.1.4.2 Glare. Twelve glare levels were used. These were selected to span the same range as the full-range set in the laboratory study.

The glare settings were based on readings made at the driver's eye position using a Pritchard photometer, with the glare car centered in the adjacent lane, one hundred feet distant. The values are listed in Table 2.2.

TABLE 2.2

GLARE LEVELS USED IN FIELD DISCOMFORT GLARE STUDY

Level Number	Illumination at the Driver's Eye		Predicted Discomfort Rating
	FT-C	Lux	
1	1.0	10.76	1.27
2	0.7	7.53	1.58
3	0.3	3.23	2.31
4	0.1	1.08	3.27
5	0.07	0.75	3.58
6	0.03	0.323	4.31
7	0.01	0.108	5.27
8	0.007	0.075	5.58
9	0.003	0.0323	6.31
10	0.0016	0.0173	6.86
11	0.0007	0.0075	7.58
12	0.0003	0.0032	8.31

Discomfort calculations based on 100 foot longitudinal separation and assumed lateral separation from observer's eyes to center of glare vehicle of 8 feet (4.58°).

The glare was experienced by the subjects from a distance of 1000 feet until the car passed. In that period of time the subjects would be exposed to a continuously changing glare condition. Measures were made of glare at 100 foot intervals using the same photometric set up described above. Figure 2.6 depicts the results for glare level 2 in Table 2.2. In lux, the glare ranged from about 0.3 at 1000 feet to 7.5 at 100 feet. Other glare levels would follow curves of similar shapes at different levels on the ordinate.

Given the different conditions of the test compared to the laboratory study, calculations were made of expected discomfort ratings using the discomfort glare equation. These are listed in the right-hand column of Table 2.2. Calculations for differences in expected glare ratings as a function of seated positions were also made for various levels and distances and found to vary no more than about 0.15 scale units (for the observer on the right side of the front seat).

Glare was provided by two 142 x 200 mm tungsten sealed-beam headlamps mounted on each glare car. The lamps were deliberately aimed left one degree and used only on high beam. The major intensity changes were achieved by neutral density filters that were fitted into holders in front of each glare lamp as shown in Figure 2.7. Minor voltage adjustments were made to arrive at exact glare values.

Because the intensity of a high-beam pattern decreases as one moves away from the H-V point, some variation in glare intensity was expected from one subject position to another at a given instant, especially at near distances. Subjects were seated in the same position for both range conditions. A comparison of the mean ratings for each seated position ordered by angular separation from the glare source shows the following:

Driver	Rear Center	Front Center	Rear Right	Front Right
5.4	5.5	5.7	5.5	5.8

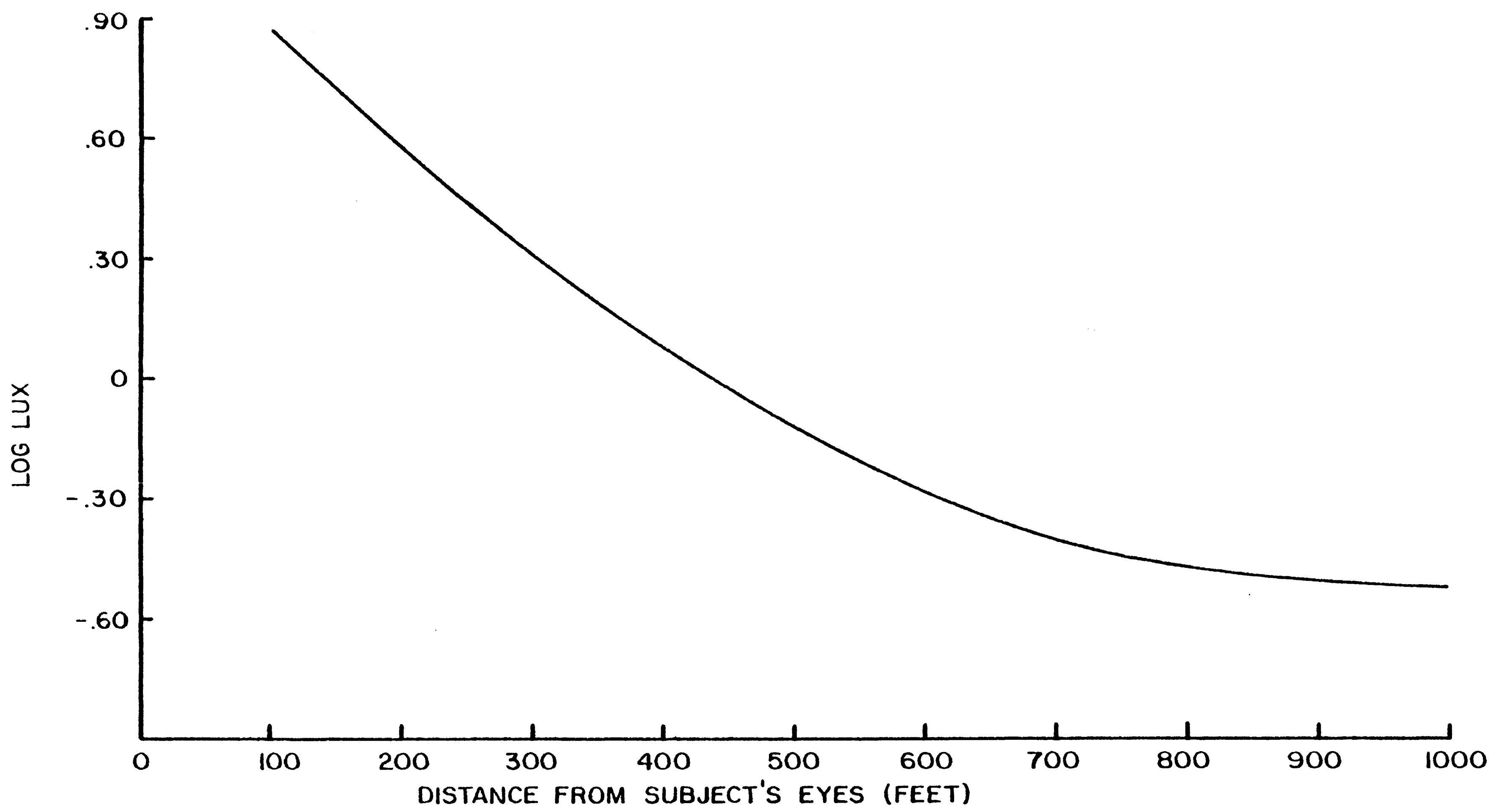


Figure 2.6. Glare experienced at driver's eye position (glare level 2) under test conditions.

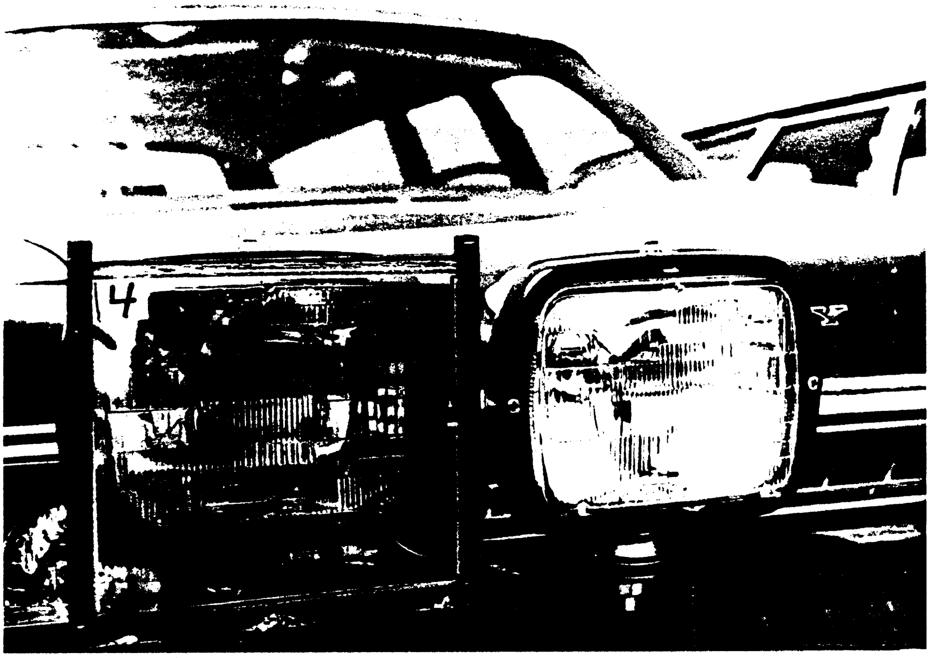


Figure 2.7. Photograph of lamps with neutral density filter in place.

These data show a pattern of differences (although they are not statistically significant) in the expected direction, i.e., the further from the glare source, the more comfortable it is judged. Part of any difference would be attributable to angular separation, as noted earlier, part due to beam distributional characteristics. In any event, the differences, if any, are apparently small.

2.1.4.1.2 Ranges. Two glare ranges were used. The full range was as described in Table 2.2. The partial range was achieved by dropping glare levels 11 and 12. To keep the total number of trials the same, additional runs were made with levels 1 through 10 in the partial range condition.

2.1.4.1.3 Duration. Most data were taken with the glare cars moving at 40 mph (58.7 ft/sec). Since the observers were stationary, the glare duration on any given trial was about 17 seconds. To provide some data on the effects of glare duration, three trials were run at 20 mph (29.3 ft/sec) for glare levels 3 and 9 for each group of subjects. This doubled the duration of exposure (i.e., to about 34 seconds).

2.1.4.1.4 Onset. Most data were taken with the glare being initiated 1,000 feet from the observers, exposing the subjects to glare levels following the curve shown in Figure 2.6. To provide some information on a different scenario, approximating meeting a car on a curve or cresting a hill, additional data were collected with the glare being initiated 400 feet from the observers. This was done with glare levels 5 and 11 for the full-range subjects, and with levels 5 and 8 for the partial-range subjects (three trials each).

2.1.4.2 Dependent Variable. Ratings were made of glare using the discomfort glare scale described earlier. The scale was printed across the top of the rating sheet provided each subject.

2.1.4.3 Vehicles. Three cars were used in the test. The subjects were seated in one (subject vehicle), parked near one end of the test road. This car has a clear windshield that is in very good optical condition. The other two cars (glare vehicles) were equipped with the glare lamps and filter holders mentioned earlier, and a precision voltage control system (accuracy = $\pm$ 0.05 volt) that could be quickly adjusted as necessary to achieve, in combination with a given filter, a desired glare level.

2.1.4.4 Test Road. The test was carried out on a private road. The road has two nine-foot lanes, is paved with asphalt that is in very good condition, is flat and straight, and about 2,500 feet long. There is no artificial lighting on or near the facility. It is a good approximation of a dark, rural road.

2.1.4.5 Procedure. The subjects were run a maximum of five at a time. Three were seated in front and two in the rear of the subject vehicle. This car was parked centered in the east-bound lane facing toward the glare cars, which used the west-bound lane. Its low-beam lamps were on at all times during the test; the dashboard lamps were off.

The glare cars began each run at the east end of the road. Necessary filters were inserted and voltage adjustments made. The car was then accelerated to the test speed (40 mph or 20 mph).

Each test began with the glare cars on "standard" low beam, although the units were aimed down two to three degrees. This provided adequate illumination so the driver could keep the car safely on the road while accelerating to test speed, turning around, and returning to the starting position.

The start point for each glare test was marked by a reflectorized traffic cone on the road center line. As the glare vehicle approached this marker its operator switched off the "standard" beams and, one to two seconds later, switched on the test configuration. These remained on until the glare vehicle had passed the subject vehicle. The driver then returned to the "standard" low beams, made a U turn, and began driving back toward the start point. After passing the subject vehicle, the driver of the glare vehicle flashed its lamps as a signal to the driver of the other glare vehicle that he/she could start the next run. At this rate each trial took an average of 1.2 minutes and the entire test, including a short break at the halfway point, took about two hours.

The subjects were brought to the test facility 15-30 minutes prior to starting. The instructions were read to them (see Appendix). Briefly, the rating scale was explained, they were told to observe the glare from onset until the glare vehicle passed, they were to look straight up the lane in front of them and <u>not</u> at the glare source, and they were not to communicate among themselves concerning the test.

The test sequence consisted of 84 trials. For the full-range set, this was made up of six replications each of the twelve glare levels, and three replications each of the four special (two durations and two onsets) conditions. For the partial-range set, the twelve trials normally required for glare levels 11 and 12 were distributed among the ten remaining glare levels. The order of presentation was randomized. The subjects were given no information about the range of stimuli.

The subjects were run under both range conditions, with a separation of about two weeks. Half of them experienced the full-range first and the partial-range second, the rest experienced the ranges in the reverse order.

2.1.4.6 <u>Results</u>. The primary results are shown in Figure 2.8. This shows the mean ratings assigned each glare condition by the subjects under full and partial range conditions. The differences between the means of all ratings for the two ranges (levels 1 through 10) was significant at the 0.05 level.

The diagonal line in Figure 2.8 identifies the ratings expected based on use of the discomfort glare equation under the calibration conditions described earlier (Section 2.13). Throughout much of the range tested the mean ratings were one to two scale intervals more comfortable than predicted. However, at high glare levels, the mean ratings closely approximate those predicted by laboratory data.

Figure 2.9 is a probability distribution of ratings of level 5 on the discomfort glare scale for both ranges. This should be compared with Figure 2.3 of the laboratory study report.

Three differences will be noted between the distribution of ratings of level 5 for the two studies:

First, the partial range data appear above the full range data in the laboratory study, below in this study. This is a consequence of the range effect and the fact that the partial range was truncated at the high end in the laboratory study and at the low end in the field study.

Second, the judgments appear to span a narrower range of glare values in the field study, two to three log units, compared to three to three-and-a-half in the laboratory study.

Third, the distributions for the field study are shifted toward higher glare values. For example, the 50th percentile intercept occurs at about -0.8 log lux in the laboratory data, and about -0.15 log lux in the field data. About 0.2 log units can be attributed to the difference in viewing angle, still leaving a difference of about half a log unit.

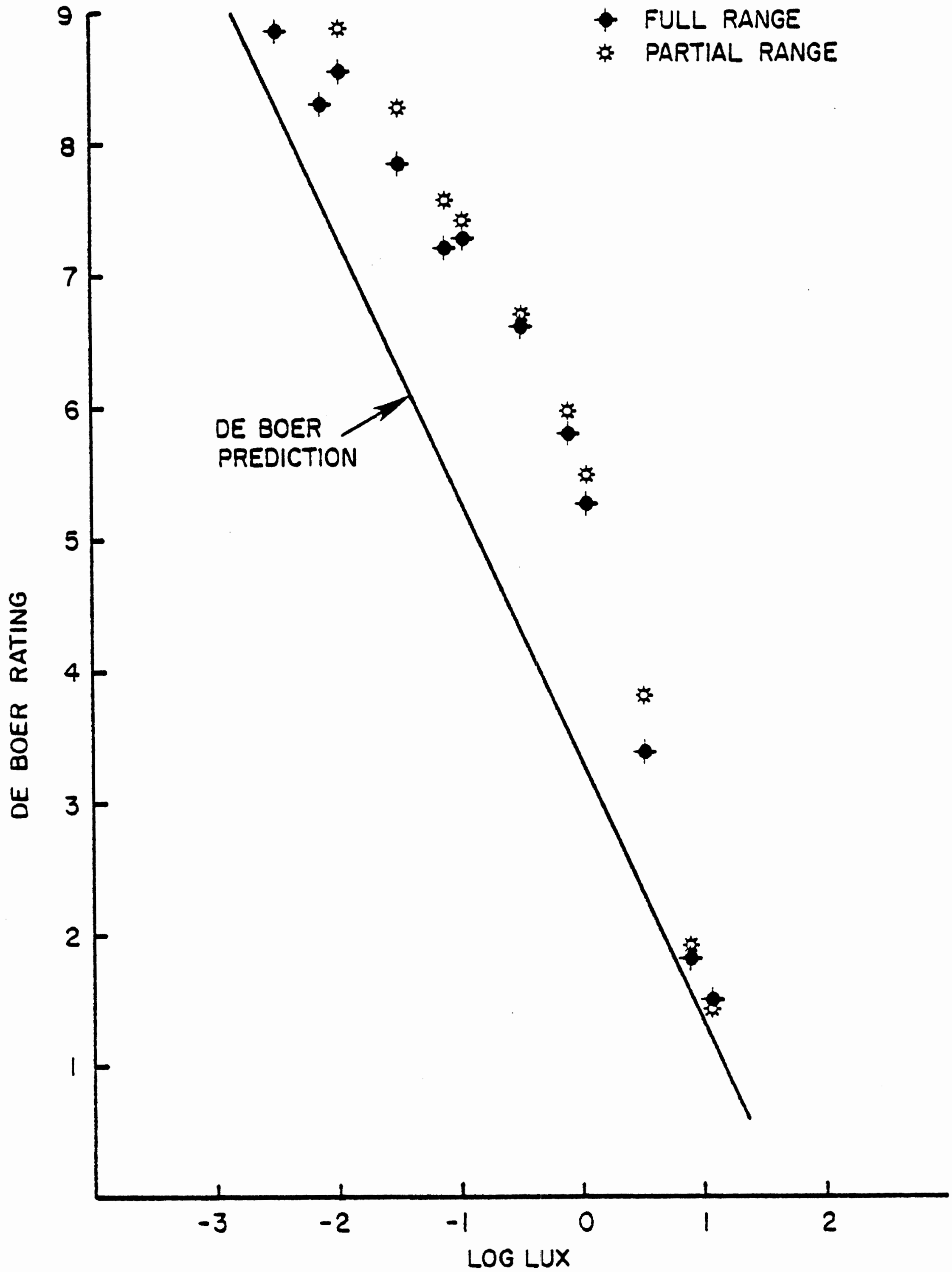


Figure 2.8. Mean ratings assigned each glare condition compared with prediction based on use of DeBoer equation.

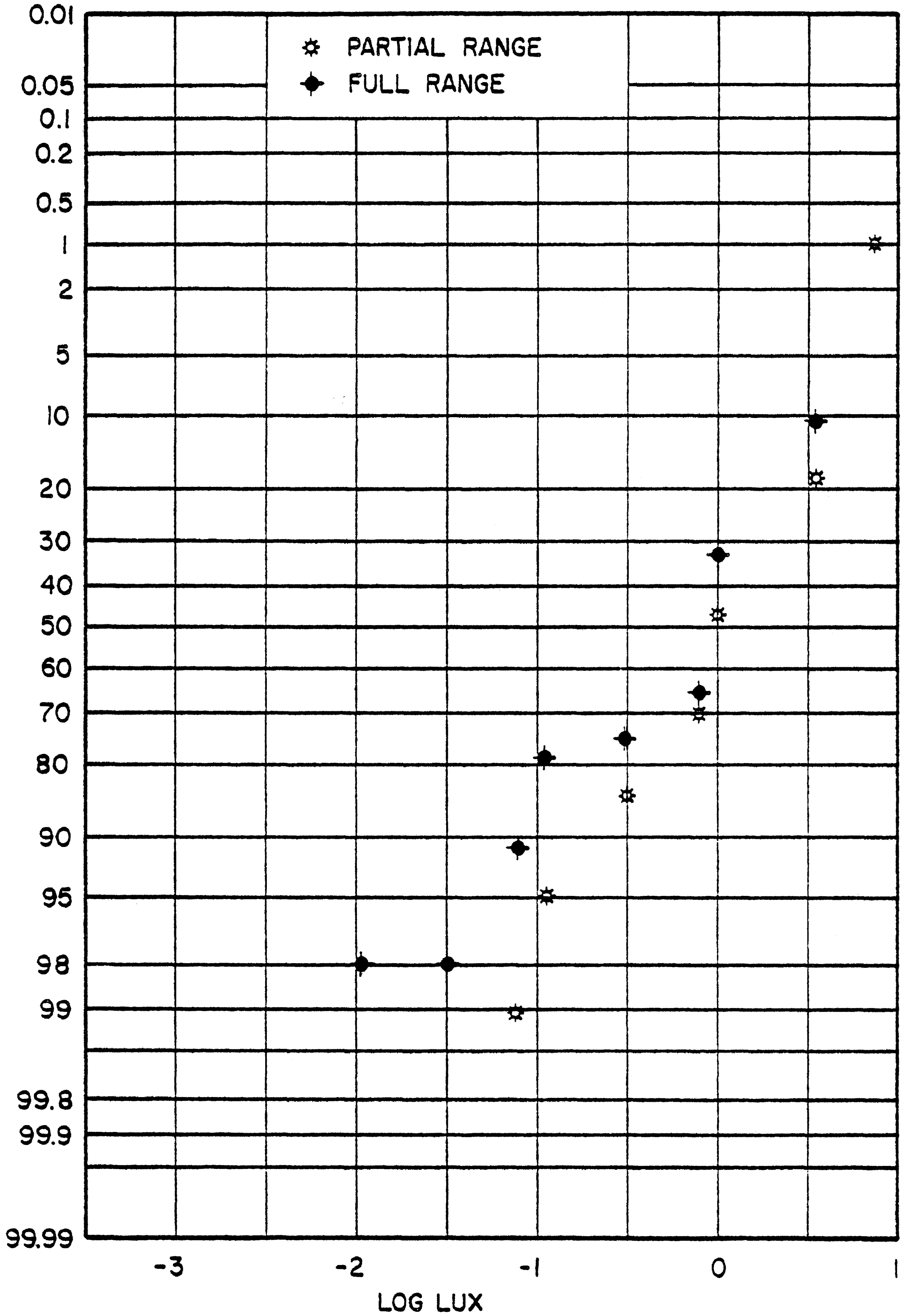


Figure 2.9. Probability distribution of judgments of level "5" on DeBoer scale.

The mean ratings that resulted from the slow-run, long-exposure test were as follows:

Glare Level	Full Range		Partial Range	
	20 mph	40 mph	20 mph	40 mph
3	3.54	3.39	4.16	3.80
9	7.82	7.86	8.36	8.25

None of the comparisons yielded significant differences ($p > 0.05$).

The mean ratings that resulted from the short exposure tests were as follows:

Glare Level	Full Range		Partial Range	
	400 ft	1000 ft	400 ft	1000 ft
5	5.41	5.80	5.73	5.95
8			7.65	7.47
11	8.34	8.29		

None of the comparisons yielded significant differences ($p > 0.05$).

2.1.4.7 Discussion. This study had two primary purposes. First, to further investigate the range effect in a context simulating what would happen were more glaring headlamps introduced in the future. Second, to measure discomfort glare in a realistic setting to determine what, if any, differences there are compared to a laboratory setting.

Studies of the range effect make it clear that discomfort judgments are not absolute, and that the experimenter can significantly affect the results of such studies by changing the end points on the stimulus range presented to the subjects. The changes to the range were relatively small in these studies. How far the effect can be pushed is unknown.

The results of this investigation do suggest that modifications to the headlighting standards which resulted in greater glare levels would cause a shift in the acceptability criteria and a lower incidence of complaints than would have been anticipated in the absence of a range effect. How great the criterion shift would be is uncertain. It is not likely it would be great enough to completely compensate for the glare change.

There is a substantial difference between glare ratings derived from laboratory and field methodology. It appears that a glare exposure that produces a given rating in a laboratory setting generally produces a more comfortable rating in a field setting. Further, the two methods do not result in the same relationship between glare level and rating. Very high glare levels tend to be rated about the same by either method. It is in the low- and mid-range that the major differences occur. This non-linearity in the field data suggests a discomfort glare criterion cut-off, i.e., that lamp design should be based on avoiding to the greatest extent possible exposures that would produce a rating of 4 or less, using a revised discomfort glare equation. The reason being that beyond the 4 level relatively small increases in glare intensity result in great increases in rated discomfort.

Based on these data it appears that it would be appropriate to alter the exponent for θ in the discomfort glare equation from 0.46 to 0.8. This modification yields a line having the same slope as that produced by the original equation, but displaced to conform to the data in Figure 6, at least to a scale value of 4.

It is possible that the differences between the laboratory and field studies may be attributable to adaptation level (L_a in the discomfort glare equation). This was accomplished by illuminating the wall behind the glare source to a level of 0.01 ft-L in the laboratory study and by use of low beams on the subject vehicle in the field study. Indeed, if the predicted values are recomputed for the field study using $L_a = 0.1$, this greatly improves the fit from scale value "5" up.

Two comments should be made concerning the level of adaptation argument. First, there may well have been differences in adaptation level in the two studies. However, the field study was clearly more realistic, in that adaptation was determined by actual low-beam headlamps. Second, regardless of the adaptation level question, there are still effects in the field situation that produce a more rapid increases in rated discomfort beyond scale value "4" than the equation predicts.

The implications of this study for headlamp design are significant. First, it appears that persons are more tolerant of glare than would be expected, based on laboratory data. To the extent that laboratory data are the basis of lamp design, they are too conservative. Second, it is apparent that critical values such as "not acceptable" on the discomfort scale are not independent of the test situation. Studies of this type in the future should be structured to present the actual range and distribution of glare in the situation of interest as accurately as possible. Greater confidence can then be attached to the results.

2.1.5 Systems Evaluation of Glare. Research on glare has to be concerned with reducing glare or at least reducing the exposure to glare of unacceptable levels under real-world driving conditions.

Almost all work on glare has focused on the headlamps, and sought to modify their pattern and output. However, illumination entering the eye of a driver in the real-world is determined by a number of factors, including the lamps, but also including the vehicle and the path of travel. Certain factors not related to lamp photometrics (e.g., aim) are known to be substantial problems (Olson and Mortimer, 1974c). There is a possibility that practical lamp modifications may have only a small impact on the systems problem.

A systems approach to studying glare would involve measuring actual glare exposure under representative driving conditions, identifying and measuring the various sources of variance. Rational decisions could then be made about promising approaches to glare reduction, and the impact of proposed changes assessed.

Data such as those described are not easily collected. They do not exist at the moment, except for certain limited situations. However, it is instructive to look at the data that are available because they offer some indication of the scope of the problem.

The most comprehensive data are those of Yerrell (1971). Yerrell measured the illuminating and glaring intensities of several thousand vehicles at a number of sites in Great Britain and on the Continent in Belgium, The Netherlands, Germany and France. The data were recorded from passing vehicles surreptitiously in such a way that total candlepower directed toward the point in question could be calculated. The representation was that of a flat, straight, two-lane road. Yerrell's data for the sites in

Great Britain are reproduced in Figure 2.10. Figure 2.11 shows the same data in the form of a frequency distribution.

The dashed vertical lines in Figures 2.10 and 2.11 represent "design glare." That is, this is the glare that would result from a meeting with a pair of lamps providing maximum allowable glare according to specifications current in Great Britain at that time. The distribution is skewed so that more than 80% of the glare levels recorded were at or below the design level. The most likely reasons for this are:

a. Few lamps have glare levels at the maximum.

b. Many lamps are dirty, reducing total output and glare.

Misaim would add to the scatter of the data, but it is not clear whether it is biased in any particular direction.

If the data had been taken differently, for example, if glare had been measured at the driver's eye under a variety of driving conditions, the results should be more skewed than shown in Figure 2.10. This is because many meets involve greater lateral separation than studied in Yerrell's data. Misaim associated with meeting geometry (hills and curves) should add to the scatter, but only randomly.

A further refinement would be to calculate the level of discomfort from each meeting, using the discomfort glare equation. Doing this should further skew the data, because many meets occur in lighted urban areas, causing discomfort glare to be reduced.

Based on the revised discomfort glare equation described in Section 2.1, it is possible to estimate the mean discomfort ratings associated with different levels in Yerrell's data. However, first it should be pointed out that Yerrell measured glare at a point 3.5° right and 0.5° up. This corresponds to a longitudinal separation of about 125 feet in the field glare study.

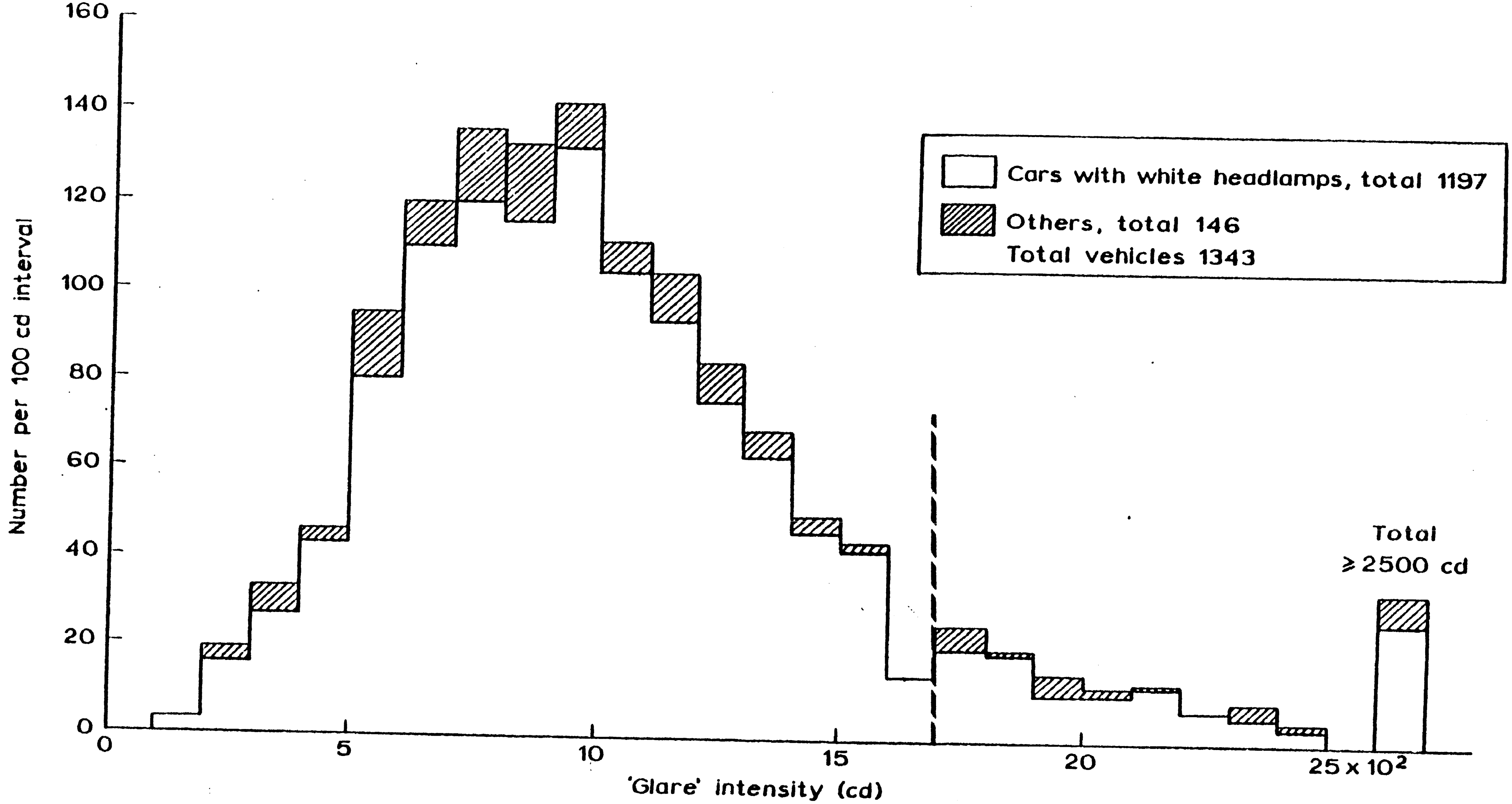


Figure 2.10. Distribution of glare intensities at sites in Great Britain. (From Yerrell, 1971.)

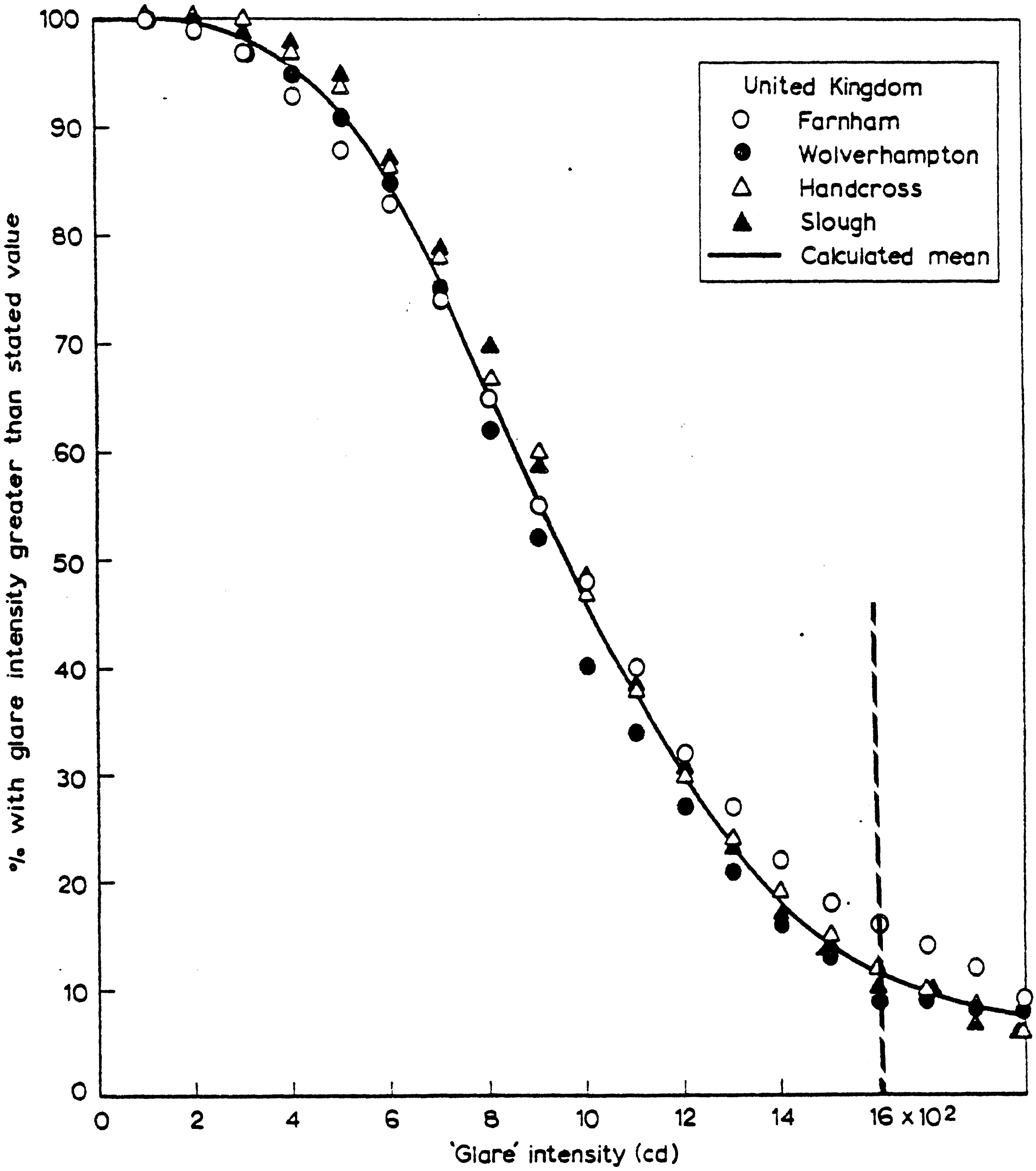


Figure 2.11. Frequency distribution of glare intensities at sites in Great Britain. (From Yerrell, 1971.)

Under the conditions described, a glare intensity of 1200 candelas would produce a mean rating of "5." A glare exposure of this magnitude or more occurred about 30% of the time in the British data. If it is agreed, based on the 3-point discomfort glare study described in Section 2.1, that glare exposures yielding a rating of "4" or less should be avoided, this occurred at a level of about 3500 candelas. Yerrell consolidates all data of 2500 candelas or more (corresponding to a rating of about "4.3" or less). Such exposures occurred less than 3% of the time.

Given these baseline data for lamps that are similar to those used in this country, it would be instructive to consider what would happen to the glare distributions as a function of certain changes that might be made. For example, suppose a switch were made to European lighting systems. Yerrell's European data provide some indication of the likely results of such a move (Figures 2.12 and 2.13). Figure 2.14 combines Figures 2.11 and 2.13, to facilitate a comparison.

It is clear, from an examination of Figure 2.14, that there is a substantial difference in glare exposure with the two lighting systems. Apparently, the European, shielded-filament design significantly reduces the glare exposure of motor vehicle operators. However, the major differences occur at relatively low glare levels. For example, a glaring intensity of 800 candelas or more occurred about 67% of the time in the British situation, but only about 25% of the time on the Continent. A glare level of 800 candelas would produce a discomfort rating of about "5.3," based on the field test data.

An exposure of 1200 candelas or more (rating of "5" or less) occurred about 12% of the time in the Continental data and about 30% of the time in the British data, still a notable difference. But, exposures of 2500 candelas or more

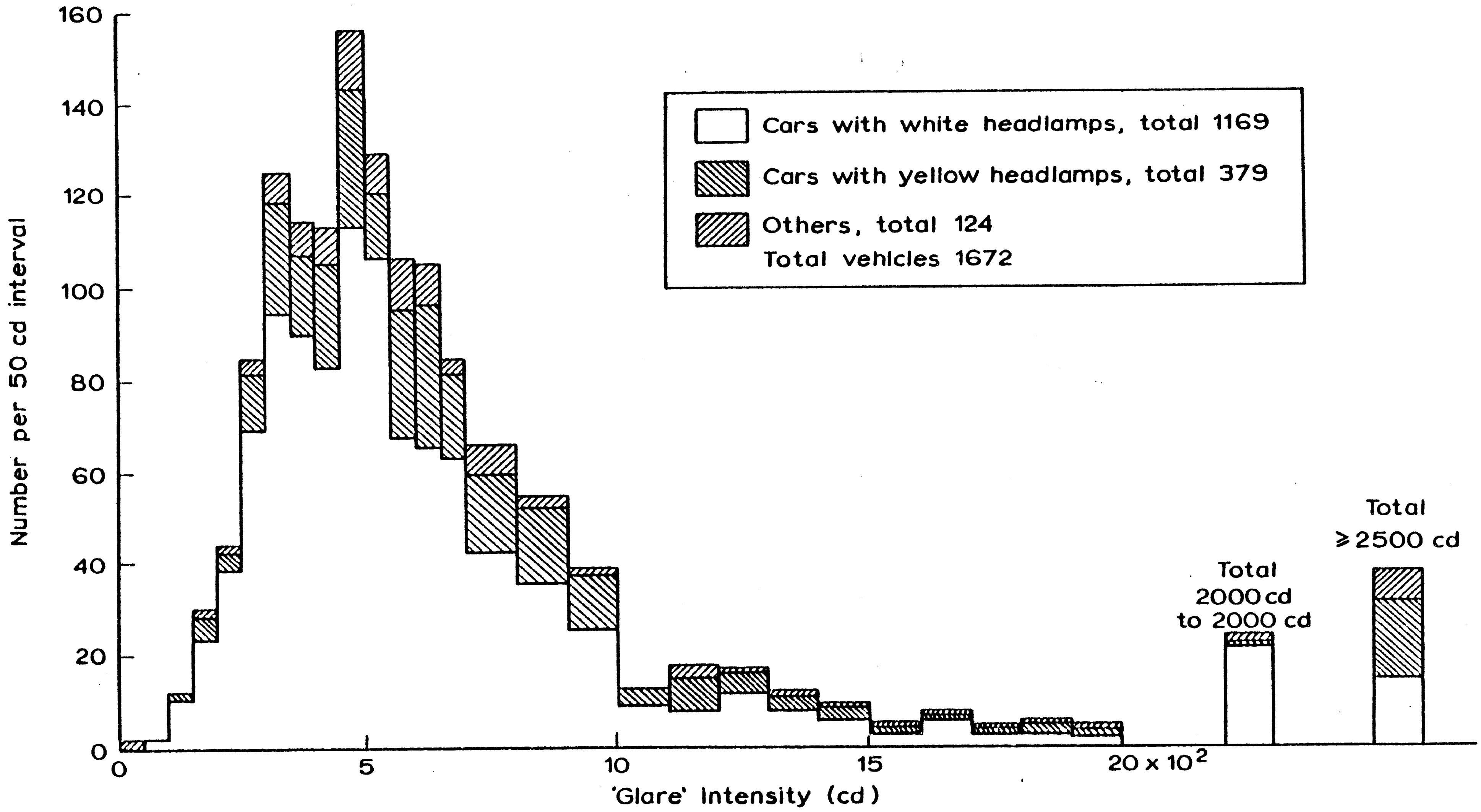


Figure 2.12. Distribution of glare intensities at sites on the Continent in Europe. (From Yerrell, 1971.)

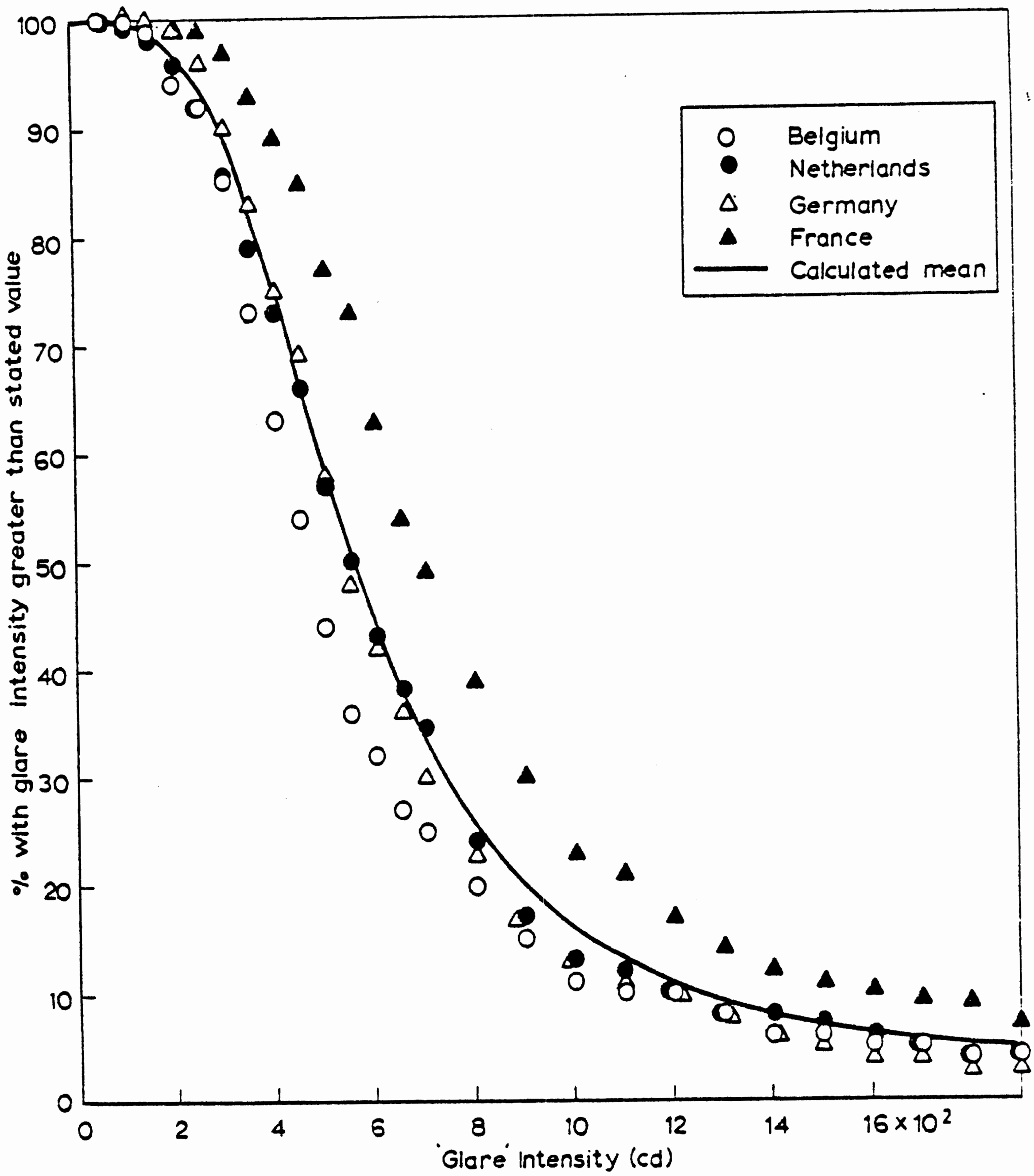


Figure 2.13. Frequency distribution of glare intensities at sites on the Continent in Europe. (From Yerrell, 1971.)

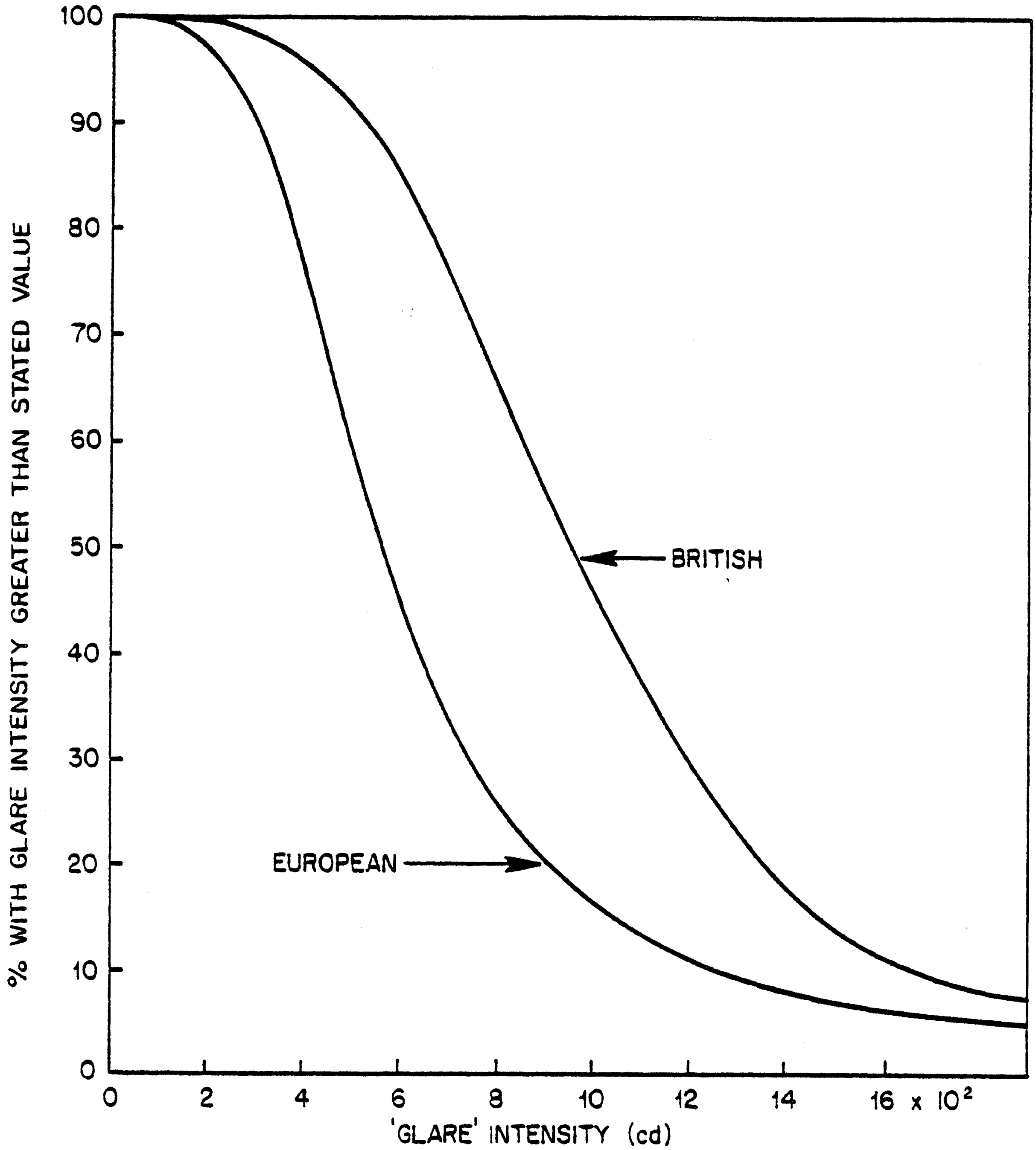


Figure 2.14. Combined distributions from Figures 2.11 and 2.13.

(rating of "4.3" or less) were about equally likely for both systems.

Assuming these to be accurate and representative data, what inferences might be drawn concerning the glare protection offered by the European as compared to a sealed beam lighting system? Clearly, there is no advantage to the European system in protection from relatively high glare levels (i.e., those likely to be rated "4.3" or less). It could be argued that the reduced exposure to mid-glare levels is still important from a point of view of general driver comfort and fatigue. If this could be achieved with no loss of performance in terms of the revealing power of the lamp, the argument has considerable merit. Unfortunately, Yerrell's data indicate this is not the case. Figure 2.15 summarizes the illuminating intensities measured from the same lamps at the same sites as the glare intensities. There is a considerable difference in favor of the British lamps at all points along the abscissa. Thus, using these data, it seems the advantage goes to the British system, since on average it provides no more exposure to severe glare than does the European system, but has higher illuminating intensities.

The preceding discussion is offered as an example of the types of analyses that might be carried out if more adequate data were available. It seems clear that efforts to conduct the kind of systems research described earlier would be very much worthwhile.

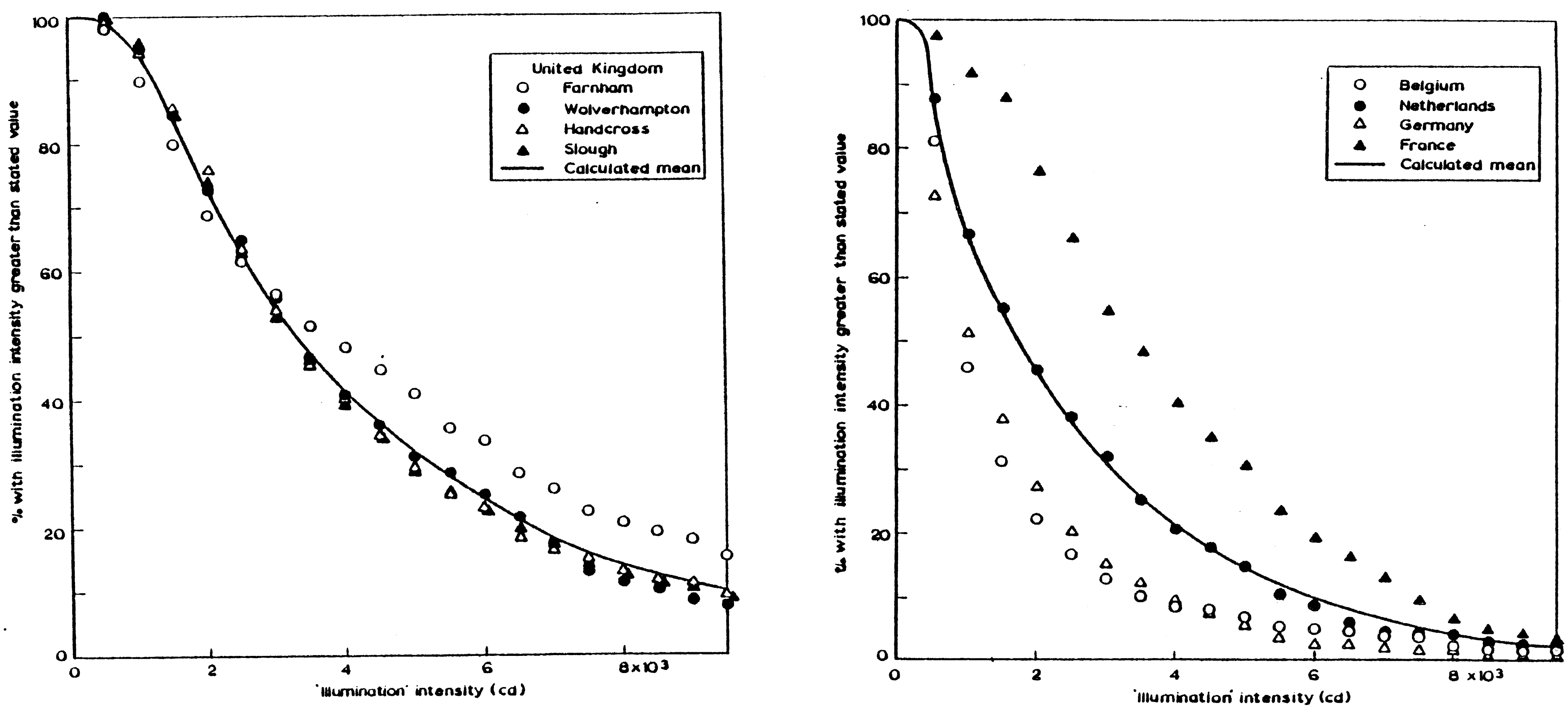


Figure 2.15. Comparison of illuminating intensities from British and Continental sites. (From Yerrell, 1971.)

2.2 Foreground Illumination

2.2.1 Introduction. The term "foreground illumination" in this report will be used to refer to illumination directed downward into an area out to about 100 feet (30 meters) in front of the car.

Not much concern has been expressed about this foreground area until fairly recently. It has always been illuminated, but largely as a by-product of trying to illuminate areas felt to be critical further down the road. However, gradually lighting researchers began to feel that illumination projected into the area near the car was important. It was important not so much for what it allowed the driver to see directly, but for its effect on vision to other areas of the forward field. As cars have grown smaller, with shorter and lower hoods, more and more of the foreground has come into the driver's view, and its importance has increased.

Briefly, there are three areas of concern with foreground illumination. These suggest that high levels will:

1. Cause the driver to look into the foreground area rather than more important areas further up the road.
2. Alter the driver's level of dark adaptation, reducing the ability to detect and identify targets in the far field.
3. Increase disability and discomfort glare on wet pavements.

There is very little reported research on any of these problem areas. Huculak (1978) conducted some studies of unopposed obstacle detection in which foreground illumination was a variable. He reports the effects are "generally insignificant," and may be of consequence only for older drivers with pronounced glare sensitivity.

Graf and Krebs (1976) varied foreground illumination and measured driver eye fixations. Unfortunately their description of the lighting systems employed is not adequate to make it clear to what extent the foreground was changed. However, their data provide some indication that the mean fixation point was further from the car with higher foreground levels.

Wilkenson (1973) took glare measurements and photographs of various beams in a wet-road meeting situation and found that the European H-4 system produced much higher glare levels than the others, including a U.S. sealed beam. He felt the situation was very bad, and the beam pattern should be modified to reduce foreground illumination.

The shortage of specific research evidence concerning foreground effects is unfortunate. Hence, such research became a part of the present project.

The first study, which will be described shortly, was designed to examine the question of the foreground attracting eye fixations. The second study, reported in detail in the chapter describing the field identification distance work, considered the effect of foreground illumination on detection-identification distance.

2.2.2 Eye-Fixation Study

2.2.2.1 Independent Variable. Foreground illumination, two levels. The lower level was supplied by two 142 x 200 mm tungsten low-beam units (meeting FMVSS 108 specifications) at standard aim. To achieve the higher foreground level, the beam just described was supplemented by a pair of Koito 997-16121 units on low beam. The Koito lamps are designed for motorcycle use. They use an H-4 halogen bulb (60/55 watts) and provide a symmetrical, sharp-cutoff pattern that is nearly flat. These lamps were aimed down so the cutoff was visible on the road surface 50-75 feet (15-23 meters) in front of the car in normal load configuration for this test.

The use of these lamps in the manner described allowed the foreground illumination to be greatly increased with very little increase in illumination directed near the H-V intercept.

2.2.2.2 Dependent Variable. The area in front of the car was divided into a 9-cell matrix, as shown in Figure 2.16. Measures were made of the number of times the eye fixation point moved into a given cell, and the length of time it stayed there. By dividing the totals for the former into the totals for the latter, mean dwell times could be calculated.

2.2.2.3 Equipment. Data were taken with a NAC Eye Mark Recorder Model 4. This unit has been modified to power operate the X-Y controls from a remote location. This makes it much easier to calibrate in the confines of an automobile, and also allows recalibration easily and accurately while the car is in motion. The output of the camera was recorded on videotape for later analysis.

The subjects were told the purpose of the equipment was to monitor pupil size. Based on questions and comments

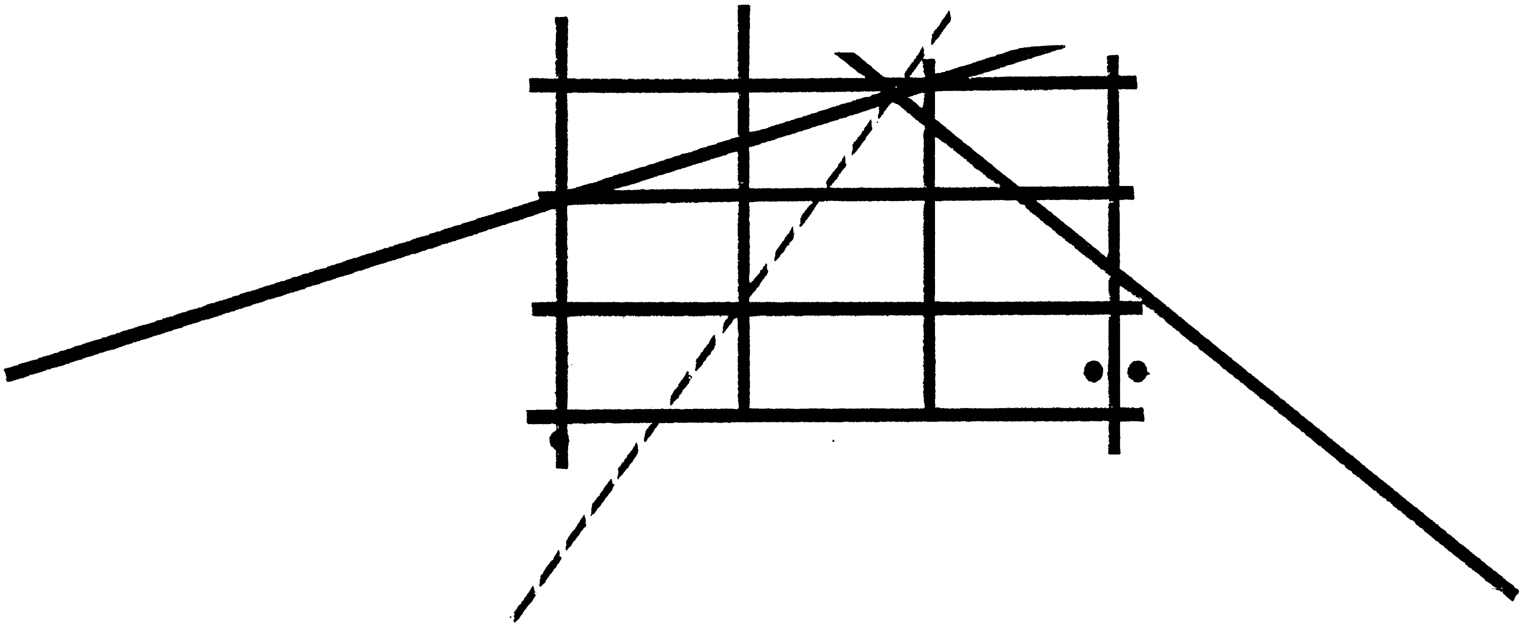


Figure 2.16. Matrix used in eye-fixation data reduction. Perspective is from driver's position. Single and double dots indicate the left edge and center of the hood respectively.

received, the subterfuge worked well, and suspicions were not aroused by the calibration procedure.

A full-size 1980 model station wagon was used. This vehicle has been modified for headlighting research by adding a light-mounting bar in front and a precision voltage control system. Small, red reference lights were fastened across the front of the hood so they would be in the camera's field of view. There were two lamps in the center and one at the right and left edge of the hood. These formed a reference for the data analysis and are indicated by the dots at the bottom of the matrix in Figure 2.16.

2.2.2.4 Test Route. The test route was a rural two-lane road. The section used was about four miles (6.5 km) long. The south half has hills and curves, the north half is relatively flat and straight. Traffic volume was low; the subjects averaged about six meetings with other cars in each direction. It was no problem to keep the test car isolated from other vehicles going in the same direction.

2.2.2.5 Procedure. All subjects reported to the Institute on at least one occasion prior to the data session for a pre-fitting with the camera. This was found useful as a means of familiarizing people with the equipment and eliminating persons on whom an eye spot could not be found or calibrated, or who seemed troubled by the equipment on their head. A total of six subjects were used.

The car was driven by one of the experimenters to a small parking lot at the start of the test route. Here the subject took the driver's position and adjusted the seat and mirrors as required. The camera was fitted and calibrated using lights in a nearby office, and the run began.

Each subject made two round trips over the course, one under each level of foreground illumination. The order of treatment presentation was balanced.

The data were reduced while replaying the tape at normal speed. One person held a template like that illustrated in Figure 2.16 in front of the TV screen and kept the dots over the hood reference lamps. A second person, working with a 3 x 3 button matrix, pressed the button corresponding to the eye position and held it down as long as the spot remained in that sector. Pressing the button advanced a counter by "1," and activated a timer that ran while the button was depressed. In this way both number and duration of fixations were recorded. (Fixations outside the matrix in Figure 2.16 were also recorded.) A reliability check was made on this procedure by reducing one subject's data twice. The two data sets were within 10%.

2.2.2.6 Results. Table 2.3 shows the mean percent time spent looking in each cell of the matrix in Figure 2.16 under both foreground illumination conditions. The major difference between the two data sets is in the two top-center cells. There is a substantial shift, indicating more time was spent looking further down the road under high foreground illumination conditions.

All six subjects increased their percent time spent fixating in the top center cell under high- as compared to normal-foreground conditions. This change is significant ($p < 0.02$), based on the Sign Test (Siegel, 1956).

Table 2.4 shows the mean number of fixations into each cell under each of the foreground conditions. This analysis suggests that there were about the same number of fixations to each area of the forward field under each lighting condition. The differences in this table are not significant ($p > 0.05$).

Finally, Table 2.5 shows the mean dwell times in each cell under each foreground condition. The major change was an increase in dwell times in the far field for the high foreground illumination condition. Dwell times in the other seven cells of the matrix remained about the same.

TABLE 2.3

MEAN PERCENT TIME SPENT LOOKING IN VARIOUS AREAS FORWARD OF THE VEHICLE AS A FUNCTION OF THE LEVEL OF FOREGROUND ILLUMINATION

Low Foreground Illumination

3.2	36.2	4.1
3.9	33.8	4.4
0.3	4.6	1.1

9.0	out of matrix

High Foreground Illumination

4.1	44.7	5.8
2.4	27.3	4.3
0.4	5.5	0.5

6.2	out of matrix

TABLE 2.4

MEAN NUMBER OF FIXATIONS IN VARIOUS AREAS FORWARD OF THE VEHICLE AS A FUNCTION OF THE LEVEL OF FOREGROUND ILLUMINATION

Low Foreground Illumination

6.8	31.7	8.3
6.3	33.0	8.7
0.3	6.7	2.5

13.3	out of matrix

High Foregound Illumination

5.3	31.3	8.5
4.5	28.5	8.0
1.2	7.2	2.5

9.0	out of matrix

TABLE 2.5

MEAN DWELL TIMES IN VARIOUS AREAS FORWARD
OF THE VEHICLE AS A FUNCTION OF THE
LEVEL OF FOREGOUND ILLUMINATION

(Times shown are in seconds)

Low Foreground Illumination

1.9	4.5	2.0
2.5	4.1	2.0
3.2	2.4	1.8

2.7	out of matrix

High Foreground Illumination

3.0	5.6	2.7
2.2	3.9	2.2
1.3	2.4	0.9

2.7	out of matrix

2.2.2.7 Discussion. This test was modest in scope. However, the results are very interesting in that they suggest that high levels of foreground illumination may cause drivers to spend a greater percent of their time looking in areas further up the road.

Actually, the results are quite reasonable. Increasing foreground illumination makes it easier for the driver to acquire necessary near-field information peripherally. Thus, he/she can devote more attention to areas where seeing is both more difficult and important. This may well be the explanation for the results reported here.

2.2.3 Identification Distance Study. The two lighting systems used in the eye fixation study were included as part of the main experiment concerned with identification distance. The methods and detailed results of that work are described in Chapter 3 of this report.

Table 2.6 illustrates the principal findings of the identification distance study as they pertain to the question of foreground illumination. These data are excerpted from Table 3.3 in Chapter 3. The differences between lamps on specific targets are small and not statistically significant ($p > 0.05$). The means summed across targets differ by no more than three feet (about 2%), and in two cases are identical. In brief, the data show no indication of any change in identification distance, positive or negative, as a function of the level of foreground illumination.

2.2.4 Discussion. The results of this investigation suggest that foreground illumination may be less of a problem than some persons seem to think. That is, there is no objective evidence that high levels of foreground illumination attract the eye of the driver or degrade target detection-identification. It may be, in a real-world condition, that high foreground illumination will aid target detection, because it may cause the driver to spend a greater proportion of his/her time looking toward the convergence point of the road.

The problem of wet-road glare remains as a consideration in setting foreground illumination levels. Aside from the study by Wilkenson, mentioned earlier, nothing has been reported on this question. It may be a significant problem, particularly so since visibility in general is reduced in rainfall. Some additional work on this issue is desirable to try to better define maximum acceptable levels.

TABLE 2.6

MEAN IDENTIFICATION DISTANCES (IN FEET) AS A FUNCTION OF TARGET TYPE, LOCATION AND HEADLAMP BEAM. YOUNG SUBJECTS ONLY.

Target		Glare	Headlamp	
Size*	Location**		Normal	High Foreground
WL	R	No	298	312
WL	L	No	248	230
L	R	No	165	154
L	L	No	88	93
M	R	No	128	133
M	L	No	60	58
S	R	No	127	136
S	L	No	80	75
Means - No Glare			149	149
WL	+300'	Yes	197	195
L	+300'	Yes	129	124
M	+300'	Yes	115	107
S	+300'	Yes	144	146
Means - 300' Glare			146	143
L	-8'	Yes	148	145
S	-8'	Yes	160	162
Means - 8' Glare			154	154
Means - All Glare			149	146

*WL = white large
L = large
M = medium
S = small

**R = to observers' right
L = to observers' left

2.3 Beam Color

2.3.1 Introduction. Headlamp beams are thought of as being white. For all practical purposes they are. Admittedly there are color differences between tungsten and halogen units, attributable to the fact that the latter are operated at higher filament temperatures. However, these differences are small enough that they are not readily apparent unless compared side by side.

In France all motor vehicle headlamps are required to be yellow. This is achieved by filtering the standard source (generally an H-4 bulb) so that the color change results in a loss in intensity.

The supposed benefits of the yellow headlamp are many. Devaux (1956), an enthusiastic advocate, discusses several. For example, it is claimed that the use of yellow headlamps:

a. Reduces disability glare effects.

b. Reduces glare recovery time.

c. Is differentially advantageous to persons with poor vision.

d. Reduces discomfort glare.

An excellent, recent review has been prepared by Schreuder (1976) on this question. He concludes that, while there is some merit in the claims for yellow headlamps, the benefits are very small. Against this must be balanced certain disadvantages, e.g., color distortion of objects such as signs.

Specific research on discomfort effects related to lamp color is scarce and seems to be mostly based on fixed lighting installations. There are no reported studies analogous to those described in Section 2.1.

The study to be described was intended to provide some information on the relationship between lamp color and perceived comfort. It was not really trying to settle the

French lighting controversy. In setting up some of the discomfort studies described in Section 2.1, we had inadvertently altered the color of some stimuli. This produced a very noticeable change in the response of pilot subjects, making it easy to detect and correct the problem. This led us to believe that color might be a very significant factor in perceived discomfort.

2.3.2 Independent Variable

2.3.2.1 Glare. Seven glare levels were used in this study. They are listed in Table 2.7. The maximum is the same as was used in other laboratory studies described in this report. However, the total range was less.

TABLE 2.7

GLARE LEVELS USED IN COLOR STUDY

Number	Lux	Ft-C
1	6.46	0.60
2	2.03	0.189
3	0.716	0.0665
4	0.352	0.0327
5	0.059	0.00546
6	0.040	0.00372
7	0.0086	0.00080

Measurements were made at the plane of the eyes of the observer, using a Pritchard Photometer.

2.3.2.2 Beam Color. Three levels were used. One was provided by a halogen lamp, the second by a tungsten lamp. The third was obtained by placing a yellow filter in front of the halogen lamp to obtain an approximation of the French system.

2.3.2.3 Subjects. Twelve subjects participated in the study. Half of these were older (i.e., 65+), half were young (i.e., less than 30).

2.3.3 Dependent Variable. The subjects provided a rating of each glare experience using the discomfort glare scale described earlier.

2.3.4 Equipment. Glare was provided by two 142x200 mm rectangular sealed beam headlamps. One of these was tungsten, the other halogen. The two units were mounted on a board. Each was driven at 12.00 volts by a regulated power supply, and aim adjustments were made to make the glare delivered to the subjects' eyes the same. The halogen lamp was increased to 12.85 volts to compensate for the yellow filter when it was in use.

A clockwork mechanism was used that sounded a buzzer for one second and then switched on the lamp for two seconds. This cycle was repeated at 15-second intervals.

It was anticipated that there may be response differences attributable to the rise and decay characteristics of the two filaments. A test was run on this, the results of which are shown in Figure 2.17. There are noticeable differences. Rise time to 90% output was about 0.216 and 0.312 seconds for the halogen and tungsten units respectively. However, it was felt that this would be acceptable, especially since the two extreme color conditions would both be supplied by the halogen lamp.

Subjects were seated at a desk at one end of the laboratory. A chin rest was used to control eye position. The headlamps were reflected from a mirror about 65 feet from the subject. A small, yellow lamp was placed at the bottom of the mirror to provide an eye fixation point. This lamp was centered between the images of the two headlamps and 1.5 feet below them, providing a glare angle of 1.3 degrees.

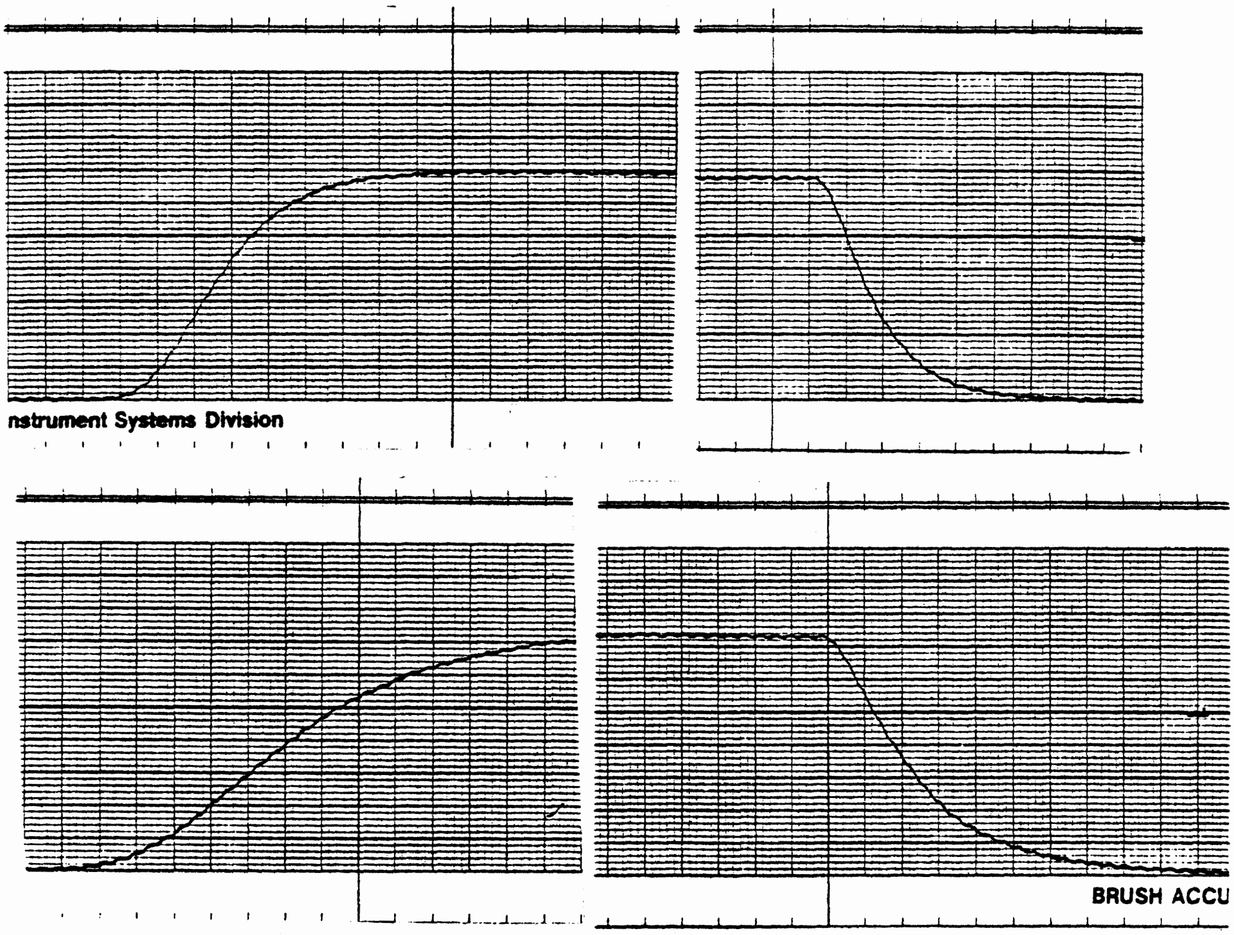


Figure 2.17. Comparison of rise and decay characteristics of halogen (top) and tungsten (bottom) lamps used in study. Chart speed: 125 mm/sec.

Glare levels were changed using neutral density filters. These were dropped into guides in front of the lamp as required. Ten repetitions of each glare level were given each subject for each color condition.

2.3.5 Procedure. Subjects were run individually. Each signed a consent form and was seated at the desk where the instructions (see Appendix) were read to them. After any questions had been answered, the lights were extinguished and the dark adaptation period began (about ten minutes). During this period a number of example trials were provided, using a low glare level, to acquaint the subjects with the general procedure. Data trials then began.

The order in which the lamp colors was taken was varied systematically. The order in which the various glare levels were presented was random.

2.3.6 Results. Figure 2.18 is a plot of the mean ratings assigned each intensity and color level. In most cases the yellow lamp was rated most comfortable of the three. However, the differences are very small and statistically not significant.

The diagonal line in Figure 2.18 represents predicted results based on the original discomfort glare equation. It will be noted that the fit is quite close at the high intensity end of the continuum, and becomes progressively worse toward the low end. This discrepancy is probably due to the range effect. As was noted in the description accompanying Table 2.7, the high intensity values used here corresponded to those used in our other glare studies. However, the low intensity values stopped short of previous minimums. The departure noted is precisely the result that would be expected from the range effect under those conditions.

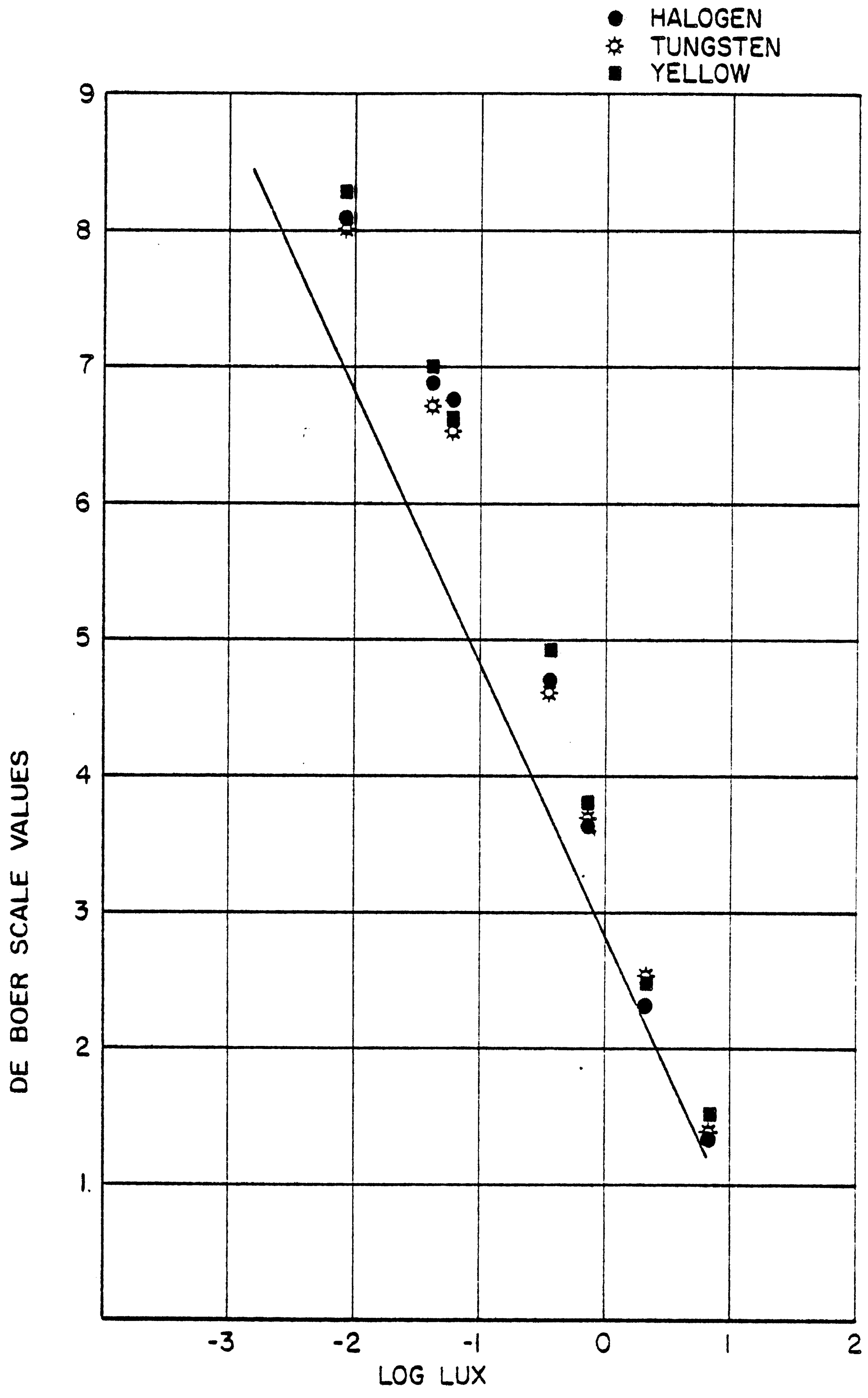


Figure 2.18. Mean ratings associated with each color and glare intensity conditions. Each data point is mean of 120 ratings.

2.3.7 Discussion. The primary interest of this study was with the color question. The results make it clear that, through the range tested, color has little or no effect on perceived discomfort.

Based on the review by Schreuder (1976), the only experimental work on the color of illumination is in the context of street-lighting installations. Significant effects are reported, but Schreuder feels that the effect would be less in automotive applications due to the smaller glare angle.

Since this was regarded as a pilot study, no color measurements were made on the stimuli. The "yellow" headlamp was intended to approximate the French system but it was made using filters we had available, not one actually used in French headlamps. Hence it would be improper to infer from these data that the French system does not have comfort advantages. Some further work on this question would be worthwhile.

3.0 VISIBILITY

3.1 Target Identification Study

The purpose of this study was to measure objectively the ability of various headlighting systems to reveal different objects in the forward field.

3.1.1 Method

3.1.1.1 Independent Variables

3.1.1.1.1 Lighting Systems. Six lighting systems were tested. Two were "controls," in the sense that they met existing U.S. (FMVSS-108) and ECE standards. The other four were selected because they had characteristics that were useful in evaluating various hypotheses. Two of these lighting systems were based on the recommendations outlined in the project interim report (Olson and Sivak, 1981). One was an experimental system provided by a U.S. lighting company that combined characteristics of U.S. and European lamps. The last was the "high foreground illumination" system used in the eye fixation study described earlier.

Specifically, the following lighting systems were included:

1. U.S. low beam. Provided by two 142 x 200mm rectangular, tungsten, sealed-beam units. An isocandela diagram of this system is in Figure 3.1.
2. ECE (European) low beam. Provided by two large, "semi-rectangular" halogen units, using H-4 bulbs. Approximate dimensions of the lens: vertical-170mm, horizontal-290mm on top and 315mm on bottom. An isocandela diagram of this system is in Figure 3.2.
3. Modified low beam. Provided by two 142 x 200mm rectangular, tungsten, sealed-beam units. This beam is based on the recommendations outlined in the project interim report, as noted earlier. It

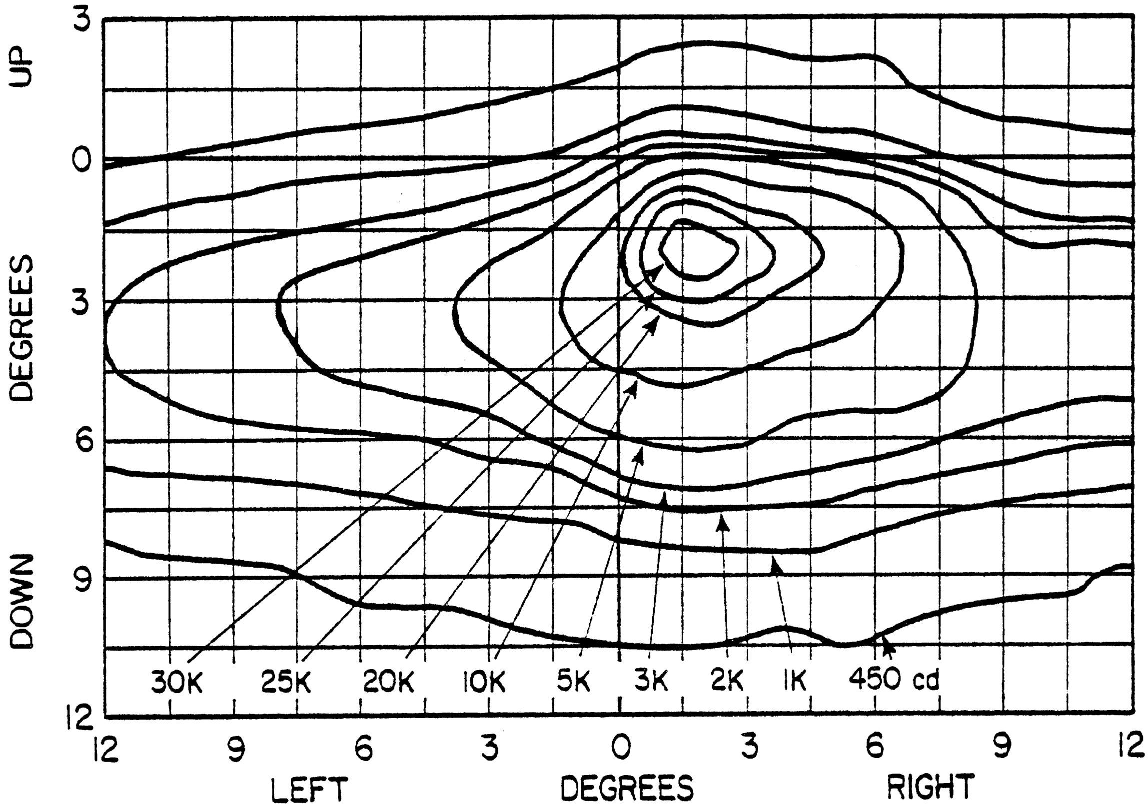


Figure 3.1. Isocandela diagram of U.S. low beam used in test. Units are candelas (cd).

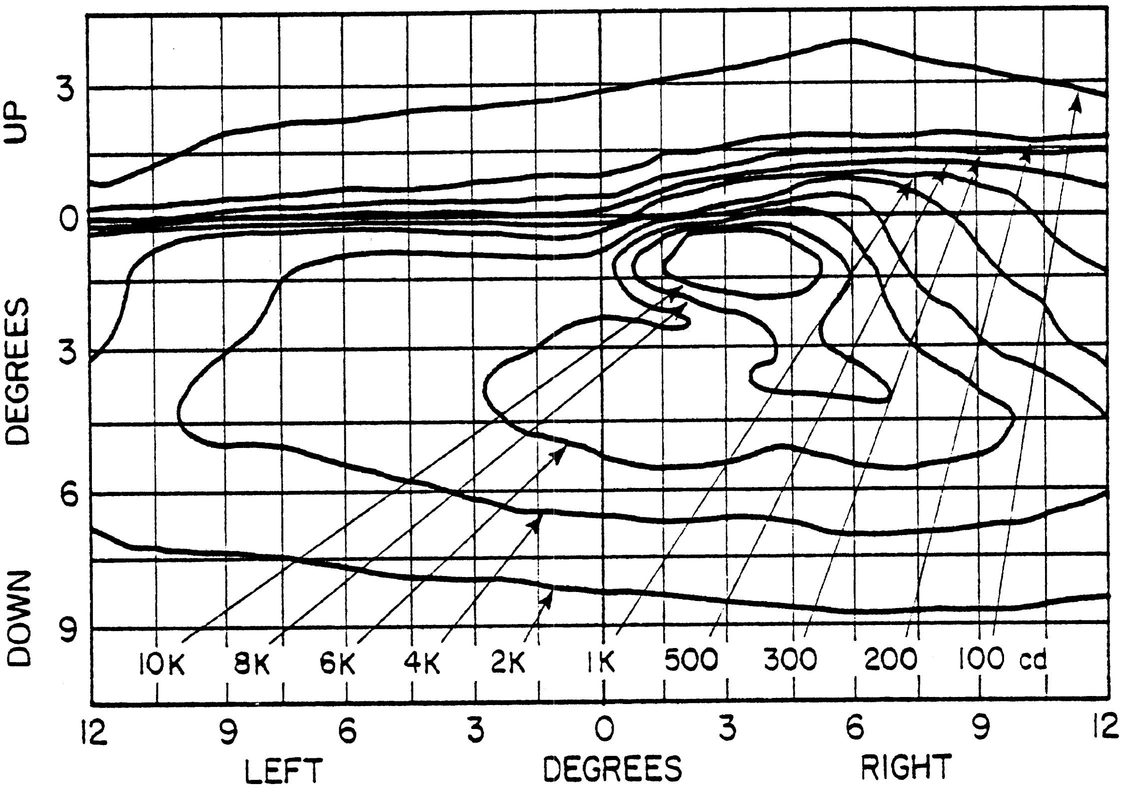


Figure 3.2. Isocandela diagram of E.C.E. low beam used in test. Units are candelas (cd).

conforms generally to these recommendations, but is somewhat less glaring and provides somewhat more illumination in key areas. Compared to the standard low beam (number 1, above) it is more glaring and has considerably more intensity near horizontal and just to the right of the V axis. An isocandela diagram of the system is in Figure 3.3. This will be referred to as "Modified-1."

4. Modified low beam. Provided by two 142 x 200mm rectangular, tungsten, sealed-beam units. This beam is also based on the recommendations contained in the project interim report. However, its characteristics fall between the standard and Modified-1 lamp. It can best be summarized as having more illumination in seeing areas than the standard unit, but no more glare. Thus, it is an interesting compromise between the two approaches. It will be referred to as "Modified-2." An isocandela diagram of this system is in Figure 3.4.

5. Single-beam. This is an asymmetrical system, using two PAR-56 (7-inch, 178mm) round, tungsten, sealed-beam units. The right and left lamps provide different patterns, and have but one filament each (no high beam is available). An isocandela diagram of both lamps is in Figure 3.5. This system was of interest because it provides relatively high levels of illumination, below horizontal, on both sides of the road, while holding glare levels to near those provided by the standard U.S. system.

6. High-foreground beam. This is a combination beam, made up of a pair of standard U.S. low beams, as described in 1 above, and a pair of Koito 997-16121 halogen motorcycle headlamps aimed low, as described in Section 2.2. An isocandela diagram of one of the Koito units is in Figure 3.6.

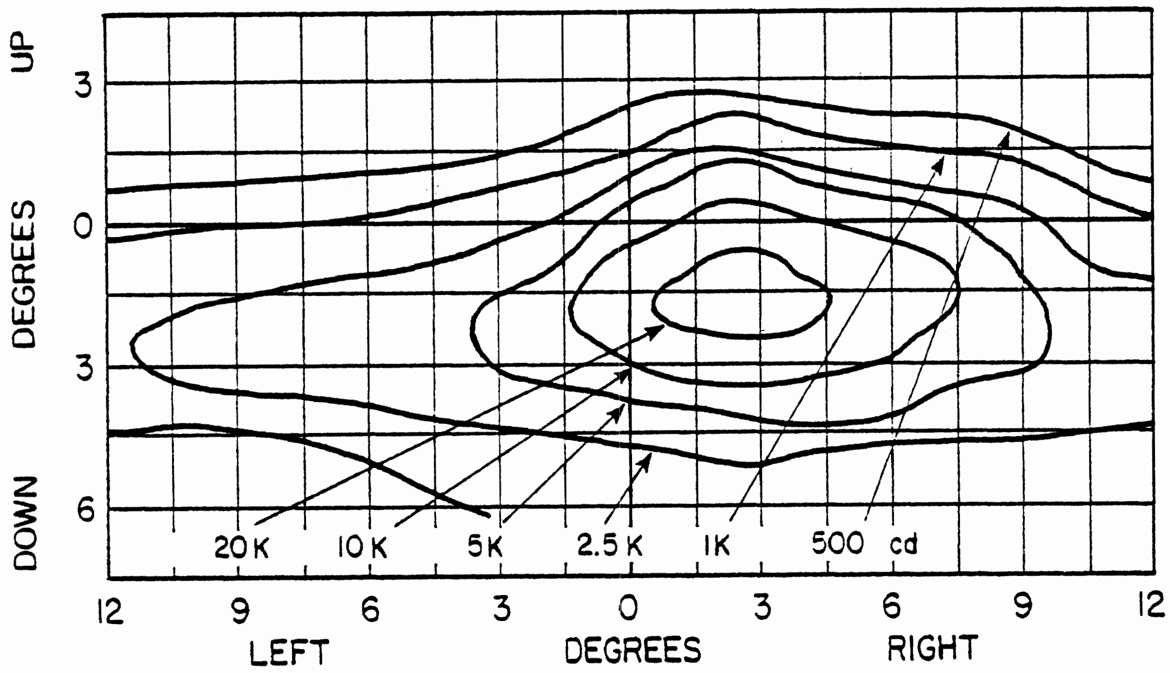


Figure 3.3. Isocandela diagram of Mod-1 unit used in test. Units are candelas (cd).

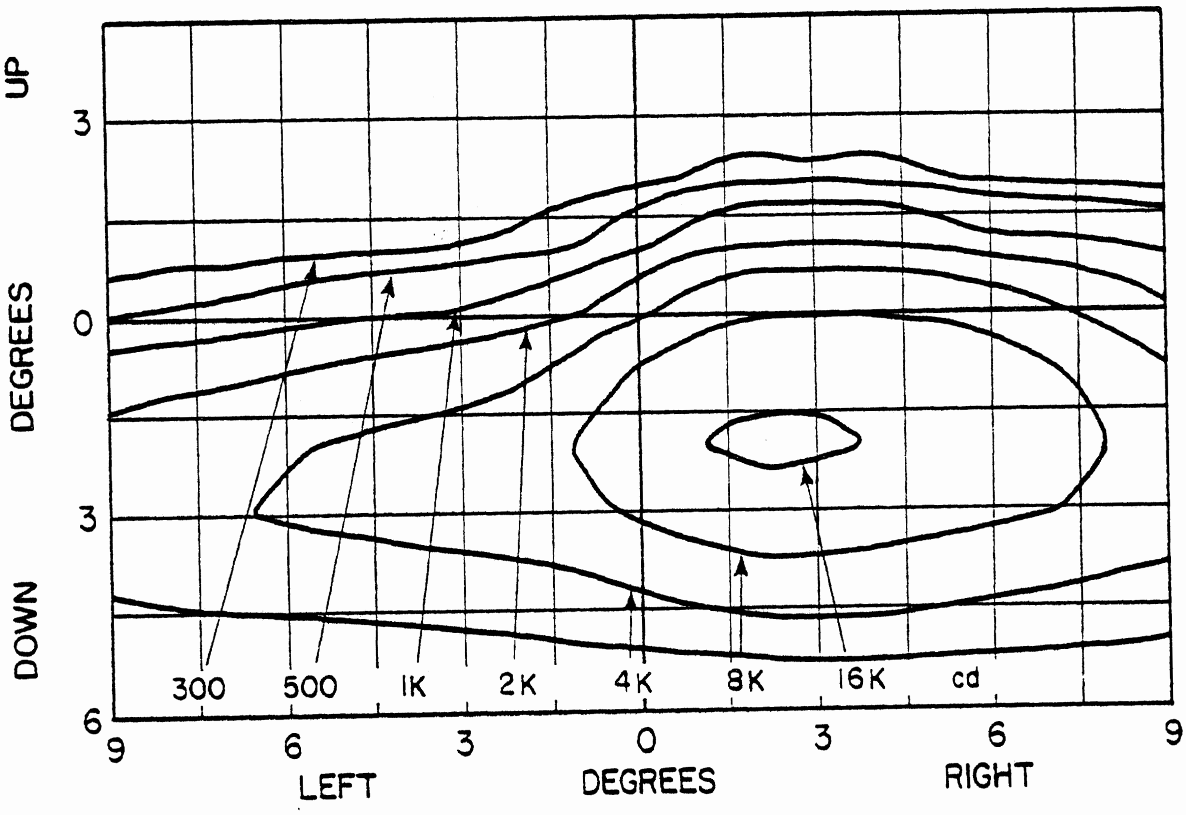
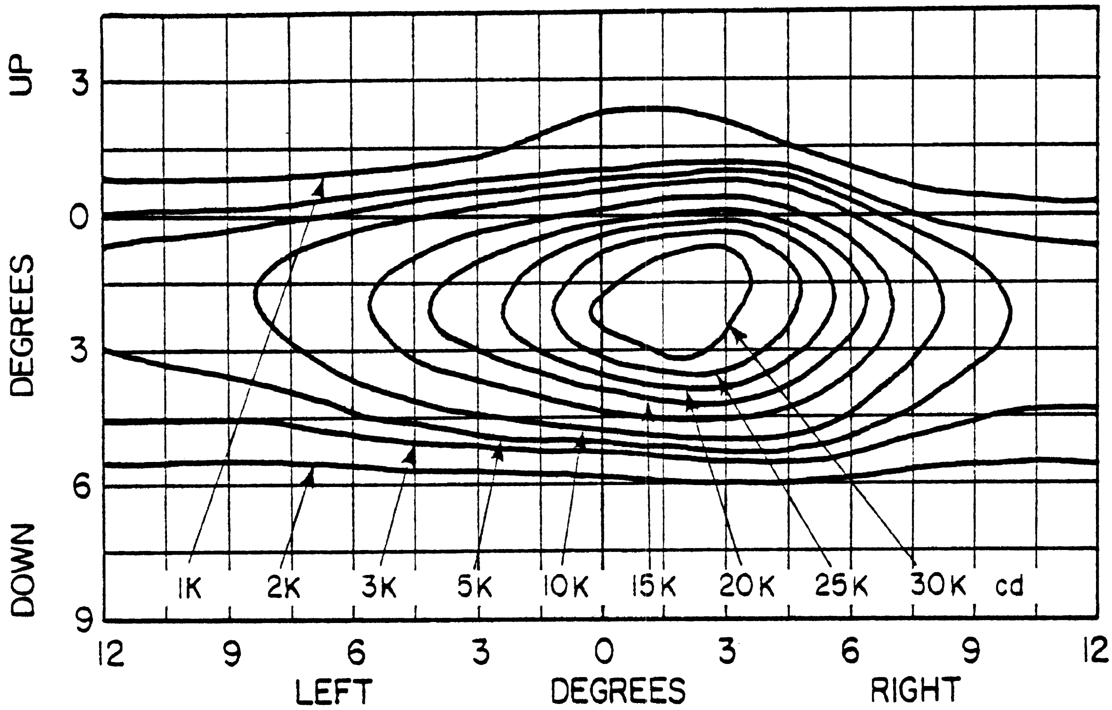


Figure 3.4. Isocandela diagram of Mod-2 unit used in test.
Units are candelas (cd).



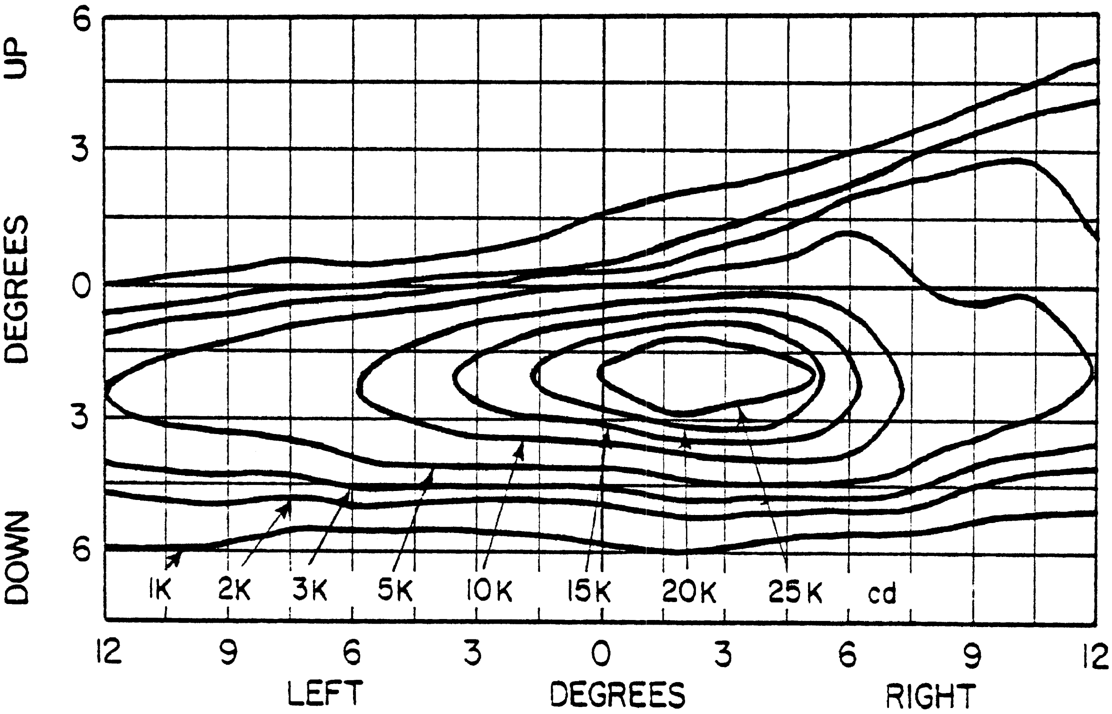


Figure 3.5. Isocandela diagrams of two units used in single-beam system. Units are candelas (cd). Left side lamp on top. Right side lamp on bottom.

Lamp mounting height was 30 inches (76 cm) for all units, measured from the road surface to lamp center.

3.1.1.1.2 Glare. Glare was provided on half the runs by a set of lamps having the same characteristics as those on the test vehicle. The glare lamps were mounted on a car that was parked in a precisely defined location at one end of the track.

There were two target positions for glare runs. One was 300 feet (91 meters) forward of the lamps (+300), the other was 8 feet (2.4 meters) behind the lamps (-8).

3.1.1.1.3 Visibility Targets. Three sizes of target were used in the study. These were described to the subjects as small, medium, and large.

The small target was a block of foam rubber measuring about 12" x 4" x 6" (30.5cm x 10cm x 15cm), covered in blue denim. A photograph of one of these is shown in Figure 3.7. It was placed on the road with the 12" x 4" (width x height) surface facing the subject.

The medium target was a plywood panel, 12" (30.5cm) wide and 30" (76cm) tall. It too was covered in blue denim. Two views of this target are shown in Figure 3.8.

The large target was an experimental assistant. He/she appeared in two versions. One wore blue denim trousers and a dark top. Another, which will be referred to as "white large," wore blue denim trousers and a white vest. Figure 3.9 is a photograph of all four targets.

Under no-glare conditions the targets could appear on either side of the test vehicle. Under glare conditions the targets were on the right side only.

All four targets described above were used at the "far" glare target position (i.e., 300 feet [91 meters] forward of the lamps). Only the small and large dark targets were used

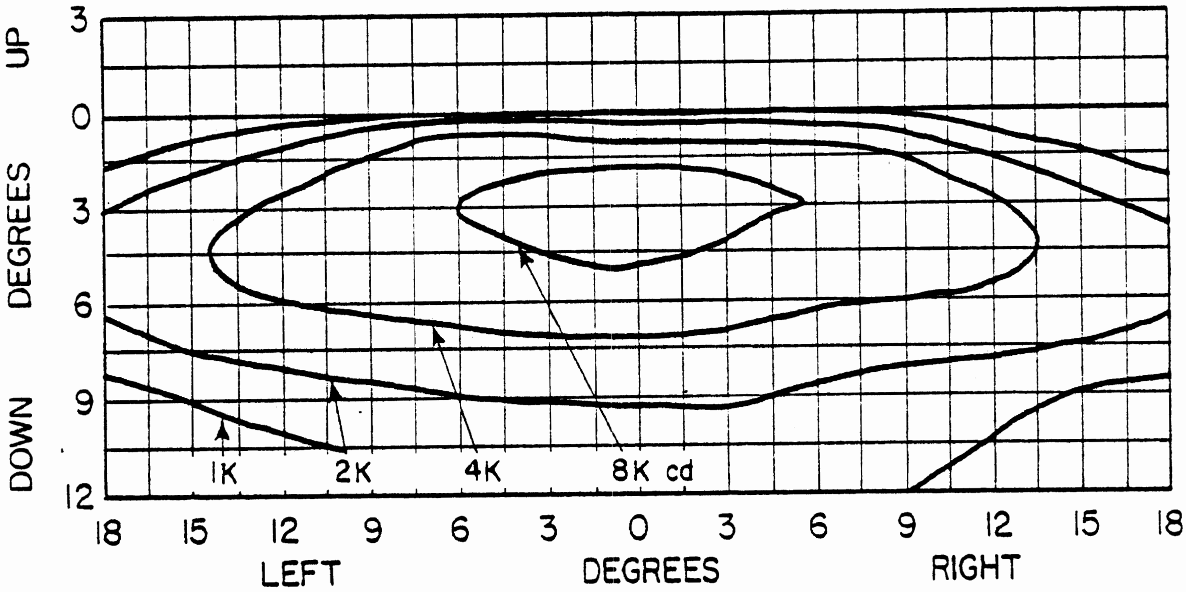


Figure 3.6. Isocandela diagram of Koito 997-16121 unit used to create high foreground illumination condition. Units are candelas (cd).

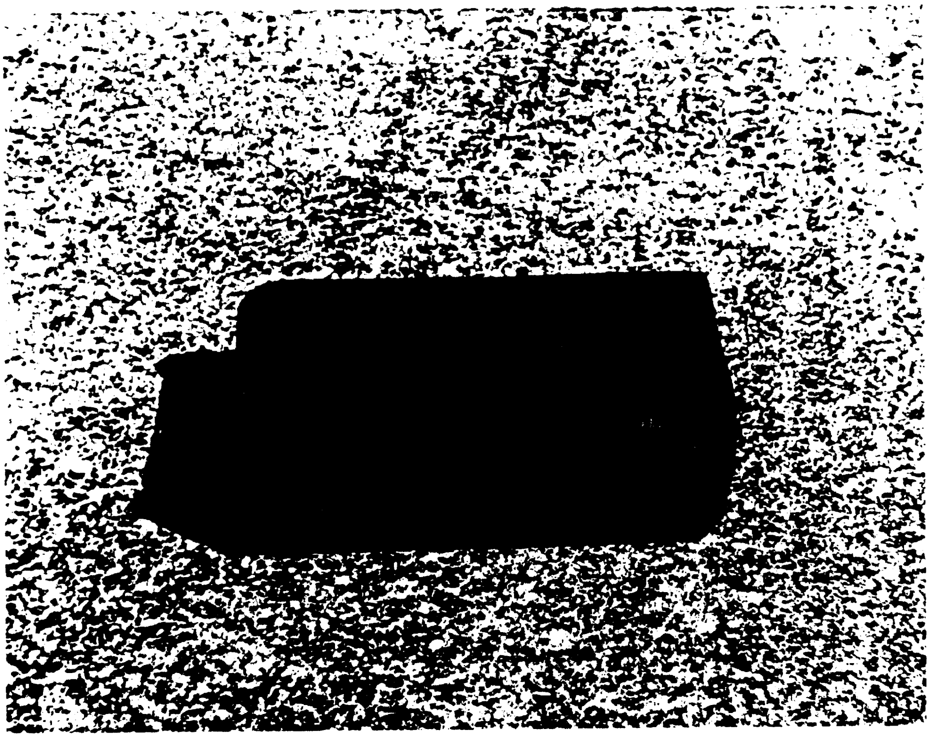


Figure 3.7. Photograph of "small" target used in target identification study.

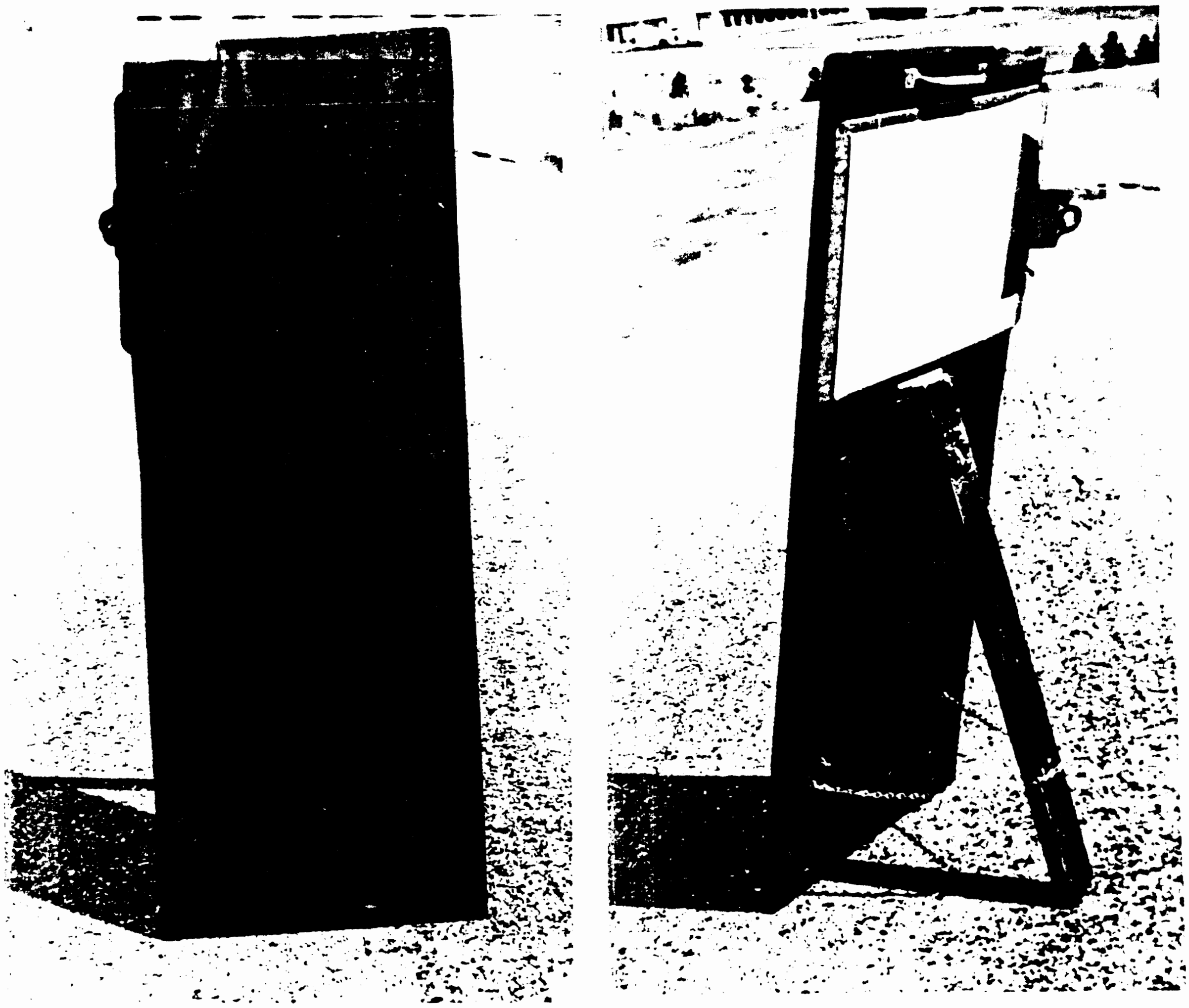


Figure 3.8. Two views of "medium" target used in target identification study; front (left) and rear (right).

Figure 3.9. All four targets used in target identification study. Left to right: "white large, large, medium," and "small."

at the "near" glare target position (i.e., 8 feet [2.4 meters] behind the lamps).

3.1.1.1.4 Subject Age. Thirty subjects were scheduled to participate in the study. Twenty-eight of them completed both sessions. Of these, 23 were young (i.e., 18-30 years of age) and five were older (i.e., 65 years of age or more).

3.1.1.2 Dependent Variable. Measures were made of the distance from the target at which the subjects pressed a button indicating their identification of the object and its location. Identification errors were recorded as well.

3.1.1.3 Equipment. Two cars were required for the test. One provided glare and, as noted earlier, was parked at one end of the track. The subjects drove/rode in the other, along with the experimenter. Both cars were equipped with light-mounting bars and precision voltage control equipment (accuracy: ± 0.05 volt). The subject vehicle was a full-size, 1980 model station wagon. It had a heat-absorbing windshield that was in very good optical condition.

Subjects were run three at a time. All three were in the front seat, with one driving. Each subject was provided with a box like that shown in Figure 3.10. The box held six silent pushbuttons, to cover all possible identifications (three target sizes, right and left locations). The subjects were told to keep their finger on the center button except when responding. The driver's response box was strapped to his/her right leg, and they drove with their left hand.

The experimenter was equipped with two control panels. One, shown in Figure 3.11, controlled the headlamps. The other, shown in Figure 3.12, was used to collect data. In Figure 3.12, the six unlabeled buttons on the right

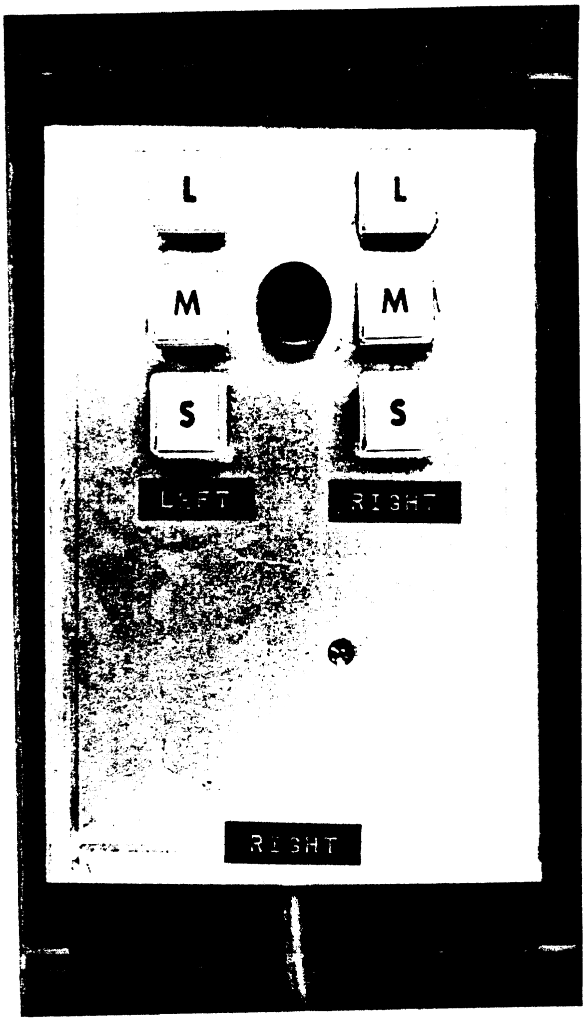


Figure 3.10. Subject response box.

correspond to the buttons on the subjects' boxes, and were used to program for the next target. The three dark, rectangular objects on the left are electronic counters, one for each subject. When a subject pressed a button on his/her box the counter started and began accumulating at a rate of 4 counts/front wheel revolution. If they pressed the wrong button, the light to the right of the counter came on. The experimenter pressed the stop button as the target was passed and reset the counters after writing down the totals.

3.1.1.4 Test Facility. The test was carried out on a private road. A schematic (not to scale) of the facility is shown in Figure 3.13.

The road consists of two ten-foot (3 meter) lanes. It is 2,500 feet (762 meters) long, flat and straight. It is paved with asphalt that is well-worn but very smooth. There is a faint center line, but no edge markings.

The road is in a rural area. There are no sources of illumination on or near it. It closely approximates a dark, rural road.

At the west end the road widens to three lanes on the south side, as shown. The glare car was parked in this location. There is also a small parking lot on the north side.

The glare targets were set in fixed positions, as indicated above. No-glare targets were set in three target areas, each of which was several hundred feet long. The target, if it appeared at all, could be set anyplace within the area. Three experimental assistants set or acted as targets, one in each of the areas shown. They moved up and down the road in their area between trials.

The subjects drove down the center of the road in both directions. Targets were set within one foot (30cm) of the edge of the pavement.

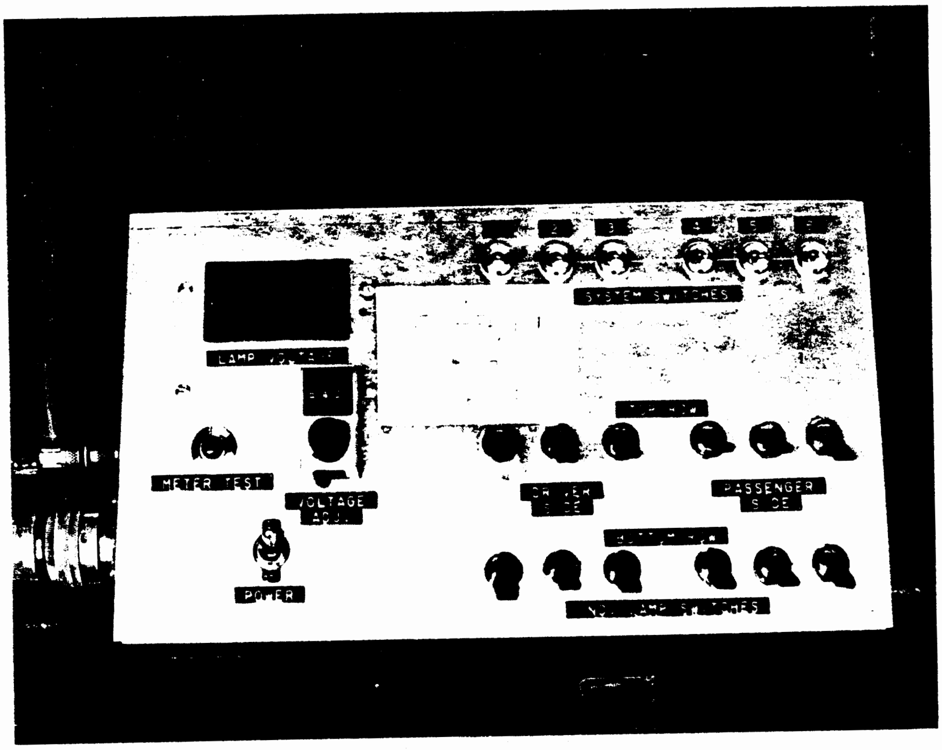


Figure 3.11. Lighting control panel.

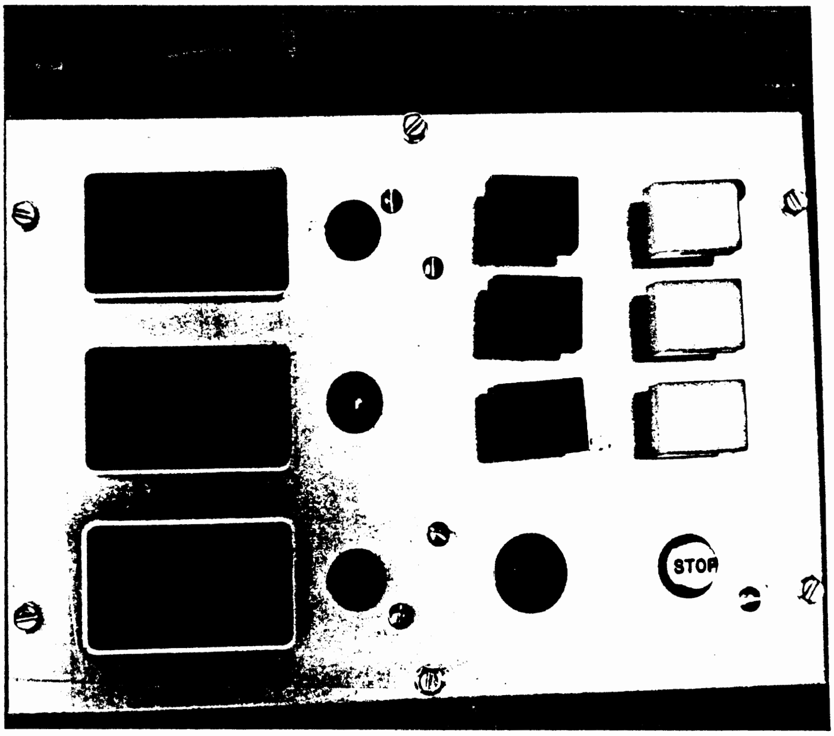


Figure 3.12. Experimenter's data collection box.

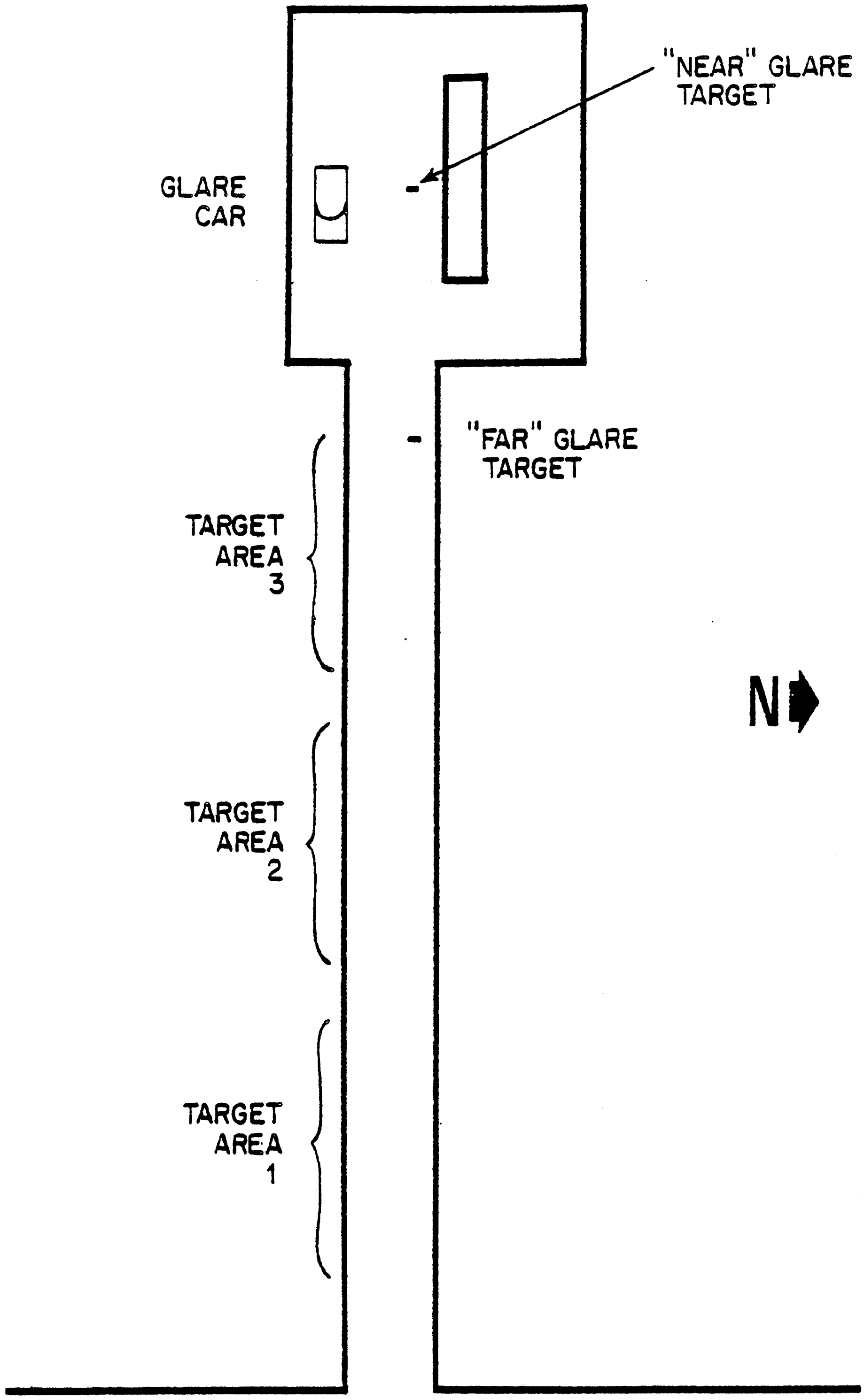


Figure 3.13. Schematic of test facility.

3.1.2 Procedure. Subjects reported to the Institute, signed consent forms, and were driven to the test site. On arrival, they were driven down the road a short distance to target area 1, where a large, medium and small target were arranged across the road. The instructions (see Appendix) were read to them and questions answered. One round trip was then allowed for practice, using random targets. When any additional questions had been answered, the test began.

Each odd-numbered trial started at the east end of the track. The driver accelerated to the test speed (about 25 mph) and steered down the center of the road. After passing target area 2, the experimenter switched on an amber lamp in the front of the car to signal the person in the glare car to turn on those lamps. The subject continued west, past the glare car, turned around in the parking lot, and headed back east for the even-numbered trial. The glare lamps were turned off after the subject vehicle passed.

On a given run the subjects might encounter no targets, one or two. On west-bound runs, no-glare targets could be set in areas 1 and 2, and glare targets where indicated in Figure 3.13 (no more than one at a time). On east-bound runs, no-glare targets could be set in any of the three areas.

Three replications were made for each of the eight no-glare target combinations (four targets, two locations) and two replications for each of the six glare target combinations (four far, two near), for a total of 36 measures/lamp/subject. This was accomplished in 26 runs/lamp. Three lamps were tested on a given outing. This required about two hours, including two short breaks. Each subject had to participate in the test on two different occasions to experience all six lighting systems.

Six schedules were prepared, describing different orders and placements of the targets. These were used, three each night, on a rotating basis. The order in which the lamps were used was also varied systematically.

3.1.3 Results.

3.1.3.1 Identification Errors. There were a total of 6,264 identification distances recorded in this study. In 190 of these cases (about 3%) the subject identified the target incorrectly. (This figure does not include instances in which the subject identified the target correctly, but accidently pushed the wrong button. These were treated as correct responses.) Table 3.1 summarizes the error data by lamp and target conditions.

An examination of Table 3.1 makes it clear that errors were more likely on some targets than others. For example, under no-glare conditions, more than half the errors involved the medium target, and more than a third of all errors involved the medium target on the left. The error frequencies on the other three targets were quite similar, as shown in Table 3.2.

Under glare conditions, the large and medium targets accounted for the bulk of the errors (about 93%).

Probably of greater interest is a comparison of the errors associated with different lighting systems. A glance at the column totals shows that the U.S. low beam, in either the standard or high foreground versions (columns 1 and 6 respectively) was associated with a higher incidence of error than any of the other systems tested. (These two beams together would be expected to account for 33 percent of the total errors based on chance alone. Actually, they accounted for 47 percent. They accumulated 44 percent of total errors under no-glare and 58 percent under glare conditions.) However, the differences in errors among the beams under no-glare conditions were not statistically significant ($\underline{p} > 0.10$), as determined by the χ^2 test.

TABLE 3.1

FREQUENCY OF INCORRECT IDENTIFICATIONS BY TARGET TYPE, LOCATION, AND HEADLAMP BEAM

TARGET			HEADLAMPS						
Size*	Location**	Glare?	1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore	Total
WL	R	No	1	1	0	0	2	2	6
WL	L	No	1	3	1	1	1	4	11
L	R	No	3	0	1	3	0	2	9
L	L	No	1	3	1	0	1	3	9
M	R	No	8	2	5	4	1	3	23
M	L	No	9	6	5	3	11	9	43
S	R	No	0	2	0	2	1	1	6
S	L	No	2	2	0	2	2	3	11
Totals			25	19	13	15	19	27	118
WL	+300′	Yes	1	0	0	0	0	0	1
L	+300′	Yes	12	3	0	3	4	12	34
M	+300′	Yes	1	2	5	3	3	6	20
S	+300′	Yes	1	1	0	0	0	0	2
Totals			15	6	5	6	7	18	57
L	-8′	Yes	2	4	1	1	4	1	13
S	-8′	Yes	1	1	0	0	0	0	2
Totals			3	5	1	1	4	1	15
Totals			43	30	19	22	30	46	190
Percent Error			4.1	2.9	1.8	2.1	2.9	4.4	

*WL = white large
L = large
M = medium
S = small

**R = to observers' right
L = to observers' left

TABLE 3.2

FREQUENCY OF INCORRECT IDENTIFICATION BY TARGET TYPE, SUMMED ACROSS HEADLAMP BEAMS. NO-GLARE CONDITIONS ONLY.

Target	Error Frequency
White Large	17
Large	18
Medium	66
Small	17

A χ^2 test on the error totals for the 300' glare condition showed significant differences among the beams ($p < 0.01$). The Cochran Q test was used to check for significance among individual targets. Only the differences among beams for the large target at the 300' glare condition were found to be significant ($p < 0.01$).

3.1.3.2 Identification Distance. Table 3.3 summarizes the identification distance data for the young subjects. An analysis of variance was run on these data and showed, for both glare and no-glare conditions, significant differences among targets and headlamps as well as a significant target by headlamp interaction ($p < 0.01$ in all cases).

Post hoc tests on the no-glare means (Newman-Keuls range test [Hicks, 1973]) showed that lamps 1, 2, 4, and 6 did not differ significantly ($p > 0.05$). Lamps 3 and 5 were significantly different from the other four and from each other ($p < 0.05$). Under glare conditions the same general pattern holds, except that lamps 3 and 5 do not differ significantly ($p > 0.05$).

The target by headlamp interaction arises from differences in performance of the headlamps on right-and

TABLE 3.3

MEAN IDENTIFICATION DISTANCES (IN FEET) AS A FUNCTION OF TARGET TYPE, LOCATION, AND HEADLAMP BEAM. YOUNG SUBJECTS ONLY.

TARGET		Glare?	HEADLAMPS					
Size*	Location**		1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
WL	R	No	298	269	373	284	361	312
WL	L	No	248	206	298	230	340	230
L	R	No	165	176	200	161	223	154
L	L	No	88	87	124	95	195	93
M	R	No	128	129	142	130	173	133
M	L	No	60	71	88	70	170	58
S	R	No	127	118	164	131	167	136
S	L	No	80	86	94	86	151	75
Means - No Glare			149	143	185	148	223	149
WL	+300'	Yes	197	194	264	213	256	195
L	+300'	Yes	129	158	192	141	188	124
M	+300'	Yes	115	123	147	134	176	107
S	+300'	Yes	144	137	172	138	157	146
Means - 300' Glare			146	153	194	157	194	143
L	-8'	Yes	148	171	174	147	156	145
S	-8'	Yes	160	173	178	157	193	162
Means - 8' Glare			154	172	176	152	175	154
Means - Glare			149	159	188	155	187	146

*WL = white large
L = large
M = medium
S = small

**R = to observers' right
L = to observers' left

left-side targets. This is illustrated for no-glare targets in Table 3.4.

The first two rows of Table 3.4 are for the eight no-glare targets. For all headlamps except number 5, the single-beam system, identification distance to left-side targets is about two-thirds that to right-side targets. For headlamp 5, left-side identification distances are an average of 90% of those measured on the right side.

One of the reasons for differences among headlamps in the first two rows of Table 3.4 is the white large target. Headlamps that project more illumination above horizontal would have an advantage with such a target. To illustrate this effect, rows 3 and 4 of Table 3.4 present mean identification distances for the six low-reflectivity targets. In row 3, for right-side targets, lamps 1, 2, 4 and 6 exhibit virtually identical performance. The more powerful lamps, 3 and 5, outperform the others, as would be expected. For left-side targets (row 4) systems 1 and 6 yield nearly identical performance, as expected. Systems 2 and 4 project somewhat more illumination to the left and yield slightly better visibility. Systems 3 and 5, being much more powerful than the others, outperform them by wide margins.

Under no-glare conditions, system 5 outperformed system 3 somewhat, even on right side targets (note rows 1 and 3 in Table 3.4). However, this difference disappeared under the glare conditions, as noted in Table 3.3, probably due to slightly higher glare levels from the system 5 units.

The data in Table 3.3 may give the impression that glare and no-glare performance was about the same. This apparent anomaly is partly due to the fact that only right-side targets were used under glare conditions. Table 3.5 presents a comparison of each target in the right-side position under glare and no-glare conditions. The data show that glare made a substantial difference in the

TABLE 3.4

MEAN IDENTIFICATION DISTANCES (IN FEET) ASSOCIATED WITH THE VARIOUS HEADLIGHT BEAMS FOR DIFFERENT COMBINATIONS OF TARGETS. NO-GLARE, YOUNG SUBJECTS.

Condition	Headlamps					
	1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
1 Right Side Targets Only	180	173	220	177	231	184
2 Left Side Targets Only	119	113	151	120	214	114
3 Right Side Targets Without WL Target	140	141	169	141	188	141
4 Left Side Targets Without WL Target	76	81	102	84	172	75

identification distance to the large target, but had little or no effect in the case of the small and medium target.

The difference in glare effect as a function of target type was unexpected and the reason is not clear. The impression gained by the experimenter from riding with the subjects during all the trials, was that the two smaller targets were more difficult to detect under glare conditions. Apparently they were not more difficult to identify.

All of the data discussed to this point have been taken using young subjects. Table 3.6 is a summary of the results from the older subjects. It should be compared with Table 3.1.

The number of older subjects in this test was small (N=5). Because of this the data are noisier, and no statistical analysis was attempted. Certainly, these results cannot be taken as representative of the population of older drivers. However, these older subjects are part of a group of older persons who had been screened at UMTRI about three years earlier and found to have unusually good vision relative to their peer group. They are all in good health, active, and still drive regularly, including at night.

Table 3.7 has been prepared to facilitate a direct comparison of the identification distances recorded by the two age groups. On average, under both glare and no-glare conditions, the older subjects recorded identification distances about half as long as those for the young subjects.

Distributional data for the young subjects are presented in Figures 3.14 through 3.27. Each of these figures is a normal probability plot of identification distances for the six lighting systems for a given target and glare condition. It will be noted that systems 3 and 5

TABLE 3.5

MEAN IDENTIFICATION DISTANCES (IN FEET) FOR RIGHT SIDE TARGETS AS A FUNCTION OF HEADLAMP BEAM AND GLARE CONDITION. YOUNG SUBJECTS ONLY.

Target Size	Glare?	Headlamps					
		1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
WL	No	298	269	373	284	361	312
WL	Yes	197	194	264	213	256	195
L	No	165	176	200	161	223	154
L	Yes	129	158	192	141	188	124
M	No	128	129	142	130	173	133
M	Yes	115	123	147	134	176	107
S	No	127	118	164	131	167	136
S	Yes	144	137	172	138	157	146

Note: Glare data are from +300' condition.

TABLE 3.6

MEAN IDENTIFICATION DISTANCES (IN FEET) AS A FUNCTION OF TARGET TYPE, LOCATION, AND HEADLAMP BEAM. OLDER SUBJECTS ONLY.

Target		Glare?	Headlamps					
Size*	Location**		1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
WL	R	No	180	165	254	212	313	136
WL	L	No	98	64	196	131	230	106
L	R	No	62	66	134	95	133	63
L	L	No	49	36	66	68	139	40
M	R	No	62	28	81	69	92	50
M	L	No	22	17	36	31	93	17
S	R	No	87	35	96	81	86	90
S	L	No	26	39	38	46	79	25
Means - No Glare			73	56	113	92	146	66
WL	+300′	Yes	99	110	157	136	164	119
L	+300′	Yes	47	56	108	71	104	51
M	+300′	Yes	27	19	69	55	60	30
S	+300′	Yes	71	56	92	83	111	72
Means - 300′ Glare			61	60	107	86	110	68
L	-8′	Yes	61	60	113	92	95	47
S	-8′	Yes	80	64	129	99	99	76
Means - 8′ Glare			71	62	121	96	97	62
Means - All Glare			64	61	111	89	106	66

*WL = white large
L = large
M = medium
S = small

**R = to observers′ right
L = to observers′ left

TABLE 3.7

COMPARISON OF MEAN IDENTIFICATION DISTANCES (IN FEET) OF YOUNGER AND OLDER SUBJECTS UNDER VARIOUS GLARE CONDITIONS

Headlamp	No Glare		300' Glare		8' Glare		All Glare	
	Young	Old	Young	Old	Young	Old	Young	Old
1 U.S. Low	149	73	146	61	154	71	149	64
2 ECE Low	143	56	153	60	172	62	159	61
3 Mod 1	185	113	194	107	176	121	188	111
4 Mod 2	148	92	157	86	152	96	155	89
5 Single Bm	223	146	194	110	175	97	187	106
6 High Fore	149	66	143	68	154	62	146	66
Means	166	91	165	82	164	85	164	83

outperform the others in general, sometimes by a wide margin. System 5 is sometimes dramatically better than the others on left-side targets. For example, note Figure 3.19, the medium target on the left side. Fifth-percentile performance with system 5 was equivalent to 30-90th percentile performance with the other headlamps. Other comparisons are not quite as large, but still show substantial differences.

Safety problems are more likely to arise from fifth-percentile than from median performance. Using Figures 3.14 through 3.27, Table 3.8 was prepared, showing the 5th-and 50th-percentile levels estimated from these data. The data are relatively noisy, because a few data points can make a difference, especially at the 5th percentile. However, it seems clear that systems 3 and 5 outperform the other four fairly consistently.

Another way of looking at the data is in terms of stopping distance. That is, if the subjects hit the brakes instead of a button, what percentage of them would have stopped short of the target? These values were estimated

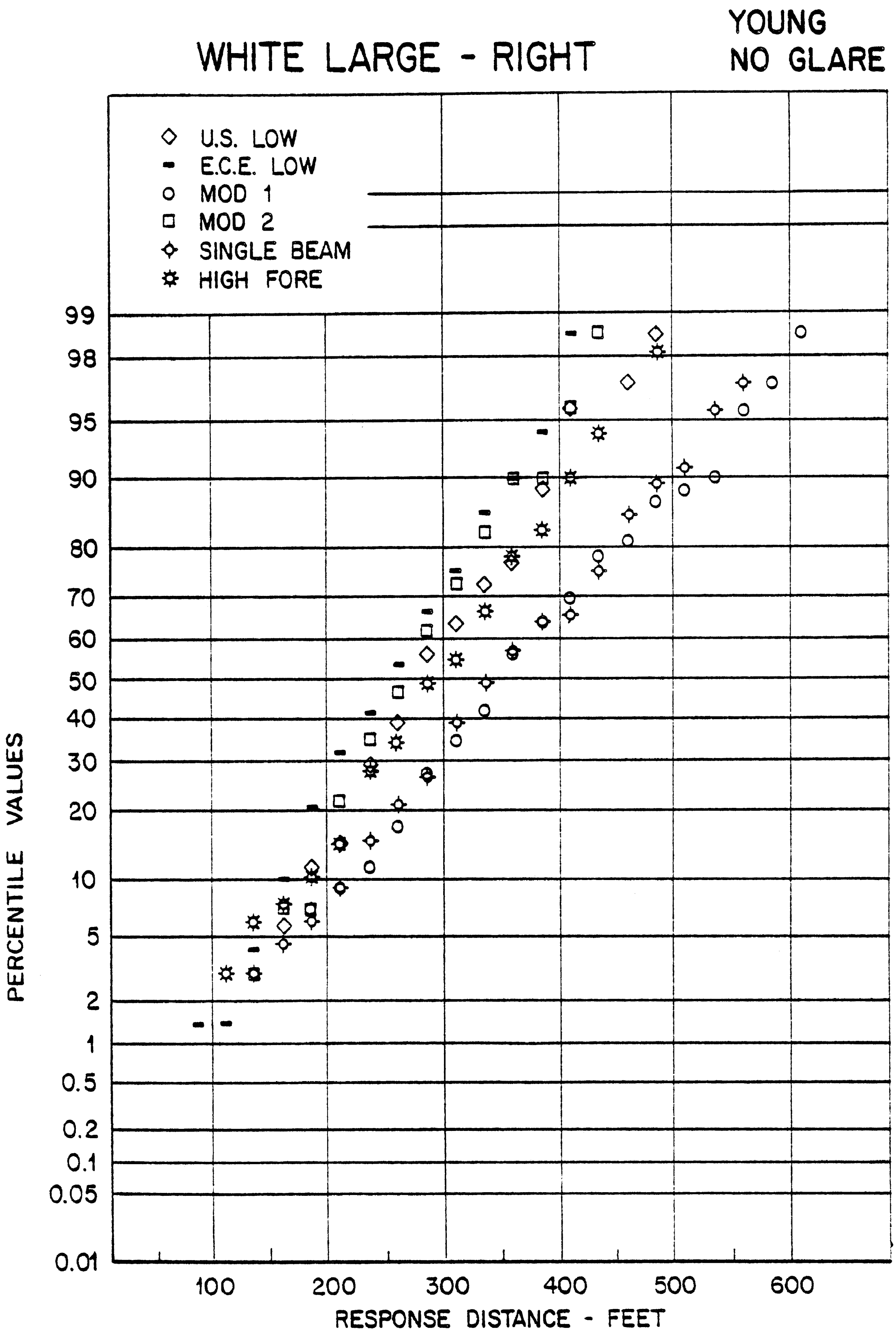


Figure 3.14. Normal probability plot of six lighting systems for white large target on the right side. No-glare, young subjects.

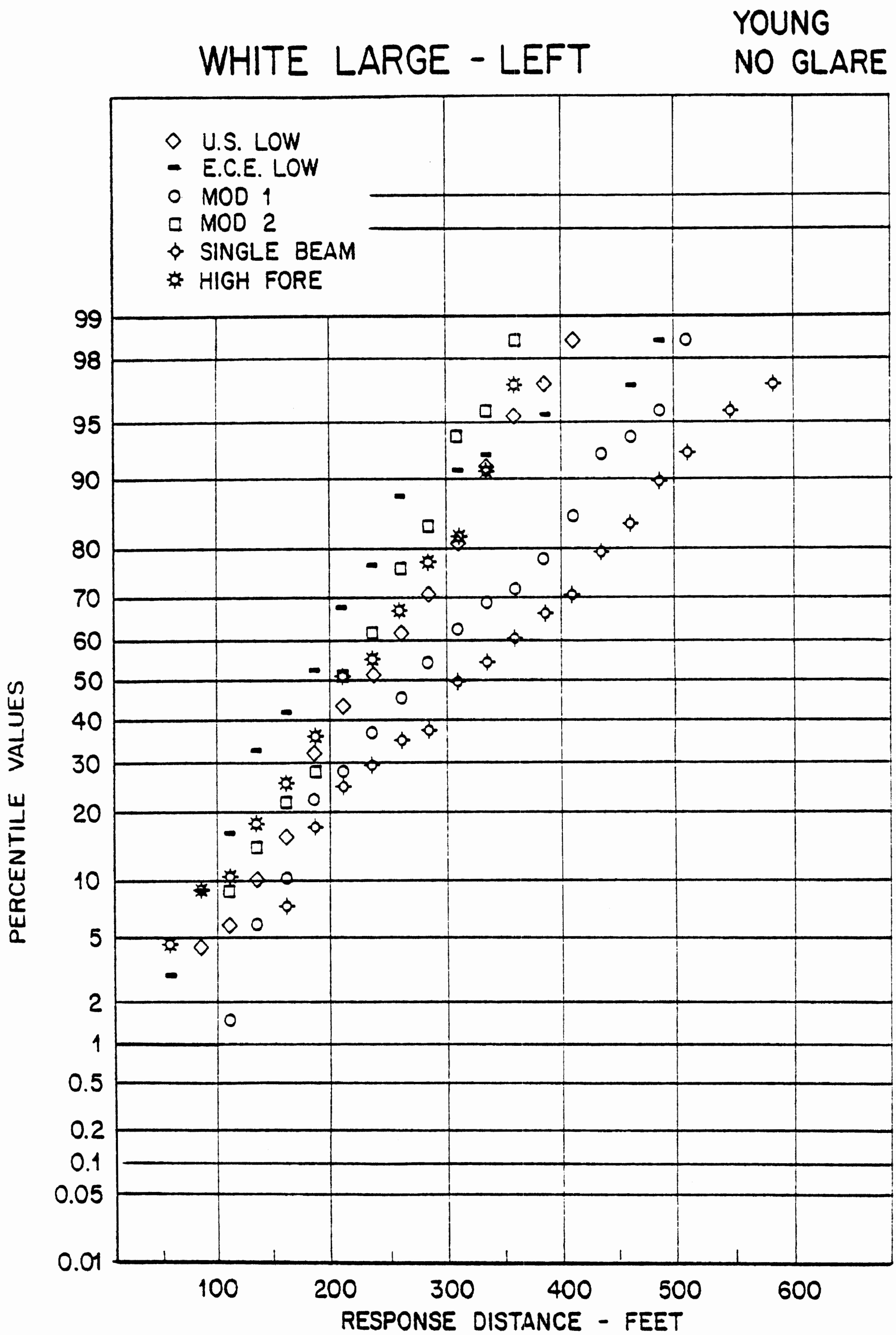


Figure 3.15. Normal probability plot of six lighting systems for white large target on the left side. No-glare, young subject.

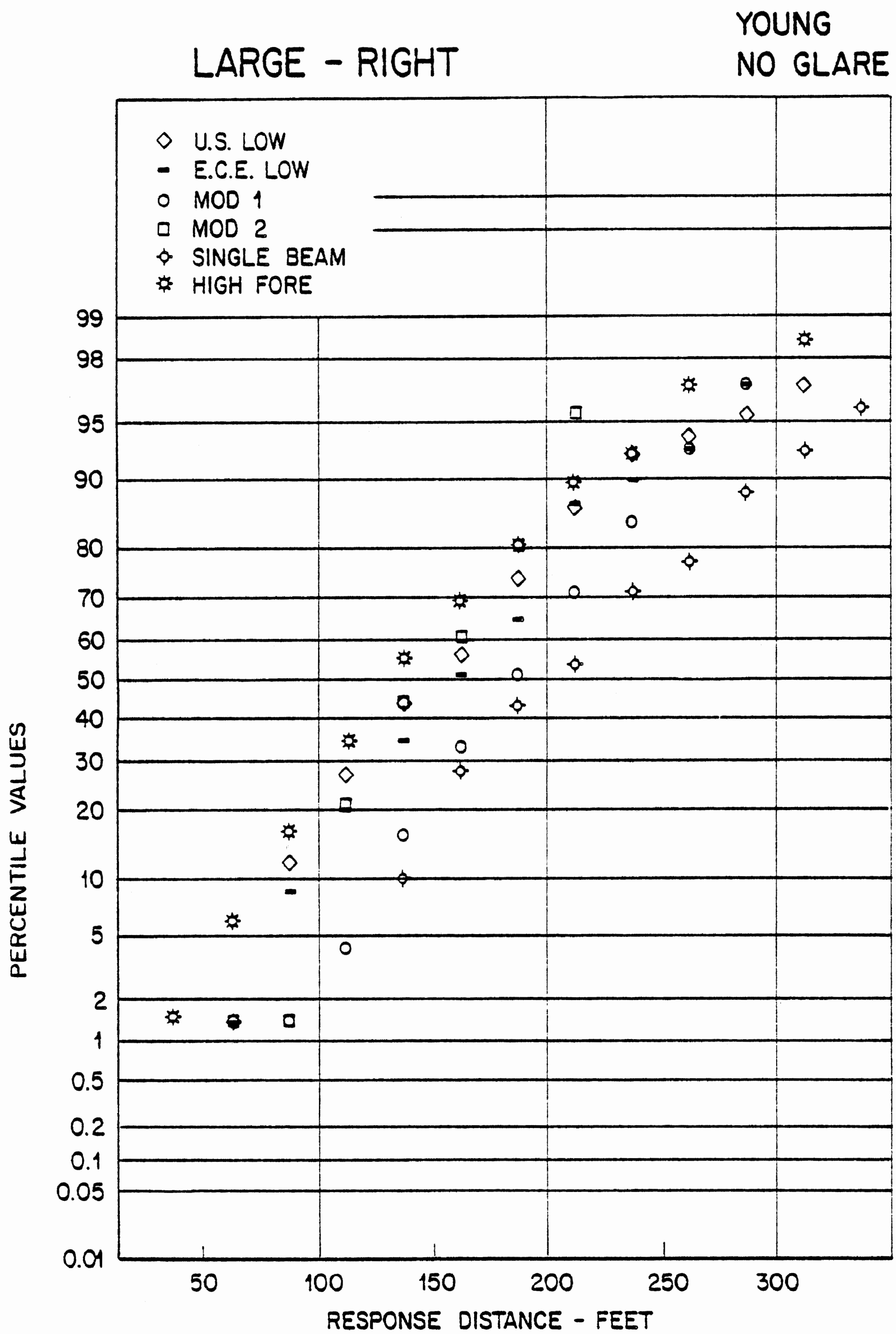


Figure 3.16. Normal probability plot of six lighting systems for large target on the right side. No-glare, young subjects.

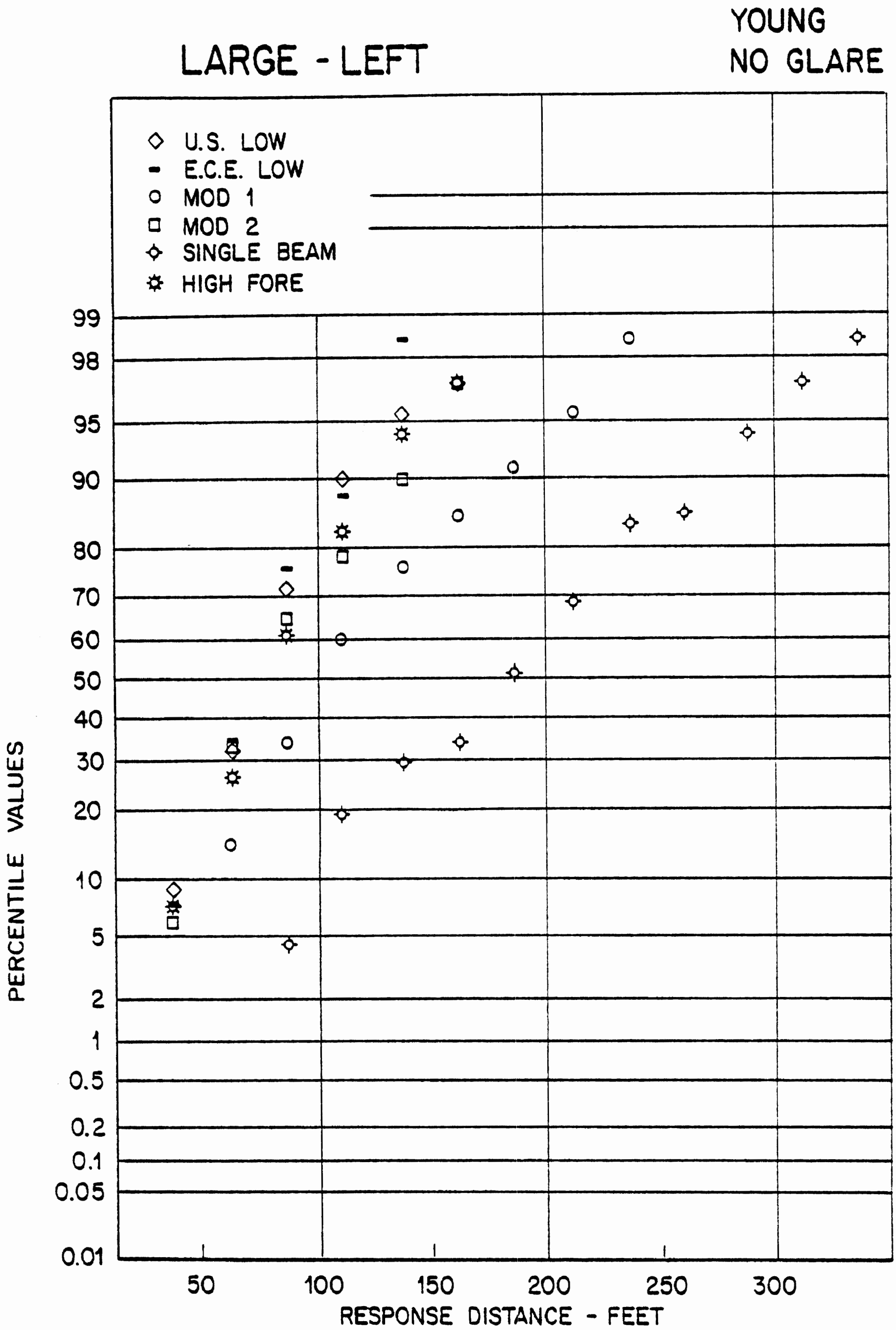


Figure 3.17. Normal probability plot of six lighting systems for large target on the left side. No-glare, young subjects.

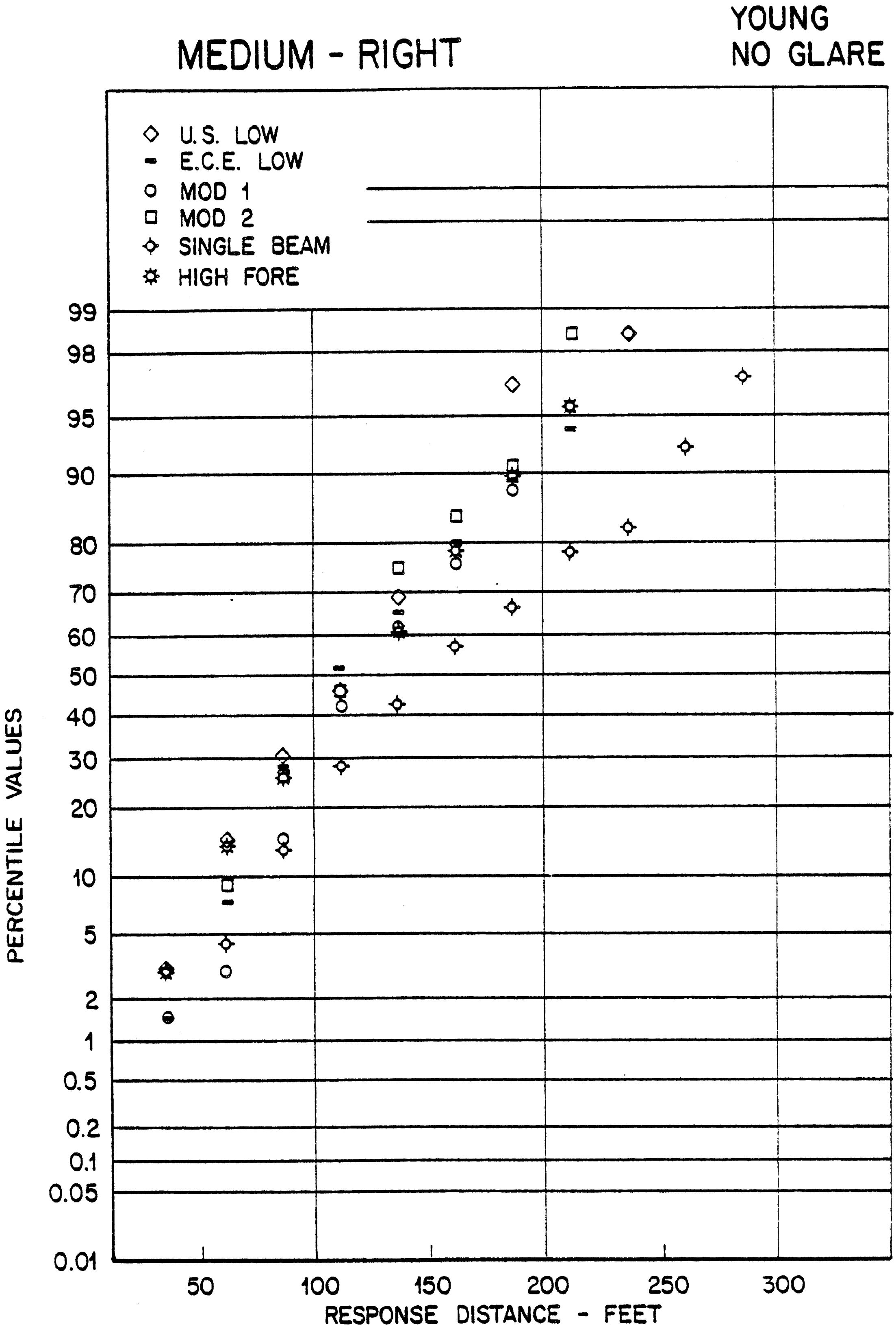


Figure 3.18. Normal probability plot of six lighting systems for medium target on the right side. No-glare, young subjects.

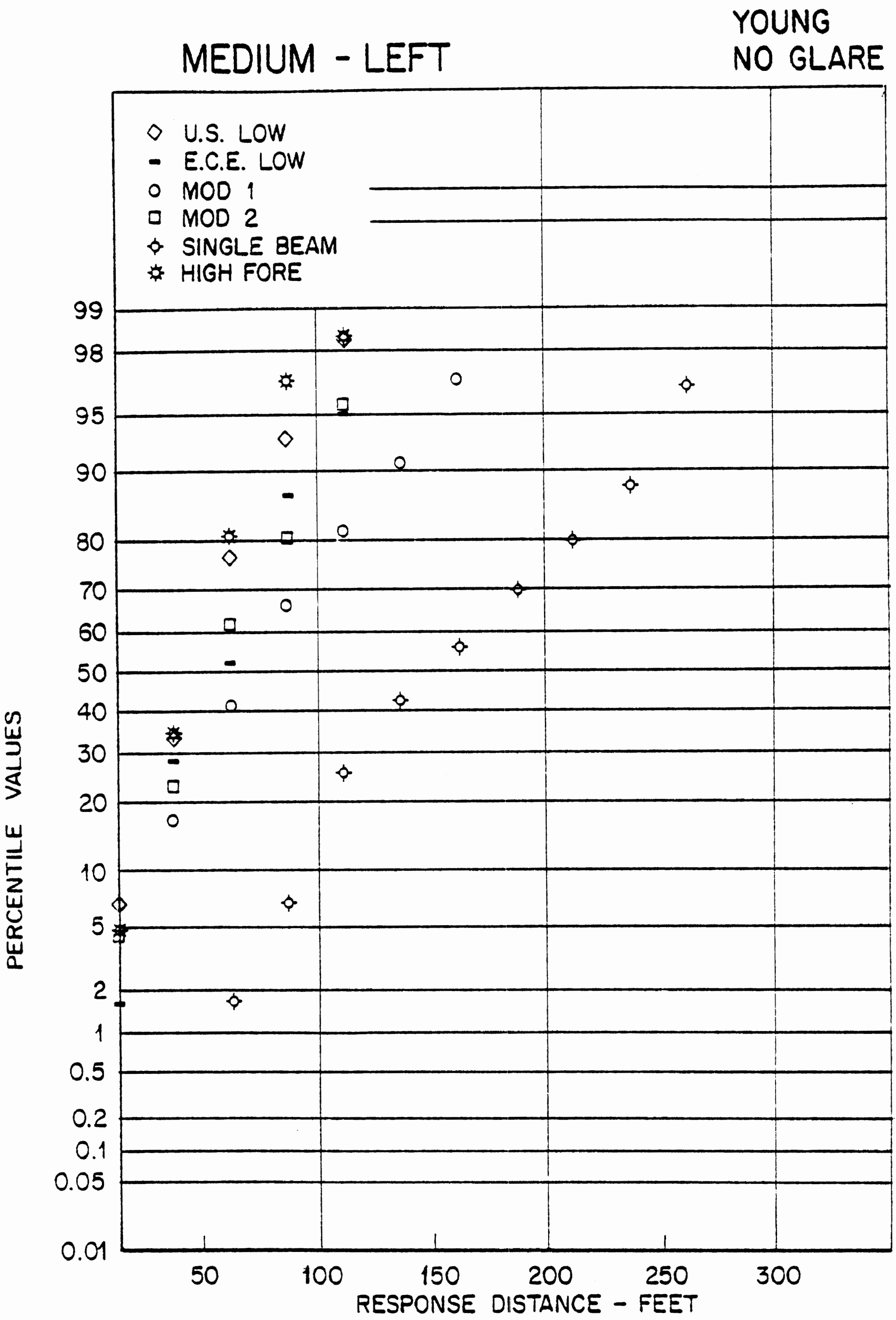


Figure 3.19. Normal probability plot of six lighting systems for medium target on the left side. No-glare, young subjects.

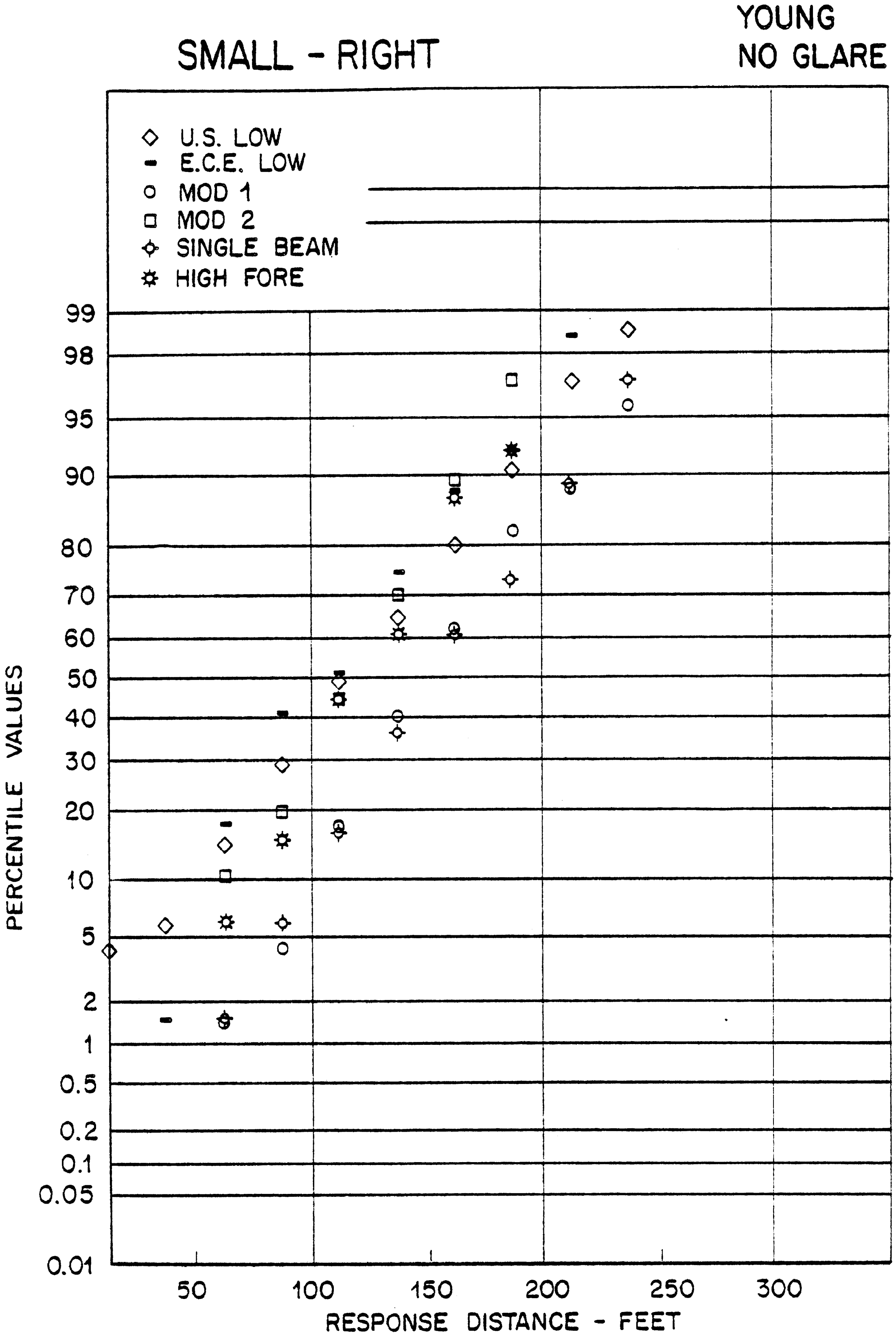


Figure 3.20. Normal probability plot of six lighting systems for small target on the right side. No-glare, young subjects.

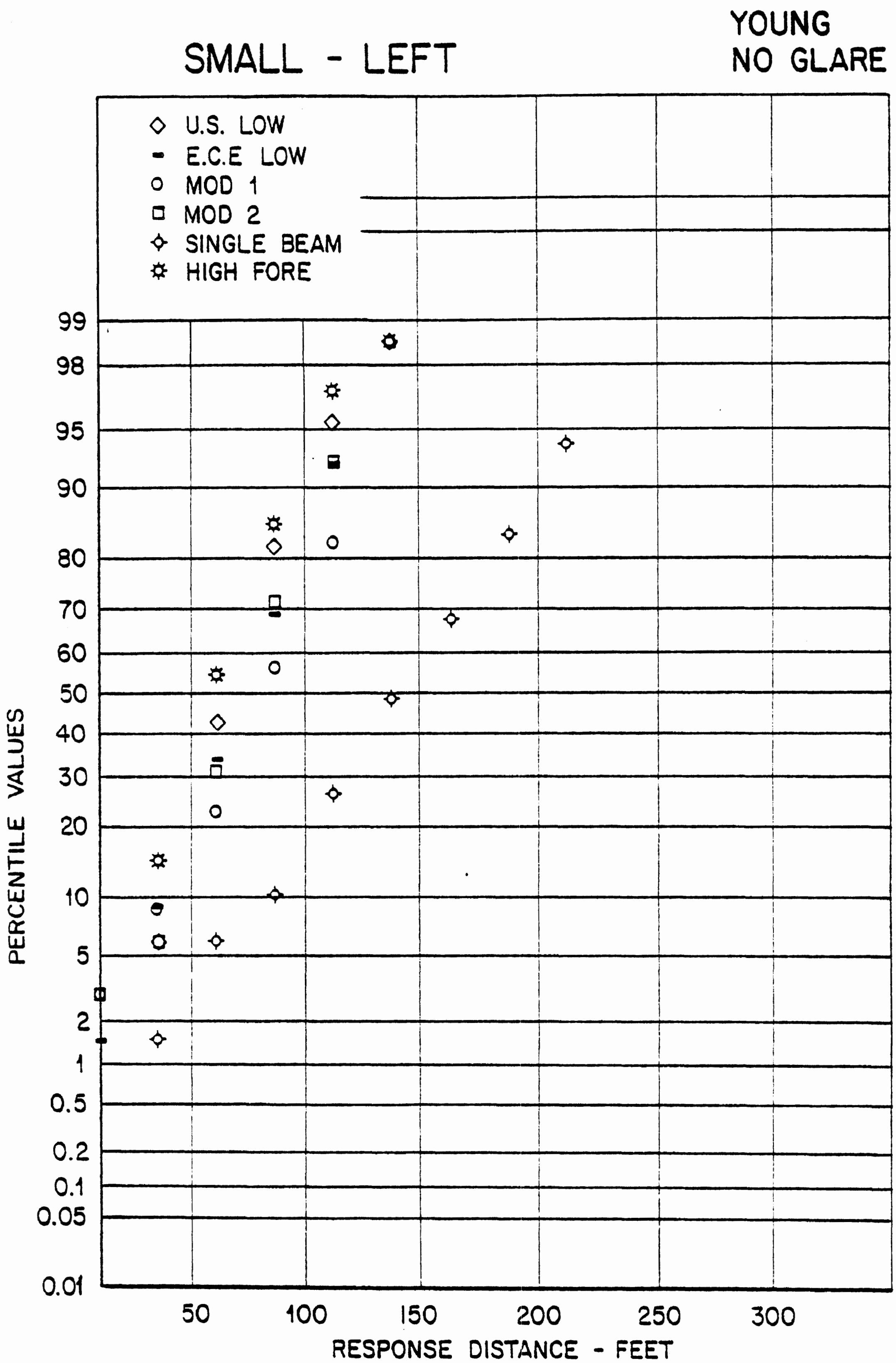


Figure 3.21. Normal probability plot of six lighting systems for small target on the left side. No-glare, young subjects.

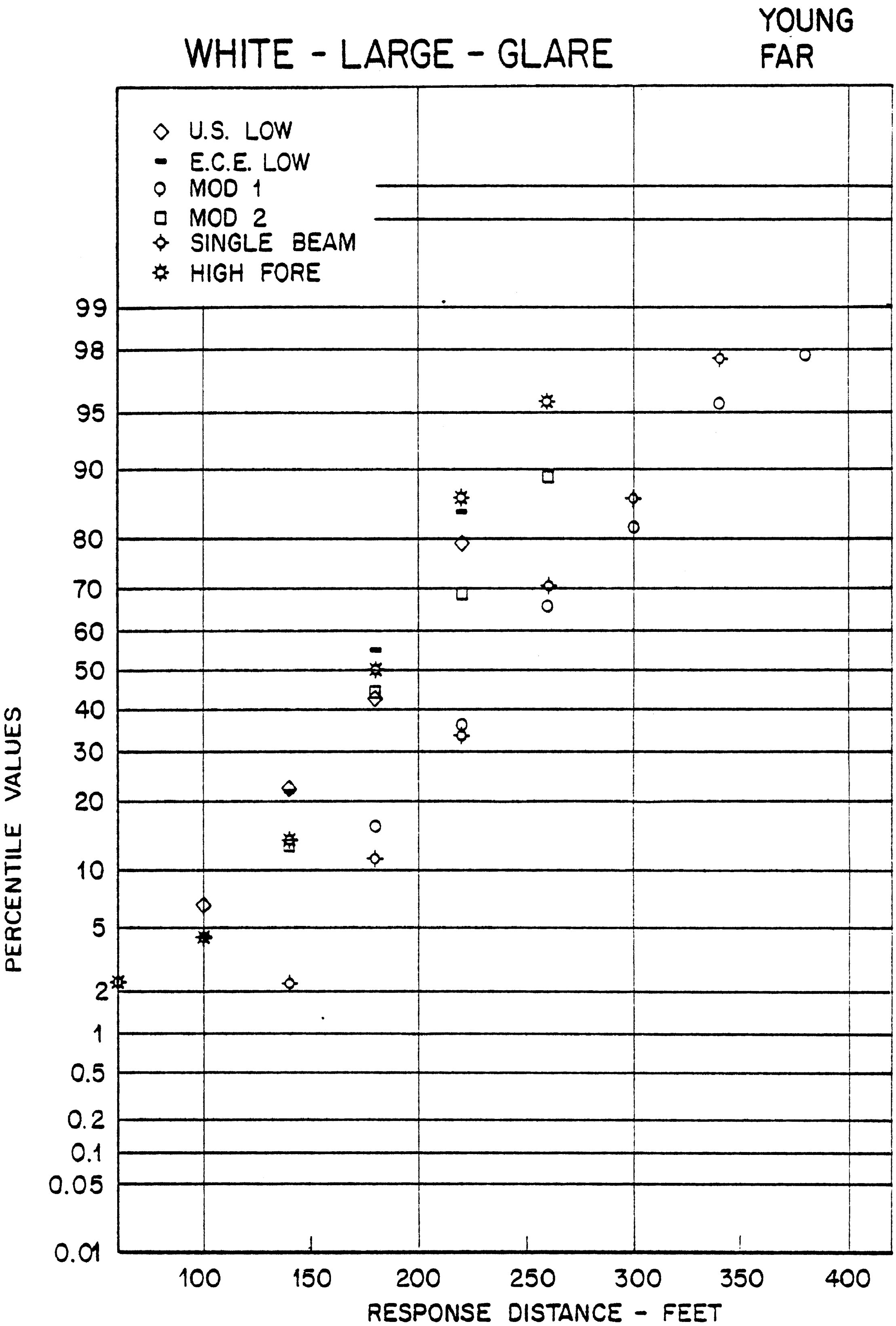


Figure 3.22 Normal probability plot of six lighting systems for white large target on the right side. Glare at 300 feet, young subjects.

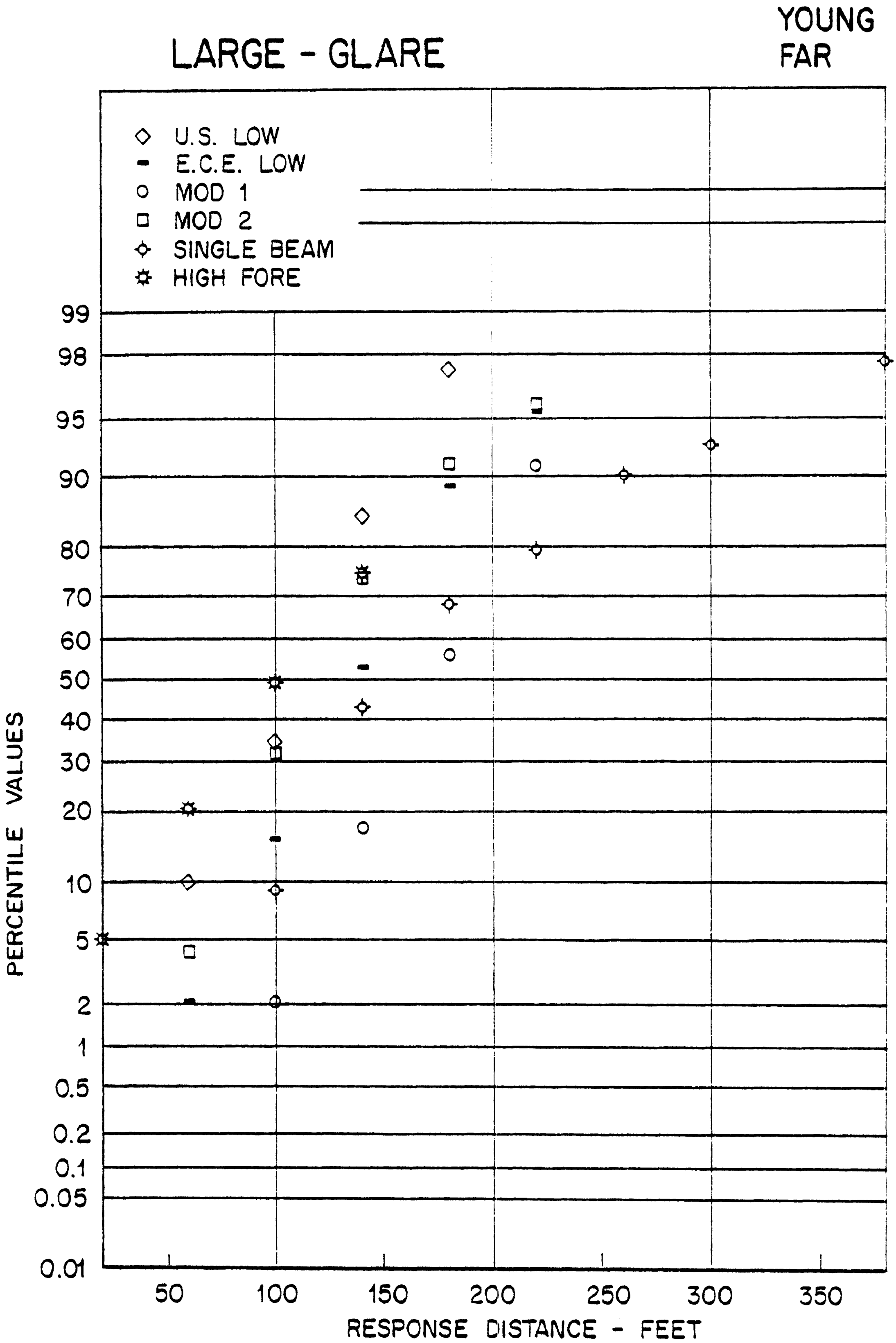


Figure 3.23. Normal probability plot of six lighting systems for large target on the right side. Glare at 300 feet, young subjects.

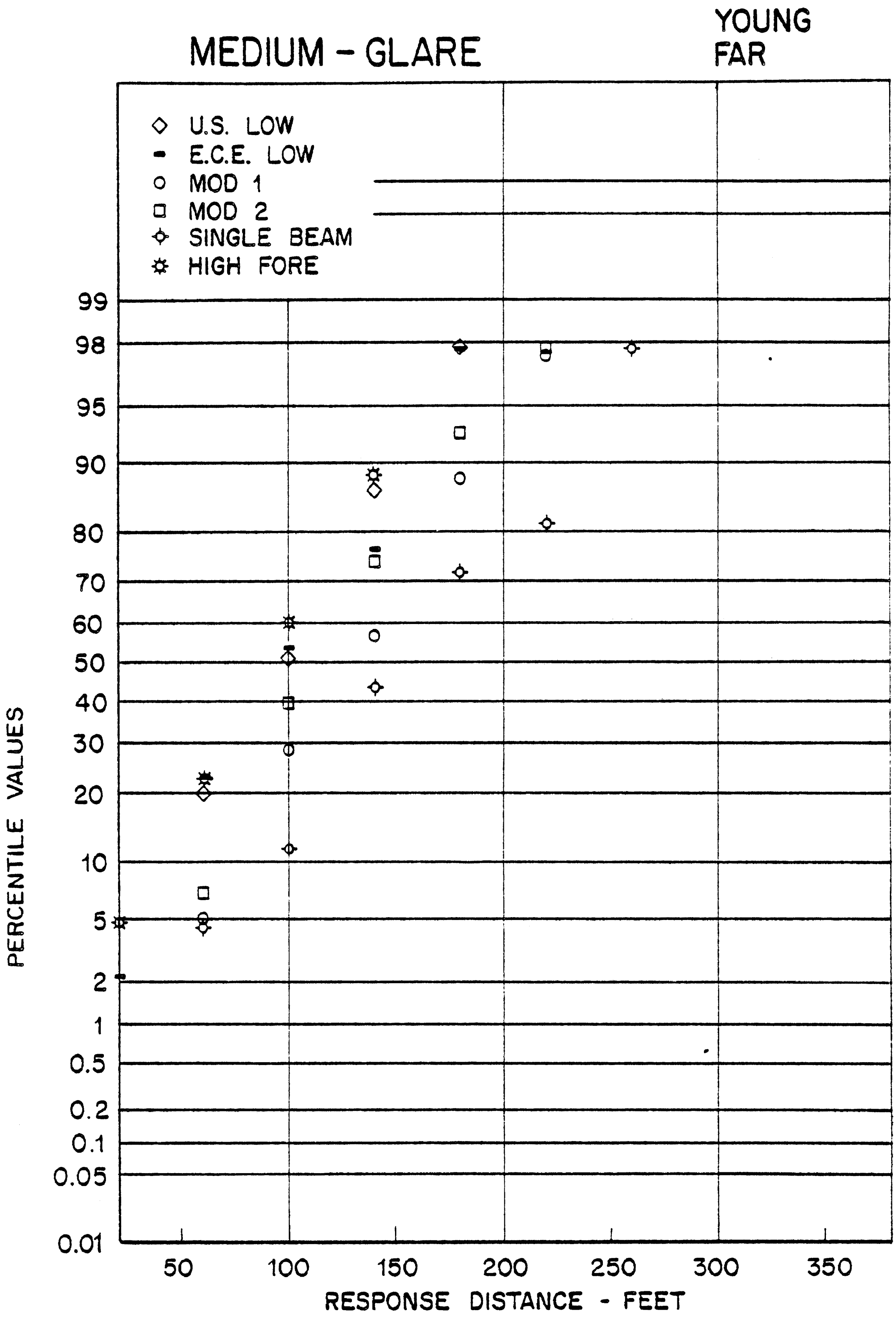


Figure 3.24. Normal probability plot of six lighting systems for medium target on the right side. Glare at 300 feet, young subjects.

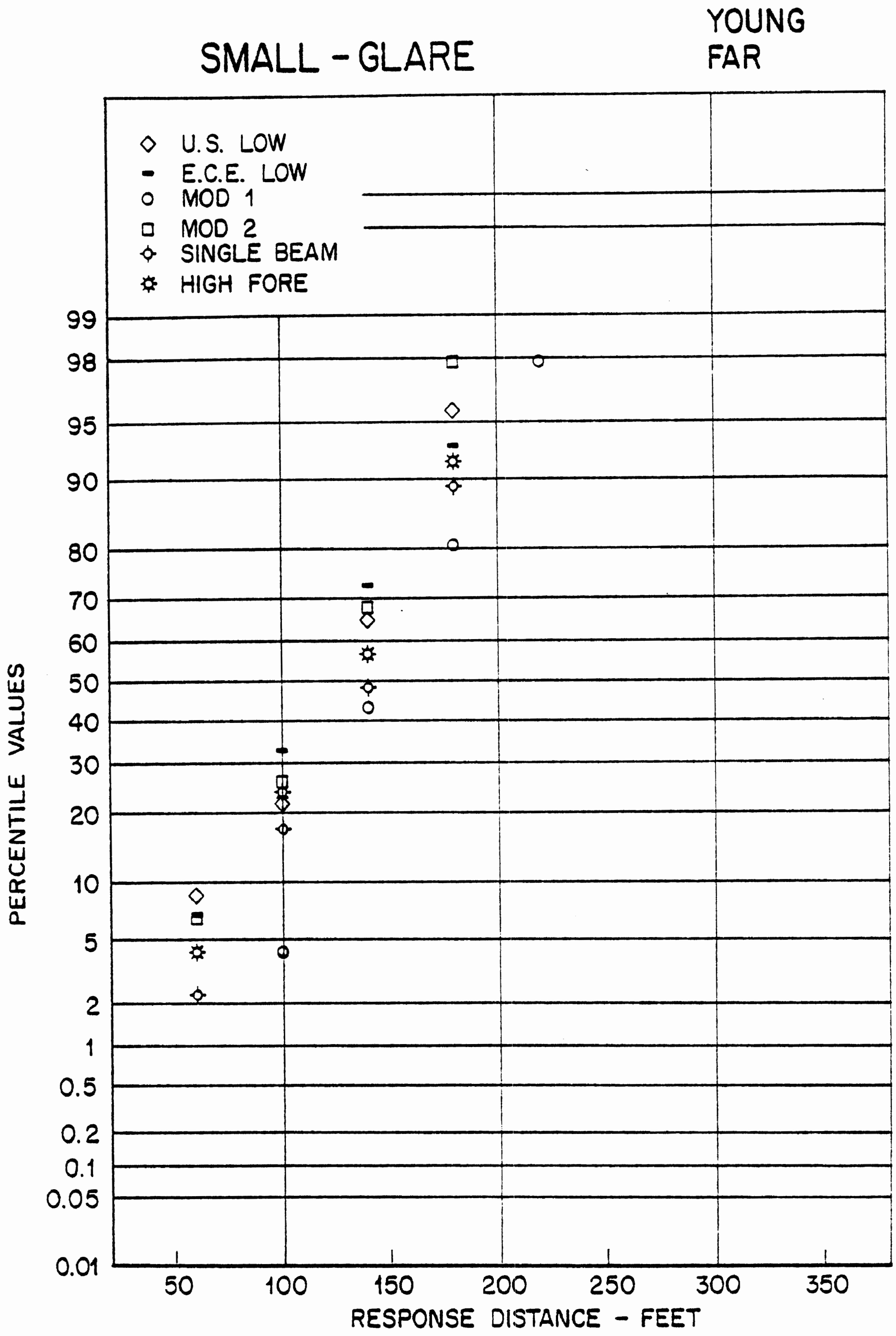


Figure 3.25. Normal probability plot of six lighting systems for small target on the right side. Glare at 300 feet, young subjects.

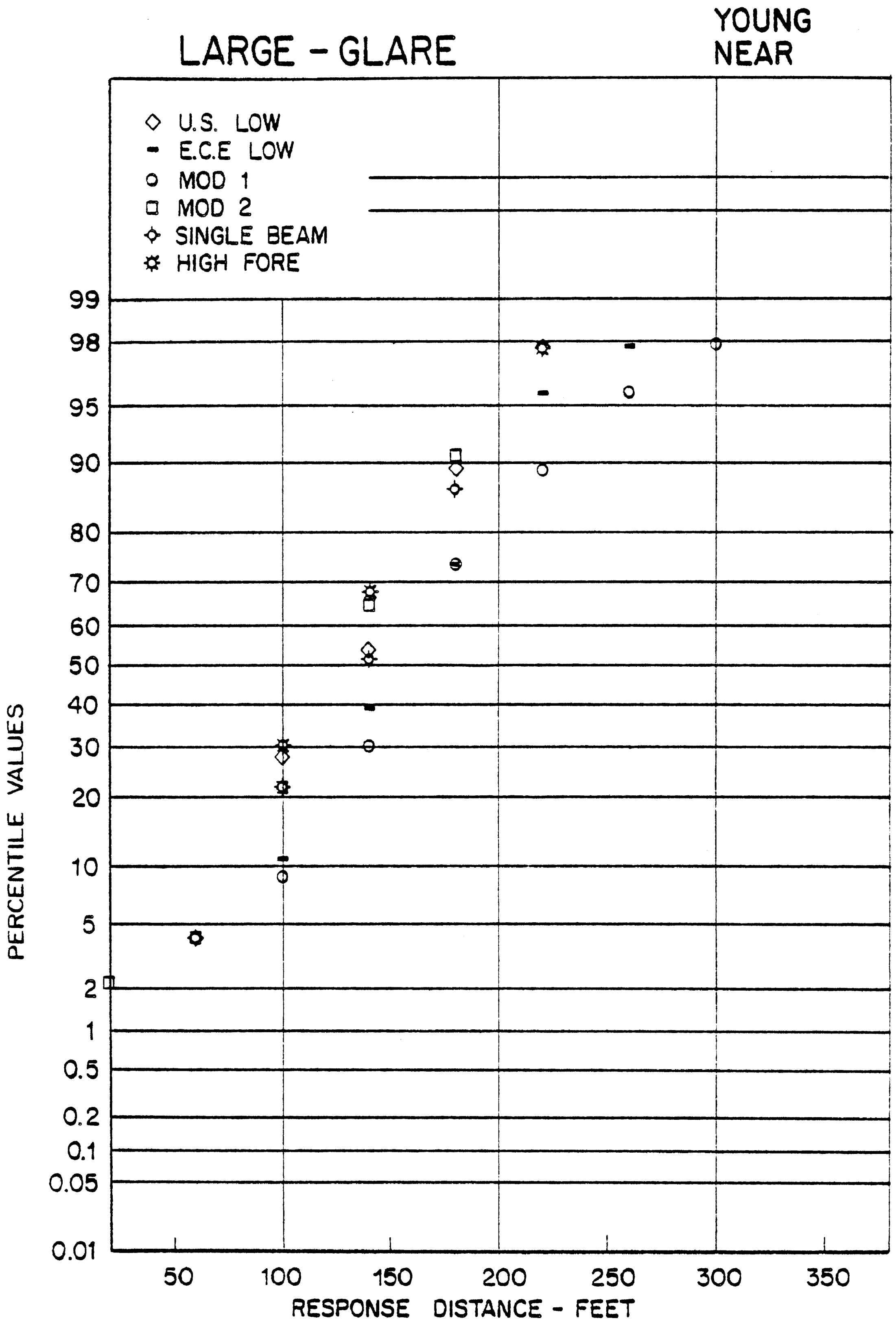


Figure 3.26. Normal probability plot of six lighting systems for large target on the right side. Glare at -8 feet, young subjects.

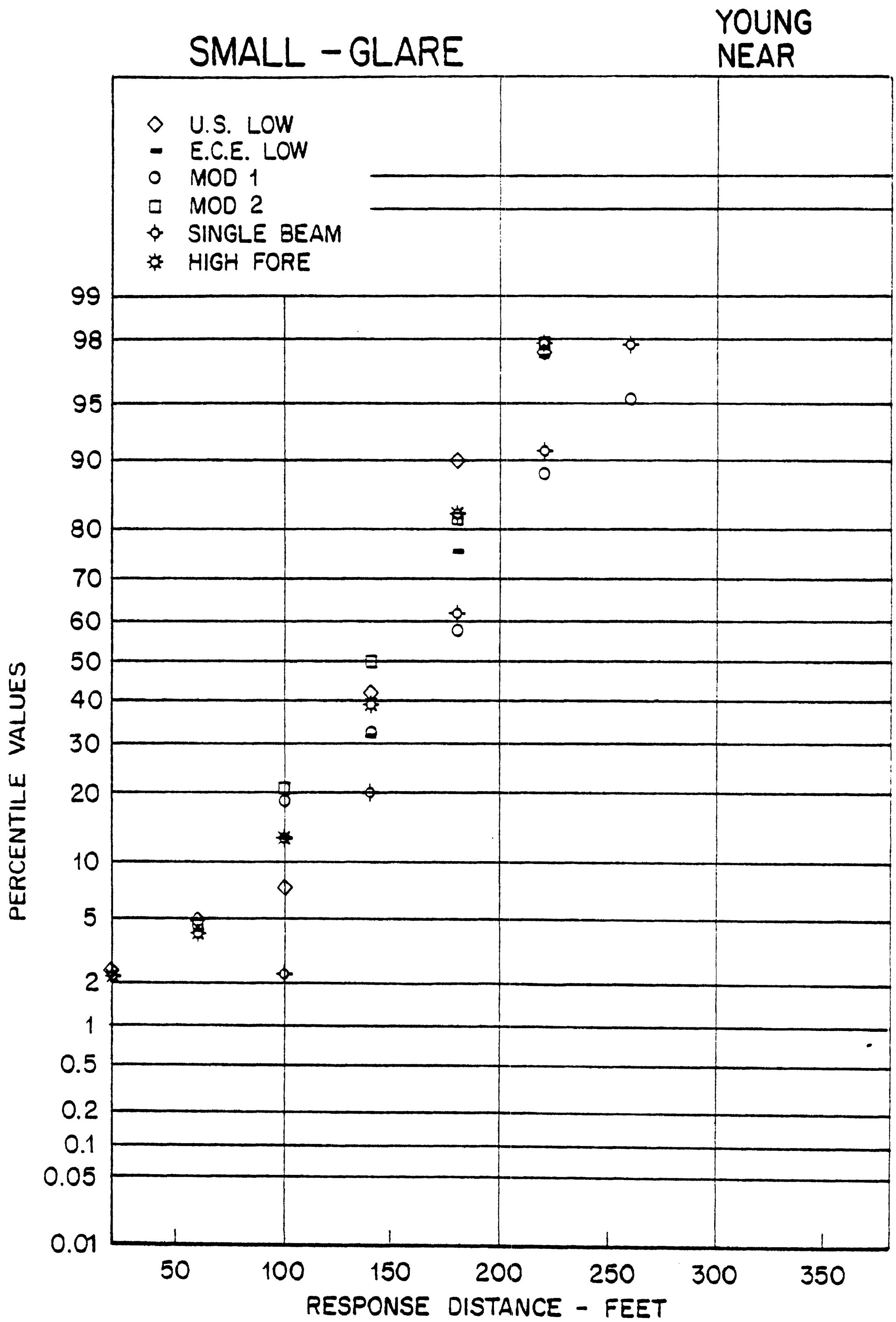


Figure 3.27. Normal probability plot of six lighting systems for small target on the right side. Glare at -8 feet, young subjects.

TABLE 3.8

APPROXIMATE FIFTH AND FIFTIETH PERCENTILE IDENTIFICATION DISTANCES (IN FEET) AS A FUNCTION OF TARGET, LIGHTING SYSTEM AND GLARE CONDITIONS. YOUNG SUBJECTS.

Target		Glare?	Percentile	Headlamp					
Size*	Location**			1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
WL	R	No	50	275	250	350	265	350	285
			5	155	140	170	150	170	130
WL	L	No	50	230	180	275	205	310	205
			5	100	70	135	90	135	60
L	R	No	50	145	160	190	145	200	130
			5	75	80	115	95	120	60
L	L	No	50	75	70	100	75	185	80
			5	30	35	40	35	85	35
M	R	No	50	115	110	120	115	150	120
			5	40	60	70	50	70	45
M	L	No	50	50	60	75	60	155	40
			5	0	10	10	0	80	0
S	R	No	50	110	105	150	115	150	115
			5	35	45	90	45	85	65
S	L	No	50	65	75	85	75	135	60
			5	30	25	35	25	65	20
WL	+300′	Yes	50	180	170	240	190	240	180
			5	95	105	150	115	155	105
L	+300′	Yes	50	115	135	175	120	150	100
			5	45	80	115	65	90	20
M	+300′	Yes	50	100	95	130	115	155	90
			5	20	30	60	20	60	20
S	+300′	Yes	50	130	120	150	125	145	135
			5	50	55	105	55	75	65
L	-8′	Yes	50	135	150	160	130	140	125
			5	65	65	90	45	65	65
S	-8′	Yes	50	150	160	165	140	165	150
			5	60	60	65	60	110	60

*WL = white large
L = large
M = medium
S = small

**R = to observers' right
L = to observers' left

from Figures 3.14 through 3.21 (i.e., no-glare conditions) for three speeds: 35, 55, and 70 mph. Although it is recognized that 70 mph is no longer a legal maximum, it was included because there is some agitation to restore it as a legal maximum. In addition, regardless of the law, some persons still drive 70 mph. The approximate stopping distances, assuming a constant deceleration of 0.75 g (24 ft/sec^2) are:

35 mph - 55 feet
55 mph - 135 feet
70 mph - 220 feet

A straightforward extrapolation of the type attempted here will produce estimates that are conservative. That is, if the identification and response intervals are independent of speed, the car will travel further while they are going on as speed increases. For example, if we estimate 0.5 second for the identification-response interval, overall stopping distance will increase (compared to the 25 mph test speed) by about 7 feet at 35 mph, 22 feet at 55 mph, and 33 feet at 70 mph.

However, the way in which these data were collected did not provide an estimate of the identification-response interval. Rather than guess at it, the values presented in Table 3.9 assume the driver's foot would contact the brake at the same point regardless of speed.

Despite the fact that the data are uncorrected for speed, and despite the subjects being in a relatively high state of alertness, the data in Table 3.9 are appalling. It appears that a maximum nighttime safe speed for even the most powerful low beam tested would be less than 35 mph.

Table 3.10 provides a similar analysis for the case of the older subjects. Because there are fewer data points for the older subjects, the percentile distributions were obtained by combining results for all six lighting systems. Data for two lamps listed in Table 3.9 are included for

TABLE 3.9

APPROXIMATE PERCENT OF SUBJECTS WHO WOULD NOT HAVE BEEN ABLE TO STOP SHORT OF THE TARGET AT VARIOUS SPEEDS. YOUNG SUBJECTS, NO GLARE CONDITIONS.

Target		Speed MPH	Estimated Stopping Distance (feet)	Headlamp					
Size*	Location**			1 U.S. Low	2 ECE Low	3 Mod 1	4 Mod 2	5 Single Bm	6 High Fore
WL	R	35	55	<1	<1	<1	<1	<1	<1
		55	135	3	4	3	3	3	6
		70	220	24	36	11	28	11	20
WL	L	35	55	<1	<1	<1	<1	<1	<1
		55	135	9	31	5	12	5	18
		70	220	48	72	32	56	26	56
L	R	35	55	1	1	<1	<1	<1	4
		55	135	45	25	16	45	10	55
		70	220	89	88	76	98	58	92
L	L	35	55	22	21	12	21	3	21
		55	135	95	98	76	90	30	94
		70	220	>99	>99	96	>99	72	>99
M	R	35	55	12	6	3	7	3	12
		55	135	68	66	62	75	43	62
		70	220	98	96	97	99	80	97
M	L	35	55	68	48	36	54	1	68
		55	135	>99	>99	91	>99	42	>99
		70	220	>99	>99	>99	>99	84	>99
S	R	35	55	12	13	1	8	1	4
		55	135	65	75	40	70	36	61
		70	220	94	99	92	>99	93	>99
S	L	35	55	34	28	20	26	5	42
		55	135	99	>99	98	>99	48	99
		70	220	>99	>99	>99	>99	96	>99

*WL = white large
L = large
M = medium
S = small

**R = to observers' right
L = to observers' left

purposes of comparison. In most cases, at 35 and 55 mph, the older subjects were much less likely to have been able to stop in time than the younger subjects.

TABLE 3.10

APPROXIMATE PERCENT OF SUBJECTS WHO WOULD NOT HAVE BEEN ABLE TO STOP SHORT OF THE TARGET AT VARIOUS SPEEDS. NO-GLARE CONDITIONS. OLDER SUBJECTS AVERAGED ACROSS ALL HEADLAMPS. YOUNGER SUBJECTS SHOWN FOR BEST LAMP TESTED AND STANDARD U.S. LOW BEAM.

Target		Speed (mph)	Subjects		
Size	Location		Older	Young U.S. Low	Young Single Bm
WL	R	35	1	<1	<1
		55	23	3	3
		70	57	24	11
WL	L	35	8	<1	<1
		55	56	9	5
		70	83	48	26
L	R	35	22	1	<1
		55	83	45	10
		70	98	89	58
L	L	35	49	22	3
		55	94	95	30
		70	98	>99	72
M	R	35	37	12	3
		55	94	68	43
		70	>99	98	80
M	L	35	76	68	1
		55	>99	>99	42
		70	>99	>99	84
S	R	35	25	12	1
		55	98	65	36
		70	>99	94	93
S	L	35	75	34	5
		55	>99	99	48
		70	>99	>99	96

3.1.4 Discussion. The basic finding of the field study reported in this chapter is that two of the experimental lighting systems tested (numbers 3 and 5) have the potential of improving driver visibility under night operating conditions by a substantial margin over present-day systems.

The benefits are "potential" in that evaluation work on the experimental systems described is incomplete. For example, adverse weather problems have not been adequately explored. More important, as should be evident from the chapter on discomfort glare, things happen to headlamps in the real world that substantially affect their performance, and over which the lighting engineers have little control. It is important that these proposed lighting systems be evaluated under more realistic conditions prior to making final recommendations. As a first step in a comprehensive evaluation, the systems have been subjected to computer simulation by both UMTRI and the Ford CHESS models. The results are described in Section 3.2 of this report.

There is a suggestion in the data that lighting systems that perform similarly in terms of visibility measures may differ when compared on a basis of the likelihood of identification errors. Specifically, the two variants of the standard U.S. low beam (beams 1 and 6, the standard and high foreground systems) were associated with more identification errors than the other beams tested. Under glare conditions the differences were significant. These results were unexpected and the reasons for them are not clear. It is an area worth exploring further.

Of course, there is no assurance that identification errors on a test like this are meaningful in terms of real-world performance. But, identification is clearly an important step in the processes that leads to driver decision. If there are differences in the ease with which identification can be made as a function of beam pattern (other than intensity), this should be known.

The difference between the young and older subjects in this series of studies is interesting and worthy of concern. While the number of older subjects was limited, their relative performance is consistent with other work conducted at UMTRI and elsewhere.

Differences between day and nighttime visual performance increase with age. At any time a high-luminance acuity check (the usual driver-vision test) says little about low-luminance capability. But it is even less helpful when dealing with the older driver. If markedly reduced visual performance cannot be detected by normal screening methods, then persons must decide for themselves when it is no longer safe to drive at night. Loss of mobility, even only under certain conditions such as after dark, is a serious restriction to most people. If the choice is left to them, the decision is apt to be skewed in their favor.

One of the findings of this project is that the older driver is at a marked disadvantage in detecting and identifying low contrast objects in the forward field and in the disabling effects of glare (project Interim Report, Olson and Sivak, 1981). However, these are gradual changes, the extent of which are probably not readily apparent to the person involved. What could be readily apparent is discomfort associated with the glare from oncoming headlamps. If the comfort threshold changed in the same way that glare disability effects increase, so that driving at night became something of a miserable experience due to glare, the older person would be more apt to stay home. Unfortunately, the data indicate that there is little change in glare discomfort at typical glare exposure levels (see Section 2.1).

When compared with required stopping distance, the response distance data reported in this study reveal some rather marked possible deficiencies. It seems clear, for example, that a dark-clad pedestrian who places him/herself in the path of an oncoming vehicle at night, relying on the driver to respond appropriately, is at considerable risk.

Improvements to vehicle lighting systems can help this situation. However, as should be clear from the identification distance study, it is unlikely to provide a complete solution. There seem to be only three other options, i.e.:

a. Improve illumination in general (i.e., by use of fixed lighting systems on all roads).

b. Reduce speed limits to correspond to the limitations of headlamps.

c. Improve the contrast of targets of interest (e.g., through the widespread use of retroreflective materials).

Unfortunately, none of these options are particularly promising as a complete solution. Certainly something can be done with each of them in some situations to bring about an improvement. However, this means that planners and decision-makers must be aware of the limitations of automotive headlamps. In our experience, they generally are not. Worse than not being aware, most persons seem to have an unrealistically optimistic opinion of the effectiveness of headlamps. This leads in turn to a lack of concern with the problem of driver visibility, and an unfortunate tendency to attribute collisions with low-contrast objects to "driver error."

3.2 Analysis of Lamp Performance Using Computer Modeling

3.2.1 Introduction. Section 3.1 of this report described an objective study that involved the measurement of identification distances in a full-scale setting.

Because such studies are time-consuming and costly to run, the number of conditions that can be examined is relatively limited. In order to economically expand the scope of the evaluation, computer modeling techniques were used. Two such analyses were carried out. One made use of a seeing distance model developed at the University of Michigan (Mortimer and Becker, 1973). The second was made with the CHESS model (Bhise et al., 1977), with the kind cooperation of scientists at Ford Motor Company.

3.2.2 Seeing Distance Evaluation. The U of M headlighting model predicts the detection distance of targets under a variety of conditions. The model allows the following parameters to be varied:

Headlamps

- Beam characteristics
- Intensity
- Number
- Position (vertical and lateral dimensions)
- Aim (horizontal and vertical)

Roadway

- Flat-straight
- Hills and valleys
- Curves

Target characteristics

- Position (vertical and horizontal)
- Reflectivity

Driver eye position

An "approaching" vehicle is included in the simulation. The headlamps on this vehicle can be specified as fully as on the primary vehicle, and they need not be the same. The lateral distance between the tracks of the two vehicles can be varied, as can the longitudinal separation at the start and end of each run.

The model outputs a great deal of data, the most important of which for purposes of this study are:

(1) Target detection distances at various points before and after the two vehicles meet.

(2) Maximum and minimum detection distances.

(3) Glare in foot candelas at the driver's eye as well as in discomfort glare scale units.

The model was developed based on closed-course seeing-distance tests (see Mortimer and Olson, 1974a and 1974b) involving predictable target locations and a relatively simple discrimination task. Thus, the predictions it yields would be expected to be significantly greater than were measured under the conditions of the field test described in Section 3.1.

The first step in this analysis was to set up the field test conditions in the model and compare the predicted and measured identification distances. This was initially done for the white large, medium, and small targets in both right and left positions, using the U.S. low,, ECE low, and Mod-1 beams. The measured (M) and predicted (P) no-glare identification distances resulting from this analysis are given in Table 3.11. Also shown for each comparison is the ratio of the two measures (P/M).

As expected, the predicted response distances are greater than those measured in the field. For the smaller targets the difference is about 2:1. The difference is not so great in the case of the white large target, averaging about 1.6:1.

TABLE 3.11

COMPARISON OF MEASURED IDENTIFICATION DISTANCES (in feet) WITH THOSE PREDICTED USING COMPUTER SEEING DISTANCE MODEL

Target		Predicted or Measured	Headlamps		
Size	Location		U.S. Low	ECE Low	Mod-1
WL	R	P	491	376	587
		M	298	269	373
		P/M	1.65	1.40	1.57
WL	L	P	412	356	483
		M	248	206	298
		P/M	1.66	1.73	1.62
M	R	P	248	196	258
		M	128	129	142
		P/M	1.89	1.52	1.82
M	L	P	134	102	178
		M	60	71	88
		P/M	2.23	1.44	2.02
S	R	P	267	219	263
		M	127	118	164
		P/M	2.10	1.86	1.60
S	L	P	157	164	196
		M	80	86	94
		P/M	1.96	1.91	2.09

The data from Table 3.11 are shown in the form of a scatterplot in Figure 3.28. The correlation computed from these data is 0.98. Based on these results there is reason to believe that the model is capable of making predictions of visibility with reasonable accuracy.

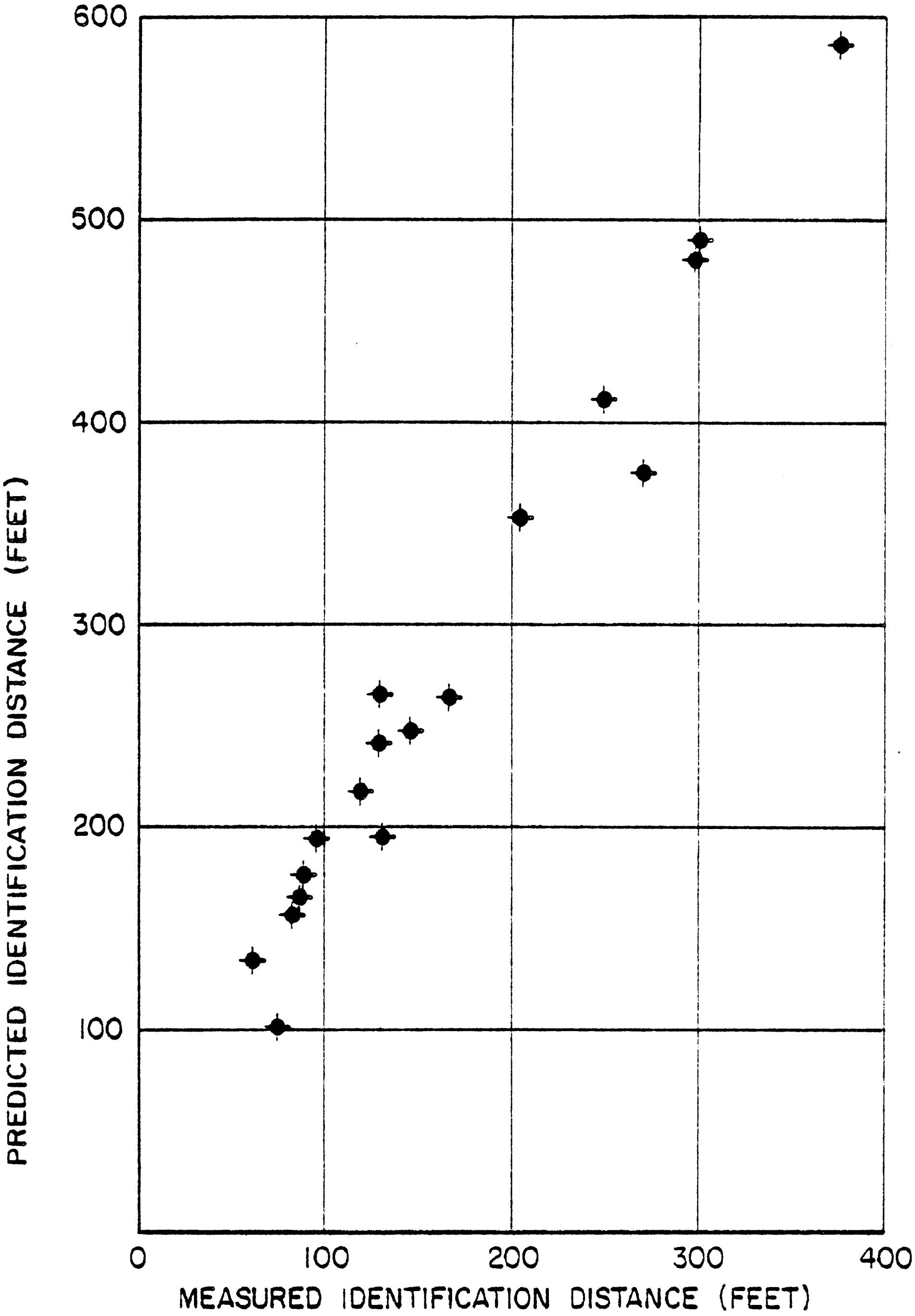


Figure 3.28. Scatterplot of measured and predicted identification distances from validation runs.

The target of major interest was the dark pedestrian ("L" target). As a next step in the validation a comparison was made between measured and predicted identification distances on this target for all lighting systems, with the exception of the high foreground. The results of this comparison are as follows (target on right, distances in feet):

	US Low	ECE Low	Mod-1	Mod-2	Single Beam
Predicted	195	200	250	208	276
Measured	165	176	200	161	223
P/M	1.18	1.14	1.25	1.29	1.24

The correlation computed from these data is 0.96.

It will be noted that the measured and predicted distances correspond more closely in this case, the latter averaging about 25% greater than the former. In any case, the model seems to be doing an acceptable job of predicting lamp performance. On this basis a decision was reached to continue the analysis.

The first step was to evaluate performance in meeting situations on curves. It was assumed that the meeting was with an identically equipped vehicle on a curve having a constant radius of 1000 feet (305 meters). The results of this analysis are provided in Table 3.12. These data indicate that, for curves to the right, the Mod-1 and Single Beam systems outperform the others. Given their distributional characteristics, this is to be expected. The left curve situation effectively moves the observer to the oncoming car in the first analysis. From this perspective only the single beam system appears significantly better than the others. For all of the systems the target becomes invisible for a short period of time when glare from the opposing headlamps is maximum.

Table 3.13 compares performance on a crest vertical curve (radius = 4,000 feet or 1219 meters). The Mod-1 and 2

TABLE 3.12

MAXIMUM AND MINIMUM RESPONSE DISTANCES (IN FEET) FOR VARIOUS LIGHTING SYSTEMS IN MEETING SITUATIONS ON HORIZONTAL CURVES

Headlamp	Curve to Right		Curve to Left	
	Maximum	Minimum	Maximum	Minimum
U.S. Low	135	105	178	0
ECE Low	121	105	160	0
Mod-1	159	117	184	0
Mod-2	142	110	186	0
Single Beam	158	118	231	0

units and the single beam outperform the control systems by a significant margin.

TABLE 3.13

MAXIMUM AND MINIMUM RESPONSE (IN FEET) FOR VARIOUS LIGHTING SYSTEMS IN MEETING SITUATIONS ON A HILL

Headlamp	Maximum	Minimum
U.S. Low	253	116
ECE Low	242	110
Mod-1	291	122
Mod-2	281	105
Single Beam	326	169

3.2.3 CHESS Analysis. The Ford CHESS model is a computer program that attempts to run a comprehensive, objective analysis of a headlighting system. To introduce the technique, the following paragraphs are quoted from the final report describing the model and research background (Bhise et al., 1977):

> "The Ford Headlight Evaluation Model simulates night driving situations, computes driver visual performance under a variety of conditions and outputs an overall Figure of Merit, or score, for each headlight system tested. The Figure of Merit for a given headlighting system is the percentage of distance traveled at night, on a simulated standardized test route, in which the visual environment can be considered adequate for drivers using that system. The visual environment is considered to be adequate when seeing distances to both pedestrian and pavement delineation targets are equal to or greater than appropriate criterion distances, and when the discomfort glare experienced by opposing drivers is less than some criterion value.
>
> The Model simulates thousands of encounters with targets and opposing vehicles and applies these criteria to each encounter.
>
> The standardized test route is a computer simulation of a series of highway sections incorporating environmental factors influencing driver visual performance, such as topography, the reflectance and ambient brightness of the road and road elements, highway type, traffic characteristics, target characteristics and weather. It is assembled in the form of a computer file in a separate operation prior to making any evaluation runs with the Model. The particular values of the environmental parameters that pertain to a given encounter are drawn randomly from distributions generated from the Ford field research and analyses. The standardized test route is thus a random sample of the U.S. night driving environment as defined by Ford research. Operationally it functions as a sequential list of the environmental conditions the observer vehicle will experience in each encounter as it proceeds along the highway.
>
> Random values of nonenvironmental variables having an influence on driver performance or Figure of Merit criterion levels are also

included in the list of conditions defining each encounter. Examples of these are driver visual detection performance capability and reaction time, headlamp misaim and the headlamp beams in use (high, mid or low) by the observer and opposing vehicles.

Although originally defined by random selection, the same standardized test route is used to evaluate all headlight systems in a given set of evaluations."

The results of the CHESS analysis are provided in Table 3.14. Figures of Merit (FOM) are shown for each of the systems used in the test for both perfect aim and random misaim. The same information is provided for six reference lamps from the CHESS library. In comparing results it should be noted that a difference of 2 FOM points is significant at the 0.90 level.

Under perfect aim the two more powerful experimental systems (Mod-1 and Single Beam) have higher FOM scores than any other system listed, although the differences are less than 2 FOM points in many cases. In view of the performance of these two systems in the field study this small difference may seem surprising. Part of the answer lies in the third column of the table, which indicates that these systems discomforted a much larger percentage of oncoming drivers than any other system.

More meaningful in terms of real-world performance is the FOM under random misaim conditions. All of the test systems FOM scores dropped considerably under this condition. In general the test systems found best under the field and computer tests conducted prior to this are no better than the standard systems, based on the CHESS analysis. The reasons for this will be found in the five columns on the right side of Table 3.14. These data indicate that the Mod-1 and Single-Beam systems caused discomfort to a larger percentage of oncoming drivers than did the other systems and, in opposed encounters, did no

TABLE 3.14

RESULTS OF CHESS MODEL APPLICATIONS

	Figure of Merit		Percentage of Opposing Drivers Discomforted		Percentage of Encounters Meeting Visibility Criteria Under "With Misaim" Condition			
					Unopposed Encounters		Opposed Encounters	
Test Lamps	Perfect Aim	With Misaim	Perfect Aim	With Misaim	Delineation Detected	Pedestrians Detected	Delineation Detected	Pedestrians Detected
U.S. Low	70.3	65.3	0.8	11.2	86.4	45.0	84.9	31.8
ECE Low	68.1	62.1	0.3	4.9	85.4	36.9	83.6	24.5
Mod-1	71.1	65.8	7.2	17.5	86.8	49.7	84.9	32.3
Mod-2	70.4	65.1	2.5	11.9	86.2	46.2	84.6	32.0
Single Beam	72.0	64.5	16.4	33.7	87.4	55.3	83.7	33.4
Ford CHESS Library								
2A (4652)	69.8	67.1	2.4	9.2	88.3	43.7	86.2	28.2
2C (4000)	70.3	66.5	4.1	8.7	87.1	45.4	85.3	33.2
2B (6052)	68.7	64.8	0.0	3.4	86.1	40.6	85.3	31.5
2A (H4656)	69.3	64.6	1.9	8.1	86.1	42.9	84.3	28.0
2D (6014)	67.2	63.8	1.3	8.7	86.1	40.9	84.9	29.8
H-4 Rect. European	66.6	62.4	0.0	8.1	85.6	41.4	84.1	28.5

better than most of the other systems in revealing pedestrians and delineation.

It will be recalled that the results of the field discomfort glare studies described in Section 2.1.4 indicated that predictions based on the original discomfort glare equation were conservative. Revising the exponent for θ from 0.46 to 0.8 resulted in a better fit to the field data for mid-range to low-glare levels. To see what effect this change would have on the CHESS analysis, three of the lighting systems were evaluated a second time using the revised exponent. These data are shown in Table 3.15.

The data on the exponent of 0.46 in Table 3.15 is reproduced from Table 3.14 to facilitate a comparison.

TABLE 3.15

RESULTS OF CHESS MODEL APPLICATIONS USING REVISED DISCOMFORT GLARE EQUATION

Type	θ Exponent	Figure of Merit		Percent of Opposing Drivers Discomforted	
		Perfect Aim	Random Misaim	Perfect Aim	Random Misaim
U.S. Low	0.46	70.3	65.3	0.8	11.2
	0.80	70.4	66.5	0.0	0.4
Mod-1	0.46	71.1	65.8	7.2	17.5
	0.80	71.8	67.8	0.0	0.7
Mod-2	0.46	70.4	65.1	2.5	11.9
	0.80	70.6	66.3	0.0	0.5

The changes in the CHESS results brought about by modification of the discomfort glare equation tend in the expected direction, i.e., the Figure of Merit for the more glaring system improved more than did that for the other systems. The overall differences between the systems remain relatively small, however.

Much more dramatic is the change in the percent of drivers discomforted, which fell to less than one percent in all cases.

3.2.4 Discussion. The results of the first CHESS analysis indicate that the proposed modified low beam system described in the Interim Report for this project would not constitute an improvement over the present low beam system, based on a system evaluation.

As we noted in Section 2.1.5 of this report, dealing with systems analysis, lamp performance in the real world can be substantially different than intended by design. Hence, the results of the CHESS analysis are not surprising.

However, the results of the second CHESS analysis indicate that there may be room for significant improvements in low-beam lighting if the discomfort glare criteria can be modified as indicated by the investigations we have carried out. Clearly, this seems a matter worthy of serious attention.

The recommended modifications to FMVSS 108 that will be offered in the next section of this report are based on all of the studies carried out in this program. We realize that there is still much to be learned about headlighting, and urge, in Section 4.3, that further research be conducted, built around a system evaluation procedure such as CHESS.

4.0 RECOMMENDATIONS

4.1 Summary

The purpose of this research program was to formulate recommendations for modifications to the low-beam lighting system for automobiles. In doing this we relied on information available in the scientific literature, a certain amount of expert opinion based on long-standing practices, and several studies carried out as part of this program. Since these studies are important to some of the recommendations made here, there is merit in briefly reviewing them at this point.

4.1.1 Rear-View Mirror Glare.

Four studies were carried out on the question of rear-view mirror glare. Three of these were concerned with disability and one with discomfort effects. These studies are described in detail in the project interim report (Olson and Sivak, 1981).

4.1.1.1 Laboratory Study of Disability Glare.

The purpose of this study was to develop information on the disabling effects of glare as a function of three factors: glare illuminance, glare angle, and subject age. The subjects were exposed to various combinations of glare illuminance and glare angle and measures were taken of the threshold luminance of a disc target.

The results of the study showed that the target threshold levels began to increase significantly for the younger subjects at a glare level of about 1 lux, equivalent to low beams at a following distance of about 300 feet. The older subjects were notably more sensitive to glare. For them the threshold levels began to increase significantly at a level of about 0.1 lux, equivalent to low beams at a following distance of about 1000 feet.

4.1.1.2 Field Study of Disability Glare.

The purpose of this study was to confirm the laboratory data with measures taken under actual driving conditions. The distance at which subjects could correctly identify the orientation of roadside targets was measured as a function of the level of glare provided by a following car.

The results confirm the laboratory study, in that there were small but significant losses in visibility distance as glare increased.

4.1.1.3 Laboratory Study of Transient Glare. The purpose of this study was to measure the disabling effects of glare arising from: (a) sudden increases in glare level, and (b) direct looks at the glare source reflected in the mirror. Measures were taken of the threshold luminance of a disc target over time as a function of glare level and subject age.

The results showed no consistent changes associated with looking directly at the glare source. However, there were significant changes associated with the onset of glare. The data show that step increases in glare, equivalent to the sudden appearance of a car on high beams, increase target luminance threshold by a factor of about two over the eventual asymptotic threshold. Recovery time is substantial, averaging 45 seconds for the young persons and about 70 seconds for the older persons. Furthermore, the asymptotic threshold for the older persons was about twice that of the young persons.

4.1.1.4 Field Study of Discomfort Glare. The purpose of this study was to obtain ratings of discomfort as a function of glare level and duration. The measures were taken with the subjects driving a car on dark rural roads and being followed by the glare car.

The results indicate that low-beam headlamps can produce ratings at or beyond levels judged "just acceptable," particularly if the exposure continues for some time.

4.1.1.5 Discussion. The work on rear-view mirror glare described above makes it clear that glare from these sources is a problem at present levels of headlamp output. Increasing beam intensity will make the problem worse. However, there are potential solutions. Regardless of what decisions might be made concerning lamp photometrics in the future, work should be carried out to determine whether and to what extent mirror reflectivity levels can be adjusted to reduce the glare problem.

4.1.2 Discomfort Glare. Three studies were carried out on the question of discomfort associated with glare from oncoming headlamps.

4.1.2.1 Laboratory Study of the Range Effect. The primary purpose of this study was to determine whether subjective judgments of discomfort depend on the range of glare stimuli provided. Two groups of subjects participated, each being exposed to a different range of glare stimuli. Ratings were taken in a laboratory as a function of glare intensity and subject age.

The range effect was manifest in the expected form, i.e., subjects who were exposed to the full range of glare stimuli rated mid-range stimuli as being more comfortable than did subjects exposed to a range truncated at the high end.

Differences between age groups were relatively small, except for the most intense glare levels. Apparently age-related changes do not produce a major effect on the sensation of glare discomfort.

4.1.2.2 Three-Point Glare Study. The purpose of this study was to develop data that would relate ratings made using the DeBoer scale to conditions that might be intuitively more understandable. Subjects were run under exactly the same conditions as the laboratory study just described, except they used a 3-point scale instead of the DeBoer. The three scale points were:

A. No discomfort
B. Some discomfort, but tolerable
C. Intolerable

The results show that the distributions of ratings of "A" and "C" overlapped only slightly, at a glare level corresponding to DeBoer "5." Conditions in excess of those that produce a DeBoer rating of "4" result in a rapid increase of ratings of "C" and should be avoided as much as possible.

4.1.2.3 Field Glare-Range Study. This study had two main purposes: First, to collect glare ratings in a more realistic approximation of a two-car meeting situation than provided by the laboratory study. Second, to examine the range effect under conditions simulating those associated with the introduction of a more glaring lighting system.

Data were taken in a full-scale vehicle meeting situation. Subjects were run twice, once under "standard" conditions, another time with the two least glaring stimuli removed.

The results showed that, except for the highest glare levels, ratings were much more comfortable than would have been predicted based on the discomfort glare equation. The range effect was again manifest, in the expected direction.

4.1.2.4 Discussion. The studies on discomfort glare provide some reason to believe that drivers can tolerate higher levels of glare than previous studies have indicated. This difference is attributable both to the methods used in collecting data and to the phenomenon known as the "range effect."

4.1.3 Foreground Illumination. Two studies were carried out to address the issue of whether high levels of foreground illumination were undesirable. The high-foreground condition in this case was created by adding two halogen motorcycle headlamps, aimed down about two degrees, to the standard low beams.

4.1.3.1 Eye Fixations. The purpose of this study was to determine whether high levels of foreground illumination affect driver eye fixations. Subjects drove a test car on a dark, rural road in light traffic with normal low-beam lighting, and with the same lighting supplemented by a high level of foreground illumination. The subjects' eye fixations were recorded continuously during each run. However, the subjects were not aware of the true purpose of the study.

The data show that under high foreground illumination conditions the drivers tended to look further from the car, toward the road convergence point.

4.1.3.2 Target Identification. The purpose of this study was to determine whether high levels of foreground illumination affected the ability of drivers to detect and identify various targets in the forward field. The same two lighting systems used in the eye-fixation study were used here as well. Measures were made of the distance at which the subjects correctly identified various target objects placed along a test road.

The results show that for all targets and test conditions the performances of the normal and high-foreground lighting systems were essentially identical.

4.1.3.3 Discussion. There is some concern that high levels of foreground illumination will affect eye fixations and visibility distance adversely. The data provided by these two studies suggest that this concern might not be justified.

4.1.4 Beam Color. This was a laboratory study to determine whether yellow color reduces the perception of discomfort in headlighting. Tungsten, halogen, and yellow-filtered halogen sources were used. Subjects were given brief exposures to various intensities of each and ratings obtained using a discomfort glare scale.

The results of this study indicate that, through the range tested, color does not have a significant effect on perceived discomfort.

4.1.5 <u>Visibility</u>. The purpose of this study was to measure the distance at which persons could identify various types of targets set at various positions on the road as a function of the lighting systems in use.

Six lighting systems were studied. Two of them were controls: i.e., standard U.S. and European low beams. One was the high-foreground variant of the U.S. low beam. The other three were experimental lighting systems. Two of these were modifications of standard U.S. low beams, differing in that they had higher intensities directed along the right edge of the road. The last was an asymmetrical "single beam" system.

The subjects drove or were driven down a road and pressed one of six buttons to indicate the size and location of each target.

The results of this study were complex. However, the most important findings can be summarized as follows:

a. The more powerful of the modified low beams and the single-beam system outperformed the others under many of the test conditions.

b. The response distances measured were such that a large fraction of the participants would not have been able to stop short of many of the targets at freeway speeds. The better lighting systems reduced but did not eliminate the problem.

c. There is some evidence that lighting systems that did not differ in the response distance measure did differ in the likelihood of identification errors.

4.2 Photometric Recommendations

4.2.1 Introduction. One of the main purposes of this program was to recommend changes to the low-beam photometric standards in Federal Motor Vehicle Safety Standard (FMVSS) 108.

The photometric standards in FMVSS 108 were taken from standards originally promulgated by the Society of Automotive Engineers (SAE). The SAE standards had been developed over a period of many years by committees composed generally of engineers from automotive and lighting manufacturers.

The language contained in the standards reads that lamps shall be "designed to conform" to the photometric values given. In practice this means the standards are a general guideline for purposes of design and quality control in manufacture. A good deal of unit-to-unit variability is expected at each photometric test point. Quality control is not based on keeping every lamp within specification, but on keeping the number of test-point failures per some batch size of lamps below some level. Quality control guidelines are not uniform in the industry, so it is possible that a sample of one manufacturer's lamps will exhibit a higher incidence of test-point noncompliance than another's.

The fact that the standards read "designed to conform" and not "will conform" also means that some lamps will produce more glare than implied by the standards, and some less illumination. The size of the distribution is not known, but measurements reported by Bhise et al. (1977) suggest it is large enough to have been a significant factor in the scatter reported by Yerrell (1973) and discussed in Section 2.1.5 of this report.

If the standards are not absolute, this raises a question whether the standards ought to have absolute limits, at least for some points. This was one of the issues addressed in the research.

4.2.2 Recommendations. The current low-beam photometric values in FMVSS 108 are reproduced in Table 4.1. The test points are also shown plotted on a roadway projection in Figure 4.1. Showing them this way aids in clarifying the rationale behind the selection of the test points.

TABLE 4.1

CURRENT LOW-BEAM PHOTOMETRIC STANDARDS FROM FMVSS 108.

Test Points Degrees	cd Max.	cd Min.
10U to 90V	125	--
1U-1 1/2L to L	700	--
1/2U-1 1/2L to L	1,000	--
1/2D-1 1/2L to L	2,500	--
1 1/2U-1R to R	1,400	--
1/2U-1R to 3R	2,700	--
1/2D-1 1/2R	20,000	8,000
1D-6L	--	750
1 1/2D-2R	--	15,000
1 1/2D-9L & 9R	--	750
2D-15L & 15R	--	700
4D-4R	12,500	--

First, note that there is no basis in the available literature for setting absolute limits based on operating safety. This does not mean that changes in headlamps will have no effect on safety. It does mean that such changes are very difficult to identify in the accident data. That being the case, there is no justification for our recommending mandatory maximum and/or minimum photometric values based on safety criteria.

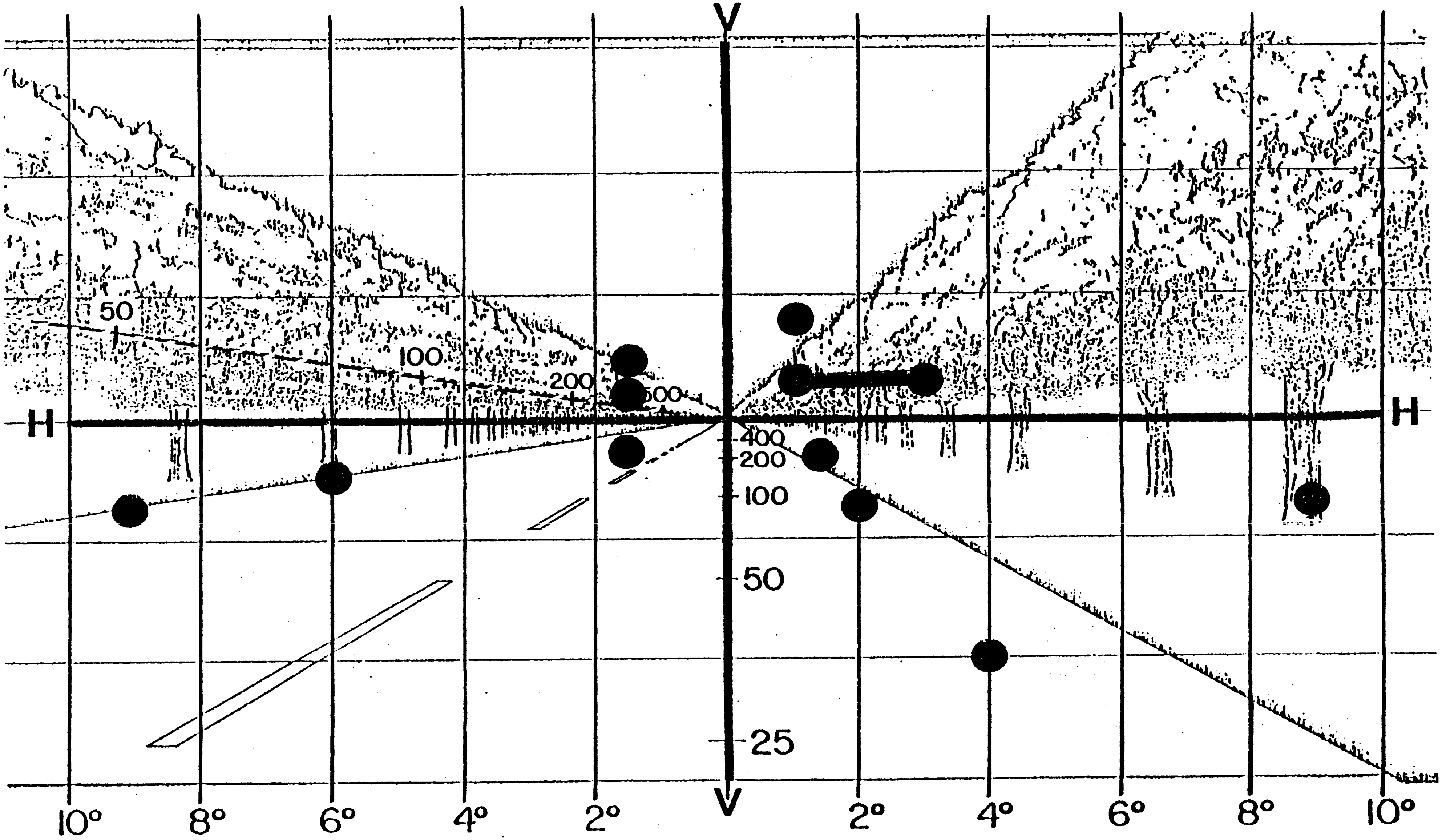


Figure 4.1. FMVSS 108 low-beam photometric test points plotted on a projection of a straight-flat road.

On the other hand, there is a basis for recommending certain changes to the standards. In simplified form the logic is as follows:

a. Low beams do not provide adequate illumination under no-glare conditions to assure timely detection of common low-contrast objects at legal speeds.

b. The only practical way of increasing visibility distance is to increase lamp output.

c. Available information suggests that the increased disability glare that will result from higher levels of illumination will not produce a loss in visibility so long as the proportions between glare and illumination remain at least at the present level. This means that increased illumination will produce more visibility under no-glare conditions and be no worse than the present system in terms of minimum visibility under glare conditions.

d. Some increases in discomfort glare can be tolerated. However, care should be exercised to minimize the likelihood of glare levels at DeBoer "4" or less.

The test point most directly affecting visibility is that at 1/2D - 1 1/2R. Illumination directed toward this point will have to be increased if visibility distance is to be improved. However, using sealed beam technology, the maximum in this area is limited by allowable maximums associated with nearby test points. Therefore, these surrounding points should be considered first.

It is illumination projected above horizontal that is most apt to cause glare. In our opinion, the recommendations that we will make for these test points are maxima beyond which it would be undesirable to go based on available data. They are certainly not to be construed as "desirable," or even as "acceptable" levels. No increases in glare should be tolerated unless they are accompanied by proportional increases in visibility illumination.

The two points to the left of the V axis above horizontal (i.e., 1/2U - 1 1/2L to L and 1U - 1 1/2L to L) present the fewest problems. Disability glare is not an issue here so long as the proportional relationship between glare and illumination remains constant or improves.

The limit in this case is determined by discomfort considerations. The goal is to avoid marketing lamps that can produce glare levels likely to be rated "4" or less on a DeBoer scale, using the revised equation described in Section 2.1 of this report. To accomplish this the following candela values are recommended:

	cd maximum
1U - 1 1/2L to L	1,300
1/2U - 1 1/2L to L	1,600

These are the only two points in the standards for which an argument could be made for making them absolute ("will conform," not "designed to conform"). The issue here is not safety directly, but minimizing the likelihood of glare levels that may produce an avoidance response on the part of oncoming drivers. To avoid the awkwardness of having "will conform" and "designed to conform" values mixed together, there is merit in setting the standards for these two test points somewhat lower, and staying with the "designed to conform" interpretation. This point will be addressed again shortly.

The two key points above horizontal to the right of the V axis (i.e., 1 1/2U - 1R to R and 1/2U - 1R to 3R) involve a broader range of considerations. Illumination in this area aids in detecting and reading signs, for example. But it causes glare, via the mirrors, to drivers of cars ahead. It also causes glare to pedestrians, bicyclists, and other roadway users in that area. However, these persons are not typically required to look near approaching headlamps, as is the driver of an automobile. Hence, their problem is far less serious.

As noted in the project Interim Report (Olson and Sivak, 1981), discomfort and disability glare associated with lamps reflected in the rear view mirrors is a problem at present levels of illumination for persons not equipped with or who choose not to use a dual-level mirror. Increases in this area must be approached with some caution, until improvements in rear vision systems can be effected. In the meantime, some idea of possible limits can be gained by comparing various lighting systems tested as part of this project.

The test system that projected the highest levels of illumination in the area of interest was the Mod-1. The following is a comparison of the FMVSS 108 maximum cd values, and values typically measured at the points in question on the Mod-1 units:

Test Point	FMVSS 108 Maximums	Mod 1 Measurements
1 1/2U - 1R to R	1,400 cd	2,500 cd
1/2U - 1R to 3R	2,700 cd	10,000 cd

Based on the rear view mirror glare data contained in the project Interim Report (Olson and Sivak, 1981), glare levels such as those associated with the Mod-1 will increase discomfort ratings by about half a discomfort scale unit on average, assuming the lead driver does nothing to reduce it (e.g., switch to the less reflective mirror setting). If the lead driver has standard headlamps, there will also be a small loss of visibility (about two to three percent, based on the results of the field rear view mirror disability glare study), again assuming he/she does nothing to reduce the glare. If the driver has a more powerful lighting system, such as the Mod-1, there will still be a net gain in visibility, regardless of whether the driver does anything to reduce glare.

Other points of concern with illumination in this area include curve situations that cause this portion of the beam to cross the eyes of oncoming drivers, and bad-weather effects. The former was studied to some extent in the computer simulations reported in Section 3.2. The more powerful systems, such as Mod-1, still had a performance advantage in general.

There are virtually no data to guide decision making in the matter of weather effects. Some very limited evaluations were carried out by us, comparing the U.S. low beam and Mod-1 systems, using available fog. No severe fog occurred during the test period. Under these conditions the Mod-1 still provided better visibility, based on subjective analysis.

On balance, we believe that photometric increases can be justified for these two test points, in an effort to improve visibility. It is difficult to determine upper limits. However, based on the analysis offered and our experience with the Mod-1 system, we believe that the photometrics of that system are close to being satisfactory. The following values are recommended:

	cd maximum
1 1/2U - 1R to R	2,500
1/2U - 1R to 3R	8,000

The analyses offered provide reason to believe that the illuminating intensity at the 1/2D - 1 1/2R point could be significantly increased over what is common practice in current low beam systems. For example the U.S. low beams in the test averaged about 16,000-cd at this point, the Mod-1 about 20,000 cd, and the single beam projected about

25,000 cd from the left lamp and 15,000 cd from the right lamp, an average of about 20,000 cd. Based on the field tests and computer seeing distance analyses, the latter two systems outperformed the standard U.S. low beam by a significant margin on right side targets.

The necessary modifications entail increasing both the maximum and minimum candela values at this point. Based on the available data, we recommend a maximum of 24,000 cd and a minimum of 12,000 cd.

In discussing the glare points repeated reference was made to maintaining a proportional relationship between glare and visibility illumination. One of the weaknesses of the standards is that there is sufficient flexibility to allow manufacturers to significantly degrade this proportional relationship. We fear that the changes recommended here, if enacted, could make this problem worse.

For example, consider the ratio between the test points at 1/2D - 1 1/2R and 1U - 1 1/2L to L. The maximum cd values are currently 20,000 and 700 respectively. A lamp at maximum at both points would provide a ratio of illumination to glare of about 28.6:1. At worst, under current specifications it could be 8,000/700, a ratio of about 11.4:1. The U.S. low-beam lamps used in this field visibility study averaged about 16,000/600, a ratio of about 26.7:1.

It is not certain what proportions would be typical of the current population of lamps manufactured in this country. If we assume the U.S. low beams used in this study are reasonably typical of tungsten lamps, it is apparent that the photometrics could be degraded significantly and still meet specifications. If, for example, the mean values became 10,000/600, the population of vehicles so equipped would offer their operators the same glare levels and less visibility than vehicles equipped with the system having a more favorable proportional relationship.

The suggested photometric modifications to the standards could make matters worse. At max/max (24,000/1,300) the ratio is about 18.5:1, at min/max (12,000/1,300) it is only about 9.2:1.

There are two alternatives: One is to regard the maximums for the two glare points as absolute levels and set lower values as standards in the usual sense. Thus 1U -1 1/2L to L might increase from 700 to 900, and 1/2U -1 1/2L to L from 1,000 to 1,200, with the understanding that no lamp could pass with values of 1,300 or 1,600 or more at these points. This approach would help, but not really solve the problem, since it would still allow lamps with greatly reduced visibility illumination to be produced.

The second alternative is to introduce an additional standard requiring a minimum ratio between glare and visibility illumination.

In our opinion, the proportional standard has a great deal of merit. For example, it seems clear that current technology makes it easily possible to maintain at least a 20:1 relationship between the 1U - 1 1/2L to L and the 1/2D - 1 1/2R test points. This might be adopted as a standard. However, doing so automatically places limits on the maximum values in the standard. For example, if the max at 1/2D - 1 1/2R becomes 24,000 cd, the max at 1U - 1 1/2L to L can be no higher than 1,200 cd.

We recommend that NHTSA consider adding a minimum illumination/glare ratio to the standard. We recommend that this ratio apply to the 1U - 1 1/2L to L and 1/2D - 1 1/2R test points, and that it be set at 20:1. Because of this the values for the two glare points (1,300 and 1,600 cd) mentioned earlier should be adjusted to 1,200 and 1,500 cd respectively.

The remaining test points are of less concern. However, the one at 1/2D - 1 1/2L to L will be affected by the other changes recommended and will require modification as well. This point is currently set at 2,500 cd maximum. The standard U.S. low beam used in the test measured about 1,950 cd at this point. The Mod-1 units averaged about 4,000 cd, the Single Beam system about 12,000 cd. The high intensity levels associated with the Single Beam system account for its superior performance on left-side targets. However, there is some concern over the effect of such intensity levels if the lamps were aimed too high, as might happen in hill meeting situations or if the car were loaded with baggage. Thus, we cannot recommend values as high as those in the Single Beam system at this time. However, significant increases at this point do seem reasonable, based on the test data. We recommend a maximum of 5,000 cd.

With one exception, all the other test points are minimum values, and present no special problems. There are no data or experiences to suggest they are too low.

The remaining maximum point is at 4D-4R, and is set at 12,500 cd. As will be noted in Figure 4.1, this point is in the foreground area. Only the Single Beam system averaged close to this value. The Mod-1 averaged about 6,500 cd and the U.S. low beams about 6,000 cd.

The results of the foreground studies reported here suggest that levels of foreground illumination much higher than 12,500 cd would not be harmful. They may even be helpful. However, more work should be carried out to investigate the effect on eye fixations before the phenomenon can be regarded as real. Thus, no changes are recommended for this point at this time.

Table 4.2 summarizes the recommended modifications to FMVSS 108.

TABLE 4.2

COMPARISON OF PRESENT AND RECOMMENDED MODIFICATIONS TO PHOTOMETRIC STANDARDS IN FMVSS 108

Test Points Degrees	Present		Recommended	
	cd Max.	cd Min.	cd Max.	cd Min.
10U to 90U	125	--	125	--
1U-1 1/2L to L	700	--	1,200	--
1/2U-1 1/2L to L	1,000	--	1,500	--
1/2D-1 1/2L to L	2,500	--	5,000	--
1 1/2U-1R to R	1,400	--	2,500	--
1/2U-1R to 3R	2,700	--	8,000	--
1/2D-1 1/2R	20,000	8,000	24,000	12,000
1D-6L	--	750	--	750
1 1/2D-2R	--	15,000	--	15,000
1 1/2D-9L & 9R	--	750	--	750
2D-15L & 15R	--	700	--	700
4D-4R	12,500	--	12,500	--

Note: 1/2D - 1 1/2R/1U - 1 1/2L to L = 20 min

4.3 Recommended Future Research

4.3.1 Introduction. There is a vast literature on various aspects of vehicle headlighting, representing the results of a substantial investment of time and money. There has probably been an equal or greater investment on the part of lighting and automotive manufacturers, although their work is typically not published. Couple this with a considerable knowledge of vision under low-luminance conditions and other relevant subject areas, and it might appear that vehicle headlighting is a problem that should be solved. Far from it. For example, there are two quite different low-beam lighting systems in use today, each with its enthusiastic advocates. Yet, based on the results of the test program described in Section 3.1 of this report, they perform very similarly on many targets, and neither does an adequate job of illuminating common low-contrast objects.

No agreement has been reached on headlighting because no agreement has been reached on criteria. The goal of headlighting research and development is straightforward enough. The optimal lighting system is one that provides the best balance between visibility and glare protection under realistic operating conditions. The difficulty lies in the last four words.

The necessity of considering a great number of operating conditions, many of which interact significantly with beam characteristics, and of weighting the results in some reasonable way, has been the major stumbling block to arriving at a consensus concerning low-beam headlighting. Investigators have coped as best they could, using a variety of test techniques and a great deal of subjective judgment in arriving at design recommendations. Clearly, this is not an efficient approach.

The first necessary step in future lighting research must be agreement on a criterion model. Basically this means making it possible to carry out a completely objective evaluation of a lighting concept under conditions that relate to real-world operation. To do this, agreement should be reached on at least the following:

a. Driving conditions to be considered
b. Test methods
c. Criteria
d. Weighting of various scenarios
e. Subject populations

The term "model" does not necessarily imply use of a computer. However, given the complexity of the analysis, that is probably the most practical approach. The Ford CHESS model (Bhise et al., 1977) seeks to conduct the type of analysis recommended here. It is an example of the evaluation tool needed.

With this fundamental agreement in place, "headlighting research" becomes a matter of providing the best possible information for the model. The rest of this section of the report will deal with areas of research we think are particularly important.

4.3.2 Discomfort Glare. Work described in Section 2.1 of this report suggests that comfort ratings such as those derived from the DeBoer scale are significantly affected by factors that were thought to be irrelevant (e.g., the range of glare stimuli provided). Thus, these ratings are of limited value as glare criteria. Furthermore, the best data currently available appear to be quite conservative when applied to a real-world situation. Since minimizing glare discomfort is of importance in headlighting, the area is one in which much careful work should be done.

For example, it would be desirable to develop a stable means of measuring glare discomfort. One possibility is to use an objective approach. Fry and King (1975) have reported work relating discomfort to variations in pupil size. It may be appropriate to follow up on this activity. It may also be possible to develop a subjective scaling technique that is not affected by stimulus range. Something like the 3-point scale described in Section 2.1 may work, since it relies on a relatively objective sensation for the critical "C" category judgments.

It is also essential that work continue to assess the relationship between measured discomfort and relevant glare parameters in a realistic setting. This should include situations simulating meeting platoons of vehicles, and prolonged exposure that might be associated with high-density traffic. The latter case is of interest because the work on rear-view-mirror discomfort glare described in the Interim Report (Olson and Sivak, 1981) found that the same levels of glare were rated more uncomfortable as exposure duration increased.

Another problem is fatigue. It seems reasonable that long-term exposure to glare would increase fatigue. However, fatigue is a very difficult subject to study experimentally, whatever the cause. Attempts to measure changes in fatigue associated with glare have not been successful (e.g., Schiflett et al., 1969). This is a topic worth pursuing, but only if reliable dependent variables can be developed.

4.3.3 Visibility. The revealing power of a lighting system has typically been evaluated using simple threshold detection criteria. To conclude whether the target would have been seen "in time" it is necessary to add an estimated identification-decision-response interval and a stopping distance. This raises several questions for study.

1. Most headlighting visibility work has been carried out in such a way that detection occurs on the foveal portion of the retina. Given the relatively small area occupied by the fovea, it is probable that detection occurs in the peripheral portion of the retina most of the time under real-world conditions. Since visual performance declines

rapidly with peripheral eccentricity, using foveal detection criteria will lead to an overestimation of target visibility. Is it necessary to structure the tests so that detection is accomplished in the periphery? If so, how can this be done? One way is to use "surprise" tests. The only study to use pure "surprise" was reported by Roper and Howard (1938). Their subjects thought they were conducting subjective seeing tests when they were confronted with a full-size mannequin in their path. However, while unquestionably realistic, at one trial per subject, such tests are expensive. The procedure also exposes the participants to some trauma, which may be difficult to justify to subject review committees.

An alternative to pure surprise is the procedure developed by Halstead-Nussloch et al. (1979), and used in slightly modified form by Olson and Abrams (1982). In these studies the subjects operate a vehicle on public roads and are asked to respond to "potential hazards." The nature and location of the targets are unknown to the subject.

2. It is generally assumed that detection and identification are perfectly correlated. Based on the results of the field test described in Section 3.1 of this report, they may not be. Should the model be based on an identification criterion? If so, identification of what? Again, the solution may be to use some variant of the modified surprise procedure developed by Halstead-Nussloch et al. (1979). This may solve both points 1 and 2 above.

3. Some of the response distributions in Section 3.1 are not parallel. Thus, on some targets at least, lighting systems that differ considerably, based on

the mean or median, differ little if at all based on 5th percentile performance. Is it more appropriate to consider 5th percentile performance rather than the 50th? Or should the model take the entire response distribution into account? If the latter, how does one estimate the real-world response distribution?

4. If a detection model is used, how much time should be allowed for the identification, decision, response interval? What is the distribution of such an interval, and what percentile cut-off is appropriate?

4.3.4 Real-World Lamp Condition. It would be desirable to collect much better information than is presently available on the condition of lamps in the real world. Yerrell's data, discussed in Section 2.1, indicate that great variability is to be expected. It would be helpful to know more about the reasons for the variability. This would allow the evaluation process to address questions related to improvements in aim control and lens cleaning systems, for example, as well as beam pattern changes. It is entirely possible that development monies would be better spent in areas other than beam modifications, but there is no way of evaluating such a trade-off at present.

4.3.5 Rear View Mirrors. Based on data collected in Phase 1 of this project, and presented in the Interim Report (Olson and Sivak, 1981), glare from rear view mirrors is a significant problem even at illumination levels representative of current low-beam systems. Regardless of what changes might be made to the lighting systems, steps should be taken to reduce the disability and discomfort glare effects associated with the vehicle mirror systems. The following questions should be considered as a minimum:

4.3.5.1 Interior Mirror. Current interior mirrors normally offer dual reflectivity, with a "day" level of about 90% and a "night" level of about 4%. The 4% level provides excellent glare protection but so little visibility that its continuous use is not advisable. The alternative is to use the 90% setting generally and switch to the 4% level when necessary. Many people will probably not switch as often and/or as soon as they should, creating a potentially hazardous loss of vision. In addition, the 90% setting maximizes disability effects associated with the sudden onset of glare. We recommend that research be undertaken to explore the following possibilities:

Can the maximum reflectivity of the interior mirror be significantly reduced? For example, if it could be reduced to about one-third of the current level, this would significantly reduce glare effects without the driver having to change the mirror setting. The 4% level might then be retained for use only in extreme conditions.

Can the minimum reflectivity level of the interior mirror be increased? For example, if the minimum level were increased to 12 or 15%, this would still provide a large measure of glare protection, but may improve rear visibility to a level that would prove generally satisfactory for use in night driving.

4.3.5.2 Exterior Mirror. Only the exterior mirror on the driver's side is felt to be a problem under normal driving conditions. The approach to making a dual-level mirror that works like the inside mirror would not work well on the outside mirror. There are no alternative approaches that are felt to be practical at this time.

Typically, driver's side exterior mirrors have a reflectivity level of about 50%. Research should be carried out to determine whether this level could be reduced significantly.

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APPENDIX:

SUBJECT INSTRUCTIONS FOR VARIOUS STUDIES

LABORATORY GLARE RANGE STUDY

This is a study of the effects of glare on your feelings of comfort-discomfort.

You will be seated at this desk, facing toward the far end of the lab. Periodically I will shine a light in your eyes to simulate headlamp glare. The glare will be preceded by a "beep" tone. When you hear the "beep," look directly at the small red lamp in the center of the black box on the table. The glare lamp will come on and stay on for two seconds. <u>Do not look directly at the glare source</u>! When the light switches off please give me a rating, using the scale you see on the wall at the end of the room.

Look at the scale now and become familiar with it. Note that there are nine points, and that each odd point is described in some way. For example, 1 means "unbearable," 5 means "just acceptable," and so on. Another copy of the scale is to your left and just behind you. It will be illuminated during the study so that you can refresh your memory if necessary.

Although only the odd points are labeled with adjectives on the scale, you should use both odd and even points in making your ratings.

The procedure is very simple. The "beep" will sound. Fixate the red lamp and, after the glare switches off call out your rating loud enough for me to hear. We'll then go on to the next trial.

This study will take about one-and-a-half hours to complete. I'll give you a break about every fifteen minutes so you can stretch or get up and move about a bit. However, if you get tired sooner than that please let me know.

Any questions?

3-POINT GLARE STUDY

This is a study of the effects of glare on your feelings of comfort-discomfort. In many ways it will be like the study in which you participated some weeks ago.

You will be seated at this desk, facing toward the far end of the lab. Periodically I will shine a light in your eyes to simulate headlamp glare. The glare will be preceded by a "beep" tone. When you hear the "beep," look directly at the small red lamp in the center of the black box on the table. The glare lamp will come on and stay on for two seconds. <u>Do not look directly at the glare source</u>! When the light switches off, please give me a rating, as you did before. The primary difference is that, instead of making the ratings on a 9-point scale, we will use just a 3-point scale this time.

The scale points are defined as follows: Please listen carefully and ask questions if what I say is not clear.

A glare source may produce no sensations of discomfort at all. You can see it, but as far as discomfort is concerned, it may as well not be there. If you experience glare sources like that in this study call them "1."

On the other hand, sometimes a glare source may be so uncomfortably bright that you would block it out if you could. For example, you might squint, close your eyes momentarily or look away from the source in an effort to reduce the discomfort. If you experience glare sources like that in this study, call them "3."

Other glare sources fit neither of these descriptions. They can be characterized as producing some discomfort (in other words, you'd be happier if they weren't there), but they are tolerable. If you experience glare sources like that in this study, call them "2."

So, to summarize:

If the glare produces no discomfort, call it a "1."

If the glare produces enough discomfort that you would like to do something to reduce it, call it a "3."

If the glare sensation falls between these two, that is, uncomfortable but tolerably so, call it a "2."

The study will be run in two parts of about one-half hour each, separated by a break of 15-20 minutes. You should note that the sensations which glare produce vary a great deal from person to person. There are no "right" answers in this test. We are interested in your reactions to the test conditions.

Do you have any questions?

FIELD GLARE RANGE STUDY

This is a study which is concerned with some of the problems people experience when facing bright headlamps while driving at night.

You will be seated in this car, which will always be stationary. The other two cars will drive up and down the track. What we are asking you to do is rate the comfort-discomfort associated with the headlamp of the oncoming car.

The test will be run as follows: The glare car will start its run at the end of the road and drive toward us. You'll note its headlamps will go off momentarily and then come on again, usually at a different level. From that point until the car passes is the rating period. After the car passes, switch on your flashlights and enter a rating, 1 through 9, using the scale given at the top of the score sheet.

Look at the rating scale now. Note it has nine intervals, and that each odd point is identified with an expression such as "unbearable, just acceptable" and so on. Study the scale now and become familiar with it. On each trail decide what that glare experience was like for you, pick the scale point which best describes it, and enter that number on the score sheet next to the trial number. Please note, that you can use the even numbers, 2, 4, 6, and 8 in making your ratings, as well as the odd ones.

Finally, two important points:

First, please do not talk among yourselves about the glare experiences or your opinion of them. Do not look at each other's ratings. Glare affects some people a great deal more than others, there are no "right" answers in a test like this, and it is very important that each of you give me our opinions and only your opinions.

Second, do <u>not</u> look directly at the glare source during the rating period. Look straight up the road in front of this car.

Any questions?

COLOR GLARE DISCOMFORT STUDY

As you know from your own driving experience, being confronted with bright headlights at night can be uncomfortable. The purpose of this study is to try to find out something about the relationship between glare and discomfort and provide some guidance to lighting designers.

The procedure is basically very simple. At regular intervals we will give you a two-second exposure to a glare level. When the light switches off give me a rating of that experience using the 9-point scale on the wall to your right. Look at the scale now and become familiar with it. Note that each odd point is defined. For example, 1 means "unbearable," 5 means "just acceptable" and so on. however, you should use both the odd and even points when making your ratings.

The scale on the wall will be illuminated during the study so you can read it should you wish to do so.

It will be necessary for you to rest your chin in the plastic cup in the yoke in front of you. This is to ensure that your eyes are always in the same place. We can adjust your chair height to make you comfortable if necessary.

If you look toward the far end of the lab you will see a mirror on the floor. You can probably also see the headlamps reflected in the mirror. They will provide the glare. At the bottom of the mirror is a small yellow lamp. During the glare exposure you should look at the yellow lamp. <u>Do not look directly at the glare source</u>.

Two seconds prior to the onset of glare you will hear a "beeping" sound. At that point be sure your chin is in the cup and you are fixating on the red lamp. When the glare shuts off call out your rating so I can hear it. You'll have about ten seconds until the next "beep."

As you may have guessed by now this is not a particularly exciting task. I'll give you a break every 15 minutes or so, so you can stretch and move around a bit.

However, if you get tired and want an extra break just say so.

Do you have any questions?

FIELD TARGET IDENTIFICATION STUDY

In this study we are going to measure the visibility distance provided by various headlighting systems.

Basically, the procedure is very simple. We will drive this car up and down this road at about 25 mph. Periodically you will encounter a target. As soon as you can identify the target, press the appropriate button on the box I have given you. I'll explain the meaning of the various buttons in a moment.

There are three sizes of targets, large, medium, and small. Examples of these are arranged in front of the car now. On your left is a large target, a person. The large target may appear as it is now, in all dark clothing, or it may have a white vest. Centered in front of the car is a medium target, and off on the right is a small target. Colorwise these last two will always appear just as they are now.

The targets may be placed to the right or left of the car, in about the positions presently occupied by the large and small targets.

Now, look at the response box I gave you. Note there are two columns of white buttons, labeled "left" and "right." This refers to the side of the car on which the targets might appear. Note also that the individual buttons are labeled "L," "M," and "S," from top to bottom. This refers to the different size targets, large, medium, and small. All you are to do, when you have identified a target, is punch the button corresponding to its size and position. In between, keep your finger on the colored button in the center, so you can easily find the proper identity button by feel.

You can and probably will make mistakes in this study. There are two kins of mistakes. You might think a target is one size and push that button and then realize it is another size. That's o.k. I'm interested in those data and you shouldn't say anything about it. On the other hand, if you accidently push the wrong button, tell me about it, but wait until we are turning around at the end of the run. Don't worry about it until then, or some of us might get distracted and miss a target.

All runs made in the direction we are facing now will encounter glare from a car positioned at the far end of the road. The glare lamps will not be on at the start of a run, but will come on when we are about half way down the road. Any targets we encounter after the glare lamps come on will be to the right of the car.

You may encounter a target at any point along the road. On a given run you may see no targets, one target, or more.

A couple of notes:

First, for the driver. Drive down the center of the road, as the car is positioned now. Try to go about 25 mph. Speed is not critical, however. It is more important to look for targets than to monitor the speedometer.

Second, for all of you. This is not a real simple task. Talking among yourselves during runs or playing the radio could be a distraction and lead to errors or long response times. So, I ask that you do not do those things.

Now, to recap. All we're going to do is drive up and down this road at 25 mph and look for targets in three sizes. When you see a target, push the appropriate button on the box in your lap. The targets can appear anywhere along the road, and on either side of the car, except when the glare lamps of the other car are on, at which time they will appear only on your right.

Any questions?