UM-HSRI-81-4

IMPROVED LOW-BEAM PHOTOMETRICS

Paul L. Olson
Michael Sivak

INTERIM REPORT
FEBRUARY 1981

THE UNIVERSITY OF MICHIGAN
HIGHWAY SAFETY RESEARCH INSTITUTE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Improved Low-Beam Photometrics

5. Report Date

6. Performing Organization Code
017796

7. Author(s)
Paul L. Olson and Michael Sivak

8. Performing Organization Report No.
UM-HSRI-81-4

9. Performing Organization Name and Address
Highway Safety Research Institute
University of Michigan
Ann Arbor, Michigan 48019

10. Work Unit No.

11. Contract or Grant No.
DOT-HS-9-02304

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
U.S. Department of Transportation
Washington, D.C. 20590

13. Type of Report and Period Covered
Interim Report
Oct. 1979 - Feb. 1981

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

It is recognized that low-beam headlamps do not provide adequate illumination for safe operation at higher speeds. This report summarizes Task 1 activities on a contract the ultimate aim of which is to provide specifications for an improved low-beam headlighting system.

A comprehensive review of the literature was carried out. Additional studies were conducted to provide information lacking in the available literature. Based on these data and the use of a computerized seeing-distance model, modifications to the present low-beam headlighting system were suggested, which should improve visibility distances under most driving conditions.

A number of additional analyses have been carried out to determine whether the proposed beam modifications would cause problems under certain common driving conditions. For example, consideration was given to the effects of beam misaim, changes in mounting height, and adverse weather. None of the conditions examined appears to pose an overwhelming problem for the new beam system.

The report concludes with a consideration of ways in which the new beam might be realized in hardware. There are a variety of ways in which this might be accomplished, all of which have advantages and disadvantages.

17. Key Words
Low-Beam Headlamps, Night Visibility, European Headlamps, U.S. Headlamps

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	107	

Prepared for the Department of Transportation, National Highway Traffic Safety Administration under Contract No.: DOT-HS-9-02304. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the National Highway Traffic Safety Administration.

TABLE OF CONTENTS

INTRODUCTION 1

EFFECTIVENESS OF FORWARD ILLUMINATION 1

DISTRIBUTION OF ILLUMINATION 3

Foreground Area 6
Peripheral Foreground 8
Upper Left Quadrant 10
Upper Right Quadrant 19
Zone of Critical Seeing 21
Hardware Considerations 50

RECOMMENDATIONS 55

REFERENCES 57

APPENDIX A: REAR VIEW MIRROR DISABILITY GLARE STUDY 61

APPENDIX B: REAR VIEW MIRROR DISCOMFORT GLARE STUDY 77

APPENDIX C: REAR VIEW MIRROR DISABILITY GLARE - FIELD STUDY 87

APPENDIX D: TRANSIENT GLARE STUDY 95

LIST OF FIGURES

1. H-V diagram superimposed on road scene 5

2. Foreground zone 7

3. Peripheral foreground zone 9

4. Upper left quadrant 11

5. Relationship between the intensity of light directed toward a target and toward an observer's eyes on visibility distance 13

6. Mean visibility distances obtained with five lighting systems and two target positions 18

7. Upper right quadrant 20

8. Zone of critical seeing 22

9. Visibility distance (in meters) provided by mid-beam system at four intensity levels compared with standard low beam as a function of logitudinal separation between two identically equipped vehicles 25

10. Typical U.S. low beam isocandela diagram on which computer simulation is based 26

11. Mid-beam added to standard low beam in seeing distance tests. Candela values shown are 25% of original, and are those which provided best balance between additional visibility and glare 30

12. Comparison of detection distances provided by modified and standard low beam systems misaimed down 1°. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road 35

13. Comparison of detection distances provided by modified and standard low beam system misaimed up 1°. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road 38

14. Comparison of detection distances provided by modified and standard low beam systems misaimed left 1°. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road 39

15. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on left edge of two lane road 41

16. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on center line of two lane road 42

17. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on right edge of road 43

18. Specific luminance characteristic of white encapsulated lens sheeting 45

A-1. Schematic of laboratory arrangement for rear view mirror disability glare study 66

A-2. Photograph showing the subject's head support and glare mirrors, with detection target in background 67

A-3. Copy of score sheet used in study 70

A-4. Changes in target disc luminance required to achieve threshold detection as a function of glare intensity. Younger subjects 71

A-5. Changes in target disc luminance required to achieve threshold detection as a function of glare intensity. Older subjects 72

A-6. Number of times target luminance must be increased above no-glare threshold to reach threshold again in presence of glare. Young versus old subjects. Glare angle is 35^{o} 76

B-1. Front (subject) vehicle in discomfort glare study 81

B-2. Vehicle which provided glare in discomfort glare study 82

B-3. Mean comfort ratings for glare originating from rear view mirrors. Four young subjects, two glare durations (10 seconds and 3 minutes) 85

C-1. Front and side views of headlighting visibility target 91

C-2. Mean visibility distances achieved with three levels of rear view mirror glare 93

D-1. Schematic of laboratory arrangement 99

D-2. Typical trial of onset data from young subject. Time increases to right, one second/division. Glare switched on at arrow 102

D-3. Luminance required on target disc to provide threshold visibility as a function of time after onset of glare 103

D-4. Number of times target disc luminance must be increased over no-glare conditions to maintain threshold visibility 104

D-5. Luminance required on target disc to provide threshold visibility as a function of time after onset of glare 105

D-6. Typical trial of look data from young subject. Time increases to right, one second/division. "Look" command given at arrow 1. Subject reported after images gone by arrow 2. 106

LIST OF TABLES

1. Standard Low Beam Candela Matrix 27

2. Modified Low Beam Candela Matrix 28

3. Results of CHESS Evaluation 31

4. Disability and Discomfort Glare Effects Associated with the Mounting Height of the Headlamps of an Approaching Vehicle 47

5. Disability and Discomfort Glare Effects Associated with the Mounting Height of the Headlamps of an Approaching Vehicle 48

A-1. Subject Characteristics 64

A-2. Luminance Values Obtainable on Target Disc 65

A-3. Results of Measurements of Disability Veiling Glare Using Fry Glare Lens 76

B-1. Results of Rear View Mirror Discomfort Glare Survey 84

D-1. Subject Characteristics 98

INTRODUCTION

It has long been realized that the low-beam headlighting system used on automobiles in the United States is not adequate for some driving conditions. As a result, a great deal of effort has gone into trying to improve headlighting in recent years. In summarizing this work, it seems fair to say that no completely satisfactory changes have resulted, and that significant problems remain.

In October, 1979, the National Highway Traffic Safety Administration (NHTSA) entered into a contract with the Highway Safety Research Institute (HSRI) to carry out a research effort which would provide recommendations for improvements to the photometrics of low-beam headlamps.

There are two phases to the contract. Phase I is an information-gathering effort. The intent is to pull together all available information relevant to automotive headlighting, identify areas where information is still required, design and carry out studies to supply that information, and then make recommendations for modifications to the low-beam pattern which should improve its performance. In Phase II, the proposed system will be comprehensively evaluated.

This report covers Phase I activities. It will describe the background work, the proposed system modifications, and ways in which they can be achieved in hardware.

EFFECTIVENESS OF FORWARD ILLUMINATION

One of the first tasks undertaken in this research effort was a literature review. As anyone who has worked on the problem knows, there is a vast literature on automotive headlighting. In addition, there is substantial literature on various aspects of vision which relate to seeing while driving at night. There are two rather interesting aspects to this information:

1. The vast bulk of it was generated subsequent to the development of the sealed beam system used on cars in the U.S. at present.

2. Virtually all of it deals only with illumination projected into a relatively small area ahead of the car.

To better understand why this situation came about it will be helpful to briefly review the history of headlamp development in this country.

The first headlamps (as distinguished from marker lamps) appeared in 1906. These were acetylene powered, and provided a relatively tightly focused beam. As the years went by, headlamps became more powerful. Also more people were driving at night. Two problems became evident: First, illumination was needed in places other than straight ahead. Second, excessive glare was being provided to oncoming drivers.

During the first world war, manufacturers began to mould prisms into headlamp lenses, spreading the illumination over a wider area in an effort to provide more adequate visibility. This marked the beginning of an era of great proliferation in headlamp sizes, shapes, and beam patterns. There were a number of serious problems:

1. It was easy for dirt and moisture to get into the lamp housing, reducing light output, distorting the beam pattern, and accelerating deterioration of the reflector surface.

2. Because of the factors listed in item 1, the headlamp's light output was reduced and its beam pattern changed as the vehicle aged.

3. Tungsten from the filament deposited on the interior of the bulb, causing it to blacken as it aged, with a consequent reduction in light output.

4. The great number of lamp sizes and shapes made it somewhat difficult and costly to secure replacement components.

5. Some beam patterns were felt to be better than others.

Starting in the mid-1930's, a substantial program was initiated in an effort to find solutions to the problems mentioned above. Some of the work was objective, e.g., tests of target-detection distance. However, much of it was subjective, based on various demonstrations and a consensus of the committee persons involved. For example, objective data were collected to evaluate visibility and disability glare. Discomfort glare, peripheral and foreground illumination, effects of hills and curves, and adverse weather performance were evaluated subjectively. What was desirable also had to be modified based on cost, hardware and power constraints. The result of this development process was a two-lamp, two-beam lighting system which came to be called the "sealed beam," first introduced on 1939 cars.

Beyond question, the sealed beam represents the largest single advance in automotive headlighting to date. It solved the deterioration problems and provided a relatively good beam pattern with units which were readily available at low cost.

An SAE standard was developed (J-579) to ensure that, whoever undertook the manufacture of headlamps, their output would closely approximate that which was felt to be desirable in the original system. Numerous modifications have been made to the standard over the years. Some were made to permit what were judged to be improvements in the beam characteristics. Other modifications were made in an effort to "tighten up" the standards and reduce the variance possible in manufactured units. This SAE standard was incorporated into Federal Motor Vehicle Safety Standard (FMVSS) 108.

In sum, the basic headlighting system in use in this country today has been in existence more than forty years. It was developed by a process many would label "unscientific." In fairness to the persons involved, it must be admitted that most of the methods, though perhaps crude, were reasonably effective, and the people involved produced a good product in a remarkably short time. However, the lack of documentation concerning the basis for various decisions is a problem to persons attempting to understand the present system and seek ways of improving it. This deficiency will be noted occasionally in the following section, where the low-beam system will be discussed from a perspective of the visual requirements of the forward field.

DISTRIBUTION OF ILLUMINATION

A basic reference tool in headlamp design is the H-V diagram, where the horizontal and vertical axes correspond to planes passing through the center of the headlamp. The H plane is parallel to the road surface and coincides with the horizon at infinite distance. The V plane is perpendicular to the road surface and coincides with the road center at infinite distance.

Figure 1 shows an H-V diagram superimposed over a picture of a flat, straight roadway segment. While it is recognized that not many of the world's roadways are perfectly flat and straight, this is a better approximation of a typical roadway environment than any other single configuration. As a basis for headlamp design it is a good starting point.

It will be noted that the V axis is marked with distances (in feet) corresponding to points on the road surface ahead of the lamp (assuming a mounting height of about 24 inches [61 cm]). A dashed line appears in the upper left quadrant, which corresponds to the trajectory of the eyes of an approaching driver (assumed eye height about 42 inches [107 cm]). This is also marked with distances. The diagram assumes one headlamp, this being located in the center of the right-hand lane.

In considering beam distributions it is convenient to talk about different parts of the forward field as though they are separate entities. To some extent they are. However, there is considerable interaction, for two reasons:

First, due to changes in roadway alignment or a host of factors affecting lamp aim, illumination intended for one area will end up in another, at least for brief periods of time.

Second, there are limits to what can be accomplished with hardware. Thus, changes in illuminance intended for one area will inevitably alter illuminance directed to surrounding areas as well.

In the discussion which follows, various areas of the forward field will largely be dealt with individually. Interactive effects will be discussed where appropriate.

There is no generally accepted way of dividing the forward field for purposes of discussing headlamp beams. Many persons refer to the foreground and the upper left and right quadrants as being significantly different areas. That practice is followed in this report, except that we shall also describe a "zone of critical seeing," which is an area extending across the figure from left to right, parallel to the H axis,

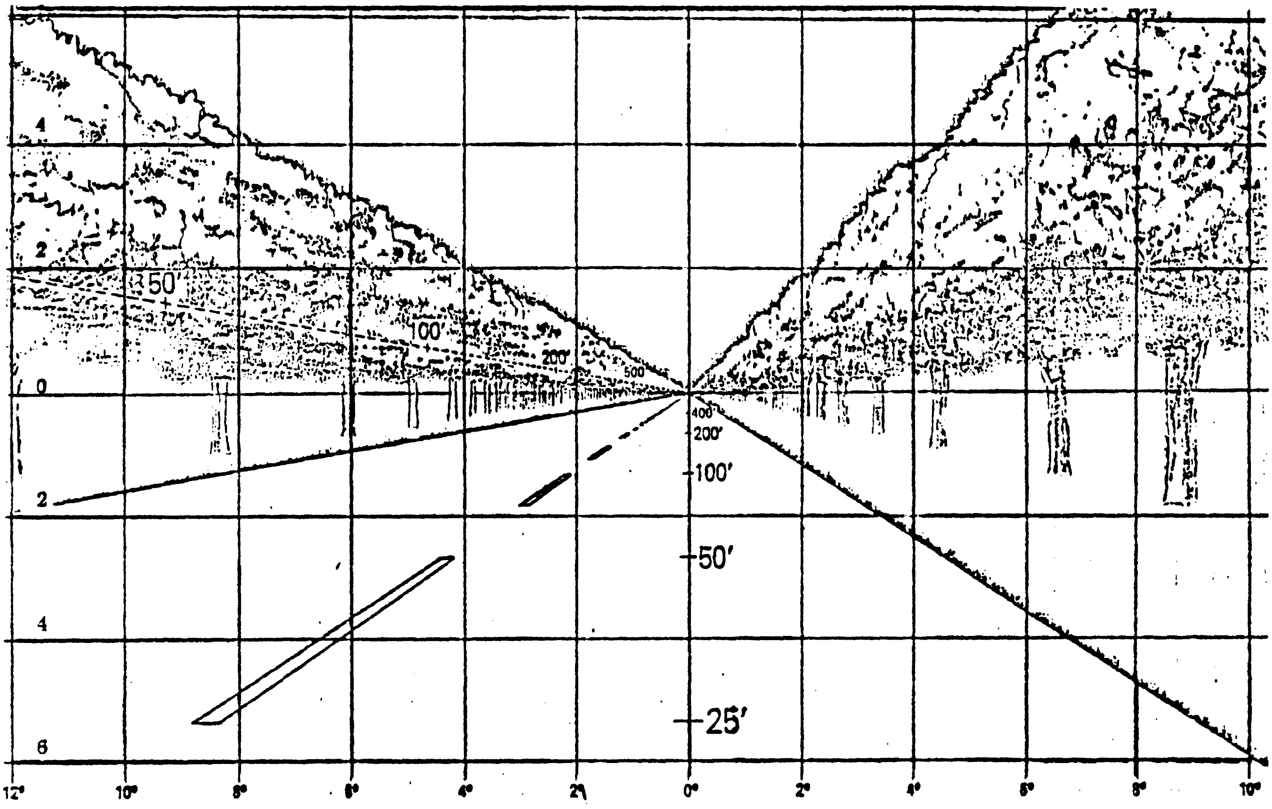


Figure 1. H-V diagram superimposed on road scene. Distances on V axis and eye trajectory are in feet.

and extending from the H axis down about 1-1/2 degrees. This is the zone within which critical objects must be detected and identified if the driver of the vehicle is to deal with them effectively.

Foreground Area

For purposes of this report the foreground will be defined as that portion of Figure 1 which is shown outside the hatched area in Figure 2. It contains one test point from FMVSS 108, as follows:

4 D - 4 R	12,500 cd max

Visual Needs. There is some debate concerning the value of illumination in the foreground area. In our opinion, foreground illumination is important for at least two reasons. First, there is evidence (e.g., Rockwell, et al., 1977) that peripheral vision is an aid to lateral station-keeping. That is, being able to detect the lane edges close to the car peripherally is a useful cue for basic vehicle control.

Second, foreground illumination is also helpful (under slow driving conditions) in avoiding obstacles such as chuck holes and road debris.

Reference is sometimes made to the need for "continuity" in illumination in the forward field. There is no research evidence, but many lighting engineers feel that a high degree of uniformity in illumination in this area is desirable (as exemplified by the ECE beam). This is particularly difficult to evaluate, and may simply reflect a preference for that to which people have become accustomed.

Illumination Levels. The SAE low beam was designed to provide levels of foreground illumination minimally adequate for the needs described above. This was based on an assumption that higher levels would reduce the visibility of more distant objects.

The testing on which the present foreground illumination level is based was entirely subjective. In our opinion, the foreground illumination provided by the SAE low beam does represent a barely adequate minimum. Significant reduction in foreground illumination below that represented by the present SAE low beam would be inadvisable.

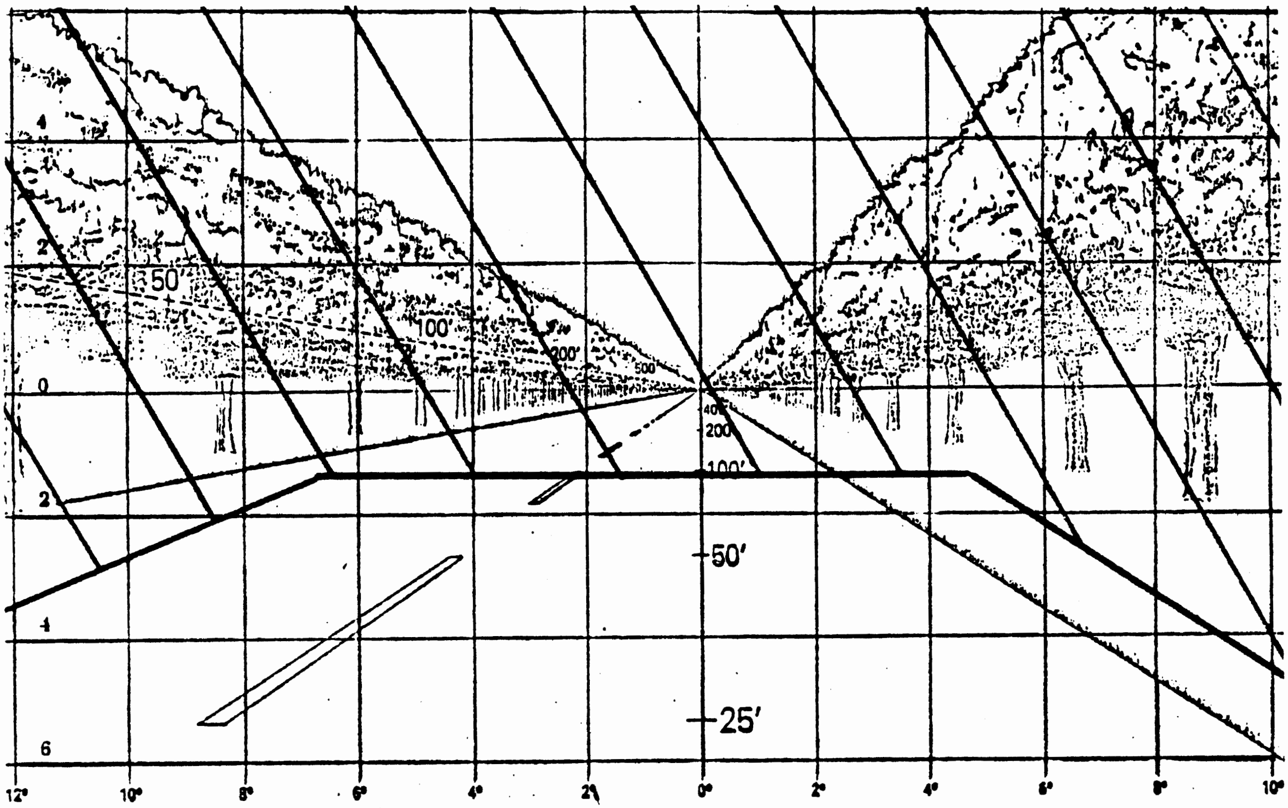


Figure 2. Foreground zone.

Higher illumination levels may be possible or desirable. The question is whether there should be an upper limt.

The ECE beam pattern provides a higher level of foreground illumination than the SAE. Among concerns which have been expressed are that its high luminance foreground alters the dark adaptation level of the driver, making it more difficult for him/her to detect low-contrast objects in the far field. Only one study seems to have investigated this problem specifically (Huculak, 1978). The data tend to show an inverse relationship between foreground luminance and detection distance, but the differences are small. Huculak states: "Only in extreme situations such as those concerning older drivers with pronounced glare sensitivity or high-intensity beams aimed excessively downward could it be a factor in reducing the distances at which obstacles are detected" (p. 17). We agree. However, high foreground-illumination levels offer no obvious benefit, and older persons (and some younger persons) with "pronounced" glare sensitivity do drive at night. Therefore, relatively low foreground-illumination levels seem desirable, with those represented by the present ECE configuration constituting an upper limit.

It has also been suggested that high levels of foreground illumination tend to draw the eye of the driver to the foreground and away from areas where attention should be directed. Research on this problem was carried out as part of the current NHTSA-funded project. These data suggest that this is not a problem, at least up to levels represented by the current ECE low-beam system.

Peripheral Foreground

The peripheral foreground area constitutes those portions of Figure 1 which are outside the hatched area in Figure 3. This includes two FMVSS 108 test points as follows:

2 D - 15 L and 15 R	700 cd min

Visual Needs. Illumination in these areas can be helpful in locating driveways, and making low-speed turns. It may also be beneficial in driving at higher speeds on winding roads.

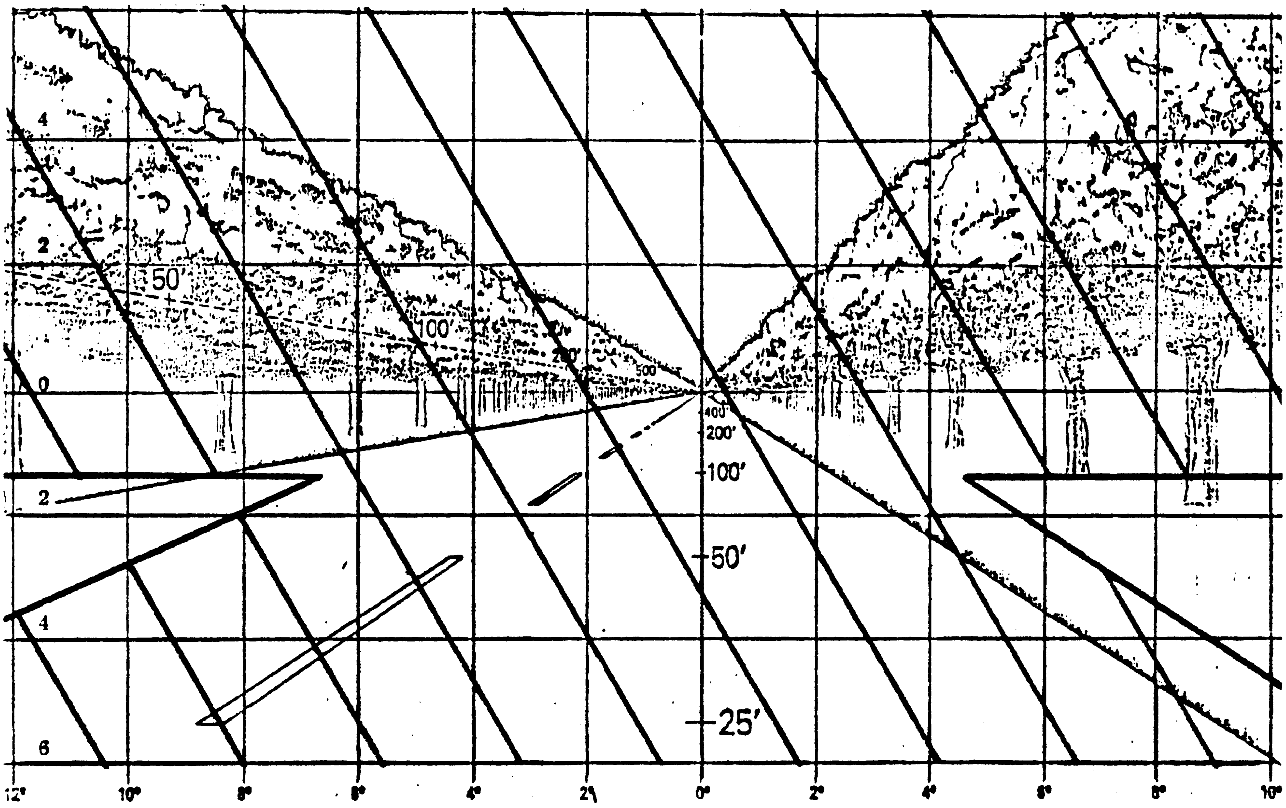


Figure 3. Peripheral foreground zone.

Illumination Levels. As in the case of the foreground zone, illumination levels in this area are based on subjective analysis. There has been one objective study, in which an effort was made to set illumination levels in the periphery based on performance on winding mountain roads (i.e., Helander et al., 1979). Unfortunately, the results do not demonstrate a clear relationship between illumination and driver performance. In the absence of information to the contrary, it must be assumed that the current minimum value is reasonable.

If evidence concerning the minimum for this zone is weak, there is nothing to guide setting maximums. However, since it is expensive (in terms of energy consumption) to provide illumination in this area, it can probably be assumed that manufacturers will tend to stay near the minimum value, making the establishment of maximum values less important.

Upper Left Quadrant

The upper left quadrant is that portion of Figure 1 outside the hatched area in Figure 4. It includes three test points as follows:

10 U to 90 U	125 cd max
1 U - 1 1/2 L to L	700 cd max
1/2 U - 1 1/2 L to L	1,000 cd max

Visual Needs. This is the glare quadrant. In other words, this is the portion of the forward field in which the eyes of oncoming drivers will be most often located. Because of this consideration, the debate over desirable levels of illumination is particularly intense.

Some illumination in the quadrant is necessary for at least two reasons:

First, due to changes in roadway alignment, illumination in this area is sometimes required simply to be able to see where the road is going.

Second, some important signs appear in this quadrant. This includes left-side-mounted no-passing pennant signs and overhead guide signs.

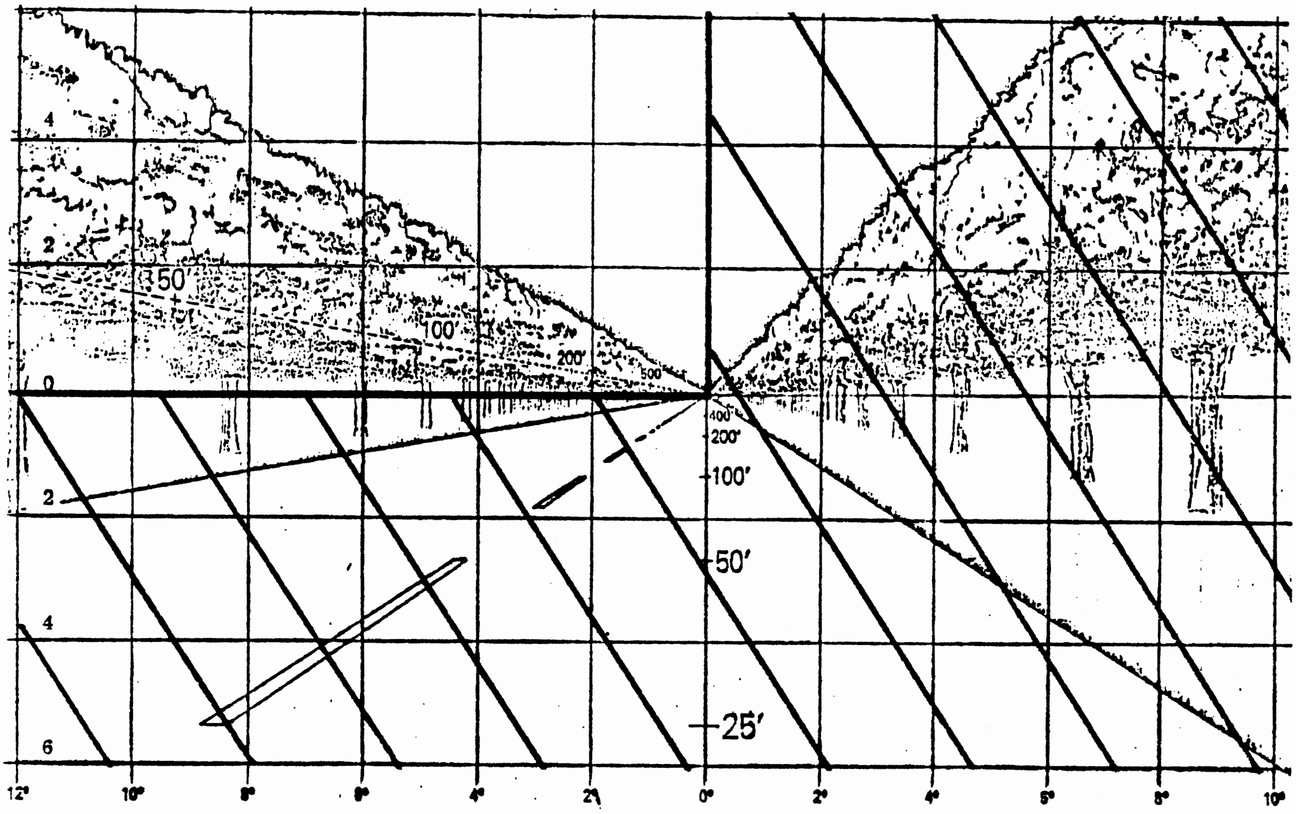


Figure 4. Upper left quadrant.

Warning and regulatory signs are always made with retroreflective materials. The Manual of Uniform Traffic Control Devices requires that all freeway guide signs be either illuminated or fully reflectorized. Signing practices in the United States vary from state to state. However, with the growing cost of energy, many traffic engineering agencies are looking into the possibility of dispensing with illumination and relying on reflectorization. Since reflectorized signs derive their luminance from the headlamps of approaching vehicles, some illumination must be directed toward them. Reducing illumination in this area will reduce the target value of signs and their legibility as well.

Some gains may be had through the use of more efficient retroreflective materials and/or more frequent replacement of material. However, traffic engineering agencies have the same constraints as virtually all other government units, in that they have more problems than funds to solve them. Hence, it can be anticipated that many signs will have lower levels of reflectivity than is desirable.

Illumination Levels. The effects of both disability and discomfort glare have been studied extensively. Sophisticated models have been developed which predict glare effects with considerable precision. The problem is not lack of knowledge, at least as concerns disability glare, but an inability to weigh the trade-offs provided by various real-world driving conditions and arrive at an optimal solution.

The problem is well illustrated by Figure 5, taken from Moore (1958). The figure shows the visibility distance to a low-contrast target as a function of illumination directed toward it and illumination directed toward the observer's eyes. For example, if 20,000 candelas were directed toward the target, and none toward the observer, the target was visible at about 325 feet. If the illumination directed toward the observer is only 5% (1,000 candelas) of that directed toward the target, detection distance is reduced by about one-third.

It will also be noted from an examination of Figure 5 that the disabling effects of glare are non-linear. The current FMVSS 108 glare maximums are 700 candelas at 1^{0} up and $1\text{-}1/2^{0}$ left and 1,000 candelas at $1/2^{0}$ up and $1\text{-}1/2^{0}$ left. These values limit the intensity that can be

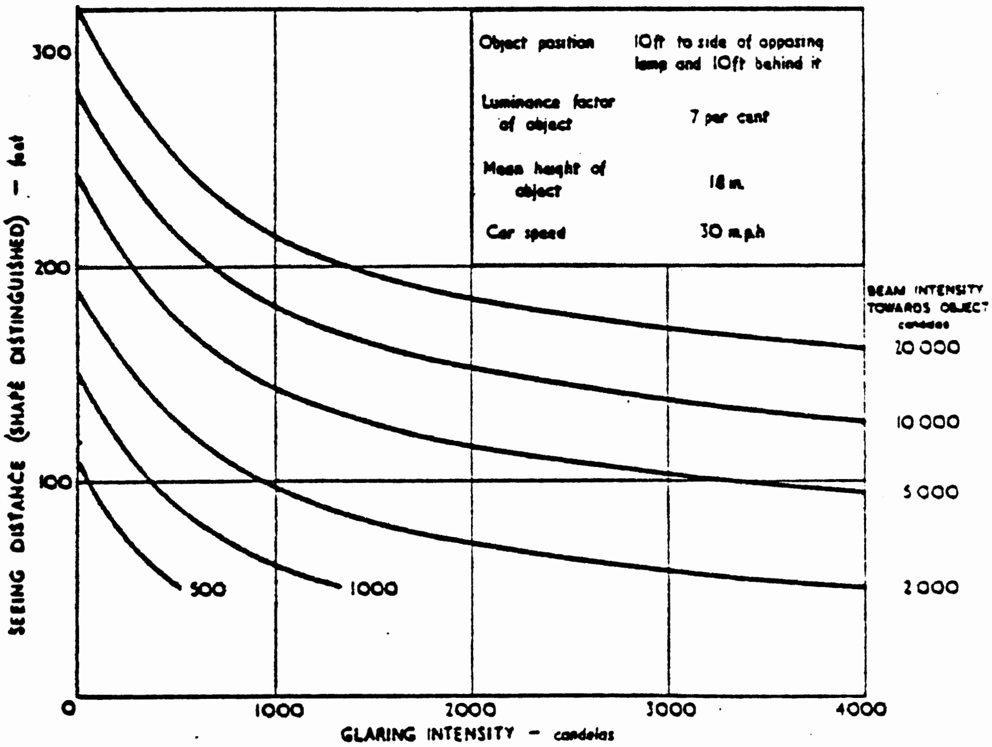


Figure 5. Relationship between the intensity of light directed toward a target and toward an observer's eyes on visibility distance. (From Moore [1958]).

directed toward the critical area at $1/2^{0}$ down, $1\text{-}1/2^{0}$ right. While the standards allow 20,000 candelas at this point, engineers find they can provide only 12,000 to 14,000 candelas without exceeding the glare values mentioned above. If increased glare levels were allowed, proportional increases in useful illumination would be possible. For example, if the glare values could be doubled, the increase possible in useful illumination would improve no-glare seeing distances substantially. Moore's data suggest that a doubling of present intensity levels would improve no-glare seeing distances by about 15%, and, even under meeting conditions, there would be a net gain in visibility.

Thus, it might appear that the solution to the inadequacies of current headlighting systems is as simple as "making them brighter." However, there are at least four significant problems with this approach.

1. There would be an increase in discomfort glare in straight meeting situations.

2. There is the possibility of disability effects associated with prolonged exposure to higher glare levels.

3. Performance under adverse weather conditions will be degraded.

4. Discomfort and disability glare effects associated with opposing drivers passing through the main portion of the beam (as on curves) would be increased greatly.

Each of these points will be discussed separately in the following section.

1. Discomfort Glare. Discomfort glare has been studied extensively. However, because it is a subjective phenomenon, it is very difficult to set limits. Some of the most important work in the automotive context has been reported by DeBoer (1956), who developed a subjective scale for the assessment of discomfort glare. This 9-point scale (9 = just noticeable, 5 = just acceptable, 1 = unbearable), has been used in a number of studies. For example, in a dimming-request study, Bhise et al. (1977) calculated the illumination at the eye of oncoming drivers and compared it with the scale values as determined by

DeBoer. They found an increase in dimming requests when illumination levels moved into the uncomfortable range (i.e., 5.0 or lower).

DeBoer's data suggest that present U.S. low beams provide glare levels which exceed the discomfort limit. While the discomfort glare is less than one scale point below 5, and is experienced for a fairly brief period of time in a meet with a single vehicle, it does imply that further glare increases could present problems in public acceptance. On the other hand, data collected by Hull et al. (1971), based on dimming requests, imply that glare levels up to about twice that experienced today may be possible. Hull et al. did note increases in percent dimming requests as glare increased, but the increases were minor until glare intensity exceeded 4,000 cd.

It has long been known that experimental subjects tend to tailor their judgments to the range of stimuli offered. Lulla and Bennett (1981) wondered if this would apply to estimates of the borderline between comfort and discomfort (BCD) in glare work and account for some of the variability between various studies. They used two groups of twenty subjects each. One group made BCD judgments using a range up to 300,000 foot Lamberts, the second used a range up to 30,000 foot Lamberts. With a 10:1 range difference, the two BCD values differed by 7:1.

Lulla and Bennett's results are important, because they indicate that judgments of discomfort are dependent on context to a large extent. Thus, considerable increases in glare could very well be acceptable to the public, after a time. It may be that, if headlamp modifications which will cause significant increases in glare are contemplated, they should be phased in gradually over a period of years.

Discomfort glare remains as a significant limitation to headlamp design. However, as should be clear from the discussion above, there is no basis for setting an upper limit at this time. The problems in designing adequate experiments are formidable, and it is evident there will be no general agreement in the near future.

In the final analysis, with current technology, better visibility can be achieved only by increasing illumination. Inevitably, this will increase glare. Since current data suggest that some increases in glare may be feasible, it seems reasonable to fabricate systems which will improve visibility and test them for public acceptance.

2. Long-term exposure. The question of cumulative disability effects from long-term exposure to glare is a difficult one, and has been a subject of concern for some time. The most comprehensive study of the problem has been reported by Schiflett et al. (1969). They investigated changes in their subjects on a number of measures under both real and simulated driving conditions, as a function of time and glare level. Some of the findings are suggestive of a deterioration effect associated with prolonged exposure to high levels of glare, but the results are generally not statistically significant. Thus, the issue remains unresolved, even for glare levels equivalent to high beams. No guidance at all is available for modest increases in glare levels such as will be proposed in this report.

3. Adverse weather. Performance in adverse weather is a design consideration of considerable importance. In general, illumination directed above horizontal is backscattered under conditions such as fog, resulting in loss of visibility distance. It should be noted that earlier versions of the sealed beam system projected considerably more light above horizontal, especially to the right of the V axis. Deliberate steps were taken to reduce this illumination, primarily based on bad-weather performance considerations. Unfortunately, techniques for deciding a priori when the problem has become excessive are lacking, so it is necessary to engage in real-world testing.

4. Exposure to maximum beam intensity. Consideration of those situations in which the full beam intensity reaches the eyes of oncoming drivers is also important in lamp design. An approach such as doubling the lamp output would push the total illumination at the point of maximum intensity up close to that provided by the high beams, a level which experience suggests would be unacceptable for meetings on curves. Present maximum low-beam intensities are apparently acceptable by this criterion. Therefore, a solution may lie not in simple increases of illumination, but in a rearrangement so that present maximums are allowed to penetrate further down the road.

Moore's data suggest an alternative path to improved visibility. Since the current glare values in FMVSS 108 fall on a relatively steep portion of the curves in Figure 5, it is apparent that modest reductions in glare can bring about significant improvements in visibility distance. This, in fact, is the approach favored by the Europeans, who limit illumination projected into the upper left quadrant to a maximum of about 440 candelas. Given the shielded filament source used by European manufacturers, it is feasible to reduce glare while maintaining relatively high levels of target area illumination. That the technique works is confirmed by Figure 6. For targets to the left side, the U.S. and European beams yielded about the same visibility distances under no-glare conditions, but the European lamp was about 20-30% better near the meeting point. For targets on the right side, the U.S. lamp was slightly better under no glare and slightly worse under maximum glare conditions.

It is clear that the European shielded-filament approach could be adapted to the U.S. sealed-beam concept (e.g., the recently introduced Cibie "BOBI" lamps), allowing reduced glare, and/or higher intensities in critical seeing areas. As will be noted later, this is one of the hardware implementations we suggest. There are disadvantages, however, including higher unit costs and increased power consumption.

To summarize:

1. Through long experience, it is apparent that the public finds present glare levels acceptable. Some available evidence suggests that increases would be feasible. This would allow increases in "useful" illumination (i.e., that directed into the zone of critical seeing) and improve visibility for vehicle operators.

Despite much research over a period of many years, there is still no consensus regarding an upper limit for glare based on either disability or discomfort considerations. Based on the evidence, the authors feel that significant increases in glare are feasible. At present, the increases should be no more than 100%. Such an increase would be well short of levels which have provoked large increases in dimming requests in studies such as that of Hull et al. (1971), and would allow quite significant improvements in useful illumination.

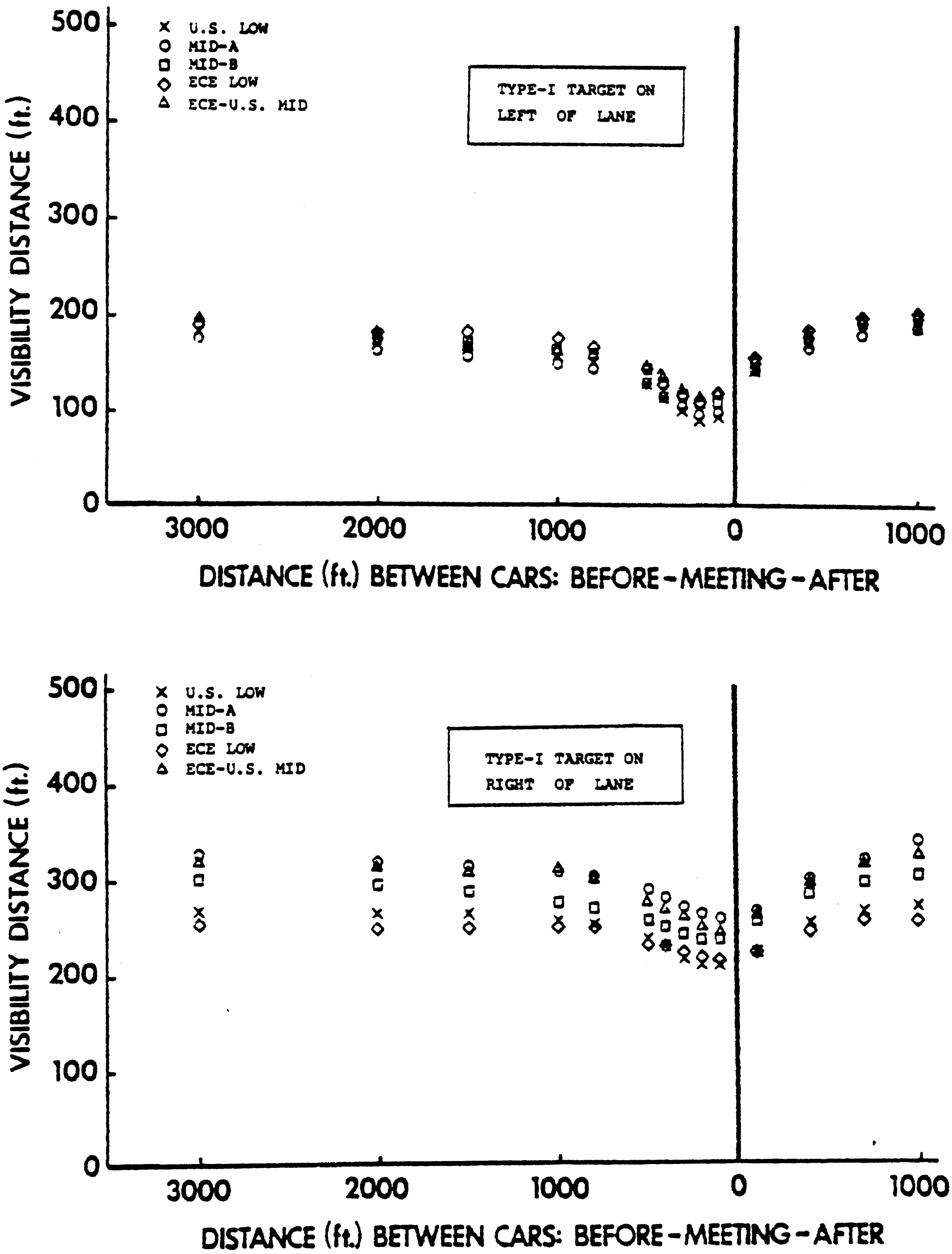


Figure 6. Mean visibility distances obtained with five lighting systems and two target positions. (From Mortimer and Olson, 1974.)

2. Reducing glare below present levels (while holding other illumination constant) is a way of improving seeing distance that is unlikely to cause problems in public acceptance. However, it will result in the loss of some useful information in the upper left quadrant.

On balance, the authors of this report believe it is preferable to attempt to improve visibility by increasing intensity in critical seeing areas, accepting the fact that glare levels will increase, rather than by attempting to reduce glare.

Upper Right Quadrant

The upper right hand quadrant is that portion of Figure 1 which is outside the hatched area in Figure 7.

Two FMVSS 108 test points are in this area. These are as follows:

1 1/2 U - 1 R to R	1,400 cd max
1/2 U - 1 R to 3 R	2,700 cd max
10 U - 90 U	125 cd max

Visual Needs. In this quadrant appear not only portions of overhead guide signs but also all ground-mount guide signs, almost all regulatory and warning signs, and post-mounted delineators.

Illumination Levels. The adequate detection and identification of traffic control devices is an important aspect of vehicle control at night. Illumination directed into this quadrant ought to be adequate to fulfill this important function. Sign reflectivity levels and delineators have been designed, at least to some extent, with present levels of illumination in mind. Therefore, the illumination directed into this quadrant by the present SAE low beam should be regarded as a minimum.

Increasing illumination in this quadrant would assist in the detection, identification, and legibility of the devices described earlier, especially by older drivers. However, there are three important considerations which limit illumination in this quadrant.

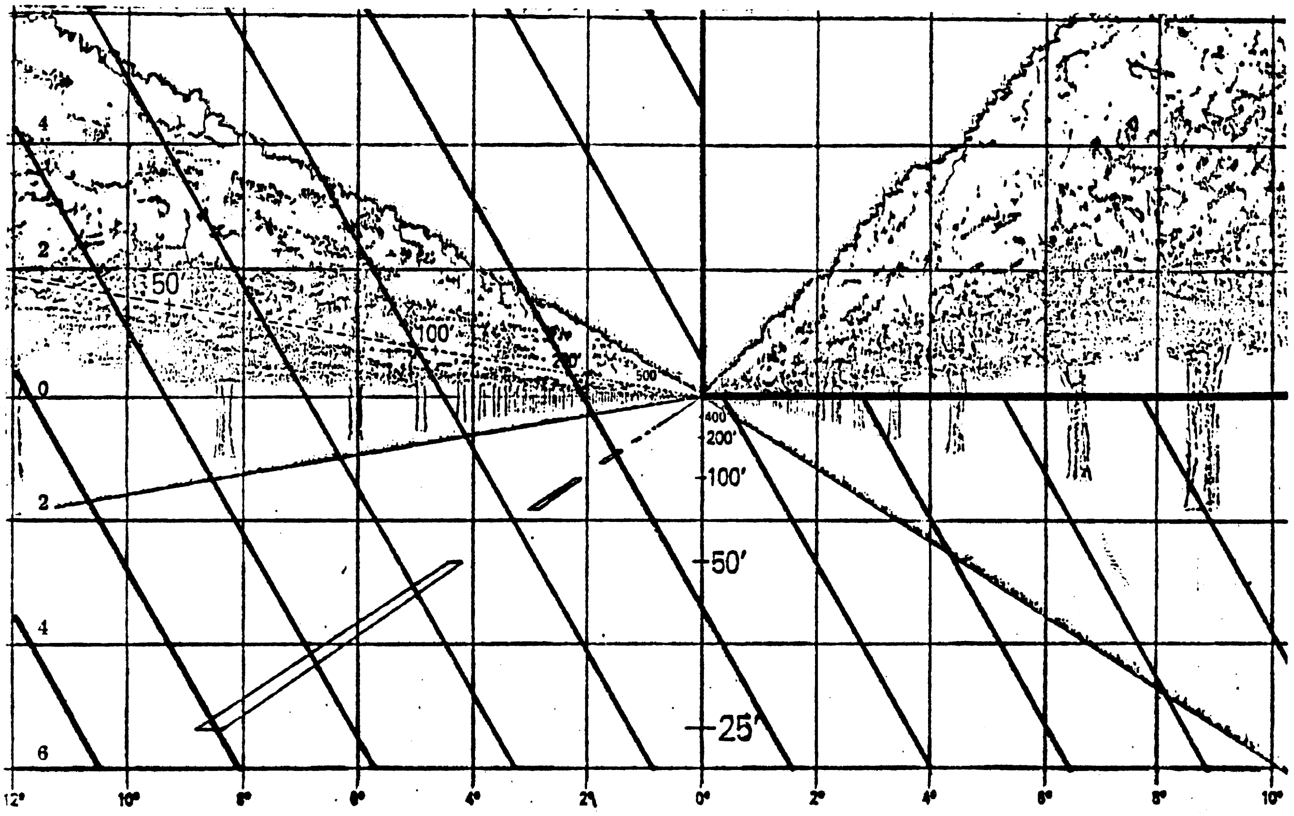


Figure 7. Upper right quadrant.

These are:

1. Glare provided approaching drivers on curves.
2. Performance under adverse weather conditions.
3. Glare in the mirrors of preceding drivers.

The problems of illumination in this quadrant are closely linked with what is done in the zone of critical seeing. Therefore, they will be considered together in the following section.

Zone of Critical Seeing

The zone of critical seeing is that portion of Figure 1 outside the hatched area in Figure 8. Roughly, it extends from a point 30 meters (100 feet) in front of the car to the horizon. It includes six test points in FMVSS 108:

1/2 D - 1 1/2 L to L	2,500 cd max
1 D - 6 L	750 cd min
1 1/2 D - 9 L and 9 R	750 cd min
1/2 D - 1 1/2 R	20,000 cd max 8,000 cd min
1 1/2 D - 2 R	15,000 cd min

Visual Needs. This is a zone of "critical seeing" in that it is this area in which critical targets must be detected and identified if the driver is to deal with them effectively at almost all driving speeds. The "targets" include pedestrians, various vehicles, animals, pavement-mounted delineation and other road markings such as cross walks and railroad warnings, construction zone barricades and channelizing devices, pot holes, and miscellaneous debris. Clearly, this is a zone where illumination levels should be as high as practical.

Illumination Levels. The zone of critical seeing is shown extending across the full width of the field. This is appropriate when considering mobile objects, moving at angles to the vehicle's path. However, mobile objects moving parallel to the vehicle's path, and fixed

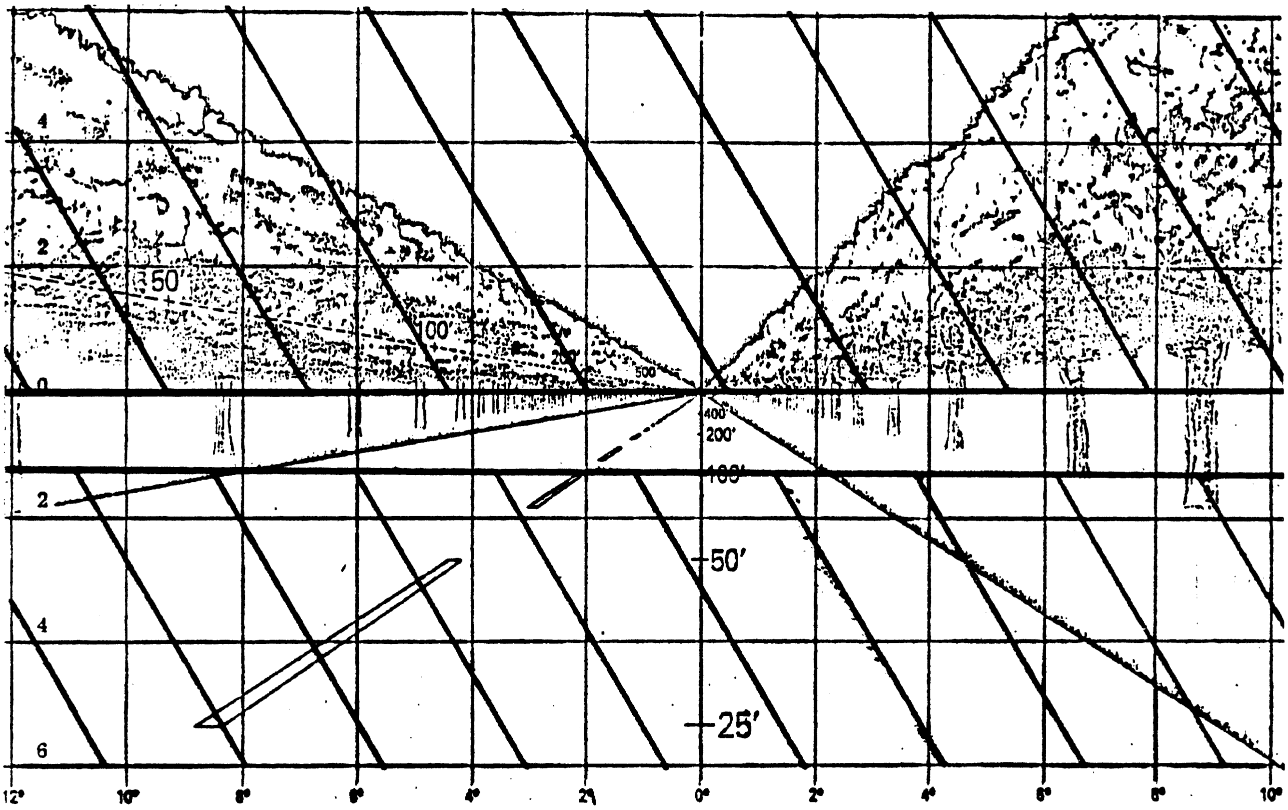


Figure 8. Zone of critical seeing.

objects, are only of concern if they are in or near the traveled lane. Further, assuming low beams are used to avoid providing excessive glare to oncoming drivers, and high beams would be used otherwise, mobile objects coming from the left side are largely cared for by the approaching traffic. Thus, that portion of the zone to the right of the V axis can and should be accorded more weight in low-beam design.

A glance at the FMVSS 108 standards makes it clear that the present low beam does attempt to provide relatively high levels of illumination in that part of the zone to the right of the V axis. The question is, can the levels of illumination in this area be modified to improve visibility without causing serious problems based on other considerations?. The rest of this report will be devoted to this issue.

A previous study of low-beam headlighting (Halstead-Nussloch et al., 1980) carried out by HSRI, featured an evaluation, by a computer seeing-distance model, of a great number of conceptual beam patterns. Several of the more promising ideas were further explored in this study. One of the best of the systems evaluated by Halstead-Nussloch et al. (based on the computer analyses) was actually a mid beam (which was referred to as system "F" in that study). That is, it consisted of a normal SAE low beam, as would be provided by two standard units, combined with a single high-intensity (78,000 cd maximum), fairly narrow beam unit aimed slightly right and down.

As would be expected, based on its output, such a combination will yield right-side visibility distances approximately equal to a high beam. At the same time, the sharp cutoff characteristic to the left side holds glare close to normal low-beam levels, at least for straight road situations.

For a mid-beam, this is a good combination. For a low beam, which cannot be dimmed, it has serious deficiencies. The major problem is that it is simply too bright for situations such as following another car or meeting other vehicles on curves. It would probably present problems under adverse weather conditions as well. However, the concept is intriguing, since it places maximum additional illumination where it is most needed. The question is whether the intensity of the additional beam could be reduced to acceptable levels and still provide a worthwhile improvement in visibility distance.

To study this possibility, the HSRI computer seeing-distance model was used (Mortimer and Becker, 1973). This model accepts up to five different lamps on each of two vehicles. Each lamp can have a different beam pattern and can be aimed separately. If desired, each lamp's intensity can be adjusted above or below that originally specified. For purposes of this evaluation, the model was set up with a standard SAE low beam, supplemented by the mid-beam installed on the left (driver's) side. Runs were made with the mid beam at 100% (60,000 cd maximum), 75%, 50%, and 25%, and compared with the unaltered low beam. These results are shown in Figure 9.

Figure 9 shows visibility distance to a low-contrast (10%) target (see Figure C-1 in Appendix C for a photograph of the target) placed on the right edge of the road. Two identically equipped vehicles are assumed, approaching one another on a two-lane road. It will be noted that the unaltered low beam provides a maximum visibility distance of about 80 meters, the 60,000 cd mid beam a bit more than 100 meters. The difference is about 30%. As noted earlier, the 60,000 cd unit yields visibility distances approximately equal to high-beam performance. Reducing the mid-beam to 25% of the maximum setting reduces the visibility distance gain by about half.

A low-beam isocandela diagram on which the computer simulation is based is illustrated in Figure 10. Obviously, two such units are used. The mid-beam configuration tested (at the 25% level) is shown in Figure 11, to provide an indication of the amount and location of the additional illumination. The maximum intensity is equal to or less than the high-intensity zone of a single low-beam unit.

The modification to the low-beam lighting system described above will provide a significant increase in visibility distance to an important portion of the forward field. To do so requires an increase in illumination at and above horizontal on the right side of the road. Table 1 is a candela matrix for the standard low beam on which the computer predictions are based. Table 2 illustrates the modifications necessary to achieve the results in Figure 9. Both Table 1 and Table 2

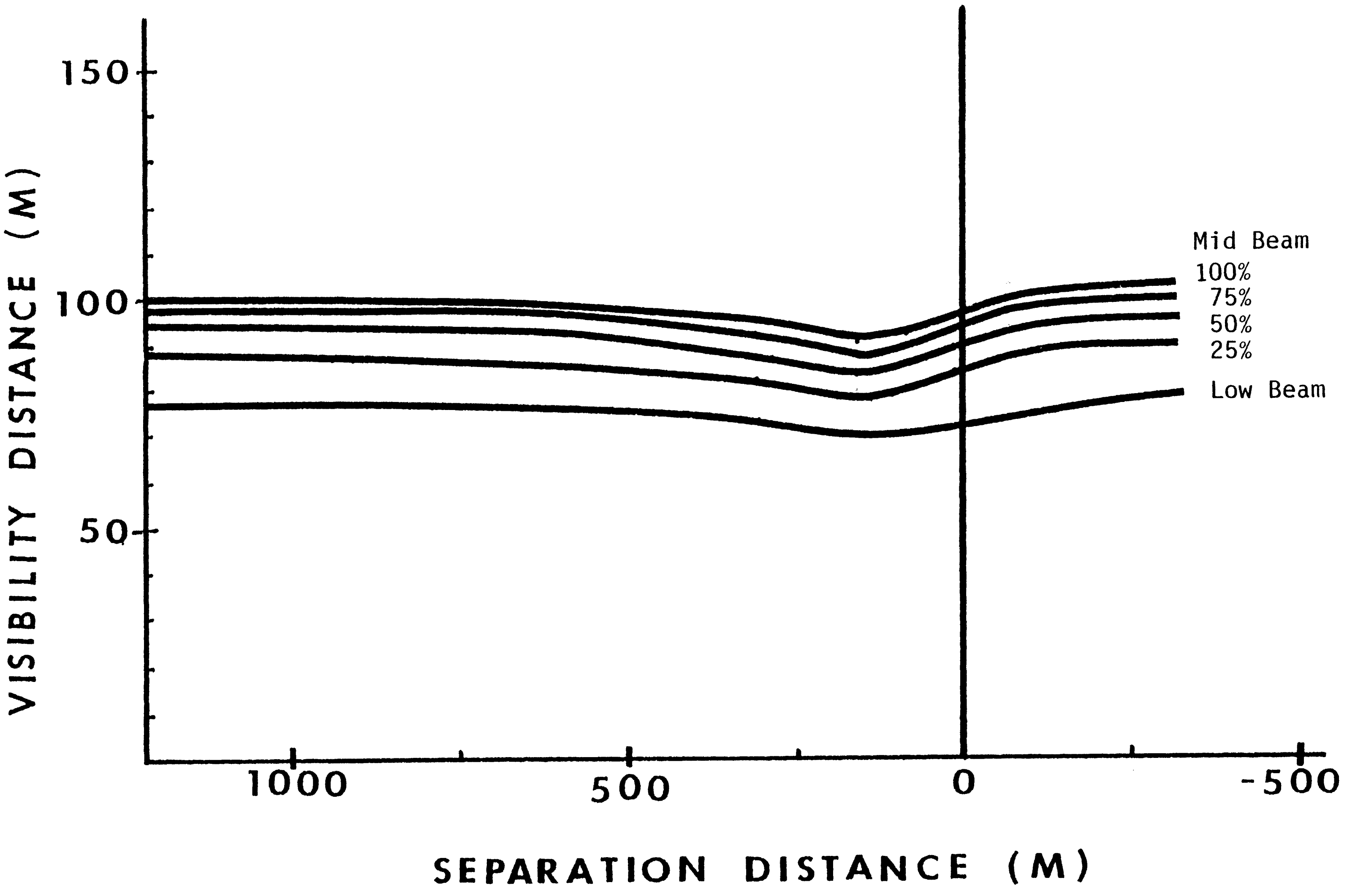
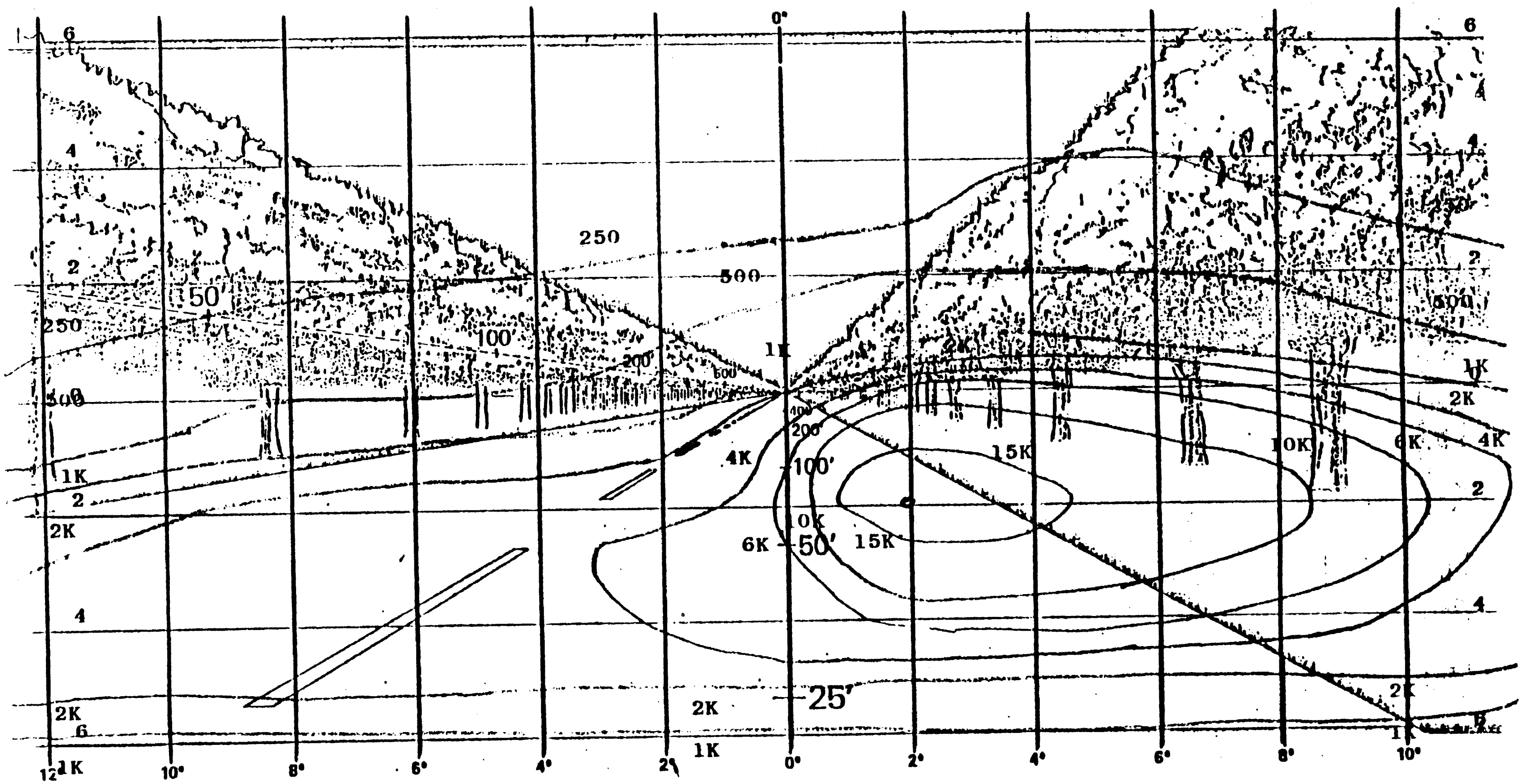


Figure 9. Visibility distance (in meters) provided by mid-beam system at four intensity levels compared with standard low beam as a function of logitudinal separation between two identically equipped vehicles.



From Mortimer, "Requirements for Automobile Exterior Lighting" (Figure 1) 5 3/4" type 2 Low Beam.

Figure 10. Typical U.S. low beam isocandela diagram on which computer simulation is based.

Table 1

Standard Low Beam Candela Matrix

		Degrees Left									Degrees Right									
		8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10
Degrees Up	2.0	200	225	225	250	250	250	300	350	400	500	550	550	550	500	500	500	450	400	350
	1.0	300	300	350	350	400	450	475	600	700	800	900	900	900	800	750	700	700	650	500
	0	500	500	500	500	530	600	700	1000	2000	4000	7000	7500	7000	6000	5500	4000	3500	2000	1250
Degrees Down	1.0	1000	1000	1100	1100	1200	1500	2000	2500	5000	12000	15000	14000	12500	11000	10500	9000	7500	6000	4500
	2.0	2000	2000	2000	2200	2500	3000	3500	4000	7000	15000	20000	18000	16500	14000	12000	11000	10500	9000	6500
	3.0	2000	2100	2200	2400	3500	4000	4300	5000	5500	10000	12000	12000	11500	11000	10500	10000	8000	7000	5200
	4.0	2000	2000	2000	2350	2650	3175	4000	4700	5200	5700	7200	7200	7200	7200	6650	6150	5100	4400	4050

Table 2

Modified Low Beam Candela Matrix

		Degrees Left									Degrees Right									
		8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10
Degrees Up	2.0	200	225	225	250	250	250	300	450	600	800	900	800	700	600	550	500	450	400	350
	1.0	300	300	350	350	400	500	650	1000	1700	3650	3750	2800	2000	1200	950	900	800	700	500
	0	500	500	600	650	700	800	1200	1800	5750	11000	12000	10500	7800	6600	5750	4200	3600	2100	1275
Degrees Down	1.0	1000	1100	1150	1200	1400	1900	2700	4000	8200	17500	19000	17800	13700	12000	10400	9400	8300	6200	4650
	2.0	2000	2200	2400	2700	3000	3600	3900	5300	8500	16800	22000	19500	17200	15000	13700	11600	10900	9350	6700
	3.0	2000	2400	2700	3200	3900	4300	4850	5700	6800	11000	13000	12900	12800	12000	11400	9800	8200	7200	5600
	4.0	2000	2000	2050	2350	2650	3175	4000	4700	5200	5700	7200	7200	7200	7200	6650	6150	5100	4400	4050

illustrate one headlamp from a system composed of two identical units. Thus, Table 2 combines Table 1 and one-half the intensity of the modified mid-beam shown in Figure 11.

Based on the analysis presented to this point, the proposed modification to the low-beam system appears promising. However, there are a variety of other considerations which must be reviewed before arriving at a final recommendation. The next section of the report will deal with these concerns.

CHESS Evaluation. CHESS is an acronym for the Comprehensive Headlamp Environment Systems Simulation, a computer-based headlamp evaluation system, developed at Ford Motor Company (Bhise et al., 1977). The system incorporates a seeing-distance model, somewhat like that developed at HSRI (Mortimer and Becker, 1973). It differs from other models in that it includes a standardized test route. The route consists of a series of highway sections in the form of environmental parameters which are thought to have an influence on visual performance and night driving. It includes such factors as pavement, lane line and target reflectance, road geometry, lane configuration, ambient illumination, and glare from fixed lighting and traffic.

When a headlighting system is run through the standardized test route, the model outputs a "figure of merit." This figure of merit is the percent of the distance traveled on the test route during which the seeing distance to pedestrians and pavement lines and the discomfort glare levels experienced by opposing drivers simultaneously meet the acceptance criteria.

With the generous cooperation of persons at Ford, the proposed low-beam system described in Table 2 was evaluated using CHESS. The runs were made with perfect aim and a random misaim condition. The results are summarized in Table 3.

Table 3 shows, at the top, various measures on the proposed low-beam modification. Below are four beams from the Ford library, for purposes of comparison. Lastly is the type "F" system evaluated in the study by Halstead-Nussloch et al. (1979) referred to earlier. (Note that the "F" system was not the "single beam" tested in that study.

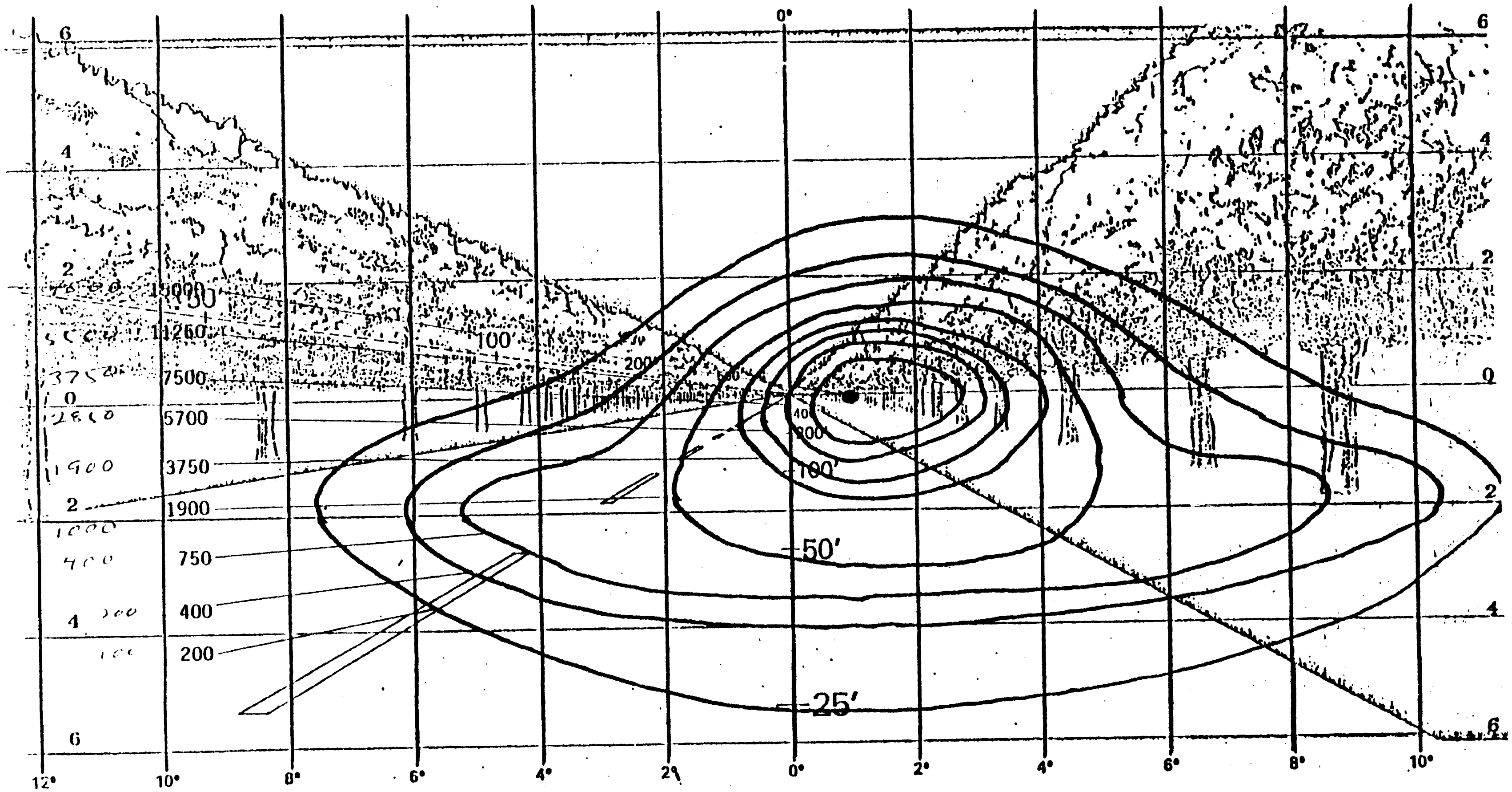


Figure 11. Mid-beam added to standard low beam in seeing distance tests. Candela values shown are 25% of original, and are those which provided best balance between additional visibility and glare.

Table 3

Results of CHESS Evaluations

System	Figure of Merit		Percentage of Opposing Drivers Discomforted		Percent of Encounters Meeting Visibility Criteria with Random Misaim			
					Unopposed Encounters		Opposed Encounters	
	Perfect Aim	Random Misaim	Perfect Aim	Random Misaim	Delineation Detected	Pedestrians Detected	Delineation Detected	Pedestrians Detected
Proposed Modified Low Beam	71.3	66.8	2.7	9.3	86.6	47.3	85.5	34.0
4652 Low Beam	69.8	67.1	2.4	9.2	88.3	43.7	86.2	28.2
4000 Low Beam	69.1	65.7	1.0	9.0	85.4	43.5	76.3	23.5
6014 Low Beam	69.7	66.1	1.3	10.3	86.7	47.3	84.8	31.0
ECE Low Beam (H-4)	66.6	62.9	0	8.1	85.6	41.4	84.1	28.5
Type "F" Beam from Halstead-Nussloch, et al.	74.5	70.1	4.2	13.9	88.8	52.9	86.9	36.1

Rather it was the mid-beam which served as the starting point for the beam being considered in the present study.)

An examination of Table 3 indicates that the proposed low beam is generally better than the comparison low beams on most measures, although the differences are not large. The largest difference is in the percent of pedestrians detected under opposed conditions. This is expected since the beam was designed to provide additional illumination in the right shoulder area from which pedestrians are apt to emerge.

As a supplement to this analysis, CHESS was also used to evaluate various intensity and aim modifications. To do this, two standard low beams were used (4000 and H 4656) and the modified system simulated by adding a mid beam at the appropriate intensity. A number of combinations of intensity and aim were run. The results indicate that the figure of merit can be increased (to 72.3) by increasing the output by 66% and moving the aim one degree right and down. Due to time constraints, there has been no immediate follow-up to these findings. However, it would be desirable to evaluate this configuration as part of the subjective phase of the field study.

Note in Table 3 that the type "F" beam is much the best, based on this analysis. As mentioned earlier, the authors rejected the use of such a mid-beam, based on glare under some conditions and probable poor performance in adverse weather. Assuming that the rejection was correct, this suggests that CHESS has some limitations as an evaluation device, at least when dealing with a beam characterized by a very high intensity, highly localized hot spot.

Despite the possible limitation noted in the preceding paragraph, the CHESS evaluation provides some further evidence that the proposed modification to the low-beam system has merit and will improve nighttime visibility for drivers.

Glare to Preceding Drivers. A comparison of the standard and modified low-beam patterns as shown in Tables 1 and 2 in the 1° up, 0° to 1° right area reveals that the latter has about two to four times the intensity of the former. This will cause a significant increase in glare for persons located in that area. Many such persons (e.g., pedestrians, drivers of cars seeking to cross the road) have no need to look at the headlamps continuously and can escape the effects simply by looking elsewhere. There is, however, a significant group of persons who cannot look away and may be exposed to the glare illumination for fairly long periods of time, i.e., drivers of preceding cars.

The literature review carried out as part of this study failed to uncover any comprehensive studies concerned specifically with discomfort and disability glare from rear view mirrors. There were two studies which reported measures of rear view mirror glare levels, but not effects (Adler and Lunenfeld, 1973; Miller et al., 1974). Recommendations for maximum levels (5,000 cd) were made in one study (Hull et al., 1971), based on limited subjective data. There have, of course, been extensive studies of discomfort and disability glare in other contexts, and mathematical models have been proposed to predict the effects in a variety of settings (e.g., Fry, 1954, Schmidt-Clausen and Bindels, 1977). However, the rear view mirror glare situation has certain unique properties, and it was thought desirable to conduct some experimental measurements. Four studies were carried out:

1. Disability glare:
    a. Laboratory measurements of the effects of glare on target detection.
    b. Field study to confirm laboratory results.
    c. Laboratory measurements of transitional disability effects.
2. Discomfort glare:

    Field study of discomfort glare.

Reports of these studies are attached as appendices. In brief, the findings are as follows:

Significant disability glare effects were measured at levels approximating present low beams. Further increases in glare illumination can only make the situation worse. However, a solution is available through use of the so-called 2-way interior mirror and judicious aiming of the outside mirror on the driver's side. Additional work on mirror reflectivity levels to reduce this problem seems desirable, but is not absolutely necessary.

Transitional disability glare effects are not significant at the levels of concern in the design of this headlamp beam.

Discomfort glare effects are significant, especially on relatively long exposure (i.e., several minutes). Again, the effect can be reduced or eliminated by appropriate use of interior and exterior mirrors.

In sum, further increases in glare directed toward the rear view mirrors of leading vehicles seems tolerable, if it provides a genuine gain in visibility distance. However, two-way interior mirrors should be required equipment, and further study of mirror reflectivity levels is desirable.

Misaim. It has been shown that headlamps are often badly aimed. This comes about for three reasons (see Olson and Mortimer, 1973):

1. There are a number of sources of aim variance.

2. Some of these sources are difficult to control.

3. Vehicle owners are unlikely to notice and/or do anything about the problem unless it is extremely serious or provokes large numbers of dimming requests from other drivers.

Limits on low-beam aim have been developed by the SAE (J599d). The recommendations are that aim is considered adequate if it is within 4 inches at 25 feet (about 0.8^{o}) in any direction from correct aim.

Since misaim is a fact of life which is not likely to be resolved in the near future, it is important that its effects be considered in the evaluation of any proposed lighting system. This was done, using the computer seeing-distance model mentioned earlier.

Figure 12 compares the modified and standard low beams under conditions of misaim down one degree. This figure should be compared with Figure 9. There is a considerably loss in visibility distance for both systems, about 24 meters for the modified and 29 meters for the standard low beam. The modified low-beam is substantially better than the standard low beam under this condition, the difference being about 30% at maximum.

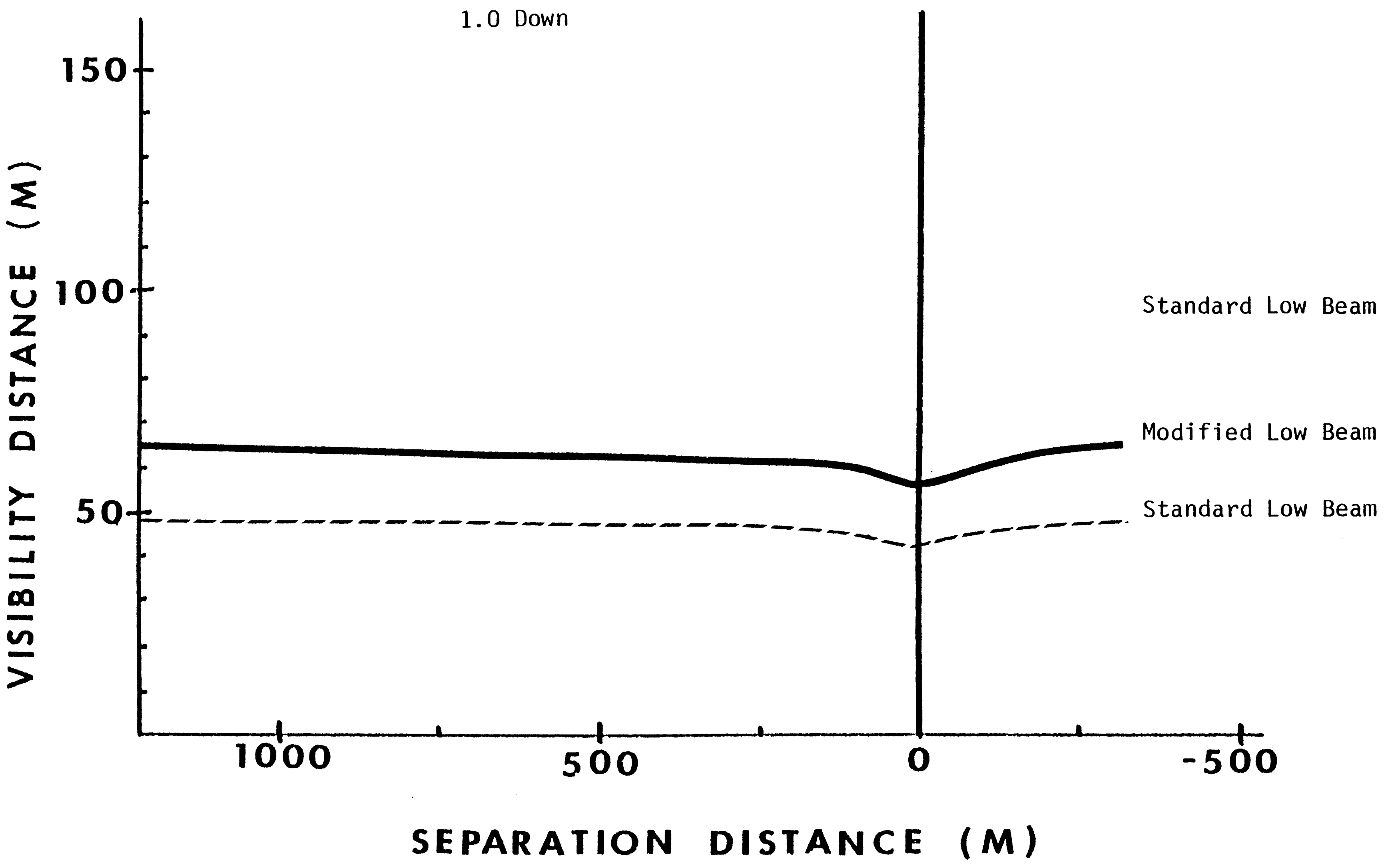


Figure 12. Comparison of detection distances provided by modified and standard low beam systems misaimed down 1°. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road.

Figure 13 illustrates the performance of both systems at one degree misaim up. Under this condition there is no difference between the two systems because they differ little to the left of the V axis and the high-intensity zone of the modified system has about the same maximum as that of the standard system. Overall, upward misaim results in improvements in no-glare visibility distance for both systems and an increased disability glare effect.

Figure 14 illustrates the performance of both systems at one degree of misaim left. The effect is more pronounced on the modified system, as would be expected based on its distributional characteristics, but the difference is slight. The modified system is still superior overall to the standard system.

Misaim to the right was considered in the CHESS evaluation discussed earlier. It will be recalled that moving the modified system right improved its performance, especially when its intensity was increased.

In sum, for the conditions investigated, the modified low beam performs no worse than the present low beam and, for most conditions, outperforms the present low beam. Thus, misaim seems to pose no special difficulties for the proposed system.

Performance as Affected by Adverse Weather Conditions. As noted earlier (p. 16), one of the constraints in low-beam design is that, under adverse weather conditions, light projected above horizontal can be detrimental. The proposed modification to the low-beam system will project more light above horizontal and has the potential for making visibility worse under adverse weather conditions.

The primary problem is that there is no way to evaluate this phenomenon short of fabricating the system and testing it under the conditions of interest. This will be a necessary and important part of Phase II of this project.

Performance as Affected by Mounting Height. Federal Motor Vehicle Safety Standard (FMVSS) 108 specifies headlamp mounting heights as follows:

Minimum 24 inches

Maximum 54 inches

In each case the measurement is made from the road surface to the center of the lens.

European (ECE) standards are somewhat different.

Minimum 500 mm

Maximum 1200 mm

The measurements are made to the bottom of the reflector in the minimum case, to the top of the reflector in the maximum case.

The U.S. and ECE minimum values are close. Given a 7-inch round lamp, for example, the ECE minimum corresponds to 23.2 inches to the center of the lens. Using the smallest rectangular lamps, the minimum corresponds to about 21.7 inches to the center of the lens.

There is a greater difference in the maximum specifications. For example, using a 7-inch round lamp, the ECE maximum yields a mounting height of 43.7 inches to the center of the lens.

Most passenger cars have headlamps mounted near the minimum height. The substantial range of mounting heights allowed is necessary to accommodate the manufacturers of heavy vehicles, especially trucks. Truck manufacturers typically build a limited number of bodies, which are placed on different suspension systems and wheel sizes, depending on design capacity. As a result, headlamps for a particular body type may end up at any point in a rather broad range of mounting heights. The situation at present in the U.S. is such that a significant narrowing of the range of mounting heights would pose problems for truck manufacturers.

Manufacturing considerations aside, these are strong pros and cons in the matter of allowing mounting heights which are actually above the roof level of many cars. On the positive side are visibility considerations, while on the negative side are glare considerations. These points will be reviewed in some detail in the following section.

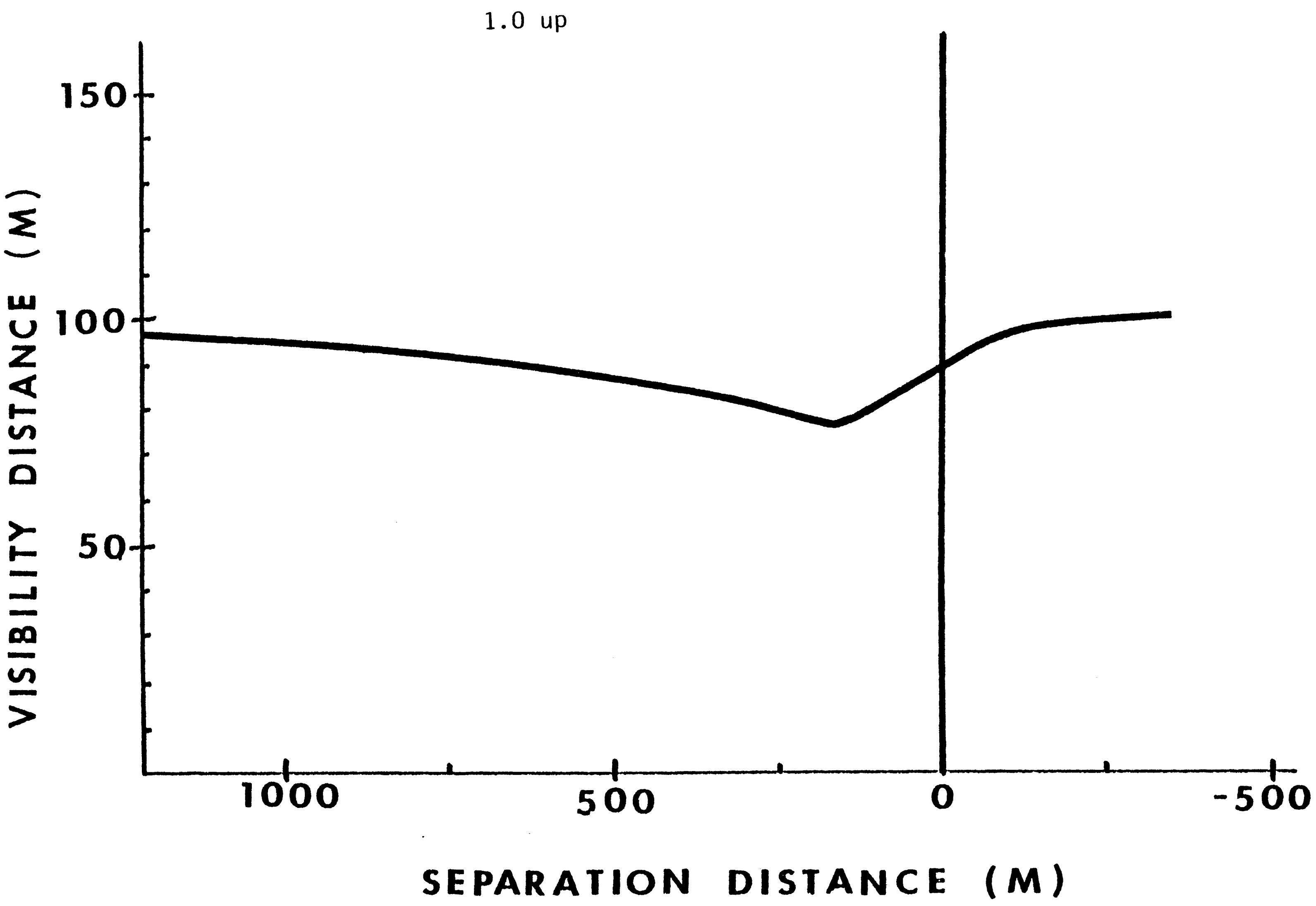


Figure 13. Comparison of detection distances provided by modified and standard low beam systems misaimed up 1^{o}. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road.

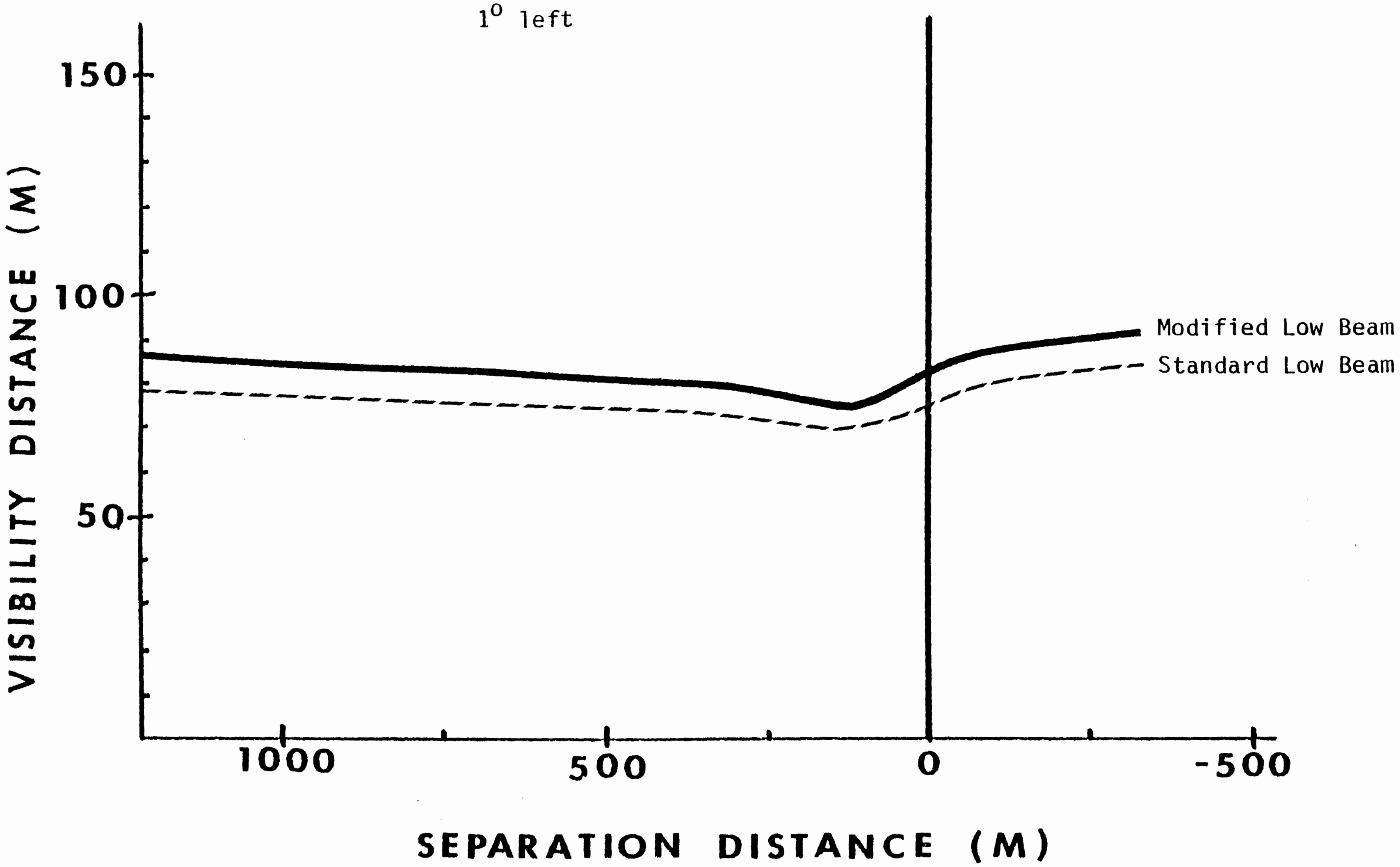


Figure 14. Comparison of detection distances provided by modified and standard low beam systems misaimed left 1°. Type 1 targets at 10%, right side of road. Simulates meeting between two identical systems on a straight, flat road.

Because the low beam is aimed at an angle down, increasing its mounting height will increase the distance down the road at which various portions of the beam intersect the pavement. This will improve visibility distance. Figures 15 through 17 have been prepared to illustrate this effect. The figures are derived by use of the HSRI computer seeing-distance model (Mortimer and Becker, 1973). It assumes the use of a low-contrast target (10% type I target as described in Mortimer and Olson, 1974). The headlamp mounting and driver eye heights are as follows:

Line	Mounting Height	Eye Height
Top	54"	90"
Middle	40"	60"
Bottom	24"	42"

The traces represent the visibility distances resulting from a meeting by two identically equipped vehicles on a straight, flat road, using the modified low beam described in Table 2.

The simulations were run using several eye heights for each mounting height. The differences associated with eye height were very small (about 1-2%), so are not reproduced here. However, the differences associated with mounting height are quite significant.

Figures 15 and 16 show targets at the left edge and center of the road, respectively. As would be expected, given that the driver must look toward the approaching headlamps to see the target, there are large disability glare effects. The values in Figure 15 (left edge target) are the same as would be obtained with a standard low beam. The values in Figure 16 (road center) are about 7% higher. Note that road-center targets can often be seen at far greater distances than shown, due to being silhouetted against road illumination provided by the approaching vehicle. The type of target on which this simulation is based has its own background, so silhouette effects are not considered.)

Figure 17 is for a target placed on the right edge of the road, as in Figure 9 shown previously. The benefits of the modified low beam are

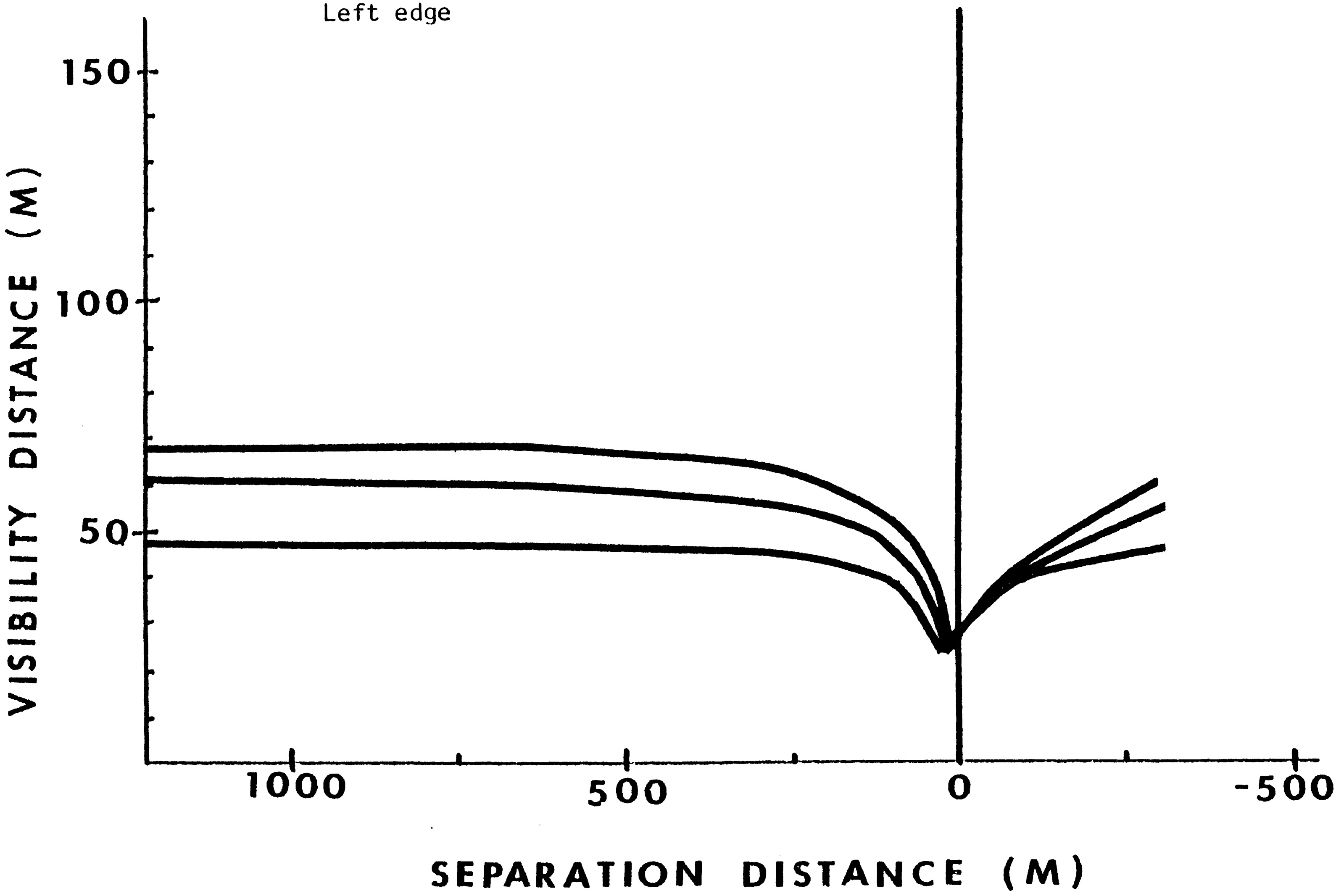


Figure 15. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on left edge of two lane road.

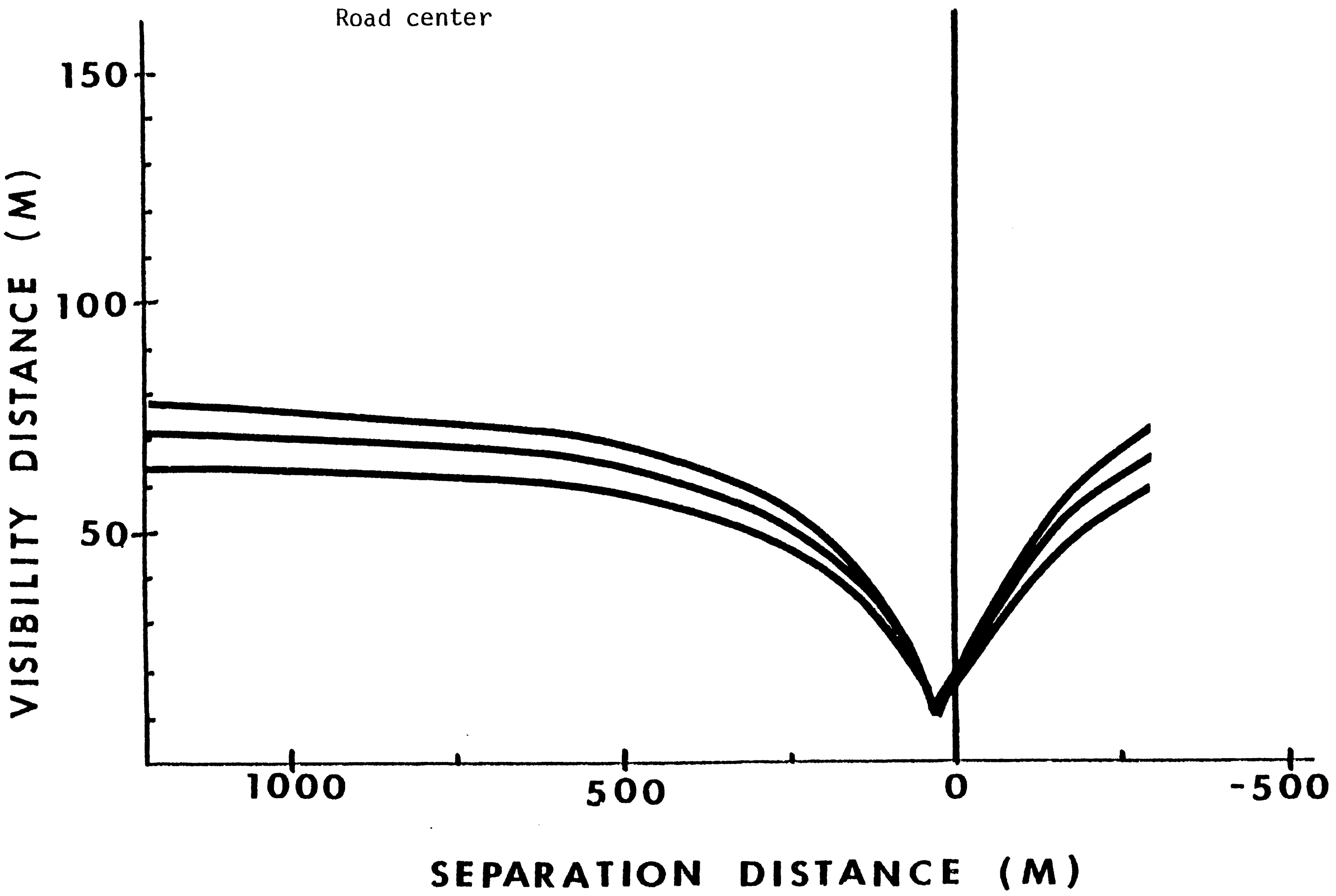


Figure 16. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on center line of two lane road.

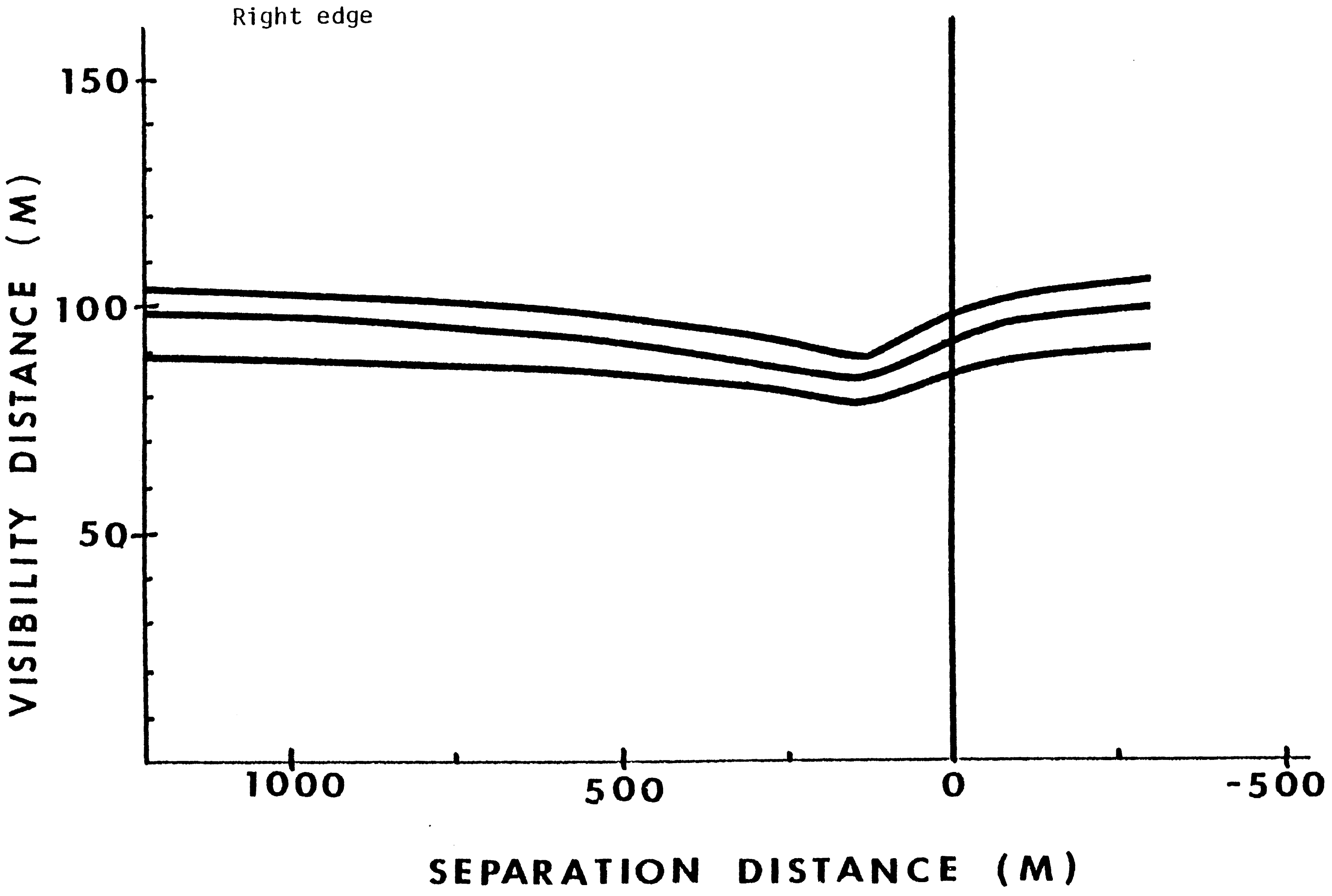


Figure 17. Visibility distance as a function of mounting height and separation distance for modified low beam system. Target on right edge of road.

maximum at this point, producing about a 15% improvement over the standard low beam.

Based on this analysis, there are significant gains in visibility distance as lamp mounting height increases. However, these data are for targets having diffuse reflective characteristics; consideration must also be given to retroreflective targets.

The perceived brightness of a retroreflector depends very much on the observation angle, which at a given distance is determined by the vertical spacing between the headlamps and the eyes of the observer. This relationship is illustrated in Figure 18. Clearly, small changes in observation angle can have a major effect on the luminance of a retroreflective device.

In a typical automobile the eye-to-headlamp vertical distance is about 18 inches (45.7 cm). With this spacing, viewing a retroreflector at 500 feet (152 m) produces an observation angle of 0.17^0.

Truck configurations result in much greater driver eye heights than automobiles, typically between 90 and 110 inches (229 to 280 cm). If the maximum mounting height for headlamps is 54 inches, a 90-inch eye height will result in a vertical separation of 36 inches (91.4 cm). This is about twice the observation angle experienced by the driver of a car, e.g., 0.34^0 at 500 feet.

Based on the example given above, an inspection of Figure 18 suggests that observation angles of 0.17^0 and 0.34^0 yield specific luminance values of about 310 and 150 $cd/ft\text{-}c/ft^2$, respectively, at an entrance angle of 0^0.

HSRI sought to obtain information on typical eye-to-headlamp vertical separation distances on large trucks from U.S. truck manufacturers. The responses indicate that the 36-inch example cited is on the low side. One major manufacturer indicated the range on currently produced trucks is 33.5 to 60.4 inches (85 to 153.4 cm). Working from these data, the observation angle for a vertical separation of 48 inches at 500 feet is 0.46^0, and 0.57^0 for 60 inches. Based on Figure 18, these angles result in specific luminance values of about 90 and 65 $cd/ft\text{-}c/ft^2$, respectively. Thus, at 500 feet, the driver of a

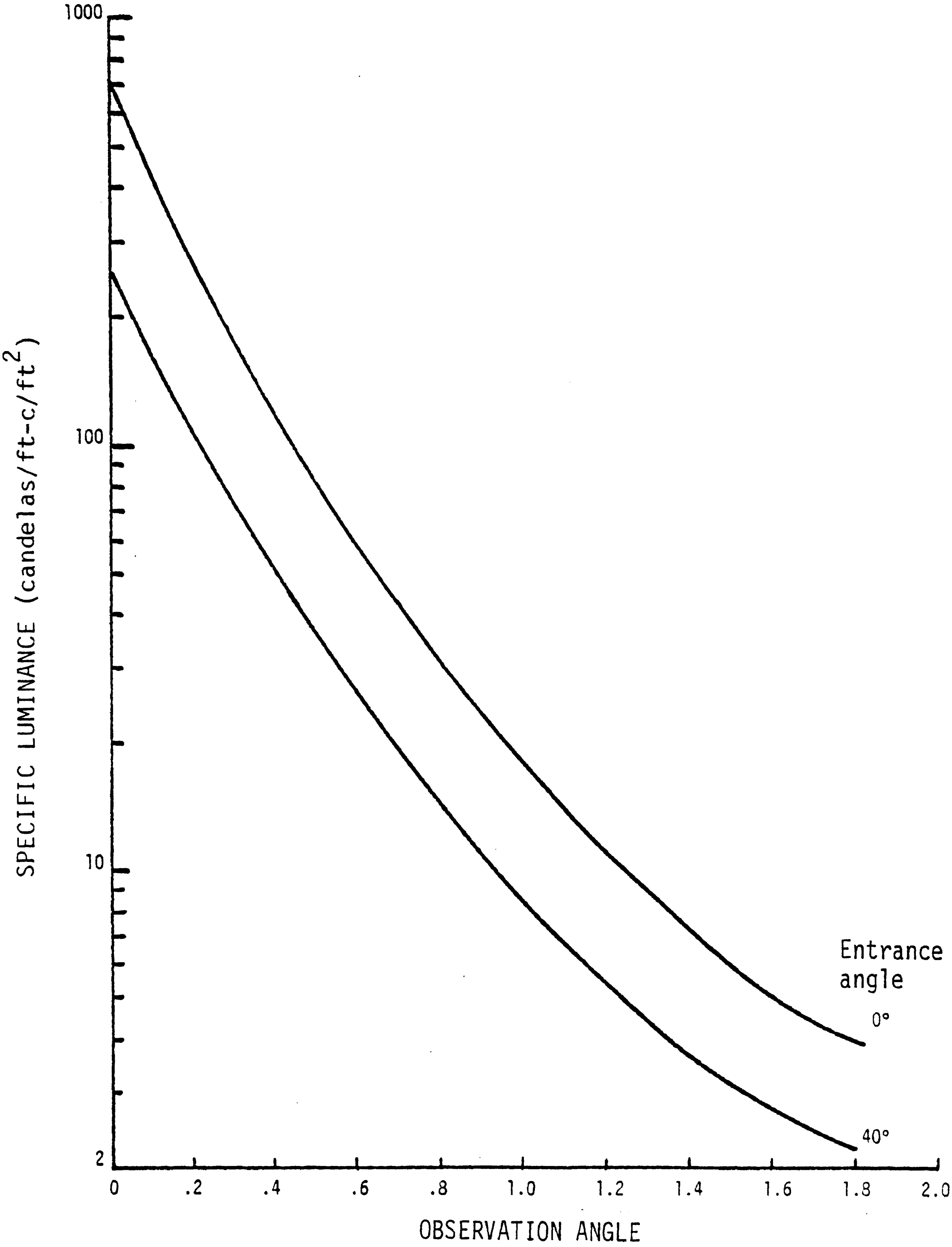


Figure 18. Specific luminance characteristic of white encapsulated lens sheeting.

large truck would see a retroreflective device at as little as one-fifth the brightness it would appear to a typical car driver.

The effect of eye-to-headlamp separations varies with distance to the retroreflector, so it should not be inferred that the five-to-one difference noted in the preceding paragraph holds for all conditions. However, it is certainly fair to say that the net effect of these variables for truck drivers is to reduce the effectiveness of all retroreflective devices in the highway environment. For example, signs have less target value and poorer legibility, delineation can be seen for shorter distances, vehicle and highway markers have less conspicuity, and the truck driver must be closer to detect and recognize them. Given that trucks have less maneuverability than cars and generally require greater stopping distances, this is precisely the opposite of what is desirable.

Reducing operator eye height on trucks is probably not a feasible approach in the foreseeable future. Moves to decrease the maximum headlamp mounting height can only result in still larger observation angles for truck drivers and make the situation worse.

The arguments for reducing truck headlamp mounting height are based on glare considerations. For exactly the same reason that higher mountings improve down-the-road visibility, they increase glare to oncoming drivers. Although the point is obvious, documentation of the disability and discomfort glare increases associated with greater mounting height are virtually nonexistent.

To provide some data on the extent of the glare effects resulting from high mounted headlamps, the HSRI seeing-distance model was used. These runs were made using the modified low beam described in Table 2. Data were generated on the seeing distances and discomfort-glare levels for the driver of a car (24-inch headlamp mounting height, 42-inch eye height), facing the same configuration, and two others in which the headlamps of the oncoming vehicle were raised to 40 and 54 inches, respectively. The visibility targets were placed on the right edge of a flat, straight road. These data are summarized in Table 4.

Table 4

Disability and Discomfort Glare Effects Associated with the Mounting Height of the Headlamps of an Approaching Vehicle

Headlamp Mounting Height	Minimum Visibility Distance	Discomfort Glare	
		Maximum Discomfort Glare Rating	Distance at 5.0 or worse
24"	258.5'	4.7	550'
40"	253.3'	4.5	600'
54"	248.9'	4.4	650'

Note: Targets are on the right side of the road.

In examining Table 4 it must be remembered that the visibility distances and discomfort glare ratings are for the driver of a normal passenger car facing headlamps at the mounting heights shown. Thus, for two passenger cars, with 24-inch mounting heights, the minimum visibility distance is 258.5 feet (78.8 meters). The maximum discomfort glare rating (on the DeBoer scale described earlier) is 4.7, three-tenths of a scale unit worse than "just acceptable." A condition of "just acceptable" or worse must be endured from a separation distance of 550 feet (167.6 meters) until the vehicles pass. At 55 mph (88.5 km/hr) for both vehicles this will require about 3.5 seconds.

It is apparent that higher mounting heights on the approaching vehicle will reduce the minimum visibility distance (by about 4%), increase the discomfort glare somewhat, and prolong the interval during which glare rated "just acceptable" or worse must be endured.

A similar analysis was run with the targets placed on the left edge of the road. As was noted in Figure 15, the combination of relatively low illumination in that area and smaller angles to the glare source yield much shorter no-glare detection distances and substantial disability-glare effects. These results are summarized in Table 5. It appears that the consequences of increased mounting heights are significantly less for targets located to the left of the driver than they are for targets to the right.

Table 5

Disability and Discomfort Glare Effects Associated with the Mounting Height of the Headlamps of an Approaching Vehicle

Headlamp Mounting Height	Minimum Visibility Distance	Discomfort Glare Maximum Discomfort Glare Rating	 Distance at 5.0 or worse
24"	78.9'	4.2	800'
40"	78.6'	4.1	850'
54"	78.2'	4.0	900'

Note: Targets are on the left side of the road.

A further consideration in evaluating mounting height is the effect of road geometry. When negotiating a left curve, the driver is exposed to the possibility of passing through the high-intensity portion of the headlamp beams of oncoming vehicles. The effect depends on the geometry of the meet, and present low-beam headlamps have been designed, in part, with this situation in mind. The question here is whether the headlamp mounting heights characteristic of trucks make the situation worse. The answer is not simple. Should the geometry of the meet cause the high-intensity zone of the beams to pass through the observers' eyes (or, conversely, pass four or more degrees below the eyes of the observer) the effect of mounting height is negligible. When the eyes are exposed to the transition zone of the headlamps, there is an effect due to mounting height, which depends on the separation distance. Certainly, greater mounting heights do not improve the curve-glare problem, but the effect varies from none to minor.

A second major concern for glare resulting from greater mounting height occurs in the case of following another vehicle. A close-following truck can provide very high levels of glare in the rear view mirrors of a car, even on low beam, simply because the mounting height allows the high-intensity portion of the beam to impinge directly on the mirrors.

The question of discomfort and disability glare from the rear view mirrors was treated in some depth as part of this project, as noted earlier. The conclusions of that effort were that rear view mirror glare is a problem even with conventional low beams at low mounting heights. However, it is a problem which can be solved through use of two-way interior mirrors and judicious aiming of exterior mirrors.

In the rear view mirror disability-glare study the maximum glare value used was about 75 lux, approximating high beams at 100 feet. Theoretically, low beams at 50 feet from a truck could produce about twice that value. However, the calculation in the glare study assumed that the output of both headlamps was visible to both eyes in both mirrors. This is unlikely to occur at very close following distances.

Based on this analysis, it appears that the glare from high-mounted headlamps does not pose a problem significantly more serious than from conventional low mountings on high beam. Both situations are manageable (i.e., the lead driver can reduce disability and discomfort glare to acceptable levels), assuming the availability of a two-way interior mirror and proper aiming of the exterior mirror.

To summarize the information which has been presented concerning high-mounted headlamps:

1. Headlamp mounting heights such as are common on large vehicles do cause increases in discomfort and disability glare for drivers of smaller vehicles (e.g., automobiles and motorcycles). However, the analysis indicates that the increases are relatively small, generally infrequent, and of short duration.

2. From the point of view of the operator of the large vehicle, high-mounted headlamps improve seeing distance in general, and are particularly important in the detection, identification and, where

appropriate, legibility of retroreflective objects (e.g., delineation and signs). These gains are substantial and permanent.

Therefore, based on the analysis which has been described, the authors conclude that reducing the upper limit on headlamp mounting heights is unwarranted.

Hardware Considerations

Introduction. In the preceding sections of this report a description has been provided of a modified low-beam headlighting system. Based on the various analyses carried out, it appears promising, and, in the opinion of the investigators, worthy of full-scale evaluation.

However, as has been mentioned earlier, there are limitations to what can be accomplished with hardware, and the proposed system may present some problems in that respect. In this section various hardware options will be considered, along with advantages and disadvantages of each.

Revisions to Standard System. The most obvious approach to bringing about changes to the low-beam headlighting system is to modify the optics of lamps to provide the desired patterns. This would allow the continuance of the present two- and four-lamp, round and rectangular systems with which people are familiar. There are a number of advantages:

1. This is probably the lowest-cost alternative.
2. Requires no learning on the part of the public.
3. Can be retrofitted to older cars.
4. Causes no additional problems in aiming.

The feasibility of this approach has been reviewed with several lighting engineers. There are two significant problems:

1. Relatively sharp transitions are required from highly illuminated to less highly illuminated areas. It may not be possible to effect these transitions with current sealed beam technology. Thus, this approach may allow the desired increases in candlepower only at the

expense of increases in glare substantially greater than illustrated in Table 2. At the time this is being written no precise estimates of the extent of the glare increase are available. Preliminary indications, based on the present low beam, are that glare at some key points (e.g., 1^{0} up, $1\text{-}1/2^{0}$ left) would approximately double. The authors feel such an increase is on the borderline of acceptability from a disability point of view and may cause problems in public acceptance on a basis of discomfort glare.

2. Raising the "hot spot" area as indicated in Table 2 may require repositioning the low-beam filament. In two lamp systems this will cause a problem (assuming the high beam remains as is). One of the physical constraints in lamp design is the need to maintain a minimum spacing between the two filaments to prevent shorting. At present, coil diameters for both high- and low-beam filaments are about 0.058 inch. The center-to-center spacing between support posts is about 0.085 inch. This represents, in the opinion of lighting engineers, about the minimum required spacing.

Mandatory Four-Lamp System. One of the difficulties in modifying the present system is that design limitations arise from the necessity of getting two different beams (high and low) from a single lamp. If a lamp has to produce only a low beam, the transition can be made significantly sharper and the problem of conflict with the high-beam filament goes away.

Experience with the low-beam units of the current four-lamp system indicates that the intensity at the $1/2^{0}$ down, $1\text{-}1/2^{0}$ right point can be set about 20% higher than it can on the two-lamp system without exceeding the glare limits in the upper left quadrant.

The high beam filament in the low-beam unit of the four-lamp system furnishes some fill light for high-beam operation and also provides heat to ensure the unit will not ice over when using the high beam under winter driving conditions. Thus, its position is not critical.

Disadvantages to this approach include:

1. Glare to upper left quadrant would be lower than the two-lamp system, but still significantly higher than the values shown in Table 2.

Disability glare would probably be within the bounds felt to be acceptable by the authors. But, public acceptance may still be a problem.

2. Retrofit is limited to cars having four-lamp systems.

3. Requires future vehicles to use a four-lamp system. this is a design restriction. It may also provide problems in cooling and streamlining as cars grow smaller.

Asymmetrical System. An asymmetrical system means that two or more lamps having different photometric characteristics would be used to make up the beam. This approach was used in the computer evaluation work, with one lamp on the right side providing illumination equivalent to two SAE low beams, another lamp on the left side providing the additional "hot spot" illumination. However, this was done primarily to facilitate making the desired modifications to the hot spot.

The advantage to the asymmetrical approach is that it would permit the illuminance transitions indicated in Table 2. However, there are several disadvantages:

1. Building a beam with two units having quite different characteristics makes unit aim very important. As indicated elsewhere (Olson and Mortimer, 1973), aim is a serious limitation to beam performance and is not easy to improve.

2. The system would be more difficult to retrofit. Safeguards would be required to ensure that lamps were installed properly, and this would necessitate some hardware changes in the vehicle.

3. The loss of one lamp could produce major alterations to the total beam pattern.

4. Cost would probably increase, since the production schedule would have to be expanded to include the new system while the old systems are continued. This would also increase inventory problems.

Add-a-Lamp System. In the 1960's, Chrysler Corporation briefly offered as an option a "Super Light." This was actually a mid-beam system, arrived at by adding a lamp to the standard units, and making the necessary switching changes. The approach suggested here would be very similar, except for the intensity of the added unit and the fact that it would be required equipment, not optional.

This is another version of an asymmetrical system. It achieves the modification by adding a separate lamp to the existing, standard lamps. The approach has some clear advantages in addition to making it fairly easy to arrive at the desired beam pattern:

1. Costs are fairly low. The basic lamps remain the same. A new lamp must be designed and fabricated to provide the additional high-intensity zone. Adding only one new lamp simplifies inventory problems as well.

2. Providing the additional high-intensity zone with a separate lamp makes it feasible to incorporate a "fog" setting for the headlamps. At the driver's option, this would shut off the extra lamp, reducing backscatter under bad-weather driving conditions.

Disadvantages to this approach include:

1. Aiming problems, as noted for the asymmetrical system.

2. Retrofit is probably impractical.

3. Having an odd number of lamps in an asymmetrical arrangement presents appearance problems.

Shielded Filament System. Lighting systems designed to meet ECE standards use a shielded filament. This allows a very sharp transition from areas of high to low illumination. The technique could be adapted to produce the proposed beam pattern or a sufficiently close approximation. There are several advantages:

1. Allows good glare control with high levels of illumination where required.

2. Can be retrofitted.

3. Presents no aiming problems. It may be easier to aim visually, due to sharper transition areas, than the present low-beam system.

Disadvantages:

1. There is an inherent loss of efficiency (watts in - lumens out) with this approach. Consequently, energy costs would be higher than

with sealed beam construction. In this connection it is worth noting that the recent introduction of halogen sealed beams has made possible substantial reductions in headlamp power consumption. Very possibly the use of a shielded filament on a halogen source would do no worse than increase wattages to the level presently required by tungsten sealed beams.

2. It is not certain, but costs to convert to production of this type of lamp may be higher than other alternatives.

Summary. This section has reviewed the advantages and disadvantages of a number of means by which the desired modifications to the low beam might be achieved.

Based on this review, there seems to be no completely satisfactory solution. However, there are practical means of coming close to what is desired. Further analysis by competent lighting engineers may lead to other suggestions for resolving the hardware problem. In any event, it seems desirable to carry out further evaluations under actual operating conditions to assess the merit of the proposed modification. With those data in hand it will be possible to make better decisions concerning hardware alternatives.

RECOMMENDATIONS

This report has described a modification to the current low-beam headlighting system used in the U.S. today. A number of analyses have been presented. In most of these the proposed system has been shown to be better than the present system. In some cases the proposed system may be poorer, but the authors feel the frequency and extent of these problems do not outweigh the benefits in other situations. Finally, there are questions like performance in adverse weather, which can only be answered by field testing under the conditions of concern.

The report began with a statement that low-beam headlighting systems were not adequate for some driving conditions. Headlamps are an important safety system, and means to this improvement should be of considerable interest. The system described in this report seems to represent an improvement. The authors strongly recommend that test lamps be fabricated and the Phase II evaluations be carried out.

REFERENCES

Adler, B. and Lunenfeld, H. Three-beam headlight evaluation. Airborne Instruments Lab. Farmingdale, N.Y. Report No. HS-238-2-411-1, April 1973.

Bhise, V.D., Farber, E.I., Sunby, C.S., Trowell, G.M., Walunas, J.B., and Bernstein, A. Modeling vision with headlights in a systems context. The Society of Automotive Engineers, Technical Report 770238, 1977.

DeBoer, J.B. and Morass, W. Berechnung der Schweite aus der Lichtverteilung von Automobilscheinwerfern. Lichttechnik, 8(10), 1956, pp. 433-437.

Dixon, W.J. and Masey, F.J., Jr. Introduction to Statistical Analysis (3rd ed.). New York: McGraw-Hill, 1969.

Fry, G.A. A re-evaluation of the scattering theory of glare. Illumination Engineering. Vol. 49, 1954, pp. 98-102.

Halstead-Nussloch, R., Olson, P.L., Burgess, W.T., Flannagan, M.J., and Sivak, M. Evaluation of the feasibility of a single-beam headlighting system. The Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-79-91, December 1979.

Helander, M., Merritt, J.O., and Abrams, C. Effect of headlight illumination on driver behavior. Human Factors Research, Inc., 1979.

Huculak, P. A visibility analysis of obstacle detection experimentation in unopposed automotive headlighting. National Research Council of Canada, National Aeronautical Establishment. Ottawa. Mechanical Engineering Report MS-141, May 1978.

Hull, R.W., Hemion, R.H., Cadena, D.G., and Dial, B.C. Vehicle forward lighting performance and inspection requirements. Southwest Research Institute, Report AR-814, July 1971.

Lulla, A.B. and Bennett, C.A. Discomfort glare; range effects. Journal of the Illumination Engineering Society. Vol. 10, No. 2, January 1981.

Miller, N.D., Baumgardner, D. and Mortimer, R.G. An evaluation of glare in nighttime driving caused by headlights reflected from rear view mirrors. The Society of Automotive Engineers. Report No. 740962, October 1974.

Moore, R.L. Headlight design. Ergonomics, 1(2), February 1958, 163-176.

Mortimer, R.G. and Becker, J.B. Development of a computer simulation to predict the visibility distance provided by headlamp beams, University of Michigan, Highway Safety Research Institute, Report No. HF-73-15, 1973.

Mortimer, R.G. and Olson, P.L. Development and use of driving tests to evaluate headlamp beams. Highway Safety Research Institute, The University of Michigan, Report No. UM-HSRI-74-14, March 1974.

Mortimer, R.G. and Olson, P.L. Evaluation of meeting beams by field tests and computer simulation. Highway Safety Research Institute, The University of Michigan. Report No. UM-HSRI-HF-74-27, December 1974.

Olson, P.L. and Mortimer, R.G. Investigation of some factors affecting the aim of headlamps. Highway Safety Research Institute, University of Michigan. Report NO. UM-HSRI-73-13, January 31, 1973.

Rockwell, T.H., Balasubramanian, K.N., Kretovics, T., and Wilfong, E.J. The utility of peripheral vision to motor vehicle drivers. Department of Industrial and Systems Engineering. Ohio State University. Report No. 784224, August 1, 1977.

Schiflett, S.G., Candena, D.G., and Hemion, R.H. Headlight glare effects on driver fatigue. Southwest Research Institute, Project No. 11-1908. Report No. AR-699, September 1969.

Schmidt-Clausen, H.J. and Bindels, J. Tn. The increase in threshold luminance as a criterion for evaluation of glare. Lichttechnik, 23, 10, 1977, p. 547.

Wolf, E. Glare and age. Archives of Ophthalmology, 1960, 64, 502-514.

Wolf, E. and Gardiner, J.S. Studies on the scatter of light in the dioptric media of the eye as a basis of visual glare. Archieves of Ophthalmology, 1965, 74, 338-345.

APPENDIX A

REAR VIEW MIRROR DISABILITY GLARE STUDY

APPENDIX A: REAR VIEW MIRROR DISABILITY GLARE STUDY

Introduction

As noted in the main section of the report, a review of the literature uncovered no evaluations of disability glare effects associated with rear view mirrors, although there have been two attempts to estimate the illumination delivered to the driver's eyes via the mirrors (Miller et al. [1974], and Adler and Lunenfeld [1973]. Using these two descriptive efforts as a guide, this study sought to measure the disability effects produced by combinations of glare illuminance and angle found in rear view mirror situations.

Independent Variables

Glare Illuminance. Four levels, selected to span the range of glare illuminance that a driver might encounter in almost any driving situation. These were as follows:

75.3 Lux (7.0 ft-c) approximating high beams at 100 feet
7.75 Lux (0.72 ft-c)
0.82 Lux (0.076 ft-c)
0.073 Lux (0.0068 ft-c) approximating low beams at 1000 feet

These values were measured at the subject's eyes. About 70% of the illuminance was provided by the "interior" mirror, on the subjects' right, the remainder by the "exterior" mirror on their left.

Glare angle. Three levels, selected to span the range of eye-to-mirror angles encountered in most passenger cars. The angles selected were 35, 45, and 55 degrees. Both mirrors were set at the same angle for a given test.

Subject age. Two groups of subjects were used. One consisted of six young persons (25 years of age or less) and the other of four older persons (65 years of age or more). They were drawn from a sample of subjects which had been screened in terms of high and low luminance, and high and low contrast visual characteristics. An attempt was made in this study to balance the two groups in terms of their low luminance visual characteristics. Table A-1 is a listing of the subjects and their relevant characteristics.

Table A-1

Subject Characteristics

Subject	Age	Sex	VISUAL ACUITY			
			HL-HC	HL-LC	LL-HC	LL-LC
1	22	M	20/18	20/20	20/25	20/60
2	21	F	20/22	20/35	20/60	20/100
3	25	F	20/14	20/25	20/22	20/60
4	20	M	20/22	20/50	20/50	20/150
5	21	M	20/25	20/35	20/35	20/100
6	23	M	20/18	20/25	20/27	20/60
7	75	M	20/20	20/25	20/40	20/150
8	72	M	20/20	30/35	20/40	20/150
9	65	M	20/18	20/40	20/40	20/60
10	66	M	20/22	20/40	20/35	20/60

Note: HL = High Luminance (161 cd/m^2)
LL = Low Luminance (0.2 cd/m^2)
HC = High Contrast (22.5:1)
LC = Low Contrast (1.3:1)

Dependent Variable

The measure of interest in this study was the luminance of a disc target at threshold. The disc subtended an angle of 0.38 degrees (5 cm at 762 cm) and was seen against a background having zero luminance. The luminance of the disc could be varied from 0.737 cd/m^2 to 0.005 cd/m^2 in 15 steps. Table A-2 lists the disc luminance values obtainable with the equipment used.

The disc was exposed for one second on each trial. Threshold was established, in the conventional way, as the point at which the probability of a correct response was 0.5.

Table A-2

Luminance Values Obtainable on Target Disc

Filter	LUMINANCE	
	cd/m^2	ft-L
0	0.737	0.215
1	0.572	0.167
2	0.343	0.100
3	0.240	0.070
4	0.185	0.054
5	0.137	0.040
6	0.087	0.0255
7	0.057	0.0167
8	0.034	0.0100
9	0.026	0.0077
10	0.022	0.0065
11	0.015	0.0043
12	0.008	0.0024
13	0.006	0.0017
14	0.005	0.0015

Equipment. Figure A-1 is a schematic of the laboratory set up. Glare was provided by a 35mm slide projector (P2). A plate with two small holes drilled through was fitted immediately behind the slide plane and provided two beams, which were reflected by adjustable mirrors M3 and M4 toward the glare mirrors, M5 and M6. M5 was a standard automotive exterior mirror, of about 45% reflectivity. M6 was a small truck exterior mirror, of about 90% reflectivity. They were positioned to the right and left of the subject as shown in Figure A-2, and could be adjusted to provide the range of angles desired.

Target disc luminance was controlled by another 35mm projector, P1. This projector was also fitted with an aperture plate just behind the slide plane to provide a very narrow beam. The beam from this unit was reflected by a fixed mirror, M1 and into the side of a box which functioned as a light trap, where it was reflected from another mirror, M2. The portion of the disc display which faced the subject consisted of an opaque plate with a 5 cm diameter hole cut in it. The hole was

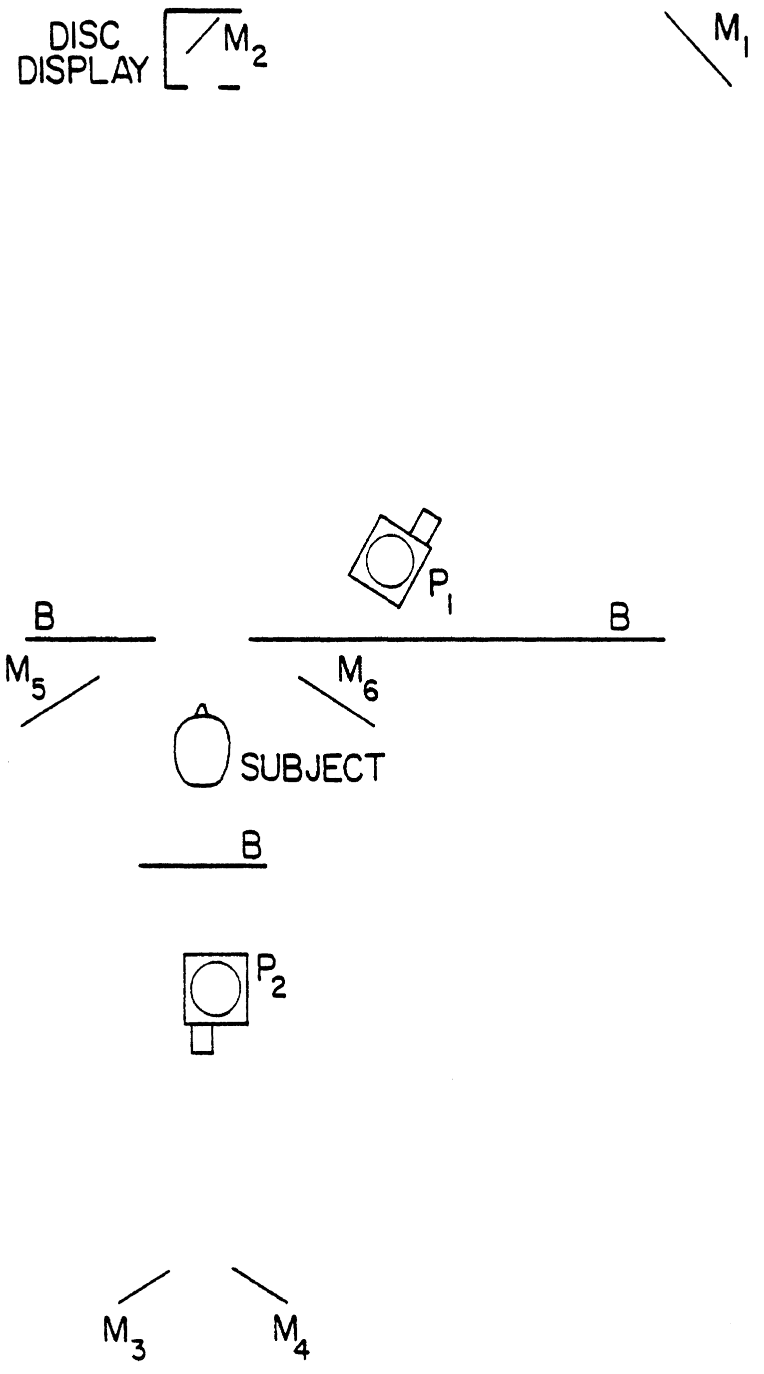


Figure A-1. Schematic of laboratory arrangement for rear view mirror disability glare study.

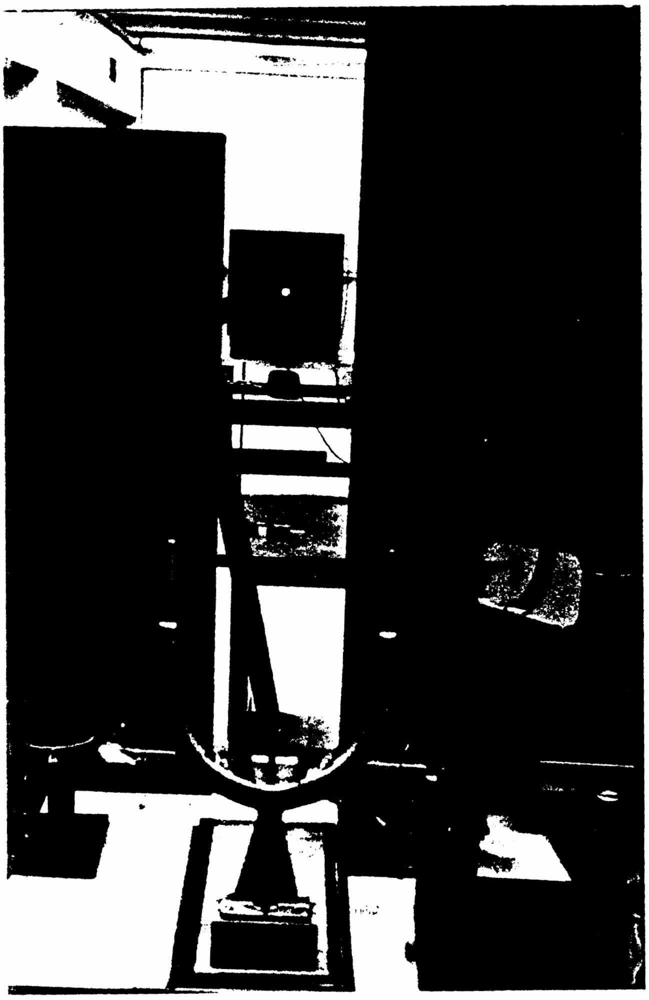


Figure A-2. Photograph showing the subject's head support and glare mirrors, with detection target in background.

covered with white paper, which acted as a dispersion filter when the beam from P1 impinged on it.

Flat black panels were used as baffles (B) in strategic places to control stray light.

Procedure. The subjects were seated at a table and the chair height adjusted to allow their chins to be comfortably supported on the rest provided. The instructions were read to them and any questions answered. The lights were then turned off to start the dark adaptation period. During this period (about ten minutes) a number of practice trials were given, to familiarize the subjects with the general procedure and ensure that the instructions had been completely understood. At this point data trials began and continued, with short breaks at the end of each combination, until all combinations had been tested. The entire session required about two hours to complete.

Each trial consisted of a one-second presentation of the target disc. An alerting tone was used, sounding two seconds before the target projector opened. The subject was required to respond by pressing one of two buttons to indicate whether the disc had been seen or not. The subject was led to believe that the disc would not be presented on some trials. This was done to minimize the likelihood of false positive responses. In fact, the target was presented on all trials, only the luminance being varied.

The "staircase" method was used to collect data (e.g., Dixon and Masey, 1969). In this procedure a response of "seen" results in the luminance of the target disc being reduced one step on the next trial, and increased one step following a response of "not seen." It is customary to run two parallel sequences, switching from one to the other on a random basis. This prevents the subject from becoming aware of the strategy being employed.

Figure A-3 is a copy of a score sheet used in the study. It is for one of the older subjects, a glare angle of 45^o, and a glare intensity of 7.75 Lux (the "1" after intensity refers to a filter slide in the glare projector). The two staircase sequences are arranged side by side on the score sheet as two fifteen-column matrices. The rows refer to filters in the target disc projector (as described in Table A-2). When a response is coded "X" it corresponds to "seen." The sequences on the left started with two "seen" responses on filters 6 and 7, followed by a "not seen" on filter 8. The experimenter then stepped back to filter 7, and recorded another "not seen," and so on. The sequence on the right side of the page started with three "not seen" responses on filters 10, 9, and 8, followed by a "seen" response on filter 7. As noted above, the experimenter moved from one sequence to the other on a random basis.

In the case of the example shown, percent correct responses were calculated and the 50% threshold was found to lie between filters 7 (0.057 cd/m^2) and 8 (0.034 cd/m^2). By interpolation, the threshold is 0.047 cd/m^2. This general procedure was used for all subjects and conditions. The data presented in the next section were arrived at by averaging across identical conditions for each group of subjects.

Results. In the presentation to follow it is important to bear in mind that the conditions of this study approximate a "worst case." The dark adaptation level of the subjects was appropriate for a dark rural environment. The addition of roadway lighting, for example, which would cause the eyes to adapt to a higher level, would reduce the glare effects to be described. The duration of target exposure is another factor affecting results. The forced-choice method used required a finite stimulus presentation. One second was selected as a "reasonable" value. Other durations would have produced somewhat different results.

Figures A-4 and A-5 summarize the results for the younger and older subjects respectively. Each figure shows the mean target disc luminance at threshold for each of the four levels of glare and three glare angles. Also shown, as a horizontal bar, is the mean no-glare threshold.

There are several points of interest in these figures:

Except at the highest glare levels tested, the effect of glare angle is of little consequence. This is not what the investigators expected, based on available data. This issue will be explored again in the Discussion section.

SUBJECT # 2

CONDITION

GLARE:

ANGLE 45°

INTENSITY 1

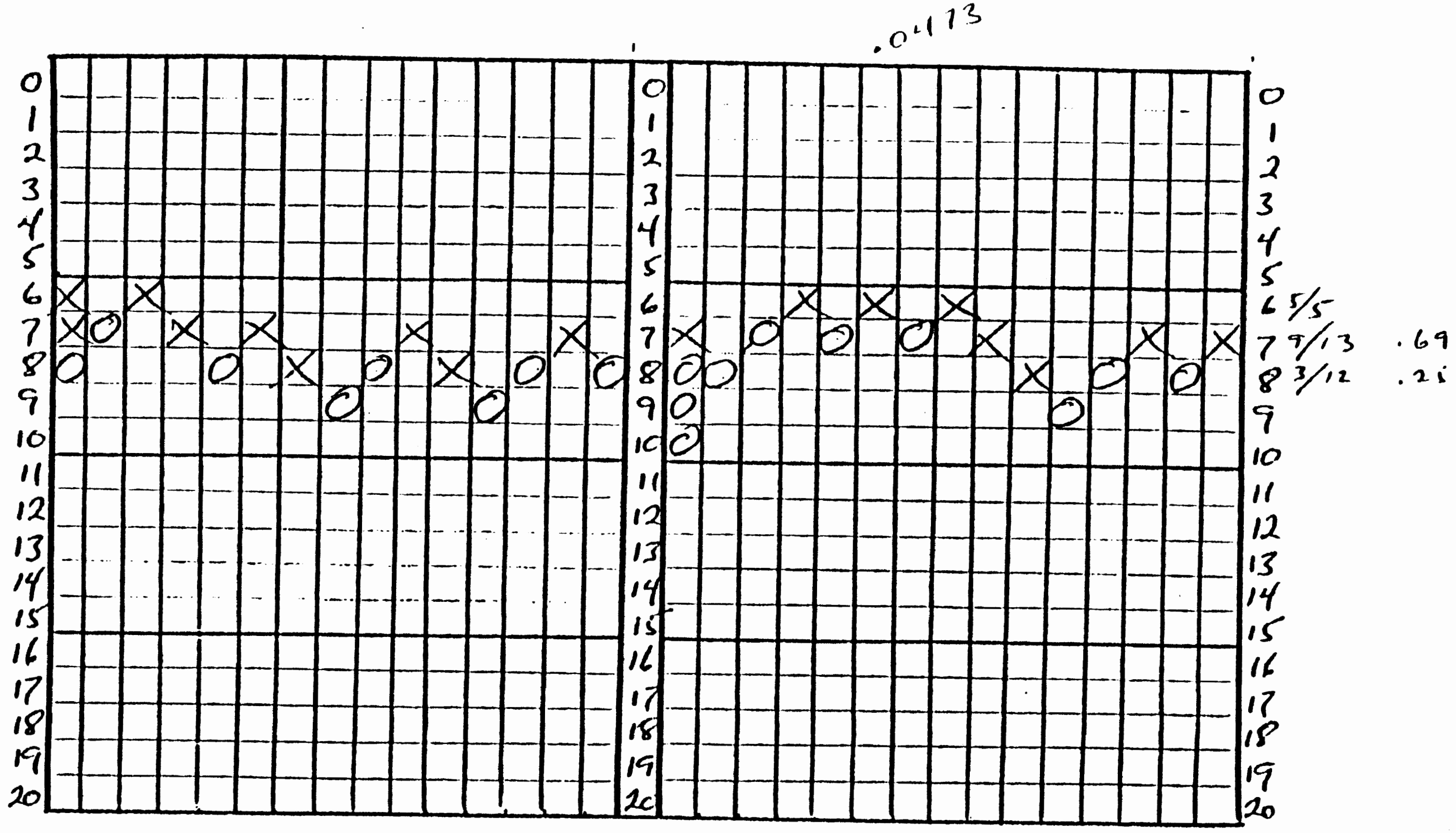


Figure A-3. Copy of score sheet used in study.

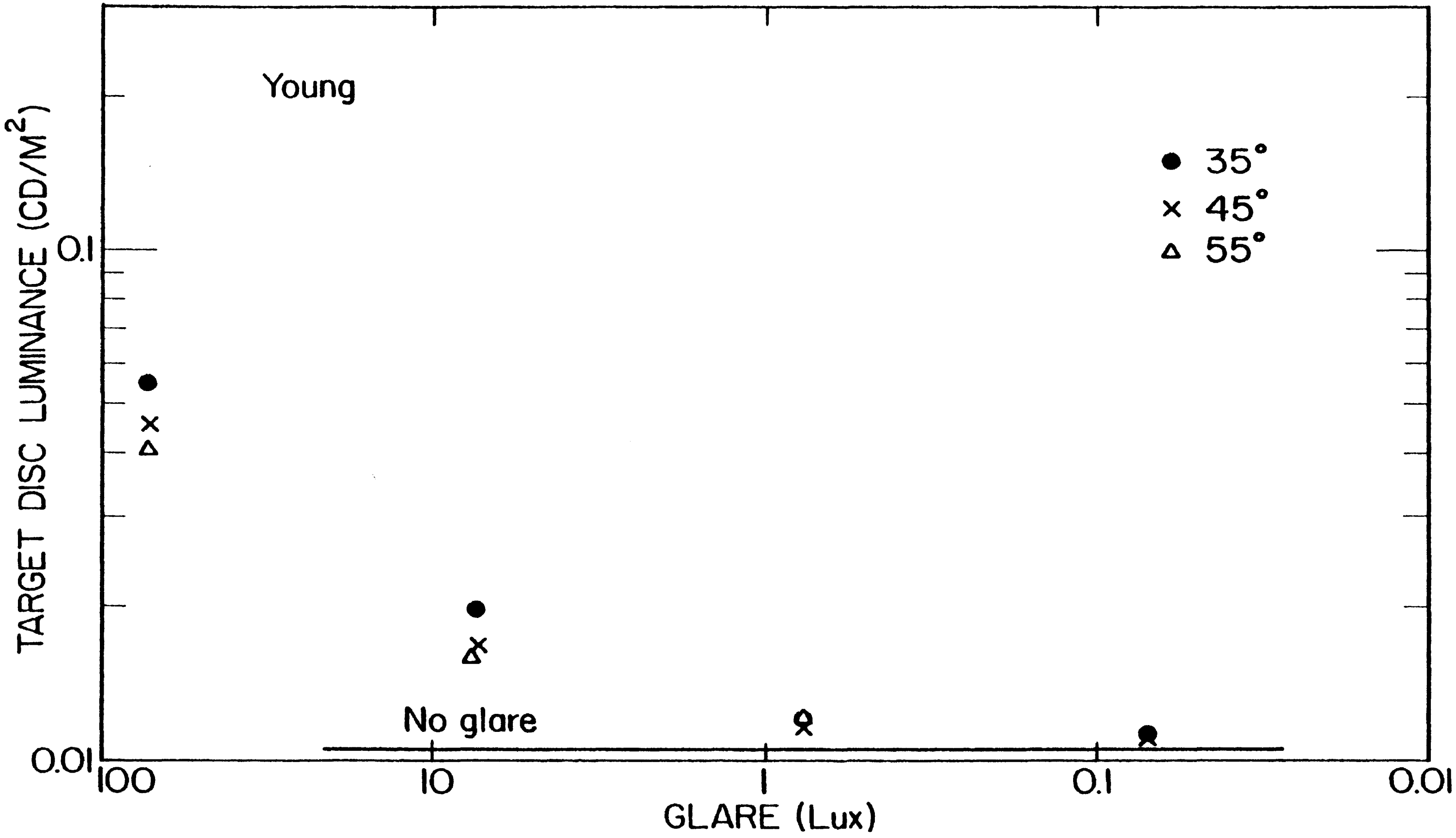


Figure A-4. Changes in target disc luminance required to achieve threshold detection as a function of glare intensity. Younger subjects.

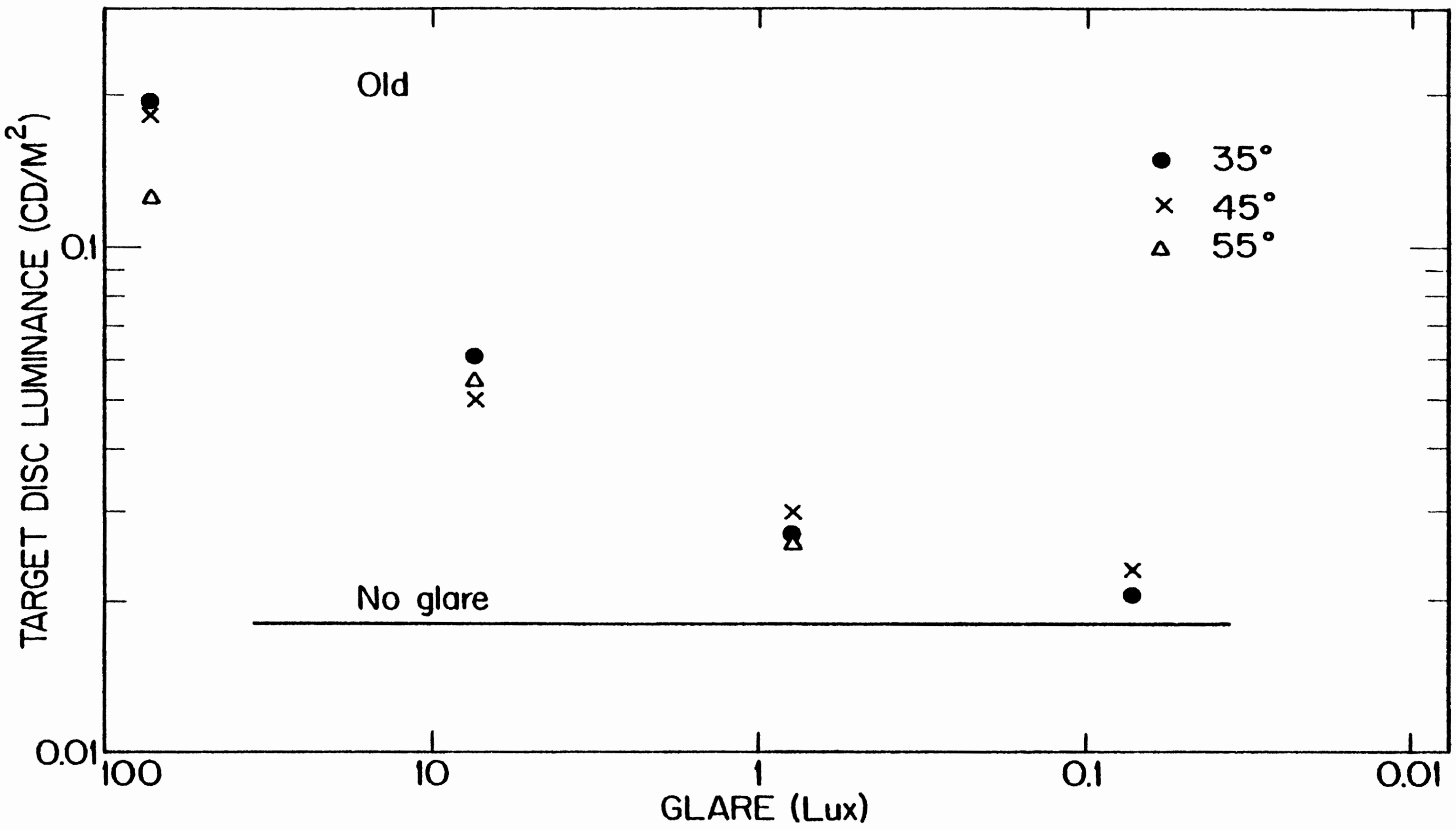


Figure A-5. Changes in target disc luminance required to achieve threshold detection as a function of glare intensity. Older subjects.

For both groups, but especially for the younger subjects, glare up to about 1 Lux has a minor effect. Above that level disability effects increase rapidly, especially for the older subjects.

The no-glare thresholds for the two groups differ substantially; being 0.0106 cd/m^2 for the younger subjects, and 0.0182 cd/m^2 for the older subjects.

The effects of glare are much more pronounced for the older than for the younger subjects. This is shown in Figure A-6, which was prepared by dividing the glare by the no-glare threshold for each condition. It will be noted that, at each level of glare, the older subjects had to increase the target disc luminance about twice as far above no-glare values as did the younger subjects.

Discussion. The primary concern of this study was to assess disability effects associated with glare originating from the rear view mirrors. If 1 Lux is accepted as a maximum desirable glare level, it should be noted that this approximates glare produced by low beams at about 300 feet, a mid beam at 500 feet or high beams at 1000 feet (based on data from Adler and Lunenfeld, 1973). If the driver has a dual-reflectivity interior mirror available, overall glare can be reduced by about 67% (exterior mirror supplies about 30% of glare and remains the same, interior mirror supplies about 70% of glare and can be reduced by about 95%). This is not sufficient to bring even low-beam glare down to 1 Lux under all conditions. However, if the outside mirror were set so that it did not reflect directly into the driver's eyes under normal conditions, glare could be reduced by about 97% through use of a dual reflectivity interior mirror. This would reduce high beam glare to about 2 Lux, and make increases in low-beam intensity practical.

Drivers will change positions on a dual reflectivity mirror or outside mirror in response to sensations of discomfort, which do not necessarily relate to disability. Adler and Lunenfeld's data suggest that conventional low beams can produce about 9 Lux at 50 feet. The authors' impression (unsubstantiated by data) is that drivers would rarely find this so uncomfortable that they would change mirror positions. Yet, even in the case of a younger driver, there would be a significant loss in visual capability. In light of this, regardless of

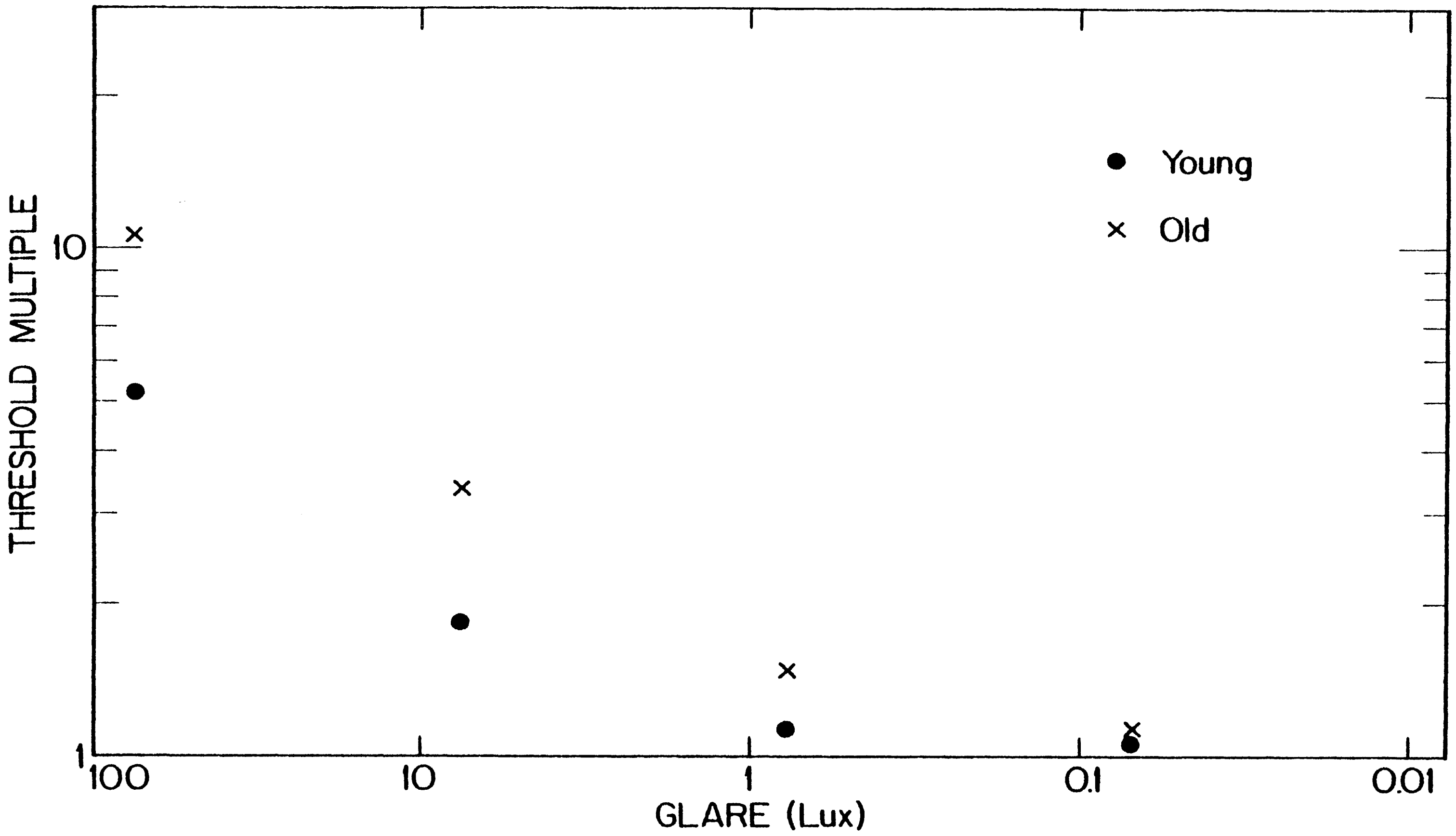


Figure A-6. Number of times target luminance must be increased above no-glare threshold to reach threshold again in presence of glare. Young versus old subjects. Glare angle is 35°.

what photometric changes may come about in future headlamps, there may be merit in exploring ways in which this source of disability glare could be better controlled.

One reason why drivers may make less use of a dual reflectivity interior mirror than would be desirable may lie in the fact that the approximate 4% reflectivity obtained from the low setting is inadequate for seeing anything but headlamps at night. Thus the driver must either suffer a loss of information from the mirror or change the setting depending on glare conditions. If it were possible to provide a higher level of reflectivity in the low position, the mirror might be used more effectively as a glare protection device.

An examination of the calibration curve accompanying the Fry glare lens for HSRI's Pritchard photometer led the investigators to expect greater differences as a function of glare angle than were observed. To verify the theoretical curve, the lens was used to make a series of measurements of veiling brightness (B_V) produced by the various combinations of illuminance and mirror angle. The results of these measurements are reproduced in Table A-3, along with relative B_V values read from the theoretical curve. It will be noted that the measured and theoretical values compare fairly well. The theoretical curve predicts an approximate doubling of B_V for each 10^0 reduction in glare angle in this range. Measurements taken with the lens indicate that B_V increases by less than two from 55 to 45 degrees and more than two from 45 to 35 degrees.

It will also be noted that the measured B_V values change directly with glare illuminance.

Neither the effect associated with glare angle or illuminance as measured with the Fry lens attachment compares well with the results of this study as described in Figures A-4 and A-5. It appears that the equivalent veiling luminance (B_V) is not in one-to-one relation to target-threshold luminance as measured in this study. Thus, the Fry-lens data cannot be applied directly to the present situation in a straightforward fashion.

Table A-3

Results of Measurements of Disability Veiling Glare Using Fry Glare Lens

ANGLE	ILLUMINANCE (Lux)	B_v (Ft-L)	B_v (cd/m^2)	RELATIVE B_v*
35	75.3	.259	.887	.170
	7.75	.027	.093	
	0.82	.0029	.0099	
	0.073	.00023	.00079	
45	75.3	.122	.418	.084
	7.75	.0125	.0428	
	0.82	.00134	.00459	
	0.073	.00012	.00041	
55	75.3	.083	.284	.041
	7.75	.0083	.0284	
	0.82	.00092	.00315	
	0.073	.00085	.00029	

*Taken from theoretical curve in Pritchard Manual.

The differences between the subject groups was not unexpected. The greater effect of glare on older eyes is well known (e.g., Wolf, 1960; Wolf and Gardiner, 1965). The older subjects in this study were selected to match, as well as possible, the younger subjects. They are not necessarily representative of older persons in general. As a matter of fact, they probably have unusually good vision, relative to their peers. Despite this, they required, on average, almost twice the luminance on the target disc to detect it under no glare conditions. When presented with glare the older subjects had to increase the target disc luminance about twice as far above no-glare values as did the younger subjects. Placed in the context of operating a car, these data translate into substantial differences in visibility distance.

In sum, these data provide a baseline for evaluating disability glare effects associated with glare originating in the rear view mirrors of automobiles. They provide guidelines for possible changes in headlamp photometrics.

APPENDIX B

REAR VIEW MIRROR DISCOMFORT GLARE STUDY

APPENDIX B: REAR VIEW MIRROR DISCOMFORT GLARE STUDY

Introduction

Discomfort glare has been a subject of considerable research. Relatively little of this effort has been concerned with glare originating from the rear view mirrors, however. The study to be described was designed to compliment the disability glare study reported in Appendix A. It sought to relate sensations of discomfort to the measures of disability obtained in the earlier study.

Independent Variables

Glare Illuminance. Five levels, corresponding to the three higher levels utilized in the disability study, and including two intermediate levels. These were as follows:

0.73 Lux (0.07 ft-c)
2.37 Lux (0.2 ft-c)
8.61 Lux (0.8 ft-c)
34.4 Lux (3.2 ft-c)
70.0 Lux (6.5 ft-c)

These values were measures at the subject's eye point, and included attenuation associated with the rear and side windows and mirror reflectivity levels.

Glare Duration. Two levels, ten seconds and three minutes.

Dependent Variables

Ratings of discomfort glare were taken using the scale originally suggested by DeBoer (1956). This is a 9-point scale as described below:

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

In addition, on each rating situation, the subject was instructed to indicate whether he/she would have switched the interior mirror to the less-reflective setting, if that option were available.

Subjects. Four subjects participated in the study. They were drawn from the group of six young persons who participated in the laboratory disability glare study.

Equipment. Two cars were used. The front car, which was driven by the subject, was an ordinary, full-size Plymouth sedan (Figure B-1). The car has a dual reflectivity interior mirror (only the more reflective setting was used) and a single exterior mirror on the driver's side.

The glare was provided by HSRI's headlighting research vehicle. This car is equipped with a plate which permits a number of lamps to be mounted across the front (Figure B-2). It is also equipped with systems which permit each lamp filament to be maintained at precise voltage settings.

Glare illuminance measurements were carried out using HSRI's Pritchard photometer. The diffusing target disc was positioned at the eye point of the subject and measures carried out with the photometer positioned outside the car, aiming through the open side window at an angle of about 45^{0}. A correction for the transmissivity of the side window was made after the fact. Various combinations of lamps, beams, and voltage settings were required to achieve the desired glare illuminance levels.

Procedure. Subjects reported to the Institute and were seated in the front car. The instructions were read to them and any questions answered. Both interior and exterior mirrors were adjusted so the illumination from the glare car's headlamps was reflected into the subject's eyes in normal driving position.

Data were collected on dark, two-lane country roads near Ann Arbor. The subject drove the lead car at constant speeds appropriate for the road being used. The glare car was driven by an experimenter and followed at a distance of 30 meters. (A width gage was placed on the window of the car so that, at the appropriate distance, the tail lights of the subject vehicle were bracketed by the vertical portions of the gage.) Another experimenter in the rear seat controlled the lamps and collected the data.

Figure B-1. Front (subject) vehicle in discomfort glare study.

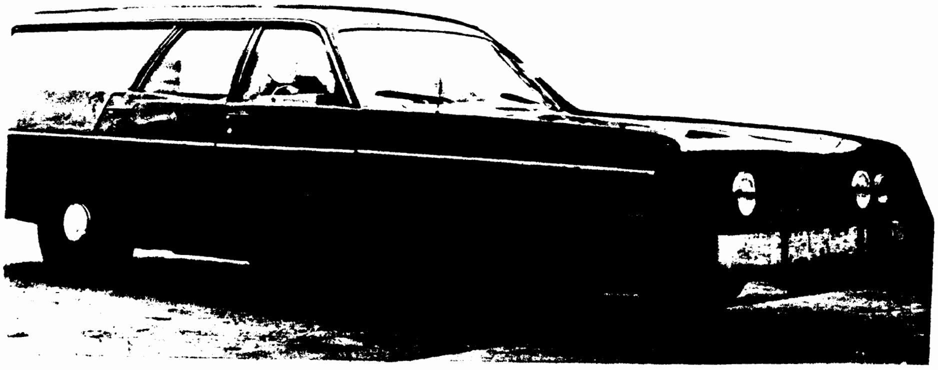


Figure B-2. Vehicle which provided glare in discomfort glare study.

At the start of each trial sequence a glare level was presented. After an appropriate interval (ten seconds or three minutes) the experimenter asked for a rating, using two-way radios with which the vehicles are equipped. The subject responded with a numerical rating, and an indication whether he/she would have liked to change mirror position. The experimenter then switched to a neutral, unrated beam (normal US low beam) for a period of 30 seconds before introducing the next glare beam. The subjects were given five replications of each of the beams for the ten second exposure, three replications each for the three minute exposure. All short exposures were given first, followed by the long exposures, or vice versa, alternating from subject to subject. Glare levels were randomized.

Results and Discussion. The intent was to run all six of the young subjects who had participated in the laboratory study. However, two of these persons were not available at the time the data were collected. In the view of the experimenters, the data showed so little inter- and intra-subject variance, that additional data collection effort was not warranted.

Table B-1 is a summary of the results of this study. It shows the mean numerical rating, standard deviation, and percent of times the subjects indicated they would have liked to change the mirror setting for each test condition.

The data indicate that exposure duration is a significant factor, the same glare levels being rated about one scale unit more uncomfortable when exposure duration was three minutes as compared with ten seconds.

Figure B-3 shows the relationship between the ratings and the glare levels. Plotted this way, the data fit a straight line relationship fairly well.

If glare which produces a rating less than 5 is judged undesirable, Figure B-3 suggests that this would occur at a level of 6 Lux for short durations, and as little as 3 Lux for long durations. Based on the data reported by Adler and Lunenfeld (1973), these levels approximate the

Table B-1

Results of Rear View Mirror Discomfort Glare Survey

GLARE LEVEL (Lux)	EXPOSURE DURATION					
	10 SECONDS			3 MINUTES		
	MEAN RATING	STD DEV.	MIRROR CHG %	MEAN RATING	STD DEV.	MIRROR CHG %
.73	7.7	0.92	0	6.5	1.13	18
2.37	5.7	1.04	45	4.8	1.08	82
8.61	4.9	1.23	70	4.1	1.14	82
34.4	2.9	1.04	90	2.3	1.19	100
70.0	1.7	0.75	100	1.2	0.40	100

glare provided by a mid and a low beam respectively at a following distance of 30 meters.

These data suggest that further increases in headlamp output can be achieved only at the expense of significant increases in discomfort glare for preceding drivers. However, as was noted in the report dealing with disability glare, the driver has some control over rear view mirror glare. For example, switching to the lower setting on the interior rear view mirror will reduce glare by about 65%. Based on Figure B-3, a reduction of 65% will improve the comfort rating by a bit more than one scale unit. If the outside rear view mirror is adjusted so that it does not reflect directly into the eyes in normal driving position, changing to the lower setting of the interior mirror will reduce glare by about 95%. Based on Figure B-3, this would improve glare comfort by more than three scale units, bringing almost any situation within the comfort range.

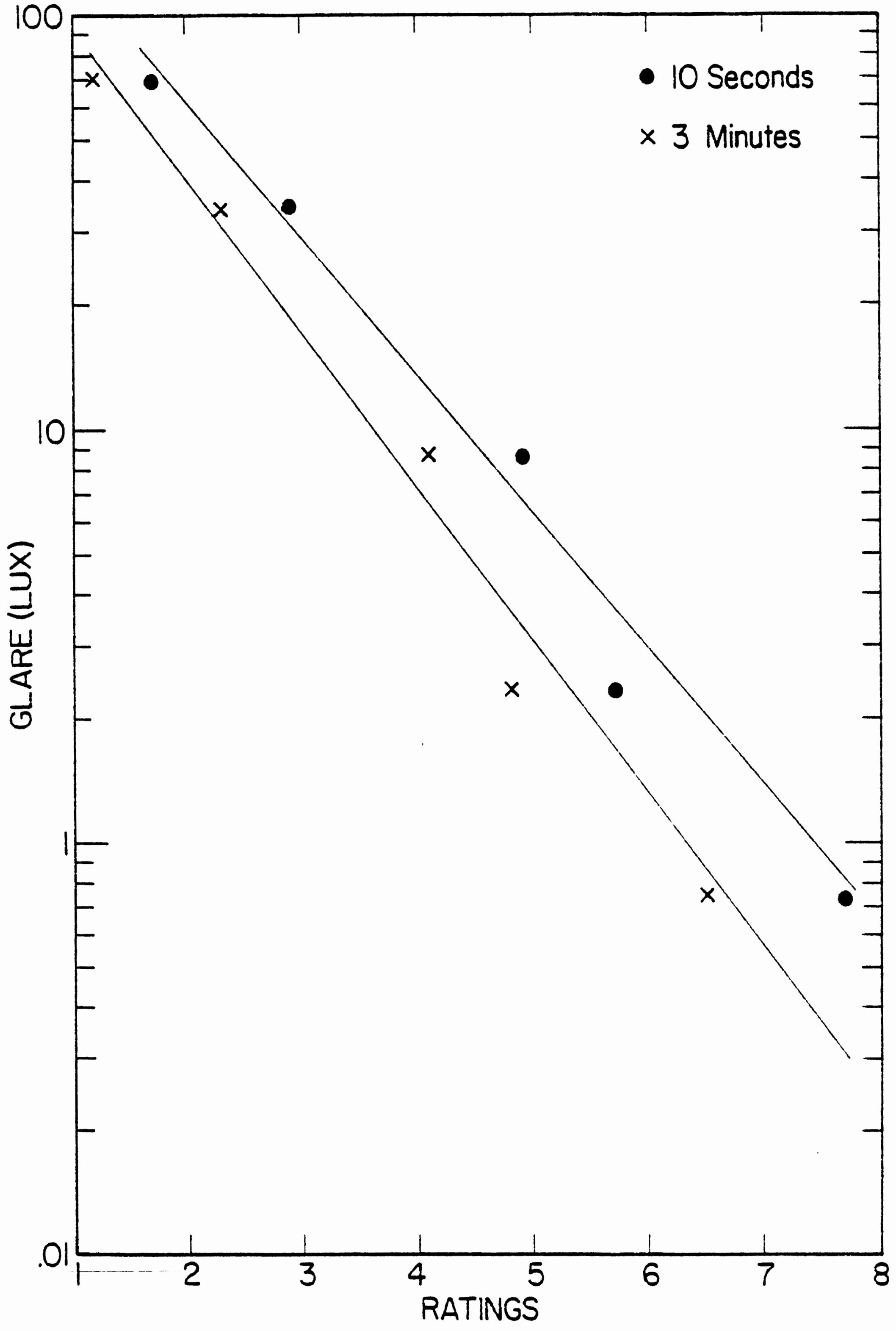


Figure B-3. Mean comfort ratings for glare originating from rear view mirrors. Four young subjects, two glare durations (10 seconds and 3 minutes).

APPENDIX C

REAR VIEW MIRROR DISABILITY GLARE - FIELD STUDY

APPENDIX C: REAR VIEW MIRROR DISABILITY GLARE - FIELD STUDY

Introduction

The study described in Appendix A measured the effect of glare from the rear view mirrors on the ability to detect low-contrast targets in the forward field. The results indicate that the effects of such glare are significant when levels exceed about 1 Lux. Since this study was carried out under laboratory conditions, it was thought desirable to verify the findings in a field investigation.

Independent Variable

Glare illuminance, four levels, corresponding to the three higher levels used in the laboratory study, and including a no-glare control. Specifically, the levels were as follows:

0.7 Lux	(0.07 ft-c)
8.6 Lux	(0.8 ft-c)
70.0 Lux	(6.5 ft-c)
No Glare	

These values were measured at the subject's eye point, and included attenuation associated with the rear and side windows and mirror reflectivity levels.

Dependent Variable

The measure of interest in this study was the distance at which the subject could detect the orientation of a headlighting test target.

Subjects. Three subjects participated in this study. They were drawn from the group of six young persons who participated in the first laboratory study.

Equipment. The same basic equipment was used in this study as in the subjective glare study (Appendix B), except that the lead vehicle, in which the subject was located, was replaced by another, having distance measuring and recording capabilities.

A picture of one of the visibility targets is provided in Figure C-1. This target was developed at HSRI several years ago, and has been used in a number of lighting studies (e.g., Mortimer and Olson, 1974). The background is flat black (reflectivity = 3%). The target proper consists of two elements, a bar and square. The square portion can be moved to the right or left end of the bar. The subject's task is to determine whether the square is oriented right or left. For this test the reflectivity of the bar and square was 12%.

Procedure. The test was set up on a private access road to an airport. The road is high-quality asphalt, 760 meters long. It consists of two lanes, each about 3 meters wide, and is flat and straight. The area in which it is located is quite dark. There are no sources of artificial illumination on or near the road in the section where data were taken.

Six targets were used. These were set up in pairs, one on each side of the road, facing in opposite directions. The pairs were separated longitudinally by about 90 meters. Each pair was attended by a person who changed the orientation of the target faces, based on a table of random numbers.

The subjects were run individually. Each was seated in the car and the instructions were read. Both rear view mirrors were adjusted to be sure that the illuminance from the headlamps of the following car was reflected into the subject's eyes in his/her normal driving position.

The subjects drove the car at about 30 km/hr down the center of the test road. The glare car followed at a distance of 30 meters. One round trip was made for practice at the start of the test. The subject then made two round trips through the course under each glare condition. This provided twelve measures of visibility distance for each subject and glare condition, a total of 36 measures of each condition for the entire study.

Each subject required about 45 minutes to complete the required sequence. The order of treatments was varied systematically to control for time-related effects.

Two problems were encountered in data collection which proved somewhat difficult to control and probably contributed significantly to the error variance.

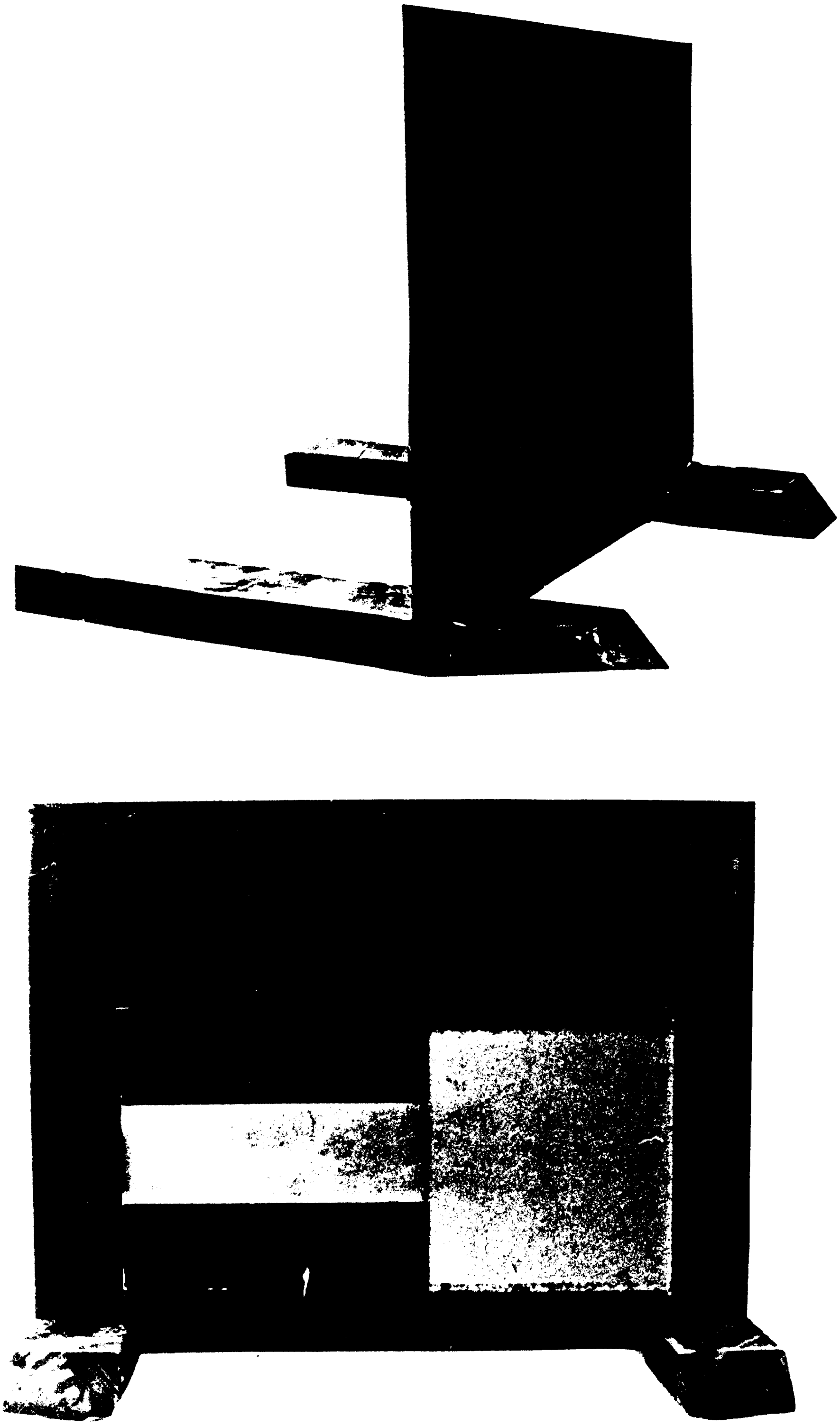


Figure C-1. Front and side views of headlighting visibility target.

The first problem arose from the fact that the lateral position of the two vehicles was very important. If the glare car was slightly right of the subject car, the former's glare lamps could significantly add to the target illumination, partially offsetting the glare effect. This was difficult to control because lateral displacement could be caused by the subject and/or the driver of the glare car. Further, it was difficult for the glare car driver to determine when his right-side lamps were illuminating the target.

The second problem was that the subjects sometimes moved their eyes out of the glare zone, despite an admonition in the instructions. They tended to sit up straight while adjusting the mirrors and then slump while driving, dropping their eyes out of the glare zone. Sometimes while trying to see a target, they leaned forward, also moving out of the glare zone. It was necessary for the experimenter to monitor this action constantly.

Results. Based on the results of the laboratory study, it was expected that the two lower glare levels would produce a relatively minor disability effect, while the highest level would produce a much greater effect.

The results are plotted in Figure C-2. The mean no-glare visibility distance was 72 meters. This decreased to 68 meters, a drop of about 5%, for the two lower glare levels, and to 61 meters, a drop of about 15%, for the highest glare level.

The results of the validation effort substantially confirm the laboratory study described in Appendix A, in that significant, though slight, reductions in visibility distance are associated with glare levels as low as 1 Lux.

The laboratory study found that the task disc luminance had to be increased by a factor of about five over the no-glare level in order to reach threshold at a glare level of 70 Lux. Very roughly, this implies a reduction in seeing distance of about 50%. The loss of seeing distance measured in this field study was considerably less than 50%. However, the problems noted earlier may account for this apparent discrepancy.

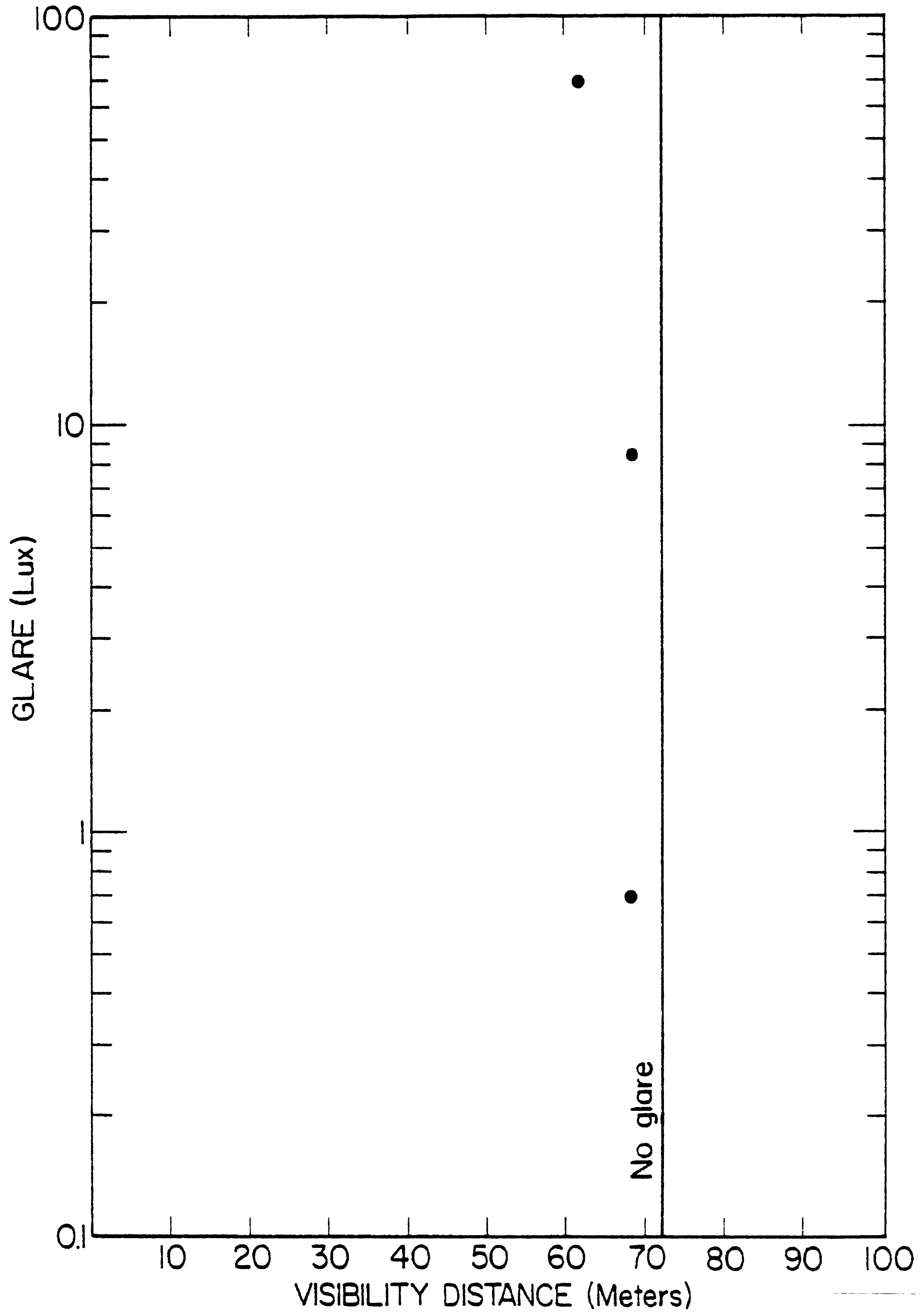


Figure C-2. Mean visibility distances achieved with three levels of rearview mirror glare.

APPENDIX D

TRANSIENT GLARE STUDY

APPENDIX D: TRANSIENT GLARE STUDY

Introduction

The study described in Appendix A was designed to investigate rear view mirror disability glare effects under steady state conditions. That is, glare levels and the angular relationship between the subject's direction of gaze and the glare source remained constant. While these data are useful, they are not fully representative of the real world. Important other situations occur when a glare source enters the field (e.g., a car turns in behind from a side road), or the driver chooses to look into the mirror, directly at the source. Such situations should produce a temporary elevation of the threshold levels measured in the steady state condition. The study to be described was designed to measure these effects.

Independent Variables

Glare Illuminance. The two highest levels of glare illuminance used in the disability glare study were used in this study. These were:

75.3 Lux (7.0 ft-c)

7.75 Lux (0.72 ft-c)

These values were measured at the subject's eyes. The mirrors were fixed at 45^0.

Subject Age. Six subjects participated in the study. All had been involved in the first laboratory glare study. Three were from the younger, three from the older group. Their visual characteristics are described in Table D-1.

The measure of interest in this study was the luminance of a disc target at threshold. The target disc was the same as that used in the first study (0.38 degrees in diameter, seen against a black background). In this case, however, the subject was provided with a control which allowed continuous adjustment of the disc luminance.

Equipment. Figure D-1 is a schematic of the laboratory arrangement. It used the same equipment as the first disability glare study. That is, glare was provided to mirrors M_5 and M_6 via mirrors M_3

Table D-1

Subject Characteristics

Subject	Age	Sex	VISUAL ACUITY			
			HL-HC	HL-LC	LL-HC	LL-LC
1	22	M	20/18	20/20	20/25	20/60
2	21	F	20/22	20/35	20/60	20/100
3	23	M	20/18	20/25	20/27	20/60
4	72	M	20/18	20/40	20/40	20/100
5	65	M	20/18	20/40	20/40	20/60
6	66	M	20/22	20/40	20/35	20/60

Note: HL - High Luminance (161 cd/m^2)
LL = Low Luminance (0.2 cd/m^2)
HC = High Contrast (22.5:1)
LC = Low Contrast (1.3:1)

and M_4 from projector P_2. The disc display was illuminated by projector P_1, via mirrors M_1 and M_2. Additional equipment necessary for this included M_7, a partially silvered mirror, which was inserted in the path between the subject and the disc display. The subject viewed the display through the mirror. The Pritchard photometer also viewed the display in M_7, the luminance being read out on the chart recorder.

A lamp installed behind the disc display illuminated the back wall of the lab to about 0.035 cd/m; appropriate for a mesopic level of adaptation.

Procedure. The subjects were seated at a table and the chair height adjusted to allow their chins to be comfortably supported on the rest provided. The instructions were read to them, and any questions answered. The subjects were told that the appropriate strategy was to dim the disc until it just disappeared, then increase its luminance until it was just visible again. This was to be repeated continuously whenever data were being collected. At this point the laboratory lights were extinguished to start the dark adaptation period. During this

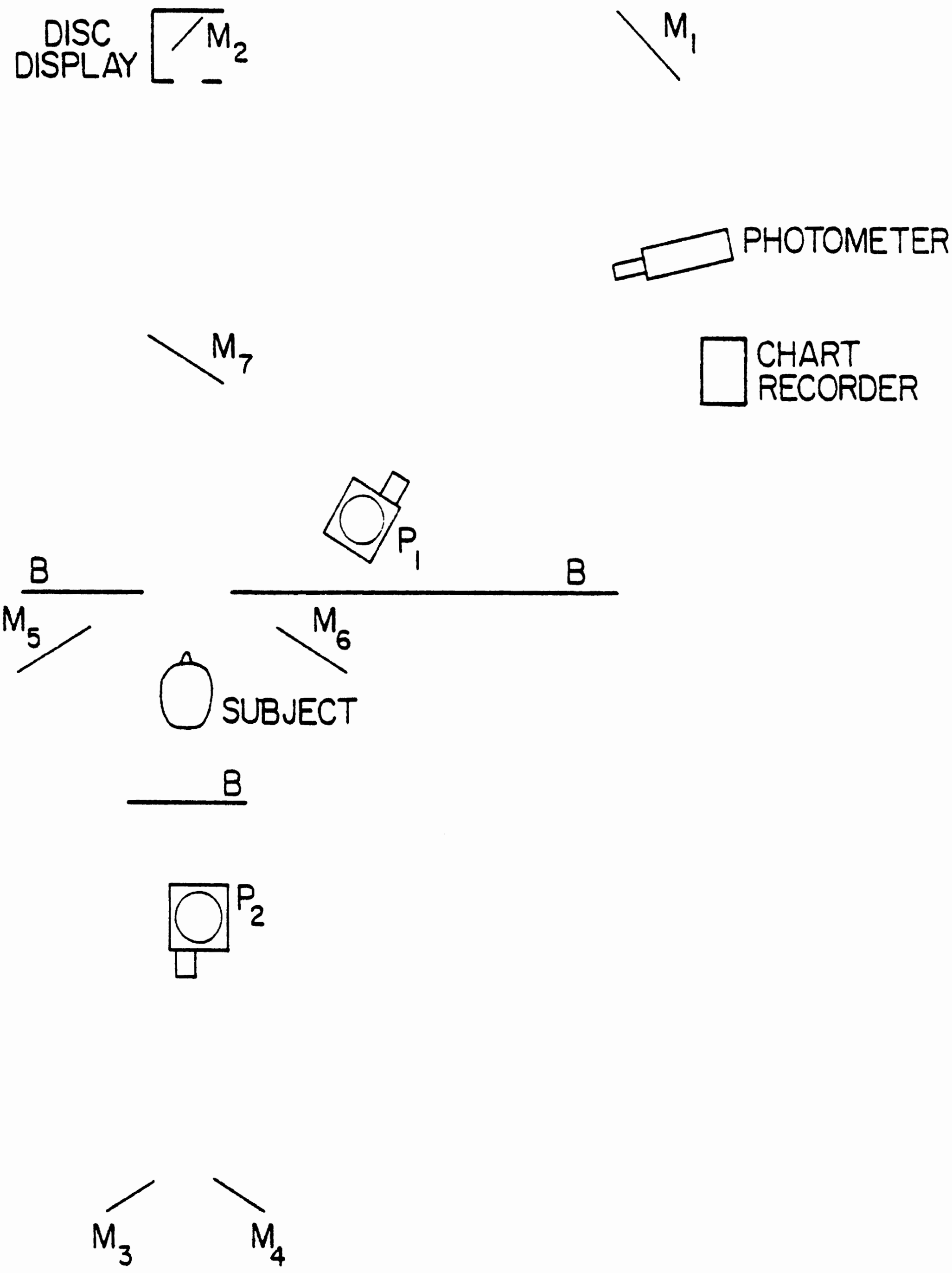


Figure D-1. Schematic of laboratory arrangement.

period (about ten minutes) the subject was permitted to practice the technique just described.

Depending on the subject, some coaching was required so that the magnitude and frequency of the high-to-low excursions were as consistent as possible.

Different procedures were required for the two sub-studies which were carried out. For the case in which the glare source suddenly appeared (which will be referred to as "Onset") the subject was allowed to dark adapt to the level of the laboratory illumination. The task disc was set to a level sufficiently high to be sure that it could be seen when the glare light came on. The glare source was then switched on and the subject tracked it in the manner described earlier until it appeared to the experimenter that a stable level of adaptation had been reached. This typically took about two minutes. The glare source was then extinguished and the subject allowed to dark adapt again. This process was repeated four times for each of the two glare levels, if there was any indication of an effect. There was a measurable effect for the lower level glare on the older subjects only.

For the sub-study in which the subject was required to look directly at the glare source (which will be referred to as "Look"), a different approach was used. The subject started with the glare source on. When stable performance had been reached, the experimenter told the subject "look," then, one second later, "look away." The subject then made whatever adjustments he/she felt were necessary to maintain the disc at a visible level. The subject also indicated when afterimages disappeared. This process was repeated four times for each glare level.

Results - Onset. Figure D-2 is a typical trial for one of the subjects under the onset condition. The arrow indicates the point in time at which the glare source was turned on. In this particular case performance appears to stabilize after about 45 seconds at a level at or just below the fourth major division from the bottom. The stabilized level corresponds to a task disc luminance of approximately 0.045 cd/m^2.

In reducing these data the experimenter determined the approximate level of stable performance, and then drew a visual best fit line through the data to the glare start point. Readings were then taken at five-second intervals. The data were averaged for each subject (across the four trials) and then across subjects for each age group to produce the figures which follow.

Figure D-3 summarizes the results for the case of the highest glare level (75.3 Lux). The short horizontal lines to the right of each curve represent the mean stability level for these subjects. It would correspond to the maximum glare--45^{0} glare angle--in the steady state study. The figure shows a much more pronounced effect (in absolute units) on the older subjects, which persists for about 50% longer than the younger subjects. However, in relative terms, the sudden presentation of this glare level resulted in a temporary elevation of the threshold to about double its eventual level for both age groups.

Another way of looking at these results is provided in Figure D-4. This shows the performance of each age group related to their no glare threshold. What it suggests is that a person who is adapted to a dark, rural environment and is suddenly confronted with about 75 Lux glare from the mirrors, will suffer an increase in threshold of about 8.5 times if he/she is young or about 11.5 times if old. Assuming the glare remains steady, the driver's eyes will adapt over a period of about 45 sec for the young and 70 sec for the old, finally leveling off at a value about 4.5 or 6 times greater than the no-glare condition for younger or older persons respectively.

Only the older drivers showed a measurable adaptation effect to the 7.75 Lux glare level. This is shown in Figure D-5. As in the case of the higher glare level, the effect of the onset was to elevate the threshold to about twice its eventual steady-state value. Adaptation was accomplished in about 45, as compared with 70 seconds with the higher glare level.

Results - Look. Figure D-6 is a typical trial for one of the subjects under the Look condition. The "look" command was given at the point marked by arrow 1. The subject reported after-images gone at the point marked by arrow 2, 75 seconds later.

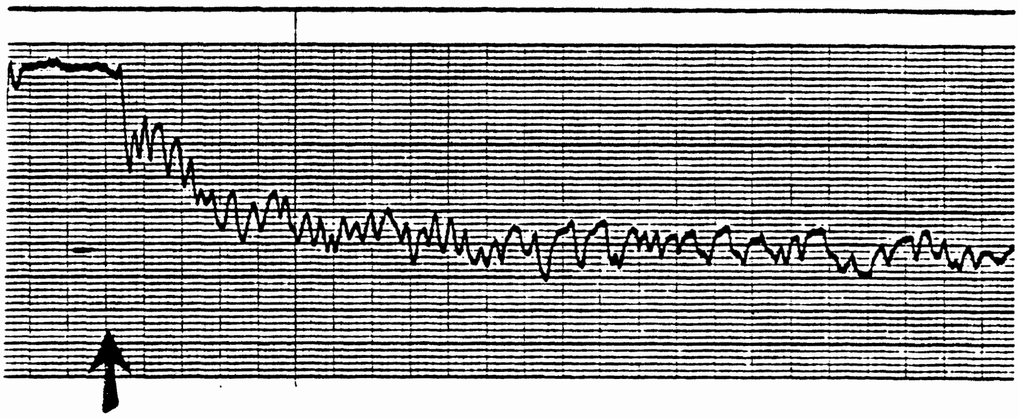


Figure D-2. Typical trial of onset data from young subject. Time increases to right, one second/division. Glare switched on at arrow.

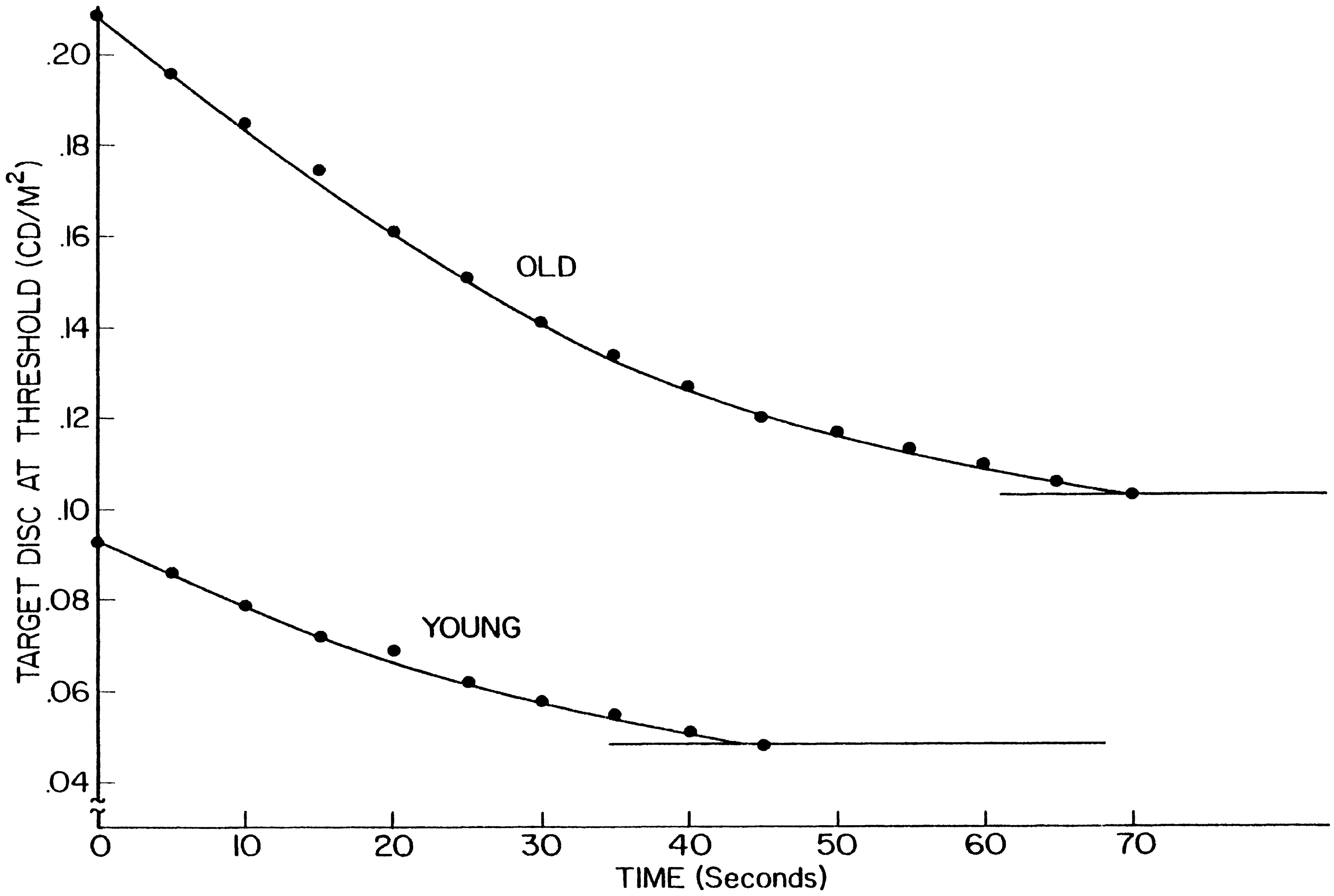


Figure D-3. Luminance required on target disc to provide threshold visibility as a function of time after onset of glare.

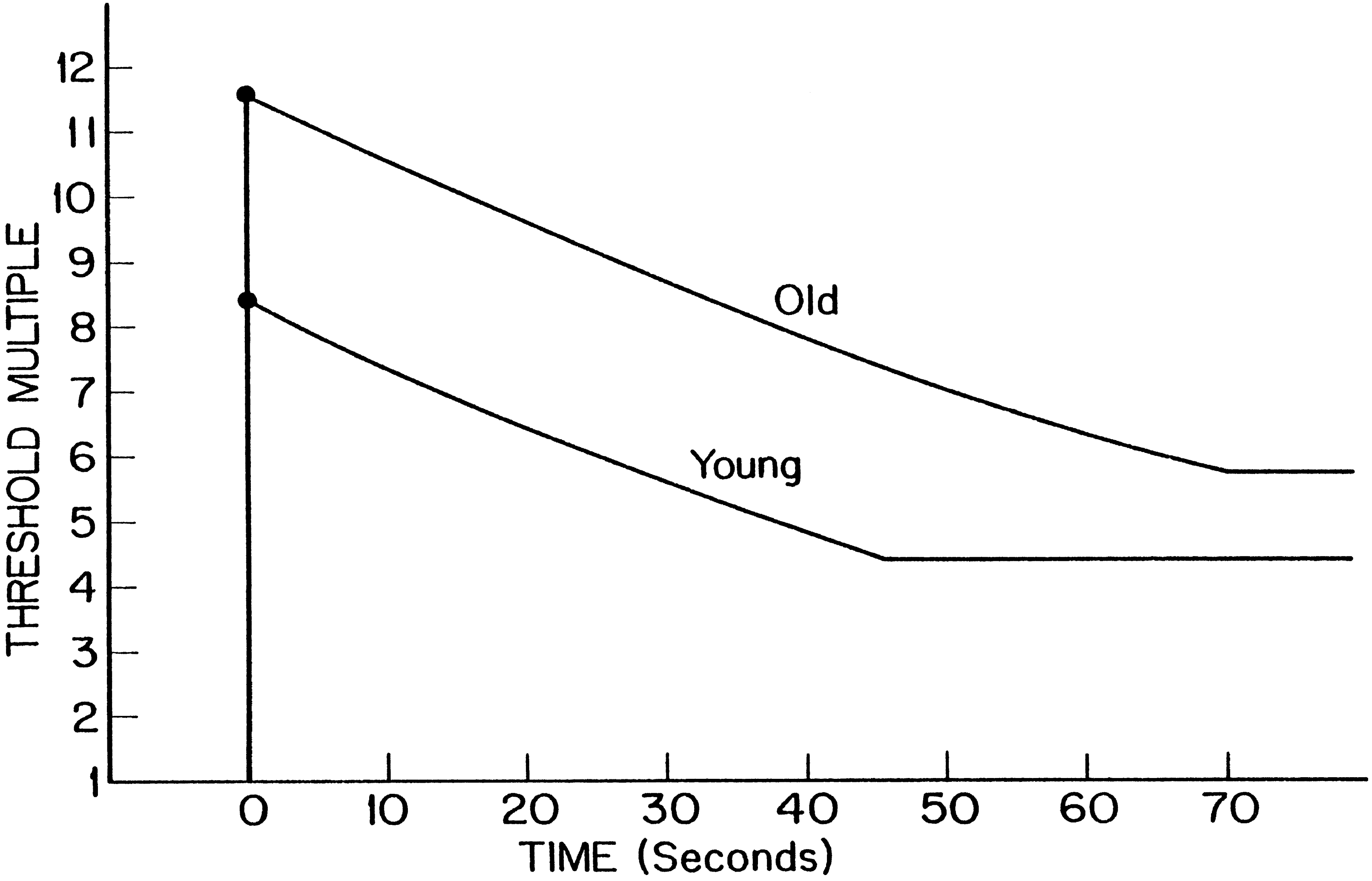


Figure D-4. Number of times target disc luminance must be increased over no-glare conditions to maintain threshold visibility.

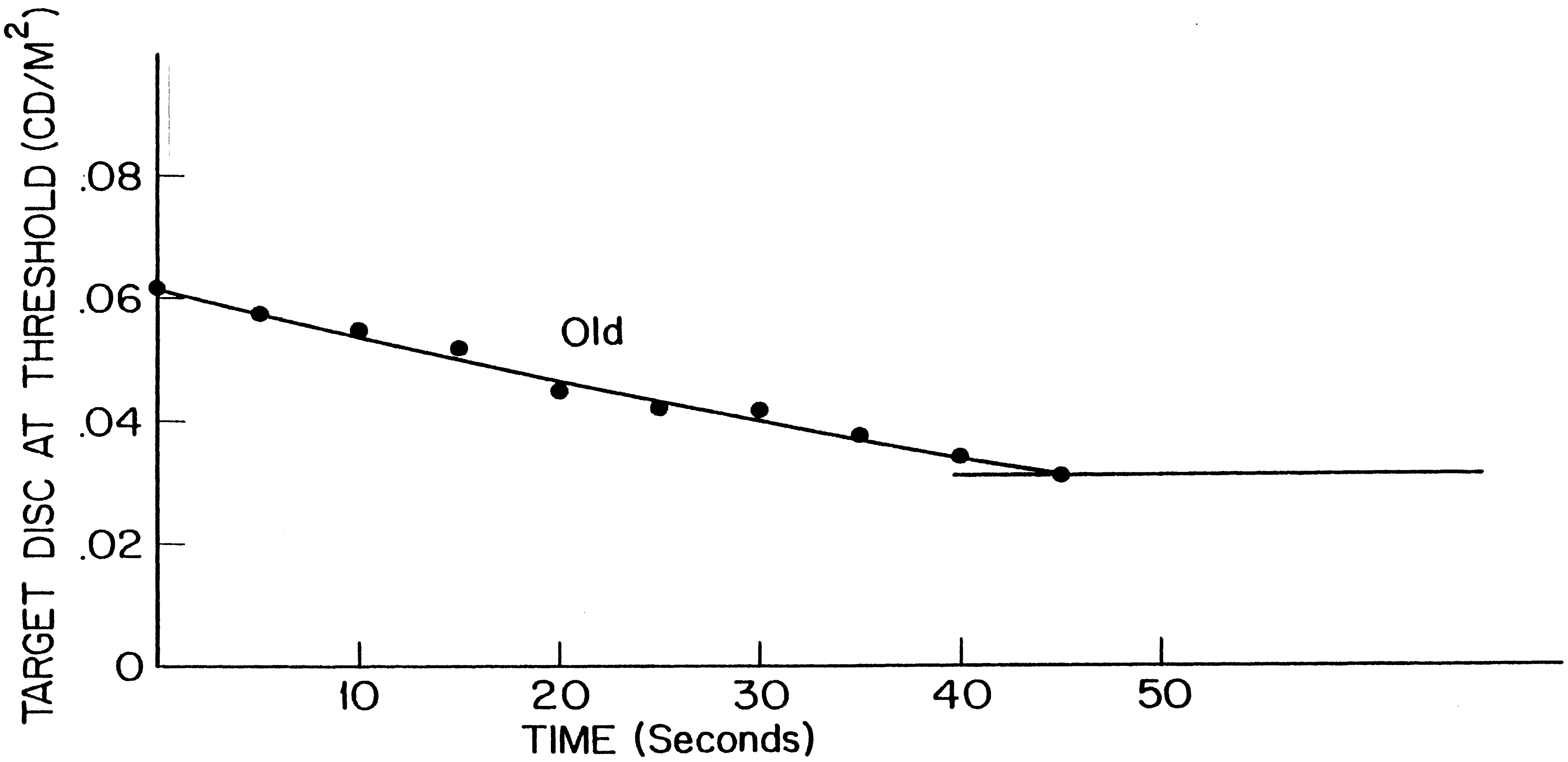


Figure D-5. Luminance required on target disc to provide threshold visibility as a function of time after onset of glare.

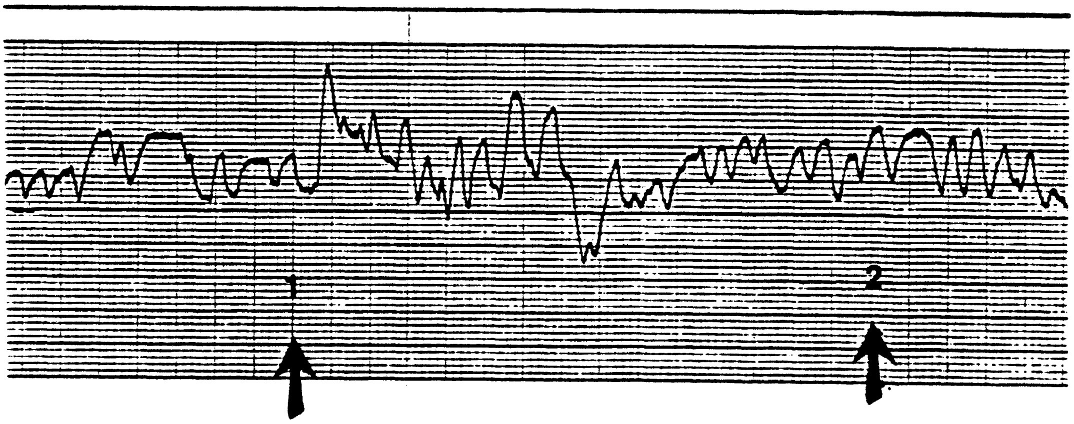


Figure D-6. Typical trial of look data from young subject. Time increases to right, one second/division. "Look" command given at arrow 1. Subject reported after images gone by arrow 2.

In the case illustrated in Figure D-6, there is some evidence of a temporary slight elevation of the threshold for a period of 15 seconds following the exposure. In most other cases the response consisted of a marked increase in the magnitude of the excursions. As a result, it is not possible to provide plots of threshold change. Subjective reports from the participants indicated that the afterimages sometimes interfered with the detection of the disc, but they did not feel they were suffering other vision loss.

Discussion. The results of this study make it clear that the sudden appearance of headlamps behind one's own car can produce a marked additional elevation in visual threshold. Further, this effect persists for a significant period of time. At freeway speeds a person would cover between one and two kilometers before the minimum adaptive level was reached.

From the point of view of the interests of this investigation, however, the effect occurs at such a high level as to be of no practical consequence. Clearly, low-beam photometrics could be upgraded substantially without producing adverse transition effects.