EVALUATION OF THE FEASIBILITY OF A SINGLE-BEAM HEADLIGHTING SYSTEM

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16. Abstract

This study sought to develop an improved headlamp beam for use in conditions of oncoming or preceding traffic.

A number of candidate beam patterns were offered for consideration from several sources. These were evaluated by two computer models. One of these models estimates the visibility distance provided to various areas and under a variety of road conditions. The other model produces a "figure of merit" for each beam, which is the percent of time it simultaneously meets certain visibility and glare criteria.

Based on this evaluation, three different beam patterns were selected for field testing. The three beams were fabricated and evaluated both objectively and subjectively. The objective tests were run on public roads, using targets which appeared normal to the environment. The subjects were not aware of the purpose of the test. The subjective evaluation was run on a wide variety of roads and solicited opinions concerning many aspects of beam performance.

The results of both studies indicated that under some conditions the test beams provided marginal improvement over the SAE units used as controls.

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TECHNICAL SUMMARY

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Automobile headlighting systems have employed two beams for many years. In theory, such a system provides the required balance between visibility and glare protection that is required for effective nighttime vehicle operation. So long as most high speed driving can be done on high beam, the system will work well and the characteristics of the low beam are less important. However, driving conditions confronting most motorists today allow little use of the high beam. In addition, it appears that many motorists do not use their high beam even when driving conditions permit. Thus many drivers are, effectively, operating their vehicles as though it had but one beam. That being the case, it is vital that the low beam be designed to serve as adequately as possible under the variety of driving conditions when it is actually being used. This study sought ways to bring about improvement in the present low-beam system to better fit it for use under a wide variety of driving conditions.

There were four major steps to the study. These were:

1. A review of the literature in areas such as headlighting and visual perception was carried out. Contacts were also established with representatives of the lighting industry.
2. A computer seeing-distance model was used to evaluate a number of candidate beam patterns. Based on these results, three beams were selected for further evaluation.
3. The test headlamps were fabricated.
4. The test beams were evaluated, using subjective and objective methods, in comparison with a standard SAE low beam.

Step one provided a baseline of information for the conduct of the rest of the study. Industry representatives supplied many helpful suggestions.

(Continue on additional pages)

HS Form 321
July 1974

Step two started with a methodical evaluation of night visibility requirements. On this basis a variety of isocandela diagrams were prepared, representing possible alternative ways in which the visibility requirements might be met.

These hypothetical lighting systems were then evaluated by means of two computer-based night visibility models. One of these, developed by HSRI, calculates visibility distance to different targets at various positions relative to the roadway with and without glare from an approaching vehicle. The second model, developed at Ford Motor Co., produces a single figure of merit which represents the percent of miles driven over a representative roadway network during which visibility and discomfort-glare criteria were simultaneously met.

The results of the simulation activities, combined with subjective analysis of factors thought to be important, led to recommendations for three candidate systems for testing. Roughly, the three systems were as follows:

1. A similar pattern to the SAE low beam, but with upgraded intensity.
2. A beam which provided more light to the right of the road.
3. A beam which provided more light to the left of the road.

In step three the required lamps were fabricated and photometered. Other equipment was readied for the field evaluation.

In step four the evaluation was carried out. The first test measured seeing distances provided to various "realistic" targets set at various points on a network of public roads. The targets consisted of items such as parked cars, pedestrians, signs, and pieces of roadway debris.

The subjects in this test were run under a "semi-alerted" condition. By this is meant they were not told the true purpose of the study. Rather, they were told that the study was for the purpose of evaluating driving strategy under a variety of circumstances. The subjects were told to look for and respond to (by pressing a button)

"significant" objects in the roadway environment. Visibility data were taken without their knowledge on straight-flat and curved sections and with and without glare.

The results indicate that the system approximating an upgraded SAE low beam affords a slight improvement in visibility compared with the current low beam, while the others did not. The results did differ somewhat, depending on the target considered and road geometry.

A subjective evaluation was also carried out. Subjects drove with each beam over a variety of roads and were asked to rate the illumination provided to various parts of the driving environment. These data compare well with the objective results.

The results of this study suggest that at least one of the beams tested may offer a slight improvement over the present low beam. Further research on this concept seems worthwhile.

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The several U of M students who helped us in the field evaluation stage doing the many things that allowed the data collection to go smoothly.

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1.0 INTRODUCTION

This report covers an evaluation of the feasibility of a single-beam headlighting system. The National Highway Traffic Safety Administration sponsored the work under contract DOT-HS-7-01554. The University of Michigan Highway Safety Research Institute completed the work.

1.1 Project Objectives

The project aimed to:

- Determine illumination requirements for nighttime driving.
- Develop alternative single-beam patterns to meet these requirements.
- Evaluate alternative single-beam concepts in a field test.

1.2 Background

Automotive headlamps worldwide are, and have been for many years, two-level systems. The driver is offered a choice between a low or meeting beam, designed to provide some visibility with minimum glare to approaching drivers, and a high beam, designed to provide maximum visibility in the absence of other vehicles.

Clearly, the low beam, whether SAE or ECE design, does not provide adequate seeing distance for safe operation at higher speeds. This two-beam system works best where most high-speed driving can be done on high beams. However, in many areas of the country, traffic conditions are such that high beams can rarely be used. Further, there is some evidence (Hare & Hemion, 1968) that many drivers do not use the high beam even under conditions where it would be possible to do so.

For all intents and purposes, persons who cannot or do not use their high beam are driving with a single-beam system. Given that this is the case for many drivers, it is reasonable to ask whether the present low-beam design is the best compromise for a system in which it is the only beam used. The research described in this report was designed to explore this question.

1.3 Study Approach

As the background section implies, automotive headlighting is a very large and complex problem. Furthermore, since Americans' nighttime driving needs and habits are constantly changing, headlamp designs that were adequate a number of years ago are no longer adequate,thus the solution to the problem is complex. Because the problem is so difficult, our approach did not set out to generate an "ultimate" solution. Instead, we sought out ways of modifying current headlamps to better meet contemporary requirements. Two computer simulations evaluated each modification's adequacy. A field test compared the modifications the computer simulations indicated were best. Thus, our approach sought to improve and update the current standard and evaluate the improvements with respect to illumination requirements of nighttime driving and a field-test experiment.

1.4 Structure of this Report

Subsequent sections of this report discuss the following:

- The illumination requirements for nighttime driving.
- Alternative single-beam patterns to meet the requirements.
- A computer simulation analysis.
- Field-testing methodology.
- Field-testing results.
- Summary and conclusions.

2.0 ILLUMINATION REQUIREMENTS FOR NIGHTTIME DRIVING

2.1 A Review of the Literature

2.1.1 History of Headlighting.

The history of headlight development has been treated in depth by a number of authors (e.g., Nelson, 1954; Moore, 1958; Roper, 1957; Kilgour, 1960 and Meese, 1972). A brief summary of this information is presented here for purposes of historical perspective. For a long time, headlighting in the U.S. and Europe proceeded along rather different paths. For this reason they will be dealt with separately here.

2.1.1.1 Headlighting in the U.S.

In the earliest days of motoring, cars typically carried no lights at all. When lights were first incorporated on vehicles early in the century, they were primarily for marking purposes. Lights designed to illuminate the road ahead first appeared about 1906. They used acetylene and, like the first electric lamps which became available later, had a concentrated beam much like a search light. The next significant development, which occurred about the time of World War I, was to spread the light out to more uniformly illuminate the road. This was done by moulding prisms into the lens. The result was the first "beam pattern" that might properly be called such. Further developments continued, resulting in substantial improvements in light distribution and intensity.

Unfortunately, in this era there was a proliferation of beam patterns, lamp sizes, and shapes which not only made headlighting expensive, but made it difficult to replace components when necessary.

In the middle 1930's work began toward the development of what we know today as the sealed beam, a concept which first was introduced on 1939 model cars. The sealed beam is probably the most significant single development to occur in headlighting. It solved some serious problems associated with aging of the lamp unit, virtually guaranteeing consistent, good quality headlighting throughout the life of the unit. At the same time, units were standardized, resulting in high quality, readily available, low-cost headlamps for all vehicles.

The next major advance occurred in the 1955 model year, when an improved sealed beam was introduced featuring a "fog cap" over the filament to reduce upward scatter of light. In 1956, mechanical aiming became available as a feature on sealed beam units.

The four-headlamp system was introduced on some models of 1957 cars. This system reduced the need for compromise in lens design and filament position necessitated by using the same unit to produce both low and high beams.

In 1959 a new two-headlamp system was brought out featuring a significantly improved low beam. This low beam was equivalent in performance to that produced by the four-headlamp system, although the high beam could not quite match the performance of the four-headlamp system. In 1970 further improvements in light output were realized for both the two- and four-headlamp system through the use of higher filament wattages.

2.1.1.2 Headlighting in Europe. The history of European headlight development generally parallels that of the American experience. The most significant difference came about with the development of the so-called Graves "anti-dazzle" bulb, which was patented in 1920. The concept was adopted for use in England and became known as the Lucas-Graves system, in Germany as the Osram-Bilux system, and in Holland as the Philips-Duplo system.

The Graves bulb provides a simple and inexpensive way of greatly reducing the amount of light scattered above horizontal. A metal shield surrounds the front, sides, and bottom of the low-beam filament. preventing any light from being projected directly forward or to the lower portion of the reflector. This system results in a beam pattern characterized by a very sharp horizontal cut-off. Compared with an American low beam, it is significantly less glaring.

In 1953-54 a number of lighting tests were carried out under the auspices of the CIE (Internation Commission on Illumination). These tests have been described by de Boer (1955, 1956). As part of this program, comparisons were made between American and European lighting systems. The results showed that visibility distances on the left side of the road were comparable under most conditions tested. However, since the American low beam was asymmetrical (i.e., it directed the most intense portion of the beam to the right), it produced greater visibility distances on the right side of the road. As a result, it was recommended that changes be made to the Graves bulb to allow more light to be projected to the right. This was accomplished by removing a portion of the shield on one side. The sharp cut-off characteristic was retained. However, instead of presenting a flat, symmetrical appearance when projected against the wall or screen, it now appeared flat on the left with a 15^0 upward slant on the right. This revised concept became the European standard.

More recently a further modification has taken place, with the high-intensity portions above horizontal being cut off at $+1^0$. This produces a shape approximating the letter "Z," instead of a shallow V. This change reduces problems with glare on curves and into the rear view mirrors of vehicles ahead.

The next major advance in European headlighting came with the introduction of iodine (halogen) sources. The first mention of these in the literature occurs in the early 1960's, although their introduction did not come until sometime later.

The use of iodine vapor inside a light bulb makes possible a chemical reaction which causes vaporized tungsten to redeposit on the filament itself rather than on the glass envelope. Thus, the problem of bulb blackening is eliminated. It also makes it possible to generate substantially more light per watt and use a smaller filament, which simplifies the problem of focusing the beam. Because the filament must be operated at a much higher temperature in order to bring about the chemical reaction just described, it was necessary to use a quartz envelope on the bulb. It is for this reason that such sources came to be called quartz-iodine or quartz-halogen. More recently, especially in the U.S., high-temperature glass has been used rather than quartz.

Substantial development has taken place in the last several years since the halogen concept was first introduced for use on headlamps. Earlier versions could use only a single filament in the bulb, making it applicable only for four-lamp systems. Present versions incorporate two filaments, so that both high and low beams can be generated from a single source.

2.1.2 Research on Headlighting Effectiveness. As noted in the preceding section, developments to date have resulted in two significantly different headlighting systems, one described in SAE standards and adopted by the U.S. government and the other described in ECE documents and required in most if not all of continental Europe. The fact that this difference of opinion exists should provide some warning to persons concerned with improvements in headlighting that agreement on a "better" system will not come easily.

The literature reviewed in the following section is concerned with various evaluations of low-beam systems. Inevitably, given the controversy over SAE and ECE approaches, many of the studies are comparisons between the two, designed to "prove" one or the other better.

Although there have been a number of investigations purportedly aimed toward improving headlighting, the quality of many of these leaves a great deal to be desired. Matters such as photometry, aim, and control of voltage are often slighted. A wide variety of targets and test techniques are used. In view of these problems, the disagreement in results from one study to another is understandable.

Research on driver vision provided by headlamps under meeting conditions first began appearing in print prior to World War II. Most of this work had to do with trade-offs between glare and intensity (Bauma, 1936; Roper and Howard, 1938; and Roper and Scott, 1939), although the first work with polarized headlighting was also carried out during this period. However, the bulk of the work was conducted in the post-war era.

One of the most significant of the early reports concerning low-beam patterns is that of Harris (1954). He summarizes a great deal of information about headlighting in the era immediately after World War II. The paper contains a report of an investigation carried out at the Road Research Laboratory comparing American, British, and two types of European headlights. The tests Harris describes were semi-dynamic, in that the experimental vehicle was moving but the glare source was not. A single target was employed, which was placed 10 feet behind the glare lamps and 10 feet into the lane used by the test vehicle. The target in this instance was an object 1.5 feet high with a reflective factor of 7%. The target position was selected to be the most difficult to see. Hence the seeing distances measured were minimums. The results from these tests were used to generate curves showing the trade-off between glare and visibility distance for the specified target object. These curves were used to calculate minimum seeing distances for the four beams of interest. The calculated seeing distances are reproduced in Table 2.1

TABLE 2.1. Calculated Minimum Seeing Distances for Various Lamps (From Harris [1954]).

Lamp	Seeing Distance		Reduced values due to misaim (per cent)
	Correct alignment	-0.5^0 misaim	
British	158	132	82
American	149	122	82
European B*	150	116	77
European A*	145	109	75

*These were both symetrical beam patterns which differed slightly in distributional characteristics

These data indicate that, for the conditions specified, the three types of lamp differ relatively little, when properly aimed. The

American and British beams, which are generally similar, differ relatively little under conditions of incorrect alignment as well. The European beams, with their sharper cutoff, are more affected by misaim.

One of the most comprehensive early headlighting research efforts was that carried out by the "Working Group Brussels, 1952." The intent was to arrive at a generally acceptable and improved headlight beam pattern. The program proved to be so extensive that its completion was distributed among the national committees of Germany, England, France, The Netherlands, and the United States. For purposes of this survey the most significant results are summarized in Figures 2.1 and 2.2, which have been adapted from Kazenmaier (1956). These curves show visibility distances measured for the symmetrical European beam in use at that time meeting a similar beam, as well as for a U.S. sealed beam meeting a similar beam. It will be noted that the European beam afforded significantly greater visibility down the left side of the road. The two beams were similar for objects in the center of the road. However, the U.S. beam provided significantly greater visibility distance down the right side of the road.

One question which the efforts of this commission could not resolve was that of illumination directed into the upper left quadrant of the beam pattern. European scientists felt then, as they do now, that glare must be minimized, where the Americans felt higher glare levels were acceptable. As a result, the Europeans decided to stay with the shielded filament concept but sought a means which would allow greater illumination to be directed down the right side of the road. This modification has been described by de Boer (1956). The solution was to remove part of the filament shield on one side so that high-intensity illumination was directed above the horizontal down the right side of the road. Because of the change in the filament shield, it was necessary to modify the lens somewhat. At the same time the bulb mounting was redesigned to ensure greater accuracy in filament position. The result of this program was an improved

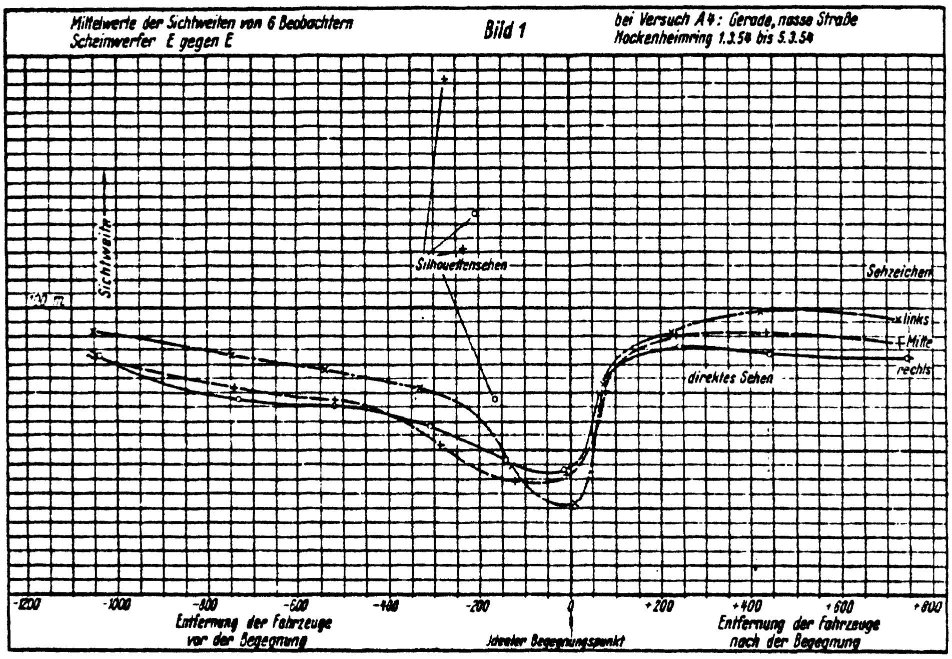

Figure 2.1. Visibility Distances Measured to Targets Placed on Left, Middle and Right of the Road for European Lamps Meeting European Lamps. (From Kazenmaier [1956]).

(Figure shows seeing distance [Sichtweite] before and after the meeting point [Jdealer Begegnungspunkt] for targets on the left [links], middle [Mitte], and right [rechts] of the test vehicle.) Also shown are results for targets seen in silhouette [silhouettensehen].

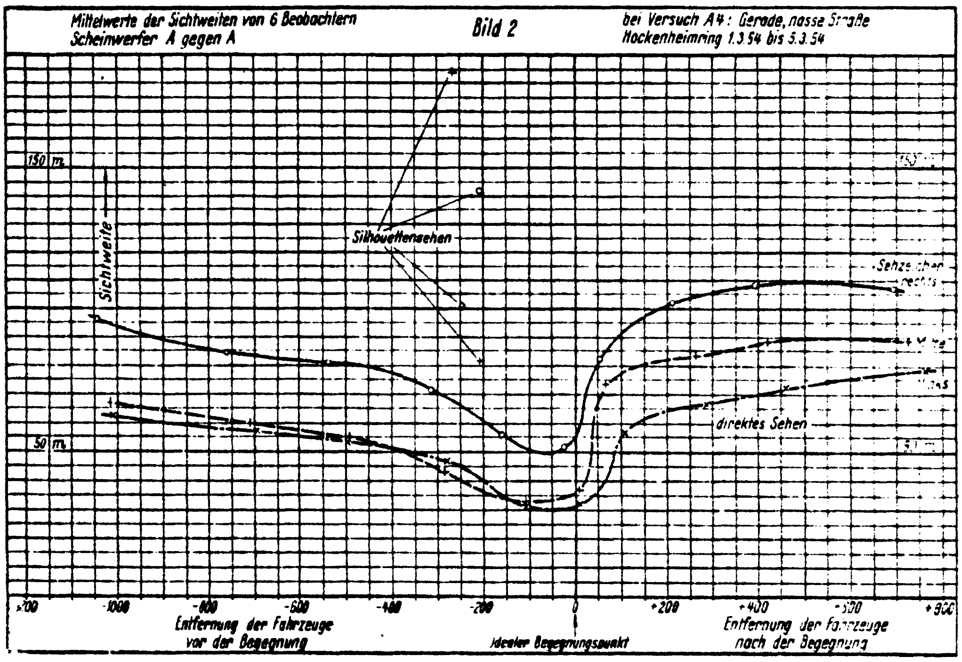

Figure 2.2. Visibility Distances Measured to Targets Placed on Left, Middle and Right of the Road for American Lamps Meeting American Lamps. (From Kazenmaier [1956]).

(Figure shows seeing distance [Sichtweite] before and after the meeting point [Jdealer Begegnungspunkt] for targets on the left [links], middle [Mitte], and right [rechts] of the test vehicle.) Also shown are results for targets seen in silhouette [silhouettensehen].

European beam pattern which was, in the opinion of European engineers, capable of equalling the visibility distance afforded by the U.S. sealed beam to all areas of the road environment.

In the early 1950's scientists at the Road Research Laboratory in Great Britain developed a computational technique for determining headlamp seeing distances based on beam intensity and glare. This has been used in a number of applications. One of the most interesting studies involved a comparison of European and British headlamps on curved roads (Jehu, 1957). The results of some of the calculations provided by Jehu are shown in Table 2.2. Note that the European lamps are of the older symmetrical type.

The results of this investigation show no clear advantage to either system, since the visibility afforded depends on the distance between the target object and the glare source, and whether the target is on the right or left side of the road. However, Jehu felt that the advantage lay with the British system, which was almost always better than the European in revealing the important near-side object. (For Americans, "near side" corresponds to the right side of the road.) Recall however, that this test involved the earlier symmetrical European beam. The results probably would have been more similar were an asymmetrical European beam used instead.

Lindae (1962) has reported the results of tests comparing U.S. two- and four-lamp sealed-beam systems with the European asymmetrical system. These results are summarized in two figures taken from his report. Figure 2.3 shows the results for targets on the right hand side of the road. The differences between the two systems appear minimal. Figure 2.4 shows the results for targets placed on the left side of the road. In this instance there is a substantial difference, with the European system producing about a 30% increase in visibility distance under no glare conditions and more than a 50% improvement under glare conditions.

TABLE 2.2. Comparison of Calculated Seeing Distances for British and European Headlamps. (From Jehu [1957]).

Object position	Distance between object and glare source (ft.)	Seeing distances with the following opposing beams: Double Lamps Modern British versus Modern British (ft.)	Double Lamps European versus European (ft.)
Nearside Object	+ 500	196	175
	+ 300	191	174
	+ 200	175	172
	+ 150	158	170
	+ 100	142	164
	+ 50	137	157
	0	134	145
	- 50	137	139
	- 100	153	152
Object in centre of road	+ 500	173	152
	+ 300	155	150
	+ 200	89	139
	+ 150	71	118
	+ 100	63	89
	+ 50	58	80
	0	73	82
	- 50	102	105
	- 100	136	--
Offside object	+ 500	136	112
	+ 300	60	< 50
	+ 200	50	< 50
	+ 150	50	< 50

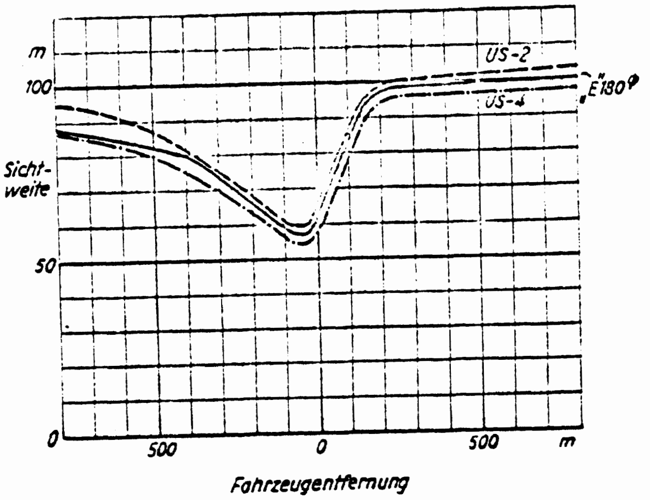

Figure 2.3. Seeing Distances Provided by European and American Headlight Systems for Targets on the Right Side of the Road. (From Lindae [1962])

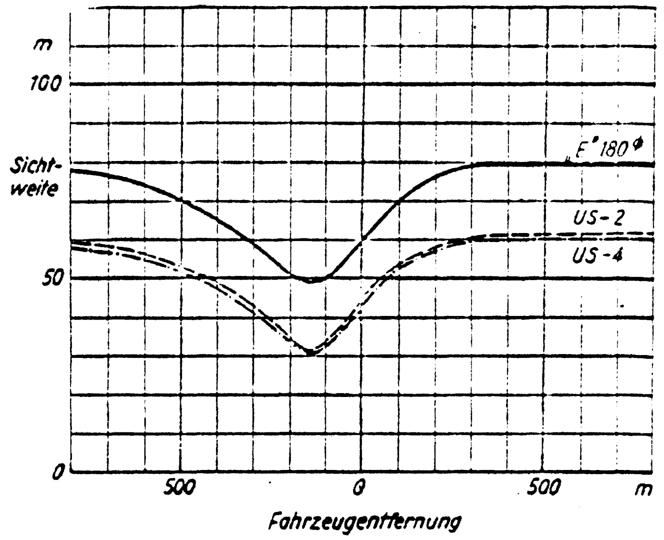

Figure 2.4. Seeing Distances Provided by European and American Headlight Systems for Targets on the Left Side of the Road. (From Lindae [1962])

The Psychological group at Uppsala in Sweden have reported several studies dealing with various problems in night visibility. The first comprehensive investigation of different types of headlighting to come from that group was reported by Johansson et al. in 1963.

Five studies were carried out. They included comparisons between high and low beams, symmetrical and asymmetrical headlamps, and different target reflectivities. The investigators used a semi-dynamic technique which was different from that usually employed, in that the criterion was the distance to a target at the moment it could no longer be seen by the subjects. The authors argue that this is a better way of assessing visibility distance than trying to measure the first moment that a target can be detected. The subjects were seated in a motor vehicle which was static throughout the study. A glare car was positioned ahead of them on the road. The subjects were asked to indicate the furthest targets that could be discerned without the headlights of the glare vehicle being on. The glare-vehicle headlights were then switched on and a new set of measures were taken. The glare vehicle then accelerated and drove toward the subject vehicle, the subjects being required to indicate the most distant target which they could discern as the glare vehicle approached.

The rationale Johansson gives for using the procedure described is that variance associated with the "surprise" appearance of a target is minimized. He argues that this makes it easier to distinguish between various test conditions. This is a debatable point. The major variance in a study of this type is associated with the level of confidence at which a subject will respond. This problem is no different for descending than for ascending format. Further, the use of a descending format will result in significantly longer visibility distances, which make it more difficult to compare these results with others.

Certain results of the Johansson et al. study could have been expected. For example, detection distances increased as target reflectivity increased. It was also found that visibility for objects on the near side of the road (right side in U.S.) were greater with an asymmetrical than with a symmetrical low beam. Results concerning visibility with high beams were somewhat surprising. These data indicate that high beams meeting high beams gave longer visibility distances throughout the meeting situation than did low beams meeting low beams. The measured visibility distances for low beams were about 25 meters maximum, 20 meters minimum. For the high beams, visibility distances varied from about 55 meters maximum to about 25 meters minimum. These results differ from those reported by other investigators and may be attributable to the different methodology employed.

Tests comparing the British headlighting system commonly used in the early 1960's with the asymmetrical European system of the same era have been reported by Fosberry and Moore (1963). The results were gathered using semi-dynamic tests similar to those used by Harris (1954), described earlier. The target was a board 18 inches high, having 7% reflectivity. Seeing distances for objects on the near side (right side for U.S. use) were quite similar for all units tested. The seeing distances to objects in the center of the road were quite comparable as well. The authors note: "with such very different beams, it is indeed surprising that, in terms of seeing distances, differences are only marginal."

One of the first tests of visibility distance provided by quartz-halogen European lamps compared to American sealed beams has been reported by Roper and Meese (1965). These tests were conducted using two vehicles, both of which were in motion at speeds of 40 mph. Targets consisted of 16" squares having 7% reflectivity set on the right side of the road. Subjects were instructed to indicate when they had detected the presence of a target by pushing a button. Figure 2.5 shows the results of this test. Relatively little difference was

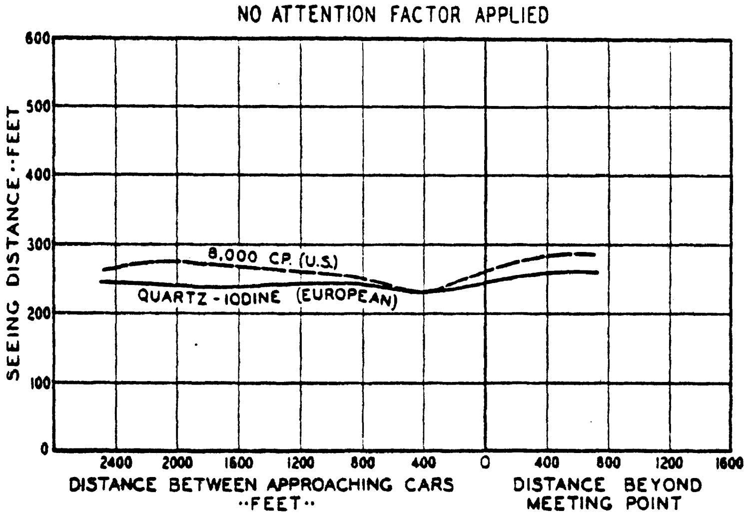

Figure 2.5. Seeing Distances to Targets on the Right Side of the Road Provided by American and European Low Beams. (From Roper and Meese [1965])

found between the two systems, perhaps 10% at maximum. However, the U.S. lamp was consistently better than the European, except at the maximum glare point.

In a study of the interaction of headlamps and fixed lighting, Faulkner and Older (1967) investigated various lighting conditions including British- and European-style low beams. The authors do not specify whether conventional tungsten- or quartz-halogen-sources were used in their European lamps. It is clear that the asymmetrical European pattern was employed. The target used in this study was unusual. It was four feet high, rectangular in shape and had on the top a circular portion with a projection on one side. The projection could be moved to various positions. The task given the subjects was two-fold. First they had to detect the presence of the target itself, and second they had to recognize the orientation of the projection. The results are reported in terms of detection and recognition distances. The target could be placed in any of six positions, ranging from 400 feet in front of the glare source to about 300 feet behind it. All runs were made facing identical headlamps.

The results indicate that the European beam produced generally greater detection distances than did the British low beam. These differences were greatest when the target was positioned just in front of and just behind the glare vehicle.

The recognition-distance data are different. In the first place, the recognition distances are about one-fifth as long as the detection distances. It was also found that the recognition distances were substantially greater for the British low beam when the target was positioned in front of the glare vehicle and somewhat greater for the European low beam when the target was positioned behind the glare vehicle.

The study by Faulkner and Older raises an interesting question about the criteria employed in headlighting studies. As was noted earlier, detection distance is the usual way in which headlight performance is measured. However, simply detecting an object may not be enough. It is also necessary for the driver to identify an object sufficiently well to determine whether it constitutes a problem or not. The extent to which this identification-decision process can be simulated in an artificial experiment is questionable. It remains one of the unresolved (and largely unexplored) issues in headlighting research.

The first experimental comparison between conventional tungsten and quartz-halogen European beams was reported by Rumar (1970). This study was carried out using a semi-dynamic procedure. A static glare car was employed, with the subjects being driven down a two-lane road toward the glare car. A target-detection criterion was used. The subjects were required to press a button when they detected relatively small, 4% reflectance targets placed along the right edge of the road. The results indicated that the new halogen lamps on high beam produced about a 25% improvement in visibility distance. When meeting other cars with low beams the halogen lamp was still superior to the conventional tungsten lamp.

In a general article concerning problems of night visibility, Christie and Moore (1970) make reference to experiments carried out at the Road Research Laboratory in Great Britain comparing the relative merits of European-and British-style low beams. In an apparent reference to the work of Faulkner and Older mentioned earlier, Christie and Moore claim that the European quartz-halogen headlamp is to be preferred for all conditions of roadway lighting, _if_ good aiming can be ensured. This is an important condition. The authors recognize that there are substantial difficulties in maintaining headlamp aim under all driving conditions. The paper goes on to discuss various ways of improving headlight aim, including devices which compensate automatically for changes in vehicle attitude.

The Southwest Research Institute has conducted a number of headlighting studies. Their purpose was to measure the performance of present-day lighting systems and recommend improvements. This work has been summarized by Hull, et al. (1971). The conditions under which the tests were conducted used two cars on a straight, flat road with both experimental and glare cars in motion. The results, for a 7% reflectance, pedestrian size target set on the right edge of the road, are summarized in Table 2.3.

The high beam comparisons are not surprising, given the fact that there is a substantial intensity difference between the two systems. The comparison between the low beams indicates that, for the conditions tested, seeing distance differences are minor.

One of the most interesting reports in recent years comparing various low-beam headlighting systems is by Rumar, et al. (1973). This was a semi-dynamic simulation in which the subjects rode in a car which was driven toward a stationary glare vehicle positioned in the center of the left lane. The distance at which the subjects could detect dark obstacles placed along the right edge of the road was measured. For no-glare situations, the results indicate that a European high beam provided approximately 15% more visibility distance to the test object on straight roads, while on sharp curves differences between European and U.S. high beams are negligible. For low beams, the results indicate that on straight roads a U.S. low beam provided greater glare and, as a consequence, somewhat less seeing distance (about 10%) than a European beam. It was also found that a U.S. low beam provided a greater percentage increase in visibility distance than a European low beam as target reflectivity was increased. On curved roads the two low beam systems gave roughly the same performance, except for sharp curves to the left, where a U.S. low beam provided somewhat better visibility.

This report, coming from an organization which has done much careful work on headlighting over a period of years, and from a country (Sweden) which uses the European system, has added fuel to the controversy concerning European and U.S. low-beam patterns, since its authors infer a substantial superiority for the U.S. low beam. In this respect, the report differs from other reports

TABLE 2.3. Visibility Distances Measured for Two Headlamp Systems Based on Tests Carried Out at Southwest Research Institute. (From Hull, et al. [1971])

Test Conditions	Low Beams		High Beams	
	U.S.	European	U.S.	European
Facing Glare Car with Identical Lamps	362	356	328	428
Unopposed	434	417	811	1,023

Distances are in feet.

comparing European and American headlighting with which the authors are familiar. However, an explanation may be found in photometric data for the test lamps. Isocandela diagrams provided in the report show that the European lamps selected (at least the one which is presented in the figure) had an output close to the minimum prescribed, while the American unit shown had specifications which were at or exceeded the maximum allowed under SAE regulations. Additionally, for some reason, the maximum intensity point of the European unit was oriented more than 3^0 to the right instead of between $1\text{-}2^0$, as indicated in the specifications. The maximum intensity point of the American unit was also aimed somewhat down and to the right relative to the specifications, but the high-intensity zone was least near the edge of the roadway.

Assuming the second lamp in each pair was approximately the same as the one for which isocandela diagrams are provided, it is questionable whether the test described by Rumar et al. can be truly characterized as a comparison of U.S. versus European beam patterns. It was more a comparison of different beam intensities.

Ohlon and Zaccherini (1972) have reported a follow-up of the Rumar et al. paper just described. They performed a mathematical analysis of the seeing-distance data in an effort to determine why the observed differences came about. The authors accomplished this by analyzing the illumination directed down the road at various heights above the roadway surface and correlated luminous intensity with seeing distance. It was found that the maximum correlation between these values occurred at a height corresponding approximately to the top of the one-meter-tall targets used by Rumar et al. The authors conclude that the superiority of the U.S. beam in these tests is attributable to light emitted just below the horizontal. On a basis of these observations the authors recommend a new passing-beam design. A rough approximation of this may be visualized by taking a typical European low beam and shifting it somewhat to the left.

The headlighting research program carried out at the Highway Safety Research Institute of the University of Michigan was one of the most comprehensive to date (e.g., Mortimer and Olson, 1974). It was divided into three phases. In Phase 1, field test data were collected utilizing fully dynamic simulations. Variables tested included headlamp beam, speed, lateral separation and target reflectivity. These results were used to aid in the development of a computer seeing distance model in Phase 2. In Phase 3, the model was validated by creating new beam patterns and verifying that the model was capable of predicting the visibility distance which they provided.

The targets used in the HSRI tests were different from those used in any other similar program. It posed an identification task to the subjects, rather than simple detection. This was done primarily because pilot testing determined that such a target reduced the experimental variance. No interaction effect of beam and target type was noted, such as reported by Faulkner and Older (1967). The target also had its own background. This had the important benefit of preserving target contrast regardless of the actual environmental or position on the road.

A number of different lighting systems were tested in various phases of the program. The results indicated that a three-beam system would be optimum. It would consist of a low beam having a flat top sharp cutoff like the old style European low beam; a mid-beam which adds a relatively powerful spot lamp like pattern to the right side; and a European style high beam.

Mid-beam systems were held as a promising improvement in headlighting for some time. The major problems are:

1. Technical difficulties in trying to get three beams from a two-lamp system.
2. Practical difficulties in potential abuse or confusion resulting from the greater complexity of the switching system.

Because of these problems recent research in headlighting has been directed back to more conventional channels, trying to find a better compromise for the meeting beam.

One of the most significant and comprehensive headlighting research efforts in recent years has been carried out at Ford Motor Company (Bhise, et al. 1977). In the first stage of this effort a seeing-distance model was developed, somewhat like the one developed at HSRI. The model was validated in a variety of situations to ensure that the visibility distances predicted corresponded to those measured in actual driving situations. A computer simulation of a "standardized test route" was then developed, over which cars could be "driven" with any headlighting system of interest. The test 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, as well as glare from fixed lighting and traffic. The authors feel that the standardized test route is a representation of a typical American night-driving environment. It is based on a series of field surveys which covered thousands of miles of actual highways.

When various headlighting systems are run through the standardized test route, the model outputs a figure of merit. This figure of merit is the percentage of the distance traveled by the simulated driver on the standardized test route in which the seeing distance to pedestrians and pavement lines and the discomfort-glare levels experienced by opposing drivers simultaneously meet certain acceptance criteria.

As a final step in the Ford program a large number of different lighting configurations were tested. It was found that the figure-of-merit output of the model differed very little, indicating that various headlighting systems produce basically the same performance. What the research seems to show is that driver visual performance on the highway at night is more sensitive to environmental conditions and the driver's visual capability than to the range of characteristics exhibited by existing and proposed headlighting systems. This work suggests that no significant advances in night visibility can be expected through changes in headlighting technology of the usual sort. Only by solutions such as that potentially available through the use of polarization can significant improvements in night visibility be brought about.

As had been noted already, every research effort in the field of vehicle headlighting has relied on seeing-distance criteria using subjects who were fully alerted to the nature of the test and the response expected from them. There are two major problems with this approach which have concerned individuals trying to do research in headlighting. One of these problems is fairly obvious. The fully alerted subject will "detect" a given target at a substantially greater distance than would be expected of a person under normal driving conditions. This fact was clearly demonstrated by Roper and Howard (1938), who found that identical targets were detected at twice the distance when the subjects were looking for them as compared with a situation where the subjects were not aware of the fact that there was a target in front of them.

The other problem is a bit more subtle. Little is known about the nature of the information which is required in order to successfully operate a motor vehicle, or the way which it is secured and utilized. It may well be that there are aspects of headlamp performance which are of consequence but which are overlooked in the traditional headlighting experiment. While these are very real problems, there is no easy way of resolving them.

A promising new approach was attempted recently by the Honeywell Corporation (Graf and Krebs, 1976) under contract to the National Highway Transportation Safety Administration. Honeywell has developed an eye-fixation-recording device which can be mounted in an automobile and operated so that it is possible to keep the subject unaware of the fact that eye fixations are being recorded. Graf and Krebs used this machine in a study which attempted to measure the detection distance of objects which appeared normal to the roadway environment (roadside junk, mailboxes, signs, man-sized dummy). The subjects were not aware of the true purpose of the study. Thus, it was thought that eye-fixation patterns and detection distances should be representative of what happens in the real world. A wide variety of headlighting systems were utilized, ranging from standard U.S. and European low beams to very powerful high beams.

Graf and Krebs report no significant differences in target detection distance as a function of the various headlighting systems employed. Given the range of patterns and intensities included, this result is unexpected and quite different from data collected in other studies using similar lamps. However, Graf and Krebs argue that these results are realistic, due to the unalerted state of their subjects.

It may be that Graf and Krebs are correct, that there is no relationship between headlamp intensity and target-detection distance. This implies that a great deal of time, effort and money has been wasted trying to develop improved lighting systems over the years. It also implies that much strategy regarding improvements in visibility while driving at night needs to be revised.

However, the present authors feel that it would be a serious error to accept the results of the Honeywell study without further verification. There are two major problems:

1. The results are contrary to expectations concerning the performance of the human perceptual system based on great numbers of studies carried out under laboratory and field conditions. Altering the intensity of vehicle headlamps will produce predictable changes in target luminance and contrast characteristics. It is not clear why the response levels expected based on these other studies should be completely upset simply because the subjects were not aware of the data being taken.

2. Because "detection" had to be inferred from eye fixation patterns, Graf and Krebs faced a formidable problem in the data analysis phase. They decided that continuous fixation within $\pm 1^{\circ}$ of the target for seven or more video frames (115-120 milliseconds) would be taken as evidence of detection. This is a rather arbitrary definition. More important, it assumes that the entire, complex process of information acquisition while driving is a simple "go-no go" proposition, i.e., targets are either detected or not detected. This is probably not an adequate model. It seems reasonable, for example, that the search strategy and the importance attached to objects near the road would change depending on the field of view afforded. Thus, a driver could become aware that "something" is ahead, alongside the road, at a great distance on high beams. However, since the "something" appears to pose no problem it may be given little attention until later.

2.1.3 Conclusions. As will be clear from the preceding summary, a great deal of work has gone into the issue of improving low beam headlighting. It should also be clear that there is still much disagreement among investigators regarding beam intensities and distribution. The chief obstacles to agreement in the future are:

a. Lack of an agreed-upon criteria for headlighting effectiveness.

b. Lack of agreement concerning glare levels, especially as it invokes discomfort glare.

c. Difficulties in balancing conflicting situations brought about by changes in road geometry.

2.2 Human Visual Performance and Nighttime Driving

2.2.1 Introduction. Under ideal conditions the human eye is remarkably light sensitive. If the following conditions hold, an observer can detect a flash of light containing only 90 quanta of light 60% of the time (Hecht, et al., 1942).

a. the observer is fully dark-adapted, and

b. the stimulus flash is presented 20^0 nasally from the fixation point, and

c. the size of the flash is 10', and

d. the duration of the flash is 1 msec, and

e. the color of the flash is green (510nm), and

f. the observer is asked to pay attention only to detecting the flash, and

g. the stimulus flash to be detected is presented in an otherwise dark field.

In comparison, "a typical lighted flashlight bulb radiates about 2 x 10^{15} quanta every millisecond (Cornsweet, 1970, p. 25)."

However, conditions outside research laboratories are always less than ideal. In the situation at hand (an automobile driver during nighttime),

a) the driver is generally not fully dark-adapted (Cole, 1972; Schmidt, 1966),

b) the location of the relevant targets is generally unpredictable within a rather large area,

c) the size of the relevant targets covers a wide range,

d) the color of the relevant targets covers a wide range,

e) the driver is occupied with several other simultaneous tasks (e.g., controlling the vehicle, conversing with passengers, listening to the radio, daydreaming, etc.), and

f) a variety of targets compete for the driver's attention as well as constitute potential glare sources.

It is then not surprising that the actual nighttime visual performance of drivers is substantially worse than under the ideal conditions created in the laboratory. Therefore, headlighting systems are employed to provide sufficient level of illumination to perform the driving task safely and efficiently. The remainder of this section deals with the following relevant issues affecting the design of an efficient headlamp: nighttime vs. daytime vision, glare, and age of the observer.

2.2.2 Nighttime vs. Daytime Vision. The human visual system is a highly adaptive mechanism. Vision operates, to one extent or another, over a nearly 11 log unit range of background luminance level (Cole, 1972). To handle this wide variety of luminance conditions, the human retina contains two types of light sensitive receptors: rods and cones. The two classes of receptors compliment each other in their capabilities. Cones mediate vision under moderate- to high-luminance levels (mesopic and photopic conditions[1]) which include day and most of night driving situations (Cole, 1972; Projector and Cook, 1972; Schmidt, 1966) while rods mediate vision under low luminance levels (scotopic conditions), but contribute to mesopic vision as well.

Dark adaptation (regeneration of light sensitivity after exposure to bright light) follows a different time course for cones than for rods. Two aspects of the dark adaptation are of interest here. First, the regeneration of cones is essentially complete in about 5 minutes, while it takes about 25-30 minutes of darkness for rods to reach the assymptotic value. Second, there is crossover between the absolute sensitivities of rods and cones. For the first 7-8 minutes after exposure to a bright light, the cones are more sensitive than rods, while after that period of time in darkness the rods become more sensitive than the cones. Since the average night driving entails frequent exposures to headlights of oncoming traffic, complete dark adaptation is rarely attained by drivers, thereby further extending the range of driving situations where cones are more sensitive than rods.

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[1] Scotopic conditions: 10^{-6} - 10^{-3} cd/m^2,
Mesopic conditions: 10^{-3} - 10^{1} cd/m^2,
Photopic conditions: 10^{1} - 10^{5} cd/m^2 (Cole, 1972).

The cones are responsible for color vision. While color-vision threshold varies with duration of exposure, the size of the target, and the particular color (Connors, 1968; Connors, 1969), as a rule of thumb a value of .04 ft-L (.14 cd/m^2) is sometimes taken as a limiting luminance for reliable color vision (Richards, 1968). In general, color vision is degraded at intermediate mesopic levels and is absent at low mesopic and scotopic levels.

Visual acuity (the ability to resolve small details) varies as a function of the luminance level. The best visual acuity is reached at high- or intermediate-luminance levels and the poorest at low-luminance levels (Cole, 1972; Richards, 1967). For example, at the luminance level of 1 cd/m^2 the smallest resolved visual angle is around 250 microradians, while at .1 cd/m^2 it increases to about 500 microradians (Moon and Spencer, 1944). It follows that a detail which can be distinguished during the day might be below acuity threshold at night.

Contrast sensitivity (sensitivity to simultaneous luminance differences) varies with the background luminance (Blackwell, 1972; Richards, 1967; Wright, 1976). As the luminance level (L) of the background decreases, there is an increase in $\Delta L/L$, the luminance difference threshold expressed as a proportion of the background luminance. Consequently, a target which during the day can be distinguished from its background on the basis of luminance contrast alone, can become indistinguishable from its background in the night.

Other visual/perceptual skills which deteriorate with a decrease in luminance level are estimates of size, distance, and speed (Wright, 1976), resulting in less veridical judgments during the night than during the day.

2.2.3 Glare. Low luminance levels create ideal conditions for glare, which occurs if the luminance of a light close to the line of sight is substantially above the luminance of the background. Since the ambient luminance level is low during the night, any intense source of light (e.g., headlights of oncoming cars) has the potential of becoming a glare source.

Glare can have psychological effects (discomfort glare) evident in reports of discomfort or annoyance, and performance effects (disability glare) evident in decrements in visual performance. While discomfort glare is primarily due to the intensity of the light source, disability glare "is caused by scattering of light within the eye so that a veiling of light is superimposed over both the task and the background, effectively raising background luminance and reducing contrast (Cole, 1977, p.1)." In addition to the scatter caused by the structure of the eye, additional scatter is the result of the light traversing automobile windshields (Allen, 1969, 1974) and spectacle lenses (Cole, 1977). Cones possess a certain level of protection against disability glare, since they are maximally sensitive to light incident along their main axis and are substantially less sensitive to light falling obliquely (as the scattered light does). On the other hand, rods are less directionally sensitive, contributing to the nighttime susceptibiliy to glare (Cole, 1977).

There is no general agreement on the interrelation between disability and discomfort glare. For example, Schmidt (1966) argues that "all disability glare is also discomfort glare, but glare can cause discomfort without impairing visual functions (p. 12)." However, there is also evidence (Mortimer & Olson, 1974) that disability glare can occur without discomfort glare.

Several attempts have been made to obtain guidelines for prevention of discomfort and disability glare. Schmidt-Clausen and Brindels (1974), for example, developed a general formula for assessing discomfort glare taking into account glare illuminance, adaptation luminance, angle of glare, and number of glare sources. Similarly, Hartman (1963) has computed the maximum source illuminances not causing disability glare for different glare angles and background luminances.

2.2.4 Age of the Observer. One of the major factors contributing to individual differences in visual performance is the age of the observer. The human eye undergoes several anatomical changes as it ages. For example, the pupil size decreases (Birren et al., 1950), the lens becomes yellow (Weale, 1963) and cataracts become more frequent (Duke-Elder, 1969).

As a consequence of these and other anatomical changes, there are decrements in a range of visual capabilities associated with advanced age: Dark adaptation is less efficient (Robertson & Yudkin, 1944), visual acuity worsens (Zerbe & Hofstetter, 1958), the size of the active visual field decreases (Burg, 1968), sensitivity to short wavelengths decreases (Crawford, 1949) and susceptibility to glare increases (Wolf, 1960).

2.2.5 Conclusions. In summary, a decrease in the luminance level at night results in deterioration of color vision, a decrement in visual acuity, reduction in contrast sensitivity, and less verdical size, distance, and speed estimates. It is obvious that providing more illumination would compensate (at least in part) for these nighttime decrements in human visual performance. An increase in illumination, while beneficial to all observers, would have the most profound effect on marginally-performing individuals (e.g., a large proportion of the elderly). On the other hand, these benefits have to be weighed carefully against the detrimental effects of glare. The problem of providing more light for improvement of a variety of visual functions and at the same time avoiding glare is the main design problem of headlighting research.

2.3 An Analysis of the Nighttime Driver's Visual Field

Given the potency of the glare-illumination trade-off, beam patterns should be designed to illuminate areas of the driver's field of view where critical targets are, and keep illumination to a minimum in areas that produce glare to other drivers. Our analysis of the nighttime driver's visual field thus sought to:

- identify critical targets (i.e., those that must be seen) for nighttime drivers

- determine the locations of the critical targets for clues about what areas of the driver's visual field must be illuminated.
- determine what areas of the field of view lead to increased glare, for clues about areas of the driver's visual field where illumination should be reduced.

Headlighting is a complex subject area, in the sense that a great number of variables must be considered. In any project of reasonable scope the investigator must choose which of these variables to emphasize. In this case a decision was made to concentrate on defining the location of critical targets and designing beams to illuminate them under relatively straight road conditions. The authors recognize that this approach leaves much ground yet to be covered. However, it was felt that this was a reasonable first step. If the results are promising, further work is justified.

2.3.1 Critical Targets and Their Locations in Nighttime Driving. To complete the tracking task of driving, drivers must see delineation. Signs provide information for decision-making and guidance. Pedestrians, animals, parked or stalled vehicles, debris, and potholes must be seen to be avoided. To adequately drive at night, drivers must see the targets listed in Table 2-4 in sufficient time to react.

Knowing where critical targets fall in the driver's field of view, will aid in designing a beam to effectively illuminate them. Bhise et al., (1977) analyzed where pedestrians were located just prior to being hit by a driver at night. Figure 2.6 shows their results: the regions of the beam pattern where pedestrians must be seen to be avoided, and hence areas where light should be directed. No available data, usefully locate stalled or parked vehicles prior to nighttime crashes. However, it is probably reasonable to assume that they would most likely be in the pathway of the vehicle or off to the right side.

TABLE 2.4. Critical Targets in Nighttime Driving.

TARGET	PURPOSE
Delineation and roadway contours	Perceptual input to tracking task
Signs	Information for route guidance, decision making, warning, etc.
Pedestrian/animals	Avoidance
Parked or stalled vehicles	Avoidance
Debris on road/potholes	Avoidance

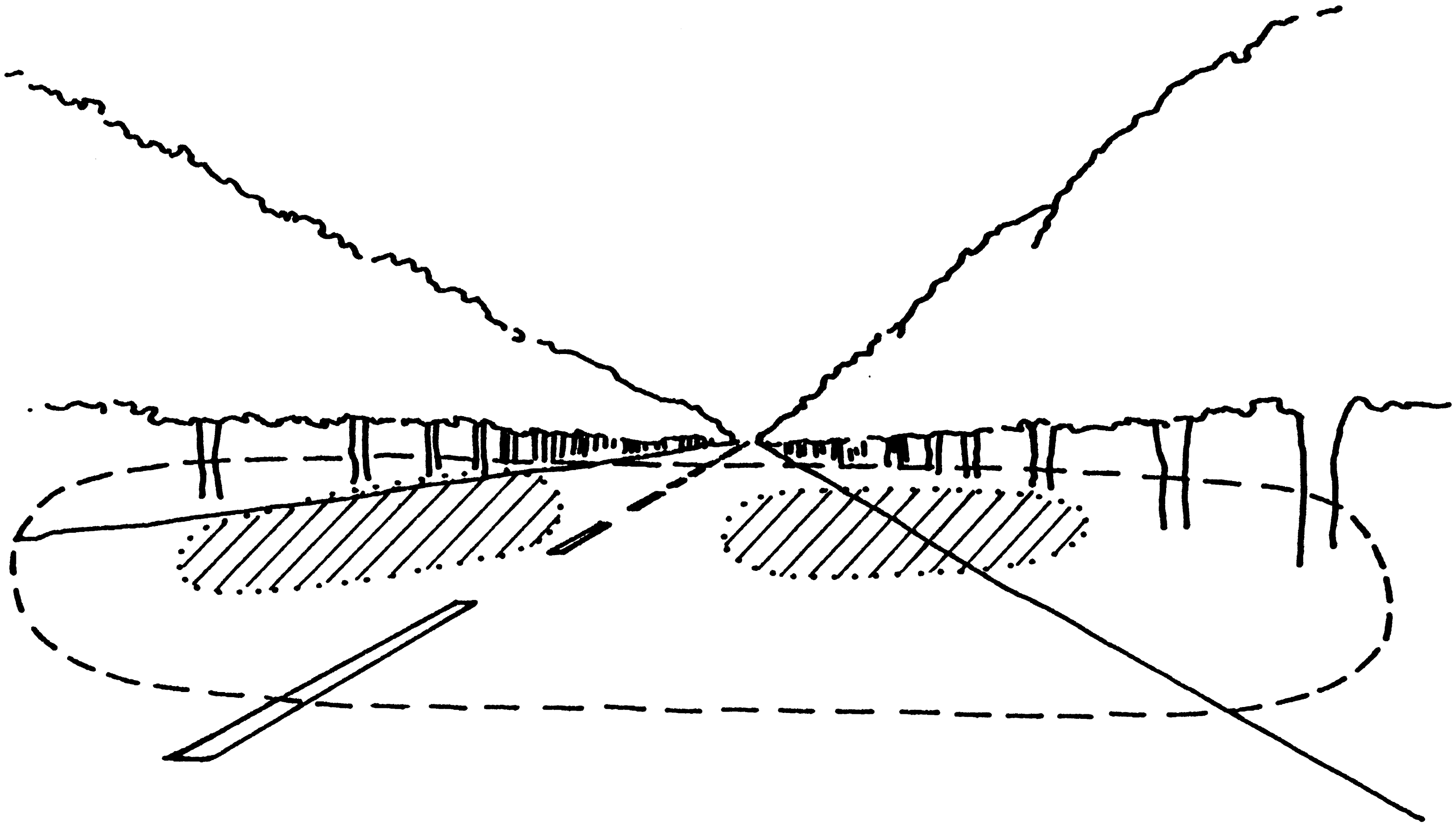

Figure 2.6 Illumination requirements for pedestrian avoidance. The region inside the larger ellipse is where between 1 and 2 percent (per square degree) of all acident-involved pedestrians are located 5 seconds before inpact. The cross hatched ellipses locate regions of between 2 and 20% (per square degree) density. This figure is based on data reported by Bhise et al. (1974).

Figure 2.7 represents the region of the driver's field of view that signs, requiring nighttime headlamp illumination, are likely to fall (Hanson & Woltman, 1967). It shows the areas the beam pattern should effectively illuminate for adequate sign reading.

Figure 2.8, based on the distribution of eye placements in vehicles, shows the region in a driver's field of view where oncoming driver's eyes are likely to fall. Excessive illumination placed in this region produces glare for oncoming drivers. To avoid glare, beams should not excessively illuminate this region.

2.4 Conclusion: The Composite Picture Indicates Three Possible Ways to Add Nighttime Illumination

Figure 2.9 shows the composite of Figures 2.6 through 2.8 along with the isocandela curve of a SAE 6014 low beam. The composite shows the following steps might improve nighttime illumination in comparison to the current 6014 low beam.

- Illuminate more up and to the right, keeping the beam within the driver's lane.
- Illuminate more to the left, but under the oncoming driver's region of sight.
- Combine the two described above, i.e., illuminate more to the right and up, and down and left.

We call these three concepts, respectively, more illumination to the right, more illumination to the left, and more illumination to both the left and right.

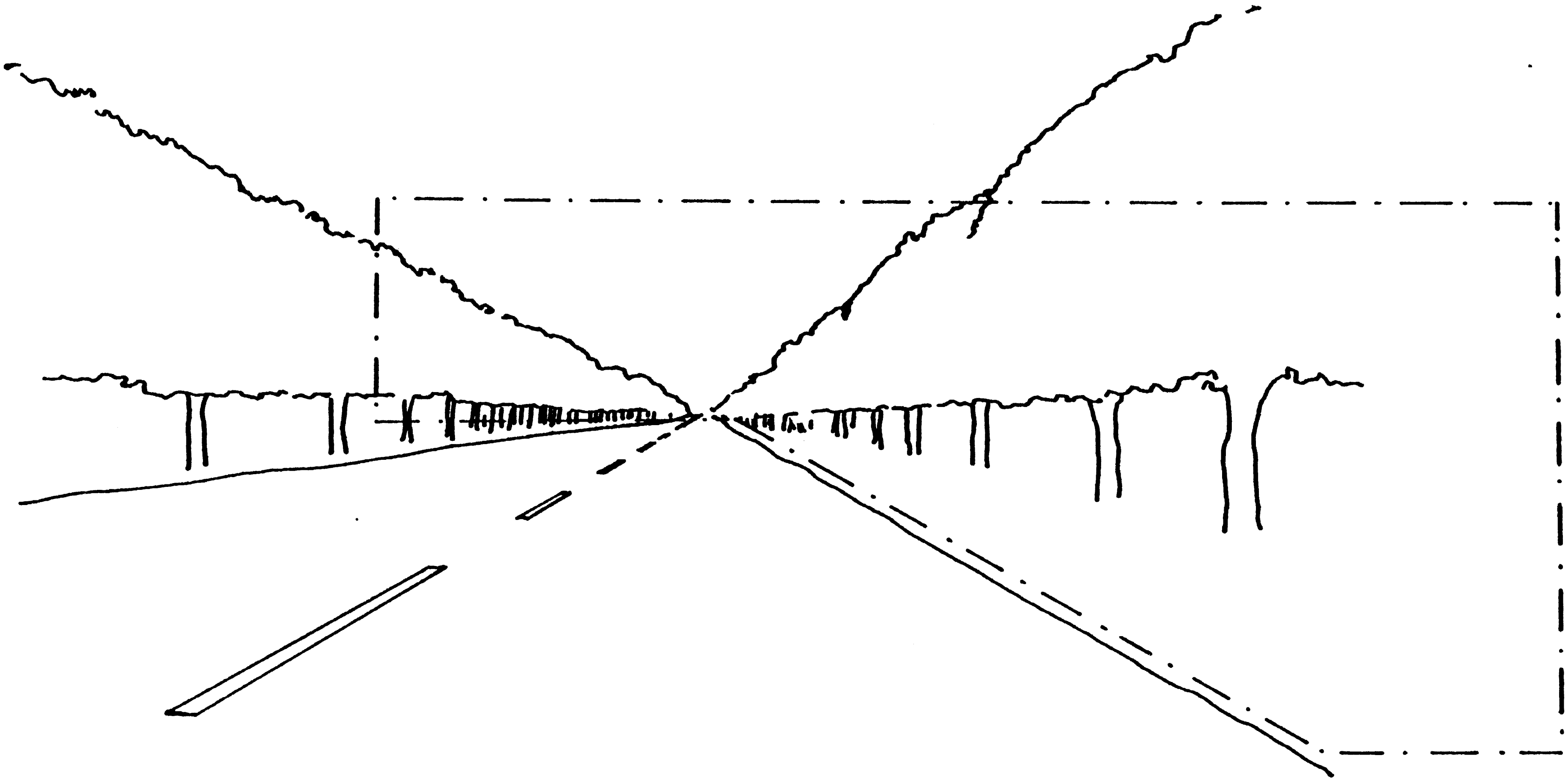

Figure 2.7. Illumination requirements for sign detection. Most signs fall in the region outlined by the dashed line.

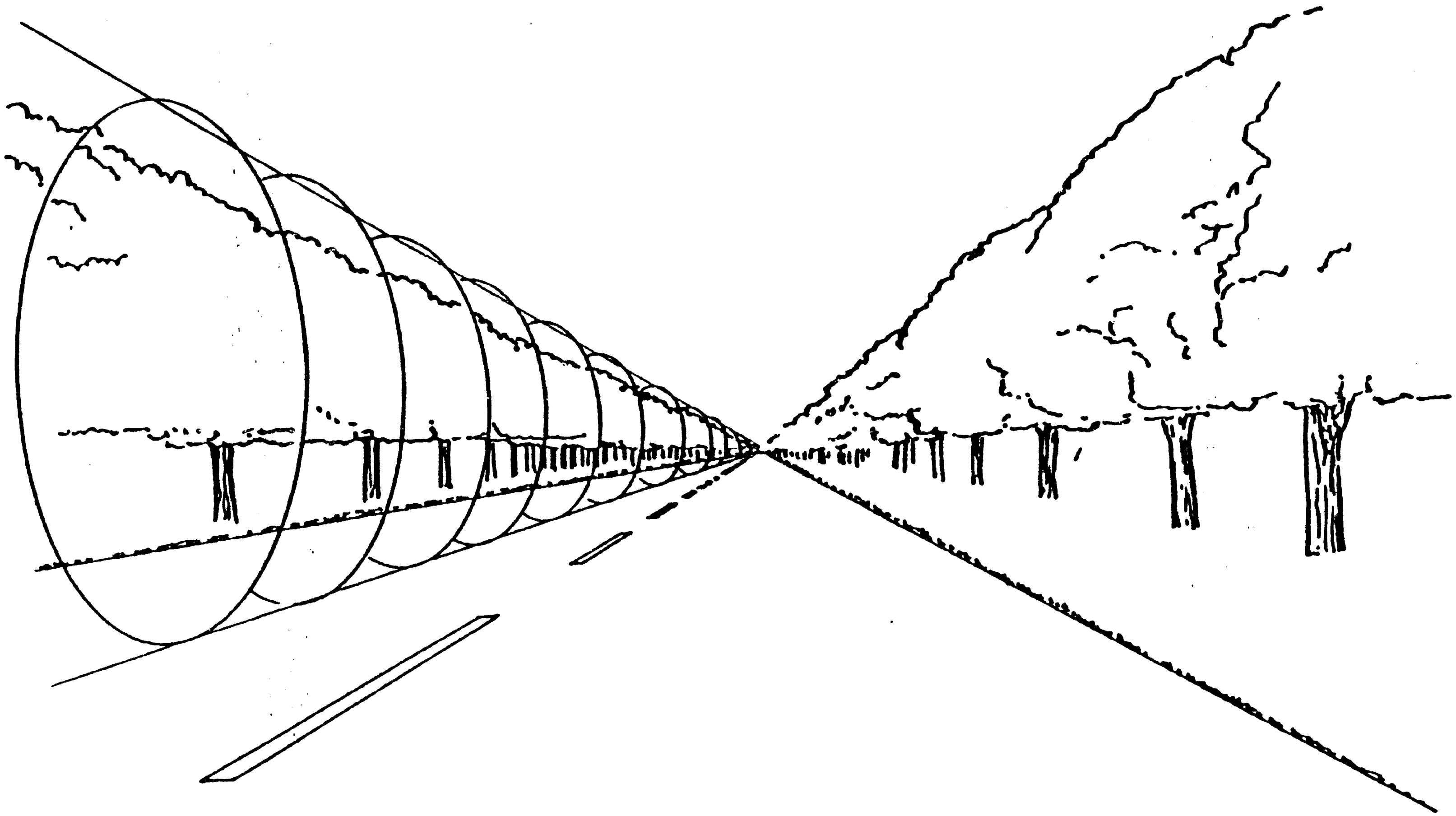

Figure 2.8. Region of oncoming drivers' lines of sight. Most oncoming drivers' eyes will fall in this conical region.

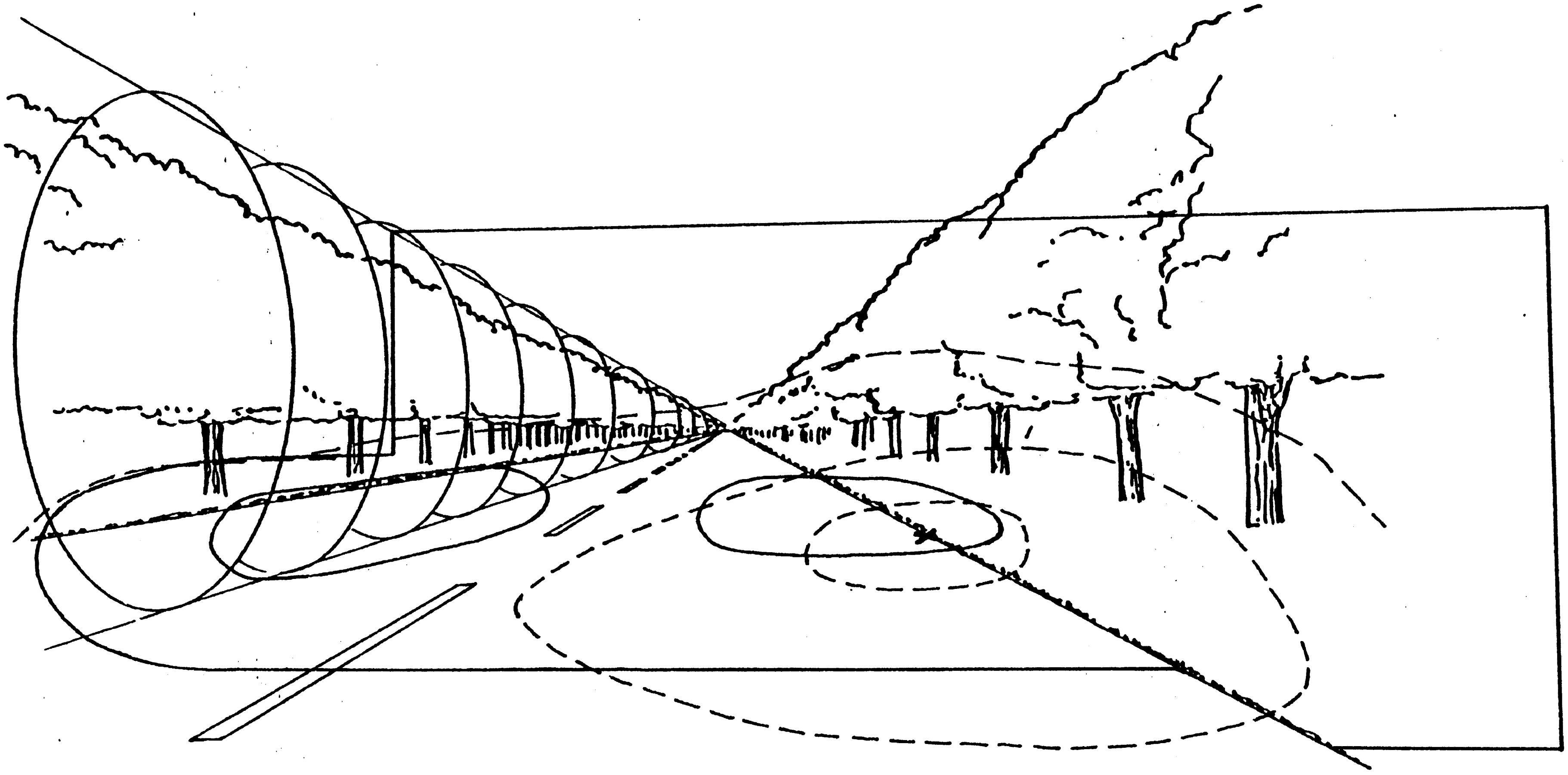

Figure 2.9. Composite of illuminate requirements with projection of 3 isocandela contours (20,000; 5,000; and 500) for 6014 low beam. This cone represents the oncoming drivers line of sight, the inner ellipses are areas of dense pedestrian concentration. The outer boundary includes both pedestrians and signs.

3.0 ALTERNATIVE BEAM PATTERN EXAMPLES FULFILLING THE ILLUMINATION REQUIREMENTS

This section describes examples of beam patterns that fulfill the illumination requirements outlined in Section 2. Both HSRI staff and headlight-industry experts worked on developing the alternative beams. HSRI staff aimed to modify the current SAE low beam and high beams to fulfill the illumination requirements. In developing their example single-beam patterns, industry experts worked from current U.S. high and low beams, current European low beams, and the mid-beam of the 3-beam system considered in the U.S. during the late 1960's and early 1970's.

Since much of the design work stemmed from the current U.S. low beam, and since it served as a standard in the experimental evaluation, we will first compare it with the illumination requirements. Figure 3.1 shows the isocandela contours for a 6014 low beam lamp. (It is recognized that an automobile has at least two lamps. For purposes of clarity, comparisons here will be made using selected isocandela contours from a single lamp.)

Figure 3.2 shows the 6014 beam pattern projected on the illumination requirements of Figure 2.4. Areas of dense pedestrian concentration, in both the right and left halves of the field of view, and signs appear not to be completely illuminated. The figure indicates the low beam might be improved by illuminating farther down the road to the right, picking up both pedestrians and signs, and to the left, but staying out of the oncoming driver's lane.

HSRI and industry developed seven examples of each of the three isocandela concepts. These are labeled A through G respectively. We now discuss each example. To provide continuity, we retain the beam-labels as originally assigned throughout the remainder of the report.

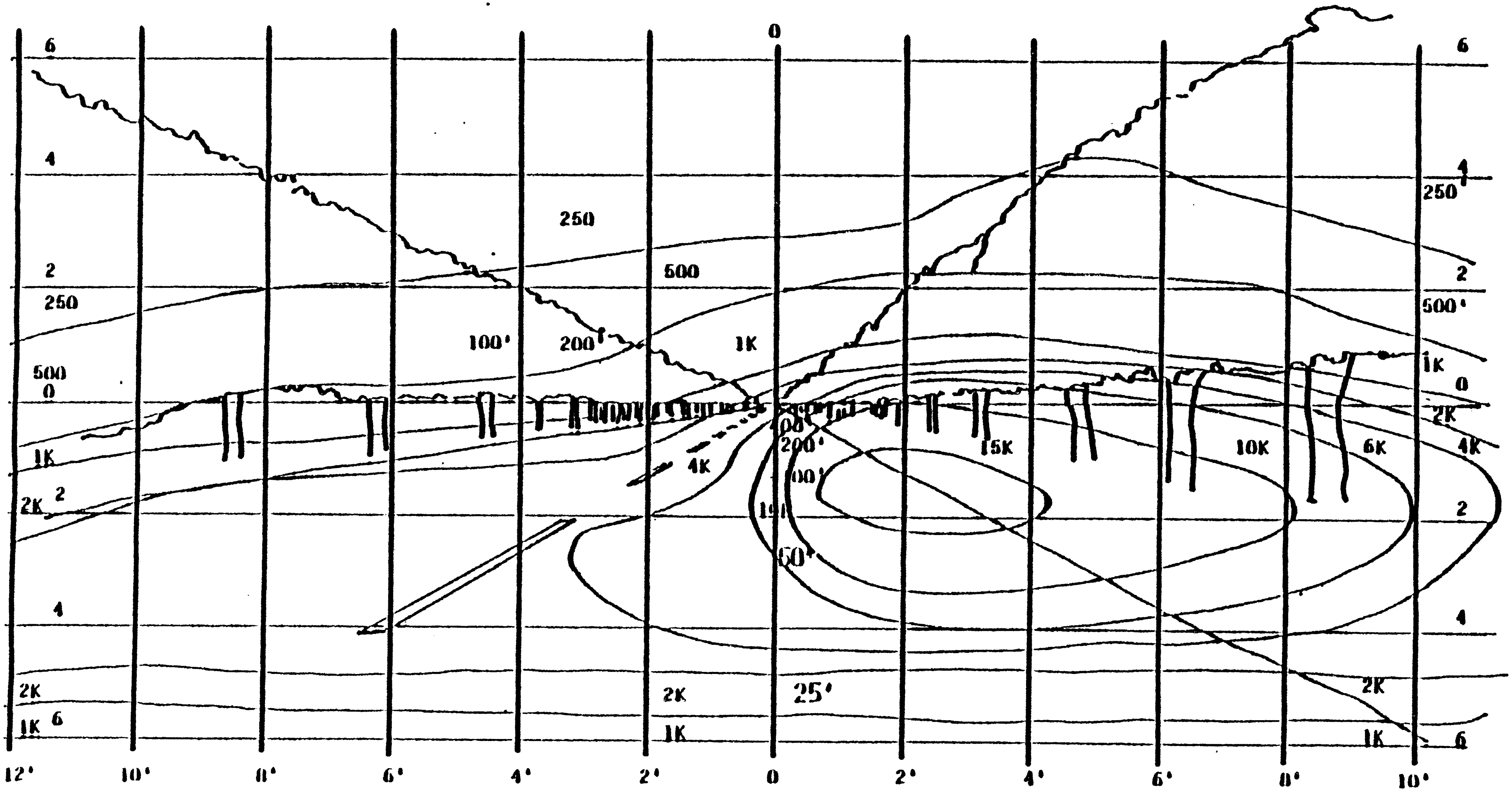

Figure 3.1. Isocandela contours of typical 6014 lamp. Grid marks are at 2° intervals.

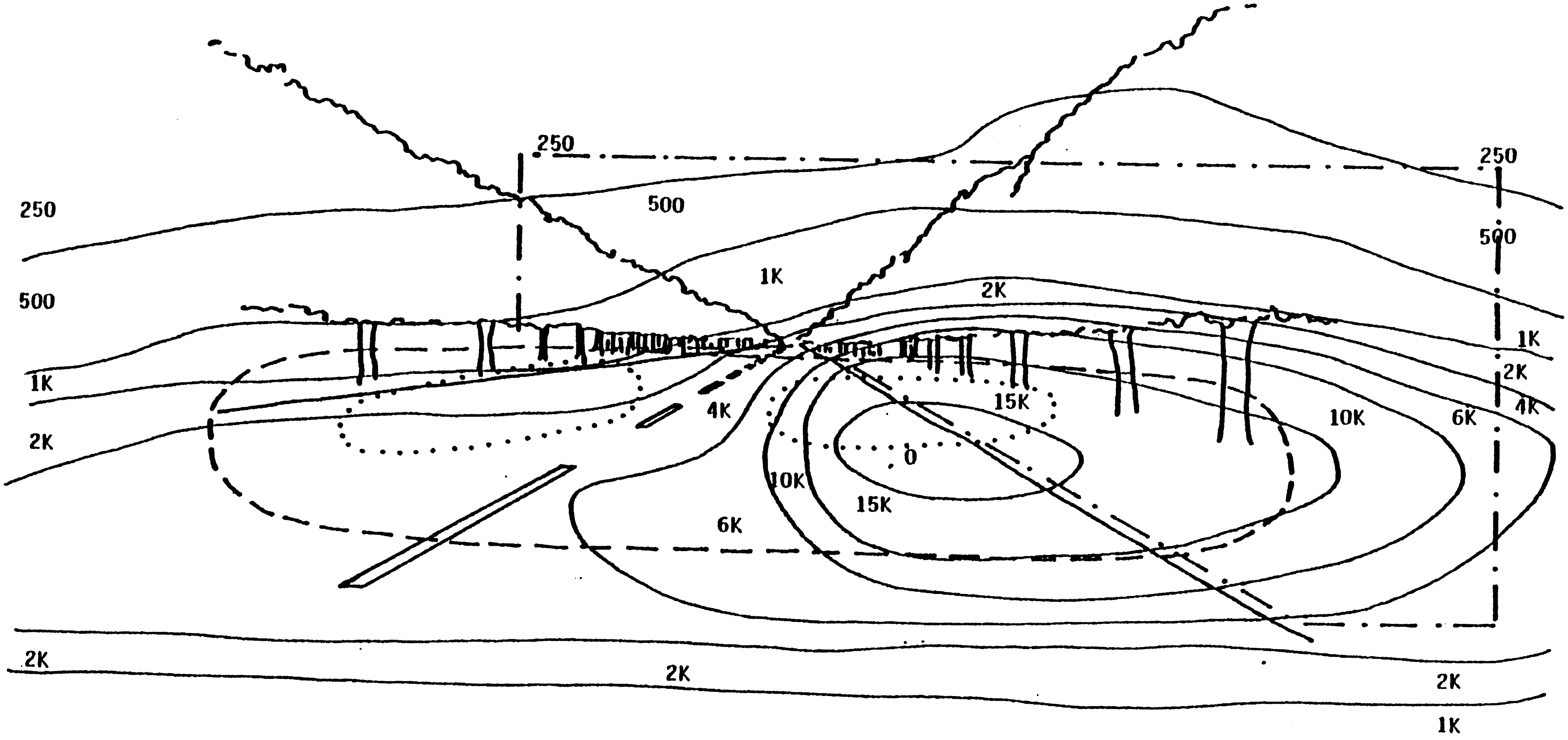

Figure 3.2. 6014 isocandela diagram from Figure 3.1 projected onto illumination requirements printed in Figure 2.4

3.1 More Illumination to the Right and Down the Road

HSRI and industry experts created four examples of this single-beam concept. Systems C, E, F, and G all project more illumination than the current low beam in the area down the road and to the right.

Figure 3.3 shows the isocandela contours for system C projected onto the illumination requirements. It shows fairly good coverage of pedestrian and signs.

Figure 3.4 shows system E's isocandela contours. It's hot-spot aims more towards center. Figure 3.4 shows system E aims somewhat above the pedestrian concentration, but affords adequate coverage of signs.

Figures 3.5 and 3.6 shows the isocandela contours for system F. System F is a three-lamp, mid-beam system. Two of the lamps, one of which is represented in the Figure 3.5, are standard low beams. Figure 3.6 projects system F's third lamp, a mid-beam, onto the illumination requirements. It shows system F illuminates the pedestrian and sign areas very well.

Figures 3.7 and 3.8 show the isocandela contours for system G, a two-lamp assymetric system. Both lamps illuminate the right pedestrian and sign areas fairly well, and the right lamp provides some illumination to the left pedestrians.

Table 3.1 shows some photometric statistics on systems C, E, F, and G. The statistics include the hot-spot location, the candela value at the hot-spot, and the average candela value in a standardized grid[1] around the hot-spot.

Of the example systems directing more light to the right, systems F and G are most intense, and project more illumination in areas of

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[1] The standardized grid had 63 points at half-degree resolution within ± 2 degrees horizontal and ± 1 degree vertical of the hot-spot.

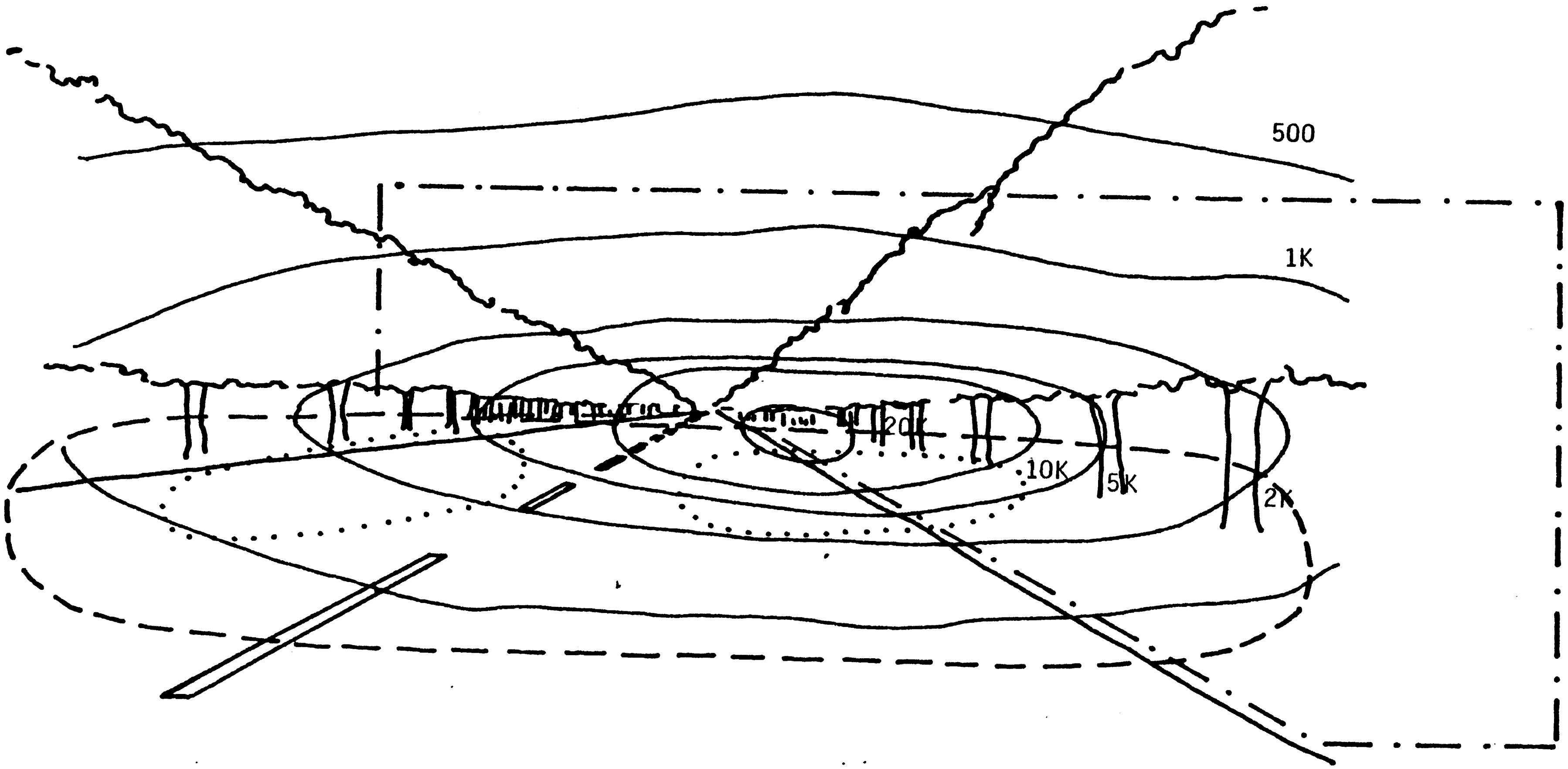

Figure 3.3. System C.

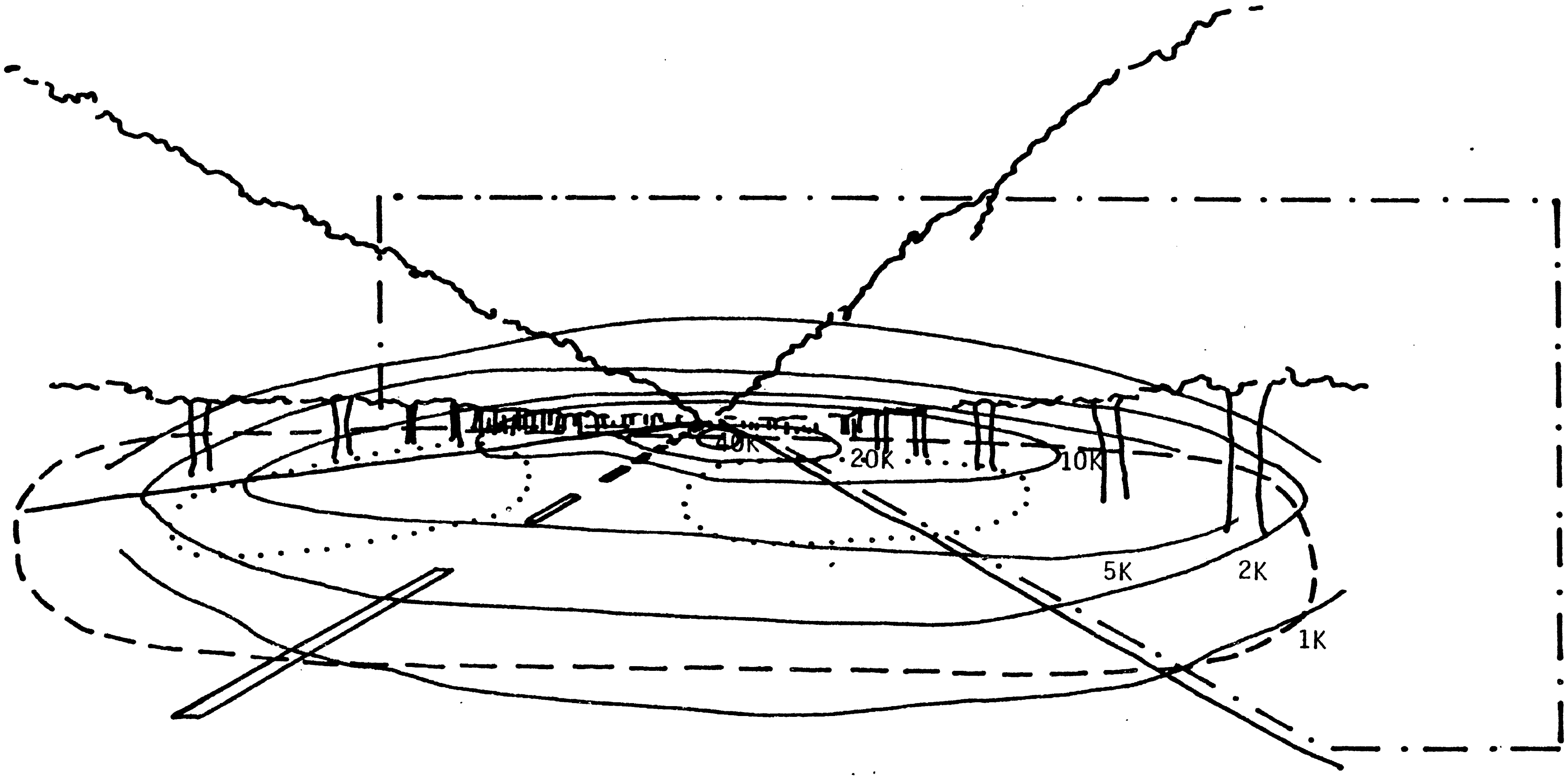

Figure 3.4. System E.

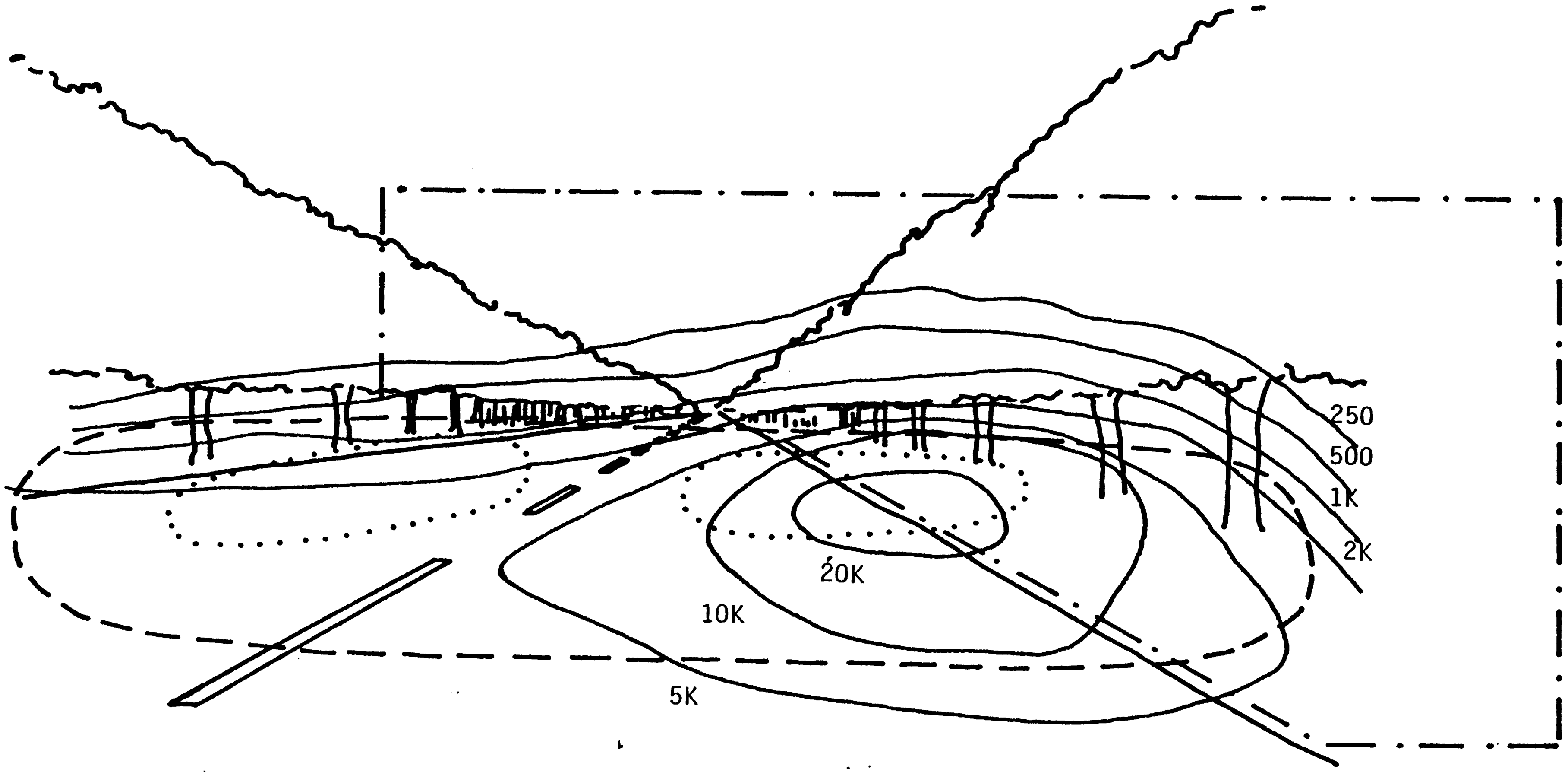

Figure 3.5. System F. Standard 6014 component.

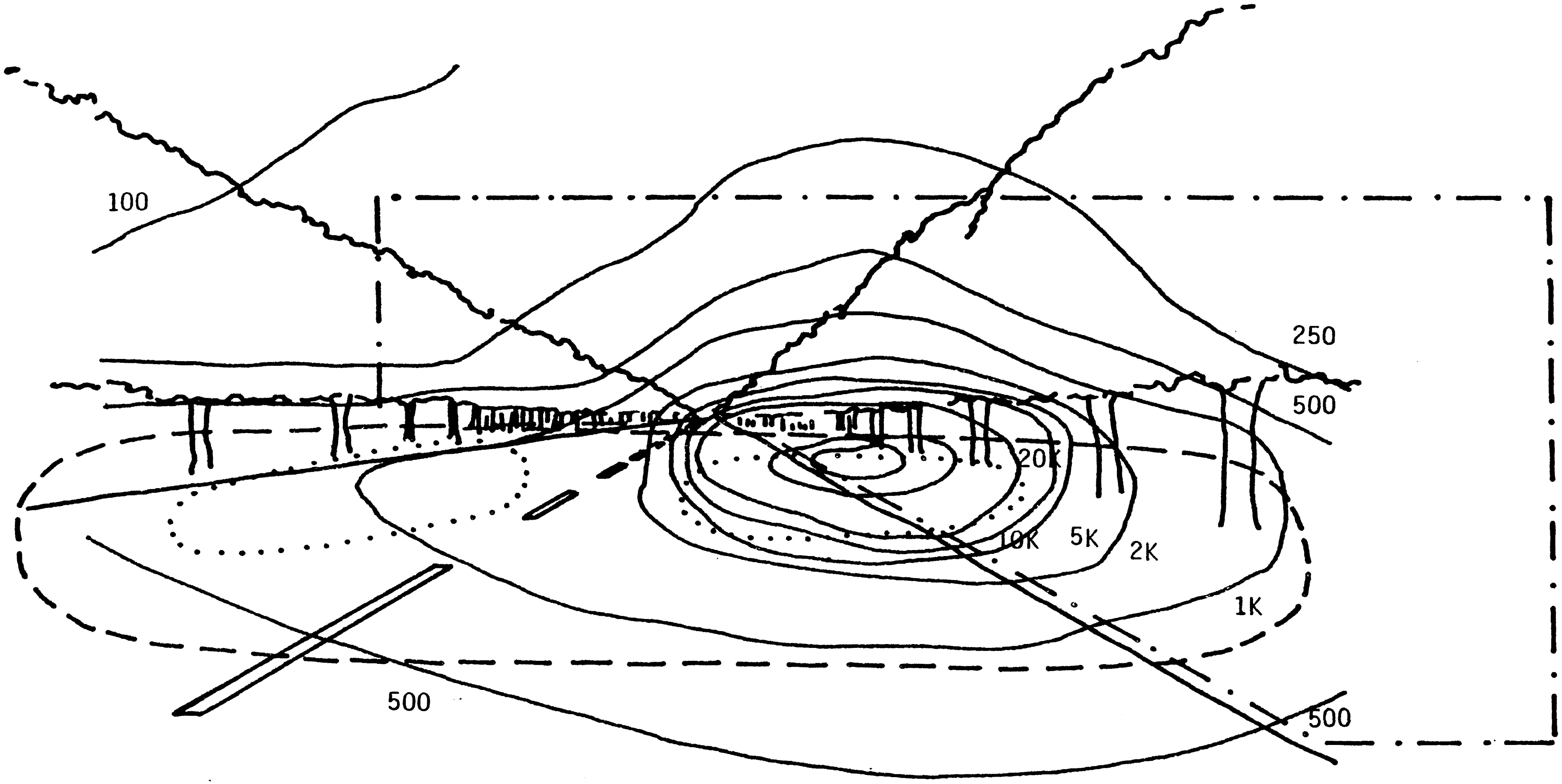

Figure 3.6. System. F. Midbeam component.

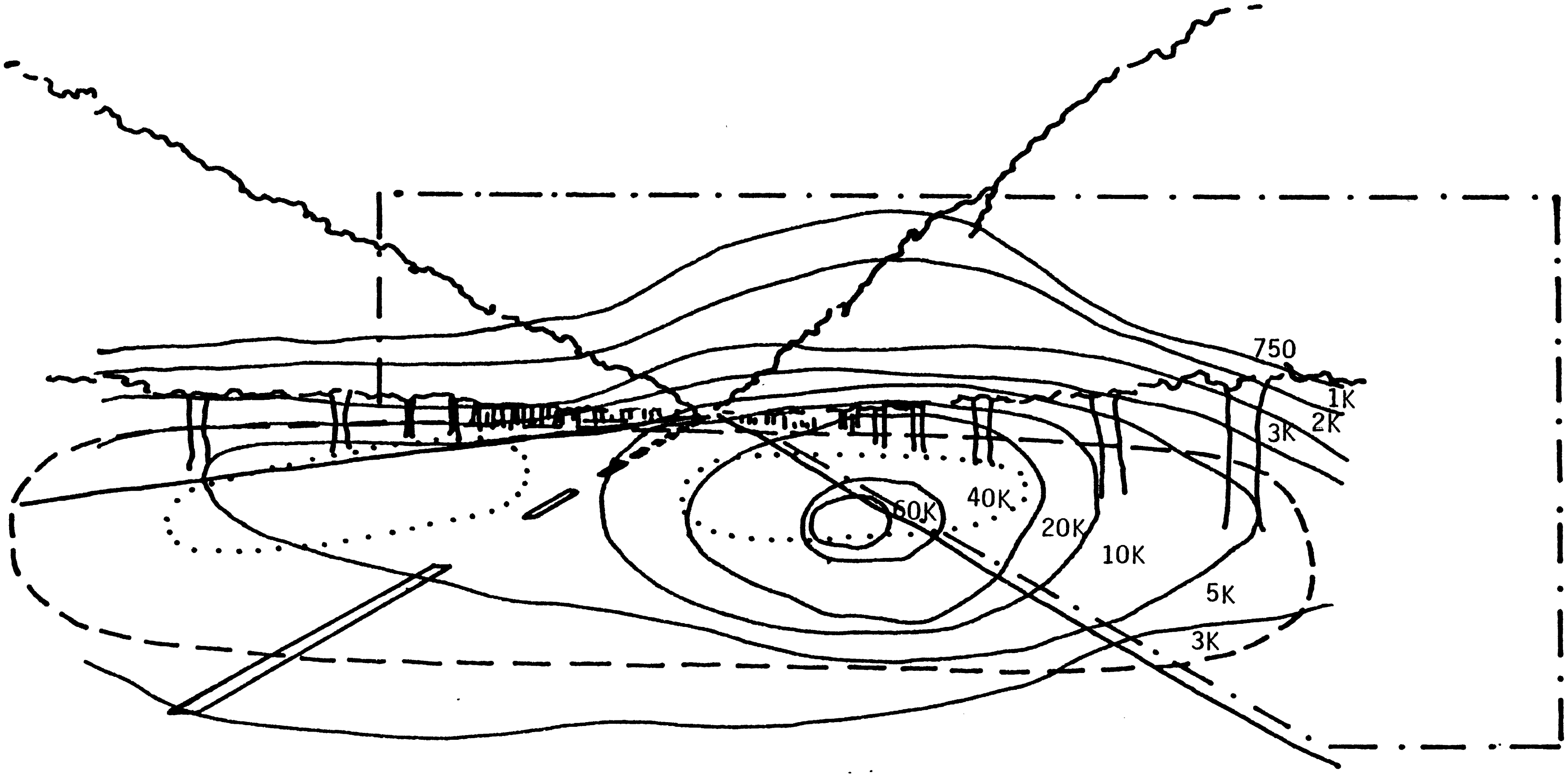

Figure 3.7. System G. Right lamp.

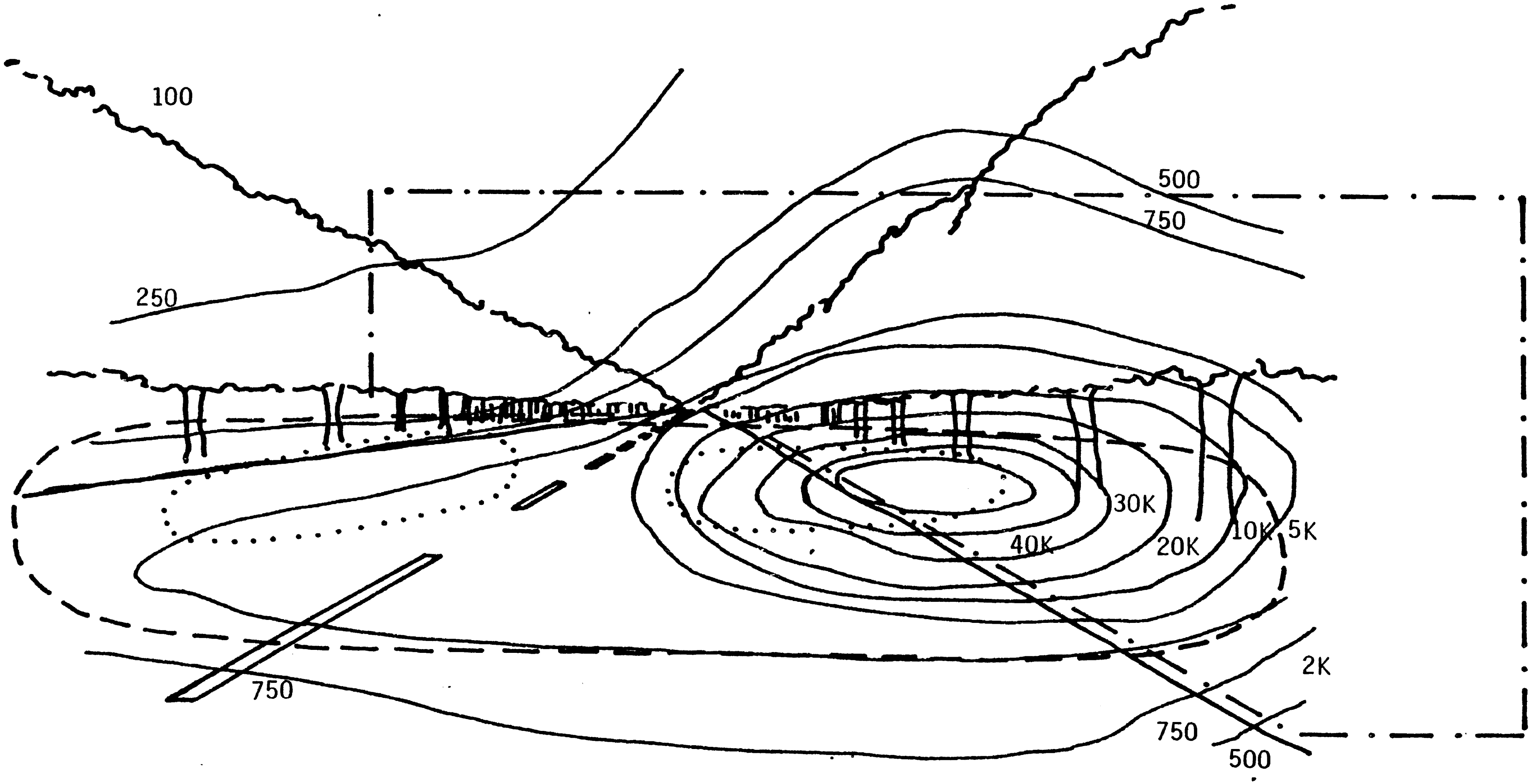

Figure 3.8. System G. Left lamp.

the field of view where many significant targets likely will fall. Similutaneously, systems F and G do not add a great deal of glare illumination into the oncoming driver's line of sight.

TABLE 3.1. Photometric statistics on systems C, E, F, and G.

System	Hot-Spot Location	Hot-Spot Candela	Average Candela Around Hot-Spot
C	$2^{o}R, 1^{o}D$	40,000	15,800
E	$0^{o}R, .5^{o}D$	40,000	12,800
F (mid-beam lamp)	$2^{o}R, 1.5^{o}D$	78,000	38,700
G (left lamp)	$4.5^{o}R, 1.5^{o}D$	60,000	41,800
G (right lamp)	$2.5^{o}R, 2^{o}D$	65,000	35,400
Standard 6014 low beam	$2^{o}R, 1.5^{o}D$	28,000	19,800

3.2 More Illumination to the Left

HSRI and industry experts created two examples of this single-beam concept. Systems A and B both project more illumination to the left.

Figure 3.9 plots the isocandela contours for system A. Although more intense than a standard low beam in the right portion of the field of view, it's pattern in the right is comparable to the 6014 low beam. System A also more intensely illuminates the area to the left and under the oncoming drivers line of sight.

Because it also is more intense in the right half, system A's coverage of the pedestrian areas in both the right and left halves represents an improvement over the standard low beam. Coverage of signs also improves.

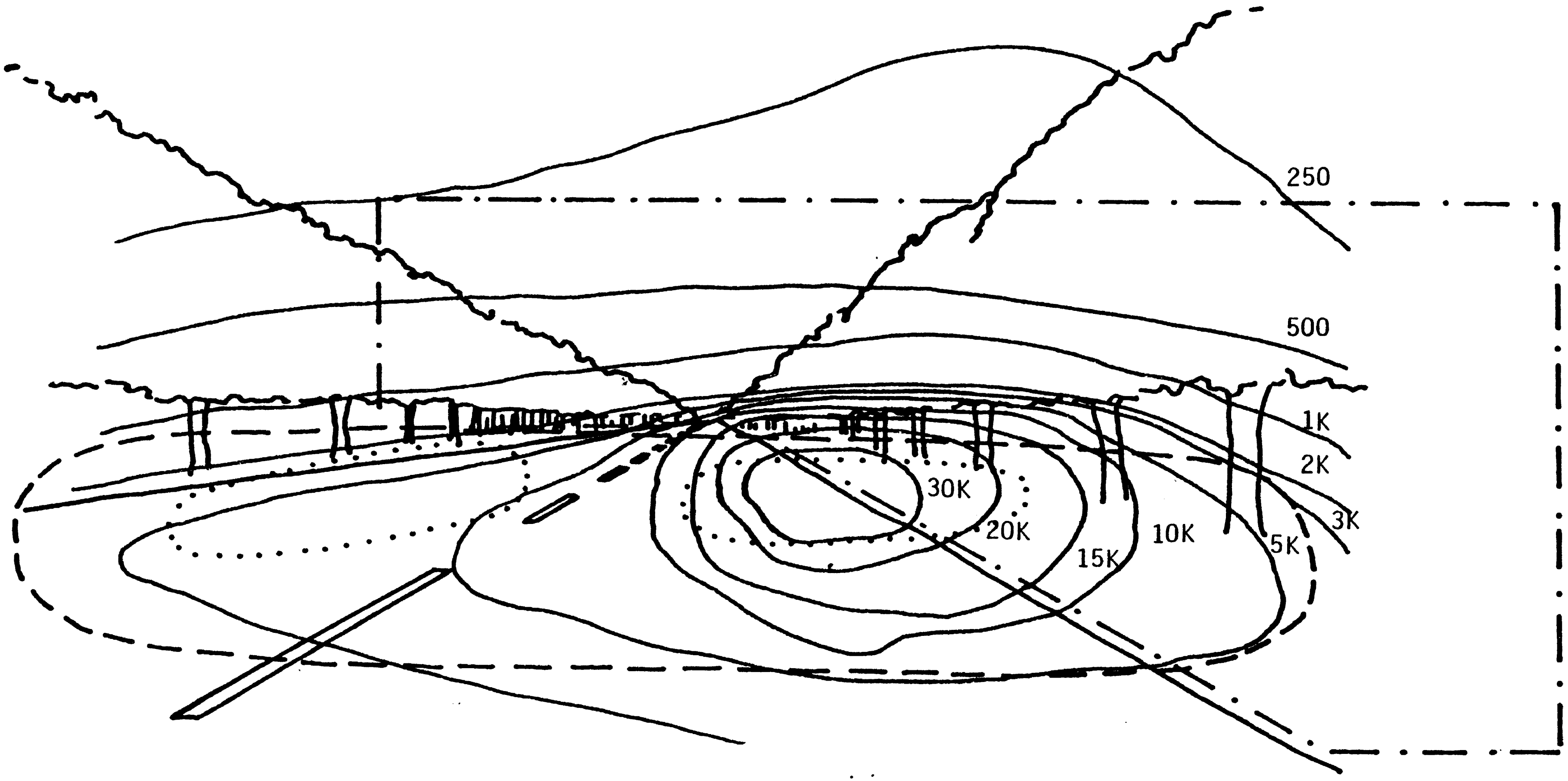

Figure 3.9. System A.

Figure 3.10 displays the isocandela contours for system B. System B aims more toward the vanishing point than the current low beam. It shows better coverage of the pedestrian areas in both halves of the field of view.

Table 3-2 shows the photometric statistics on systems A and B. System B has less average intensity than the standard low beam, while system A is more intense.

TABLE 3-2. Photometric statistics for systems A and B.

System	Hot-Spot Location	Hot-Spot Candela	Average Candela Around Hot-Spot
A	2^0R, 1.5^0D	40,000	25,600
B	0^0R, 1^0D	40,000	15,800
Standard 6014 low beam	2^0R, 1.5^0D	28,000	19,800

3.3 More Illumination to Both the Left and Right

Figure 3.11 shows the isocandela contours for system D. It's hot-spot is located a bit higher than the 6014. The area of intense illumination around the hot-spot is smaller. The contours closest to the hot-spot have a characteristic "U" shape, providing illumination to both the right and left while leaving a weakly illuminated "trough" corresponding to the trajectory of the oncoming driver's eyes.

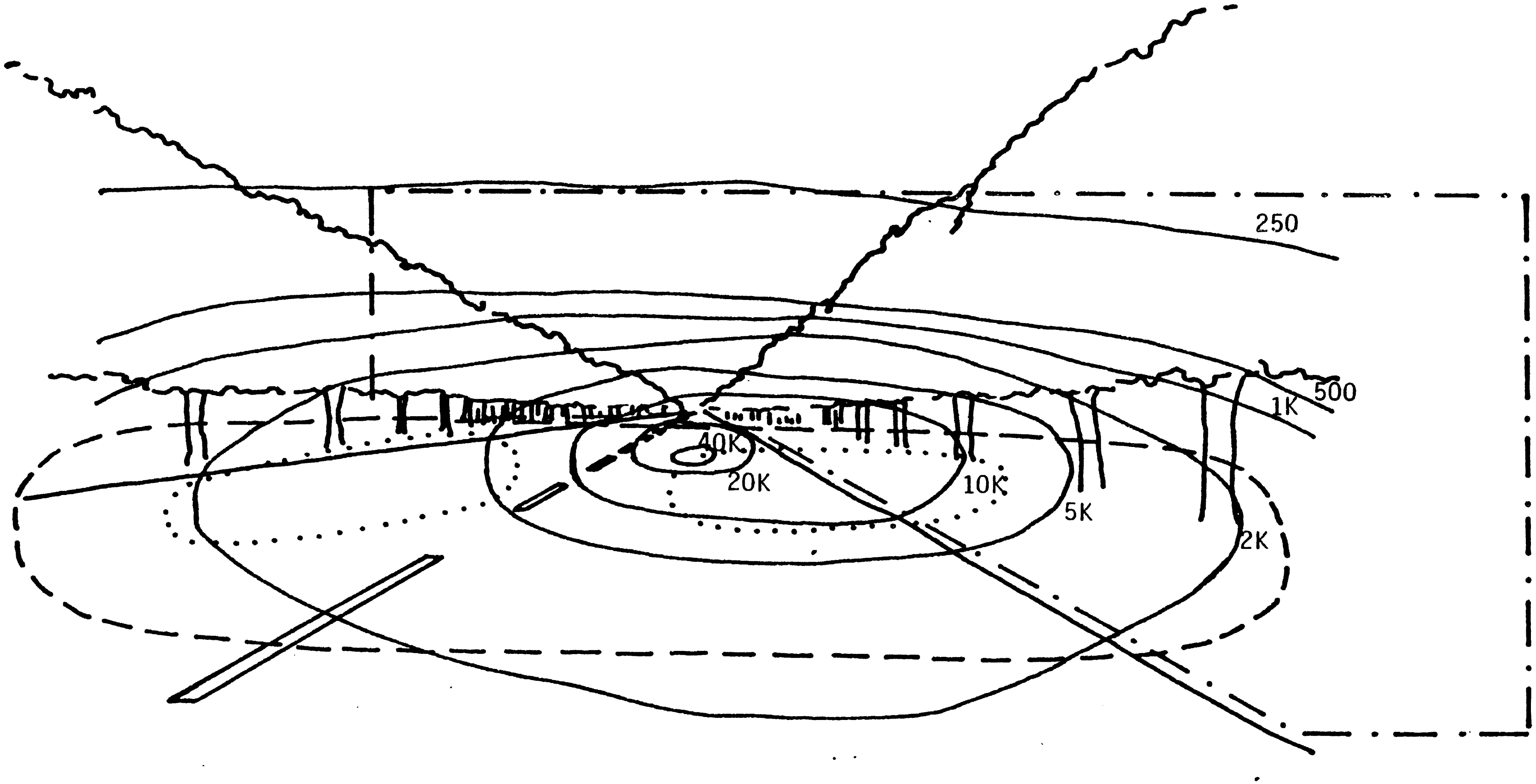

Figure 3.10. System B.

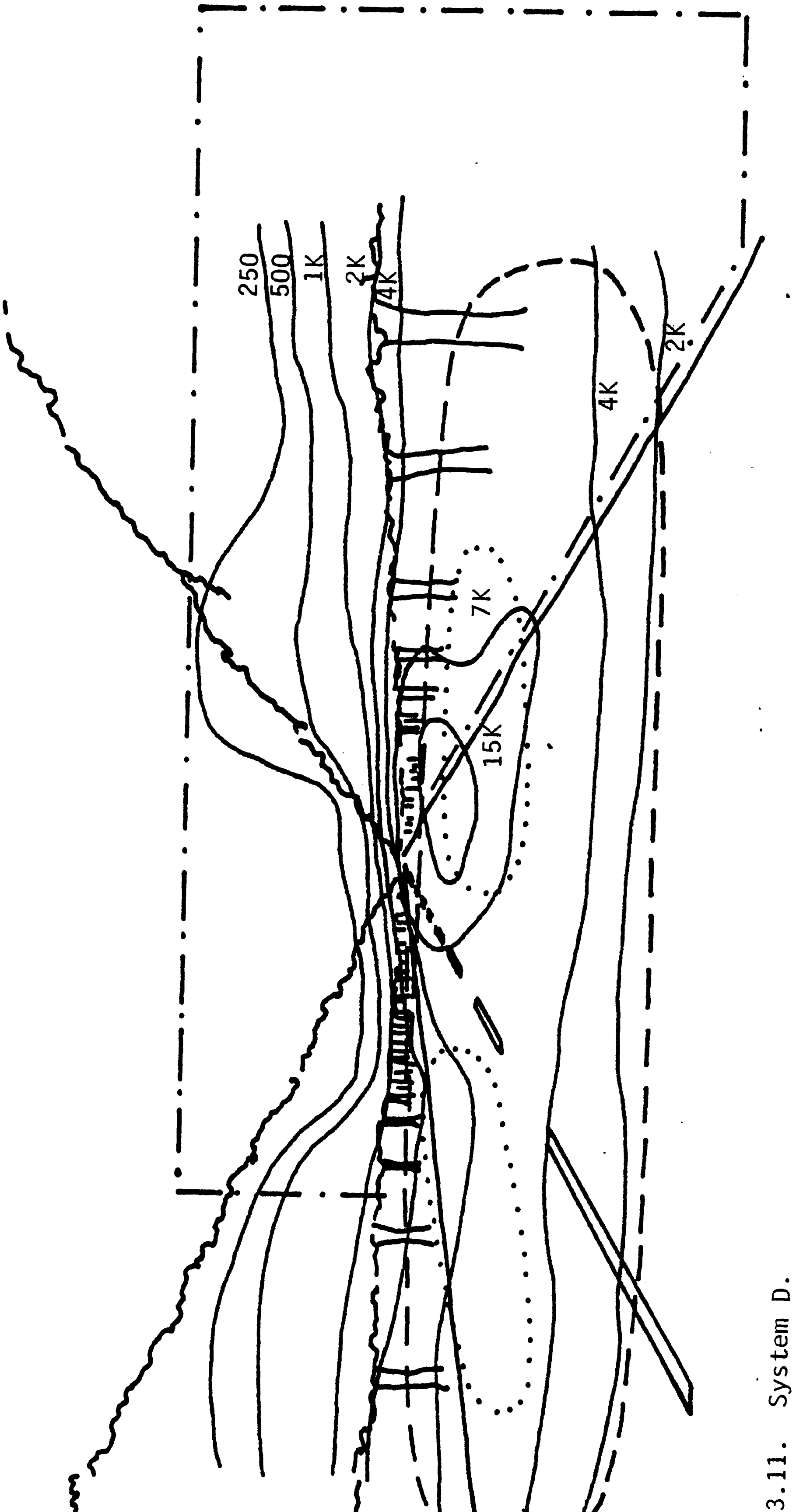

Figure 3.11. System D.

Table 3-3 compares system D's photometric statistics with those of the 6014 standard low beam. In general, system D is much less intense than the standard low beam.

Table 3-3. Photometric statistics for system D.

System	Hot-Spot Location	Hot-Spot Candela	Average Candela Around Hot-Spot
D	$1^{o}R, 1^{o}D$	30,000	11,400
Standard 6014 low beam	$2^{o}R, 1.5^{o}D$	28,000	19,800

In sum, HSRI and industry experts developed seven examples of single-beam concepts. Table 3-4 compares the photometric statistics of the seven examples. Systems F and G are the most intense, followed by system A. System D is the least intense, providing even less average illumination than a standard 6014 low beam.

TABLE 3-4. Photometric statistics for all alternative single-beam systems.

System	Hot-Spot Location	Hot-Spot Candela	Average Candela Around Hot-Spot
A	2^o R, 1.5^oD	40,000	25,600
B	0^o R, 1^oD	40,000	15,800
C	2^oR, 1^oD	40,000	15,800
D	1^oR, 1^oD	30,000	11,400
E	0^oR, 0.5^oD	40,000	12,800
F (mid-beam)	2^oR, 1.5^oD	78,000	38,700
G left	4.5^oR, 1.5^oD	60,000	41,800
G right	2.5^oR, 2^oD	65,000	35,400
Standard 6014 low beam	2^oR, 1.5^oD	28,000	19,800

4.0 COMPUTER SIMULATION ANALYSIS

Two computer simulations evaluated the seven alternative single-beam systems. One simulation, developed at HSRI (described in Mortimer and Becker, 1973 and Becker and Mortimer, 1974), predicted the seeing distance afforded by each beam. This section describes the results from the HSRI simulation. The other simulation, developed at the Ford Motor Company (described in Bhise et al., 1977), computes a figure of merit that reflects the adequacy of illumination each system provides for nighttime driving. The results of the Ford simulation are reported in Appendix A.

4.1 HSRI Simulation Analysis Procedures

The HSRI computer program simulates a car meeting situation. It "drives" two vehicles towards each other, and every 100 or 50 feet, predicts at what distances the subject driver can see the target given the lamps on his/her car and the glare lamps. Figure 4-1 plots three example results from the HSRI simulation. The abscissa is the distance between the subject's car and the glare car. The ordinate reflects the distance that the target is visible to the subject driver. Example curve 1 shows the driver saw the target throughout the meeting, but suffered some effects of glare for short separation distances. The second curve shows glare became so severe that the driver could not see the target at about 1,800 feet from the glare car. Curve 3 shows that glare did not prevent the driver from seeing the target until the vehicles met.

We transformed the series of visibility distances computed in the meeting situation for each target into a visibility score. To compute the visibility score, we divided the minimum visibility distance in that meeting by the maximum visibility distance, and then multiplied that ratio by the average visibility distance through the meeting.

Expressed in a formula:

$$\text{Visibility Score} = \frac{\text{Minimum}}{\text{Maximum}} \text{ X Average}$$

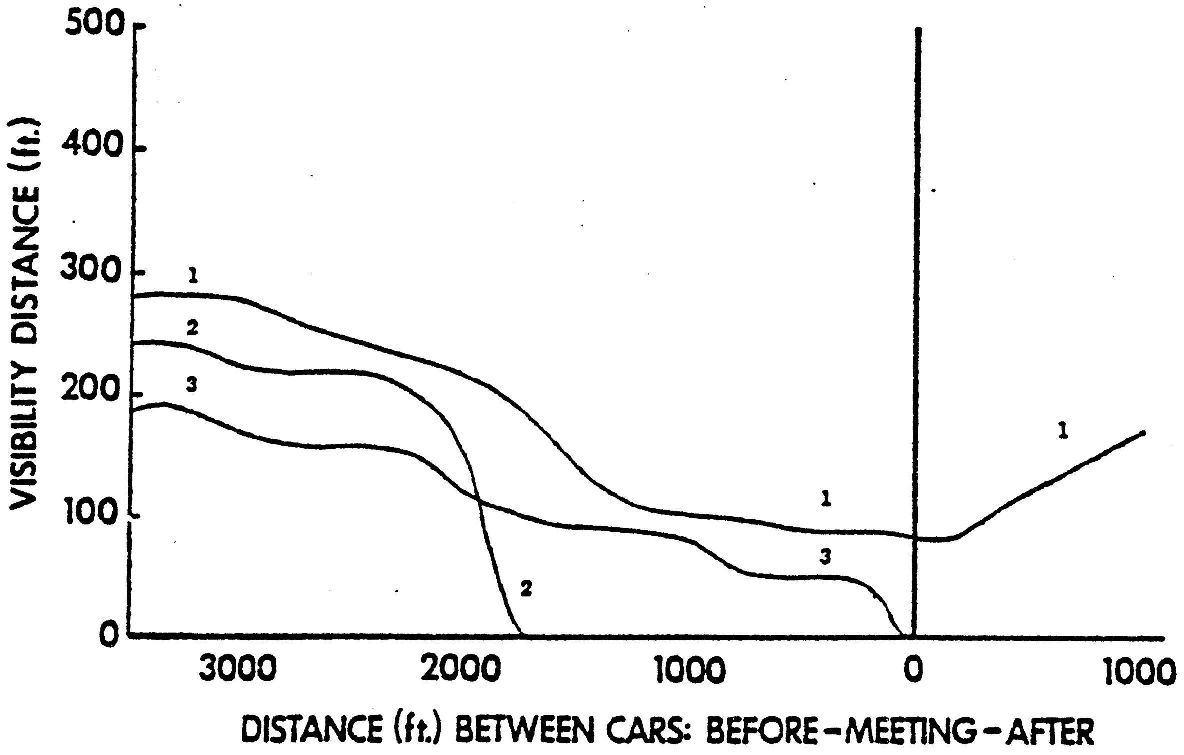

Figure 4.1. Graphic representation of HSRI computer simulation results.

The visibility score reflects both the range and the average score, and furthermore, can go to zero if glare obscures the target at any point in the meeting.

We used the HSRI simulation to compute 15 visibility scores for each of the seven single-beam systems described in section 3. Four real-world targets were simulated: road delineation, signs, potholes, pedestrians, and animals. Table 4-1 shows target characteristics. We computed two visibility scores for the road delineation, one each for the centerline and shoulder stripe. Two scores represented, respectively, the visibility of a seven-foot sign on the right shoulder and six feet to the right of that shoulder. Three scores predicted the visibility of potholes in the two tire tracks and lane center. In the case of 8% reflective pedestrians and animals, we computed nine visibility scores for three vertical and three horizontal positions. The nine scores were reduced to three by taking the average of the three vertical-location scores at each horizontal location. In a similar manner, we reduced the fifteen visibility scores for the 20% reflective pedestrian and animals to five.

Table 4-2 shows the visibility scores for each system at each location. Figures 4-2 through 4-6 give a graphic representation of these scores (system H is the 6014 low beam control). Upon inspection of this table and these graphs, systems F and G appear to have the highest scores, followed closely by system D, system A, and the 6014 control.

An analysis of the average visibility-score rank each system achieved across the 15 scores shows a profile similar to that seen through inspection. Table 4-3 shows the average ranks. By inspection of this table, systems F, G, and D appear to cluster at the top, followed by system A and the 6014 low beam. Systems B, C, and E are clearly the worst.

To compare HSRI simulation results with the Ford results, we put together Figure 4-7 based on their report. This figure shows

TABLE 4-1. Targets Simulated in HSRI Analysis.

Simulated Target and Number of Visibility Scores	Reflectivity	Vertical Location(s)	Horizontal Location(s)
Road delineation (2)	95%	Road surface	Centerline Shoulder stripe
Sign (2)	50%	7 feet above road	On right shoulder 6' off to right of shoulder
Potholes (3)	6%	Road surface	Left-tire track Center of lane Right-tire track
Pedestrians and animals (3)	8%	1 foot above road 2.5 feet above road 5 feet above road	Center of lane Right shoulder 6' right of shoulder
Pedestrians and animals (5)	20%	1 foot above road 2.5 feet above road	Left shoulder Center of oncoming lane Center of lane Right shoulder 6' right of shoulder

TABLE 4-2. Visibility scores from HSRI computer simulation (numbers represent predicted visibility distances).

	Road Delineation		Sign		Potholes			8% Reflective Pedestrians & Animals			20% Reflective Targets				
	Center-line	Shoulder	Shoulder	6' right of shoulder	Left tire track	Lane Center	Right tire track	Lane Center	Right Shoulder	6' right of shoulder	Left Shoulder	Oncoming Lane Center	Left Center	Right Shoulder	6' right of Shoulder
A	252	231	282	297	80	152	202	109	146	107	102	78	191	260	247
B	143	296	274	286	53	109	147	147	132	0	0	62	140	160	213
C	151	293	244	260	50	101	140	78	145	102	81	57	92	228	220
D	309	404	296	303	143	190	198	0	189	199	129	117	153	273	279
E	192	254	239	249	63	103	154	89	140	95	82	61	141	237	209
F	347	447	311	348	97	203	248	148	0	0	104	104	249	312	261
G	278	407	310	347	102	154	211	138	220	193	103	190	200	304	313
6014 low	291	400	292	295	99	148	201	126	197	0	0	0	187	255	0

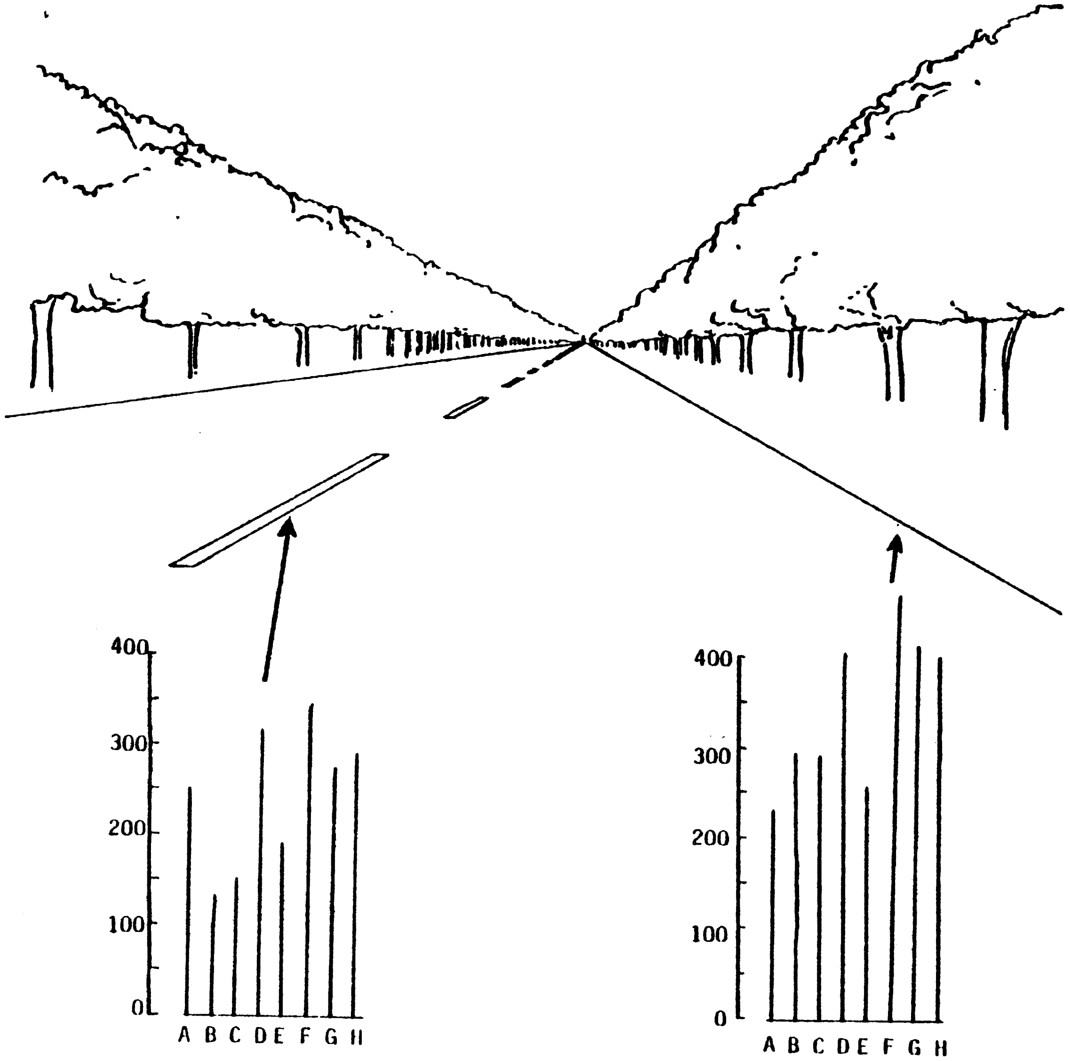

Figure 4.2. Delineation results.

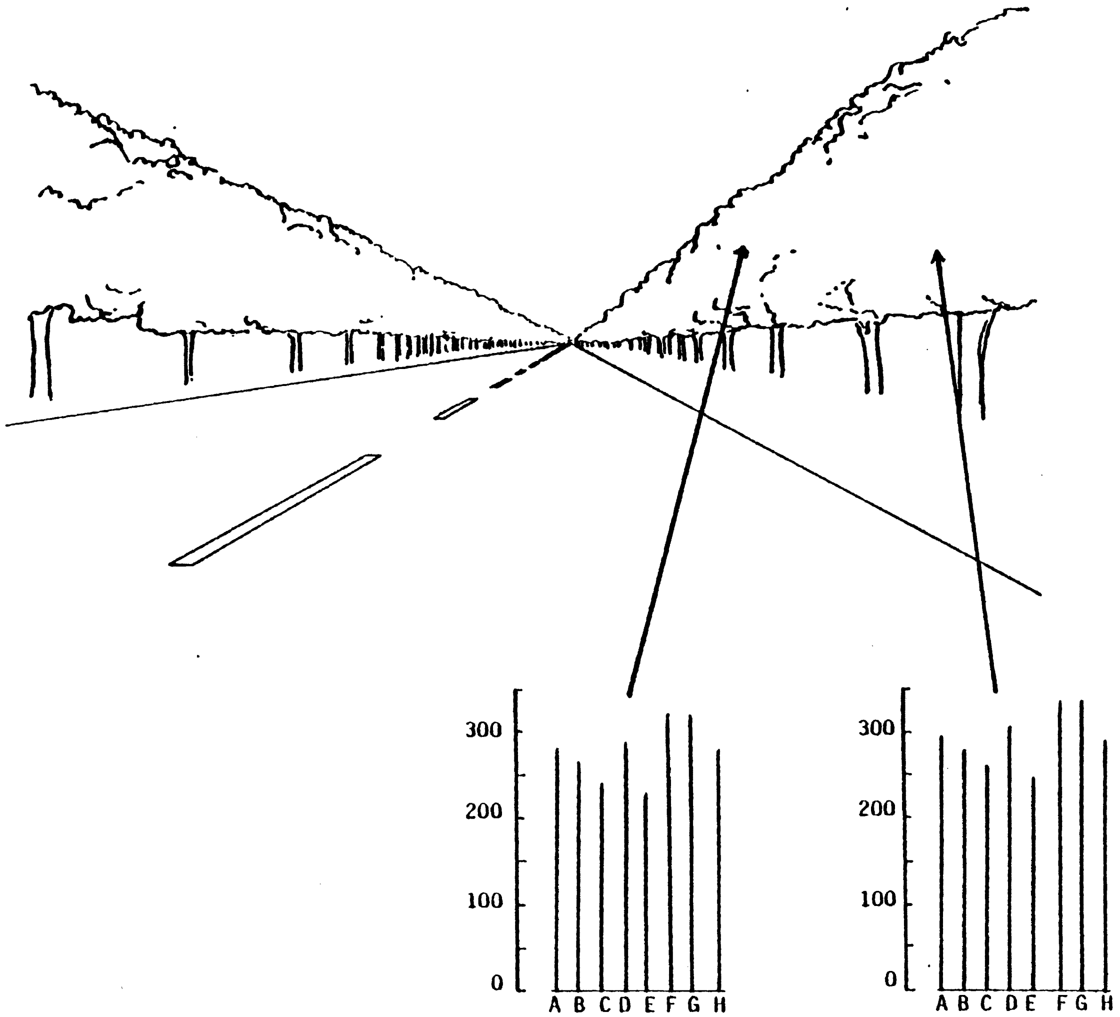

Figure 4.3. Sign results.

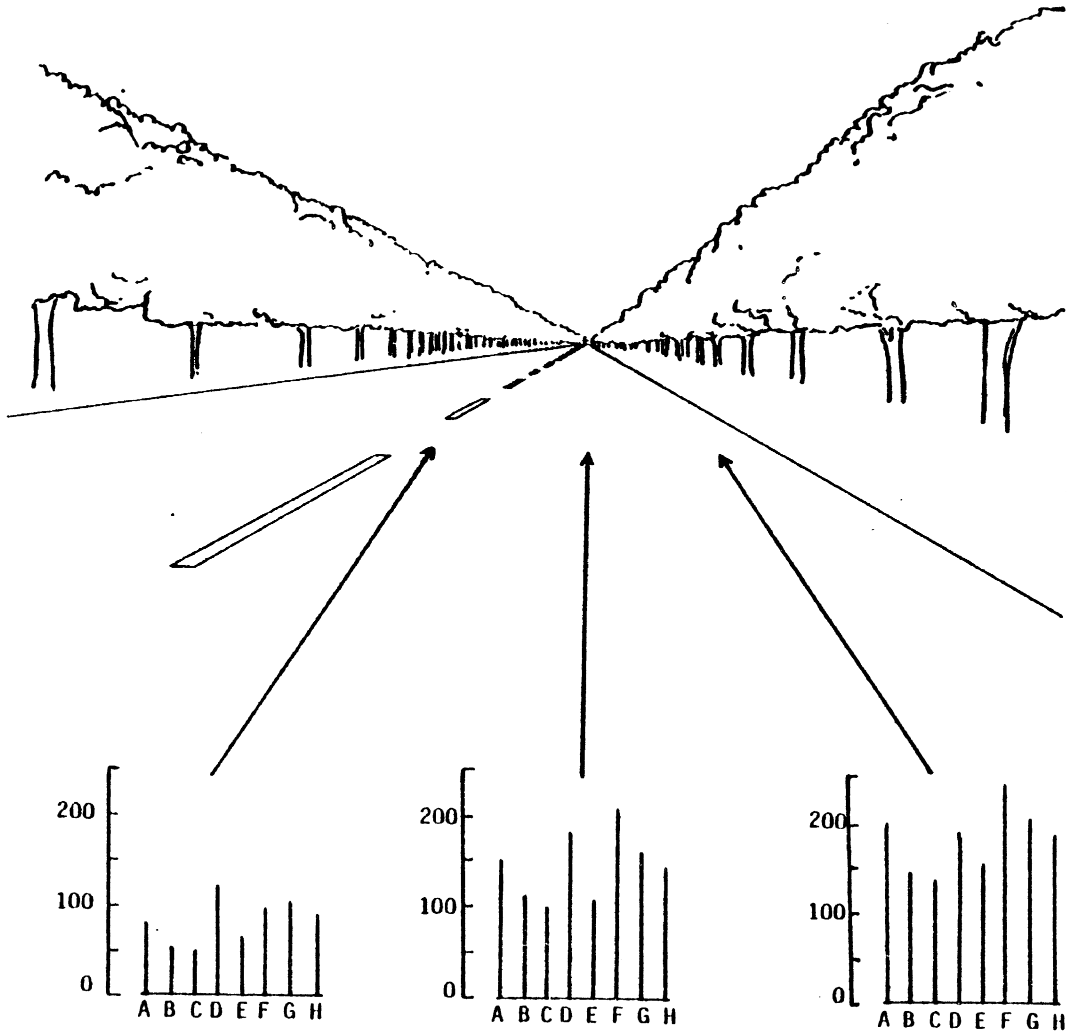

Figure 4.4. Pothole results.

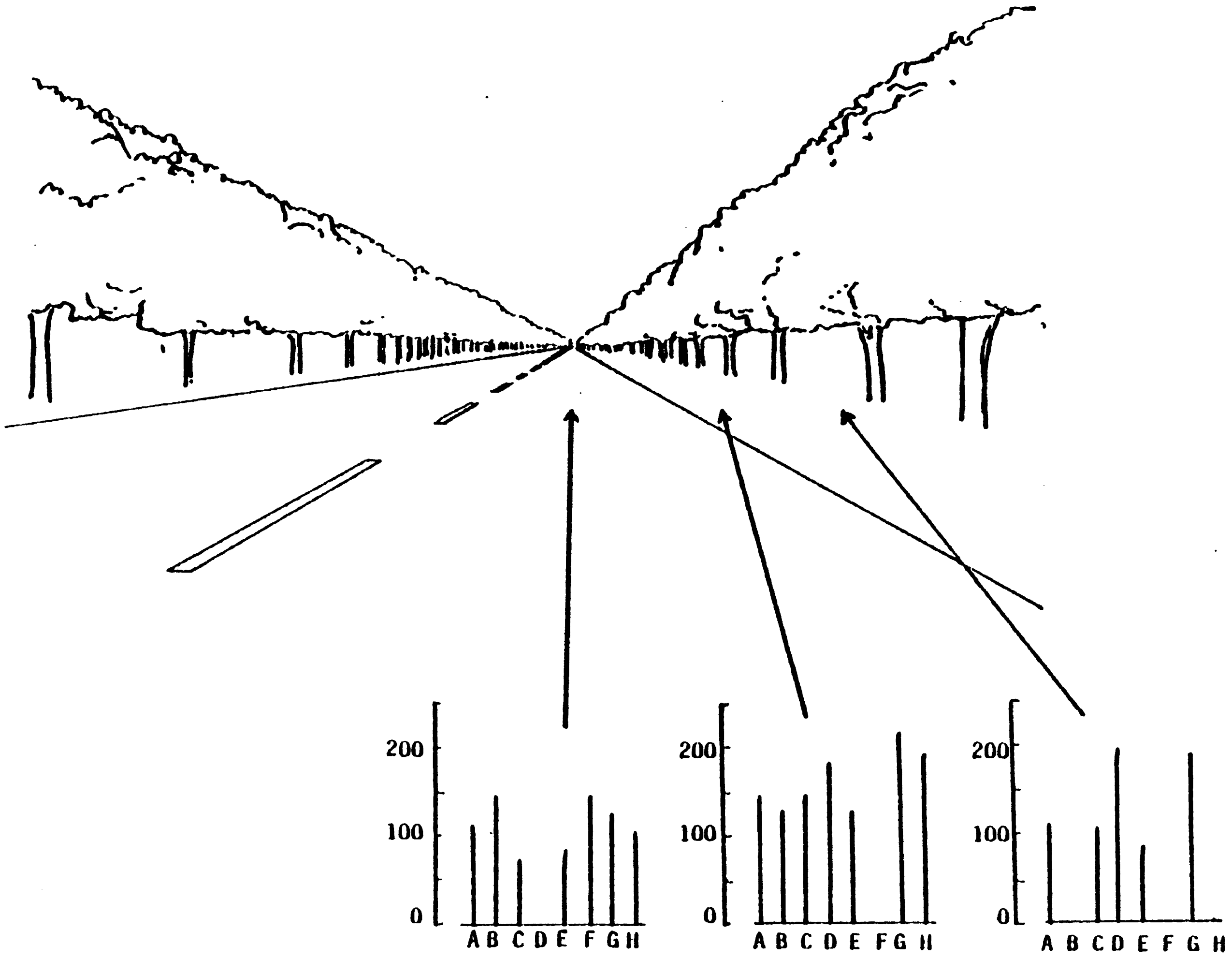

Figure 4.5. 8% reflective pedestrian/animal results.

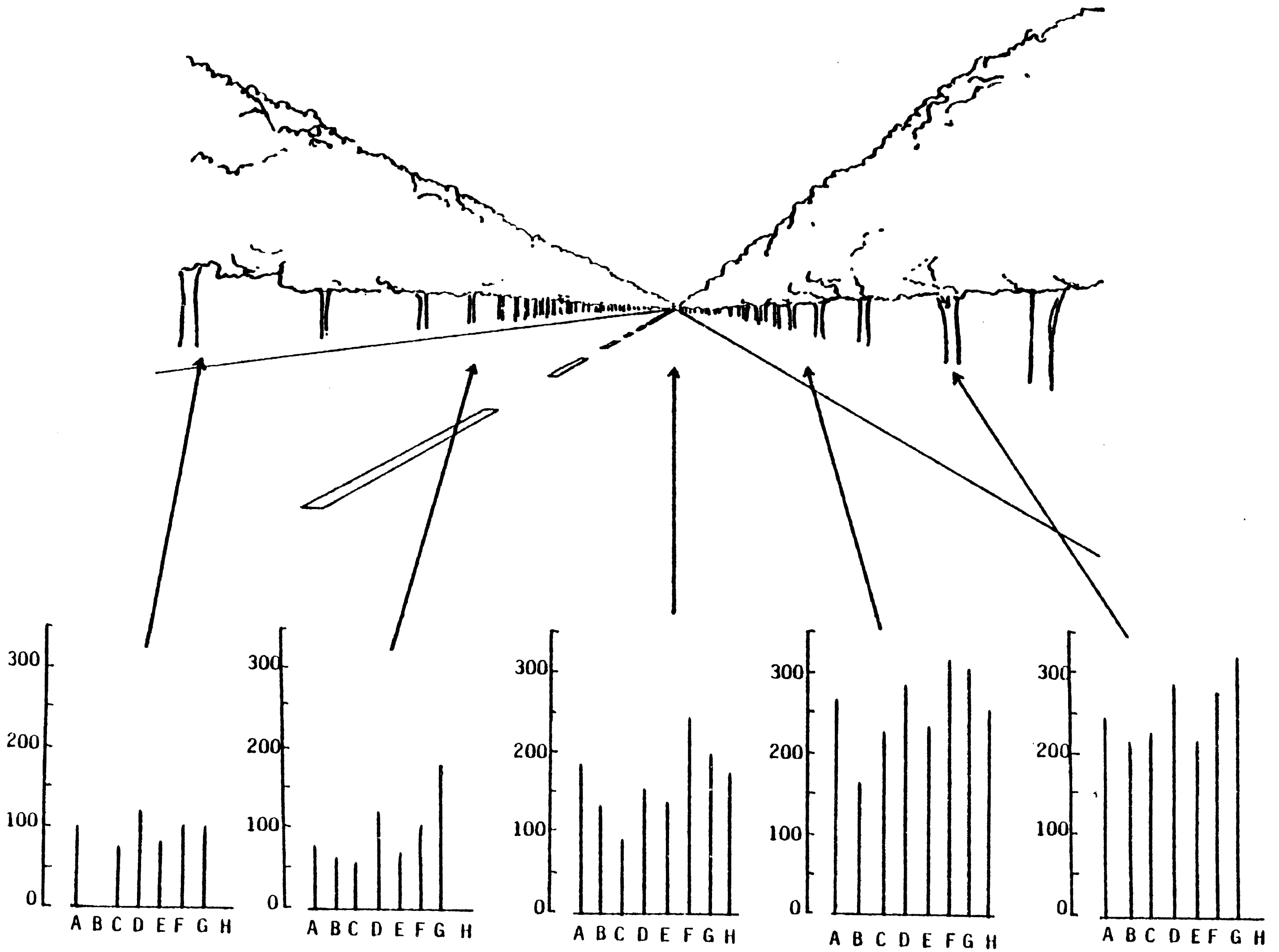

Figure 4.6. 20% reflective pedestrian/animal results.

TABLE 4-3. Average visibility-score ranks across the 15 target locations.

System	Average Visibility Score Rank
A	4.3
B	6.1
C	6.9
D	2.9
E	6.3
F	2.4
G	2.1
6014 low beam (H)	4.9

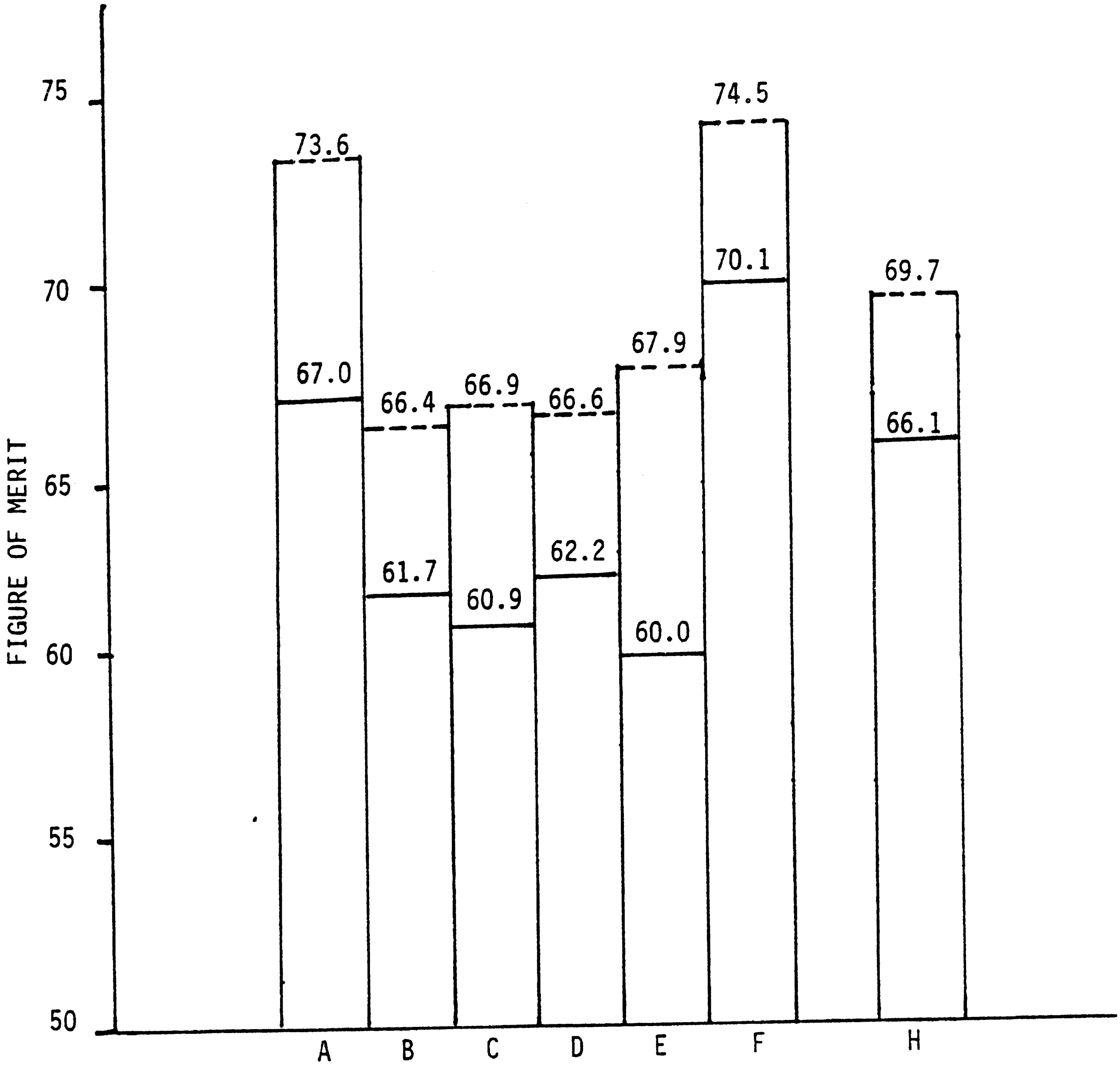

Figure 4.7. Comparison of the Ford simulations figures of merit of headlamp systems under perfect aim (dashed lines) and misaim (solid lines).

that system F was best (system G was not evaluated by Ford), followed by system A and their low beam control. The largest discrepancy between the Ford and HSRI results was that system D performed as poorly as systems B and C in Ford's results, whereas it performed about as well as systems F and G in the HSRI simulation.

Overall, the HSRI simulation orders the beams as:

G F D A 6014-low B E C

The Ford simulation (which did not evaluate G) orders them as:

F A 6014-low D B C E.

4.2 NHTSA Decision on Systems to Test

HSRI presented the results of the computer-simulation analyses to NHTSA in a public briefing. NHTSA decided, on the basis of this and other information, to field test systems A, D, and G in a comparison with the 6014 low beam. HSRI then arranged to acquire the lamps.

System A was close enough to the distribution of a standard 6014 unit that it could be effectively simulated by running a 6014 at 15.8 volts.

Systems D and G were custom fabricated by headlamp manufacturers. System G, as delivered, departed significantly from the intended design but was felt to be close enough to test. The isocandela contours of system G are shown in Figures 4.8 and 4.9 for the right and left lamps respectively. These should be compared with Figures 3.7 and 3.8. The differences between the design and delivered system can be briefly summarized by saying that the latter provides less illumination and more glare than the former.

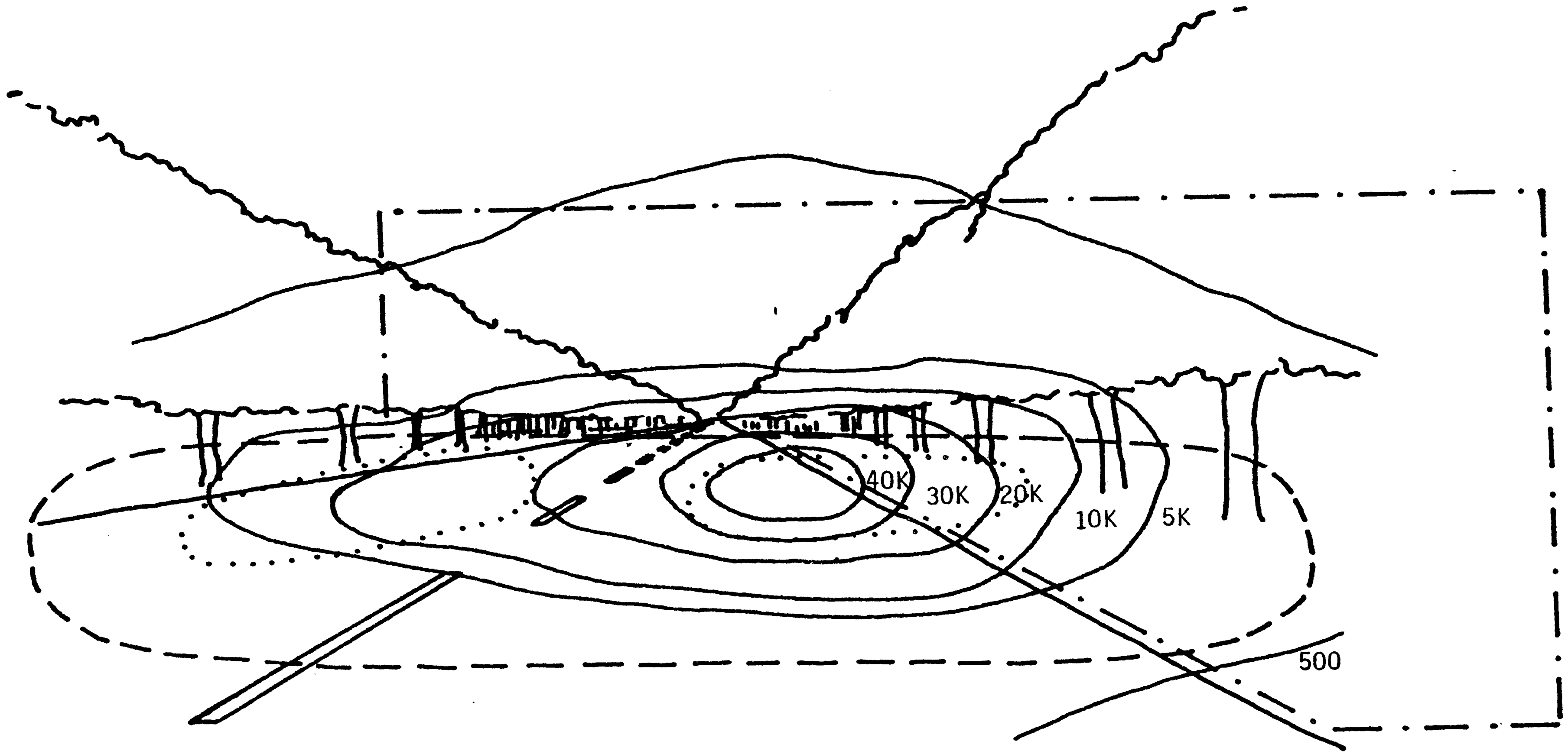

Figure 4.8. System G, right lamp, as tested.

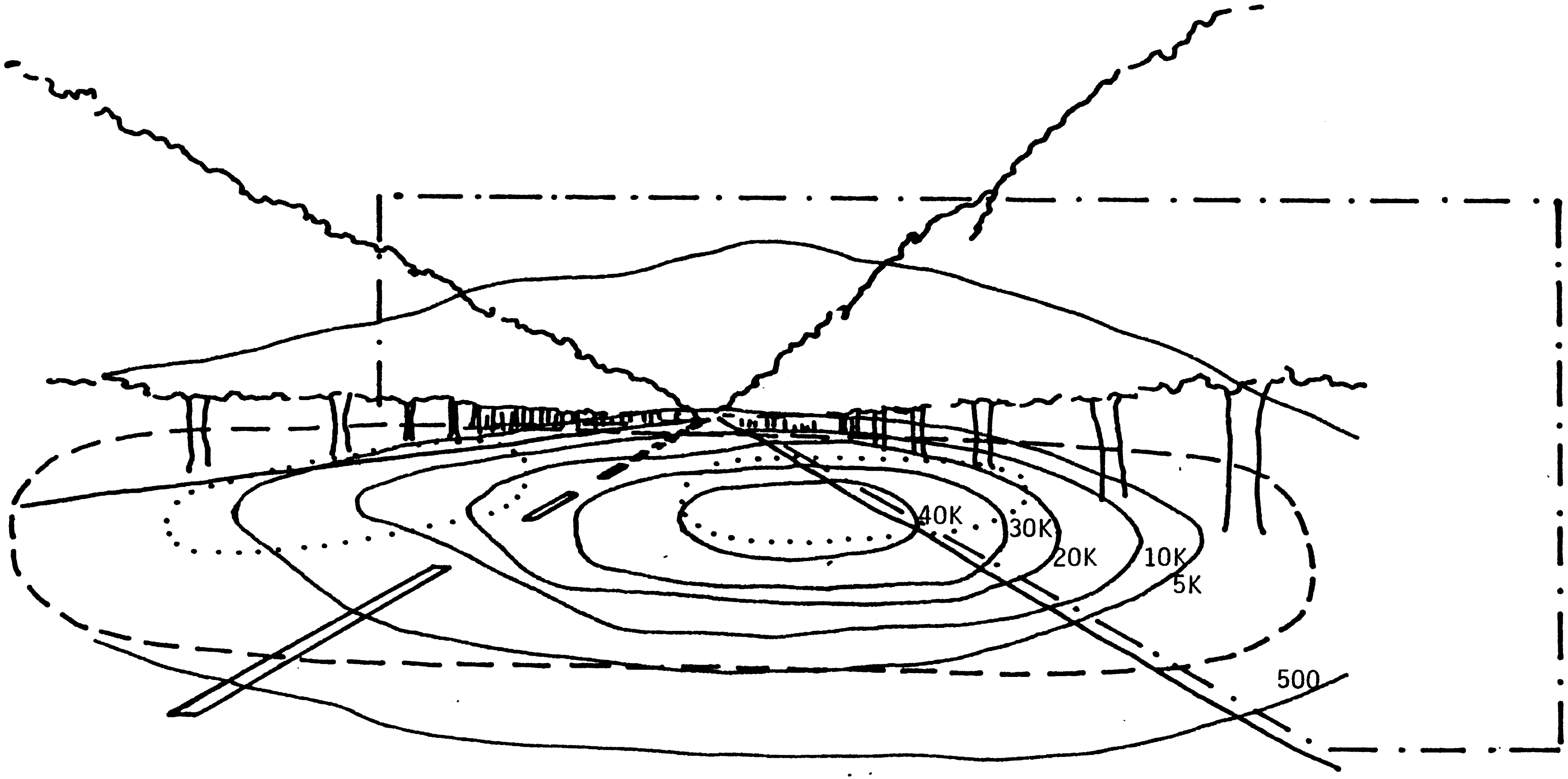

Figure 4.9. System G, left lamp, as tested.

5.0 FIELD EVALUATIONS OF THE EXPERIMENTAL BEAMS

HSRI tested systems A, D, and G in two field tests. We compared the visibility each system afforded with the performance of a 6014 low beam control. The first field test evaluated visibility distances for several types of objects using semi-alerted drivers in several different road situations. The second field test, using informed drivers, provided subjective ratings of system performance.

5.1 Detection Distance Study

5.1.1 Subjects. Twelve males between the ages of 19 and 25 recruited on the University of Michigan campus participated. All had had at least 5,000 miles of night driving experience and 20,000 miles of total driving experience. Subjects were selected to have visual acuity of 20/20 or better under high luminance/high contrast conditions. Subject's visual acuities were also measured under conditions of low contrast and/or low luminance. Stimuli were presented at a contrast of 22.5:1 in high-contrast condition and at 1.3:1 in low-contrast conditions. In high-luminance conditions the luminance of the stimulus surround was 47 ft-L within one degree of the stimulus and 33.5 ft-L beyond one degree. In low-luminance conditions the surround was at .063 ft-L within one degree. Beyond one degree, luminance was too low to be reliably measured. The medians and ranges for the subjects on the measures are given in Table 5.1.

5.1.2 Route. Testing was carried out on a 26 mile course of two-lane paved road in a rural area. The course formed a closed loop, and was divided into two 13-mile halves. A map of the course is included in Appendix C.

The course was free of street lights, and carried very little traffic. It contained large sections of straight, flat road, and the surrounding area was largely free of houses and other buildings. Features of the course were predominantly gentle hills, curves, and road signs such as stop signs, speed limit, and passing-zone demarcation signs.

TABLE 5.1. Distributions of subject's acuity measurements under various lighting conditions.

	Acuity Measures		
	Highest	Lowest	Median
High overall luminance			
High contrast	20/10	20/20	20/14
Low contrast	20/12	20/35	20/20
Low overall luminance			
High contrast	20/16	20/40	20/25
Low contrast	20/40	20/80	20/60

The testing was done in dry weather, with no fog, and with very little moonlight.

5.1.3 Equipment, Instrumentation, and Experimental Team. Four automobiles were involved in the experiment. One was always driven by the subject, while the other three were driven by staff and used in setting up deliberately placed targets. The subject's car was a 1971 Plymouth Fury station wagon that had been specially equipped for headlighting studies (see Figure 5.1). A metal frame was mounted across the front end of the vehicle to allow up to four headlight pairs to be mounted at the same time. For this study, three headlight pairs were mounted: experimental system G, experimental system D, and standard 6014 lamps. All lamps were mounted in approximently standard positions. The distance from the center of each lamp to the road surface was 25 inches. Starting from the most lateral position, the sequence of lamps on the driver's side of the vehicle was: system G, system D, and 6014. On the passenger's side, starting

Figure 5.1. Subject's vehicle.

from the lamp nearest the vehicle midline and proceeding laterally, the sequence was also system G, system D, and 6014. Thus, the distance between the lamps in each system was constant and the midpoints of two of the systems were offset slightly from the midline of the vehicle. Between-lamp distance was 56 inches. The midpoint of system G was offset eight inches to the driver's side of the vehicle midline, and the midpoint of the 6014 pair was offset the same distance to the other side. Headlamps were aimed to manufacturer's specifications.

The power to all lamps was controlled from the experimenter's station in the rear seat (see Figure 5.2). Voltage to each lamp could be adjusted with a precision of ± .01 volt. All lamps were run at 12.80 volts, except that the 6014 lamps were also operated at 15.80 volts to produce a third experimental beam pattern, designated as system A.

The subject's station was the driver's seat. The subject had a standard array of controls and displays, with the exception that he had no control over the headlights (see Figure 5.3). A pushbutton was mounted on one of the spokes of the steering wheel, where the subject would conveniently reach it with his thumb while still grasping the wheel (see Figure 5.4). Closing the pushbutton started two digital counters mounted at the experimenter's station. One was used as a 10-millisecond counter, while the other counted wheel revolutions. The counters thus provided time and distance measurements with precisions of .01 second and one wheel pulse (3,365 ft.) respectively. Stop and reset buttons for the counters were mounted at the experimenter's station.

The other three vehicles used were each equipped with one of the experimental headlight systems. A 1975 Ford Maverick (Figure 5.5) was equipped with system G. A 1979 Chevrolet Impala station wagon (Figure 5.6) had system D. Finally, a 1976 Plymouth Salon sedan (Figure 5.7) was equipped with standard 6014 lamps that could be operated at either 12.8 volts or 15.8 volts, thus providing the standard (control) beam pattern or experimental system A. These cars were

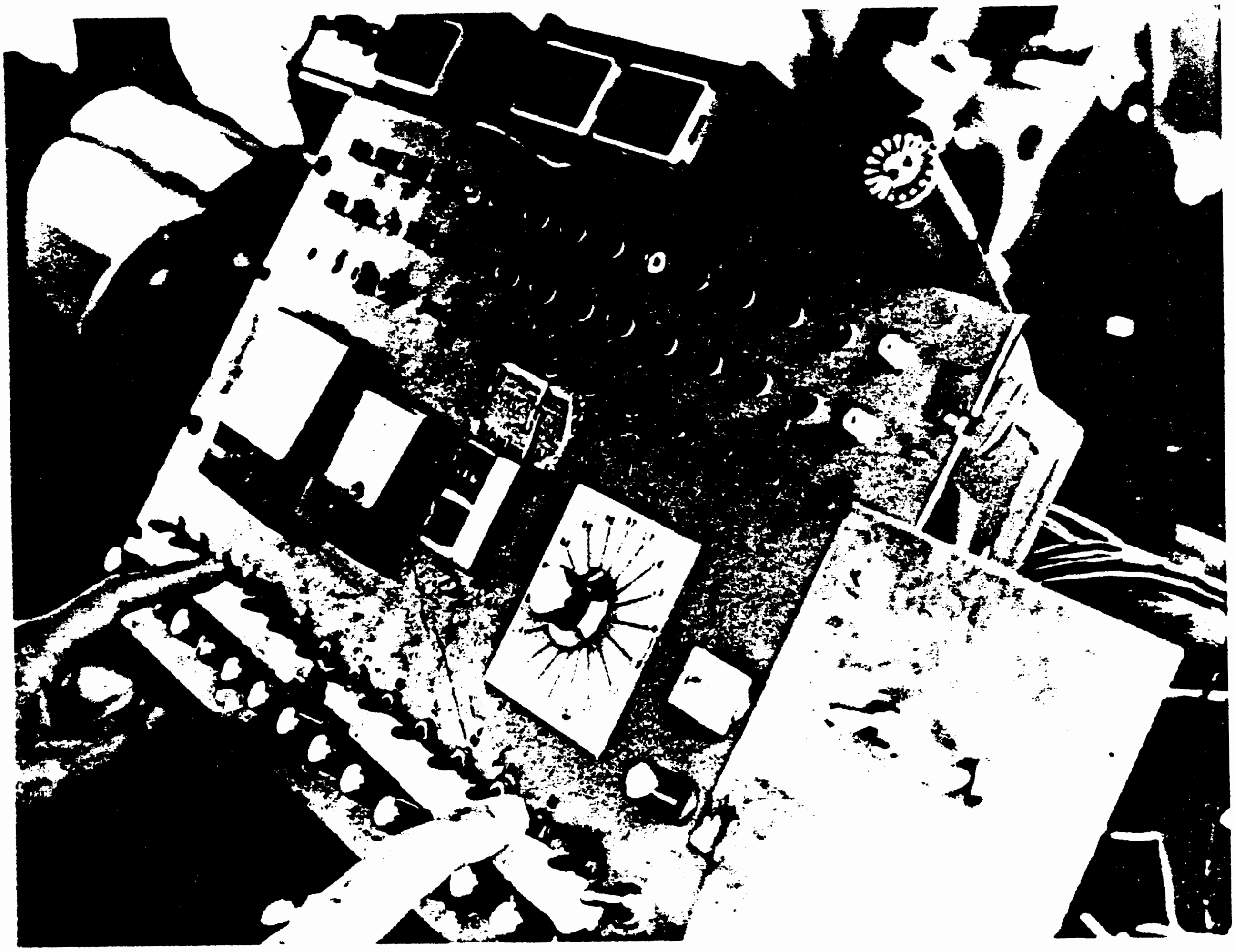

Figure 5.2. Experimenter's panel for controlling lights.

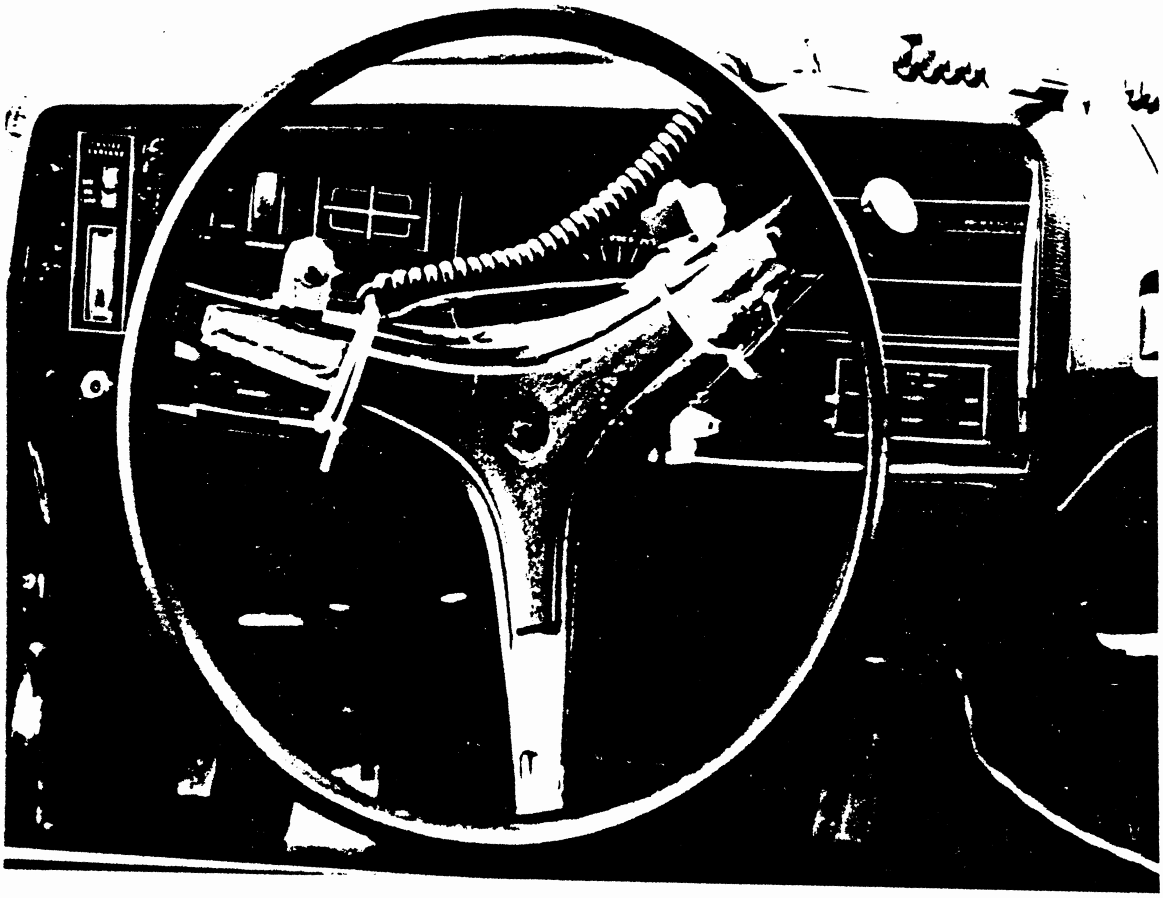

Figure 5.3. Subject's station.

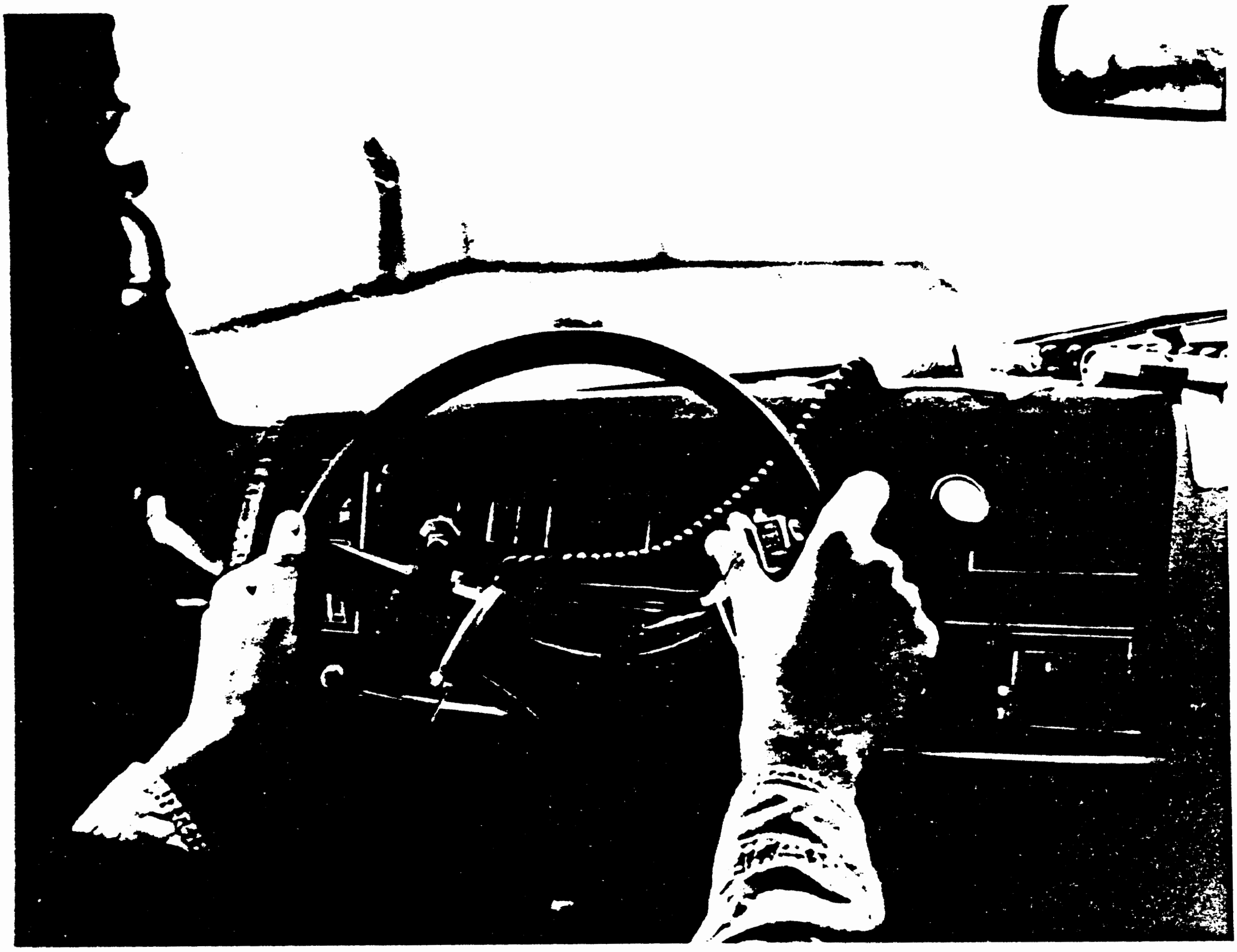

Figure 5.4. Subject with thumb on button.

Figure 5.5. Target-placing car with system G.

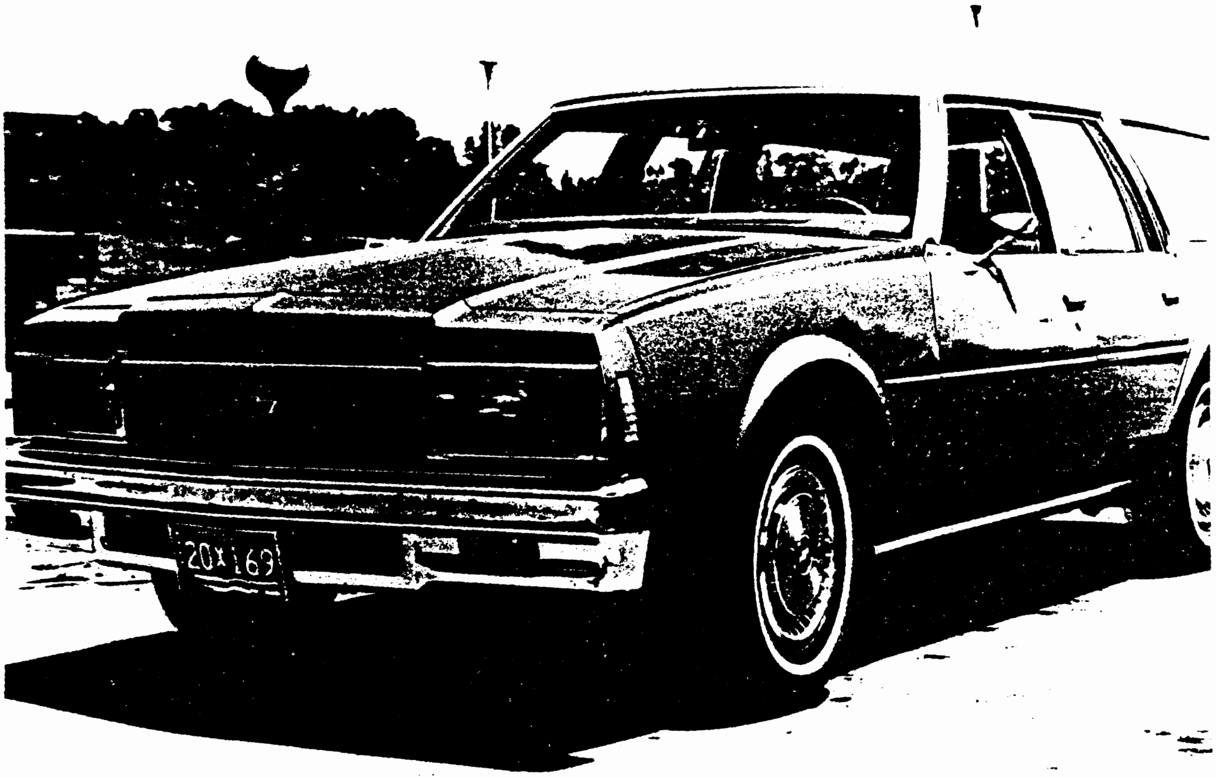

Figure 5.6. Target-placing car with system D.

Figure 5.7. Target-placing car with system A and 6014 control.

used as sources of glare or as parked-vehicle targets as called for by the experimental design.

Each of the four vehicles was equipped with a two-way radio, allowing communication between vehicles to help coordinate the setup of placed targets. Two hand-held radios were also used so that staff who were serving as pedestrians could stay in communication. The radio in the subject's car was equipped with an earphone so that the experimenter could monitor communications without the subject's knowledge. In the few instances in which the experimenters had to send a message, it was sent using a simple code by closing the microphone switch.

In addition to the subject, six people were involved in each session as experimental staff. An experimenter rode in the subject's vehicle, gave instructions to the subject, collected data, and was the only member of the staff that a subject was aware of before the end of an experimental session. The rest of the staff consisted of the three drivers of the target-placing cars and two riders who served as pedestrians to be detected by the subject.

5.1.4 Design. Four beam patterns were used: standard 6014 low beams and three experimental patterns designated A, D, and G. The dependent measure was detection distance for selected examples of objects commonly encountered on roadways, referred to here as detection targets. Four kinds of detection targets were used: signs, parked cars, pedestrians, and common roadside debris (four tire-tread scraps, two old mufflers, one crumpled paint bucket, and one section of exhaust pipe). The targets were placed on the right shoulder in five different road situations: level straight, level straight with glare source present, downgrade beyond a hill crest, right curve, and left curve. See Figures 5.8, 5.9, and 5.10 for examples of target placements. The overall design was an incomplete layout selected from the complete factorial combination of these three factors with

Figure 5.8. Debris placement.

Figure 5.9. Parked car placement.

Figure 5.10. Glare car with pedestrian target.

subjects (beam x object x road situation x subject). Two patterns of presentations were selected and each was given to half the subjects. The patterns were constructed by combining the selections from object x road situation given in Figure 5.11 with beam patterns. Half of the subjects received Alternative A selections with two of the beams and Alternative B with the other two systems. The other half of the subjects had this pattern reversed. Order of beams was balanced across subjects in a Latin-square pattern.

5.1.5 Procedure. Each subject participated in two sessions. The first consisted of a series of visual tests and an interview about past driving experience. Subjects who did not meet the criteria mentioned above (Section 5.1.1) were not used in the second sessions.

The second session was a night-driving session. Each subject was run on a separate night. Sessions began as soon as it was fully dark. Subjects were instructed to drive as they normally would, and to do two additional things as they drove: 1) to respond to any feature of the visual field that attracted their attention as drivers by pushing the button attached to their steering wheel as soon as they detected the feature, and by giving a verbal identification for it, and 2) to rate the discomfort they experienced when they looked into an oncoming pair of headlights by assigning it a number between 1 and 9. They were told that 1 corresponded to "no noticeable discomfort," 9 to "intolerable discomfort," and 5 to "maximum acceptable discomfort."

Each subject drove the test route twice, thus covering a total of 52 miles. Each of the four 13-mile sections was assigned to a different headlight beam pattern, and contained a selection of planted targets, as specified in the design. Each of the 13-mile sections was divided into two approximately equal subsections, yielding a total of 8 subsections. This division into subsections was done for practical reasons having to do with placing planted targets, and was irrelevant to the design.

For each subsection, the procedure was as follows: The subject and the experimenter who was riding with the subject, waited at the

ALTERNATIVE A:

	OBJECT TYPE			
Road Situation	Sign	Parked Car	Pedestrian	Debris
Straight	X	X	X	X
Straight, glare		X	X	
Hill	X			X
Right curve	X			X
Left curve		X	X	

ALTERNATIVE B:

	OBJECT TYPE			
Road Situation	Sign	Parked Car	Pedestrian	Debris
Straight	X	X	X	X
Straight, glare	X			X
Hill		X	X	
Right curve		X	X	
Left curve	X			X

Figure 5.11. Combinations of levels of object and road situation used in incomplete layout for detection-distance study.

beginning of the subsection while the five assistants, using the other three cars, set up the proper targets for that subsection. (Appendix B is a course guidebook used by the assistants in placing targets at the proper locations. Appendix C is an example set of instructions for the staff that constitutes a set-up protocol for one condition in the design.) When the targets were ready, one of the staff signaled the subject's vehicle by radio. The experimenter then directed the subject to start driving. (Throughout the experiment the subject was unaware of the activities of the staff. The waiting periods, each approximately four minutes long, were explained to the subject as being necessary to allow the experimenter to perform various checks on the subject's vehicle.) When the subject reached the end of a subsection, the experimenter directed him to pull off of the road for another brief layover. The setup for the next subsection then began.

When a placed target involved a source of glare, the car with the same headlamp system as the subject's car was using for that section was employed to provide the glare. The glare car was positioned just off of the road on the left (from the subject's point of view) and directly across from the object or pedestrian that the subject was supposed to detect (see Figure 5.10). The car was parked rather than moving for safety reasons and because of the timing difficulty involved in arranging a meeting of the subject car and a moving glare car.

When the placed target was a piece of road debris, the object was placed on the shoulder at the edge of the paved road surface (figure 5.8). Pedestrians positioned themselves on the shoulder, walking slowly toward the subject vehicle as it approached them.

Each time the subject's response was to a target designated in the design, the experimenter recorded the time and distance from the subject's button press until the subject's vehicle reached the target. The subject of course did not know which features of the visual field were designated targets, and his instructions were to respond to any attention-getting features. All of his non-target responses were ignored. Similarly, the subject's glare discomfort ratings for the placed glare cars were recorded, and his other ratings were ignored. As a second measure of glare from the headlighting systems, each time the subject's vehicle met an oncoming car (except for the planned meetings with another experimental vehicle) the experimenter, riding with the subject, recorded whether or not the oncoming driver made a dimming request with a high-beam flash.

5.1.6 Results. One type of object--debris--went undetected on 47% of the occasions that it was presented. Since it drew so few responses, it was not included in the analysis of detection distances.

Mean detection distances for the four headlight systems are presented in Table 5.2 and Figure 5.12. These means represent the overall design collapsed over road situations, target types, and subjects. Analysis of variance showed the main effect of the headlight system to be statistically significant, $F(3, 33) = 2.95$, $p < .05$.

TABLE 5.2. Mean detection distance for each headlight system.

Headlight System	Distance (ft.)
6014 low	388
System A	410
System G	390
System D	265

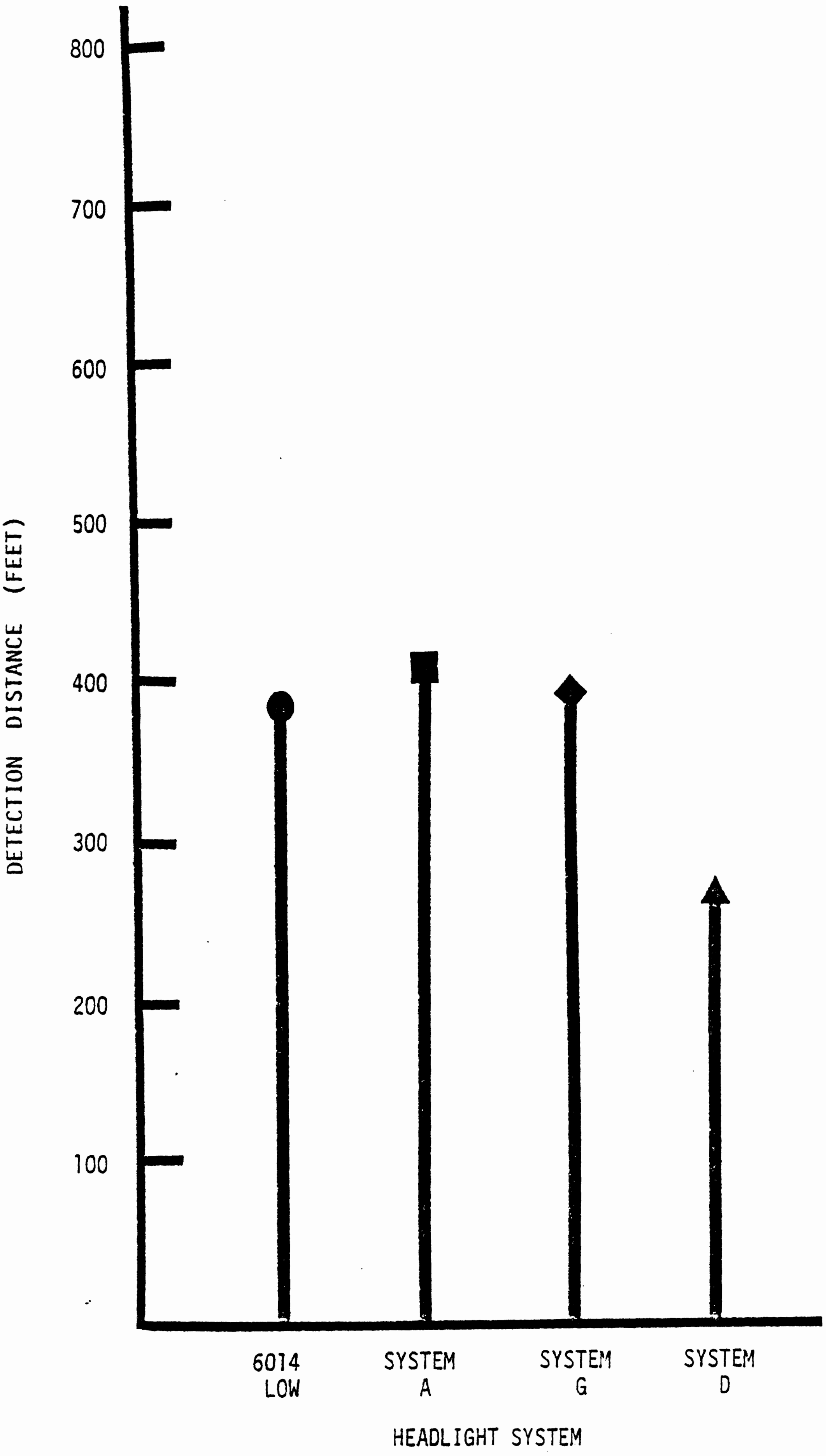

Figure 5.12. Mean detection distance for each headlight system.

Means for each level of road situation and target type are given in Table 5.3 and 5.4, and in Figures 5.13 and 5.14. The effects of road situation, $F(4,44) = 60.31$, $p < .001$, and target, $F(2,22) = 146.3$, $p < .001$, were highly significant.

TABLE 5.3. Mean detection distances in each road situation.

Road Situation	Distance (ft.)
Straight	547
Straight with glare	377
Hill	322
Right curve	164
Left curve	200

TABLE 5.4. Mean detection distance for each type of detection target.

Target	Distance (ft.)
Sign	615
Parked car	401
Pedestrian	98

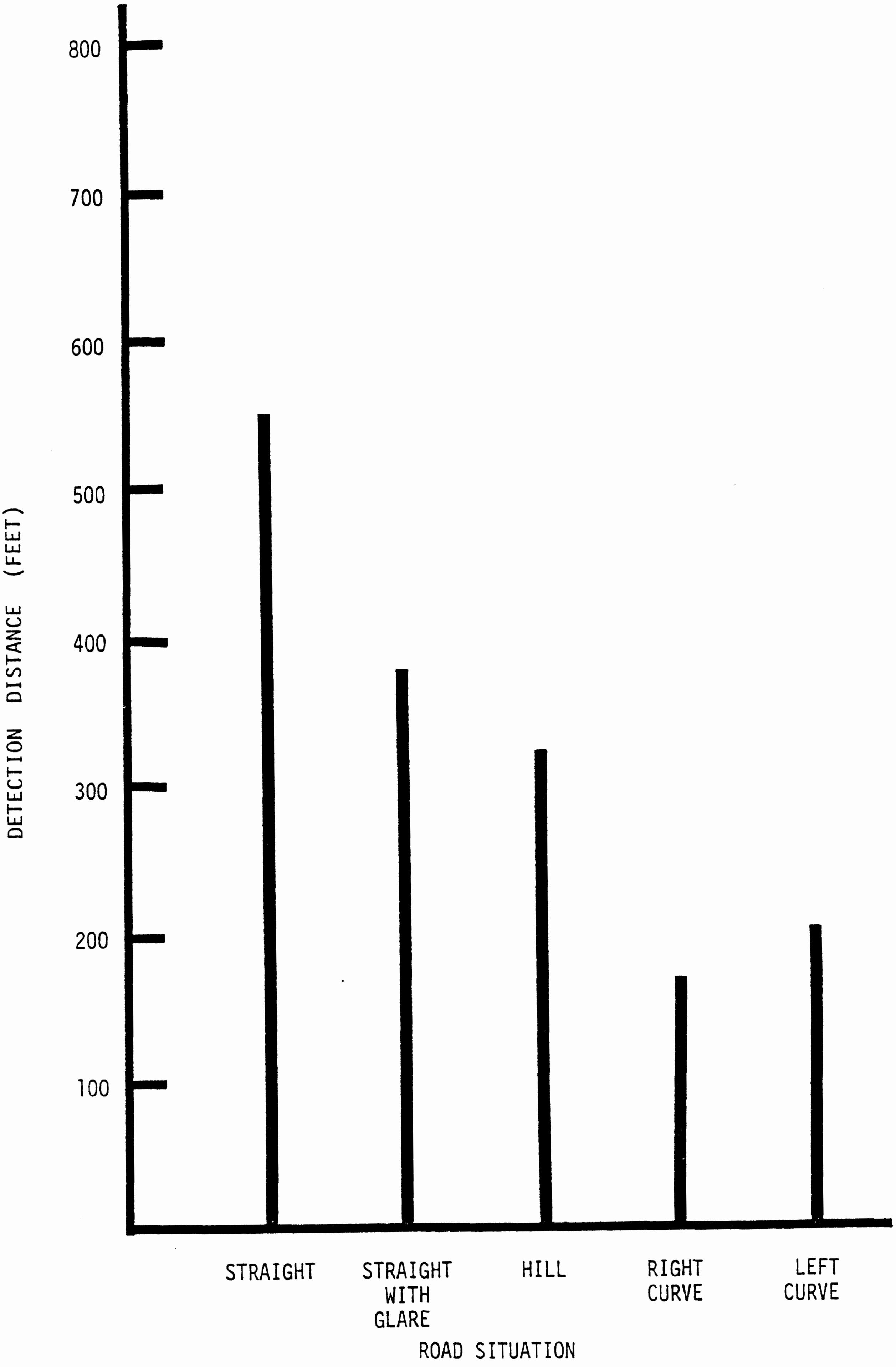

Figure 5.13. Mean detection distances in each road situation.

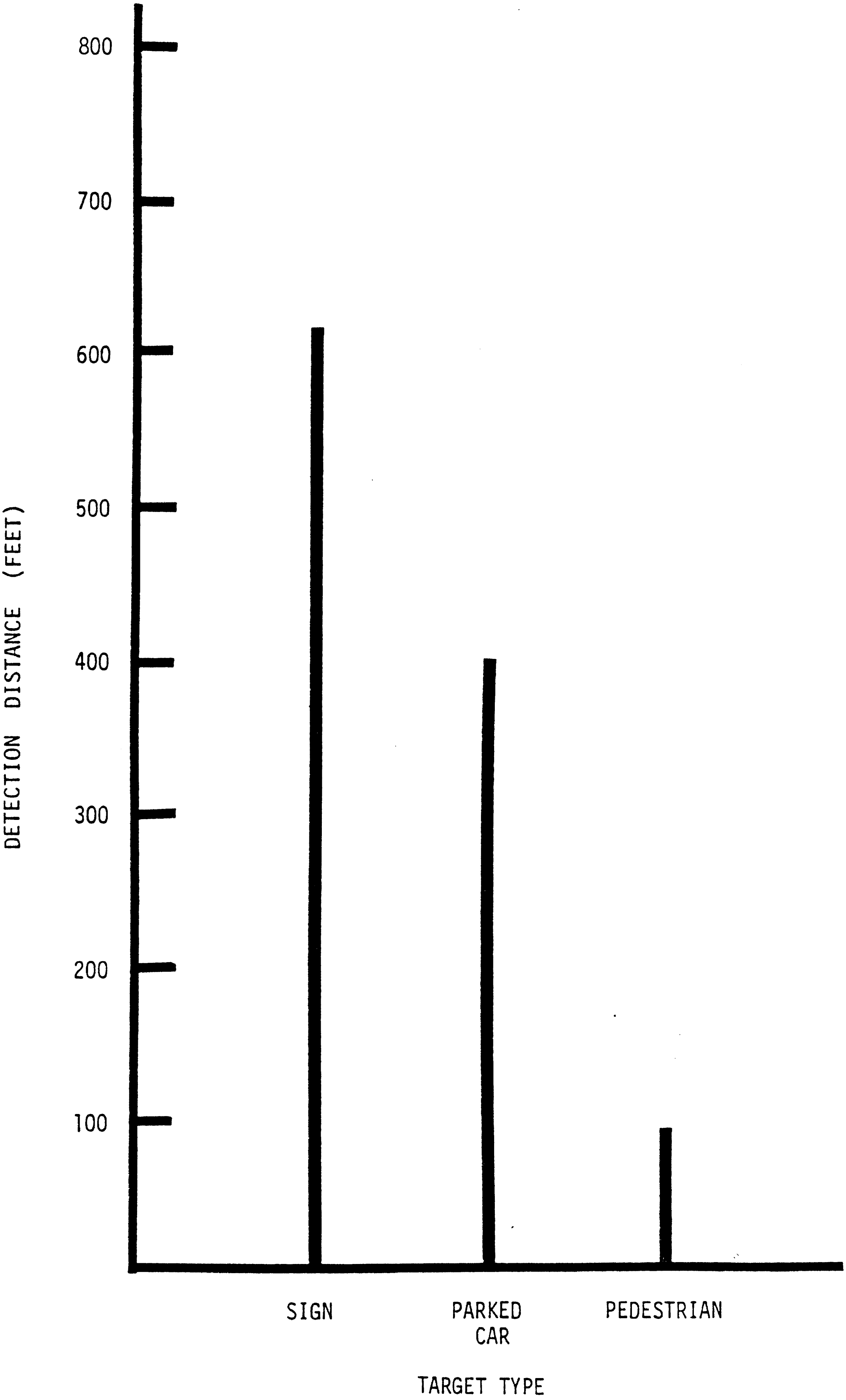

Figure 5.14. Mean detection distance for each type of detection target.

Two interactions are of potential interest in evaluating the various headlighting systems: headlighting system with road situation and headlighting system with target type. The mean detection distance for each system and each road situation are given in Table 5.5 and Figure 5.15. The interaction trend in these data is not statistically reliable, F (12, 132) = 1.39, $p > .10$. The means for each system and each target type are given in Table 5.6 and Figure 5.16. The interaction of these two factors is also not reliable, F (6,66) = .98, $p > .25$.

TABLE 5.5. Mean detection distances for each headlight system in each road situation.*

Road Situation	Headlight System			
	6014 Low	System A	System G	System D
Straight	584	640	606	356
Straight with glare	439	441	404	223
Hill	341	321	324	300
Left curve	169	156	147	191
Right curve	183	224	242	156

* Distances are in feet.

TABLE 5.6. Mean detection distances for each headlight system and each type of target.*

Target	Headlight System			
	6014 Low	System A	System G	System D
Sign	688	711	625	433
Parked car	414	448	437	308
Pedestrian	96	113	112	70

* Distances are in feet.

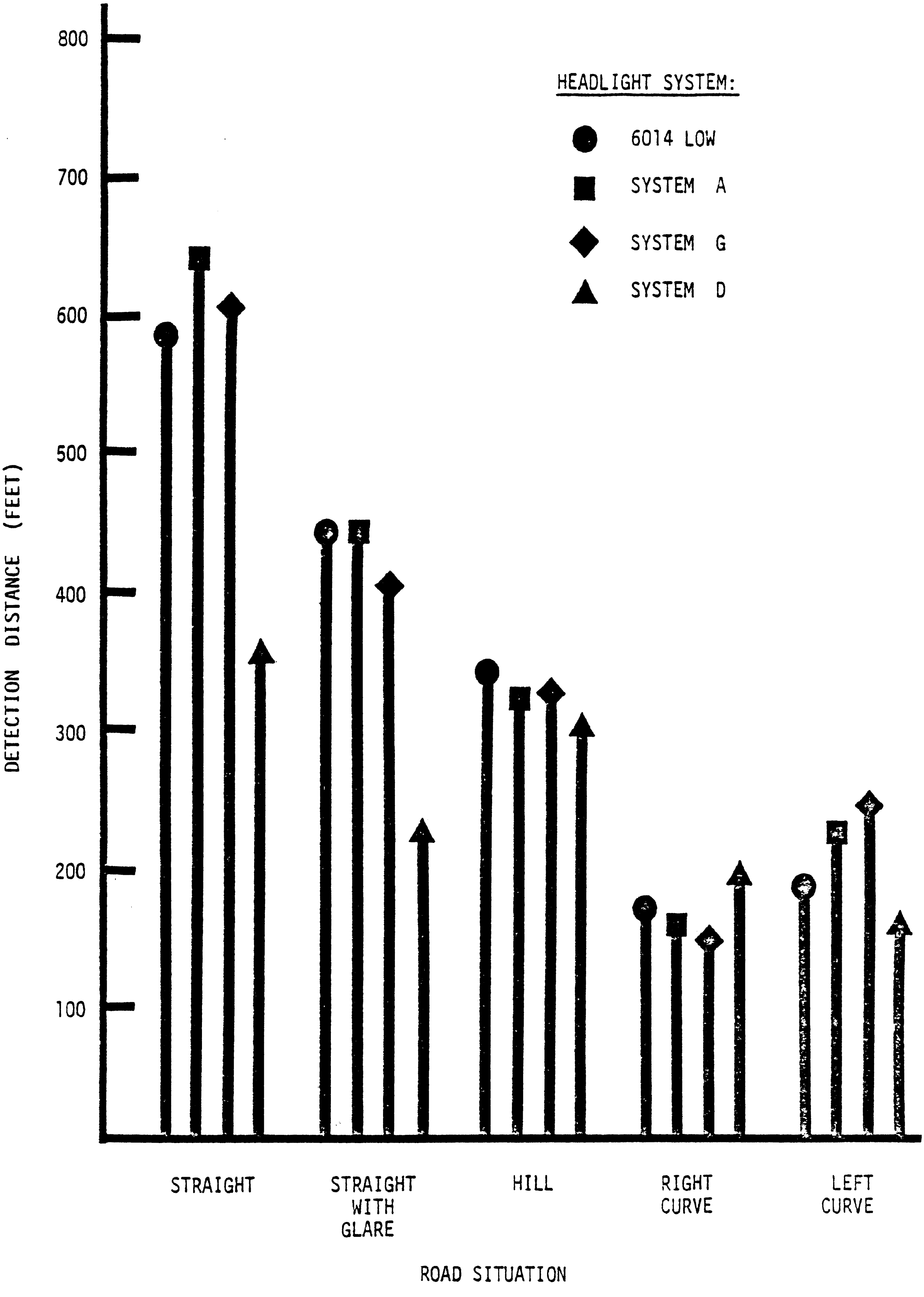

Figure 5.15. Mean detection distances for each headlight system in each road situation.

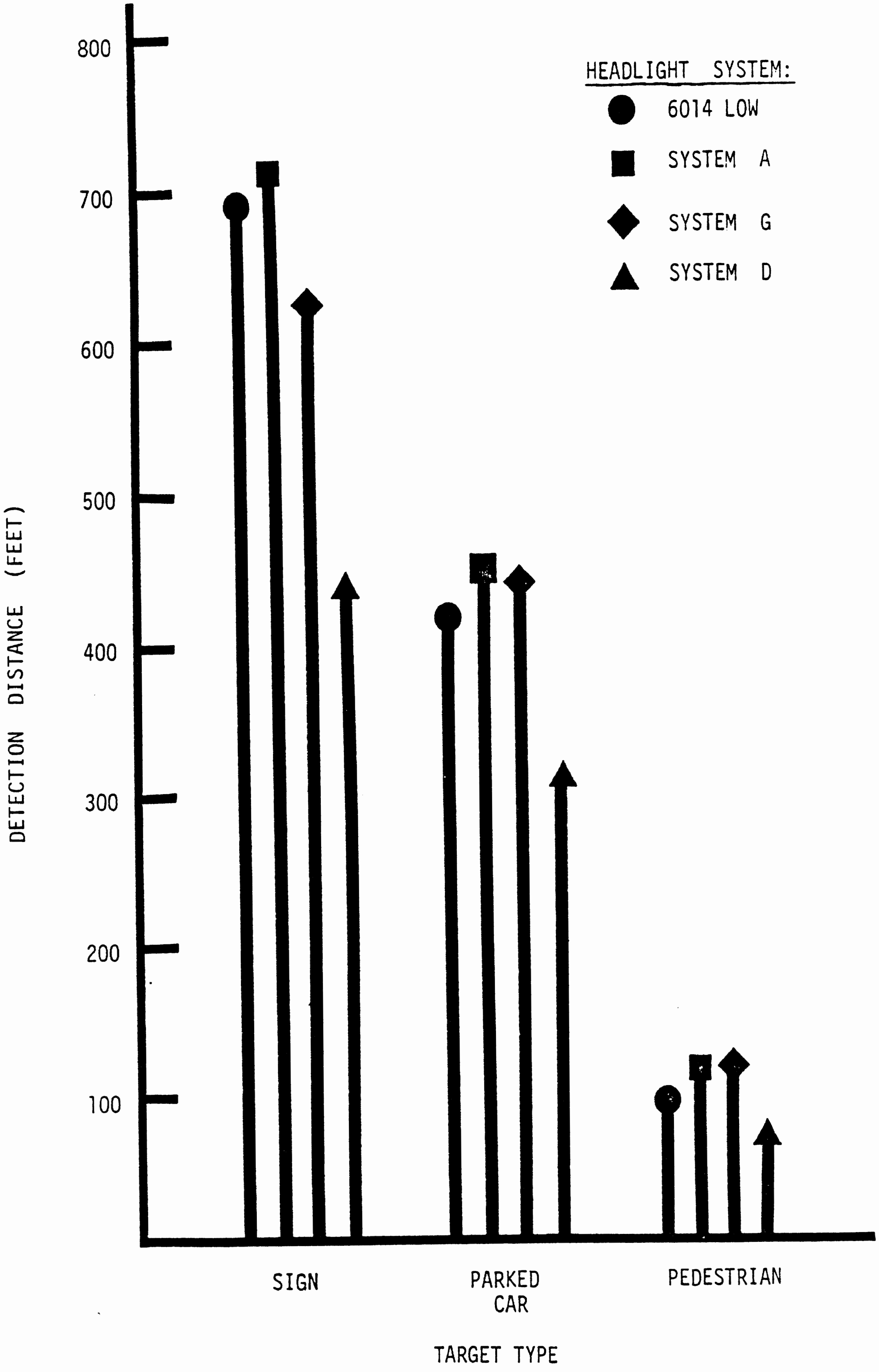

Figure 5.16. Mean detection distances for each headlight system and each type of target.

Subject's ratings of discomfort glare upon encountering the various headlight systems are presented in Table 5.7. The effect of headlight system in these data is highly significant, F (3, 9) = 27.5, $p < .001$. The other measure of glare, dimming requests by oncoming drivers, is reported in Table 5.8. (This table categorizes the 730 meetings between the subject vehicle and vehicles not intentionally involved in the experiment that occurred during the 12 nights of testing.)

TABLE 5.7. Mean glare ratings for each headlight system.

Headlight System	Rating
6014 Low	4.50
System A	5.46
System G	6.63
System D	6.63

Note: Scale ranges from 1 ("no noticeable discomfort," through 5 "maximum acceptable discomfort," to 10 "intolerable discomfort").

Table 5.8. Oncoming cars categorized for each headlight system by whether or not they gave a dimming request.

	Headlight System				
	6014 Low	System A	System G	System D	Total Requests
Dimming request	1	10	13	0	24
No request	179	168	164	195	706
Total oncoming cars	180	178	177	195	730

5.2 Subjective-Rating Study

5.2.1 Subjects. Four males between the ages of 19 and 30, recruited on the University of Michigan campus, were paid for their participation. All met the same criteria as the subjects in the detection-distance study. None had served as subjects in that study.

5.2.2 Route. Testing was done on a 20 mile course. The course formed a closed loop, and was divided into four sections of approximately equal length. Each section was typical of a different type of road: 1) an unlighted rural road with many hills and curves, 2) an urban and residential area with some street lighting, 3) an unlighted, straight rural road, and 4) an unlighted, major divided highway.

Traffic was light on all sections of the route at the time of testing. Testing was done in dry weather, with no fog, and very little moonlight.

5.2.3 Equipment. The 1971 Plymouth Fury station wagon used in the detection-distance study was used, equipped with the four headlight systems as described above.

5.2.4 Procedure. Each subject drove the test-course loop four times. An experimenter rode with him and switched the headlighting systems before each quarter section of the loop. Headlighting systems were balanced across route sections for each subject in a Latin-square pattern. Subjects thus used each system four times, each time on a different type of road.

Before beginning the driving sessions, the subjects were acquainted with a set of six scales to be used in rating the headlight systems. Subjects were asked to select a number from 0 to 10 to represent a headlight system's performance from "extremely poor" to "extremely good" on dimensions identified as: 1) overall illumination, 2) foreground illumination, 3) illumination to the left, 4) illumination to the right, 5) maximum distance down the road receiving illumination, and 6) illumination of overhead signs. The form that subjects used in giving their ratings appears as Appendix D.

Subjects were instructed to simply drive the test course, paying attention to the headlight pattern and keeping the six rating scales in mind. They were given a rating form to fill out after each quarter section of the course. They were told that the headlight system would be changed for each quarter section, but they were not informed about the total number of systems, and the systems were not identified for them.

5.2.5 Results. The scale for illumination of overhead signs drew very few responses and was dropped from the analysis of results. Mean ratings for each system on each scale are presented in Table 5.9 and Figure 5.17. These means are collapsed over type of road. Separate analyses of variance for each rating scale yielded significant main effects of headlight system in each case (see Table 5.10). Main effects of road types and road type x headlight system interactions did not approach significance.

Table 5.9. Mean ratings for each headlight system on five scales.

	Headlight System			
	6014 Low	System A	System G	System D
Overall	6.00	7.50	5.94	4.44
Foreground	6.81	7.75	6.81	5.81
To left	5.25	6.63	7.00	5.44
To right	6.63	7.94	5.00	6.38
Maximum distance	5.89	7.44	5.63	3.19

(9 = extremely good, 1 = extremely poor)

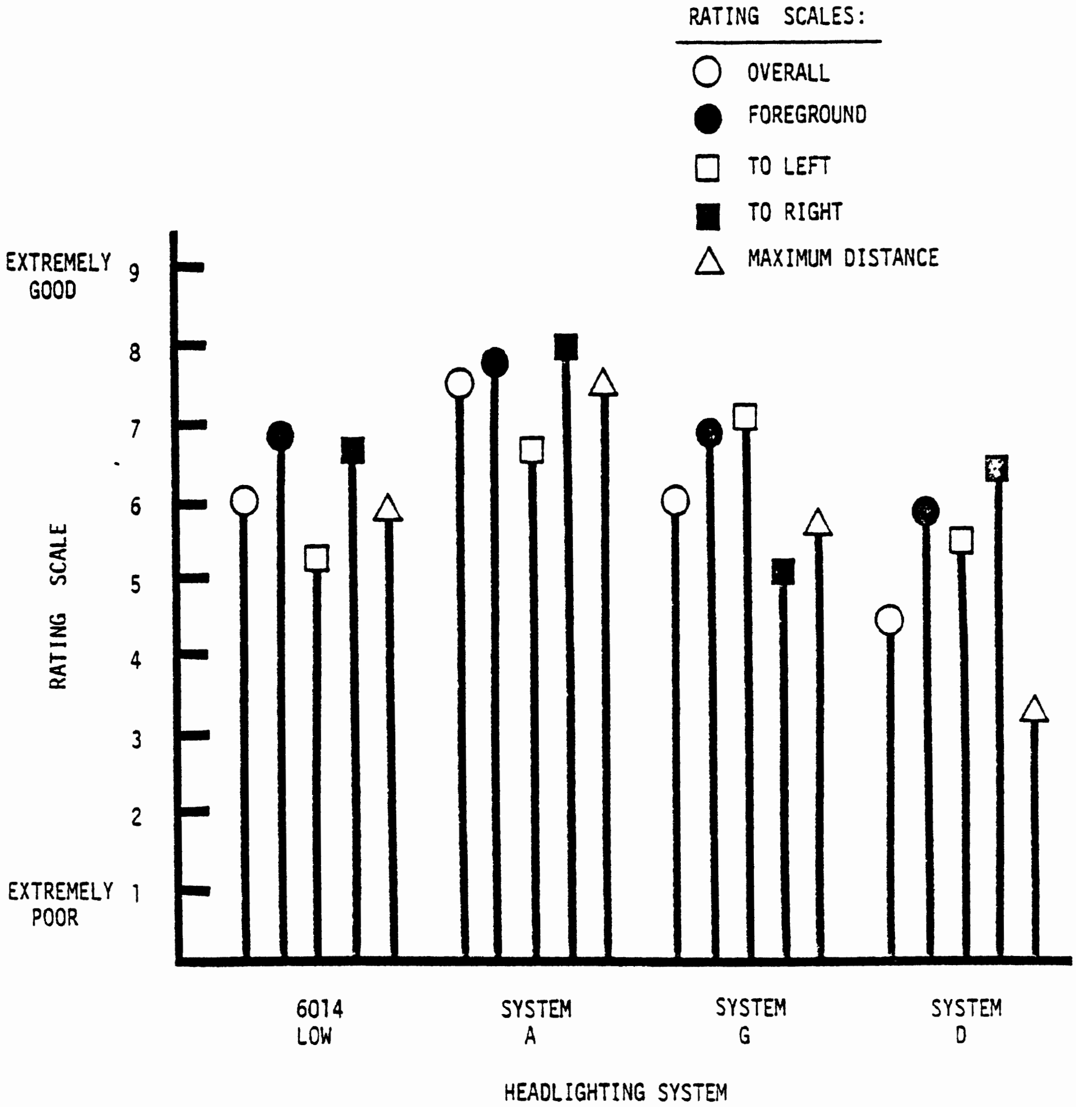

Figure 5.17. Mean ratings for each headlight system on five scales.

TABLE 5.10. F ratios for main effects of headlighting system from separate analyses of variance for five rating scales.

Scale	F*	P
Overall	27.5	<.001
Foreground	6.7	<.05
To left	8.0	<.01
To right	13.6	<.01
Maximum distance	26.8	<.001

* 3, 9 d.f.

5.2.6 Special Reanalysis. The computer analysis gave us reason to anticpate that system G would provide a significant improvement over the standard 6014. The data from the various field test suggest otherwise. As was noted earlier, the lamps as delivered differed in significant respects from the specifications on which the computer analysis was based.

The HSRI simulation was run again at this point, using data from the lamps as delivered. These results showed a significant drop in predicted performance, closely approximating that measured in the field test.

6.0 SUMMARY AND CONCLUSIONS

This study sought to develop an improved headlamp beam for use in conditions of oncoming or preceding traffic. The importance of the low or meeting beam is especially clear when consideration is given to the fact that many drivers are rarely in a situation which allows use of high beams. Many other drivers, for some reason, do not always use high beams, even when it would easily be possible. Thus, a large fraction of the driving public has, for all practical purposes, a single-beam system.

In this investigation two computer headlamp evaluation models were used as a means of screening a number of possible beam patterns. The three most promising of these were fabricated for field test.

The field test was run on public roads, using subjects who were not aware of the actual purpose of the test, and targets which appeared normal to the environment. A subjective evaluation was carried out as well.

The results of the testing indicated that the best of the test lamps was only marginally better (although the differences were not statistically significant) than the standard SAE low beam used for comparison. One of the lamps was significantly poorer in many of the measures.

The following conclusions are based on the results of this investigation.

First, the data suggest that overall improvements in low-beam headlighting will not come easily. This should not be surprising, given the many years of development which have gone into the present system. Unless there is a significant "breakthrough," equivalent to polarization, improvements in low-beam headlighting will be modest, and likely short of what is required to provide adequate visibility under all driving conditions.

Second, the results of the simulation work, in particular, indicate that it might be more profitable to attempt local rather than global improvements. Thus, the designer might attempt to improve the likelihood of detecting pedestrians by directing more illumination to those areas which, based on collision data, seem most important for pedestrian safety. Alternatively, sign visibility and edge delineation might be emphasized.

Third, although the field data were disappointing, the results of the computer simulation suggest that system G is very promising. This configuration should, in the opinion of the investigators, be fabricated to more closely approximate the desired photometrics, and be further evaluated.

Certain recommendations for future research can be made, based on the investigators' knowlege of the problem area and experience in this study.

A major limiting factor in headlighting design is glare. Disability glare is well understood; in our opinion, discomfort glare is not. Given that discomfort glare is a key consideration in lamp design, it seems imperative that more effort go into understanding it. Data are needed defining the upper limits of discomfort glare for both short- and long-term exposure. Special emphasis in this research should be given to those persons likely to be most affected by glare (e.g., the elderly). Data from such a study may indicate that is is feasible to increase headlamp intensity. At the very least, it would provide a better rationale than is available today for setting intensity levels for light projected above horizontal.

Another source of controversy is foreground illumination. It is argued that high levels of foreground illumination may: (1) raise the level of adaptation unnecessarily, and/or, (2) cause the driver to spend more time looking at the highly illuminated area close to the car than is desirable. This seems to be a matter of opinion only; the investigators are aware of no studies on the issues. It would not be a difficult matter to investigate, and it should be done.

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APPENDIX A

CHESS EVALUATION OF SIX HSRI SINGLE-BEAM HEADLIGHT SYSTEM DESIGNS

CHESS EVALUATION OF SIX
HSRI SINGLE-BEAM HEADLIGHT
SYSTEM DESIGNS

OPERATIONAL FACTORS DEPARTMENT
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FORD MOTOR COMPANY
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AUGUST 22, 1978

CHESS EVALUATION OF SIX HSRI SINGLE-BEAM HEADLIGHT SYSTEM DESIGNS

Objectives

Six single beam headlamp system designs and five reference systems were analytically evaluated by Ford's CHESS* (Comprehensive Headlamp Environment Systems Simulation) model to determine the percentage of night driving mileage with each system in which certain visibility and glare criteria are met. The six candidate single beam headlight systems were developed and are currently being studied by the Highway Safety Research Institute (HSRI) of the University of Michigan under an NHTSA contract (Evaluation of the Feasibility of a Single Beam Headlighting System, Contract No. DOT-HS-7-01554). Ford was asked to conduct the CHESS analyses by NHTSA to provide a broader data base for evaulating and comparing the systems.

Summary of Findings

The six HSRI systems tested were: four new low beam designs; a conventional low beam system augmented by a continuously-on midbeam ("turnpike beam") lamp; and a current low beam with very high candlepower.

The Figures-of-Merit (overall performance scores indicating the percentage of night driving mileage in which the visibility and glare criteria are met) of the new low beam designs ranged from 60.0 to 62.2. Current low beams range from 65.7 to 67.1 (A difference of two Figures-of-Merit points is significant at the 90% confidence level.) The reference low beam provided by HSRI produced a Figure-of-Merit of 67.9 even though its glare discomforted 16.2% of opposing drivers. (Current low beams discomfort from 9.0 to 10.3% of opposing drivers.) The Figure-of-Merit for the HSRI mid beam was 70.1. This lamp discomforted 13.9% of opposing drivers. These last two systems have relatively high Figures-of-Merit despite increased discomfort glare largely because they produce significant increases in the percentage of exposed pedestrians detected in time to stop.

The CHESS Program

Evaluations of the systems provided by HSRI and a number of additional reference systems were conducted with the CHESS model. CHESS was developed to provide a more comprehensive evaluation of headlamp performance than is possible in a limited set of

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*In earlier papers CHESS has been referred to as the Headlight Evaluation Model.

seeing distance tests or simulations. Input to the model consists of the candlepower patterns of the test headlight system. This system is then evaluated in thousands of visibility and glare "tests" on a standardized test route which simulates the broad range of conditions encountered in night driving. The output of the model, termed the "Figure of Merit," is the percentage of distance traveled on the standardized test route in which the criteria of lane line and pedestrian visibility, and opposing driver glare are simultaneously met.

CHESS is based on an extensive program of road tests, surveys of the night driving environment and analyses of the published literature. A detailed description of the development and characteristics of CHESS is given in Reference 1.

Test Conditions

The six HSRI headlamp systems along with five systems from the Ford headlamp data files were each evaluated under the 6180 identical randomly selected encounters that comprise standardized test route "B".*

Table 1 presents descriptions of the eleven systems evaluated in this project. The Table gives the values and locations of maximum candlepower points and the average candlepower values of each beam pattern. The energy consumed by a headlamp system would be directly related to the average beam candlepower. The candlepower distributions of the headlamps of the eleven systems are presented in Appendix A.

The CHESS model was exercised to evaluate each of the above eleven systems under the following two conditions:

(a) Perfect aim: This condition assumed that all headlamps under the simulation were aimed properly, i.e., the optical axis of each headlamp (the point H = 0, V = 0 on the isocandela diagram) was parallel to the vehicle X (fore-aft) axis.

1/ V. D. Bhise, E. I. Farber, et al, "Modeling Vision with Headlights in a Systems Context," presented at International Automotive Engineering Congress and Exposition, Society of Automotive Engineers, Paper No. 770238, March, 1977.

*Note that Route B is very similar to the Route A described in Reference 1. The only difference between the routes is that previously stated speeds have been corrected and are six miles per hour higher than in Route A.

TABLE 1

Description of Headlamp Systems

	System Number	Description	Maximum Candlepower		Average Candlepower[1] Single Lamp Unit (cp)
			Value in CP	Location	
HSRI Studied "Candidate" Single Beam Headlamp Systems	A	7" diameter current type 2 low beam (#6014)	39,300	2°R, 1.5°D	6256
	B	Modified low beam	40,000	0°R, 0.5°D	4495
	C	Modified low beam	40,000	1.5°R, 0.5° D	4154
	D	U-Shaped modified low beam	40,000	1°R, 0°D	4219
	E	Modified low beam	40,000	0°R, 0.5°D	4749
	F	Mid beam experimental lamp[4] with current (#4000) low beam	78,212 (mid) 21,838 (low)	2°R, 1°D 2.5°R, 2°D	5744 (mid) 4095 (low)
Reference Systems from Ford Headlamp Data Files	1	4"x6" rectangular type 2A low beam (#4652)	18,394	3°R, 1°D	3815
	2	5 3/4" diameter, type 2 low beam[2] (#4000)	21,834	2.5°R, 2°D	4095
	3	7" diameter type 2 low beam[2] (#6014)	26,014	2.5°R, 2°D	4658
	4	European Halogen (H4) rectangular	18,928 (left) 16,181 (right)	3.5°R, 1°D 1.5°R, 2°D	3072 (left) 2785 (right)
	5	Mid beam experimental (type 4) lamp[3] with current (#4000) low beam	45,400 (mid) 21,838 (low)	2°R, 0.75D 2.5°R, 2°D	5660 (mid) 4095 (low)

NOTE: 1. Average candlepower was obtained by determining mean of candlepowers in 451 (i.e. 41 x 11) cells at 1/2° x 1/2° size within the lamp field bounded by 10° left to 10° right and 3° down to 2° up.

2. Candlepower distributions of systems 2 and 3 were based on mean candlepower values from a random sample of 20 lamps of each category.

3. The candlepower distribution type 4 lamp used in System 5 was developed according the photometric specifications proposed in the NHTSA Docket 69-19, Notice 3.

4. Note that mid beam unit used in System F produced 78,212 cp-maximum which is well above the 60,000 cp-maximum proposed in NHTSA Docket 69-19, Notice 3

(b) With Misaim: This condition represents realistic variability associated with headlamp aiming. The headlamp aim under this condition was treated as a random variable. That is, the headlamp aim for each encounter was randomly selected from distributions developed by Hull, et al (2).

These distributions include the effects of vehicle pitch attitude deviations which are due primarily to loading. The selection procedure was as follows:

(1) Horizontal aim of each headlamp was randomly selected from a normal distribution with a mean of 0.8 degrees right (as seen by the driver) and a standard deviation of 0.86 degrees.

(2) The vertical aim of all (i.e., both) headlamps of each vehicle were randomly selected from a normal distribution with a mean of 0.73 degrees up and a standard deviation of 1.55 degrees.*

During each model run, both the observer and on-coming vehicles used the same (i.e., identical) headlamp system. Further, in all the model runs, all vehicles used only one beam mode. Thus, in evaulating systems A through E and systems 1 through 4, high beam use was not simulated; and the systems using a mid beam, namely Systems F and 5, were always set on mid beam mode i.e., two low beam lamps plus one mid beam unit.

Results

Results of the CHESS exercises are summarized in Table 2. Table 2 gives for each of the eleven systems tested the Figures-of-Merit under perfect aim and random misaim and, spearately, the percentages of encounters in which the three visual environment criteria--delineation detection, pedestrian detection and discomfort glare level--were met under the random misaim condition. Also shown is the percentage of drivers

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2/ R. W. Hull, R. H. Hemion, D. G. Cadena and B. C. Dial, "Vehicle Forward Lighting Performance and Inspection Requirements." Southwest Research Institute, July 1971.

*Note: Re-analysis of Hull, et al 2/ data showed that the vertical aim components of left, right, low and high beams were highly correlated, whereas the horizontal components of different headlamps on the same vehicle were found to be independent.

Table 2

Results of CHESS Model Applications

						Percentage of Encounters Meeting Visibility Criteria Under "With Misaim" Conditic			
						Unopposed Encounters		Opposed Encounters	
		Figure of Merit		Percentage Of Opposing Drivers Discomforted		Delineations Detected	Pedestrians Detected	Delineations Detected	Pedestrians Detected
System Number	Description	Perfect Aim	With Misaim	Perfect Aim	With Misaim				
A	7" diameter current type 2 low beam (6014)	73.6	67.0	6.5	16.2	87.0	50.5	84.8	34.3
B	Modified low beam	66.4	61.7	22.5	23.7	86.2	44.7	81.5	24.6
C	Modified low beam	66.9	60.9	25.4	20.6	84.5	44.0	80.2	26.4
D	U-Shaped modified low beam	66.6	62.2	19.6	17.1	85.4	43.8	82.4	27.6
E	Modified low beam	67.9	60.0	21.5	25.5	85.3	45.1	80.7	25.9
F	Mid beam experimental lamp with current (#4000) low beam	74.5	70.1	4.2	13.9	88.8	52.9	86.9	36.1
1	4"x6" rectangular type 2A low beam (#4652)	69.8	67.1	2.4	9.2	88.3	43.7	86.2	28.2
2	5 3/4" diameter type 2 low beam (#4000)	69.1	65.7	1.0	9.0	85.4	43.5	76.3	23.5
3	7" diameter type 2 low beam (#6014)	69.7	66.1	1.3	10.3	86.7	47.3	84.8	31.0
4	European Halogen (H4) rectangular	66.6	62.9	0.0	8.1	85.6	41.4	84.1	28.5
5	Mid beam experimental (type 4) lamp with current (#4000) low beam	73.0	69.3	9.8	17.5	88.9	53.2	87.2	33.9

discomforted under perfect aim. (Note that the Figure-of-Merit is the percentage of miles driven in which all three criteria are simultaneously met.)

The four low beam systems developed by HSRI had significantly lower Figures-of-Merit than current U.S. low beams. These lamps were generally comparable to the U.S. low beams in meeting the delineation and pedestrian detection criteria in both opposed and unopposed situations. However, they produced discomfort glare about twice as often as did the current low beams. In each of the four HSRI lamps the hot-spot (peak candlepower point) is more intense and aimed closer to H-V (straight down the road) than U.S. lamps. Even with perfect aim these lamps are often discomforting because mild curves and hills can place an opposing driver in the high intensity portion of the beam pattern. In fact, systems C and D are more likely to produce discomfort when perfectly aimed than when randomly misaimed.

System F, which uses a very intense mid beam unit to augment two current low beam lamps, had a Figure-of-Merit of 70.1 with random misaim, the highest of all the lamps tested, and reliably higher than the 65.7 to 67.1 range of the current U.S. low beam systems tested (Systems 1, 2 and 3). System F had a high Figure-of-Merit despite discomforting 13.9% of opposing drivers (from 40 to 50% more than current low beams) largely because it produced significantly more pedestrian detections in both opposed and unopposed situations. System F's pedestrian and delineation detection performance was comparable to the Ford reference mid beam system (System 5) but it discomforted about 20% fewer drivers.

HSRI System A under random misaim had a Figure-of-Merit of 67.0, a significantly higher value than the other HSRI low beam systems, and discomforted about 16.2% of opposing drivers. The overall performance of System A, as measured by the Figure-of-Merit, is comparable to the U.S. low beams tested despite the fact that it discomforts 60 to 80% more opposing drivers. This is because, like the mid beam system, System A resulted in significantly more pedestrian detections than the U.S. systems. This lamp is considerably more intense than any of the low beams in the CHESS headlamp files. The peak candlepower is 39,000 while the peak values of systems 1, 2 and 3 range from 18,000 to 26,000 cp. The average candlepower of this system is within 10% of the three-lamp mid beam systems.

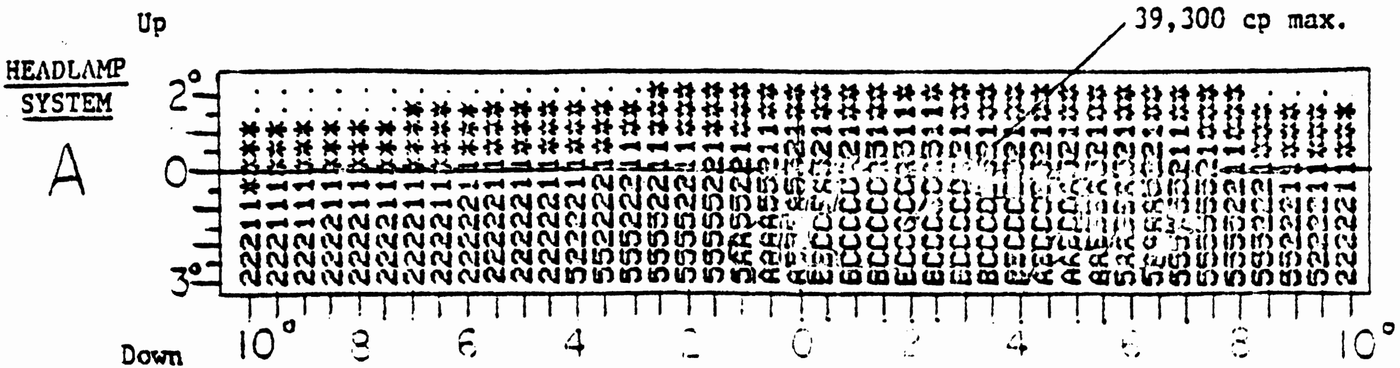
It is noteworthy that the decrease in the Figure-of-Merit in going from perfect aim to random misaim is 6.6 points for System A, whereas for the other lower intensity U.S. low beams the decreases range from 2.7 to 3.6 points. Evidently, System A is more sensitive to misaim.

APPENDIX A

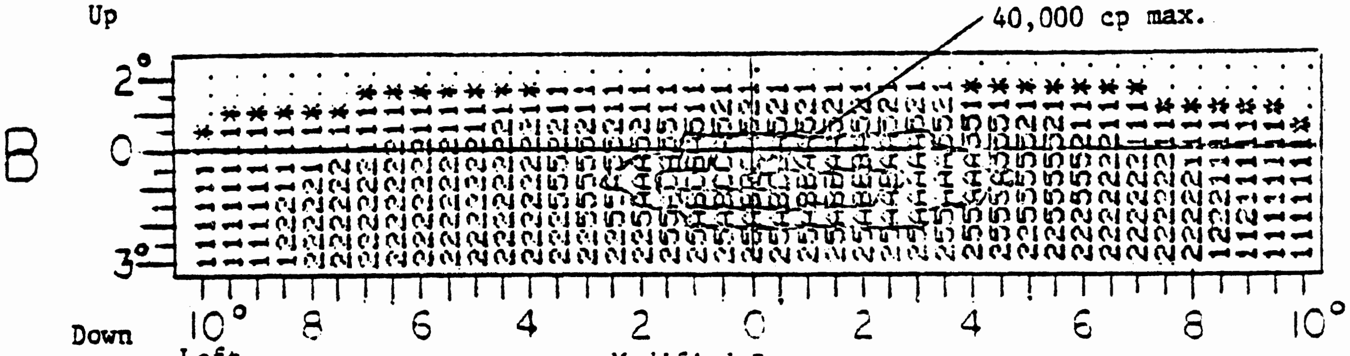
CANDLEPOWER DISTRIBUTIONS

Notation: The characters used in displaying intensity in candlepower (cp) in each 1/2° x 1/2° region in the beam field are as follows:

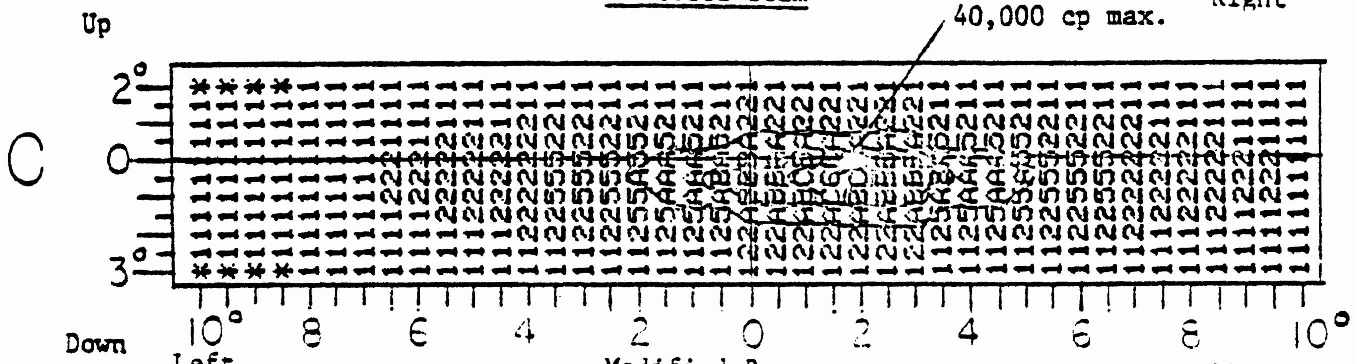
C : intensity ≥ 20,000 cp
B : 15,000 cp ≤ intensity < 20,000 cp
A : 10,000 cp ≤ intensity < 15,000 cp
5 : 5,000 cp ≤ intensity < 10,000 cp
2 : 2,000 ≤ intensity < 5,000 cp
1 : 1,000 ≤ intensity < 2,000 cp
* : 500 ≤ intensity < 1,000 cp
• : 100 ≤ intensity < 500 cp



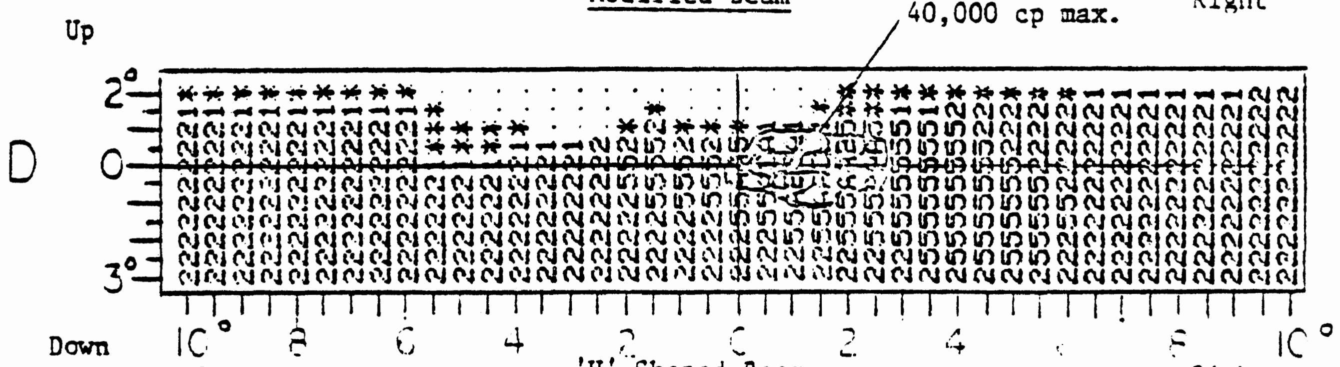
Low Beam (#6014) HSRI Reference



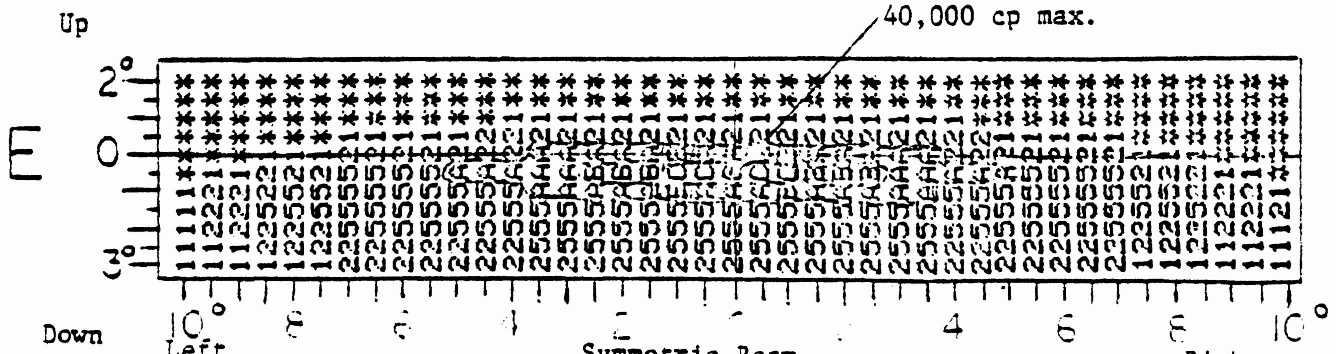
Modified Beam



Modified Beam



'U' Shaped Beam

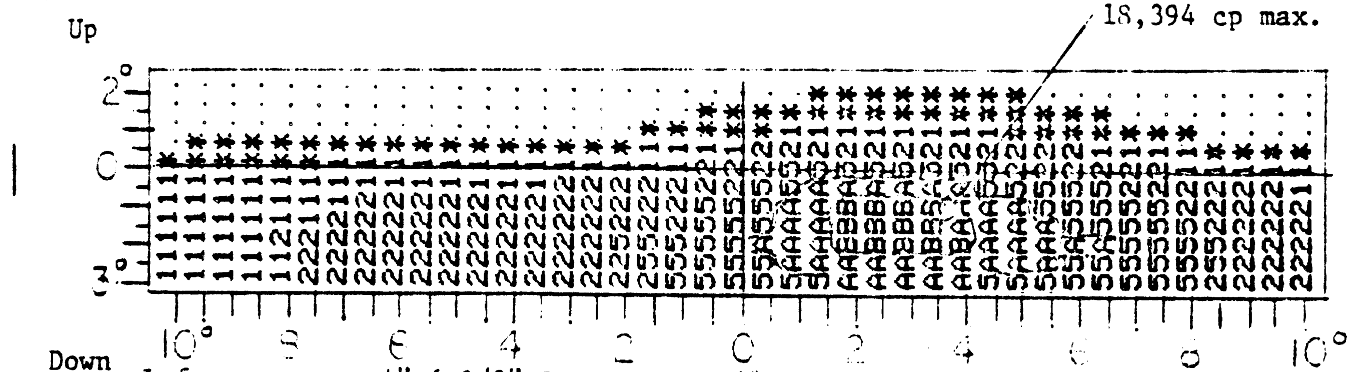


Symmetric Beam

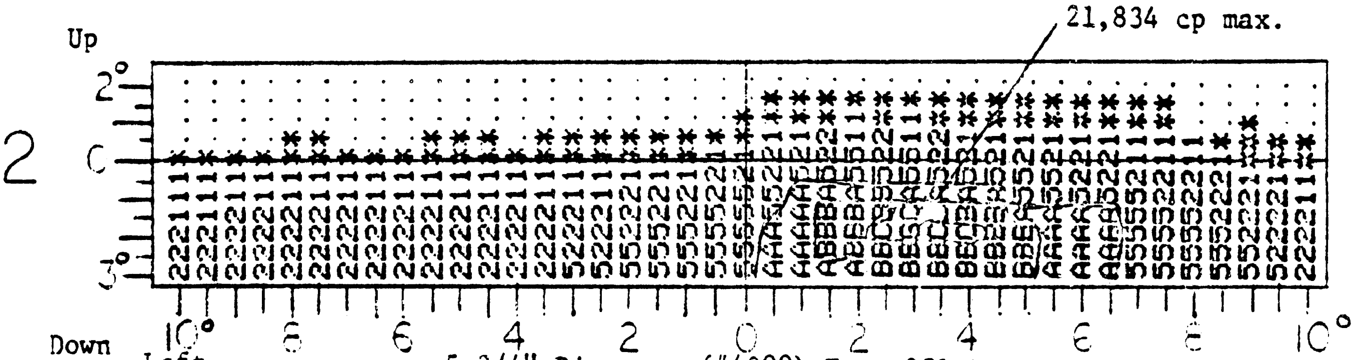
Figure 1. Candlepower Distributions of Headlamps used in HSRI Studied Single Beam Headlighting Systems

(Note: Left and right lamps have identical distributions)

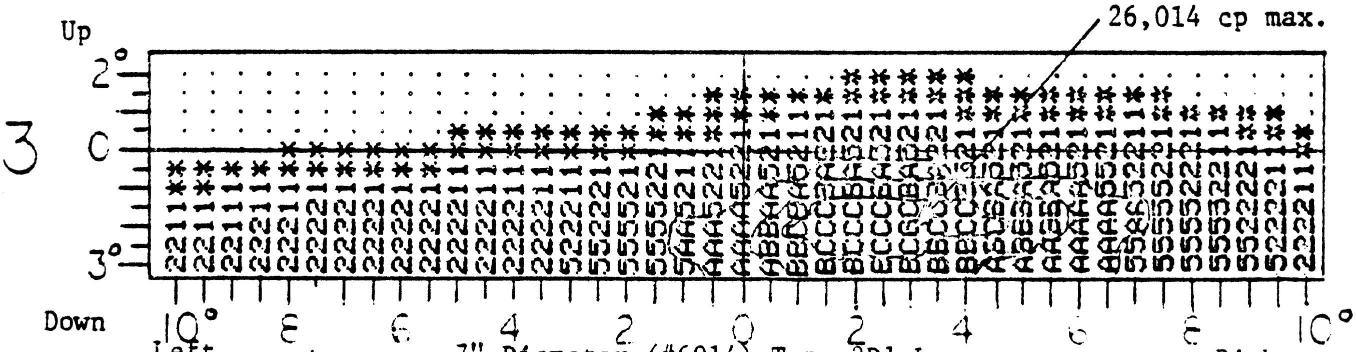
HEADLAMP SYSTEM



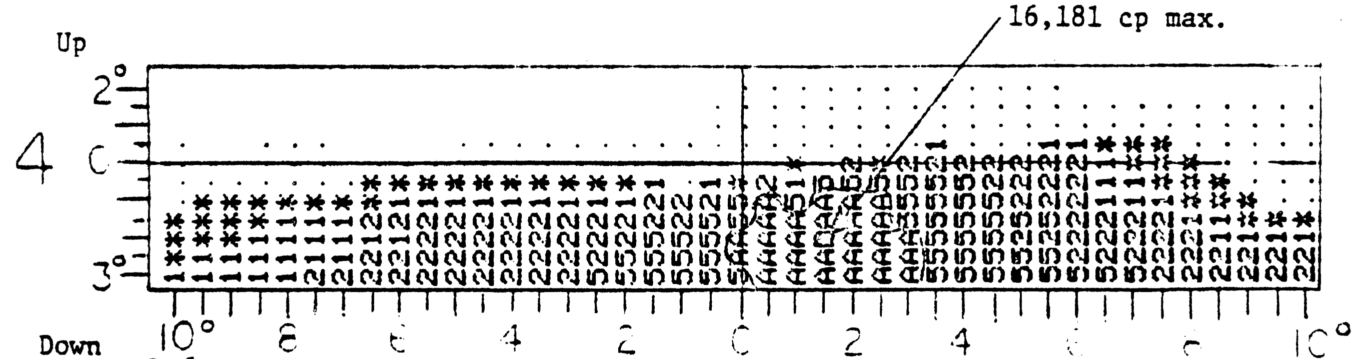
4"x6 1/2" Rectangular (#4652) Type 2A1 Low



5 3/4" Diameter (#4000) Type 2C1 Low



7" Diameter (#6014) Type 2D1 Low



European Halogen (H4) Rectangular
(right lamp)

Figure 2. Candlepower Distribution of Current Headlamps Used as Reference Systems

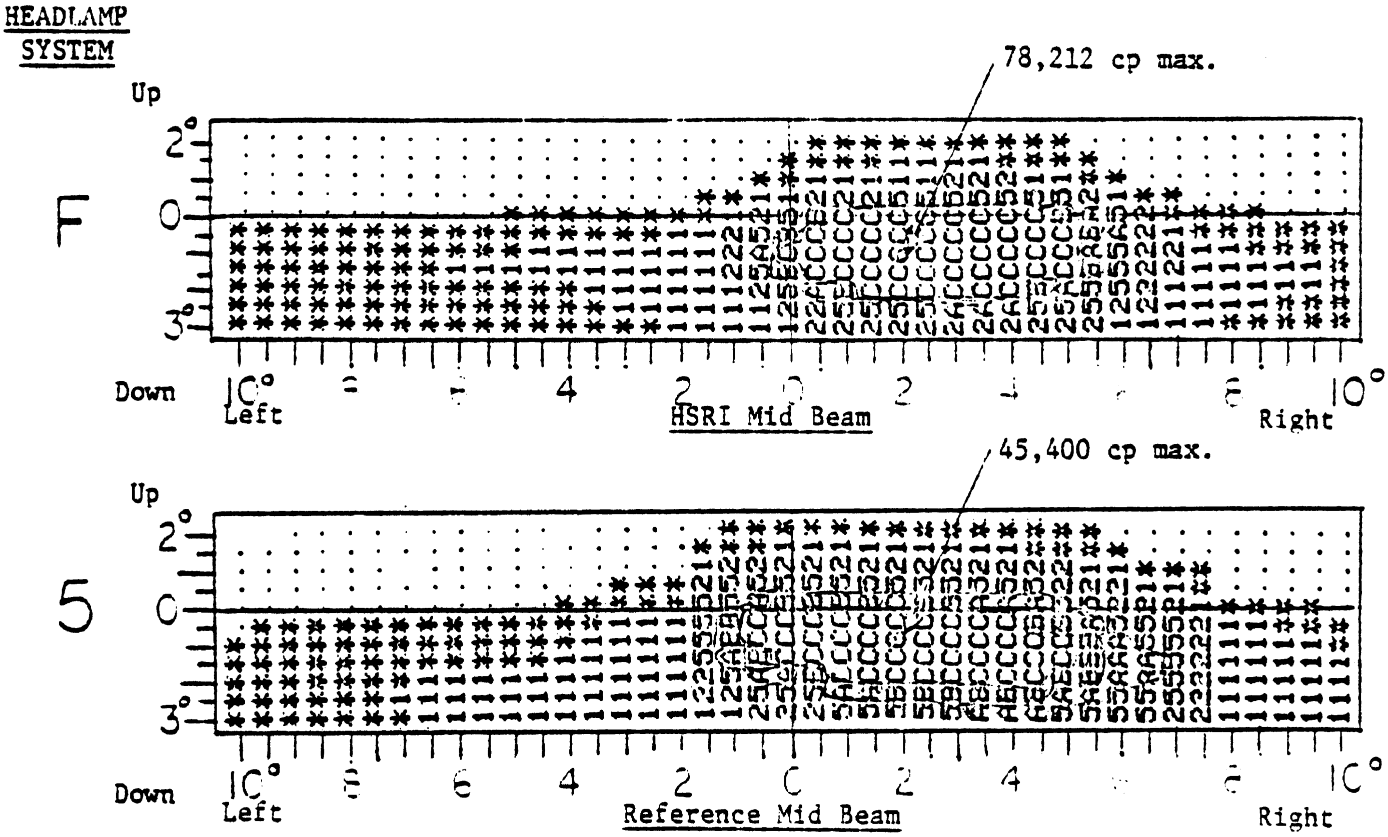


Figure 3. Candlepower Distributions of Mid Beam Headlamp Used in Systems "F" and "5"

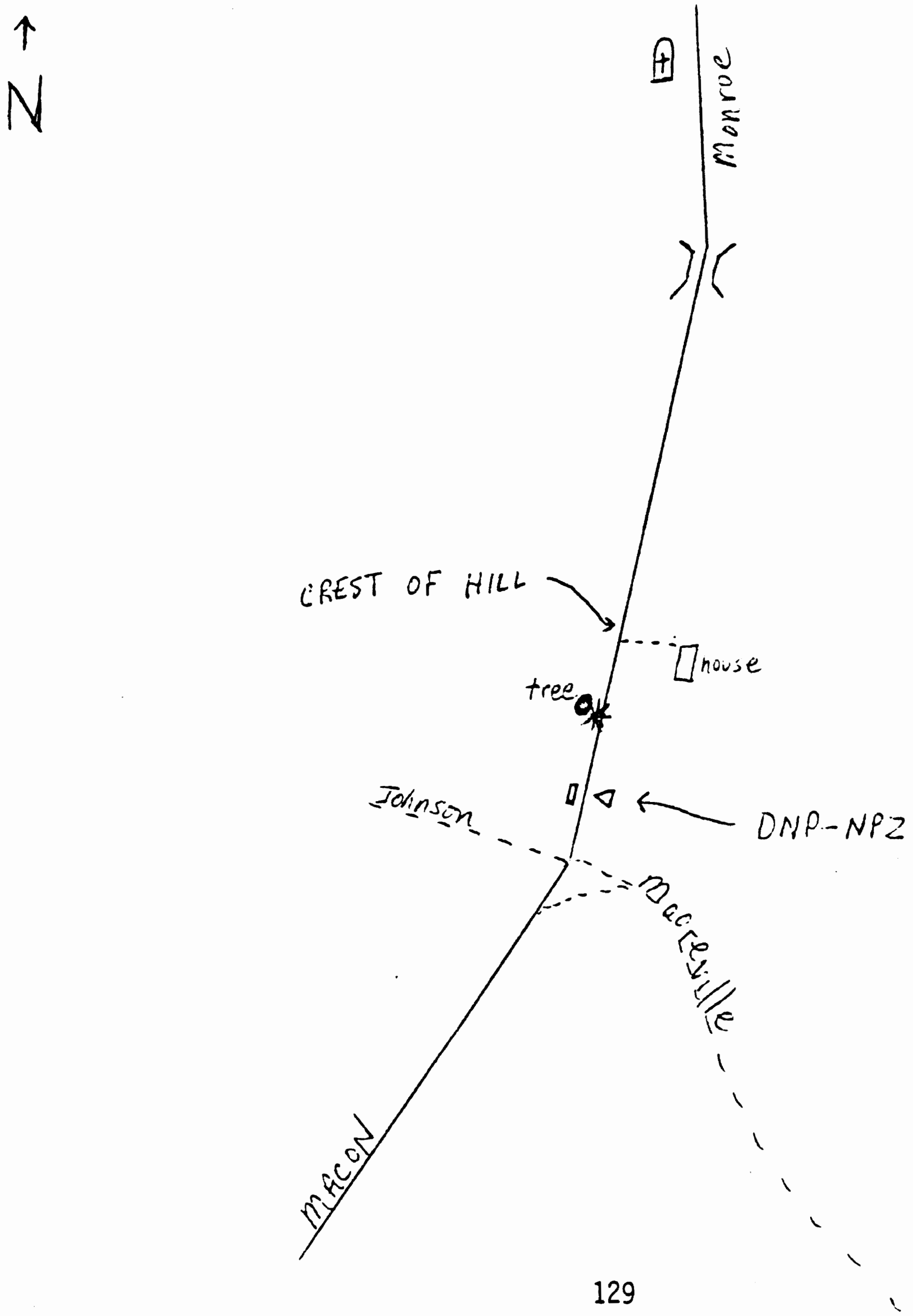
APPENDIX B

COURSE GUIDEBOOK FOR TARGET PLACEMENT

Site 1: hill

A - debris
B - pedestrian

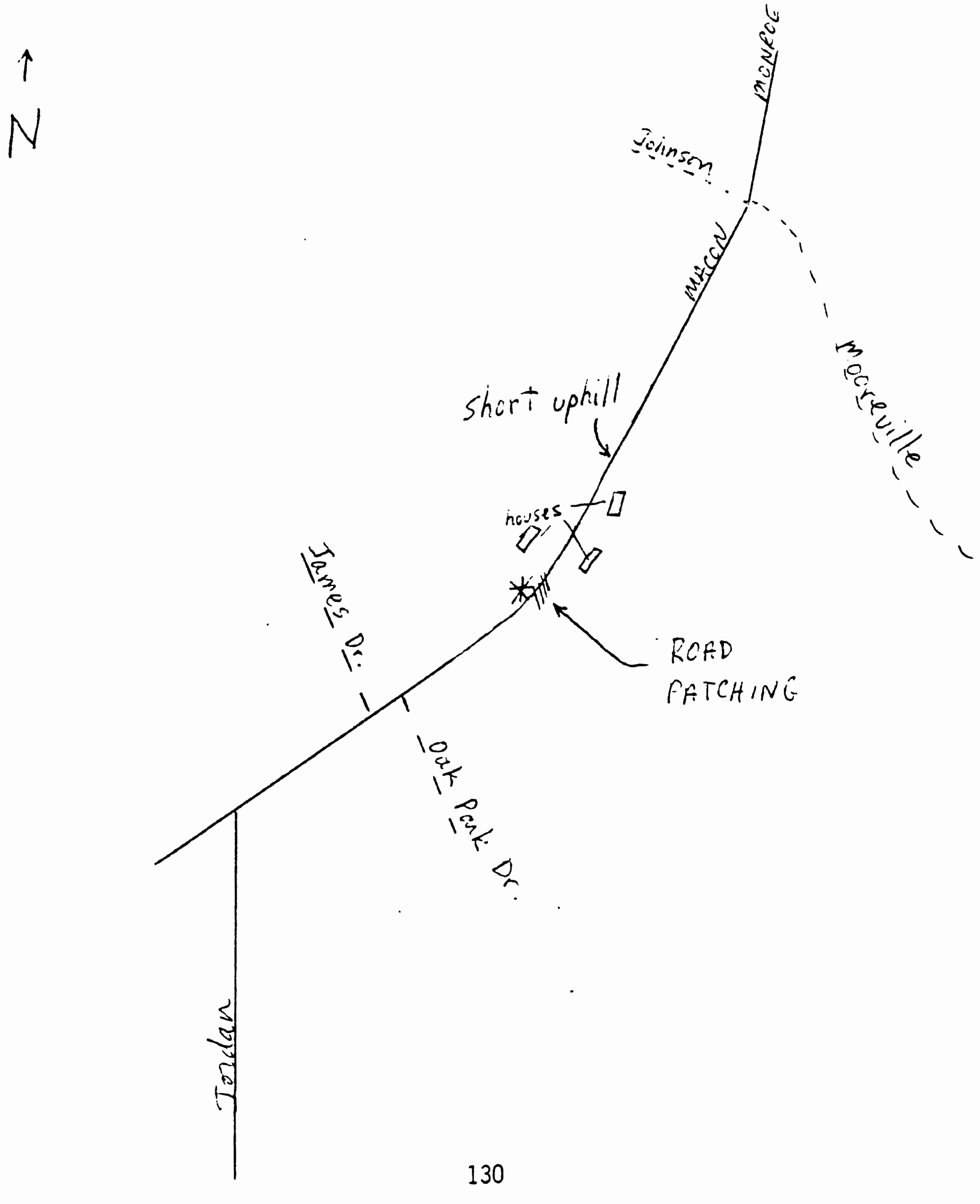
- downhill side of second hill of course (.9 miles from cemetery).
- house with drive on left at the crest of the hill.
- DNP-NPZ signs at bottom of hill.
- target area is about halfway between crest and DNP-NPZ signs.
- exact marker is a <u>very</u> large tree (4 ft. diameter trunk) which hangs over the entire roadway; place targets next to this tree.
- in Pattern B, when returning to pick up pedestrian, it will be necessary to return to the north side of bridge to negotiate turnaround; avoid using driveways.



Site 2: right curve

A - debris
B - parked car

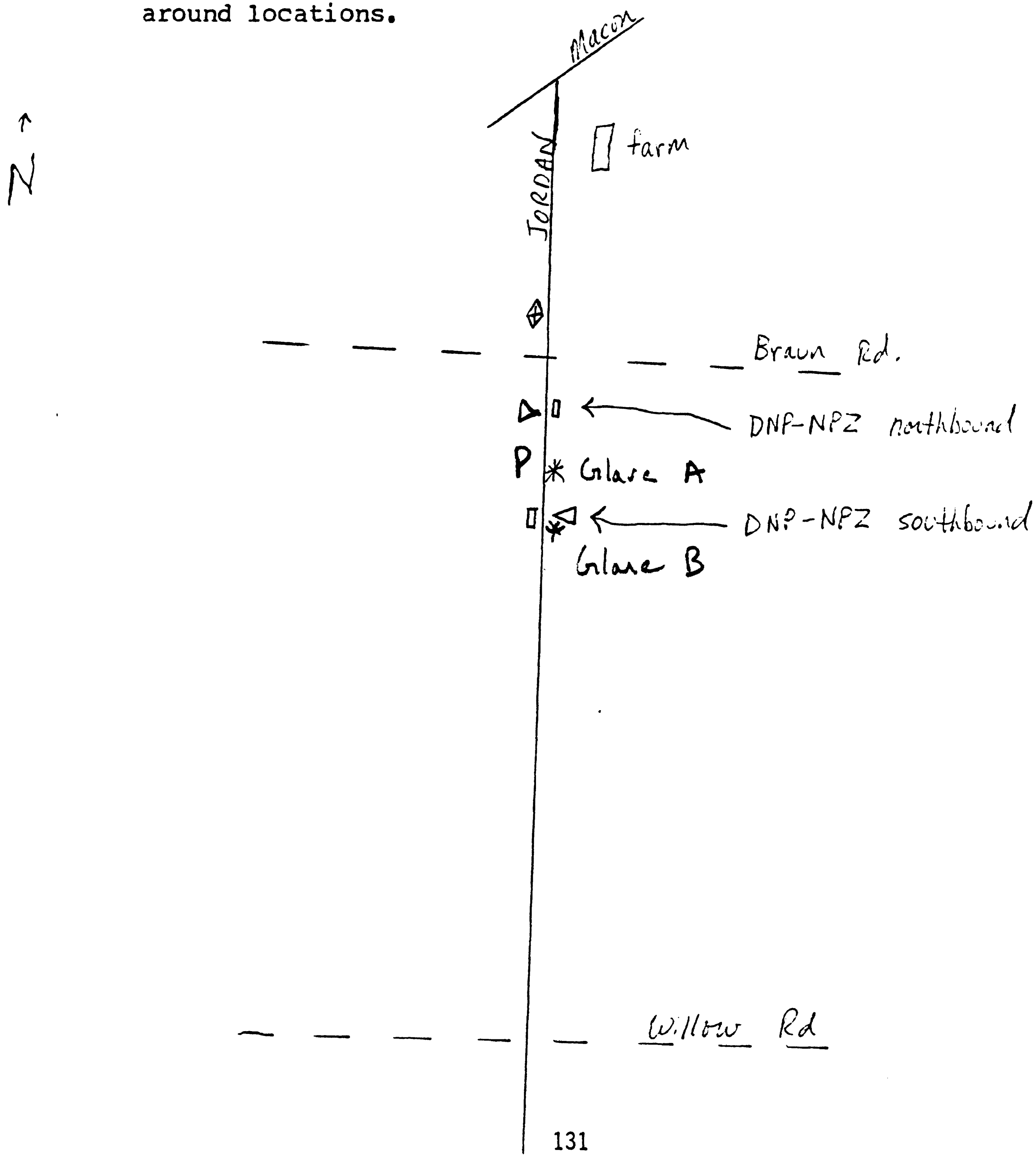
- at corner of Mooreville Rd., route curves slightly to right and becomes Macon Rd.; the <u>next</u> right curve is Site 2.
- curve is immediately preceded by a short uphill.
- 3/4 into the curve, there is a small area of road patching--this marks the target area
- place targets no more than 50 ft. past this area of patching.
- in Pattern B, parked car must return to Site 1 to pick up pedestrian good place for turnaround is at Oak Park Dr. (2/10 mile past target site on left).



Site 3: straight

A - glare w/ pedestrian
B - glare w/ DNP-NPZ signs

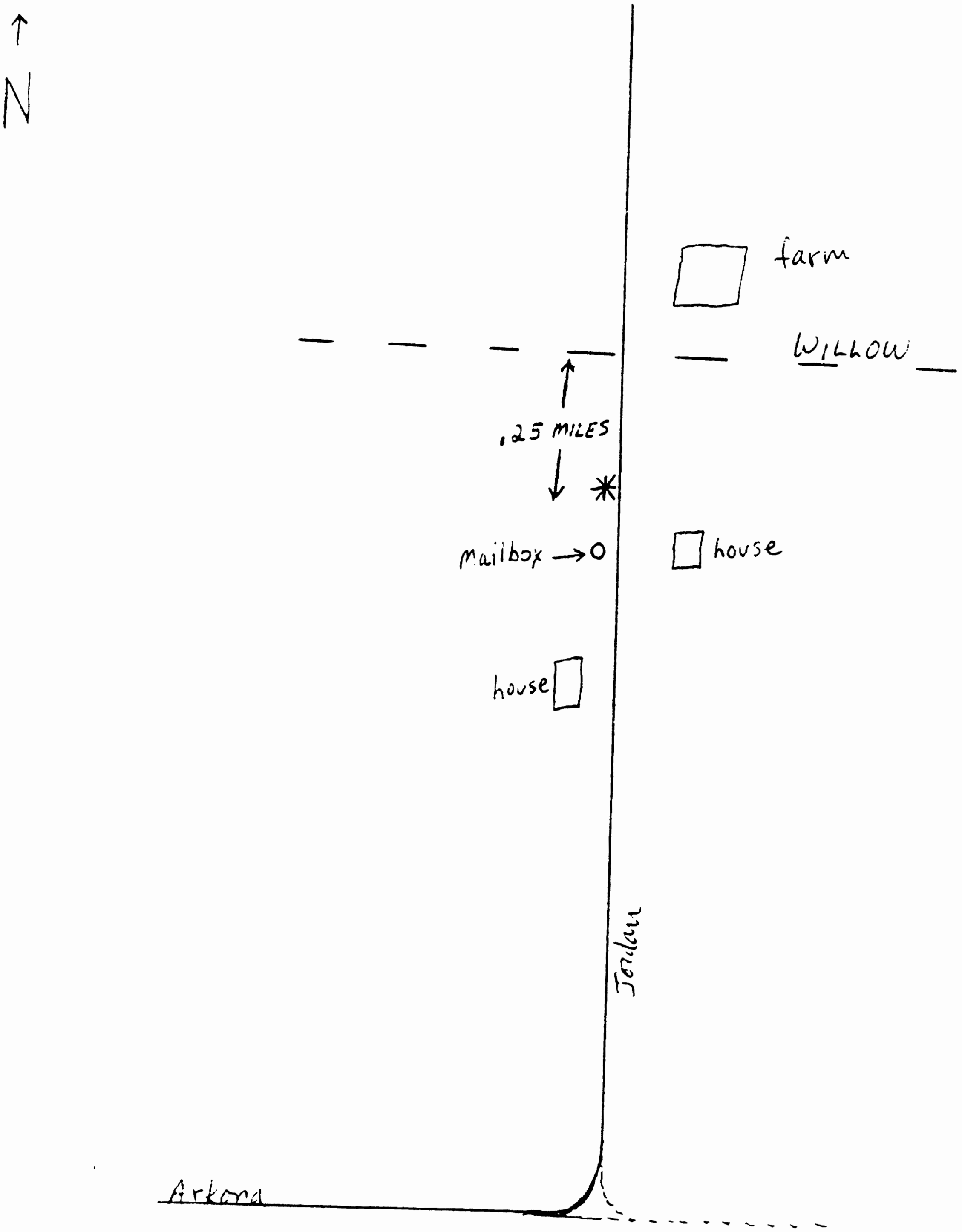
- located on Jordan Rd. just past Braun Rd. (first crossroad on Jordan).
- for Pattern A, set up exactly between DNP-NPZ signs for southbound traffic and DNP-NPZ signs for northbound traffic; glare should be approximately opposite pedestrian (REMINDER: we are using stationary glare sources).
- for Pattern B, set up opposite the DNP-NPZ signs for southbound traffic
- in both patterns, the glare car will have to turn around twice; it is suggested that Willow Rd. and Braun Rd. be used as turn-around locations.



Site 4: straight

A - pedestrian
B - debris

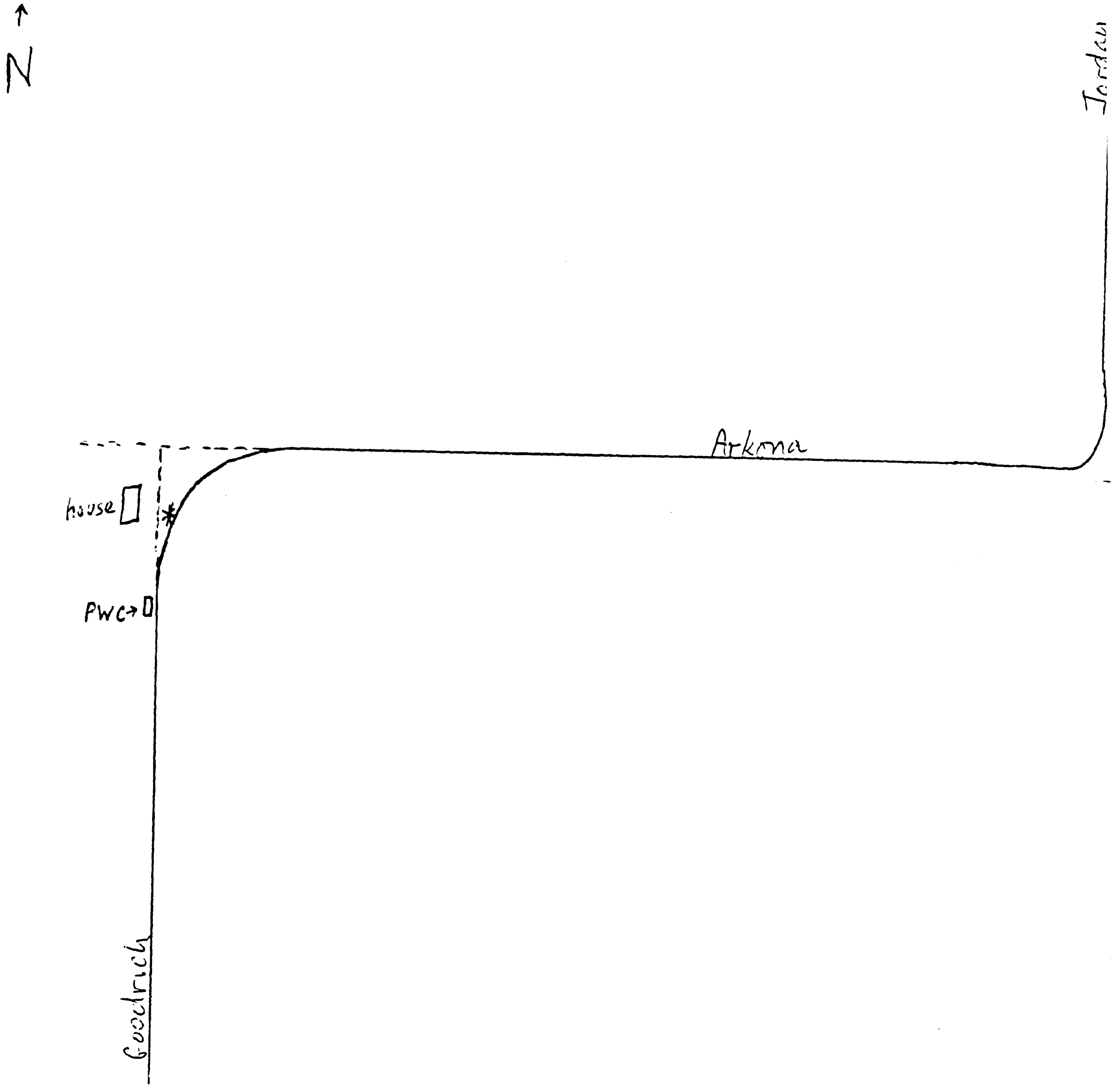
- located on Jordan just past Willow.
- place targets exactly .25 miles past Willow Rd.
- stay well before house on left and mailbox on right.



Site 5: left curve

A - parked car
B - PWC sign just past curve is target

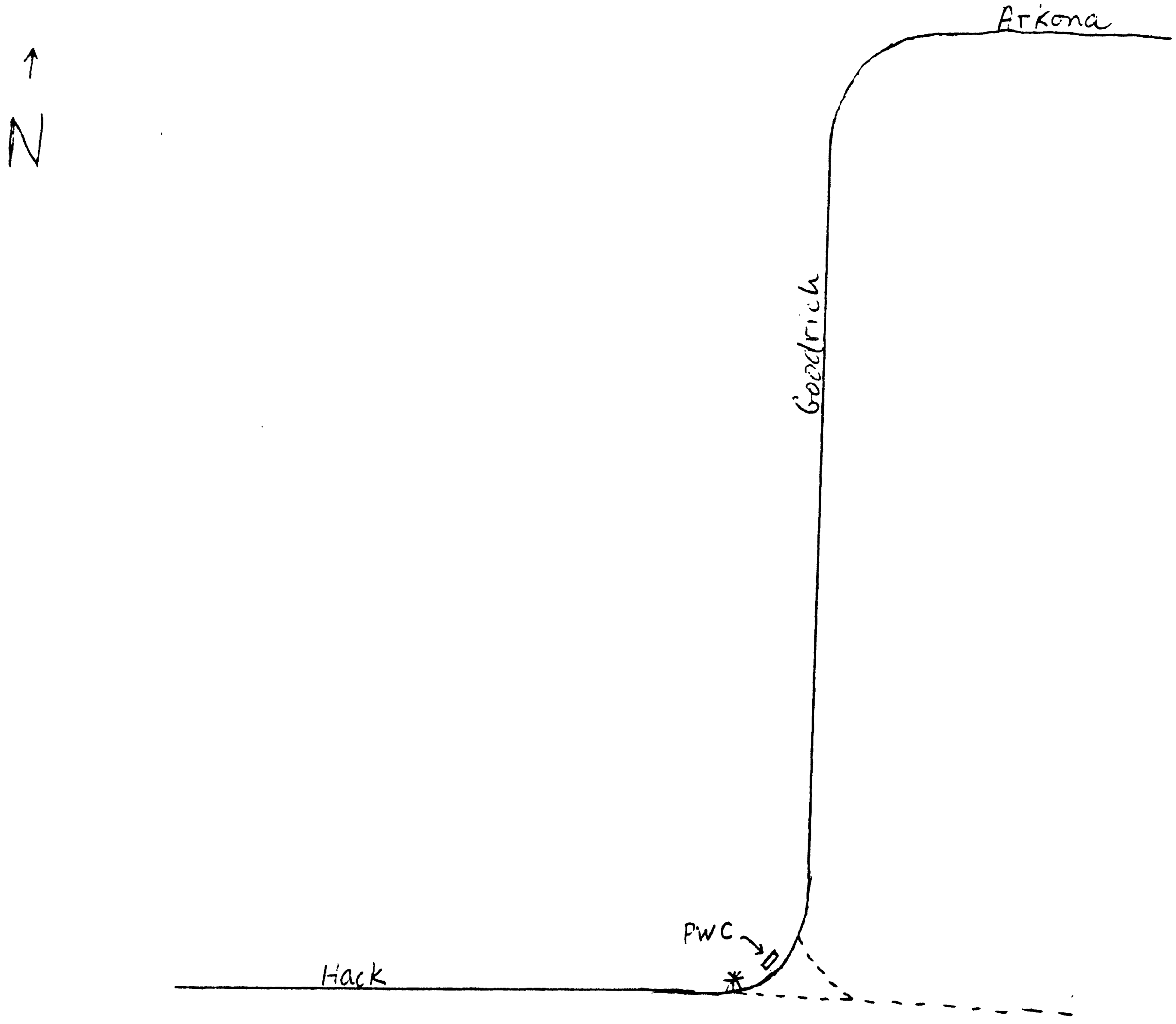
- located on left from Arkona onto Goodrich.
- place car on shoulder just <u>before</u> dirt spur merges with Goodrich.
- avoid shining headlights on nearby house insofar as possible.



Site 6: right curve

A - PWC sign is target
B - pedestrian

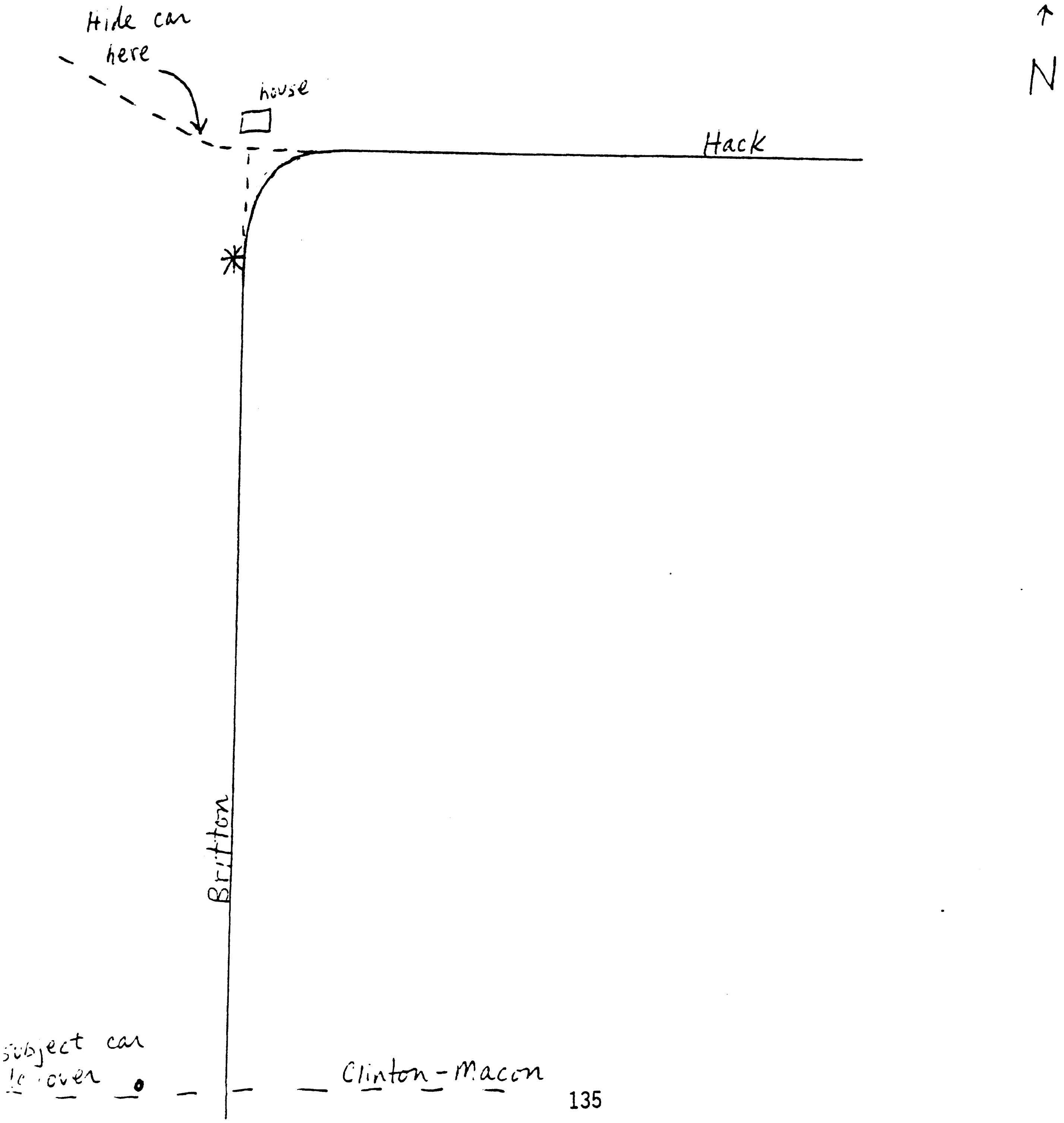
- located on right from Goodrich onto Hack.
- pedestrian should be on back side of curve, past the PWC sign, just at the point where the curve straightens out.



Site 7: left curve

A - pedestrian
B - debris

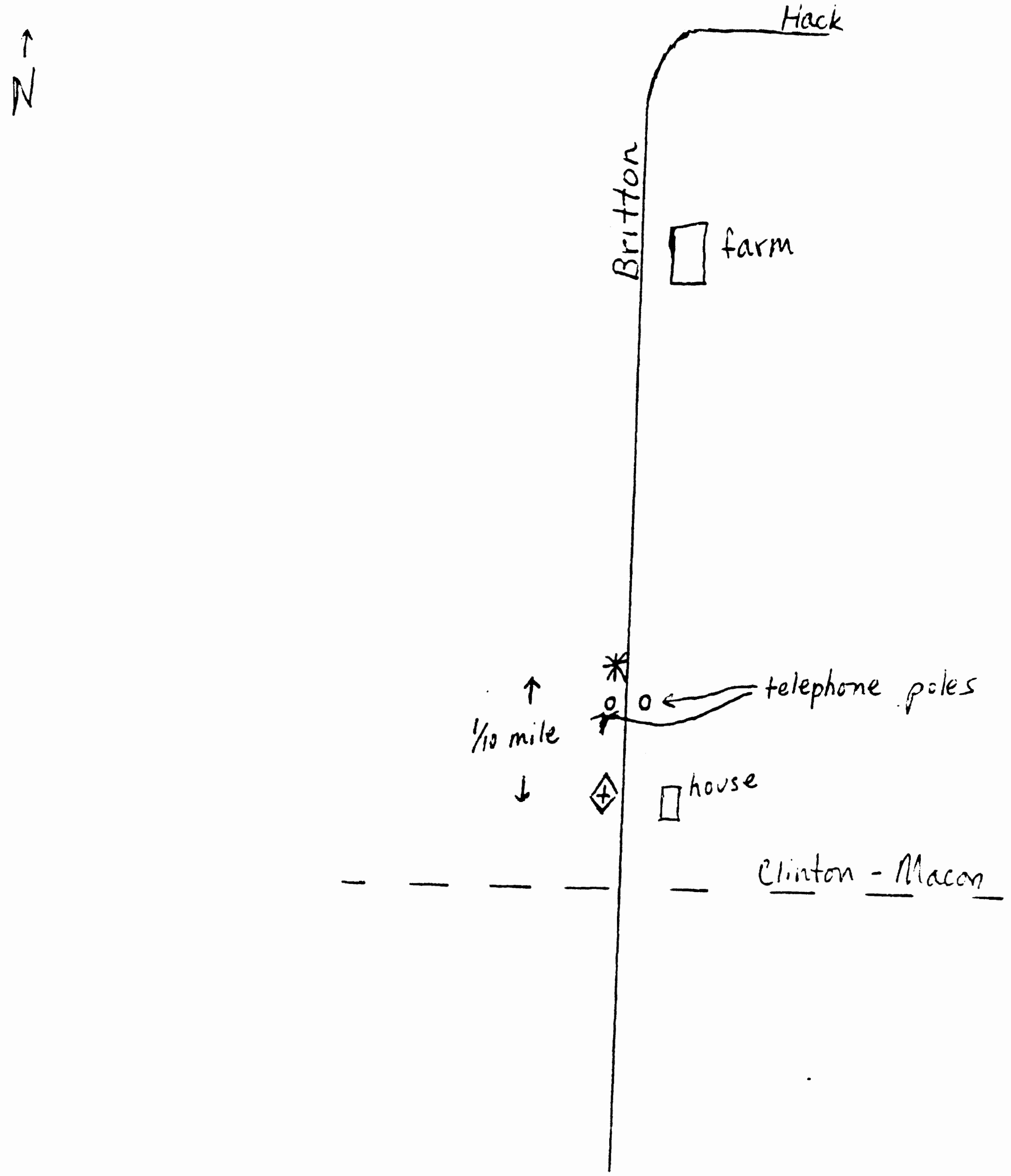
- located on left from Hack onto Britton.
- targets should be just around curve, just past dirt spur merging with Britton.
- in Pattern A, hide car on Hack, just around slight right and out of view of westbound traffic (i.e., subject car); after retrieving car, negotiate a Y-turn on Hack -- this segment carries little traffic.



Site 8: straight

A - + sign is target
B - parked car

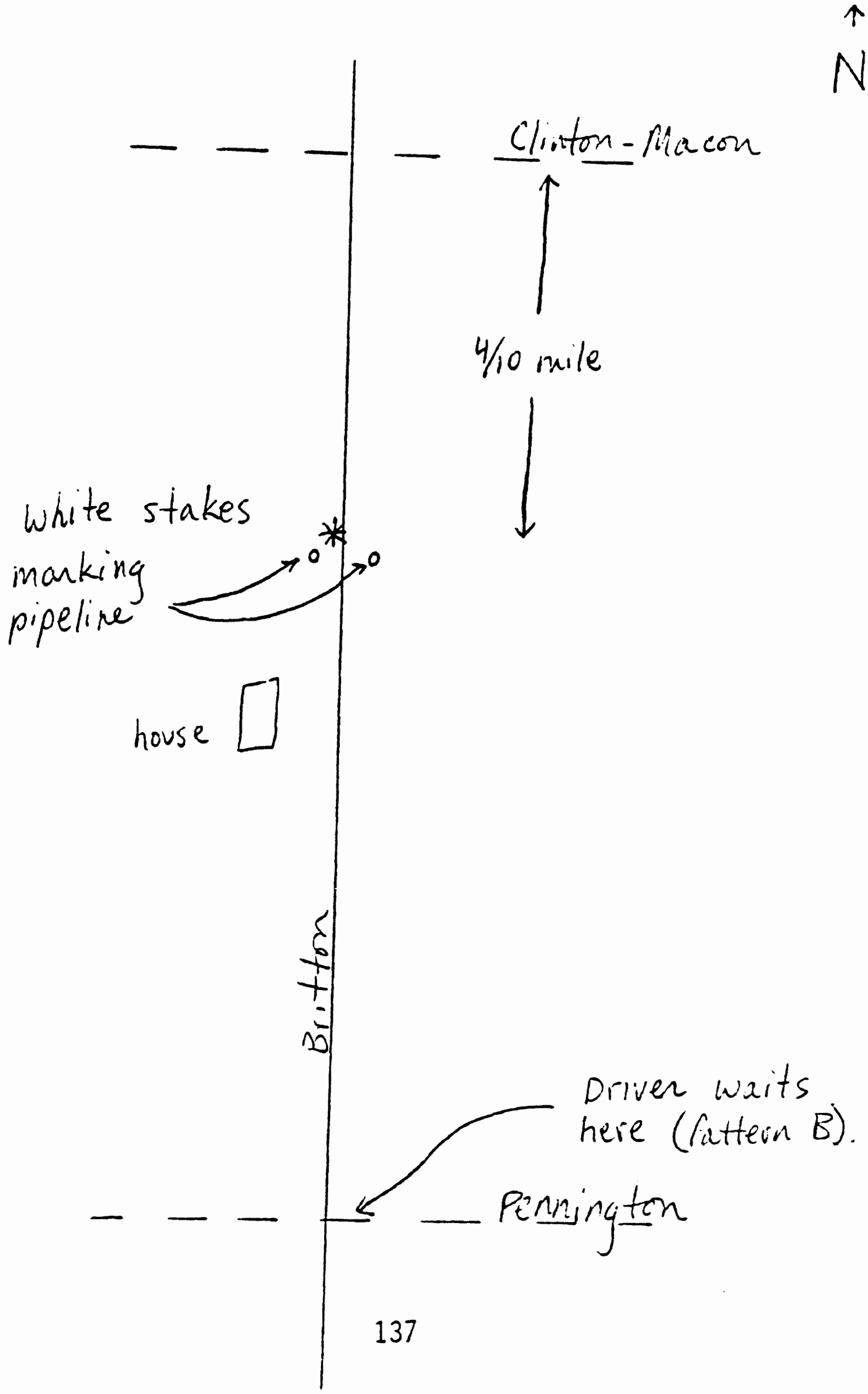
- located on straight before Clinton-Macon Rd.
- for Pattern B, begin slowing down after passing uphill with farmhouse on left.
- target site is marked by two telephone poles close to the roadway, one on each side. Carefully select a good place to park the car -- you have a little flexibility on your placement; avoid proximity of house on left.



Site 9: straight

A - debris
B - pedestrian

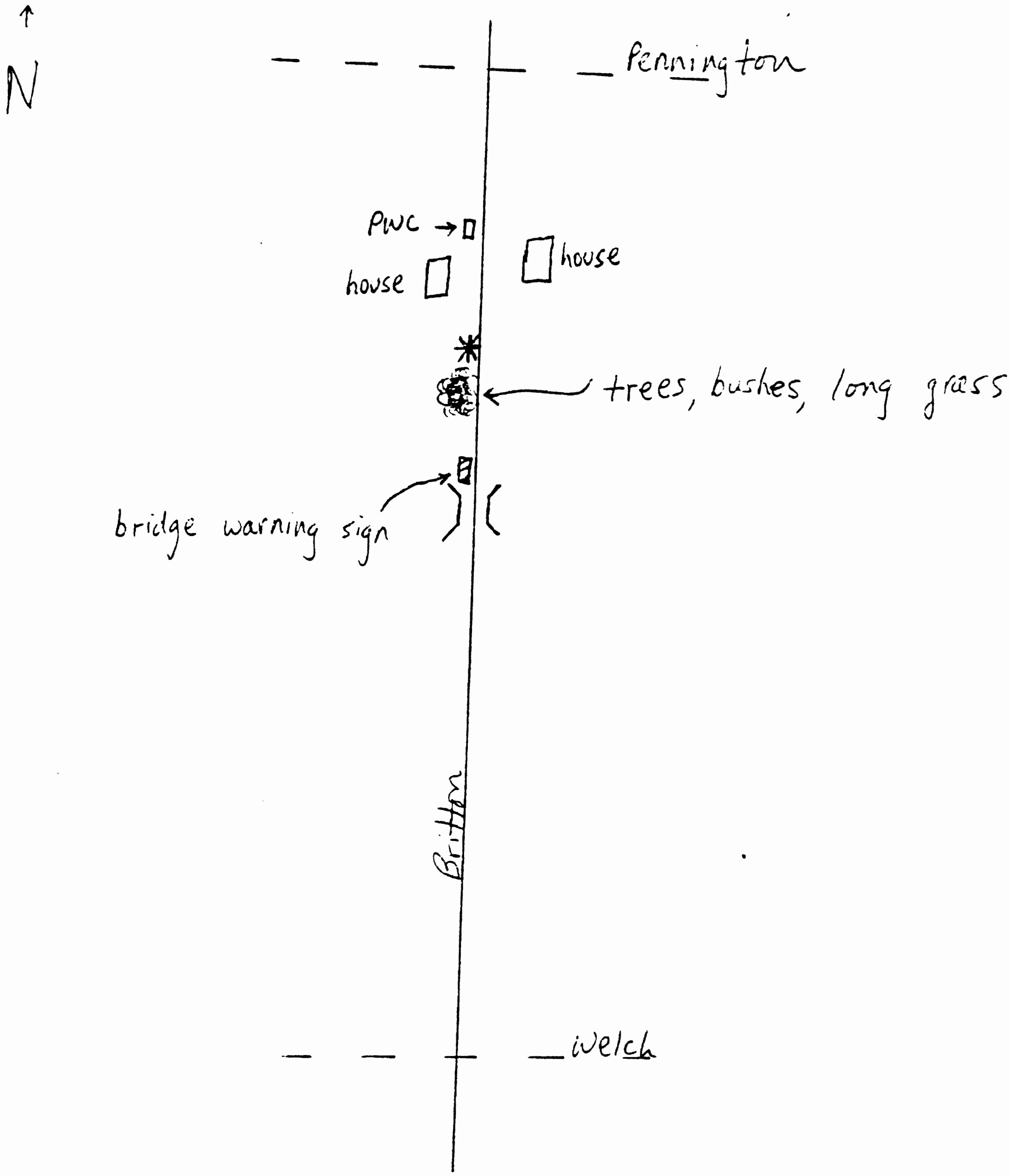
- located on straight just past Clinton-Macon Rd.
- target area is 4/10 mile past intersection; there are two four foot high white stakes (one on each side of the road) that indicate a pipeline -- targets should be located very near these stakes.
- in Pattern B, driver waits out of view on Pennington Rd.; when subject car passes, driver returns to pick up pedestrian.
- in both patterns, there are pick-ups which leave chase cars heading North -- however, since this occurs at the end of the half-route, there is no need to turn around. Simply proceed to the other side of the course via Clinton-Macon or Hack.



Site 10: hill

A - sign marking bridge is target
B - parked car

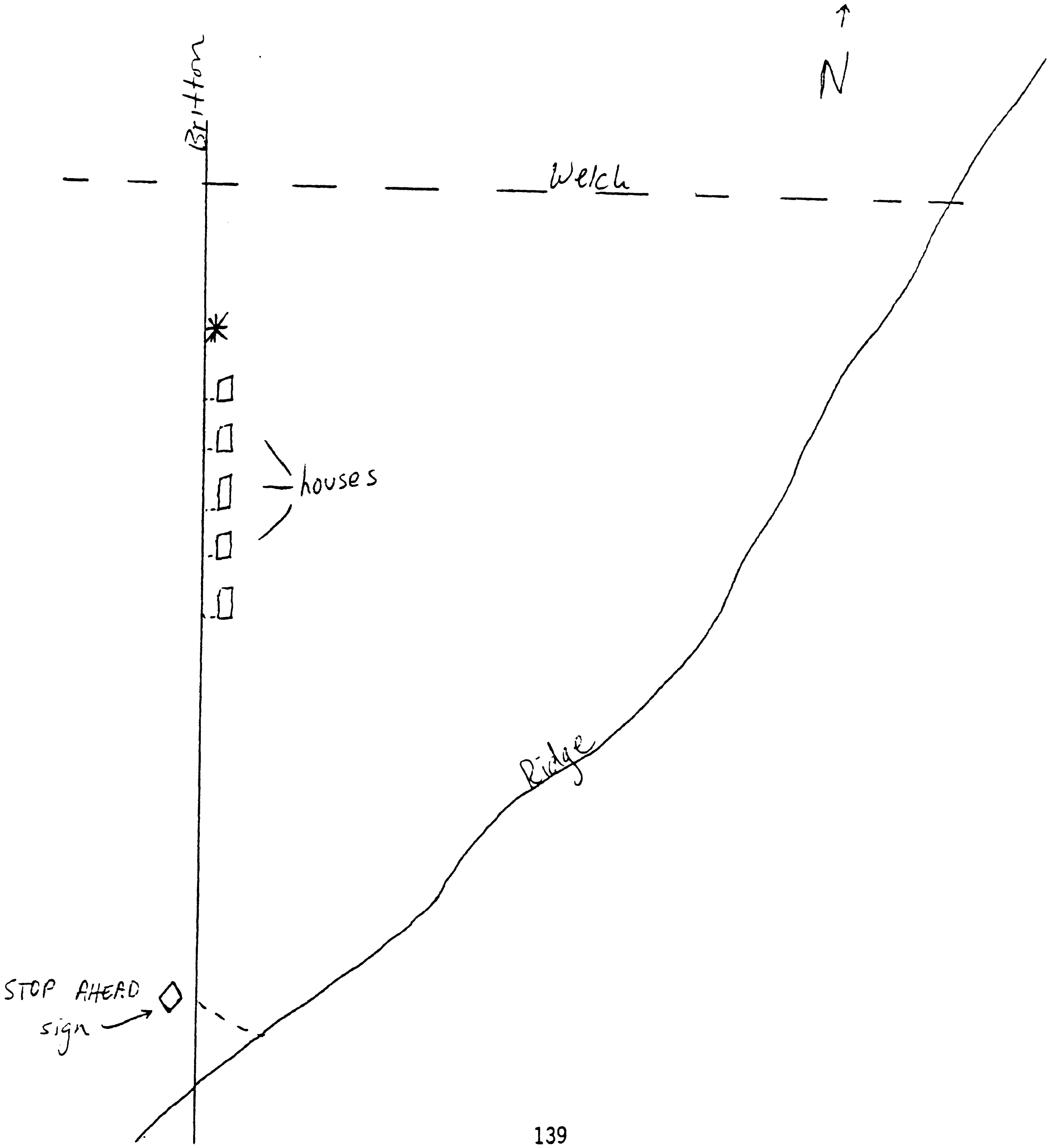
- located on downhill past Pennington Rd.
- PWC sign at the crest of the hill.
- one house on each side of the road near the crest.
- bridge located at bottom of hill.
- about 300 ft. before bridge, there is a clump of trees, bushes, and tall grass near right side of roadway; car should be parked just before this clump.
- after subject car passes, Chase Car 2 can proceed to other side of course via Welch Rd.



Site 11: straight

A - glare w/ parked car
B - STOP AHEAD sign marking Ridge Rd. is target

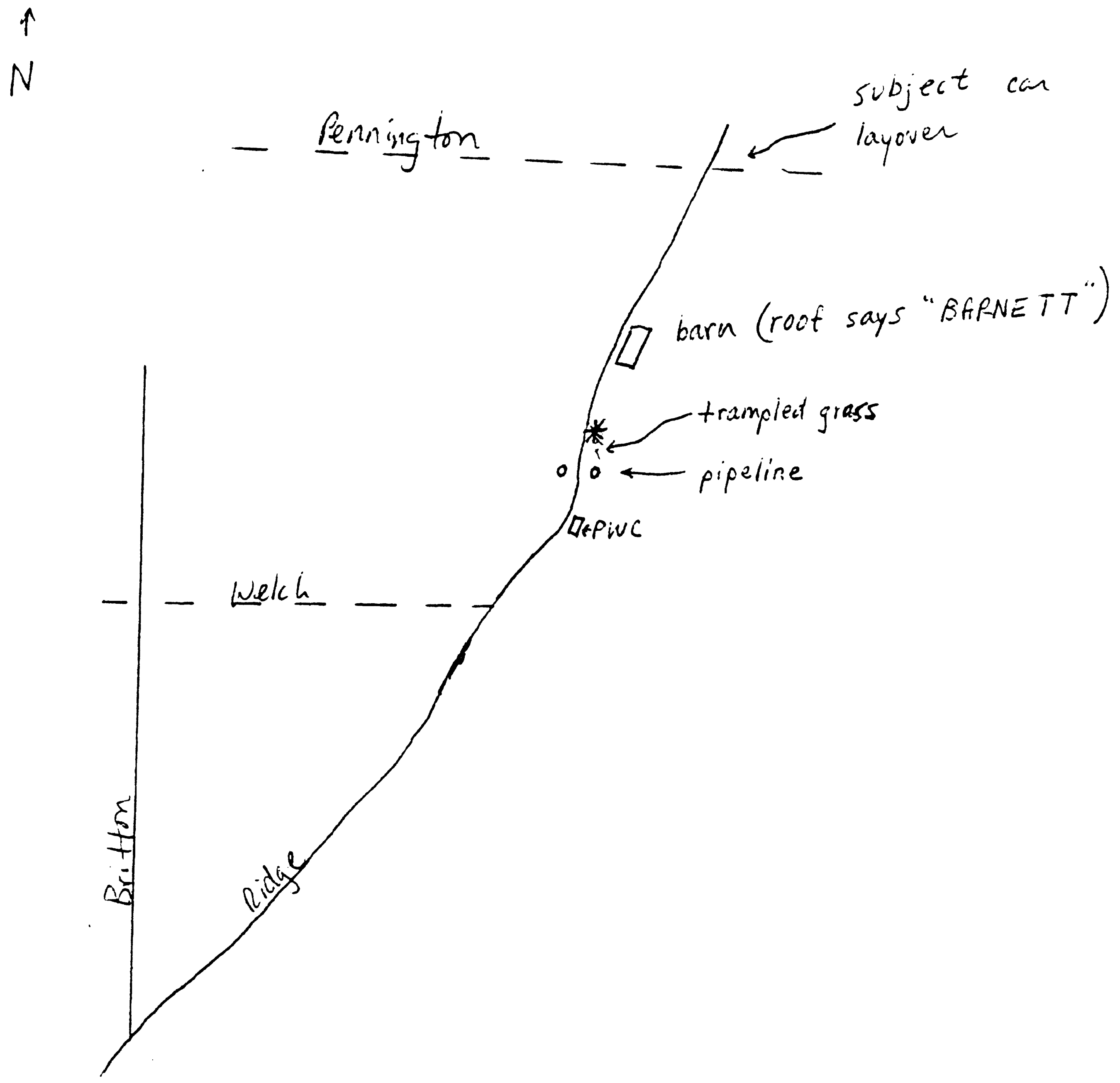
- located on straight just past Welch Rd.
- there is a row of houses on left beginning 2/10 mile past Welch; glare should be set up before the proximity of the first (northernmost) house.
- it may be possible to select a "dark" driveway to negotiate turnarounds -- if not, it will be necessary to go to the Ridge Rd. intersection. BE CAREFUL HERE.



Site 12: straight

A - parked car
B - glare w/ debris

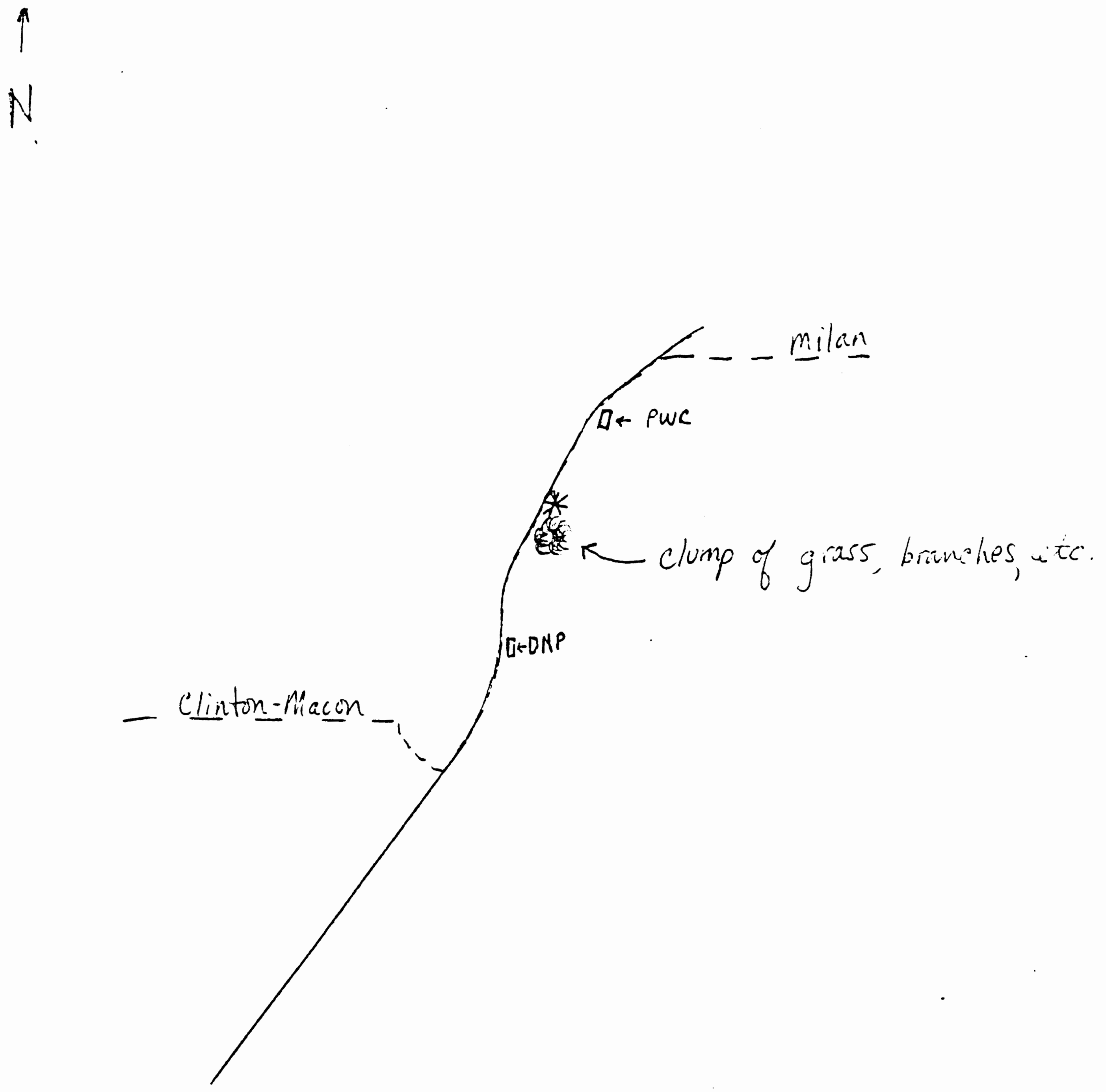
- located approximately 4/10 mile past Welch (on Ridge Rd.).
- for Pattern A, park car in clearing (trampled grass) just past pipeline markers.
- for Pattern B, place glare source between large barn on east side of roadway (barn roof says "Barnett") and gas pipeline markers. Be selective -- you have a little flexibility. After subject car passes, turn around at Welch Rd.



Site 13: right curve

A - debris
B - parked car

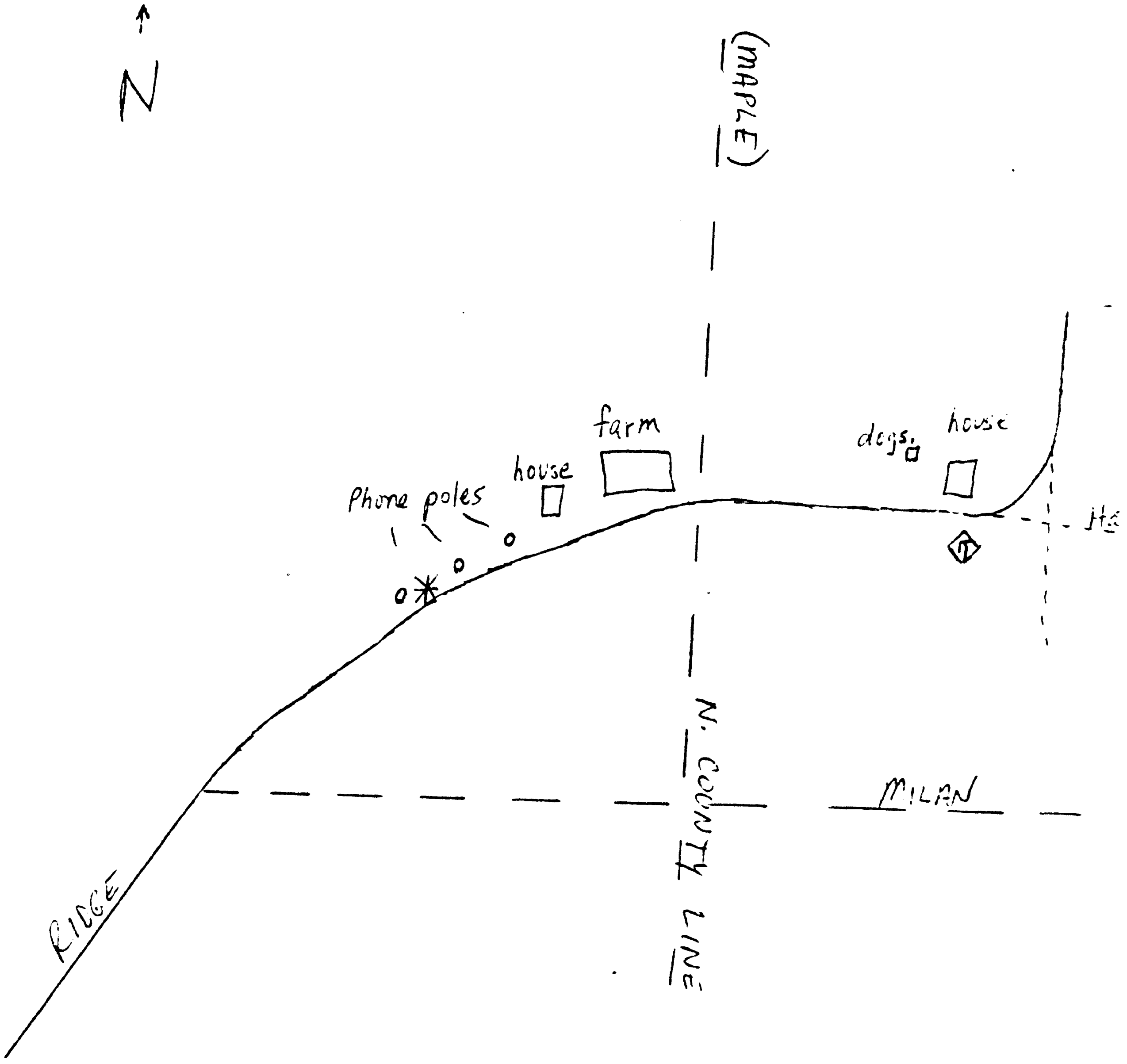
- located approximately 4/10 mile past Clinton-Macon Rd.
- the curve is relatively slight -- watch for it carefully.
- a clump of grass, branches, etc. marks the target site.
- in Pattern A, when returning for debris, Clinton-Macon Rd. can be used for a turnaround.



Site 14: straight

A - glare w/ parked car
B - glare w/ ↰ sign

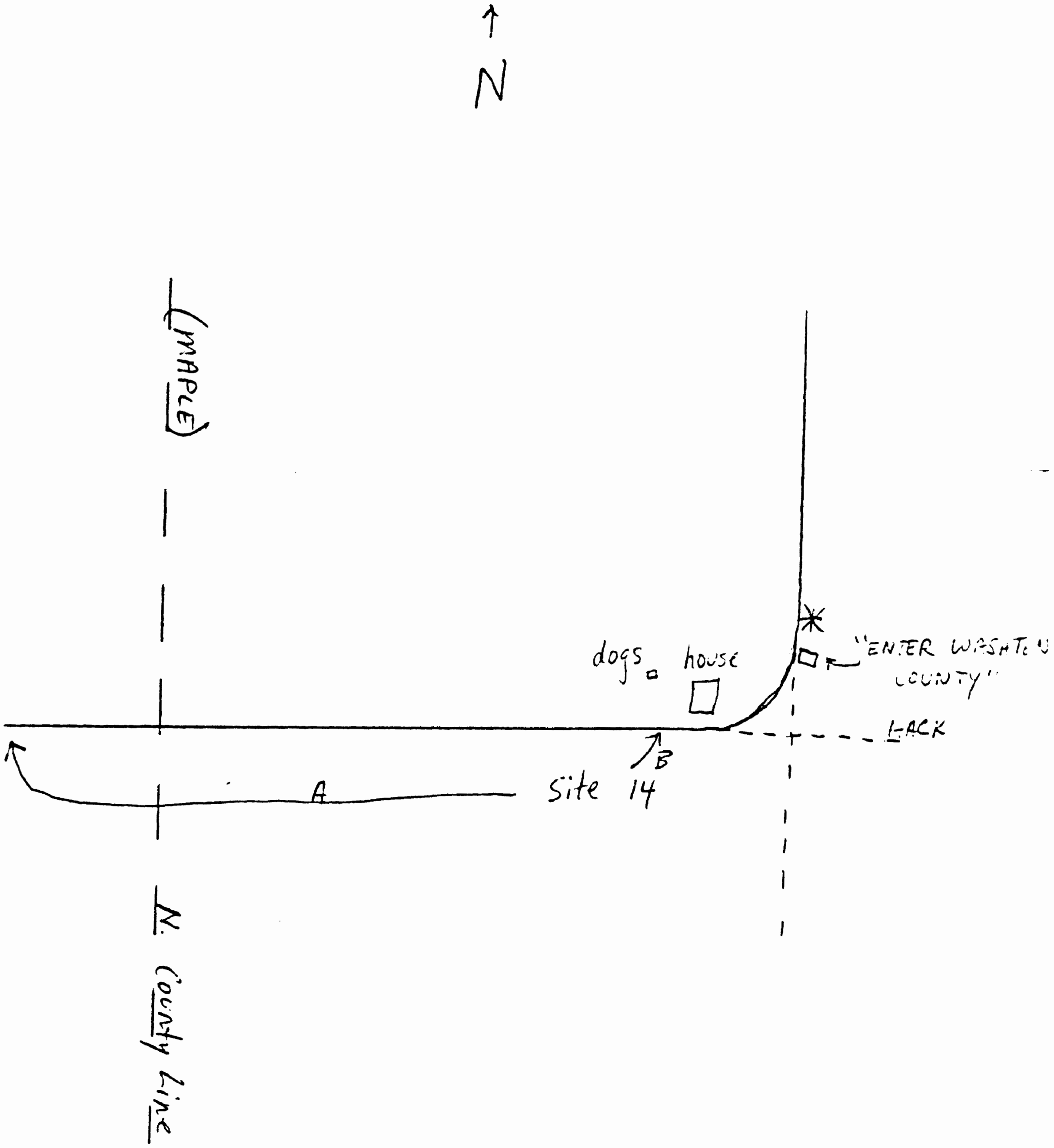
- the site for Pattern A is actually a very gradual right between Milan Rd. and N. County Line Rd. (N. County Line = Maple).
- set up at least 2 telephone poles before house on left.
- in Pattern B, set up opposite ↰ sign. Try to avoid startling dogs.
- for turnarounds, there are three good locations: Milan Rd., N. County Line Rd., and the Hack/Ridge corner (Site 15).
- WARNING: Site 15 is very close to site 14 in Pattern B.



Site 15: left curve

A - pedestrian
B - debris

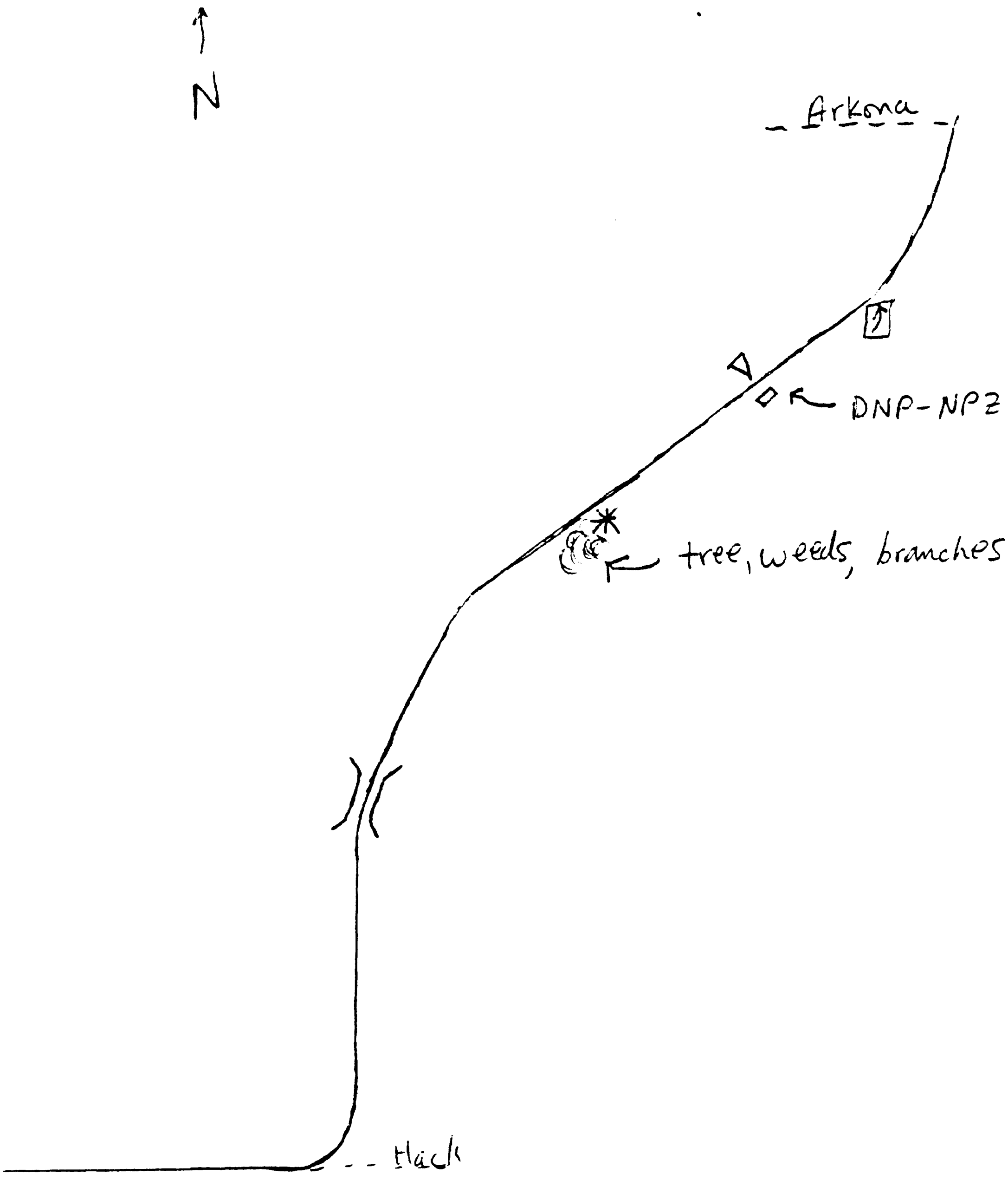
- located at sharp left where Hack meets Ridge, just after target site 14.
- targets should be placed just beyond "ENTER WASHTENAW COUNTY" sign.



Site 16: straight

A - debris
B - parked car

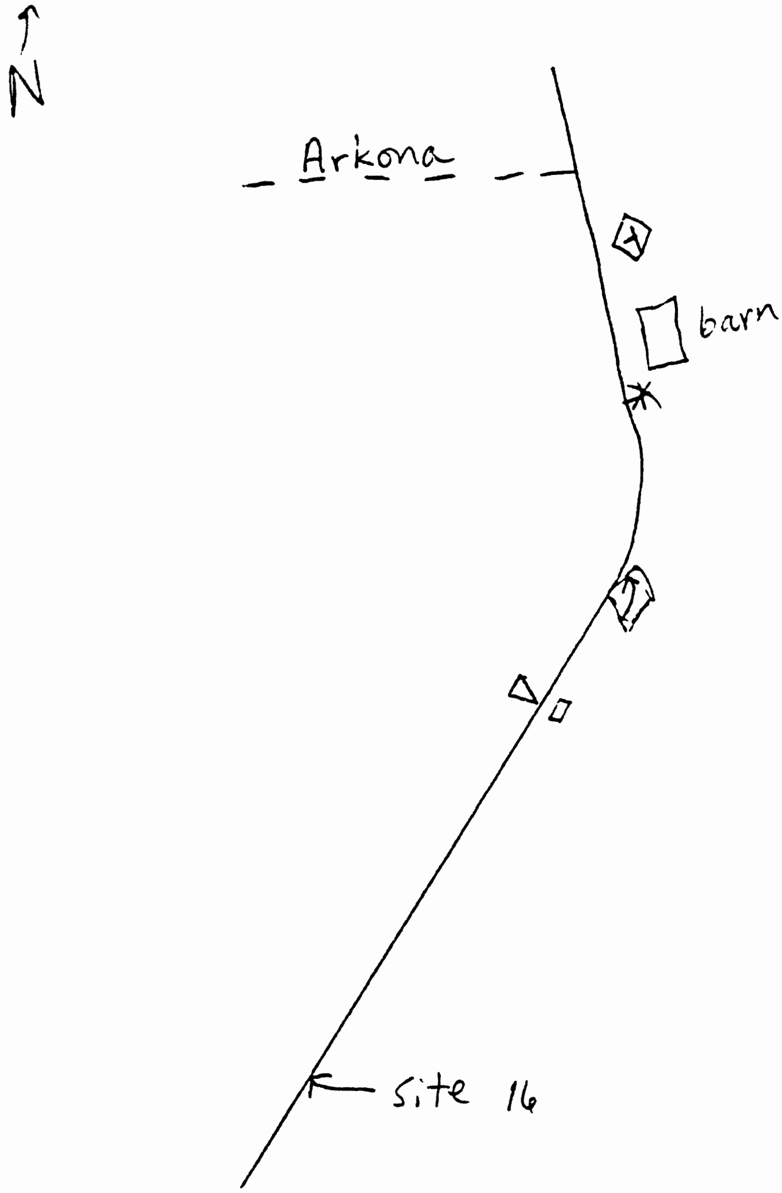
- after sharp left (Site 15), route crosses over bridge; target area is approximately .55 mile past this bridge.
- there is a small tree with a clump of branches near the roadway which marks the target area.
- if you pass DNP-NPZ and ↰ signs, you have gone too far.



Site 17: left curve

A - parked car
B - ⊣ sign is target

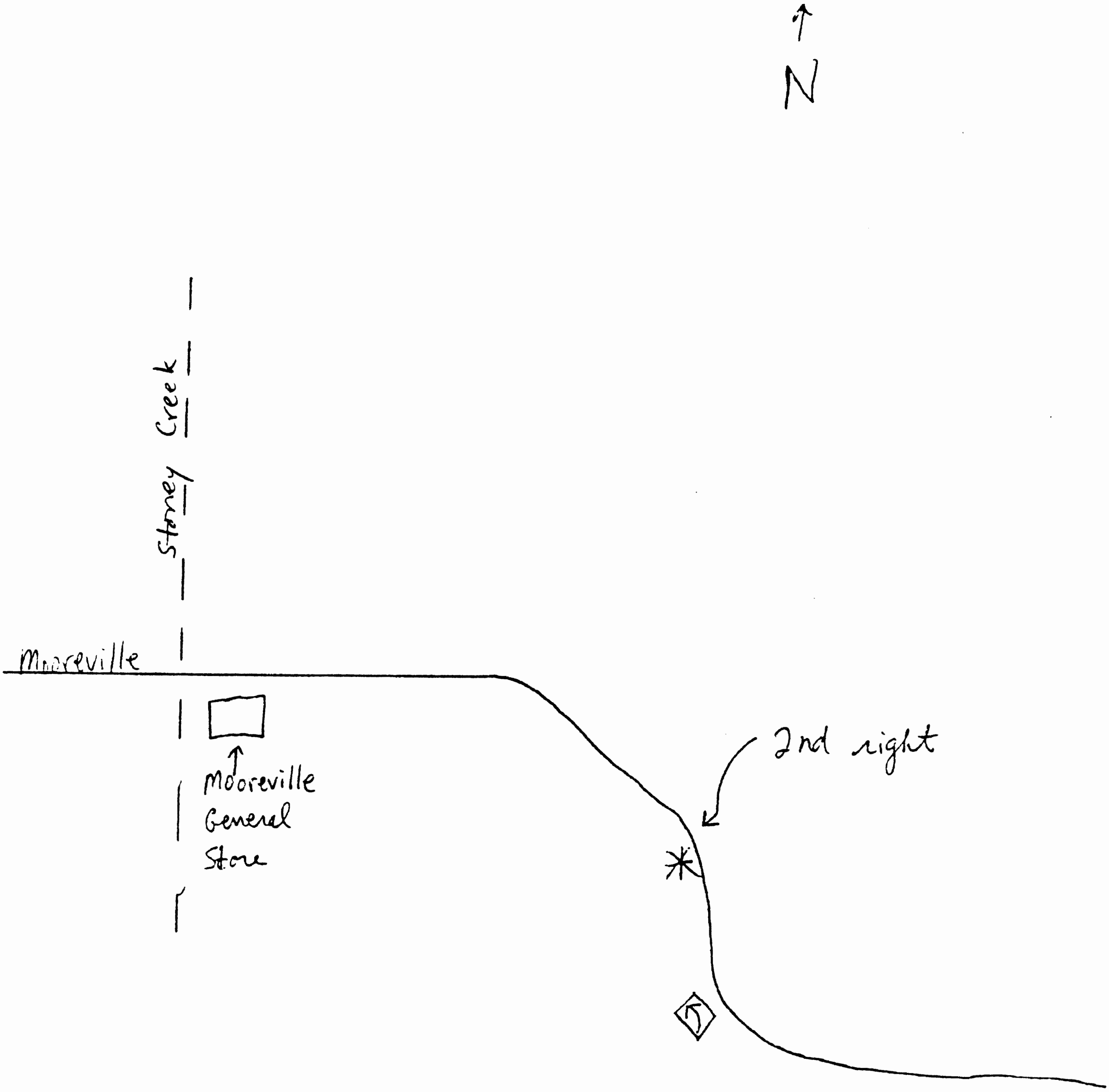
- located on left curve between Site 16 and Arkona Rd.
- curve comes immediately after Site 16 (2/10 mile).
- park car well around curve, but before ⊣sign; deserted barn on right side of roadway is a good marker -- park just before or next to this barn.



Site 18: right curve

A - ↰ sign is target
B - pedestrian

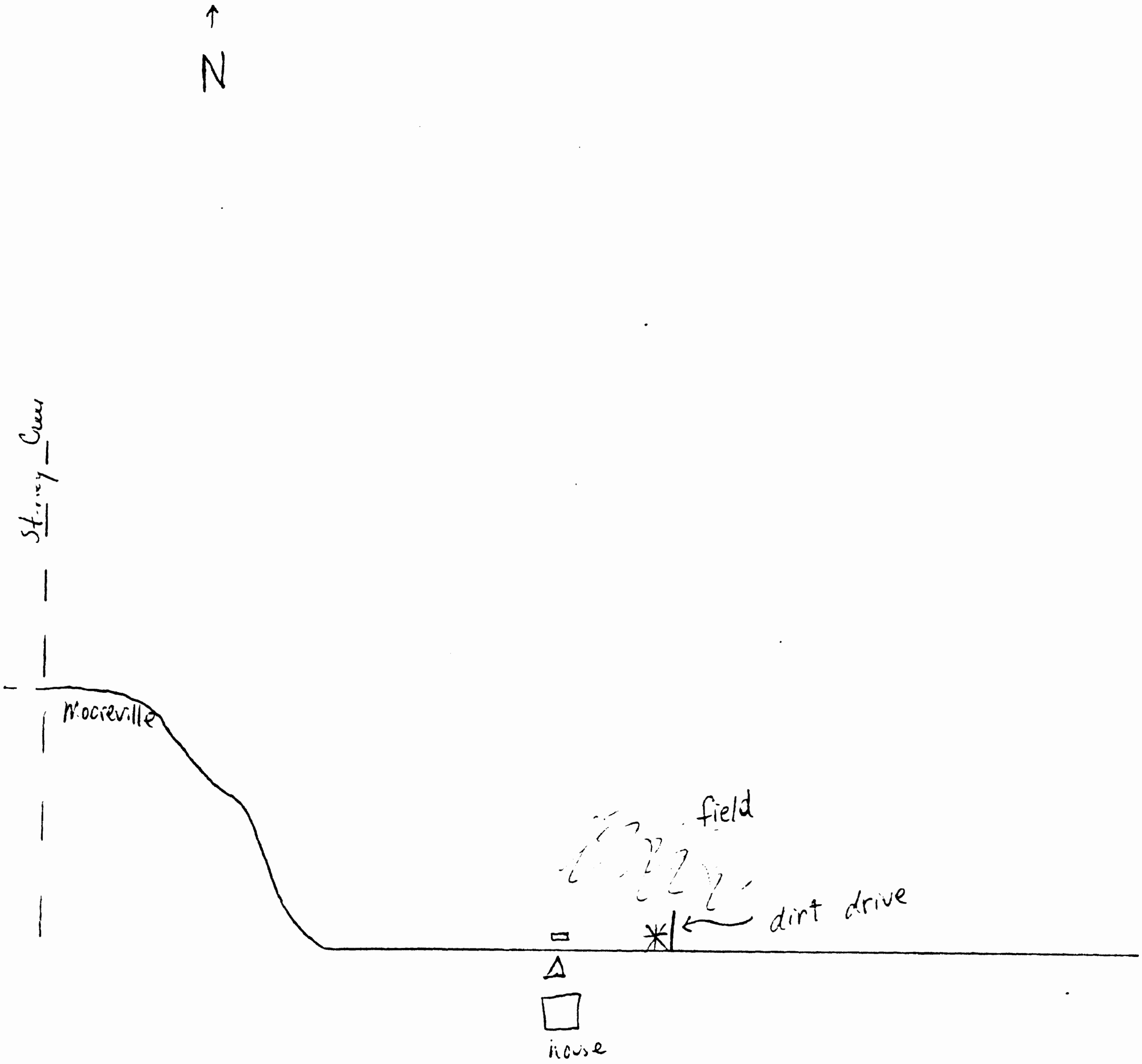
- located on second right curve past town of Moorevile.
- pedestrian should be just around curve, but avoid silhouetting self with ↰ sign.



Site 19: straight

A - glare w/ pedestrian
B - glare w/ debris

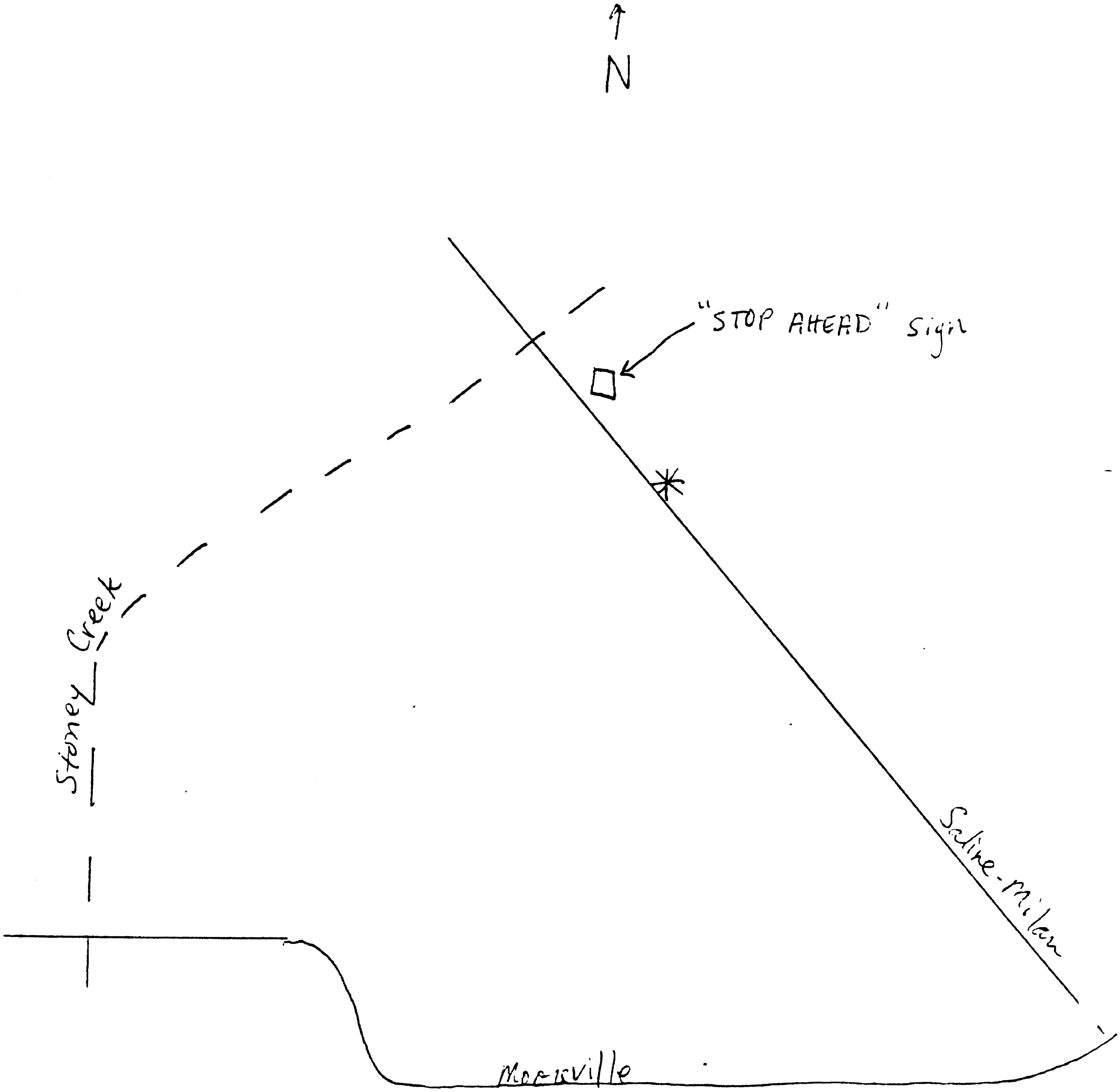
- located on long straight between Moorevile and corner of Saline-Milan Rd.
- at the west end of the straight, there are DNP-NPZ signs for westbound traffic. 1/10 mile east of these signs is a small dirt driveway which leads into a farmer's field; this dirt path is a good marker for the location of the glare source.
- the dirt drive can also be used as a turnaround.



Site 20: straight

A - "STOP AHEAD" sign is target
B - debris

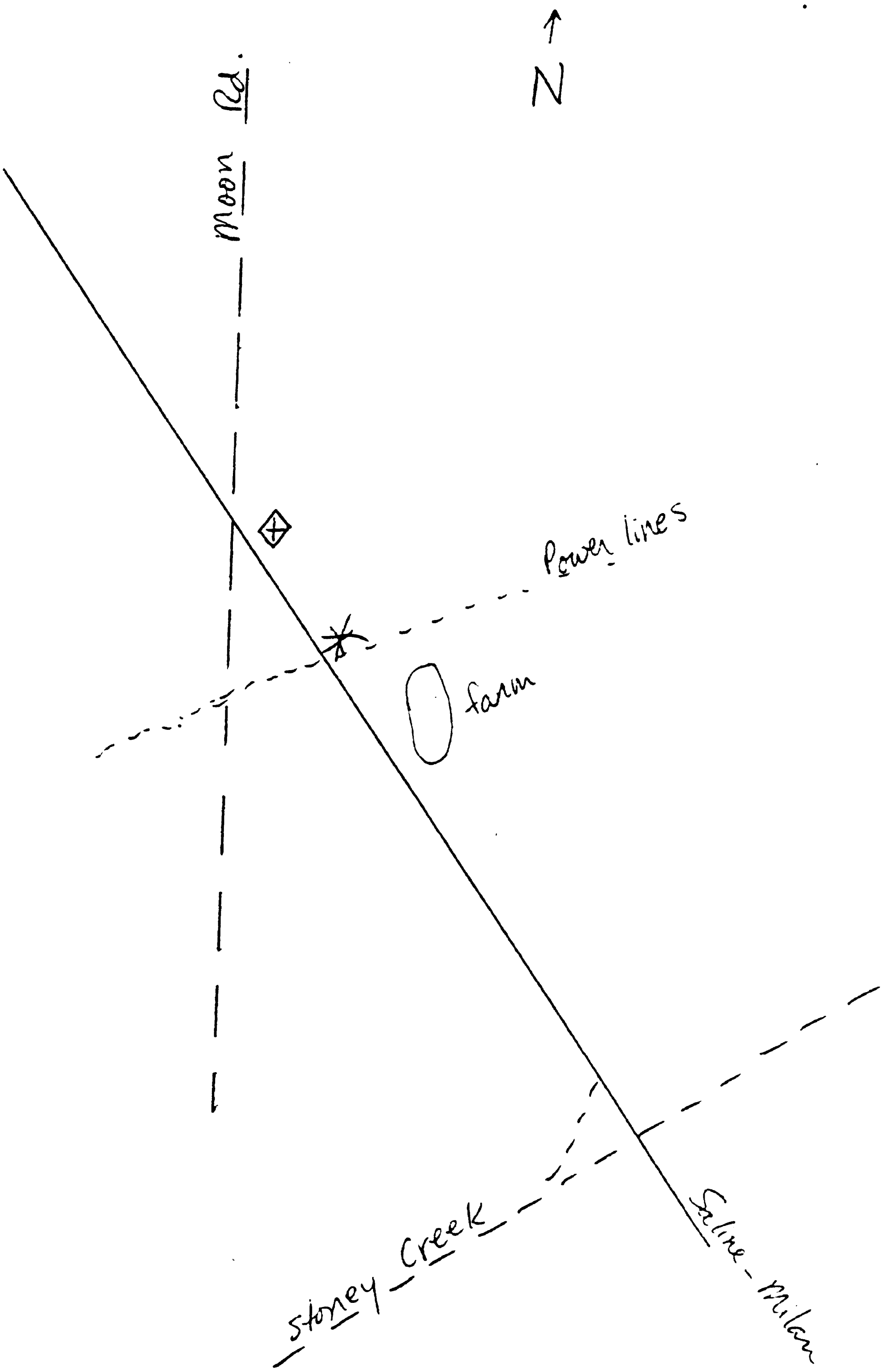
- located on Saline-Milan straight, just southeast of Stoney Creek Rd.
- target area for debris is 2/10 mile before "STOP AHEAD" sign.
- this is a bad area for turnarounds; if necessary, go all the way back to Mooreville Rd.



Site 21: straight

A - parked car
B - + sign is target

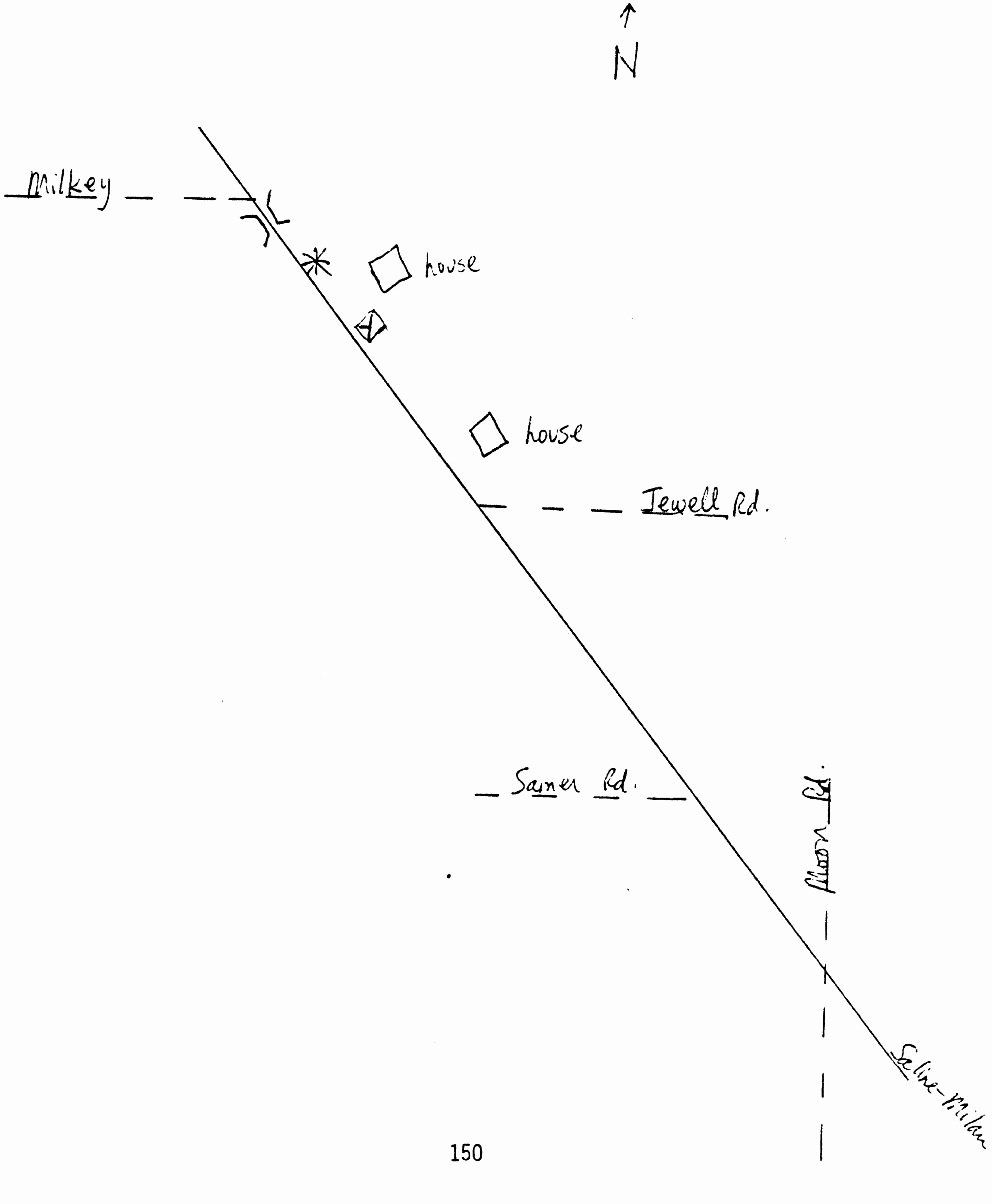
- straight is located just before Moon Rd.
- well before the + sign marking Moon Rd., there is a farm on the right followed by power lines crossing the roadway; these power lines make a good marker for the target area-



Site 22: hill

A - ⊣ sign
B - parked car

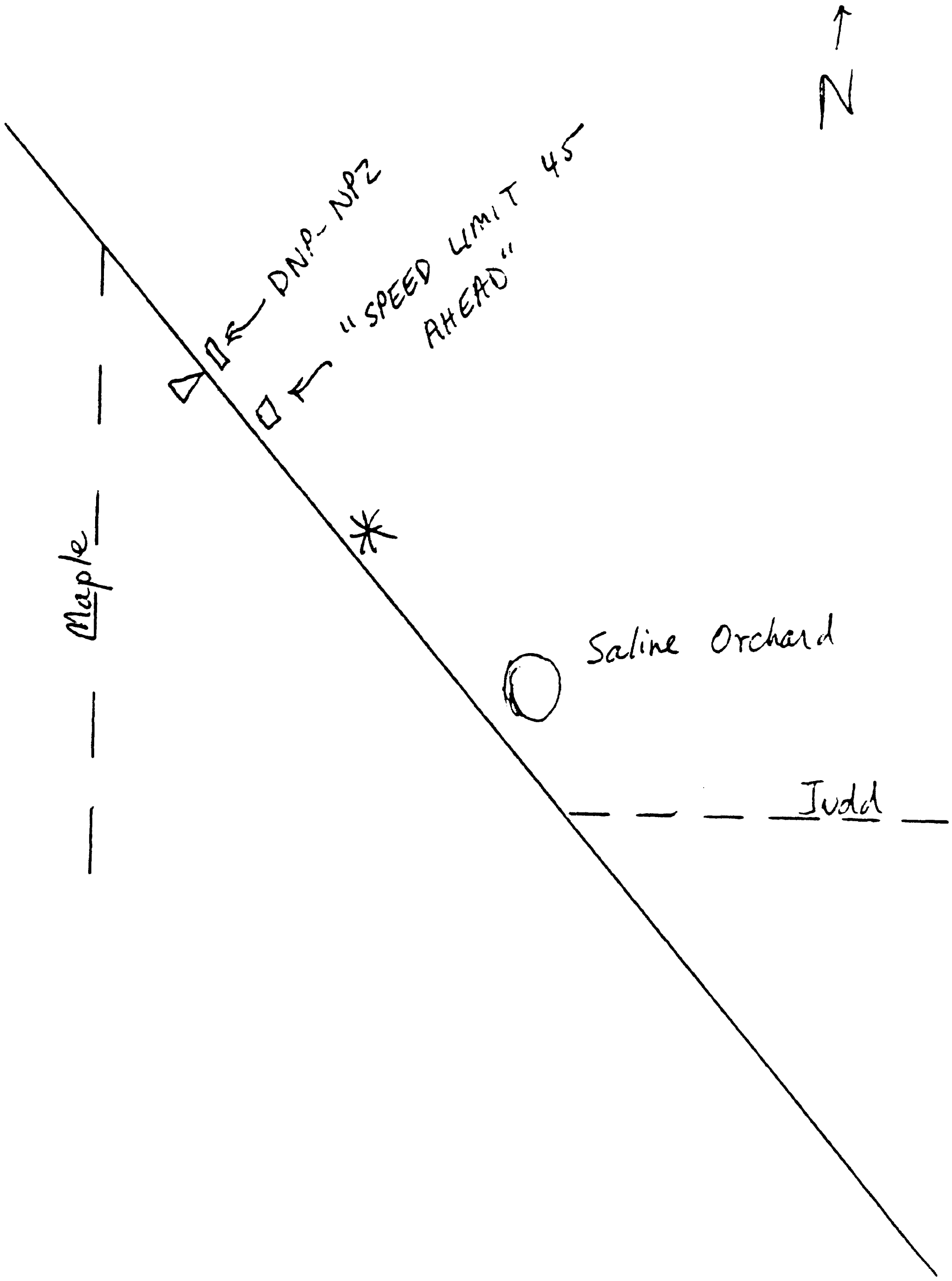
- located on downhill, past Jewell Rd. and before Milkey Rd.
- small bridge at very bottom of hill.
- two houses on right side of roadway.
- target area is near bottom of hill, just before bridge.
- Jewell Rd. serves as a good turnaround location.



Site 23: straight

A - pedestrian
B - pedestrian

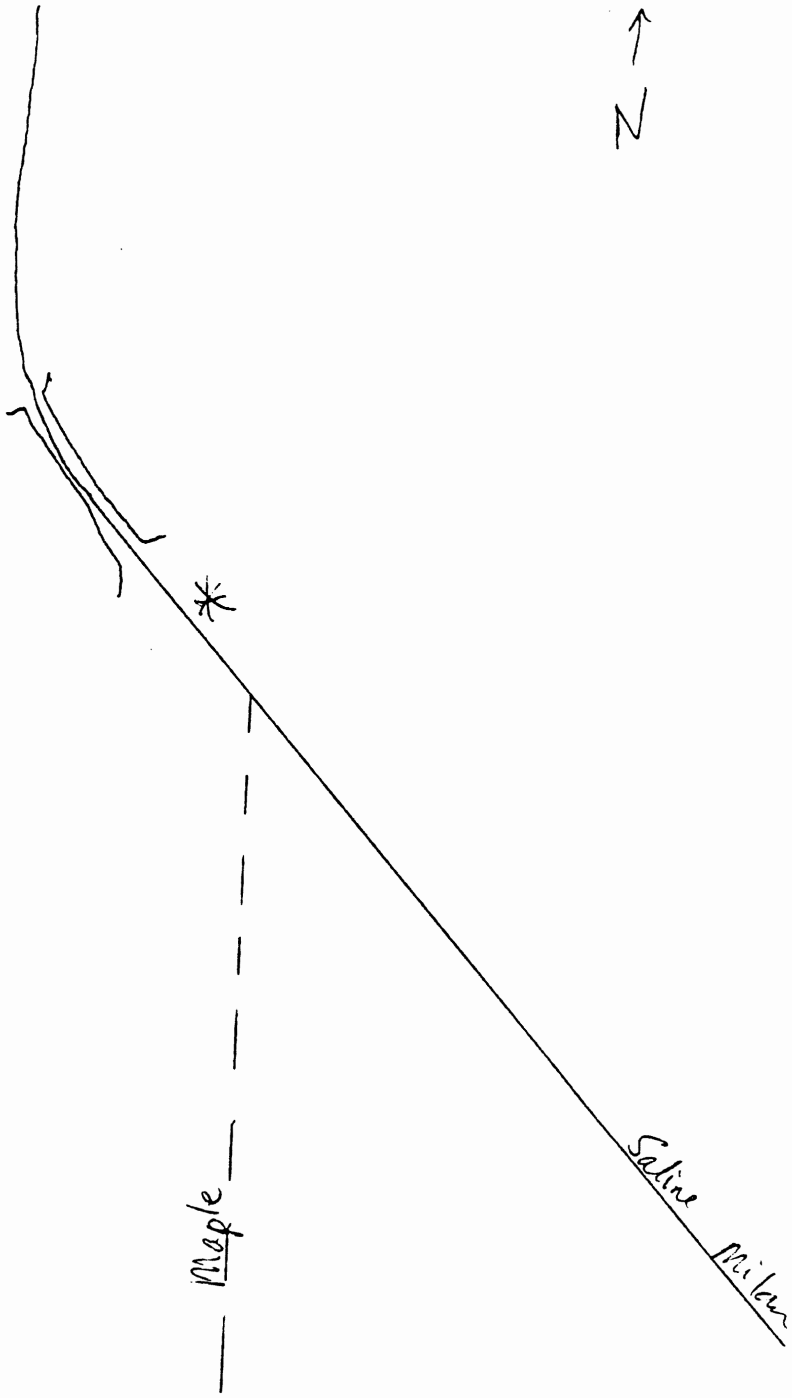
- located on straight after Judd Rd. and before Maple Rd.
- straight comes immediatley after a long downhill.
- target area is exactly between Saline Orchard and "SPEED LIMIT 45 AHEAD" sign.
- for turnarounds, use Maple Rd.



Site 24: hill

A - debris
B - pedestrian

- located on last downhill of course, just after Maple Rd.
- long guardrails on both sides of roadway at bottom of hill.
- car can be left on Maple Rd. until subject car passes.
- use Maple for turnarounds.



APPENDIX C

SET UP PROTOCOL FOR STAFF IN FIELD STUDY INCLUDING COURSE MAP

HALF-ROUTE I, PATTERN A

Make sure you have debris, flashlights, and two-way radios.

****** indicates subject car passing.

Glare Car	Chase Car 1	Chase Car 2
Begin with 2 experimenters	Begin with 2 experimenters	Begin with driver only
☐ 1. Drop debris at Site 1.	☐ 1. Drop off pedestrian at Site 4.	☐ 1. Proceed to Site 7; hide car on Hack and become pedestrian.
☐ 2. Drop debris at Site 2.	☐ 2. Proceed to Site 5; set up parked car.	******
☐ 3. Proceed to Site 3; set up glare with pedestrian.	******	☐ 2. Secure car.
******		
☐ 4. Secure pedestrian		
☐ 5. Pick up pedestrian at Site 4.		

1/4 - route layover for subject car on Clinton-Macon Road

☐ 6. Proceed to Site 11; meet car 2 and set up glare with parked car.	☐ 3. Drop off debris at Site 9.	☐ 3. Proceed to Site 11; meet glare car and park behind glare source.
******		
☐ 7. Pick up debris at Site 9.	☐ 4. Proceed to Site 12 (use Welch Rd. shortcut); set up parked car.	******
	******	

1/2 - route layover for subject on Pennington Road - Switch Beams

HALF-ROUTE II, PATTERN B

Make sure you have debris, flashlights, and two-way radios.

****** indicates subject car passing.

Glare Car	Chase Car 1	Chase Car 2
Begin with driver only	Begin with 3 experimenters	Begin with driver only
☐ 1. Proceed to Site 14; set up glare in front of sign. ******	☐ 1. Drop off debris at Site 15.	☐ 1. Proceed to Site 13; set up parked car. ******
	☐ 2. Proceed to Site 16; set up parked car. ******	☐ 2. Pick up debris at Site 15

1/4 - route layover for subject near Mooreville general store

☐ 2. Drop off debris at Site 20 (via Stoney Creek Rd. shortcut, then right onto Saline-Milan).	☐ 3. Drop off pedestrian at Site 18.	☐ 3. Proceed to Site 24 (use Maple Rd. shortcut); hide car on Maple and become pedestrian on Saline-Milan. ******
☐ 3. Proceed to Site 19. Set up glare with debris. ******	☐ 4. Drop off pedestrian at Site 23.	
☐ 4. Secure debris.	☐ 5. Come back to Site 22; set up parked car. ******	☐ 4. Secure car.
☐ 5. Pick up pedestrian at Site 18.	☐ 6. Pick up pedestrian at Site 23.	
☐ 6. Pick up debris at Site 20.		

1/2 - route layover for subject in Saline - Switch Beams.

HALF-ROUTE I, PATTERN B

Make sure you have debris, flashlights, and two-way radios.

****** indicates subject car passing.

Glare Car Begin with driver only	Chase Car 1 Begin with 2 experimenters	Chase Car 2 Begin with 2 experimenters
☐ 1. Proceed to Site 3; set up glare in front of DNP-NPZ signs. ******	☐ 1. Drop off pedestrian at Site 1.	☐ 1. Drop off debris at Site 4.
☐ 2. Pick up debris at Site 4.	☐ 2. Proceed to Site 2; set up parked car. ******	☐ 2. Drop off pedestrian at Site 6.
☐ 3. Pick up pedestrian at Site 6.	☐ 3. Return to Site 1 to pick up pedestrian.	☐ 3. Drop off debris at Site 7.
	☐ 4. Pick up debris at Site 7.	☐ 4. Proceed to Site 8; set up parked car. ******
1/4 - route layover for subject on Clinton-Macon Road		
☐ 4. Proceed to Site 12 (via Hack/Mohart/Clinton-Macon shortcut); set up glare with debris ******	☐ 5. Drop off pedestrian at Site 9. Driver waits out of view on Pennington Rd. ******	☐ 5. Proceed to Site 10; set up parked car. ******
☐ 5. Secure debris	☐ 6. Pick up pedestrian at Site 9.	
1/2 - route layover for subject on Pennington Road - Switch Beams		

HALF-ROUTE II, PATTERN A

Make sure you have debris, flashlights, and two-way radios.

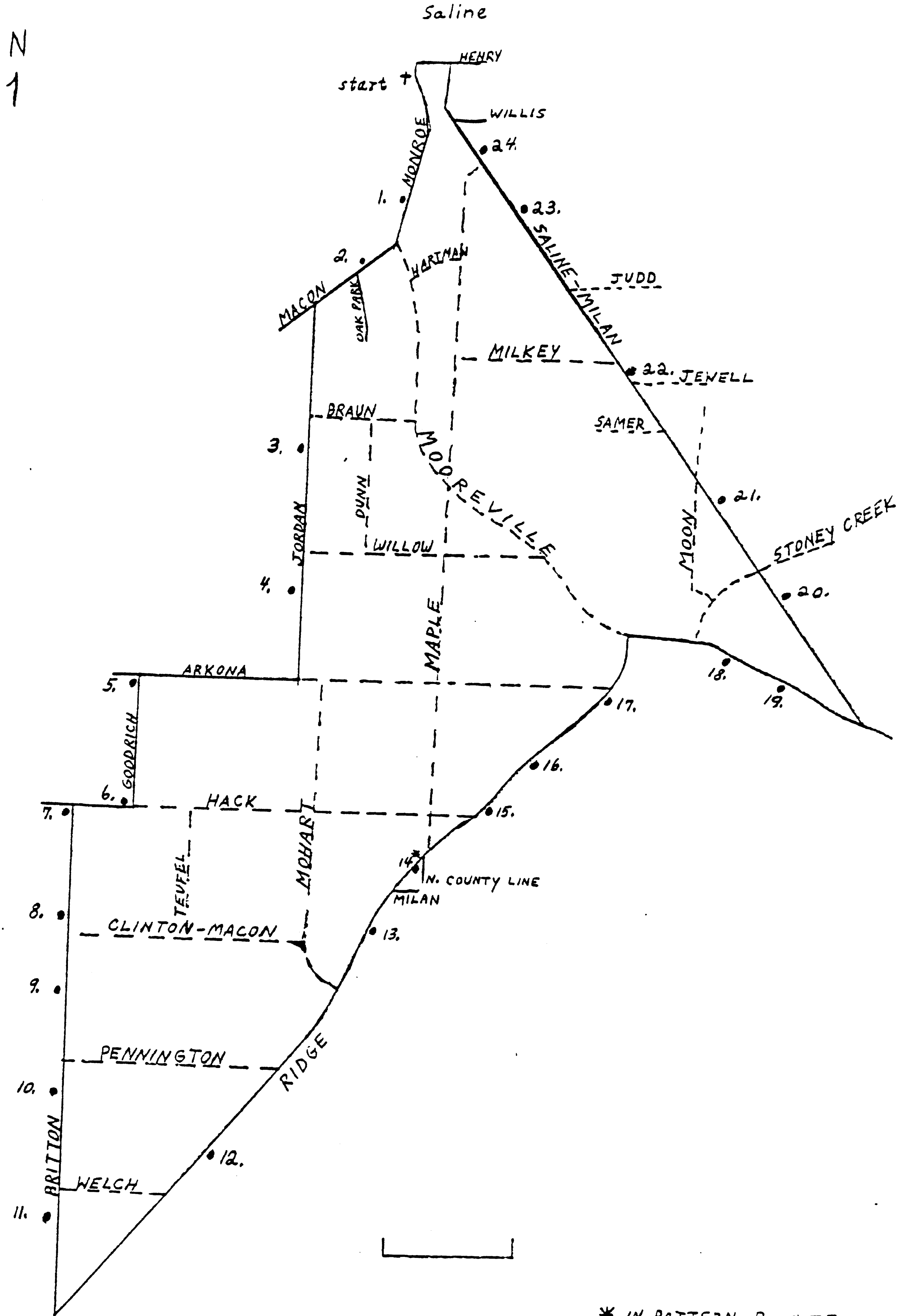
****** indicates subject car passing.

Glare Car	Chase Car 1	Chase Car 2
Begin with 2 experimenters	Begin with 2 experimenters	Begin with driver only
☐ 1. Proceed to Site 14; meet chase car 2 and set up glare with parked car. ******	☐ 1. Drop off pedestrian at Site 15.	☐ 1. Drop off debris at Site 13.
☐ 2. Pick up debris at Site 13.	☐ 2. Drop off debris at Site 16.	☐ 2. Meet glare car at Site 14; set up parked car behind glare source. ******
	☐ 3. Proceed to Site 17; set up parked car. ******	☐ 3. Pick up pedestrian at Site 15.
		☐ 4. Pick up debris at Site 16.

1/4 - route layover for subject near Mooreville general store

Glare Car	Chase Car 1	Chase Car 2
☐ 3. Proceed to Site 19; set up glare with pedestrian. ******	☐ 4. Proceed to Site 21; set up parked car. ******	☐ 5. Drop off pedestrian at Site 23.
☐ 4. Secure pedestrian.	☐ 5. Pick up pedestrian from Site 23.	☐ 6. Drop off debris at Site 24. Hide car on Maple Rd. ******
		☐ 7. Secure debris.

1/2 - route layover for subject in Saline - Switch Beams



* IN PATTERN B, SITE 14 IS LOCATED MUCH CLOSER TO SITE 15.

TARGET SITES AND PLACEMENTS

Size #	Description
1	moderate downhill at .90 miles; targets should be placed just past the 2nd "crest"--very large tree on right side of roadway is a good marker. A - debris B - pedestrian
2	right curve at 1.65 miles (before corner of Oak Park Dr. on left); targets should be placed immediately after an area of road patching--there is a wide shoulder in this area. A - debris B - parked car
3	straight, after Braun Rd; A - glare w/ pedestrian--pedestrian should be halfway between intersection and DNP-NPZ signs. B - glare w/ signs--DNP-NPZ signs .30 miles after Braun Rd. are targets.
4	straight, after Willow Rd; targets should be placed approximately 1/4 mile past intersection. A - pedestrian B - debris
5	left curve, Arkona onto Goodrich; A - place parked car on shoulder just before dirt road merges with main road. B - PWC sign just after curve is target.
6	right curve, Goodrich onto Hack; A - PWC sign after curve is target B - pedestrian should be before PWC sign, but careful to avoid silhouetting himself in sign.
7	left curve, Hack onto Britton; targets should be well into curve, near dirt road merging from right. A - pedestrian B - debris
8	straight, before Clinton-Macon Rd; A - + sign is target B - place parked car well before + sign and away from houses.

Site #	Description
9	straight, after Clinton-Macon Rd.; place targets about 4/10 miles past intersection, near gas pipelines A - debris B - pedestrian
10	downhill, after Pennington Rd., just before bridge A - "weight limit" and "bridge warning" signs are targets B - park car approximately 300 ft. before bridge
11	straight, after Welch Rd. A - parked car behind glare source should be just before the first house (houses are on left of roadway) B - stop ahead sign before Ridge Rd. is target
12	straight on Ridge Rd. after Welch; place targets approximately 4/10 miles past Welch, well beyond PWC sign A - parked car B - glare with debris
13	right curve, 1/2 mile past Clinton-Macon Rd.; place targets just around cruve--avoid proximity of PWC sign A - debris B - parked car
14	straight (very slight right), after Milan Rd. A - parked car behind glare just before N. County Line Rd. B - left curve arrow is target behind glare--this is very close to target site 15
15	left curve, near Hack Rd.; place targets well into curve A - pedestrian B - debris
16	straight, 1/4 mile past bridge; place targets past tree/branches on right side of roadway A - debris B - parked car
17	left curve, before Arkona Rd. A - park car just beyond curve B - ⊣ sign is target

Site #	Description
18	right curve (2nd right after leaving Mooreville); A - ↰ sign is target B - pedestrian should be walking on back side of curve
19	long straight, between Mooreville and Saline-Milan Rd.; targets should be located approximately 1/10 mile before house on right A - glare with pedestrian B - glare with debris
20	straight on Saline-Milan before Stoney Creek Rd.; A - stop ahead sign is target B - debris should be placed well before STOP AHEAD sign--tree on left with "84 lumber" sign makes good marker
21	straight, before Moon Rd.; A - park car well before + sign B - + sign for Moon Rd. is target
22	downhill, just after Jewell Rd. A - ⊣ sign marking Milkey Rd. is target B - park car away from house on right
23	straight, 1/2 mile before Maple Rd., after long downhill; A - pedestrian B - pedestrian
24	downhill, after Maple Rd., guardrails on both sides; A - debris B - pedestrian

APPENDIX D

SUBJECTIVE RATING FORM

Subject ______________________

Beam ____________ Road ____________

Position in series ________

1. Overall illumination

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10

2. Foreground illumination

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10

3. Illumination to the left

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10

4. Illumination to the right

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10

5. Maximum seeing distance

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10

6. Illumination of overhead signs

Extremely poor Extremely good

0 1 2 3 4 5 6 7 8 9 10