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DEVELOPMENT OF A COMPUTER SIMULATION TO PREDICT THE VISIBILITY DISTANCE PROVIDED BY HEADLAMP BEAMS

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The output of the simulation is compared with the results of field experiments for various lateral separations between the vehicles, low and high beams, and targets positioned on the right, left, and center of the lane. Generally, good agreement between the computer simulation and experimental seeing distances are obtained. The simulation should have useful application to evaluate current and proposed headlight beams and other variables, such as lamp aim, affecting beam performance.

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ABSTRACT

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The output of the simulation is compared with the results of field experiments for various lateral separations between the vehicles, low and high beams, and targets positioned on the right, left, and center of the lane. Generally, good agreement between the computer simulation and experimental seeing distances are obtained. The simulation should have useful application to evaluate current and proposed headlight beams and other variables, such as lamp aim, affecting beam performance.

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FOREWORD AND ACKNOWLEDGEMENTS

This research is one in a series of HSRI studies concerned with headlighting performance sponsored by the Motor Vehicle Manufacturers Association. It is issued under the general contract title: "Passenger Car and Truck Lighting Research: Headlighting Phase I, Beam Pattern Evaluation."

During the conduct of this work meetings were held with the MVMA Lighting Committee, Headlighting Research Task Force, consisting of: Mr. G. Gardner and Mr. R. Rossio, Chairman; Mr. P. Lawrenz; Mr. P. Maurer; and Mr. B. Preston Discussions with the task force were helpful and contributed to the study. We also acknowledge the assistance of Mr. R. J. Donohue, Environmental Activities Staff, General Motors Corporation and of the Guide Lamp Division of General Motors Corporation for arranging and carrying out photometric checks on the headlamps used in the field tests.

INTRODUCTION

There are in general two methods for evaluating the performance of a headlighting system, whether proposed or existing. These are field testing and computer simulation. Field testing is probably what most people think of when the words "performance evaluation" are used. Field testing can provide a subjective evaluation of the system as well as objective numerical results. However, obtaining objective data, at least, is expensive and time-consuming and the statistical reliability of the methods used is often not known. The headlamps must be obtained, if existing beams are to be used, or fabricated, if proposed beam patterns are to be evaluated. Targets must be designed and built. A proper place must be found to run the tests under controlled conditions. Suitable instrumentation must be devised to record and reduce the desired data to usable form. Personnel must be provided to set up the test conditions, drive the vehicles and operate the instruments. It is desirable for the vehicles to be driven at constant speeds on perfectly parallel or known paths. This is physically difficult for the driver, who must at the same time be looking for the targets. In addition, the road surface itself may not be perfectly flat. Thus, irregularities in the geometry are produced which result in irregularities in the distance at which the target can be seen. The lamp beam patterns may change from run to run due to aging, changes in system voltage, or variations in vehicle loading resulting in an effective lamp misaim. Many runs must be made for different subjects using a relatively small number of targets and the results statistically analyzed.

Computer simulation, however, is relatively inexpensive (once the program has been written and validated), fast and completely repeatable. It is feasible, both in time and cost, to make a number of runs varying just one parameter in a systematic fashion to assess its effect, then another set varying just a second parameter, and so on. Proposed beam patterns can be evaluated without actually fabricating them.

Previous attempts at beam evaluation by simulation were made by V. J. Jehu (1955),* W. S. Stiles and C. Dunbar (1935), and de Boer and Morasz (1956) who basically used Jehu's approach. Jehu's simulation used a combination of mathematical calculations and experimental results for a special case. This special case produced a graph of visibility distance versus glare intensity with target intensity as a parameter. He would calculate the actual glare intensity, convert it into an equivalent glare intensity for his special case, then try various target distances until he found one at which the illumination available was just sufficient to allow the target to be seen. Stiles and Dunbar computed the actual contrast between a target and its background, using certain assumptions about the background, then used experimental contrast threshold data to determine visibility. However, since neither they nor Jehu had access to high speed digital computers, their simulations were of necessity even more approximate than the one to be described here. This does not make their efforts any less important or valuable. Indeed, our approach is largely based on Jehu's work, though with fewer approximations and including some additional considerations.

One of the more important extensions of the present model, compared to previous work, has been an attempt to compute visibility distances during the entire meeting between two vehicles at night and after they have passed each other.

Inclusion of the time after the vehicles have passed one another makes it necessary to simulate the eye recovery from glare explicitly, both while the opposing vehicle's headlamps are in view and after they have passed. This is done by assuming that the experimentally observed (Spencer, 1969) exponential change in eye sensitivity after the glare source is removed is

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*References are listed on page 32.

equivalent to a corresponding exponential decrease in veiling glare in the eye.

A second feature of this study has been an attempt to model the effect on visibility of the foreground lighting produced by illumination of the roadway ahead of the vehicle by its own headlamps. The basic approach taken has been to consider the light returned from the pavement as a glare source at the driver's eyes, whose effect is to reduce visibility. This is similar to considering the pavement luminance as that luminance to which the driver's eyes adapt, in the absence of other light sources, and which, therefore, determines the visual sensitivity. Thus, even when the glare vehicle has been out of sight for a long time, the veiling glare in the eyes does not decrease to zero because there is still "foreground glare" caused by the reflection back off the pavement ahead of the vehicle of light from the vehicle's own lamps. At present, the reflectivity of the area of pavement considered in this calculation is assumed constant. At distances far enough ahead of the vehicle that the angle from the pavement to the eye is quite small, this is approximately true (Finch and Marxheimer, 1952).

OVERVIEW OF PROCEDURES

The visibility distance simulation includes the road, two vehicles, a target, an observer, and the mathematical relations describing them and their interactions.

The road is assumed to be flat and level with a constant reflectivity. The two vehicles move on parallel paths, with constant lateral and vertical separation distances, at constant speeds. The longitudinal separation distance is defined as the independent variable. Each vehicle has a specified number of headlights, up to five, located in fixed positions relative to one another and aimed at any horizontal, vertical and rotational angles. They may have polarizing filters and the windshield may have an analyzer. The output of each headlight is described by a bivariate table of intensity, in candelas, for pairs of horizontal and vertical angles. Each lamp may be switched off or on twice at specified separation distances. The main vehicle produces a veiling glare from its own headlight output reflecting back off the road ahead.

The observer is assumed to have a single eye located at an arbitrary point in the main vehicle. The eye line-of-sight may be fixed or track the target. The eye can be in one of three states: adaptation to increasing veiling glare, readaptation to slowly decreasing veiling glare, and recovery during rapidly decreasing veiling glare. The transition from adaptation to readaptation thus occurs at the point of maximum veiling glare, and passage from readaptation to recovery occurs when the veiling glare as calculated from the glare vehicle beams begins to fall off more rapidly than that calculated from the recovery equation. During readaptation, the "recovery" equation computes veiling glare as exponentially decaying from the value at the previous point at a fixed rate, the value of which is also dependent on the previous value of veiling glare. During recovery the parameters are constant, their values dependent on the veiling glare at the point of transition.

There is an observer relation among intensity directed at the target needed to see it, target distance, and glare intensity (e.g., Jehu, 1955). It is assumed that target intensity is an increasing exponential in target distance with coefficients that are functions of glare intensity. These coefficients appear to be well described by simple integer root equations in glare intensity. The target is located at a fixed lateral and vertical distance from the eye, with a constant reflectivity. Target reflectivities other than that assumed in the "basic observer relation" can be included by one of two equivalent methods, each of which uses the square of the ratio of the desired value to the basic value. One method multiplies the actual intensity directed at the target; the other divides the intensity needed to see the target. The latter allows the program to work with smaller numbers, for reflectivities larger than basic, and hence has some small computational advantage. The longitudinal distance from target to eye is defined as the dependent variable and is the visibility distance.

Fry's (1954) equation computes veiling glare from glare intensity, distance of glare source from eye, and glare angle between eye line-of-sight and line connecting eye to glare source. The path of the target through the main vehicle beam patterns is found in terms of the values of horizontal and vertical angles at specified values of the dependent variable, and the interpolated intensity values are stored for later use in the program. A rectangular linear interpolation on the log of the intensity is used here. The same is done for the path of the eye through the glare vehicle beam patterns using the longitudinal separation distance. Then, for any distance value, the corresponding intensity is found by a single linear interpolation. Foreground glare is included as a function of the visibility distance, with coefficients found by processing three points.

Since the system of equations derived from all this is much too complex to be explicitly solved for visibility distance in terms of separation distance, a convergence procedure is used to find the largest target distance at which the intensity directed at the target is just equal to the intensity needed to see the target.

DESCRIPTION OF COMPUTATION SCHEME

The Headlamp Visibility Distance Performance Simulation is at present formulated to suit the current HSRI digital computer, which is an IBM-1800.[1] It is written in Standard Fortran IV and

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[1] As of September 1, 1973, the HSRI digital computer will be a DEC PDP 11/45 and the program will also be formulated for it.

would be compatible with any IBM computer using this language (with some minor modifications). The limitations of the IBM-1800 in storage space and computation speed necessitated several compromise procedures which would not be necessary on a machine such as the IBM-360. The program is now in five links, three of which process the input data, the fourth does the visibility distance calculations proper and the last prints and plots the output. The beam patterns, in a group of ten, are previously written into a separate disk file and accessed as needed by the program. The headlamp beam intensities directed at the eye from the glare vehicle and at the target from the main vehicle are precomputed in the input section for a number of specified separation and target distances, respectively, and stored for later use.

The form of the program is shown in Figure 1.

GEOMETRY

The simulation includes two vehicles, with a maximum of five headlamps each, moving at constant speeds with their longitudinal axes parallel to one another. The coordinate system has its origin at the driver's eye. Its X-axis is parallel to the longitudinal axis of the main vehicle and positive down the road from the driver. The Y-axis is vertical and positive up. The Z-axis is in the lateral direction and positive to the driver's right. The separation distance between the vehicles thus begins large and positive, becomes smaller and ends negative.

Figures 2 and 3 show the geometry in elevation and plan, respectively.

HEADLAMP BEAMS

The light output from each headlamp is usually described in the form of an iso-candela diagram. The program, however, cannot use this directly but needs a bivariate table of candela values for pairs of horizontal and vertical angles relative to

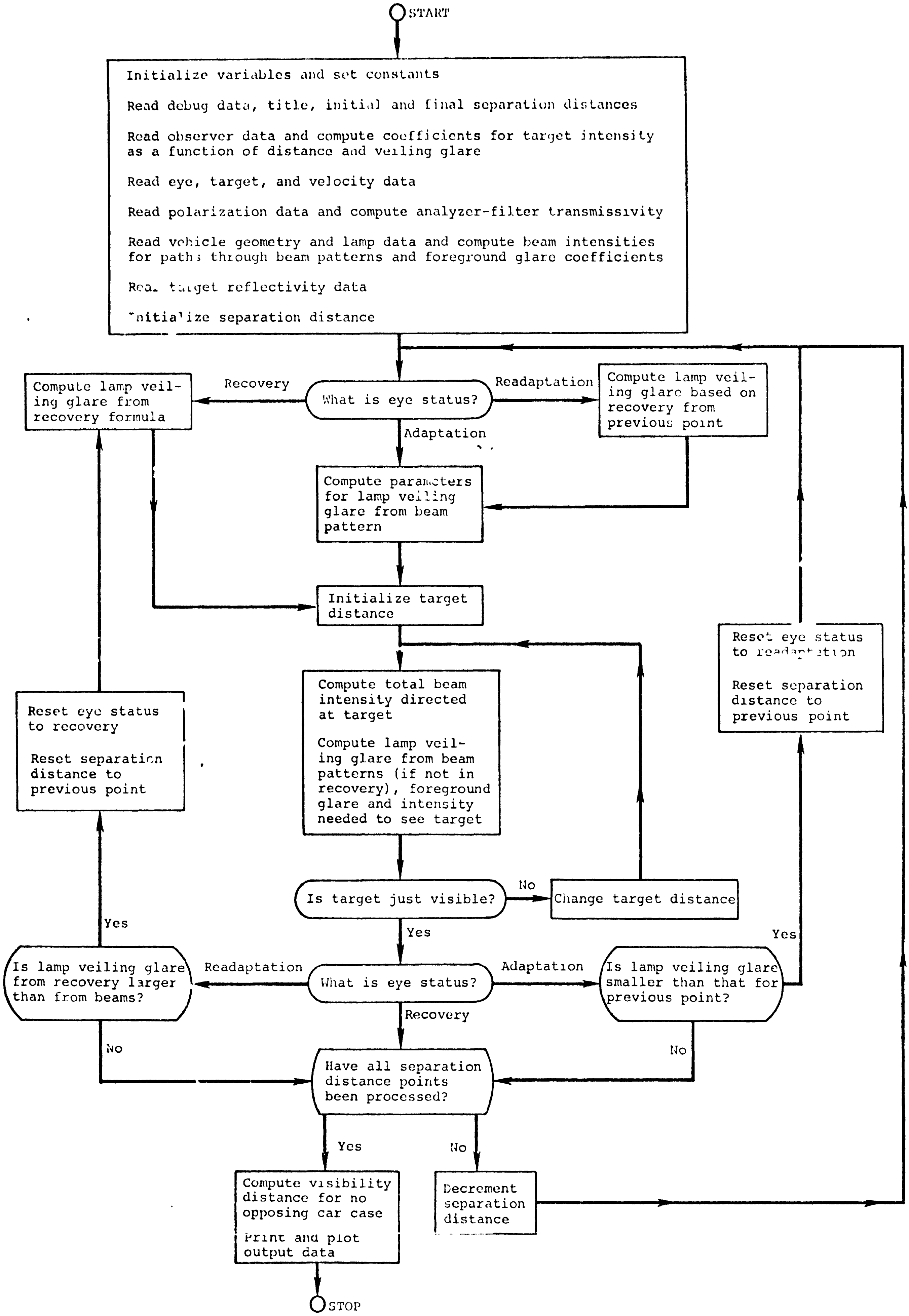


Figure 1. Block diagram of headlamp visibility distance performance simulation program.

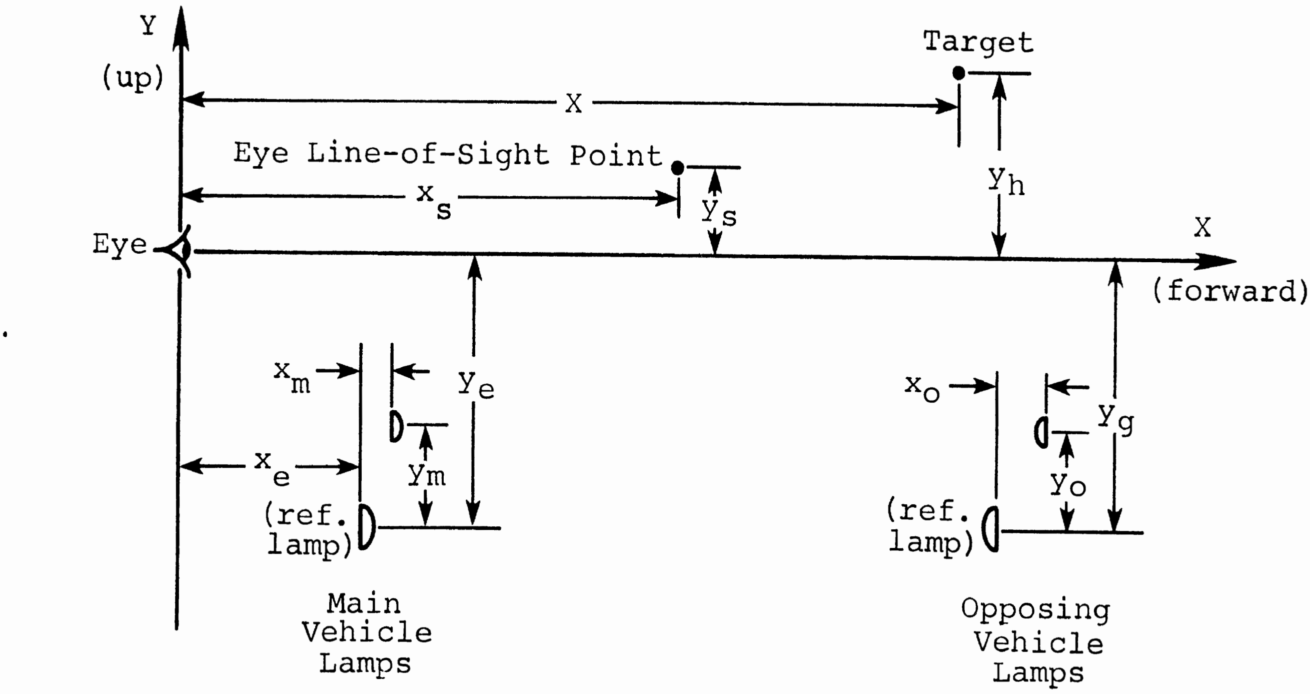


Figure 2. Geometry-elevation for headlamp visibility distance performance simulation

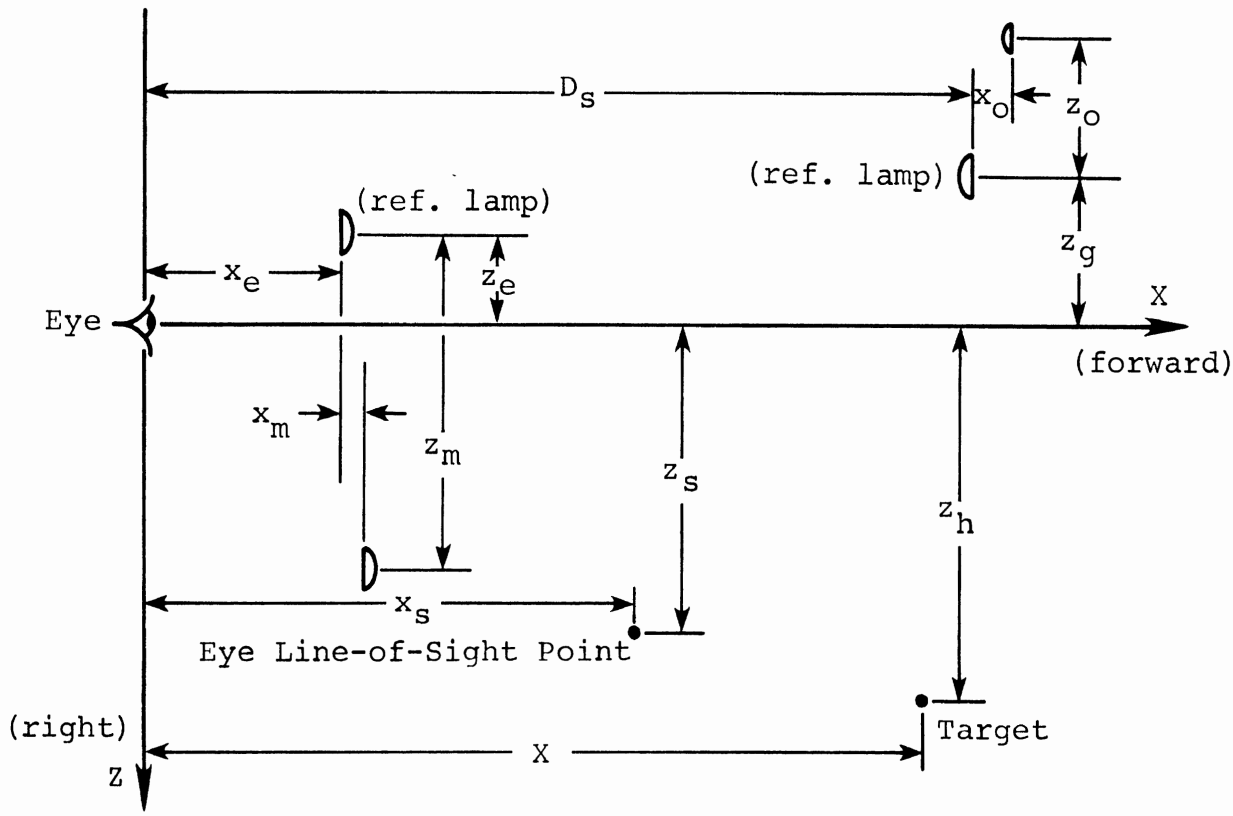


Figure 3. Geometry-plan for headlamp visibility distance performance simulation.

the X-axis. In this program there may be as many as 61 horizontal and as many as 22 vertical angle values. The increment in angle must be constant across the beam pattern table. The horizontal increment may be either the same as the vertical or twice it. The beam patterns are written into a disk file as the log of the candela value by a separate program and then read off the disk file as needed by the program.

The intensity values and aim of the beam pattern as written in the disk file, may be modified at the time of use in two ways. First, the user can modify the intensity by a constant factor across the entire beam pattern. This was developed to simulate a polarizing filter and windshield analyzer combination, where the filter is at some angle relative to the analyzer, or the effects of filament deterioration, dust on the lens, etc. Second, the lamp can be misaimed in pitch, yaw, and roll; i.e., it can be tilted up or down, turned right or left, and rotated about its axis counterclockwise or clockwise. In each case the former is positive.

The path of the target through the main vehicle lamp beam patterns is calculated for twenty preselected visibility distance values, and that of the eye through those of the glare vehicle for the same number of separation distance values, in terms of the horizontal and vertical angles for each point. Then the intensity in this direction is found by a double linear interpolation of the log of candela values:

$$
\begin{aligned}
\ln I(H,V) = {} & AL(I,J) + [AL(K,J) - AL(I,J)] \left[\frac{H-H(I)}{H(K)-H(I)}\right] \\
& + [AL(I,L) - AL(I,J)] \left[\frac{V-V(J)}{V(L)-V(J)}\right] \\
& + [AL(K,L) + AL(I,J) - AL(I,L) - AL(K,J)] \left[\frac{H-H(I)}{H(K)-H(I)}\right]\left[\frac{V-V(J)}{V(L)-V(J)}\right]
\end{aligned}
$$

where $H(I)<H<H(K)$

$V(J)<V<V(L)$

The antilogs of these values are stored for each lamp for later use in the program, where the actual intensity for the actual distance value is found by a single linear interpolation on the candela values:

for glare intensity:

$$GL(L) = ALX(J,I) + [ALX(K,I) - ALX(J,I)] \left[\frac{DS-XX(J,1)}{XX(K,2)-XX(J,2)}\right]$$

for L=1,5 I=L+5

$$XX(J,2) < DS < XX(K,2)$$

for target intensity:

$$TI = \sum_{I=1}^{5} \left\{ALX(J,I) + [ALX(K,I) - ALX(J,I)] \left[\frac{X-XX(J,1)}{XX(K,1)-XX(J,1)}\right]\right\}$$

for $XX(J,1) < X < XX(K,2)$

It would be slightly more accurate to compute the intensity directly from the beam pattern table each time, but limits on computer storage space available forced the use of the disk file (ten 61 by 22 matrices are just too much for the IBM-1800 used in this study), and accessing the disk file each time makes the program run much too long and hence cost too much. These limitations would not exist for an IBM-360, for example.

If the beam pattern table is large enough so that all angle value pairs needed for calculation of intensity directed at the eye for glare, at the target for visibility, and at the road for foreground glare, are included within its limits, then only interpolation is needed and the accuracy is compatible with the accuracy of the source of the intensity values. If, however, some of the angle value pairs (one or both of them) fall outside the table, (which is almost inevitable for foreground glare close to the vehicle) then extrapolation is required and the accuracy depends on the smoothness of the outside two rows and columns of the table. For angle value(s) not too far beyond the table limits and/or well behaved tables, the simple double linear extrapolation based on the end row or column and its neighbor is sufficiently accurate.

If the extrapolation is only in one direction, this is also adequate. However, for large extrapolations off the corner of the table with the end row or column decreasing much more slowly than its neighbor, the resultant extrapolated value of intensity found by the above equation can actually be very much larger than any of the four intensity values used. This, however, is absurd since the general trend of the beam pattern is for the intensity to continue to decrease off the ends of the table. If the table were extended by photometry or judicious hand calculations, it would be seen that the difference in rates of decrease between the new end row or column and its neighbor would become small enough to allow simple extrapolations with sufficient accuracy, if needed. However, the program should be able to deal with this case as well as with larger tables, so a new extrapolation scheme was devised to be used whenever the normal one predicts an increase in intensity when there should be a decrease. This scheme uses the corner value of intensity and its neighbor horizontally to predict (linearly on the log) a new value of intensity at the horizontal angle value, just beyond the actual value which is an integer number of horizontal angle increments away from the end value. The same thing is done using the corner point and its neighbor vertically. Then the fourth point surrounding the actual angle values is found by a diagonal extrapolation using the corner point and an interior point with the neighboring vertical angle value and a horizontal angle, whose value is found by dividing the needed number of horizontal increments by the needed number of vertical increments, and moving that many points horizontally.

If this still predicts an increase in intensity, then the point is omitted, and a value of zero is used for the intensity.

FOREGROUND GLARE

The foreground pavement luminance due to illumination of the pavement by the headlamps of the observer's vehicle was first treated as a constant veiling glare added to that from the glare vehicle lamps. Then a separate program was devised to compute the veiling glare from the output of up to five headlamps reflected back off a rectangular section of the pavement in front of the vehicle. The road reflectivity is assumed to be constant and the calculations are done for small parts of the pavement and then added up as an approximation to integration. Figure 4 shows the geometry for this calculation. The equivalent foreground glare (GOL) is obtained from the following expression:

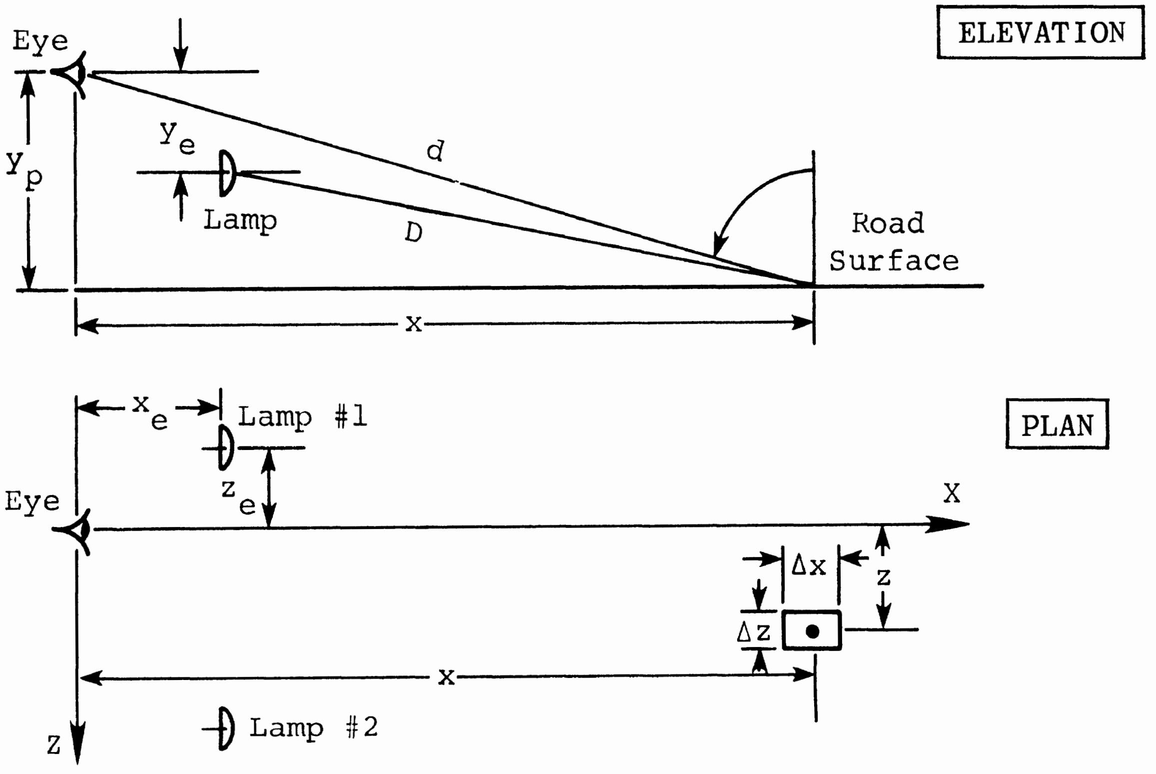


Figure 4. Geometry for foreground glare calculation.

$$GOL = \sum_{X,Z} \left[\frac{I(X,Z)}{D^2\theta^2}\right] \left[\frac{R\cos\theta\cos\alpha}{d^2} \Delta X \Delta Z\right]$$

where $\cos\alpha = \dfrac{Y_p}{d}$

$$\cos\theta = \frac{X_s X - Y_s Y_p + Z_s Z}{r_s d}$$

$$r_s^2 = X_s^2 + Y_s^2 + Z_s^2$$

$$d^2 = X^2 + Y_p^2 + Z^2$$

$$D^2 = (X-X_e)^2 + (Y_p-Y_e)^2 + (Z+Z_e)^2$$

R is the road reflectivity (assumed constant), d is the distance from the edge to the pavement spot, D is the distance from the lamp to the pavement spot, ΔX, ΔZ are dimensions of incremental pavement area, I(X,Z) is the intensity directed at the pavement spot, α is the angle between d and vertical, and θ is the glare angle.

The foreground veiling glare will be constant if the eye line-of-sight is fixed. If the eye is tracking the target, however, the foreground glare will vary with the target distance. Figure 5 shows this variation for several target locations and typical U.S. low beam headlamps.

The form of equation which best fits these plots was found to be:

$$GOL = G_a + (aX-c)\exp(-X/b)$$

where G_a is the asympototic value for an eye line-of-sight looking straight ahead, GOL is the foreground glare, X is the target distance from the eye, and the coefficients a, b, c are found by processing three equally spaced points on the curve, as follows:

First compute: $Z = G_2(G_2-G_a) - G_3(G_1-G_a) + (G_1-G_2)G_a$

then if $Z>0$ $\quad b = \dfrac{X_1}{\ln\left(\dfrac{G_2-G_a+\sqrt{Z}}{G_3-G_a}\right)}$

$$a = \frac{1}{(X_2-X_1)}\left[(G_2-G_a)\exp\left(\frac{X_2-X_1}{b}\right) - (G_1-G_a)\right] \exp\ (X_1/b)$$

$$c = aX_1 - (G_1-G_a)\exp(X_1/b)$$

if $Z \leq 0$,

$$c = \frac{-(G_1-G_a)^2}{(G_2-G_a)} \qquad b = \frac{X_1}{\ln\left(\frac{G_1-G_a}{G_2-G_a}\right)} \qquad a = 0$$

These calculations are now included in the input section of the program.

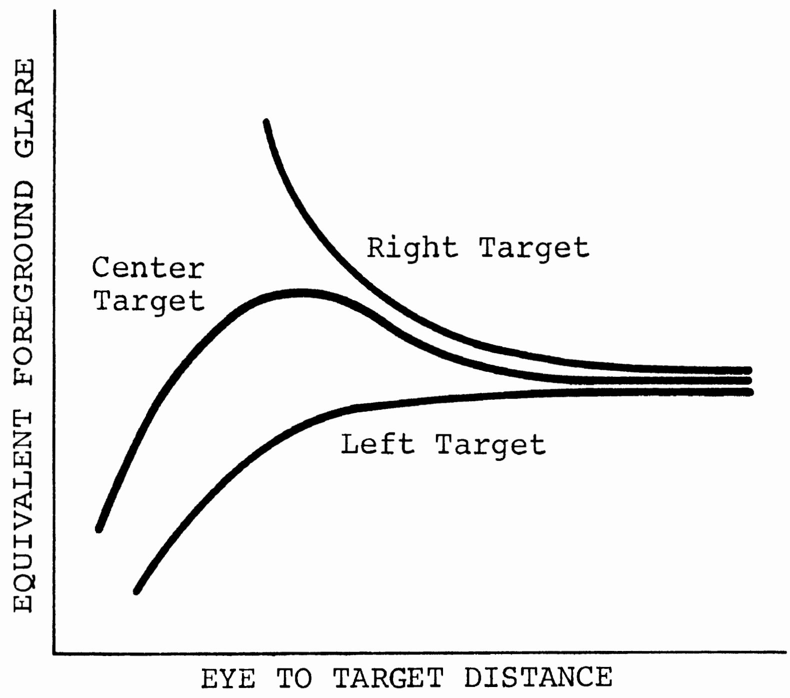


Figure 5. Equivalent foreground glare as a function of target distance and lateral position for a typical low beam.

VISUAL ADAPTATION LEVEL

The driver's two eyes are assumed to be combined and located at an arbitrary point in the main vehicle. This point is the origin and all other distances and dimensions are relative to it.

The eye may be looking in a fixed direction throughout the run or it may always be looking at the target, wherever the target may be.

The eye's ability to see the target is influenced by the level of veiling glare and whether this level is increasing or decreasing and how rapidly. The eye can be in one of three states: adaptation to increasing or slowly decreasing veiling glare, and recovery during rapidly decreasing veiling glare. In the program, adaptation is sub-divided into two: adaptation to increasing levels and readaptation to slowly decreasing levels. Transition from adaptation to readaptation naturally occurs at the point of maximum veiling glare. Transition from readaptation to recovery occurs when the veiling glare, as calculated from the glare vehicle beam patterns begins to decrease more rapidly than that calculated from the recovery equation. Figure 6 illustrates glare states used in the model and the glare adaptation transition points. The recovery equation computes the veiling glare as an exponential decay from the value at some point at a constant rate, the value of which is also dependent on that value of veiling glare. During recovery that point is naturally the point of transition from readaptation to recovery. During readaptation, that point is always the next previous point to the one being calculated. The form of the rate coefficient's dependency on veiling glare was found by matching simulation outputs with experimental results during recovery. Thus:

$$VG = A \exp(-BX)$$

during readaptation:

$$A = VG \text{ (previous point)}$$

during recovery:

$$A = VG \text{ (passage)}$$

and $B = EK\ [1+\log(\frac{A}{GK})]$

where, EK is an input parameter found using data from McFarland and Domey (1958), GK = GOL + maximum veiling glare associated with EK, VG is the equivalent glare from the opposing vehicle's headlamps, and GOL is the equivalent glare from the foreground pavement illumination from the main vehicle's headlamps.

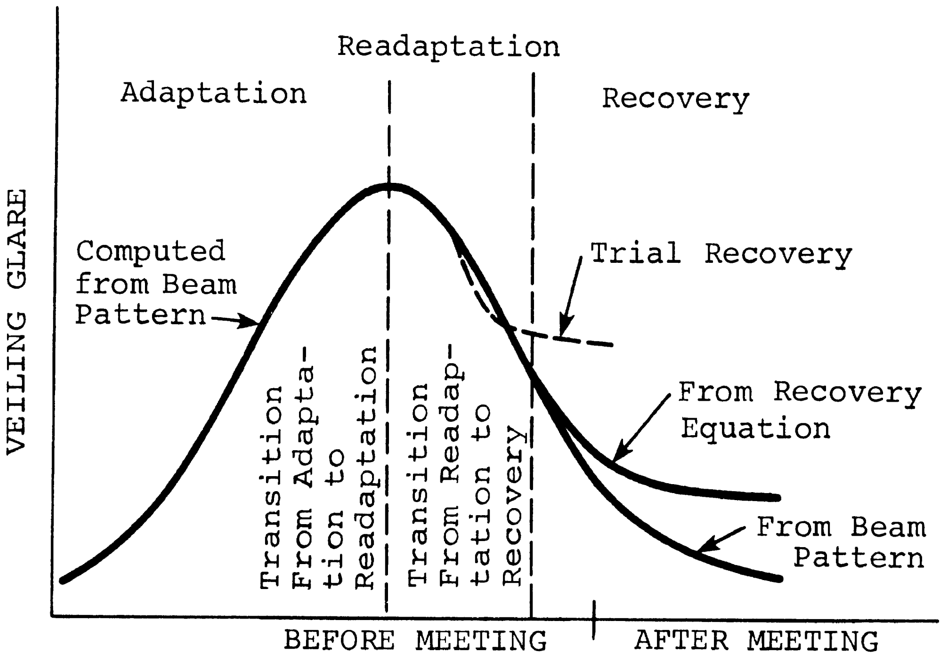
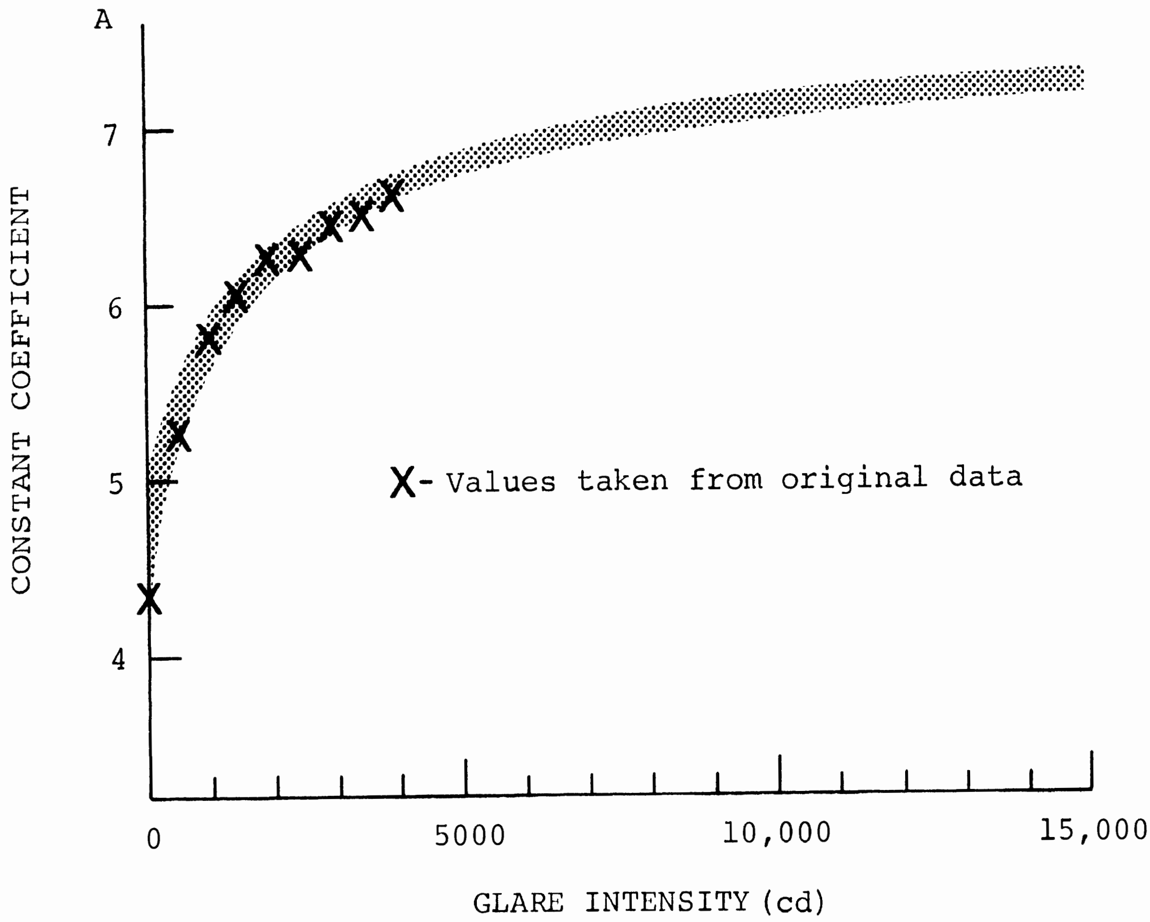


Figure 6. Glare states and transition points.

OBSERVER RELATION

A basic observer--glare/illumination relation was found experimentally by V. J. Jehu (1955) and plotted as curves of visibility distance versus glare intensity directed at the eye with the intensity needed to see the target as a parameter. He used a single glare lamp of uniform intensity in a fixed geometric relation to the target, the main vehicle lamp was also of uniform intensity, and the criterion for target visibility was discernment of target shape and/or orientation. Variables implicit in this relation include target reflectivity, eye parameters, road reflectivity for foreground glare, target background, and beam parameters other than intensity, such as color temperature.

The basic observer relation as plotted was put into equation form by picking off values of visibility distance for each target intensity curve using glare intensity as a parameter. When target intensity was plotted against visibility distance with glare intensity as a parameter, the curves appeared to be exponential in nature. This was confirmed when log target intensity was plotted against visibility distance, and the line became straight. At first, the coefficients of each glare intensity line were calculated and stored. A linear interpolation scheme was used to find the coefficients for the exact glare intensity value derived by the program. This was very good as long as the glare intensity value calculated was within or not far beyond the limit of the basic observer relation. Most low beams are within the limit, but high beams at close separations can produce very large glare intensity values, especially for targets located between the vehicles. The maximum value in the basic observer relation is 4000 candelas; whereas values as high as 20,000 candelas have been produced by the program. Linear extrapolation in this case is not reliable. The coefficients become too large and the visibility distance too small, when compared to experimental results. Then the coefficients were plotted against glare intensity. These plots appeared to be asymptotic exponential in nature (Figure 7). Various values of parameters in these equations were used, based on processing different sets of points, but they all seemed to flatten out too soon, making the coefficients too small and the visibility distances too large, compared to the experimental data. More analysis was then performed on the coefficient values, under the assumption that the coefficients were proportional to some integer root of



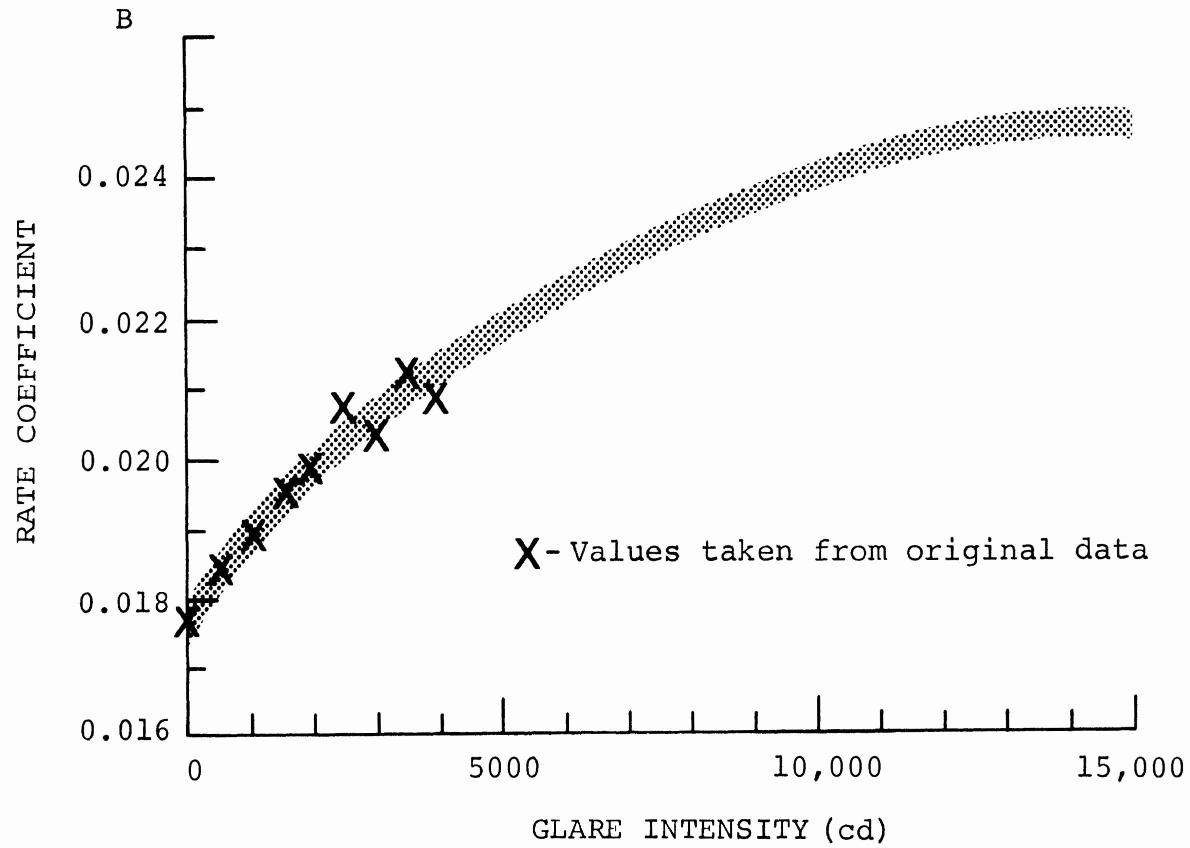


Figure 7. Preliminary observer relation coefficients plotted against glare intensity, based on data from Jehu (1955).

the glare intensity. It was found that the fourth root fitted the constant coefficient quite well and the square root suited the rate coefficient. This is what the program uses at present.

$$TI = \exp(A+B\cdot DV)$$

$$A = a_1+a_2(GI)^{1/4}$$

$$B = b_1+b_2(GI)^{1/2}$$

where $a_1 = 3.4$

$a_2 = .36$

$b_1 = .016$

$b_2 = .00008$

TI = Intensity needed to see the target

DV = Visibility (target) distance

TARGET REFLECTIVITY

The program uses a basic observer relation to determine the intensity needed to see the target as a function of target distance and adjusted glare intensity, and the target reflectivity is an implicit parameter in this relation. Thus, a different target reflectivity would require a different observer relation. Since the target distance and adjusted glare intensity are obviously independent of target reflectivity, it is the intensity needed to see the target that would be changed. Increasing the target reflectivity should decrease the intensity needed to see the target, all other things being the same. A relation was tried in which multiplying the target reflectivity by a number causes the intensity needed to see the target to be divided by the square of that number. This produced results which agreed very closely with the experimental curves and are in accord with Allard's Law (I.E.S., 1966).

VEILING GLARE EQUATION

The veiling glare equation computes veiling glare in the eye as a function of the intensity from the glare source directed at the eye, the distance from the source to the eye and the angle between the line connecting the source and eye and the eye line-of-sight. The general form of this equation is:

$$VG = \frac{KI}{D^2 f(\Theta)}$$

where K is a constant, the value of which depends on the age of the observer, I is the intensity, D the distance and $f(\Theta)$ is a function of the angle, the form of which varies depending on the investigation, e.g.:

Styles (1929) - Holladay (1927) used:

$$f(\Theta) = \Theta^2.$$

Fry (1954) used:

$$f(\Theta) = \Theta(\Theta+1^\circ.5).$$

Richards (1952) has found:

$$f(\Theta) = \Theta^n,$$

where n is also a function of Θ.

However, the glare angle itself is defined as:

$$\cos\Theta = \frac{X_s X_g + Y_s Y_g + Z_s Z_g}{D_s D_g}$$

where subscript s refers to eye line-of-sight coordinates relative to eye, subscript g refers to glare source coordinates relative to eye,

$$\text{and } D = \sqrt{X^2 + Y^2 + Z^2}$$

The program used the Stiles-Holladay equation at first, until it was noted that some target locations, notably those to the left of the driver, can produce very small glare angles at small separation distances. This was producing excessively large veiling glare and, hence, excessively small visibility distances. The change to the Fry equation mitigated this effect without reducing the accuracy for target positions which were not producing such very small glare angles.

The factor K does not appear in the program because it occurs once in the numerator when the veiling glare is calculated and once in the denominator (effectively) when the adjusted glare intensity is calculated from the veiling glare and thus cancels, at least for similar observers. Since the experimental results used for validating the simulation are the average of those for many different observers, it was decided not to include the K factor explicitly as it is not known what the value would be, either for the experimental results (numerator) or for the basic observer relation (denominator).

CONVERGENCE PROCEDURE

The convergence procedure used is as follows for each separation distance: select a target distance, compute the intensity directed at the target from the beams of the main car and the intensity needed to see the target under prevailing glare conditions. If the former exceeds the latter, then the target is assumed visible at this distance. Then the distance is increased and the computations repeated. If the target is not visible at this distance, then the distance is reduced and the computations repeated. When the target changes from visibility to invisibility (or vice versa), a half-interval procedure is begun between the last two points to converge on the distance at which the target is just visible.

Except for the initial separation distance, the first trial target distance is always the previous converged on value. This minimizes computation time.

It has been noted in some instances that there are two points at which the target is just visible (see Figure 8). In this case it is the larger distance which is desired and the program will find it.

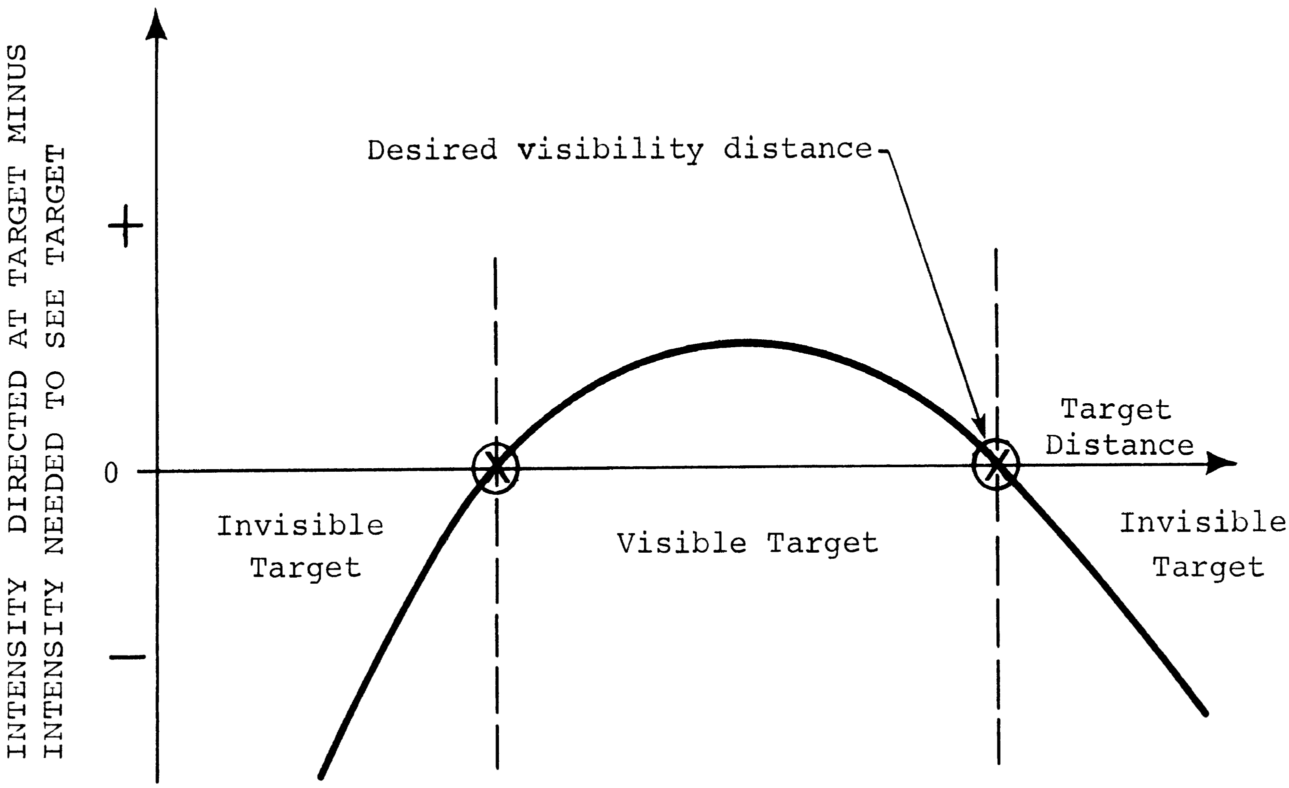
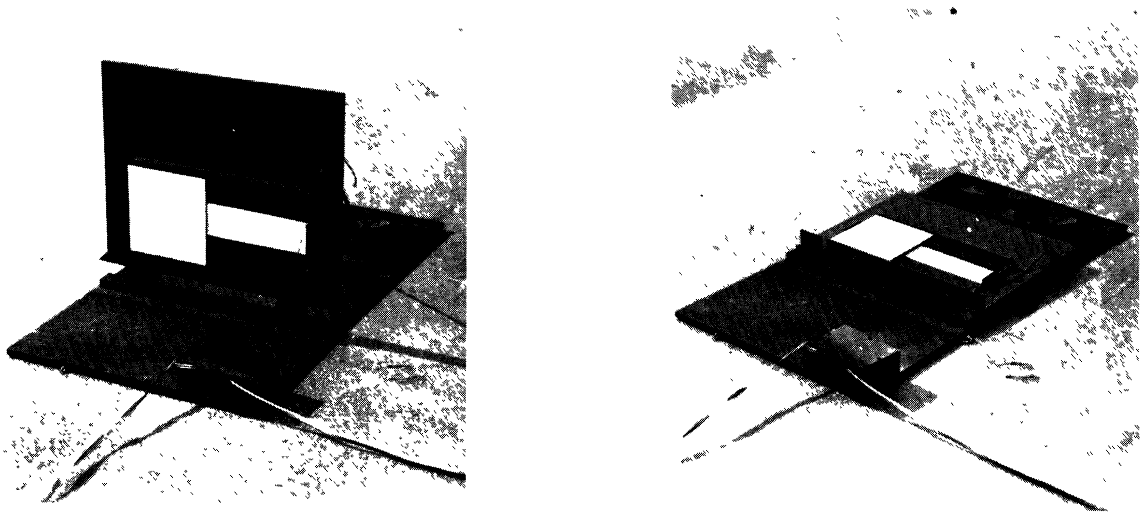


Figure 8. Target visibility as a function of target distance.

VALIDATION

All mathematical models and simulations must be validated by comparing their results with experimental results obtained under the same conditions. This has been done at various stages during the development of the model, resulting in changes being made to the model. The experimental results were obtained in field tests, using specially designed targets (Figure 9) of known reflectance, to derive target orientation visibility distances.



(a) (b)

Figure 9. Targets used in field tests: (a) for left or right of lane positions, and (b) for center of lane position. Target folds down when car comes close and drives over it with the target between the wheels.

The results of the tests were statistically analyzed and curves obtained of the mean visibility distance as a function of the longitudinal inter-car distance and target reflectance, beam, target position, etc. The procedures and results of the field tests are described by Mortimer and Olson (1973). The fit of computed and experimental data is now fair (see Figures 10-14). It is difficult to decide how much of the difference is due to inaccuracies and approximations in the program and how much is the result of differences in the conditions under which the field test data were obtained, since the field test results are also somewhat irregular and the reliabilities of the experimental data for all three target positions (right, center, left of lane) are not the same. Least data were collected for the center target position because of the greater complexity of accomplishing that task, than the right or left targets. The experimental results are the average of data taken for the driver and for the right front seat passenger for whom visibility data were taken simultaneously in the field test. In the comparison curves shown here (Figures 10-14) between computer simulation and field test results of mean visibility distance for driver and passenger combined, the eye was positioned at the center of the car when deriving the computed values, i.e., at the average of the driver and passenger eye positions. This probably makes some difference but was considered to be a reasonable compromise for this purpose.

There are a number of other sources of error that can affect these comparisons. While some of the lamps used in the field tests were photometered, to obtain the beam candela grid pattern, the accuracy of these measurements is inherently limited. Also, the actual aim of the lamps as used in the field tests, while controlled as carefully as possible, will not have been reproduced exactly in the simulation. Other factors, as discussed earlier, will also introduce discrepancies whose magnitudes are difficult to estimate. A number of critical night driving meeting situations were evaluated in the field tests, specifically to derive data for the validation of these computer simulations.

The comparison for the 12% and 54% reflectance targets on the right side of the lane for the low beam are shown in Figure 10, and the analogous high beam versus high beam meetings are shown in Figure 11. The agreement between the experimental and computer simulation results appears to be good.

The comparison for the low and the high beam meetings for the 12% reflectance target on the left (Figure 12) shows somewhat greater visibility distances predicted by the simulation before the meeting point for the low beam, but the shapes of the curves match well.

Data for the 12% reflectance target in the center of the lane are shown in Figure 13 for the low and high beam meetings.

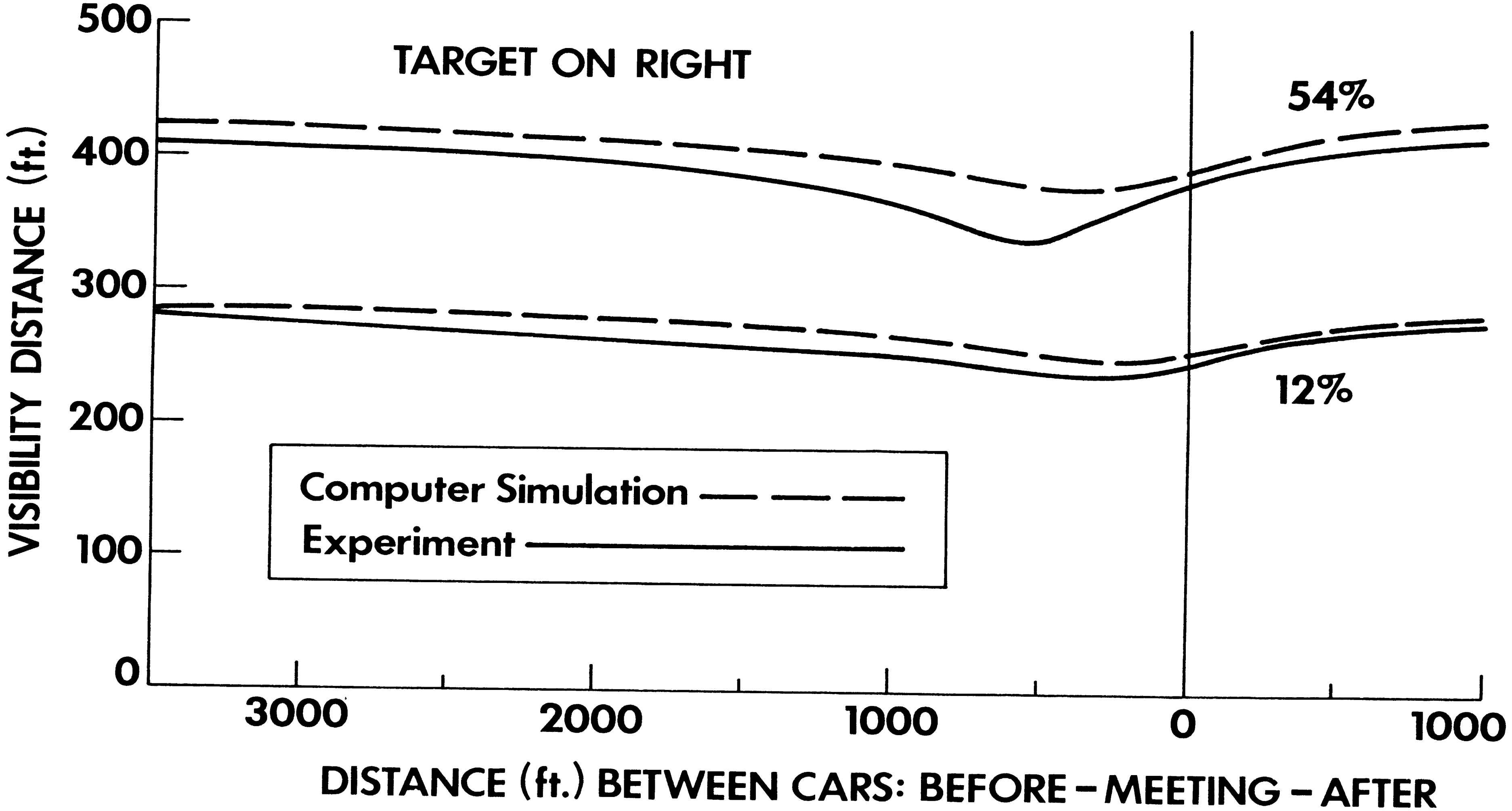


Figure 10. Comparison of experiment and simulation for 6014 low beam meetings, 12% and 54% reflectance target on right of lane, 7 ft. lateral separation between cars.

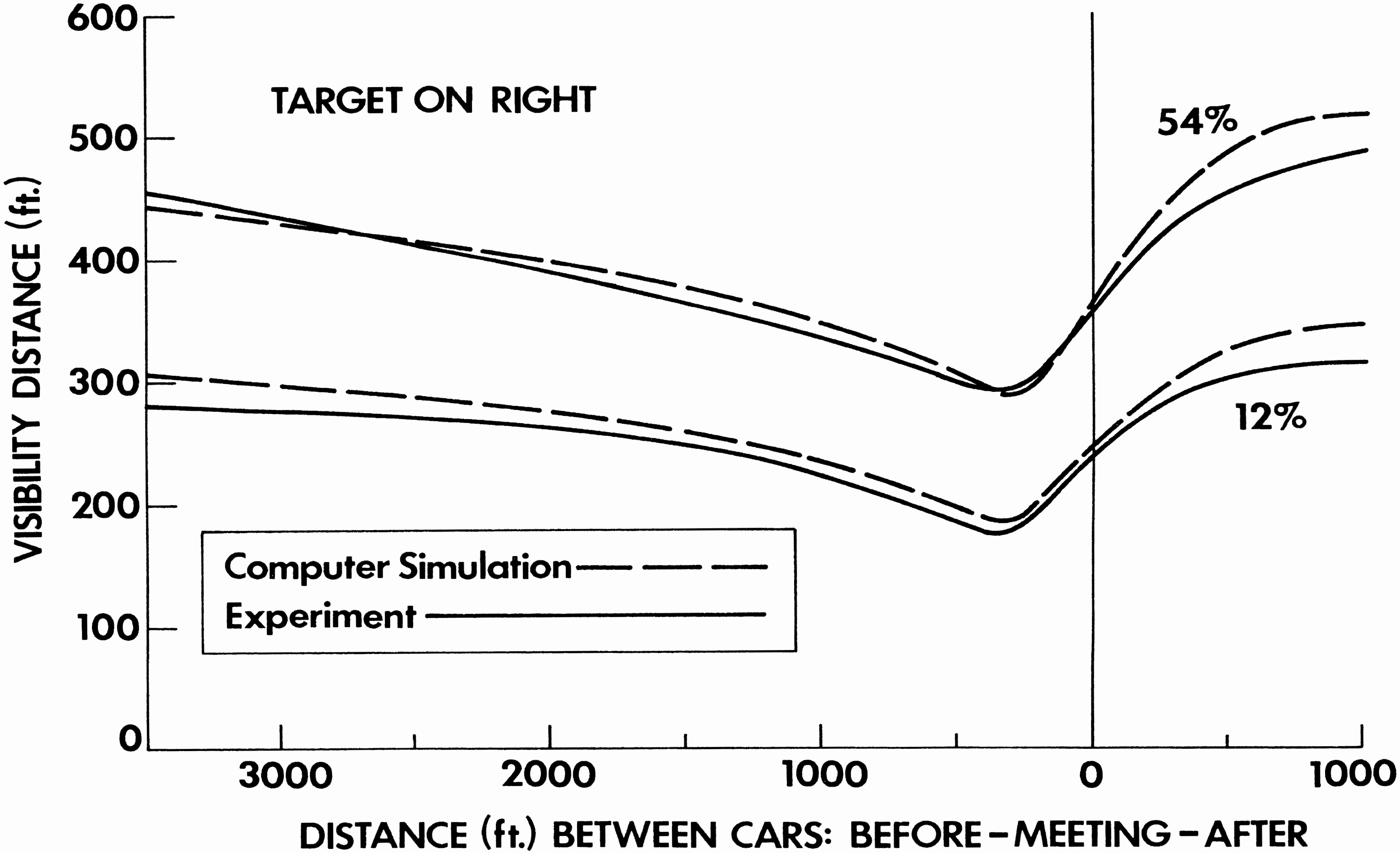


Figure 11. Comparison of experimental and simulation for 6014 high beam meetings, 12% and 54% reflectance target on right of lane, 7 ft. lateral separation between cars.

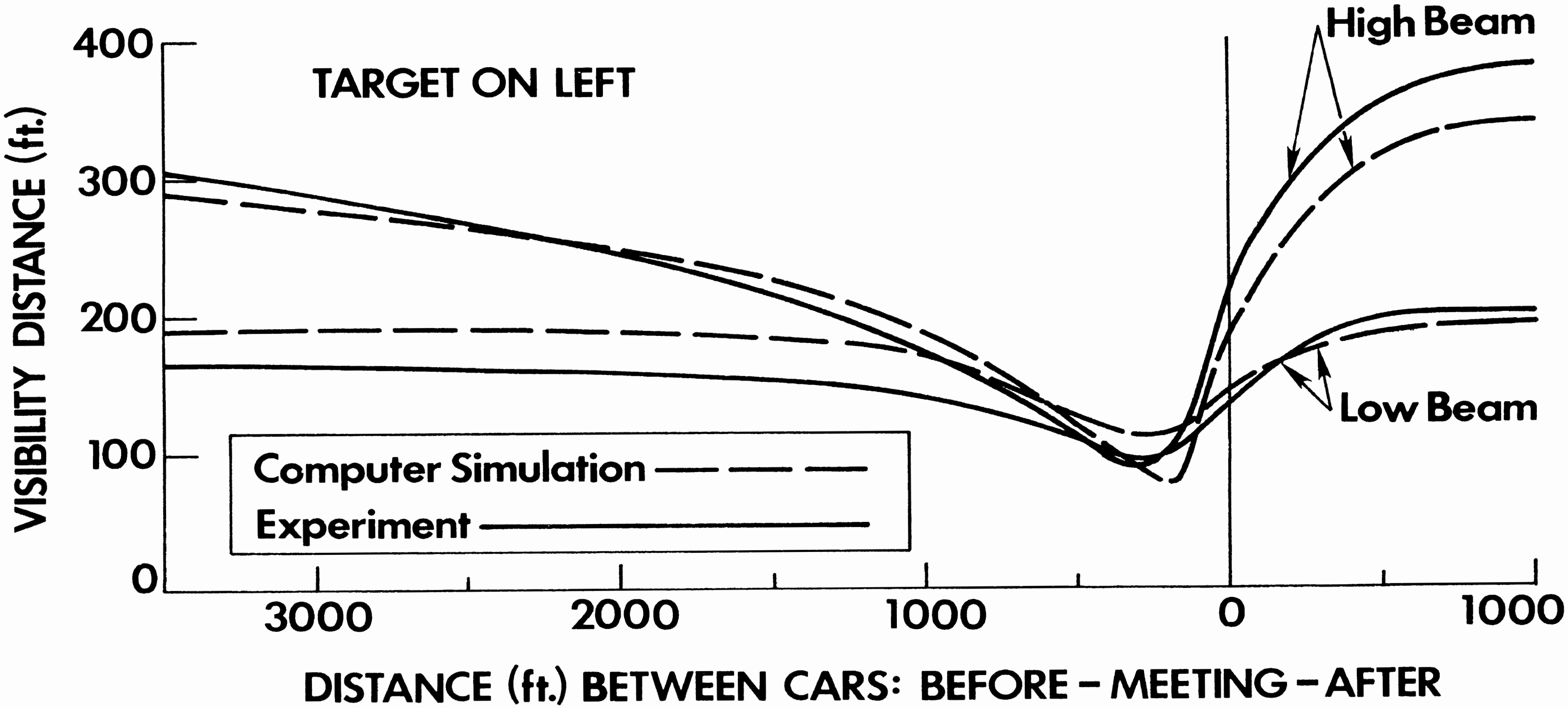


Figure 12. Comparison of Experiment and simulation for 6014 low and high beam meetings, 12% reflectance target on left of lane 14 ft. lateral separation between cars.

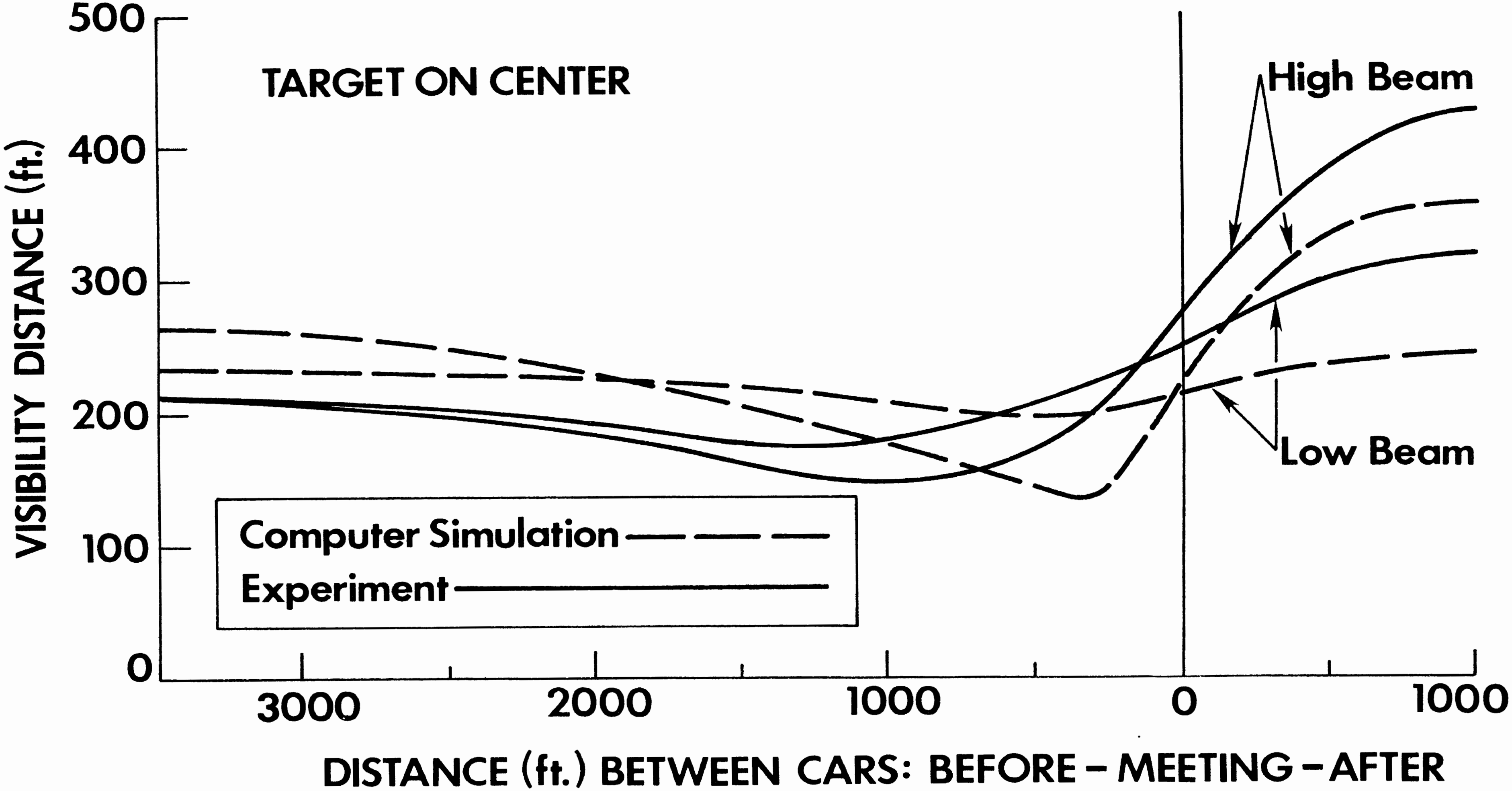


Figure 13. Comparison of experiment and simulation for 6014 low and high beam meetings, 12% target on center of lane, 7 ft. lateral separation between cars.

The discrepancy between experimental and computed visibility distances are greatest for this condition. Since fewest experimental data were taken for this target position, and since the fit between the experimental and computed values are good for the right and left target positions, it is believed that the computed values are probably more accurate in this case.

Figure 14 shows the low beam meeting at 36 feet lateral separation for the 12% reflectance target on the right side, and the high beam meeting for the 54% reflectance target on the right side of the lane for experimental and computer simulation evaluations. These results can be compared with those of Figures 11 and 12 to show the changes in visibility due to increasing the lateral separation between vehicles from 7 feet to 36 feet.

DISCUSSION AND CONCLUSIONS

The HSRI Headlamp Visibility Distance Performance Simulation program was designed to be an aid in the evaluation of existing and proposed vehicle headlighting systems.

While its results do not agree exactly with those from field testing under similar conditions, they are sufficiently close to allow the program to be used.

There are areas of approximation in the program which could use more work in order to increase the program's accuracy and, hence, make the validation better. The two most obvious are foreground glare, specifically the matter of road reflectivity as a function of distance ahead of the vehicle, and the proper values of the observer relation coefficients. There is also the question of which veiling glare equation should be used, and should the value of K be different for the numerator and denominator.

The program results do behave qualitatively as one would expect; i.e., more intense main lamps produce larger visibility distances, more intense glare lamps produce higher glare and hence smaller visibility distances, a higher reflectivity target

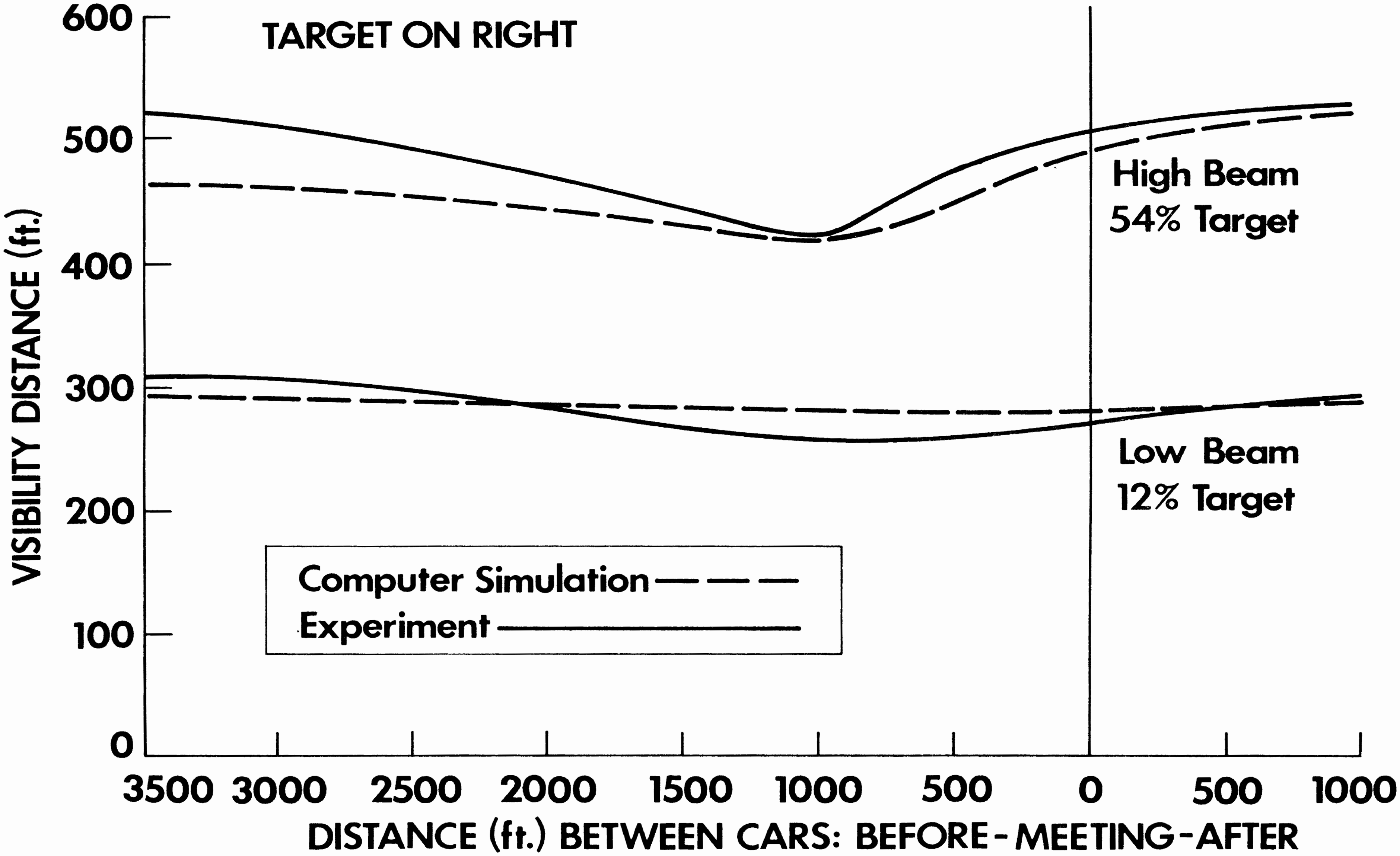


Figure 14. Comparison of experiment and simulation for 6014 low beam and 12% target, and the 6014 high beam and 54% target, both targets on the right side, 36 ft. lateral separation between vehicles.

produces larger visibility distances, larger median separations produce larger visibility distances, and so on. Thus the program results can be used to rate headlighting systems relative to one another. It should be noted that the absolute visibility distances are with reference to the specific target used in the field tests, and any further use of the model will provide results only for this target.

It is believed that the model will have direct application in the evaluation of beam patterns and allow quick estimates to be made of the likely relative increase in visibility offered by proposed headlamp systems (e.g., Mortimer and Becker, 1973a, 1973b). Although not mentioned here previously, part of the printed output consists of the glaring intensities to which the driver is exposed during the meeting. These values are also important in discerning glare effects from headlighting systems, since the performance of such systems is not only a function of the visibility they provide at various stages of the meeting, but also the glare discomfort to which the driver is exposed.

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