TOWARD MORE EFFECTIVE HEADLIGHTING

A Brief Discussion of Four Years of
HSRI Research on Headlighting, Including
Development of a Computer Simulation Technique
for Evaluating the Performance
of Present and Experimental
Headlamp Systems and Beams

Highway Safety Research Institute
The University of Michigan
December, 1974

Writer: J. E. Haney
Consultant: R. G. Mortimer

Designed by
University Publications
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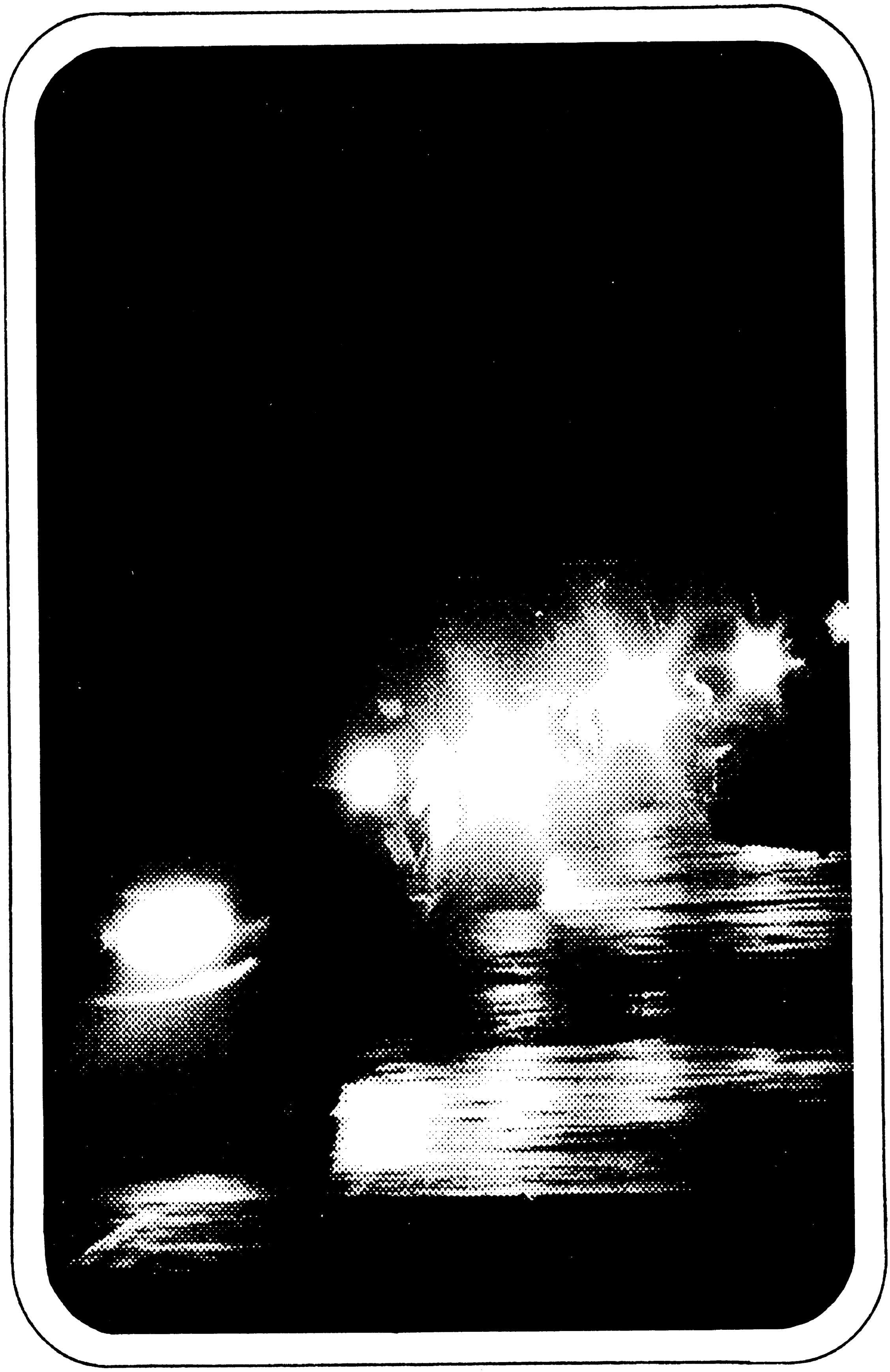


INTRODUCTION AND SUMMARY

IN EVERYMAN'S CONCEPTION of safe and comfortable night driving, the headlamps of his vehicle illuminate the roadway far ahead, and the headlamps of other vehicles never decrease his vision by glaring into his eyes, either through the windshield or from the rearview mirrors.

Every experienced driver knows how far present night-driving conditions depart from that ideal, but he probably knows less about how present headlamp systems might be improved.

In 1971 the University of Michigan Highway Safety Research Institute began exploring that question in a program of research sponsored by the Motor Vehicle Manufacturers Association and directed by Rudolf G. Mortimer, Head of the Human Factors Group at the Institute. The research consisted of several interrelated studies. The first one explored the problem of misaimed headlamps—how many vehicles in use have misaimed headlamps, how much they are misaimed, and the reasons for the misaiming. A second study investigated the potential advantages of a three-beam system as an alternative to the present high-low, two-beam system. In field tests, driver-subjects used a three-beam system; then the researchers developed and evaluated 13 different control/display designs for a three-beam headlamp system.

At this point, estimates of how costly it would be to conduct comprehensive field experiments with a wide variety of headlamp systems led HSRI researchers to conclude that it would be economical to develop a computer-simulation program for evaluating the performance of headlamp systems. The accuracy of such simulations would depend upon how closely the critical parameters of headlamp beams and night vision could be represented in the computer programs. It was by no means certain that such factors as the interaction of illumination and glare effects, or the rate at which the human eye recovers from glare effects, could be accurately modeled mathematically, but the researchers set about building equations to represent all of the factors involved.

When all of the sub-elements of the simulation model were developed and integrated in computer programs, the simulation model could produce results; it could plot visibility distances for a driver facing oncoming headlamps, provided it was supplied mathematical values for all of the parameters involved. But then the accuracy of those simulations had to be assessed; the inputs and outputs of the model had to be compared with the inputs and results of field experiments involving real vehicles, drivers, beams, roadways, and targets. This process of validating the simulation model posed a problem, because most prior field experiments had differed in their methodologies, and few had produced the kinds of quantitative data needed for validation of the computer model. Therefore, in the next study, HSRI researchers designed a standardized methodology and conducted field experiments to obtain the necessary data.

In subsequent work, the mathematical values established in the field experiments were used to refine and validate the simulation model. The simulation programs were improved enough so that they could produce results very close to those obtained in the field experiments. The computer simulation technique was then ready to be used as a research instrument. It was employed to compare the performances of the standard U.S. low beam, the standard European low beam, and the experimental mid beam when those beams were aimed correctly, misaimed up 1°, and misaimed down 1°. The computer simulation not only plotted the visibility distances of targets for the various opposed beams but printed out the glare values for the beams at various separation distances between the vehicles.

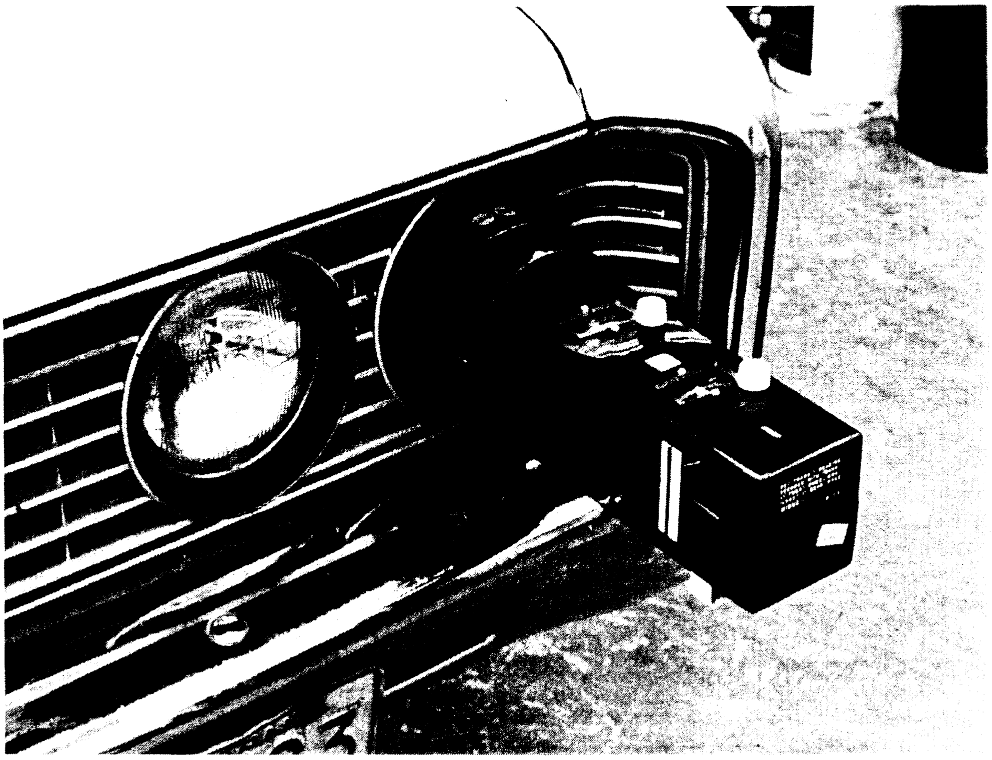
After assessing the results of the computer simulations and the previous studies, the researchers concluded that unless current problems of beam misaim can be solved, new beams with higher intensities or different illumination patterns will not produce significantly safer or more comfortable nighttime driving conditions.

THE PROBLEM OF MISAIMED HEADLAMPS

IN EXPLORING THE QUESTION of misaimed headlamps, HSRI researchers found that the problem is old, widespread, and more complex than it first might appear. Headlamps are considered correctly aimed, according to SAE Standard J599, when the high-intensity zones of the beams fall within four inches of a horizontal-vertical mark on a wall or screen 25 feet directly in front of the vehicle. In current practice, most manufacturers and maintenance shops use a mechanical aiming device that attaches to the lamps. This eliminates the need for 25 feet of open space, and also eliminates problems of aligning the long axis of the vehicle with the marked wall.

Factory Aiming

To assess the accuracy of factory aiming practices, the researchers checked the headlamp aim of 153 new cars at eight dealerships in Ann Arbor and Plymouth, Michigan, before the cars were prepared for delivery. They found that significant numbers of headlamps on those cars were misaimed. The percentages of cars with at least one misaimed headlamp, by



A mechanical aiming device attached to a headlamp.

dealership, were 14 per cent, 50 per cent, 25 per cent, 5 per cent, 65 per cent, 14 per cent, 40 per cent, and 30 per cent. Overall, 43 of the 153 vehicles (28 per cent) had at least one lamp aimed outside the SAE tolerance.

Service Trade Aiming

To establish how well maintenance shops aim headlamps, the researchers tested all Ann Arbor area dealerships, private garages, and service stations that claimed to be able to aim headlamps. Thirty-two shops were included—24 garages or service stations, and eight dealerships. A full-sized station wagon with a conventional four-headlamp system was employed to test the performance of those service outlets. First, the researchers used a level floor and a carefully calibrated mechanical aiming device to misaim the headlamps at the HSRI laboratory. The lamps were aimed at specified points two to four inches outside the 4-x-4-in. tolerance area specified by SAE Standard J599c. The car was then driven to one of the service outlets, where the driver complained that his headlamps seemed to be aimed badly. He requested they be checked and re-aimed if necessary, and stayed to observe (whenever possible) the checking and re-aiming process.

After the work was completed, the serviceman who had done the work was queried on his experience and practice in headlamp aiming. The car was then returned to the HSRI laboratory and the aim of the headlamps checked at the same spot and with the same mechanical aimer used to misaim the headlamps initially. That test procedure was repeated with each of the 32 service outlets.

The study results showed that only 12 of the 32 outlets aimed all four lamps within SAE tolerances; that is, 63 per cent of the vehicles that had their headlamps re-aimed at those service facilities had at least one lamp outside the SAE tolerances. Eighteen per cent of the 128 individual lamps were misaimed more than four inches left or eight; 26 per cent were misaimed more than four inches up or down; overall, 35 per cent of the lamps were misaimed more than four inches, either horizontally, vertically, or both. Thus the study showed that the service outlets did a poorer overall job of aiming headlamps than the factories did.

The eight dealership service departments included in the group of 32 service outlets performed somewhat better than the 24 private garages and service stations. Four of the dealerships (50 per cent) aimed all four lamps on the car within the SAE tolerances. The other four dealerships misaimed nine of the 16 lamps they work on (five vertically and four horizontally).

The aiming device most commonly used by the service outlets was the mechanical aimer; 26 of the 32 outlets used it. Three used optical aimers, and three others used no aiming device. In general, the servicemen who used devices seemed adequately familiar with them, although a few servicemen expressed or demonstrated some minor misconceptions about their devices. Most of the operators stated that they did little headlamp aiming; "once a month or less" was the usual response. A few claimed to aim "several per week," and one claimed "one or two per day." There was no relationship between claimed frequency and the quality of the aiming service provided.

HSRI researchers concluded from those findings that unless aiming service in the Ann Arbor area is decidedly worse than the national average, poor quality of service is a significant source of misaim of headlamps on cars in use.

Misaim as a Function of Normal Use

To investigate whether and how far headlamps become misaimed during normal use of vehicles, the researchers conducted a one-year study of 44 vehicles owned by HSRI staff members. Each owner-volunteer was asked to notify the experimenter if he replaced a headlamp, or if the vehicle incurred sheet metal damage, broken springs, or anything else that might change the aim of its headlamps.

At the beginning of the study, the headlamps of all of the vehicles were correctly aimed in the HSRI laboratory. This aiming was performed on a level concrete floor with mechanical aimers that were checked regularly for calibration. Before the lamps were aimed, each car was rocked to settle the suspension, the headlamps were cleaned, and the gasoline level and odometer reading noted and recorded.

The headlamp aim of the subject vehicles was checked at intervals of two, five, eight, and twelve months, using the same space, equipment, and methods, including the same levels of gasoline as in the initial aiming. The mileage accumulated by the test vehicles during the study period varied considerably—from 3,500 miles to more than 23,000 miles.

Because of attrition (vehicles sold, sheet metal damaged, headlamp replaced, etc.), only half of the 44 vehicles remained in the study after twelve months. Therefore the study findings were based on the 33 vehicles that had undergone re-checks at the two-month, five-month, and eight-month intervals. The results showed that few major changes in headlamp aim occurred during the eight-month period. During the initial two months, one headlamp on one of the 33 vehicles became misaimed beyond the SAE tolerances. At the five-month check, two of the headlamps on that vehicle were in misaim; and, at the eight-month check, a total of three headlamps on two vehicles were in misaim.

Although the headlamps on only two of the 33 vehicles exhibited aim changes beyond the SAE tolerances, the detailed study findings show that many of the headlamps did shift considerably during the study period. The researchers concluded that the aim changes found in this study as well as other studies reported in the literature result from aiming processes that produce an unstable condition involving the aiming screws and spring in the lamp fixture. They suggested that if the lamp support system could be redesigned to eliminate that instability, this would eliminate or greatly reduce the numbers of lamps misaimed as a result of this lamp-misalignment problem.

Misaim and Aiming Devices

To examine the reliability of aiming devices as well as problems with their use, HSRI researchers conducted experiments in which test subjects used visual and photometric aimers in attempts to align the long axis of vehicles with marks on a wall 25 feet away. Ten human subjects were instructed on how to use the aimers. They then made five alignments on each of five different vehicles with both types of aiming device.

The results showed that such an alignment task is not easily performed accurately. The research subjects achieved closer alignments of cars that had prominent hood centerlines than cars lacking them. They also achieved closer alignments with the photometric than with the visual aimer. However, the errors in alignment were so great with either device that a substantial percentage of the alignments would have produced lamp misaims beyond ± 4 inches at 25 feet.

Misaim and Vehicle Loading

To determine how vehicle loads affect headlamp aim, the researchers selected and tested seven representative cars (a VW "bug," Mustang, Plymouth, Plymouth station wagon, Camaro, Pontiac, and a half-ton pickup). They aimed the lamps with the vehicles containing only a 150-lb. driver and a full tank of gas, and used that as a baseline for aim measurements under nine other load conditions. The results (presented in detail in the study report) showed that when the American-made vehicles contained their full-rated load, their headlamp aim was changed upward from 3.3 to 6.5 inches above the baseline aim. This showed that vehicle loading is a significant source of aim variance in the American makes tested, and that since the changes are upward, this produces substantial increases in glare for other drivers.

Conclusions

An analysis of the major sources of variance in headlamp aim allowed the researchers to estimate the contribution each source makes to the percentage of misaimed headlamps among various vehicle populations. They estimated, for example, that in a population of one-year-old cars with original headlamps factory-aimed with mechanical aimers, about 21 per cent of the vehicles will have at least one headlamp misaimed beyond the SAE tolerance, either horizontally or vertically. In a population of vehicles with headlamps that have been replaced but not re-aimed, 39 per cent of the vehicles will have at least one lamp misaimed beyond the SAE tolerances. Considering the combined effects of mis-calibrated aimers, human factors in the re-aiming process, and the instability of lamp aim in normal service, the researchers concluded that even if car owners were to have beams re-aimed when a lamp is replaced (few owners or mechanics think this is necessary), this would not significantly decrease the percentage of misaimed lamps on cars in use. HSRI researchers concluded that unless the quality of headlamp aiming and alignment is improved, new beam patterns or higher-intensity beams would not provide better visibility and reduced glare in practice, and that further efforts should be directed toward solving some of the problems of obtaining and maintaining correctly aimed beams.

EXPLORATION OF A THREE-BEAM SYSTEM

TO DEVELOP BASIC GUIDELINES for the design of a three-beam switching system, HSRI researchers began by studying how test subjects used a three-beam system while driving a test car. The results of the driving study were then employed, along with human-factors principles, to develop a list of design criteria and a procedure for evaluating various design concepts for a three-beam control/display system. The researchers applied the criteria to 13 different control-system designs to identify the four most effective designs.

The Driving Study

To find out how 10 test subjects would use a three-beam headlamp system, five male and five female test subjects drove a test car at night on four kinds of roadways in and around Ann Arbor: urban streets, urban expressways, rural two-lane roads, and rural expressways. The test subjects were from 21 to 42 years old, from 57.5 to 73 inches tall, and had various vocations. (None was a lighting expert.) The test vehicle had four conventionally positioned headlamps that supplied a low beam, mid beam, or high beam. The low beam was supplied by the two outboard (No. 6014) lamps. The mid beam consisted of those two lamps plus the inboard lamp on the driver's side. This third lamp was a "Type III" 50,000-candela lamp aimed so that it illuminated the right-hand side of the road about 25 per cent farther than did the low beam. The high beam consisted of all four headlamps—the outboard lamps on their high beam, the mid-beam lamp

The test vehicles used in field experiments.

inboard on the driver's side, and a "Type IV" 100,000-candela lamp inboard on the passenger's side.

The work with test subjects included a sequence of six activities:

1) The subjects completed a questionnaire designed to obtain information on how they ordinarily use the present two-beam, high-low system in various night-driving situations on urban streets, urban expressways, rural roads, and rural expressways.

2) Each test subject was shown how the three beams on the test car appear to oncoming drivers. The subject sat in his own car on a straight two-lane road while the experimenter drove past him with the test car at 15 m.p.h. from 300 feet away, using the low beam, mid beam, and high beam on successive passes.

3) The subject then drove the test car for five miles on a two-lane rural road while the experimenter switched the beams to demonstrate the visibiilty they provided on straight sections and curves, with and without the opposition of beams from oncoming vehicles. This procedure also demonstrated to the subject how oncoming drivers reacted to the various beams and the beam switching performed by the experimenter.

4) The test subject then used the three-beam system himself while driving the test car over a route that included roadway changes from urban streets and expressways to rural two-lane roads and expressways. The verbal requests of the subject for changes from one beam to another were executed and recorded by the experimenter in the rear seat of the test vehicle.

5) After completing the driving experiment, the subject completed a questionnaire designed to obtain information on how the subject would use a three-beam system in various situations on various kinds of roads.

6) An interview with the subject was then conducted (and taped) to obtain his comments on the driving experiment and his opinions on beam-switching control/display devices. As part of this discussion, the experimenter explained three different control concepts for beam switching. One concept featured a three-position, pressure-actuated foot switch. A second featured a dashboard-mounted switch for selecting between a pair of beams (L/H or M/H) plus a pressure-activated foot switch. The third featured a three-position, horizontally actuated steering-column lever.

The Questionnaire Results

On the first questionnaire—the one on use of the present two-beam system—most of the subjects indicated that they use the *low beam* on urban streets and urban expressways, on rural two-lane roads in medium or heavy traffic, and during conditions of twilight, fog, rainfall, or snowfall. They indicated that they use the *high beam* on rural roads and rural expressways when traffic is sparse, and to signal an oncoming driver that the headlamps of his vehicle are glaring.

On the second questionnaire—the one on use of the three-beam system—most of the subjects indicated that they would use the *mid beam* on urban streets and urban expressways, and on rural two-lane roads and expressways in medium or heavy traffic. They would use the *high beam* on rural roads and expressways when traffic is sparse, and also to signal oncoming motorists. Most would use the *low beam* only in daylight driving conditions of twilight, fog, rainfall, or snowfall.

In response to additional questions about use of the mid beam, most of the subjects indicated that they thought the mid beam produced no more glare for oncoming or preceding drivers than the low beam, that it produced more visibility than the low beam, and that it would be a significant improvement of their vehicle's headlighting system. Most also thought that the low beam should be retained for driving in fog, snowfall, and on well-lighted city streets.

Analyses of Beam Switching

When the test subject requested a beam change during the driving experiment, the experimenter recorded it in association with one or more phrases describing the conditions in the situation. For example, a few of the conditions noted were "Vehicle oncoming," "Approaching entrance ramp," "End of ramp," "Street lights," "To see pedestrian/vehicle/object/sign," plus 23 other phrases, including "No apparent cause." Analyses of those records showed that most of the beam changes on expressways (74 per cent) were between the mid and high beams. On two-lane rural roads that percentage was 88. In contrast, most beam changes on urban roads and streets were between the mid and low beams. The findings showed, in general, that test subjects used the mid beam in most situations where they would use the low beam in a two-beam system.

Design Concepts for Three-Beam Controls

To develop design concepts for a three-beam control/display system, the researchers assembled a list of 44 criteria derived from the human-factors, aerospace, and automotive research literature. One important criterion, for example, is that the on/off control for a headlamp system must be placed in a position that minimizes the possibility of the headlamps' being inadvertantly switched off. The present usual location of the activator control switch—low on the dashboard and to the left of the steering column—reflects that consideration. Similarly, other criteria relate to minimizing driver errors, difficulty, distraction, and time losses by contributing to the design of controls that are simple and easy to find, understand, reach, and operate quickly and correctly. This means, among other things, that a new control system should be as compatible as possible with existing control systems, or at least with the best common features of present systems.

The researchers' assessment of present control/display systems identified some deficiencies that experienced drivers are more or less aware of: The push/push floor switch for beam changing, positioned differently in different cars, can be difficult to locate and can require awkward or excessive leg movement for some drivers. Present dashboard displays do not indicate if the low beam is activated, and this contributes to the frequency of vehicles being driven without headlights unintentionally. (A complete display could provide the driver full feedback. Lighted dashboard messages could state "No Lights," "Parking Lights," "Low Beam," and "High Beam," for example.)

To differentiate the 44 design criteria in terms of their relative importance, five HSRI staff members experienced in switching design independently rated them on a four-step scale as essential, primary, secondary, or tertiary. The pooling of those ratings produced four separate lists of, respectively, 6, 16, 9, and 9 criteria. These were used to evaluate 13 different designs for the controls of a three-beam headlamp system.

The 13 designs discussed and illustrated in the study report employ various combinations of dashboard, floor, and steering-column-mounted controls for activating the headlamps and selecting the beams. The four designs rated most safe and effective all have a push/pull activator control on the dashboard on the left side of the steering wheel (as with most present systems). For beam switching during driving, one design has L, M, H pushbuttons in the steering wheel hub. A second design has the L, M. H pushbuttons on the dashboard above the activator control. A third has a lever on the left side of the steering column to provide three horizontal positions for selecting low, mid, and high beams. The fourth has the same column-mounted lever with three vertical positions for selecting the low, mid, and high beams. All four control systems are within blind reach, provide access to any of the three beams with one motion, and provide visual and proprioceptive feedback.

Conclusions

In sum, the researchers concluded that the driving tests established how most drivers would use a three-beam system; that the rating criteria adequately delimited design possibilities for control systems; and that the four designs rated most effective by the weighted criteria would be safe and convenient.

DEVELOPMENT OF A COMPUTER SIMULATION MODEL

BECAUSE FIELD EXPERIMENTS for evaluating headlamp systems are expensive and time-consuming, HSRI researchers set about developing a mathematical model of the parameters involved in visibility/glare situations, so that a computer program could simulate the conditions and results of field experiments. They knew that once such a computer program was completed and validated, the simulations would be relatively inexpensive, fast, and completely repeatable. It would be feasible, in terms of time and cost, to change just one parameter value in each of several computer runs to establish the effects of those changes, then to change another parameter systematically, etc. Used in this way, a computer simulation program could tell an experimenter more in one day than he could learn from months of field experiments.

Elements of the Model

The model was designed to compute the distances at which a driver can see and interpret a target at night when the beams of his vehicle are unopposed or opposed by the beams of an oncoming vehicle. Thus the major elements in the model are the road, two vehicles, a target, the headlamp beams, and the "eye" of the driver-observer. (The mathematical equations for those elements are omitted here; interested readers can find them in Report No. UM-HSRI-HF-73-15.)

The road in the model can be represented as straight or curved, flat or undulating. The two vehicles are represented as moving on parallel paths, with constant lateral and vertical separation distances. The longitudinal separation distance is defined as the independent variable.

Both vehicles are represented as having up to five headlamps located in fixed positions relative to each other and aimed at any horizontal and vertical angles.

The headlamp outputs are described by a table of intensity values, in candelas, for pairs of horizontal and vertical angles. Each lamp can be switched off or on at specified separation distances.

The driver-observer is represented as having a single eye located at any arbitrary point in the main vehicle. The eye line-of-sight can be represented as fixed or as tracking the target. The eye itself is represented as affected by veiling glare from the beam of the opposed vehicle directly, indirectly by headlamps imaged in rearview mirrors, and by foreground glare from light from the observer's headlamp beams reflected off the pavement. The eye is represented as being in one of three states: adaptation to increasing glare, readaptation to slowly decreasing glare, and recovery during rapidly decreasing glare. This task of accurately representing the performance of the human eye involved precisely integrating the equations for "adaptation," "readaptation," and "recovery."

The distance at which the observer can "see" the target is a function of four factors: the relations between the intensity of illumination directed at the target, the distance of the target, the reflectivity of the target, and the intensity of the veiling glare directed at the eye of the observer. Because the system of equations representing those factors was much too complex to be solved explicitly for visibility distance in terms of separation distance, the model uses a convergence procedure to find the largest target distance at which the intensity directed at the target is equal to the intensity the observer "eye" requires to "see" the target.

Simulation of the Headlamp Beams

The light output of headlamps is usually represented by an iso-candela diagram, but a computer program cannot use such a diagram directly. Therefore the researchers constructed a bivariate table of candela values for pairs of 61 horizontal and 22 vertical angles relative to the longitudinal axis of the two vehicles. The lamps can be misaimed in any direction of pitch, yaw, and roll.

The path of the target through the headlamp beam of the main vehicle is calculated for 20 visibility-distance values. Likewise, the path of the "eye" through the beam of the glare vehicle is calculated for 20 separation-distance values in terms of the horizontal and vertical angles for each point.

Finally, foreground glare due to illumination of the pavement by the headlamps of the observer's vehicle is represented by an equation that includes the reflectivity of the pavement, the distance from the lamps to the pavement, the angle of incidence, the intensity of illumination directed at the pavement, and a factor representing whether the eye line-of-sight is fixed or is tracking the target. (With the latter, foreground glare varies considerably.)

The Need for Validation of the Model

After the basic equations and tables were integrated in a computer program, the model behaved qualitatively as it was expected to: Values representing more intense lamps produced larger visibility distances. So did values representing targets of higher reflectivity. Values representing more intense glare lamps reduced visibility distances, while increases in the median separation distances of the vehicles reduced glare intensities and increased visibility distances. However, the model had to be validated quantitatively; its inputs and results had to be carefully compared with inputs and results of actual field experiments to determine whether the computer model was accurately simulating real-world effects. The problem for the researchers at this point was that not enough precise and compatible field data were available. Field experiments conducted by various researchers during the preceding decade had used widely varying methods, procedures, and targets. Therefore most of the results reported in the literature were uncomparable and unsuited for evaluation of the computer simulation program. Thus HSRI researchers had to conduct a new series of field experiments designed to obtain real-world data essential for refining and validating the simulation model.

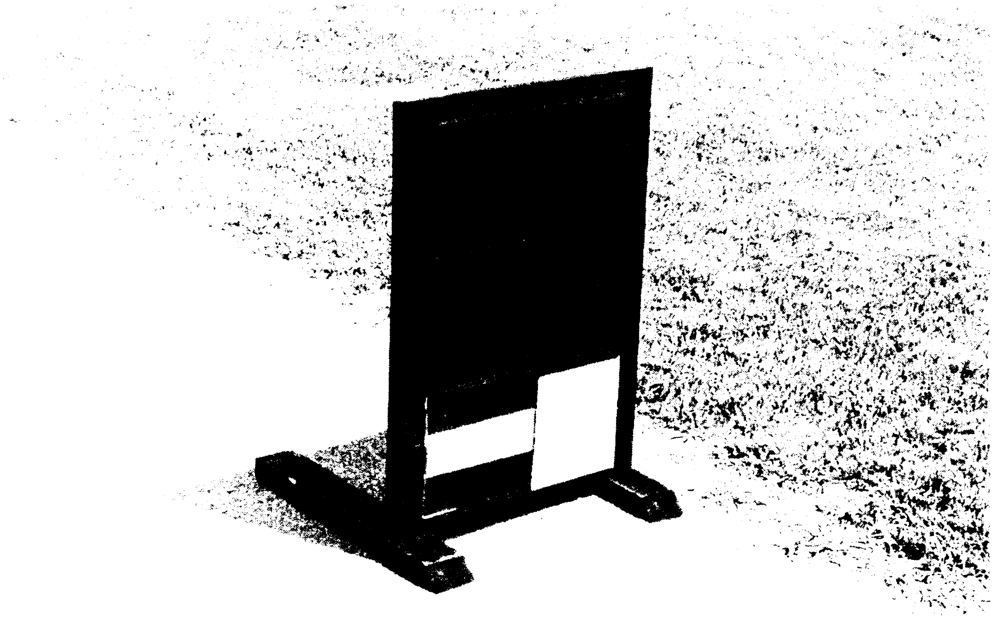
FIELD TESTS FOR VALIDATION OF THE MODEL

The Field Studies

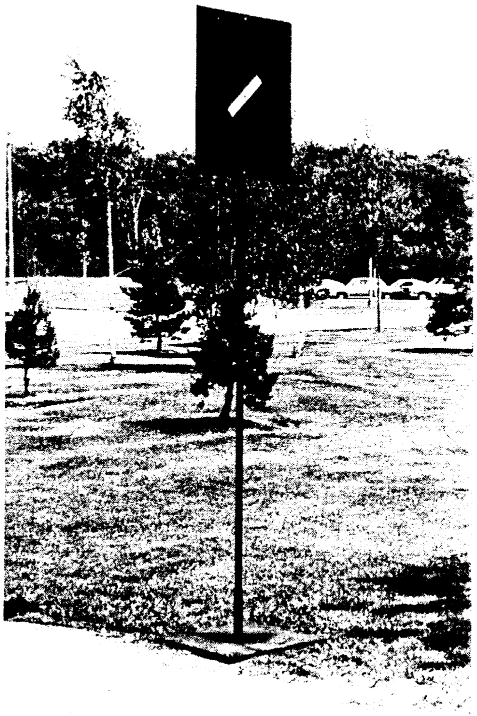
To obtain data adequate for validating the simulation model, the researchers conducted seven field studies. The first four in the series employed two test vehicles, 56 test subjects, and three types of targets in experiments conducted on special courses in the 2.5-mi. straightaway at the GM Proving Grounds in Milford, Michigan. The test vehicles were equipped with up to 14 headlamps, automatic speed controls, master control panels for the headlamp systems, two-way radios, infrared target-sensing devices, and strip-chart recorders that automatically logged the subjects' target-identification responses. The subject-drivers and subject-passengers rode in the front of the test vehicles while the experimenters in a rear seat operated the headlamp control panel. Test runs for measuring target visibility against opposed headlamps began with the vehicles facing each other at opposite ends of a 6,400-ft. course.

Study One

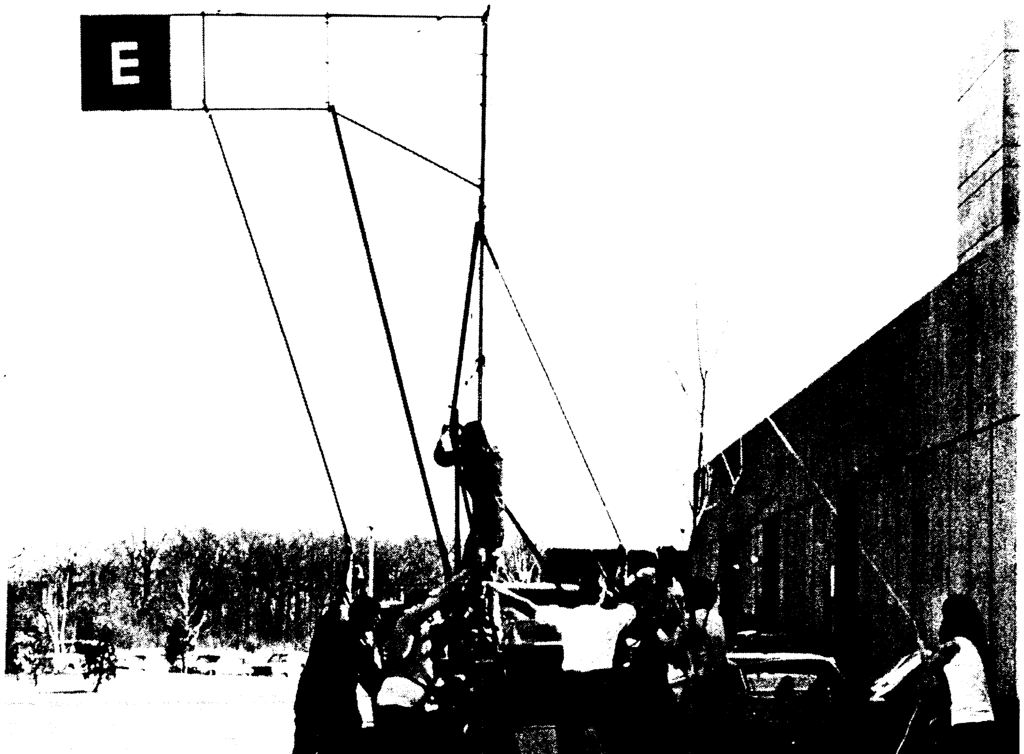
In the first study, the researchers measured the visibility distances of Type-I targets (a reversible white bar and square on a black background



A Type-I target used in the field experiments.



A Type-II target on its 7-ft. standard.



Rigging the Type-III target.

panel) as a function of several variables: (1) target reflectance (6 per cent, 12 per cent, 26 per cent, 54 per cent, and 84 per cent); (2) target location (right or left of the lane); (3) target height (6 or 18 inches above the ground); and (4) headlamp beam (the low and high beams of two standard No. 6014 sealed-beam lamps). Those 40 combinations of variables were presented once to each of 16 subjects.

The results of the tests showed that under unopposed conditions, the low beam and high beam provided almost equal visibility distances for targets located to the right of the lane. The average for the low beam was 310 feet; for the high, 320. But, for targets located at the left side of the lane, the high beam provided much more visibility distance (250 feet, compared to 180). As was expected, glare from opposed headlamps reduced the visibility of left-hand targets more than it did right-hand targets. For targets on the left, the lowest visibility distance was 120 feet with either beam, while, for targets on the right, the low points were 280 feet for the low beam and only 255 feet for the high beam. The findings with respect to target reflectance showed, as expected, that the higher the reflectance of a target, the farther it could be seen under either glare or non-glare conditions.

Study Two

The second study was a replication of the first one, except that the lateral separation of the opposed vehicles was increased from seven to 36 feet, the target-reflectance factor was reduced to two levels (12 per cent and 54 per cent), and four of the 12 test subjects made extra runs at a higher speed to establish whether this affected their target-sighting performance (it did not).

The results of the second study showed that with the increased median separation, the high beam always provided more visibility distance than the low beam, regardless of the longitudinal distance between the vehicles. (In the first study, the low beam provided greater visibility for right-side targets when the vehicles were from 500 to 200 feet apart.) The finding suggests that drivers in cars separated by even a modest median should not switch from high to low beam to maximize visibility (although they may want to do so to minimize discomfort glare for the other driver).

As expected, the 36-ft. median separation produced less discomfort glare and significantly greater visibility distances for drivers of cars with opposed high beams. The low visibility point was at 1,000 feet before the meeting, when a 12 per cent reflectance target could be identified at a distance of 280 feet. With the 7-ft. median separation, the low visibility point continued from 500 to 300 feet before the meeting, when the target could be identified at a distance of only 190 feet.

Study Three

The third study investigated high- and low-beam visibility distances for Type-I targets placed in the center of the lane (they folded down automatically) as well as Type-II and Type-III targets. Type II was a white diagonal bar on a black background panel mounted on a 7-ft. stand placed to the right of the lane to represent a traffic sign. Type III was a silverwhite, reversible 12-in. "E" on a green background panel mounted on a truck so that it could be suspended 17 feet over the test lane to represent an expressway exit sign. A 7-ft. median separation was used.

Test results for the Type-I targets placed directly in the path of the vehicle showed that the low beam provided better visibility than the high beam for a long span of pre-meeting distance—beginning when the cars were 1,800 feet apart and continuing until they were only 50 feet apart. At a separation distance of 600 feet, for example, the high beam provided an average target visibility of only 125 feet, compared to 145 feet for the low beam.

For the Type-II targets, the high beam always provided greater visibility under any glare conditions. The point of lowest target visibility was at 1,000 feet before the vehicles met and passed; the high beam provided target identification at 1,150 feet, the low beam at 1,040 feet.

For the Type-III (overhead) target, the most interesting test result was the similar performances of the low and high beams. With 1,000 feet between the cars, the low and high beams both allowed identification of the target 625 feet away. At 600 feet before the vehicles met, the low beam outperformed the high beam by allowing target identification at 680 feet, compared to 575 feet with the high beam. This effect was due partly to the extremely high reflectivity of the Type-III target (the legend had a brilliance of 675, and its green background sheeting had a brilliance of 80). Test subjects reported a serious "back glare" from the target when it was highly illuminated, and this made it difficult to see clearly enough to interpret. Such a target is evidently self-limiting, in the sense that illumination beyond a certain amount does not improve and actually impairs its readability. On the other hand, its high reflectivity allows drivers to read it from long distances when it is not illuminated very well. Its high brilliance, typical of interstate highway signs, has both effects.

Study Four

The fourth study replicated the third, except that it used a median separation distance of 36 feet to simulate a divided highway, and the Type-III target was not used. The results for both the Type-I and Type-II targets showed that the high beam consistently provides greater visibility, with this median separation, under all glare conditions.

Glare Responses

The test subjects in the first four studies had been asked to indicate during the test runs whenever the glare became intolerable. Analyses of those responses showed some expectable results—e.g., significantly more test subjects reported glare discomfort with high beams than with low, and with median separations of seven feet than 36 feet. A less expected finding, however, was that the subjects' responses to glare varied considerably in terms of the distances by which the opposed vehicles were separated. Some of the spread in the responses probably resulted from differences in the way the subjects interpreted the phrase "intolerable discomfort," and some from real differences in their capacity to tolerate glare.

Study Five

With the first four studies having focused on the performance of the standard U.S. low and high beams (No. 6014 lamps), the fifth study compared the performance of those beams with five other headlamp systems:

1) The standard U.S. low beam plus a third lamp (a Q4051) in nominal aim.
2) The standard U.S. low beam plus the Q4051 aimed 3/4° up and 1/2° left.
3) The standard European low beam (two H_4 lamps).
4) The standard European high beam (two H_4 lamps).
5) The standard U.S. high beam plus a supplemental high-beam lamp (Type IV).

The study was conducted on an asphalt runway of a private airport, on a course 60 feet wide and 3,300 feet long, using Type-I and Type-II targets of 12 per cent reflectance and median separations of seven and 30 feet. The driver-subjects and passenger-subjects pressed switches to record their target identifications. They also rated the effectiveness and glare discomfort of the various headlamp beams, relative to the standard U.S. low beam, on a scale ranging from one (very much less) to seven (very much more). Immediately after each test run they marked their rating on a slip of paper and passed it to the experimenter. This eliminated the possibility of their influencing each other's judgments.

The results of test runs to measure visibility distances for Type-I targets showed that under no-glare conditions the U.S. high beam plus Type-IV lamp provided the highest target visibility distance (an average of 425 feet). The worst performer was the H_4 low beam (270 feet). The four other beams were grouped closely at between 350 and 370 feet.

Test runs against opposed beams showed that the H_4 low beam provided less visibility than any of the other beams at both median separations—seven feet and 30 feet. The test subjects rated the H_4 high beam as more glaring than any of the other beams.

Study Six

The sixth study, conducted on three types of roads under normal driving conditions, measured the discomfort glare of several different headlamp beams by noting the relative frequency with which oncoming drivers requested dimming by flashing their headlights. All of the beams used in the fifth study were employed, except for the combination of the U.S. high beam with the Type-IV lamp. One new combination used was the No. 6014 low beam along with the H_4 low beam. This four-lamp beam produced low glare intensities.

The study was conducted at night (between 9:30 p.m. and 3:00 a.m.) on expressways, two-lane rural roads, and two-lane city streets in the Ann Arbor area.

The results showed that the H_4 high beam elicited by far the highest percentages of responses from other drivers: on the expressways, 50 per cent; on rural roads, 90 per cent; and on urban streets, 80 per cent. The next-most-responded-to beam was the four-light combination of the 6014 and H_4 low beams (14 per cent, 23 per cent, 10 per cent), indicating that requests for dimming are at least sometimes elicited by the number of lamps lighted.

Study Seven

This study compared glare from several headlamp beams as reflected by the inside rearview mirror of a preceding car. Test subjects accompanied by the experimenter drove the lead car on expressways, urban roads, and a brightly lighted, heavily traveled four-lane urban street while a car equipped with the various headlamp systems followed at a distance of three to five car lengths. The outside mirror of the lead car was turned down to make it inoperative.

The subjects were asked to compare the mirror-glare from the various beams with the mirror-glare from a standard pair of No. 4000 low-beam headlamps. They used a 9-point scale ranging from -4 (glare the equivalent to no lights at all) through 0 (glare the same as with the No. 4000 low beam) to +4 (glare is extremely discomforting). On a command from the experimenter in the lead car, the experimenter in the following car switched from the No. 4000 beam to the desired beam for a few seconds, then switched back to the reference beam. The test subject then called out his judgment, and this was recorded by the experimenter.

The eight beams were presented twice to each subject in random order while using the day setting on the rearview mirror, and once while using the night setting. The test runs required about three hours with each of eight test subjects. All of the lamps were carefully aimed mechanically and checked visually before the tests.

The averaged results showed that the type of road had very little effect on the ratings. The only beam rated significantly less glaring than the reference beam was the H_4 low beam, rated -1.5. The beams rated most glaring were the No. 6014 high beam plus Type IV (+3.7), the H_4 high beam (+3.5), and the No. 6014 high beam (+2.6).

Overall Conclusions

After assessing the findings of the seven studies, the researchers concluded that the test procedures had validly discriminated between different types of beams, and that the detailed quantitative findings would be adequate for validating the computer simulation model. The studies had shown that in meeting situations the H_4 beams and No. 6014 beams exhibit no marked superiority over each other, and the mid beam, while providing better visibility for right-hand targets, may not be a practical alternative unless the technology of lamp aiming and aim maintenance is considerably improved. The studies had also shown that the closer a target is to a glare source, the more difficult it is to see with any beam system.

Validation of the Model

To put the field test data in a form useful for refinement and validation of the computer simulation program, the researchers used the data to produce curves representing the averaged target visibility distances as a function of the many variables: the type of beam, longitudinal separation of the vehicles, median separations, target locations, target reflectances, etc. The equations and parameter values in the simulation model were then adjusted and refined until a fairly close match was achieved between the inputs and outputs of the field tests and those of the computer runs. The closeness of the fit is illustrated in Figure 1.

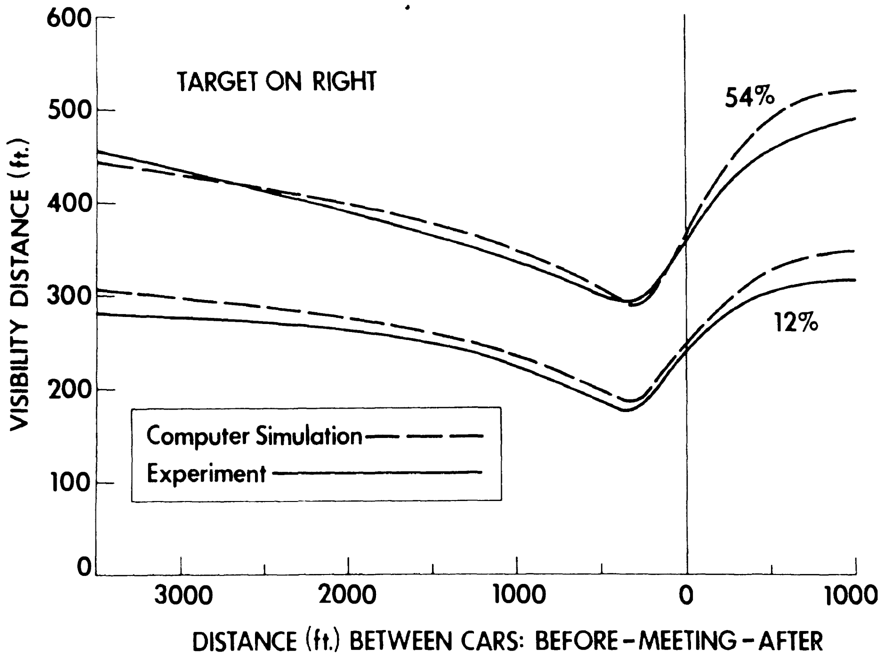


FIGURE 1. How the computer-simulated results compared with results obtained from field experiments in tests of U.S. standard high-beam meetings with a 7-ft. lateral separation between the cars. The broken line is the computer output; the solid line, the field results.

Besides plotting visibility distances, the simulation program prints out values for the glare intensities to which drivers are exposed during the vehicle meetings. These values are important for evaluating various headlamp systems, since the overall performance of a beam must be assessed not only for the visibility distances it provides but the amount of glare discomfort it provides for oncoming drivers.

USE OF THE MODEL IN ASSESSING HEADLAMP SYSTEMS

GIVEN THAT THE SIMULATION model could accurately show the performance of hundreds of different headlamp systems, this did not automatically dictate how the simulation program should be used. But, since the basic objective in headlighting research is to develop meeting beams that will maximize visibility and at the same time hold discomfort glare to a tolerable level, the researchers decided to begin by comparing how the U.S. low beam, European low beam, and experimental mid beam performed when they were correctly aimed, aimed up 1°, and aimed down 1°.

The U.S. low beam employed was the standard No. 4000 lamp, the European low beam was the standard ECE H_1, and the mid beam was the U.S. low beam plus a Type-III lamp mounted inboard on the driver's side and aimed toward the right side of the lane. In each simulation the opposed vehicles were represented as being driven in the middle of 12-ft.-wide lanes, so that the vehicles had a lateral separation of six feet. The targets were represented as located on both the right and left sides of the lane, six inches above the pavement, with a reflectance of 12 per cent.

Figure 2 shows the results of simulated performances of the three beams when they were in correct (nominal) aim:

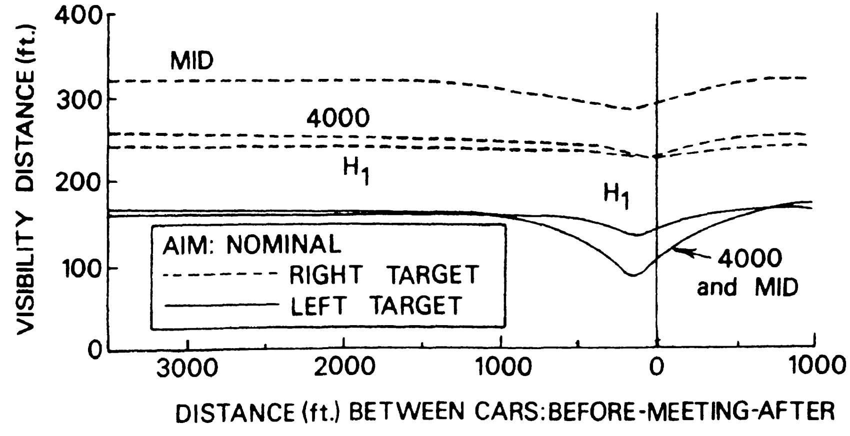


FIGURE 2. A computer-simulation comparison of the performances of the U.S. low beam (No. 4000), the European low beam (H_1), and experimental mid beam, when the beams were in correct (nominal) aim.

Note that for targets on the right, the mid beam provided about 25 per cent more visibility than the other beams. For targets on the left, the H_1 beam provided more visibility, beginning at about 900 feet before the meeting point.

Figure 3 compares the performances of the three beams when the headlamps were aimed 1° upward from their correct aim:

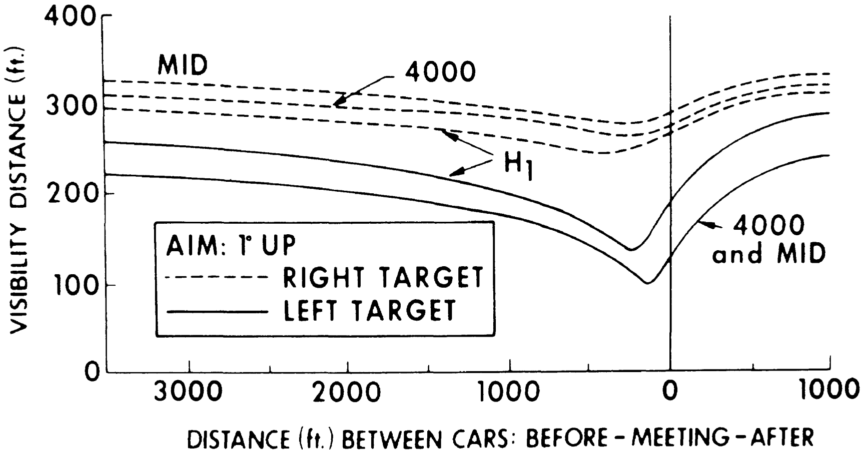


FIGURE 3. A computer-simulation comparison of performances of the three beams when they were aimed 1° upward.

Figure 3 shows that the mid beam still provided the most visibility for targets on the right, and the H_1 still provided the most for targets on the left.

Figure 4 compares the performances of the three beams when the headlamps were aimed 1° downward from their correct aim:

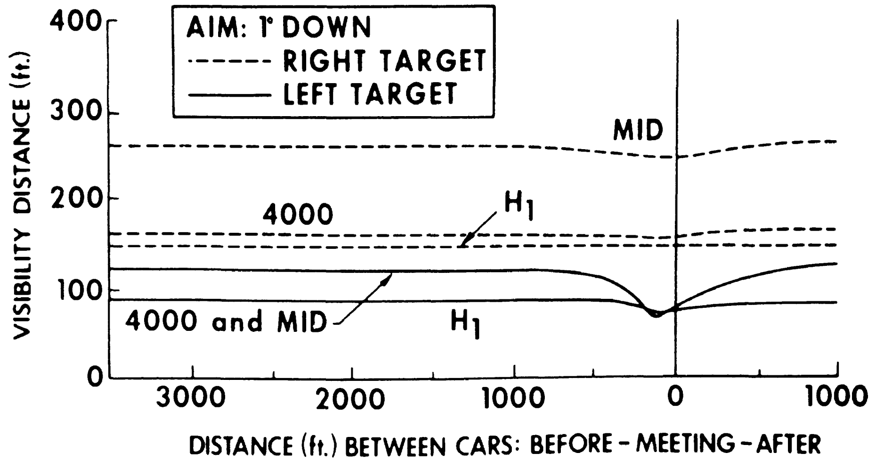


FIGURE 4. A computer-simulation comparison of performances of the three beams when they were aimed 1° downward.

Note that this reduced the visibility distances provided by all three beams, and that the mid beam provided substantially better visibility for the right-side targets. It also provided better visibility for the left-side targets, except at a point 200 feet before the meeting, where its performance was equaled by the H_1 beam.

As Figure 3 shows, the visibility distances achieved by aiming the headlamps 1° upward might suggest that the standard U.S. and European headlamps are now aimed too low. However, aiming the lamps 1° upward greatly increases the discomfort glare they provide for oncoming drivers. The simulations showed that the glare effects were almost four times as great for the U.S. low beam and the mid beam, and almost six times as great for the European low beam. Thus it would be impractical to aim the beams 1° upward, not only because of the greatly increased direct glare but the increased glare preceding drivers would receive from their rear-view mirrors. This indirect glare can now easily exceed direct glare.

CONCLUSIONS

THE FOUR YEARS of HSRI research on headlighting produced several results. The single most important one was a product: the computer simulation technique for evaluating the nighttime performance of any present headlamp system or any systems likely to be proposed. When this computer simulation technique was used to evaluate the performances of the U.S. low beam, European low beam, and experimental mid beam, it quickly and economically showed the researchers the advantages and disadvantages of those beams when they are correctly aimed and when they are misaimed upward or downward. Those findings, considered along with the findings from the studies of misaimed headlamps, led the researchers to conclude that higher-intensity lamps or different beam patterns will not make night driving more safe or comfortable unless the technology of lamp aiming and re-aiming is first greatly improved.

The studies of the three-beam system showed that use of the mid beam as a meeting beam offers some real advantages over the U.S. and European low beams. But, when the mid beam is misaimed upward, it produces too much mirror-glare for drivers in preceding vehicles. The mid beam would be impractical to adopt until present aiming and mirror problems are eliminated or reduced.

When Dr. Mortimer was asked if present headlamp systems are safe—if, for instance, they permit a driver traveling 55 m.p.h. at night to see and avoid hitting a cow standing in the middle of the road—he responded by saying "How straight is the road and what color is the cow?" His response pointed out the larger question surrounding headlighting research: Given our present road geometries, vehicle braking and maneuvering capabilities, and varied traffic conditions, what can be done to make night driving safer for everyone? Dr. Mortimer suggests that all of the following are relevant:

> Improvement in the design of headlamp fixtures, better instructions on the care and use of aiming devices, and better training of service mechanics.
>
> Expanded use of load-leveling suspension systems, development of day/night outside rearview mirrors, and a change in the reflectance power of the "night" surface in the inside rearview mirror, from its present 4 per cent to about 20 per cent (so that more drivers would use it).
>
> Expanded use of reflective white striping along the right edge of the road pavement, and expanded use of anti-glare screens along the medians of insufficiently separated divided highways.
>
> Improvement in the reflectors and rear-lighting systems on bicycles and motorcycles, and expanded use of high-reflectance clothing by pedestrians and bicyclists.
>
> Better instruction of drivers on the safe uses of present headlamp beams.

Everyone, says Dr. Mortimer, would welcome a simple, quick, inexpensive, magical solution to night-driving problems, but there isn't any.

BIBLIOGRAPHY

Olson, Paul L., and Rudolf G. Mortimer. *Investigation of Some Factors Affecting the Aim of Headlamps*. Report No. UM-HSRI-HF-73-13. January 31, 1973. 63p.

Mortimer, Rudolf G., and Judith M. Becker. *Computer Simulation Evaluation of Visibility Distances Provided by Three Headlamp Systems (C, D, E)*. Report No. UM-HSRI-HF-TM-73-3. February 19, 1973. 79p.

__________. *Computer Simulation Evaluation of Visibility Distances Provided by Fifteen Headlamp Systems*. Report No. UM-HSRI-HF-TM-73-4. May 17, 1973. 36p.

Mortimer, Rudolf G., and David V. Post. *Investigation of Switching Modes for a Three-Beam Headlamp System*. Report No. UM-HSRI-HF-73-16. June 4, 1973. 55p.

Mortimer, Rudolf G., and Judith M. Becker. *Development of A Computer Simulation to Predict the Visibility Distance Provided by Headlamp Beams*. Report No. UM-HSRI-HF-73-15. July 25, 1973. 33p.

Olson, Paul L., and Rudolf G. Mortimer. *Analysis of Sources of Error in Headlamp Aim*. SAE 740312. February, 1974. 10p.

Mortimer, Rudolf G., and Judith M. Becker. *Computer Simulation Evaluation of Current U.S. and European Headlamp Meeting Beams, and a Proposed Mid Beam*. SAE 740311. February, 1974. 7p.

Mortimer, Rudolf G., and Paul L. Olson. *Development and Use of Driving Tests to Evaluate Headlamp Beams*. Report No. UM-HSRI-HF-74-14. March, 1974. 163p.

Mortimer, Rudolf G. *Some Effects of Road, Truck and Headlamp Characteristics on Visibility and Glare in Night Driving*. SAE 740615. August, 1974. 11p.