TRANSPORTATION RESEARCH RECORD
502

# Visibility: Effects of Vehicle and Lighting Characteristics

TRB
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

# CONTENTS

# FOREWORD

A continuing recognition that night traffic safety is heavily dependent on the driver's ability to see and be seen draws constant support for research. Papers in this RECORD report research on a variety of related subjects such as ways to make vehicles more noticeable, ways to improve the effectiveness of on-vehicle lighting systems, and ways to make application of fixed roadway lighting more effective. The findings should be of value to vehicle lighting system designers, street lighting system designers, safety specialists, and highway operations and administrative personnel.

Woltman and Austin report on their extensive examination of day and night visibility aspects of motorcycles. They suggest ways to improve visibility under both conditions by using materials that enhance noticeability of rider and vehicle while still preserving essential "natural" visual information.

Walton and Messer determine warranting conditions for fixed roadway lighting. Their premise is that the driver's visual work load can be considered in terms of the need for information and the supply of that information expressed in units of time. When demand time exceeds supply time without lighting, then lighting is warranted. Formulas for the necessary computations are presented.

An awareness of the limitations of vehicle forward lighting systems led Adler and Lunenfeld to study a 3-beam 4-head-lamp system. They considered glare to drivers of opposing and preceding vehicles as well as improvements in visibility for the drivers of the 3-beam cars and concluded that greater seeing distances were possible without excessive glare with the 3-beam system.

Mortimer and Becker also studied a 3-beam head-lamp configuration, drawing conclusions similar to those of Adler and Lunenfeld. Their work did, however, draw attention to the detrimental contributions to both forward visibility and opposing glare made by upward or downward misaim of as little as 1 deg.

In an area that has been controversial for some time, Stoke gives the findings of a large study of the relationship between reflectorized license plates and night rear-end collisions. One hundred thousand reflectorized plates and 100,000 control nonreflective plates were issued in 1971, and a full year's accident data were collected and analyzed for both groups. Stoke concluded that there was no statistically significant difference between the numbers of night rear-end crashes of vehicles in the 2 groups. This conclusion is sharply challenged in 2 discussions by Vanstrum and Sacks in which questions are raised regarding the comparability of the test groups, the definition used to classify daytime and night accidents, and the statistical test requirements. The author's closing remarks reject the contentions of the discussants, and the author stands by his original conclusion.

In the final paper, Helmers and Rumar report on their work in Sweden on object visibility in rural night driving situations under both wet and dry conditions. A number of study findings related to high- or low-beam usage with and without opposing headlights for differing pavement surfaces are included.

# SOME DAY AND NIGHT VISUAL ASPECTS OF MOTORCYCLE SAFETY

H. L. Woltman and R. L. Austin, 3M Company

This study includes a comparison of the daylight visibility properties of 2 fluorescent and 4 conventional pigments against representative backgrounds for clear and overcast sky conditions, representative solar altitudes, and cardinal directions. In detection and identification, fluorescents are comparable to conventional high-visibility pigments under optimum viewing conditions; however, fluorescents show a substantial improvement when illumination levels decrease toward dusk or when conditions for visibility are least advantageous. As a result, fluorescent colors are now used for certain safety appliances and devices where particularly hazardous conditions are common. Aspects of night visibility suffer from extremes of contrast, low levels of available light, and ineffectiveness of any conventional color to render objects visible at night. Visual clues are dependent on learned patterns of light sources rather than on natural information acquired from daytime driving. Transferral of visual skills from day to night is substantially inhibited by the widely differing aspects unless some "natural" visual information is preserved. The night factors and materials that tend to visually preserve natural information have long been employed for traffic signs and safety appliances. Their extension to cyclist and vehicular use is a promising means of enhancing rapid night visual comprehension. A systemized means of evaluating both the day and night aspects of the visual elements comprising the motorcycle and cyclist is presented. A perception model is reviewed as a possible means of evaluating the several aspects of the visual model.

•VISIBILITY plays an important role in motorcycle accidents. Numerous accident investigations reviewed by the authors list the motorist's not seeing the cyclist as a principal accident factor.

As explained in an Iowa Department of Public Safety Report (1), "Motorcycle drivers, when involved in a fatal accident with another type of vehicle, were considered by the investigating officer not to be at fault in about ⅓ of total violations. This may be partly due to a visibility problem; the drivers of other vehicles do not see the motorcycle." Similarly, in a Minnesota review of accident factors, Shields (2) states, "The greatest apparent hazard for the motorcycle rider is the left turning automobile at an intersection; approximately one out of four fatal accidents occurred when a car or truck was turning left in front of an almost invisible oncoming motorcycle. Passing situations involving motorcycles cause many accidents, usually fatal. These occur when an automobile driver is pulling out to pass another automobile, and fails to see an oncoming motorcycle." Poor visibility of the rider and the small frontal area are cited as apparent causes. McCracken of Liberty Mutual Insurance Company states (3), "Two out of three motorcycle accidents involve collisions with an automobile. Our accident records show that in three out of four auto-cycle collisions our insured automobile driver said he 'did not see' the oncoming cyclist in time to avoid him.... In two out of three collisions the automobile was making a left turn, crossing in front or into the path of the oncoming motorcycle." He cites poor visibility of the motorcyclist as the principal problem.

A 1968 New York study (4) of 3,546 motorcycle accidents reports 1,370 accidents at

Publication of this paper sponsored by Committee on Visibility.

intersections. Of these, 352 involved vehicles traveling in opposite directions with 1 turning left, and 587 involved vehicles entering at an angle. These 2 categories accounted for nearly 70 percent of all motorcycle accidents in the state.

Janoff et al. (5), reported a significant decrease (3.8 percent) in daytime accidents in 4 states having daytime motorcycle headlight laws. But, standard taillights do not increase noticeability. The inadequacy of the taillight is undoubtedly due to insufficient intensity and size. For the motorcycle to be more noticeable, 2 shortcomings must be corrected—the small image of the motorcycle and rider and the low luminance of the colors used in the rider's outerwear and the machine finish. Studies of conspicuousness have been performed to determine the most effective combination of color and size under day and night driving conditions. Siegel and Federman (6) report that dimensions of a conspicuous surface must subtend $\frac{1}{5}$ deg of arc as perceived from the required distance. Areas in excess of $\frac{2}{5}$ deg did not increase noticeability. This yields a dimension of at least 24 sq in. for a distance of 600 ft. Breckenridge and Douglas (7) recommend a factor of 100 to 1,000 times the area required at the visual threshold, suggesting 1.4 to 14 sq ft based on known detection distances for various colors for traffic control devices. Six-hundred feet is chosen as representative of stopping distances required for the 2 head-on situations cited above.

The color chosen for maximum daytime conspicuousness should be foreign to the color makeup of the roadway and surroundings and to the color of other motor vehicles using the roadway. A distinctive color for the use of motorcyclists, which could be seen and recognized at a considerable distance both day and night, would prevent some motorcycle-motor vehicle accidents. Investigations show fluorescent yellow-orange to have greatest effect. Richards et al. (8), in an exhaustive study of wear for deer hunters, recommend "daylight fluorescent orange."

More directly related to the driving environment is a study conducted by Hanson and Dickson (9). This study, to select the most conspicuous color for traffic control signs, compared colors of known high luminance, including conventional and fluorescent pigments. Conventional pigments work by a subtractive process in which certain wavelengths of incident energy are partially absorbed and the remaining energy is reflected. Reflectance values of fluorescent pigments exceed 100 percent at a specific wavelength because energy is absorbed in the near ultraviolet and blue-green regions of the spectrum, and is reemitted in the yellow-red region, thus adding to the energy that is conventionally reflected.

Natural illumination contains greatly varying proportions of blue light for various locations, sky conditions, and times of the day. When targets are in the shade or are overcast, blue light is predominant in the distribution. When daylight visibility is poor, such as during dusk, on an overcast day, or in the shade, the fluorescent materials' ability to use the blue-rich side of the spectrum substantially improves visibility.

Table 1 gives the results of an extensive field study. The threshold distances at which the color of targets could be identified are averaged for a number of viewers and for all backgrounds, for overcast and clear days, and for all times and directions. Both fluorescent colors had better than 2 to 1 recognition ranges for distance compared to regular red.

## MOTORCYCLE DISADVANTAGES

The response of the motorist to vehicle hazards is conditioned by the average vehicle encountered—its size, typical lighting, typical speeds, and placement. Motorcyclists therefore suffer certain disadvantages. The small size of the motorcycle places it below the threshold of what is expected. Because of its smaller than average silhouette and angular size, the motorcycle's speed may be misjudged. As a result, closing rates and reaction-braking times may be frequently misjudged. And, the colors of the rider's protective garments are usually of such low luminance that they offer little contrast with the surroundings, particularly those at night.

### Brightness

Forbes (10) has shown that traffic signs seen "first and best" are signs with the

**Table 1. Mean recognition ranges and rank order of 0.01-square foot circular targets.**

| | | Recognition Range (ft) | | |
|---|---|---|---|---|
| Rank | Color | Both Days | Overcast Day | Clear Sunny Day |
| 1 | Fluorescent yellow-orange | 441 | 438 | 443 |
| 2 | Fluorescent red-orange | 394 | 391 | 396 |
| 3 | White | 342 | 345 | 338 |
| 4 | Yellow | 315 | 311 | 319 |
| 5 | International orange | 242 | 242 | 242 |
| 6 | Red | 190 | 192 | 187 |

**Figure 1. Silhouette area—0 degrees (head-on view).**

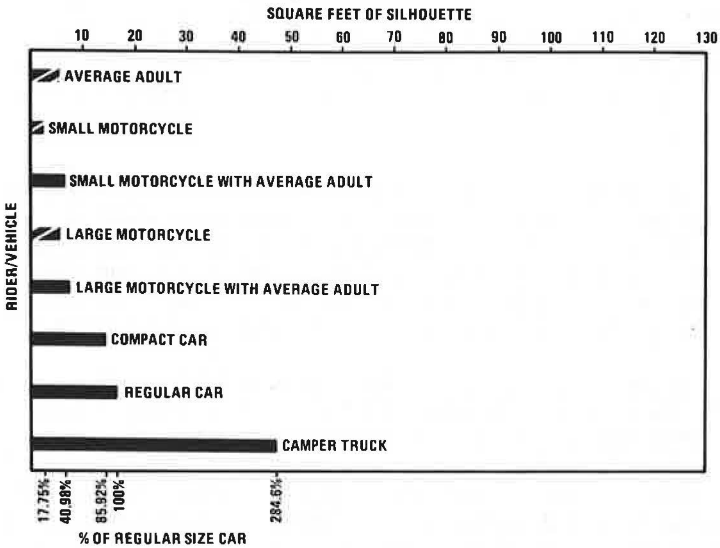
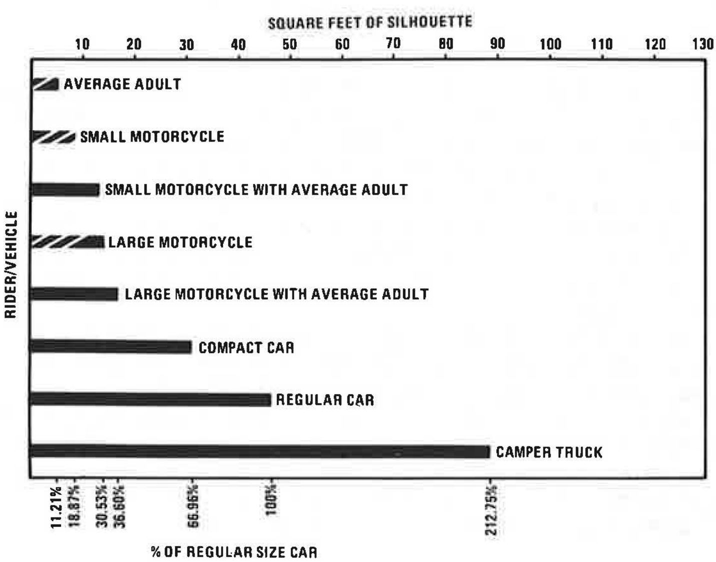



**Figure 2. Silhouette area—45 degrees.**



greatest brightness contrast when seen against their surroundings and large signs with brightness held constant. The perception model expresses expected recognition range as a function of percentage of contrast of the sign and surroundings multiplied by the minimum dimension of the sign in feet. The direct relationship of size and contrast that yields the expected recognition range suggests that improved brightness contrast may compensate for the motorcyclist's small size.

Visual Area—Tests

The visual area was investigated with the rider astride the machine and with the machine and rider separate. The areas were measured for a number of encounter positions—head-on, at angles, from the side, and from the rear. The visual areas were photographed with a 35-mm camera on a tripod. The center of the visible mass for each vehicle was placed at the center of the viewing field for each of the 5 angles viewed—0, 45, 90, 135, and 180 deg. The camera was positioned at 4½ ft above the roadway surface to correspond to the average motorist's eye height. Each picture incorporated a template 5 ft in length to later project a standard-sized image. Pictures were projected onto a gridded screen to determine the area with an accuracy of ±5 percent. The analysis did not include the wheel spoke areas or background areas visible through windows.

Visual Area—Results

The results of the analyses are shown in Figures 1 through 7 and Table 2. The comparative silhouette areas presented are for a typical standard-sized automobile, a camper truck, a compact car, a large motorcycle (BMW R-60, with fairing and saddle bags) with rider, a small motorcycle (Harley Davidson TX-125) with rider, and rider and motorcycle separately. Views are at 0 deg (head-on); 45 deg (a right-angle intersection encounter); 90 and 135 deg (return from a passing lane); and 180 deg (directly behind).

Silhouette areas presented by the motorcycle and rider vary from 30 to 40 percent of the standard passenger car as shown on the composite average. The various views, shown in Figure 7, compare the silhouette areas of a standard-sized car and a small motorcycle with adult rider. There is a significant reduction in area when the encounter is at 0 or 180 deg. Analysis of the motorcycle and rider separately shows the area of the rider's helmet and clothing to be greater than that of the machine for 0- and 180-deg encounters. To improve the brightness contrast of 50 percent of the silhouette area, a minimum of 3.44 sq ft for the end view to a maximum of 7.40 sq ft for the side view would need to be treated. It would then be above the threshold values cited by Siegel et al. (6) and would be similar to the area presented by a conventional 30-in. stop sign.

## NIGHT VISIBILITY

From 0 and 180 deg, the single headlight and taillight provide cues as to location, but the single light may be confused with an automobile with 1 headlight or taillight out, and the single light offers little aid in determining either distance or relative speed. It is far more difficult for a motorist to estimate a motorcycle's distance and speed at night than in the day. The daylight cues include seeing the size of the motorcycle and its movement relative to a textured background, both of which require a certain amount of ambient light. The information used in daylight is difficult to preserve at night because of single and often ambiguous point sources. For nighttime, a system of visual enhancement is required to provide these missing cues.

This problem is related to automobile headlighting. As Schwab and Hemion (11) observe, "Headlighting design is currently based on a compromise between the need for adequate illumination of the road ahead and the need to avoid 'dazzling' the eyes of the oncoming drivers with 'glare' light." The low-beam intensity and configuration "cannot possibly provide adequate lighting to enable the driver to operate his vehicle safely during many common night driving situations because of the nature of the necessary design compromises." Low-beam lights are used in more than 60 percent of all night driving in low-volume rural areas. Low-beam use increases to 90 percent when traffic volumes increase.

Figure 3. Silhouette area—90 degrees (side view).

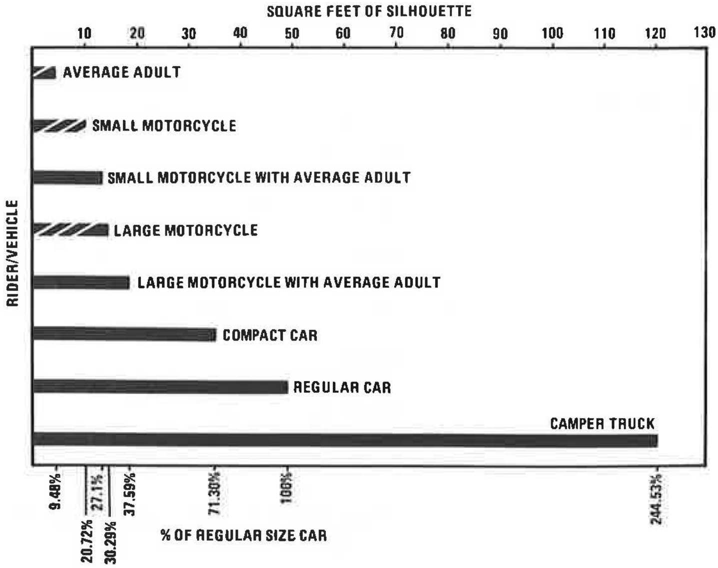



Figure 4. Silhouette area—135 degrees.

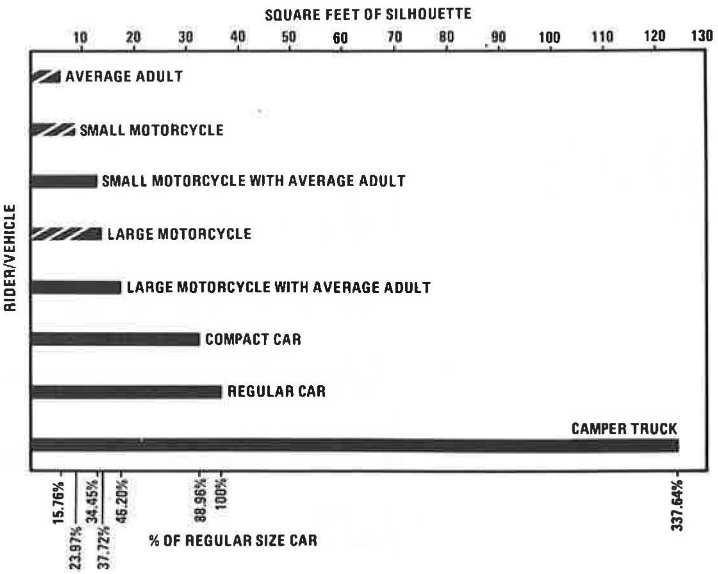



Figure 5. Silhouette area—180 degrees (rear view).

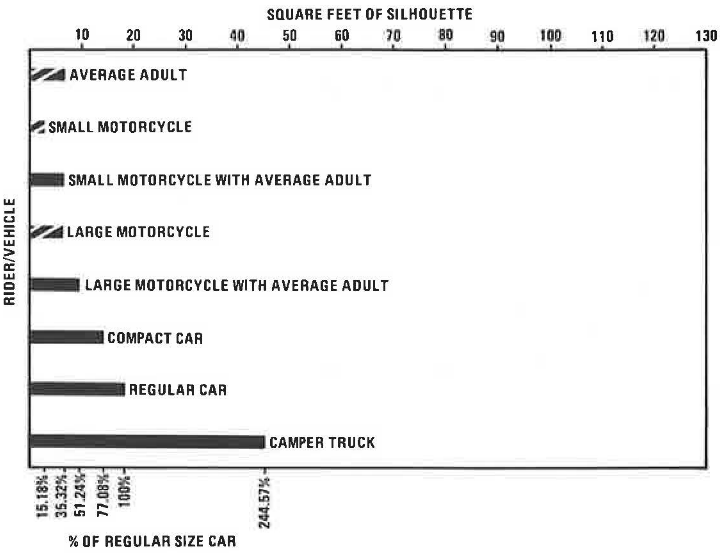


**Figure 6. Silhouette area composite average.**

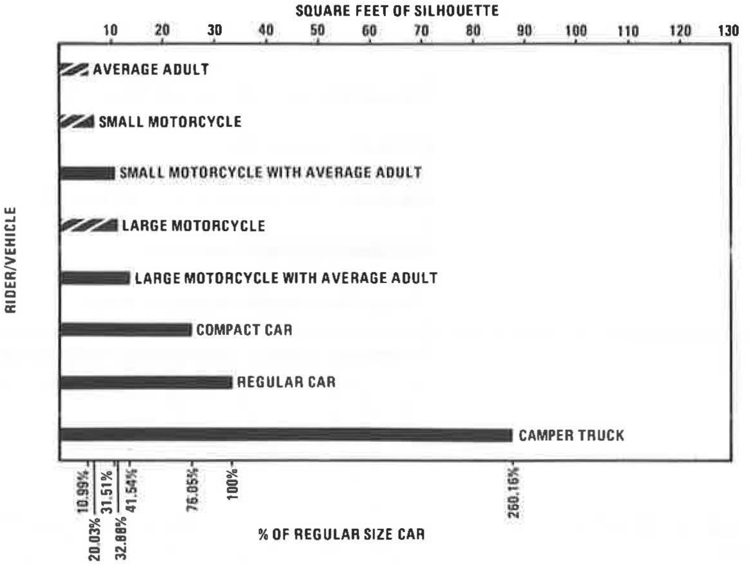



**Figure 7. Comparsion of silhouette areas of small motorcycle with rider and regular car.**

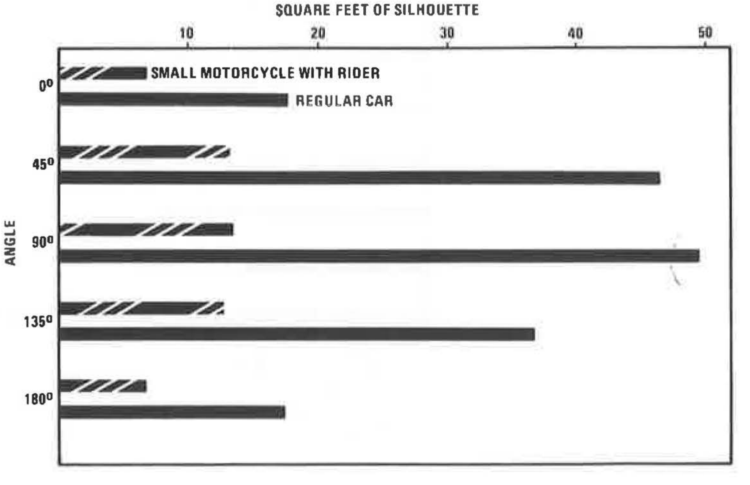



**Table 2. Dimensions and silhouette areas for various vehicles.**

| Vehicle | Overall Dimensions Height (ft) | Width (ft) | Length (ft) | Silhouette Area (sq ft) 0 Deg | 45 Deg | 90 Deg | 135 Deg | 180 Deg | Composite Average |
|---|---|---|---|---|---|---|---|---|---|
| Average adult | 5.86 | 2.09 | 1.26 | 6.73 | 5.21 | 4.69 | 5.82 | 6.73 | 5.71 |
| Small motorcycle | 5.22 | 2.51 | 6.48 | 2.89 | 8.77 | 10.24 | 8.85 | 2.89 | 6.73 |
| Small motorcycle with average adult | 5.23 | 4.81 | 6.48 | 6.88 | 13.06 | 13.41 | 12.72 | 6.88 | 10.59 |
| Large motorcycle | 4.60 | 2.51 | 7.42 | 6.09 | 14.19 | 14.97 | 13.93 | 6.09 | 11.05 |
| Large motorcycle with average adult | 5.86 | 2.51 | 7.42 | 8.60 | 17.01 | 18.58 | 17.06 | 8.60 | 13.96 |
| Compact car[a] | 4.81 | 4.81 | 12.54 | 14.30 | 31.12 | 35.24 | 32.85 | 14.30 | 25.56 |
| Regular car[b] | 4.81 | 6.27 | 17.56 | 17.60 | 46.48 | 49.43 | 36.93 | 17.60 | 33.61 |
| Camper-truck[c] | 9.41 | 6.90 | 18.81 | 46.37 | 98.20 | 120.87 | 124.69 | 46.37 | 87.44 |

[a]Volkswagen. [b]1969 Oldsmobile. [c]9½-ft 1972 Ford pickup with camper.

Figure 8. Standard motorcycle–day and night views.

Figure 9. Retroreflective motorcycle, suit, helmet, and tires–day and night views.

Table 3. Night luminance of standard and fully reflectorized motorcycle and rider.

| Viewing Angle (deg) | Motorcycle (ft-L) | Lights (ft-L) | Retroreflective Treatment On Motorcycle (ft-L) | Helmet (ft-L) | Suit (ft-L) | Total (ft-L) |
|---|---|---|---|---|---|---|
| 0 | 0.01292 | 39.0443 | 0.0003 | 0.0015 | 0.0161 | 39.0751 |
| 45 | 0.01225 | 0.8440 | 0.0083 | 0.0017 | 0.0263 | 0.8925 |
| 90 | 0.01473 | 0.0559 | 0.0106 | 0.0018 | 0.0263 | 0.1093 |
| 135 | 0.01315 | 0.0143 | 0.0038 | 0.0018 | 0.0220 | 0.0549 |
| 180 | 0.0154 | 0.3076 | 0.0025 | 0.0017 | 0.0368 | 0.364 |

Note: View is from low beams at 600 ft with motorcycle headlight and taillight on. Lamps were adjusted to standard alignment. Luminance values were obtained with a Pritchard telephotometer at driver eye position in a 1973 Oldsmobile.

Table 4. Luminance of standard and fully reflectorized motorcycle and rider.

| Viewing Angle (deg) | Luminance (percent) | |
|---|---|---|
| | Standard | Reflectorized |
| 0 | 99.97 | 0.03 |
| 45 | 95.94 | 4.06 |
| 90 | 64.65 | 35.35 |
| 135 | 50.00 | 50.00 |
| 180 | 88.75 | 11.25 |

In a study of available braking distances for night driving, Johansson and Rumar (12) found that for speeds over 30 mph braking distance exceeds the visibility distance (for European dipped headlights). They suggest reflectorizing cyclists and pedestrians to enhance their visibility. Tests conducted by Rumar (13) on the visibility of pedestrians wearing reflectorized clothing indicate a fivefold improvement in recognition distances (from 75 to 625 ft). Figures 8 and 9 show retroreflective helmet, clothing, and motorcycle surfaces, which preserve the natural information of daylight by providing the luminance, size, and shape that are frequently invisible under low beams.

A field-of-view study by Ford Motor Company (14) describes the angular span required to see and safely accommodate intersecting vehicles. A field of view of 126 deg encompasses 85 percent of the vehicles on a converging course. This yields a half-angle of 63 deg and should therefore be the entrance angle requirement for side-marker reflectors on vehicles.

At approach angles of 45, 90, and 135 deg, side-marker reflectors have luminous areas far lower than what may be required for adequate attention and recognition. The values measured by the authors are given in Tables 3 and 4, which illustrate the contributions of various components. Required seeing distances for right-angle encounters approximate 400 ft at 45 deg to either vehicle when either is traveling at 40 to 50 mph. The combination of increased visibility and shape identification, as is shown by the perception model, should result in a marked improvement in nighttime recognition.

## CONCLUSIONS

The visual area of the motorcycle and rider is approximately a third that of a conventional automobile. The conventional automobile is the size of hazard to which the motorist most frequently and successfully accommodates. The more frequent failure to correctly cope with the smaller motorcycle hazard might be improved by perceptual aids employing highly visible and contrasting colors such as fluorescent orange in sufficient size to be readily seen. At night, if both motorcycle and operator were reflectorized, depth perception would be enhanced. This increased bright area would communicate relative distance and speed better than traditional motorcycle lighting.

## REFERENCES

1. A Motorcycle Accident Study. Iowa Dept. of Public Safety, 1970.
2. Shields, J. Blueprint for Safety. Minnesota Department of Public Safety, Sept. 1972.
3. McCracken, D. M. Liberty Lines. Liberty Mutual Insurance Company, 1967.
4. Motorcycle Accidents. New York State Dept. of Motor Vehicles, No. 1969-12, 1969.
5. Janoff, M. S., Cassel, A., Fertner, K. S., and Smierciak, E. S. Daytime Motorcycle Headlight and Taillight Operation. Franklin Institute Research Laboratories, 1970.
6. Siegel, A. I., and Federman, P. Development of a Paint Scheme for Increasing Aircraft Detectability and Visibility. Jour. of Applied Psychology, Vol. 49, No. 2, 1965.
7. Breckenridge, F. C., and Douglas, C. A. Development of Approach and Contact Light Systems. Illuminating Engineering, Vol. 40, 1945, p. 785.
8. Richards, O. W., Wootner, R. W., and Panjian, J. What the Well Dressed Deer Hunter Will Wear. National Safety News.
9. Hanson, D. R., and Dickson, A. D. Significant Visual Properties of Some Fluorescent Pigments. Highway Research Record 49, 1963, pp. 13-29.
10. Forbes, T. W. Factors in Highway Sign Visibility. Traffic Engineering, Sept. 1969.
11. Schwab, R. N., and Hemion, R. H. Improvement of Visibility for Night Driving. Highway Research Record 377, 1971, pp. 1-23.
12. Johansson, G., and Rumar, K. Available Braking Distances in Night Driving. Dept. of Psych., Univ. of Uppsala, Sweden, Rept. 13, 1963.
13. Rumar, K. Night Driving: Visibility of Pedestrians. International Road Safety Congress, 1966.
14. Forbes, L. M. Field of View From Automotive Vehicles. Ford Motor Company, Rept. 5-72-6, Sept. 1972.

# WARRANTING FIXED ROADWAY LIGHTING FROM A CONSIDERATION OF DRIVER WORK LOAD

Ned E. Walton and Carroll J. Messer, Texas Transportation Institute,
Texas A&M University

This paper evaluates whether efficient and effective vehicle control is probable within a given night driving environment. A warranting scheme for roadway lighting is developed based on whether efficient and effective vehicle control can be achieved. Driver visual work load is used as the measure of effectiveness for vehicle control. Driver task levels are defined for the computation of work load or information demand. The task levels are positional, primarily routine speed and lane position control; situational, changes in speed, direction of travel, or position as a result of changes in situations; and navigational, selecting and following a route. Information demand is defined to be the time, in seconds, required to fulfill a sequence of positional, situational, navigational, and redundant positional information searches. Information supply is defined to be the time, in seconds, representing the visibility distance ahead for a given operating speed. When information demand exceeds information supply without roadway lighting, then roadway lighting is assumed to be warranted. Formulas for the computation of information demand, information supply, warranting conditions, and priorities are included.

•FIXED roadway lighting has many benefits. It improves roadway visibility, traffic operations, and police surveillance. The relative benefits and need for fixed roadway lighting depend on the objectives and values of a particular group.

The system for justifying fixed roadway lighting discussed in this paper seeks to create a suitable night driving environment where driving tasks can be performed in an efficient manner. The key to this objective is contained within the framework of the driver-vehicle-roadway complex. Because the driver's vision is the most important part of this complex, there must be sufficient visual information available to accomplish the driving task.

## DRIVING TASK

Three basic levels of driving have been identified—positional, situational, and navigational (1). These levels describe driving tasks and driver behavior. The information needs and priorities for each level are as follows:

1. The positional level must always be satisfied before other levels can be attended to. It consists primarily of routine speed and lane position control.
2. The situational level must be satisfied before navigational level is attended to but not before positional level is satisfied. It consists of change in speed, direction of travel, or position on the roadway because of a change in geometrics or in the operational or environmental situation.
3. The navigational level is performed only if levels 1 and 2 are satisfied. It consists of selecting and following a route from origin to destination.

Publication of this paper sponsored by Committee on Visibility.

## SUITABLE VISUAL NIGHT DRIVING ENVIRONMENT

A suitable visual night driving environment requires that a given driving population should always be able to perform all 3 levels of the driving task within a time frame without sacrificing safety and efficiency. In an overload situation, the driver sheds higher level tasks until an acceptable work load is reached. An environment that causes the driver to shed certain driving tasks could not be considered a suitable night driving environment. Shedding driving tasks, or load-shedding, results when the information processing and vehicle control demands exceed the capabilities of the driver to service and perform them. It is not specifically the amount of work that the driver is required to perform that results in load-shedding, but rather the rate at which the work must be accomplished. The rate at which the driver can perform depends on the time required and the time available to obtain the information needed for safety and efficiency. Although positional information is immediately used to implement a steering or speed control action, most situational and navigational information tasks require only information processing or scanning actions on the part of the driver. Few overt control responses are necessary. More situational information is needed as the driving environment becomes more complex. Navigational tasks increase as the number of alternate routes increases.

For a given operational and geometric situation, a driver's information demands are fixed; the only variable is the information supply in time. The information supply in time depends on the length of roadway visible and varies inversely with speed. The faster the motorist drives, the smaller the information supply is. Fixed roadway lighting is a design variable that not only improves the information processing capabilities of the driver, but also increases the supply of information available to the motorist by making a longer section of roadway visible. This increase in the supply of information reduces the rate at which driving work tasks must be done and thereby reduces the chance of load-shedding.

## WARRANTING CRITERION

The basic criterion used for evaluating whether fixed roadway lighting is warranted is whether the model indicates that a suitable night driving environment is provided. For this model, a suitable night driving environment is defined as one that enables the driver to perform all 3 levels of the driving task without having to load-shed. Information demands on a driver using a roadway without fixed roadway lighting for varying traffic conditions are compared to the information supply. If the information supply is not adequate, then fixed roadway lighting is warranted.

## DESIGN DRIVING TASKS

The design driving tasks and sequence in which the driver is assumed to service information needs follow a cyclic order dictated by the primacy concept (1). The cycle would take a form such as (a) positional information search and control; (b) situational information search; (c) navigational information search; and (d) positional information search and control.

The premise is that safe and effective positional control can be maintained only if redundant positional information of the roadway ahead can be obtained each time the driver returns to positional information search and control. During situational and navigational information searches, the driver is assumed to be traveling without additional positional information. From a satisfactory design viewpoint, the driver should not be required to drive uninformed along a section of roadway he or she has never seen before. In this model, therefore, the driver must obtain positional information on the roadway ahead while still on a section previously evaluated during the last positional update.

## COMPUTING INFORMATION DEMAND

Information demand is defined as the time required to fulfill a sequence of positional, situational, navigational, and redundant positional information searches. That is, the demand is

$$D = \sum (P_i + S_i + N_i + P_{i+1}) \quad (1)$$

where

$D$ = information demand in seconds on a section of roadway,
$P_i$ = time required to obtain positional information on cycle i,
$S_i$ = time required to obtain situational information on cycle i,
$N_i$ = time required to obtain navigational information on cycle i, and
$P_{i+1}$ = next required positional information search update on cycle i + 1, which must be achieved within the section of roadway visible during $P_i$.

This model attempts to quantify the information demands arising from different geometric, operational, and environmental situations.

Positional Information Needs

Field studies in diagnostic team research efforts (2) have revealed that most positional information is obtained at night from lane lines, edge lines, curb lines, position of other vehicles, and a general view of the roadway. When viewing conditions are good, the driver can obtain positional information with peripheral vision. But, Gordon (3) and Rockwell et al. (4) have shown with eye mark studies that under night driving conditions a driver fixates on edge, curb, shoulder lines, and the roadway ahead more frequently.

Time required for visual perception of an information source is composed of latency, movement, and fixation times (5). Latency is the delay between the time the stimulus is presented and the time the eyes begin to move. Normally, the latency time averages about 0.2 second. The stimulus in this model is not a light or object but a continuous search for information, so no latency time is assumed to exist. The time required for eye movement varies between 0.029 and 0.10 second for movements of 5 to 40 deg respectively (5). A movement time of 0.05 second was assumed because of the relatively small angular movements required. After the eye has moved to the object, the eye must fixate on it. The mean fixation time for observing road and lane markers was found by Mourant, Rockwell, and Rackoff (6) to be 0.28 second. Luckeish and Moss (7) observed in the laboratory a mean fixation pause of 0.17 second in a range of 0.1 to 0.3 second. It is felt that the Mourant data more accurately reflect the positional information fixation under night driving conditions and, therefore, an average fixation duration of 0.25 second is assumed. Thus, the perception time required to sample the positional source would be 0.30 second.

The driving task model assumes that the driver can maintain satisfactory positional control if he or she can obtain redundant positional information. However, it is known that the positional information work load of lane tracking increases when the geometric complexity of the road increases. As the geometric complexity increases, a greater number of samples of positional information are required by the driver. Elementary field tests suggest that a driver can maintain satisfactory positional control on a tangent section of roadway for a period of about 0.3 second with sampling positional information. As average horizontal alignment increases in complexity, sampling times decrease.

Rather than the increase in sampling being expressed in terms of an increase in the number of samples of a fixed duration, it is accounted for by increasing sampling time above the minimum of 0.3 second to obtain an equivalent work load.

Personal driving experience also suggests that lane widths of less than 12 ft (3.7 m) require more positional information because the driver has less room and time for correctional control within the lane. This factor is accounted for by comparing the amount of space available in a 12-ft (3.7-m) lane to the given space provided by a lane of width W. An average vehicle width of 7 ft (2.1 m) is assumed.

The following equation is used for computing positional information demand:

$$P_i = 0.3\left(\frac{D^\circ}{2}+1\right)\left(\frac{5}{W-7}\right) \quad (2)$$

where

$P_i$ = positional information demand in seconds,
$D^\circ$ = average degree of horizontal curvature, and
W = average lane width in feet (m).

Because the driver obtains redundant positional information, it is assumed that only small steering control corrections are necessary. To implement these small control corrections, a minimal amount of cognitive and physical effort is required by the driver. This permits the driver to implement physical control correction while he or she begins to search for situational information needs. Therefore, no additional time is required to effect a positional information search and control update.

## Situational Information Search

Situational information needs arise from changes in the geometric, operational, or environmental situation. Because the driver does not know where a hazard may be, he or she carefully looks for possibly hazardous areas. Eye mark studies (3, 4) have shown that the driver believes the roadway ahead to be a potentially hazardous area. Areas where traffic movements may conflict with the driver's path are also searched for situational information by the driver. Rockwell's eye mark studies indicate that drivers scan more potentially hazardous areas as they increase in number (4).

A summary of the situational task scan areas, conditions that warrant fixed roadway lighting, and guidelines are given in Table 1. Six types of situational information sources are considered. Four of these situational scan areas—intersectional, internal, medial, and marginal friction—can be on 1 or both sides of the driver, requiring 2 eye movements. The development of these 4 situational search demands is lengthy and is presented in another publication (2). It is assumed that the driver scans each of these situational areas to ensure safe and efficient operation when a potential hazard is visible 25 percent of the time. The fifth situational search area is the roadway ahead. Traffic signals, stop signs, and yield signs form the sixth situational scan area. At least 2 per mile are required on a roadway for continuous lighting to be warranted. Thus, almost all streets in an urban area have at least 2 warranting situational scan areas—the road ahead and traffic control devices that allocate the right-of-way.

Because of the increased complexity of the object and scene being viewed, the mean fixation time of situational information tasks is slightly longer than that of positional tasks. Mourant et al. (6) found that the mean fixation duration of vehicles, signs, and other objects was about 0.31 second. Because several scan areas are considered, and each is somewhat closer to the next, the visual angle required to shift from one to another is relatively small. As a consequence, the visual eye movement time is assumed to require 0.04 second. Thus, the total time required to satisfy the situational level information tasks, $S_i$, is obtained by multiplying the total number of warranting situational information scan areas (Table 1) by 0.35 second. $S_i = 0.35 \times$ sum of scan areas.

## Navigational Information Tasks

According to the primacy concept, the driver can search for navigational information only after he or she has fulfilled the positional and situational driving information needs. The information sought would be the direction-finding type. The amount required would depend on the driver's previous experience in reaching the destination, previous information on the route, and the complexity of the required navigational decisions.

Mitchell and Forbes (8) derived an expression for the time to read 3 familiar words on a sign to be N/3 or 0.33 second per word. A value of 0.32 second per word is used in this study. Eye movement time is assumed to be 0.03 second. Thus, each word is assumed to require an average of 0.35 second to find and read.

**Table 1. Situational information demands.**

| Scan Area and Facility Type | Minimum ADT Volume Warrant | |
|---|---|---|
| | 1 Side | Both Sides |
| Intersectional friction | | |
| Freeways[a] | 1,000 | – |
| Streets and highways[b] | 1,000 | 2,000 |
| Streets and highways[bc] | 50 | – |
| Interchanges[d] | 5,000 | 10,000 |
| Internal traffic friction | | |
| 4-lane freeways | 20,000 | – |
| 6-lane freeways | 30,000 | 57,000 |
| 8-lane freeways | 40,000 | 76,000 |
| 10-lane freeways | 50,000 | 95,000 |
| 4-lane streets | 5,000 | – |
| 6-lane streets | 5,000 | 9,000 |
| 8-lane streets | 5,000 | 9,000 |
| Medial friction | | |
| Undivided unsignalized facilities | 5,000 | – |
| Undivided signalized facilities | 4,000 | – |
| Facilities with median divider less than 30 ft | 10,000 | – |
| Median-type facilities (curbed or discontinuous) | – | – |
| Marginal friction | | |
| Driveways and minor intersections[ef] | 30 | 60 |
| Curb parking or bus stops[fg] | Any | Any |
| Pedestrians[fg] | Noticeable | Noticeable |
| 2-way frontage roads[f] | – | 5,000 |
| Roadway ahead | 0 | – |
| Traffic signals[h] | Any | – |

[a]To warrant continuous lighting, there must be at least 1 warranting entrance ramp per mile.
[b]Total cross roadway traffic. To warrant continuous lighting, there must be at least 2 warranting intersections per mile.
[c]Total left-turn traffic at intersection per peak night hour.
[d]Total cross roadway traffic. To warrant continuous lighting, there must be at least 1 warranting interchange per 1½ miles.
[e]Vehicles per peak night hour per 500 ft of roadway. Divide minor intersection volumes by 3.0 before adding.
[f]To warrant continuous lighting, there must be at least 2 warranting 500-ft sections per mile.
[g]On near side only for divided facilities.
[h]To warrant continuous lighting, there must be at least 2 signals, stop signs, or yield signs per mile.

**Table 2. Uninformed-motorist minimum ADT.**

| Type | Rural | Suburban | Urban |
|---|---|---|---|
| Interchange | | | |
| Diamond | 18,000 | 23,000 | 30,000 |
| Cloverleaf | 13,000 | 17,000 | 22,000 |
| Directional | 9,000 | 11,000 | 15,000 |
| Partial cloverleaf | 9,000 | 11,000 | 15,000 |
| Y | 9,000 | 11,000 | 15,000 |
| Trumpet | 9,000 | 11,000 | 15,000 |
| Intersection | 5,000 | 10,000 | 15,000 |

It would seem reasonable to assume that an informed driver, one who knows the facility, would need only 1 visual cue or 1 word to satisfy his or her navigational needs. The informed driver would then require only about 0.35 second per cycle to satisfy his or her navigational needs. The geometric complexity of the intersection or interchange would have little effect on the navigational information needs of informed motorists. All junctions should provide for at least this navigational task capability.

The uninformed or nonlocal motorist requires more time and information to make an efficient navigational decision than an informed motorist. In searching for the desired information, the uninformed motorist may read at least 1 uninformative word for every lane but 1. This is because most multilane facilities, especially freeways, have 1 overhead guide sign per lane approaching an interchange. After locating the correct overhead guide sign, the motorist must read at least 2 informative navigational words describing the appropriate route number or control city and the direction or lane assignment. Thus, the time, $T_N$, required by an uninformed motorist to satisfy navigational information needs at an interchange or intersection would be

$$T_N = 0.35\left(\frac{\ell}{2} + 1\right) \tag{3}$$

where $\ell$ is the total number of through lanes.

For an interchange to be considered an uninformed-motorist interchange, at least 1 uninformed motorist per minute would have to pass in each direction 75 percent of the night-design hour. If a Poisson distribution is used, this would require a minimum of 230 uninformed motorists per hour for both directions. It is assumed that 25 percent of the motorists on freeways in rural areas are uninformed, 20 percent in suburban areas, and 15 percent in urban areas. The ratio of the night-design hourly volume to average daily traffic (ADT) for all cases is assumed to be 0.05 percent.

The geometric complexity of the interchange and what the driver expects should be considered in evaluating navigational information tasks and difficulties. Diamond interchanges are perhaps the most expected and the easiest to navigate. Cloverleafs are assumed to be approximately a third more demanding. Partial cloverleaf, Y, trumpet, and directional interchanges are not expected by the uninformed driver and frequently are more difficult to negotiate. These types of interchanges are assumed to be 50 percent more demanding than the simple diamond interchange.

Table 2 gives the minimum interchange and intersection ADT volumes to warrant their being called uninformed-motorist interchanges and intersections. The volumes are the sum of the roadways' through, exiting, and entering volumes at the interchanges and intersections for each direction. The crossing roadways have an ADT of at least 20 percent of the values shown. All intersections and interchanges require at least 0.4 second of navigational information task time. To warrant continuous lighting there must be at least 2 warranting intersections per mile or, on freeways, at least 1 warranting interchange per 1½ miles.

## COMPUTING POSITIONAL INFORMATION SUPPLY WITHOUT FIXED ROADWAY LIGHTING

Lane lines, edge lines, and curb delineation are the most critical and most needed positional information. All other situational and navigational tasks depend on the sufficiency of these visual inputs.

### Model of Positional Information Supply

The supply of positional information is computed from the following equation:

$$C = \frac{\overline{L}}{1.47\ V_r} \tag{4}$$

$C$ = positional information supply in seconds,
$V_r$ = running speed of the traffic in miles per hour (km/h), and
$\bar{L}$ = average visibility distance of the critical source of positional information ahead of the driver without fixed roadway lighting.

The supply of positional information increases as visibility distance increases and decreases as speed increases. The critical source of positional information in this model is assumed to be the lane lines.

The visibility distance of a lane line depends on its contrast, brightness as determined by low-beam headlights, width of the lane lines, and the amount of disabling glare in the driver's field of view. This model was developed from the visibility research findings and theory of others and then calibrated with data obtained in a controlled field study to ensure that satisfactory visibility distances would be obtained.

The basic visibility equation was developed from research presented by Adrian (9). The following were presented: (a) brightness of the background; (b) minimum target size having a 100 percent probability of detection; (c) relationships among brightness differences; and (d) relationship between the target and its background. In this model, the target is the lane lines and the background is the pavement. The following equation, which relates the visual angle to the brightness and brightness differences, was developed from Adrian's research:

$$\alpha = \frac{1.66 B_p^{0.327}}{(B_\ell - B_p)^{0.654}} \tag{5}$$

where

$\alpha$ = minimum visual angle in minutes of arc,
$B_p$ = brightness of the background pavement in footlamberts (cd/m$^2$), and
$B_\ell$ = brightness of the lane lines in footlamberts (cd/m$^2$).

The size of the visual angle of the target is assumed to be determined by the width of the lane line, R, in inches (mm) and the resulting visibility distance of the lane line, L. Substituting a value of 287 R/L for $\alpha$ results in the following equation for the visibility distance, L:

$$L = 173 \frac{R(B_\ell - B_p)^{0.654}}{B_p^{0.327}} \tag{6}$$

The effects of headlights of the oncoming vehicle can be included in the visibility distance equation by adding disabling glare, G, to the initial brightness of the object and background. Glare, G, is the sum of all glare effects from oncoming vehicles in the driver's field of view. The visibility equation thus becomes

$$L = 173 \frac{R[B_\ell + G - (B_p + G)]^{0.654}}{(B_p + G)^{0.327}} \tag{7}$$

or

$$L = 173 \frac{R(B_\ell - B_p)^{0.654}}{(B_p + G)^{0.327}} \tag{8}$$

The intensity of low-beam illumination on the lane lines and pavement surface near the anticipated visibility distance was estimated from photometric headlight data provided by a national manufacturer of highway signing materials. From these data the illumination in footcandles (lx) was estimated by

$$D = \frac{5000}{d^2} \tag{9}$$

where d is the distance from the vehicle to the location on the lane line where the intensity of illumination is desired. Here, this desired distance is the visibility distance, L.

Knowing the intensity of illumination, E, in footcandles (lx), we computed the brightness of the lane line from $B_\ell = \rho_\ell E$, where $\rho_\ell$ is the reflectance factor of the lane lines. The brightness of the pavement surface was computed from $B_p = \rho_p E$, where $\rho_p$ is the reflectance of the pavement surface. Thus, the visibility equation becomes

$$L = 173R \frac{\left(\frac{5000\rho_\ell}{L^2} - \frac{5000\rho_p}{L^2}\right)^{0.654}}{\left(\frac{5000\rho_p}{L^2} + G\right)} \tag{10}$$

Glare per oncoming vehicle was computed from the generalized Holladay-Stiles formula

$$g = \frac{10\pi\, E_v}{\Theta^n} \tag{11}$$

where

$g$ = glare in footlamberts ($cd/m^2$),
$E_v$ = illumination striking the plane of the driver's eyes,
$\Theta$ = incident angle of the glare source in degrees, and
$n$ = generalized exponent.

The amount of oncoming headlight glare depends on the lateral separation between an oncoming vehicle and the vehicle affected, s, and the longitudinal separation, X, between the 2 vehicles. The distance between the 2 vehicles would then be

$$h = \sqrt{X^2 + s^2} \tag{12}$$

It is recognized that vehicle headlights form a directionally oriented beam of light and do not act exactly as a point source of light. However, to simplify the calculations, the light was assumed to be a point source and the effective candlepower was determined by calibration to the photometric data at approximately 200-ft (61-m) longitudinal separation and 9-ft (2.7-m) lateral separation. From this calibration, the average effective left-side candlepower for dim lights was assumed to be 2000 candelas at the driver's eye height.

Substituting E cos $\Theta$ for $E_v$ in the Holladay-Stiles glare equation where $\cos\Theta = X/(X^2 + s^2)^{1/2}$ and letting $E = 2000/h^2$ result in

$$g = \frac{10\pi}{\Theta^n} \frac{X\ 2000}{(X^2 + s^2)^{1/2}(X^2 + s^2)} \tag{13}$$

Assuming that $\Theta = \sin\Theta$ in radians (actually $\Theta = \sin^{-1}\Theta$, but the assumption $\Theta = \sin\Theta$ reduces the complexity of the equation with little effect on the result) and converting $\Theta$ in radians to degrees yield

$$g = \frac{10\pi \times 2000}{(57.3)^n \frac{s^n}{(X^2 + s^2)^{n/2}} (X^2 + s^2)^{1/2} (X^2 + s^2)} \tag{14}$$

Several values for the exponent n were tested in the range from 1.0 to 2.0. A value of n = 1.0 was found to correlate best with the field data recorded in this research and a value of 1.0 also simplifies the glare equation. Thus, using 1.0 for the exponent n results in

$$g = \frac{10\pi \text{ X } 2000}{57.3\,(X^2 + s^2)s} \tag{15}$$

Since the total glare (g in Eq. 11) is the sum of the individual glare values (g in Eq. 15), the visibility distance equation (Eq. 10) becomes

$$L = 173R \frac{\left(\dfrac{5000\rho_\ell}{L^2} + \dfrac{5000\rho_p}{L^2}\right)^{0.654}}{\left(\dfrac{5000\rho_p}{L^2} + \sum \dfrac{10\pi \text{ X } 2000}{57.3(X^2 + s^2)s}\right)^{0.327}} \tag{16}$$

or

$$L = \frac{2800R\,(\rho_\ell - \rho_p)^{0.654}}{L^{1.346}\left[\dfrac{\rho_p}{L^2} + 0.022\sum \dfrac{X}{(X^2 + s^2)s}\right]^{0.327}} \tag{17}$$

In the field test, a white beaded paint was used for 4-in. (102-mm) wide dashed lane lines on a concrete pavement. The reflectance factor was assumed to be 0.3 for the pavement and 0.7 for the reflective paint. These assumptions and R equal to 4.0 yield

$$L = \frac{5100}{L^{1.346}\left[\dfrac{0.3}{L^2} + 0.022\sum \dfrac{X}{(X^2 + s^2)s}\right]^{0.327}} \tag{18}$$

The model was then calibrated with field data to ensure acceptable legibility results. The calibration analysis revealed that the coefficient should be 4000 instead of 5100. Figure 1 shows the final calibrated results as compared to the field data.

The difficulty in computing the visibility distance is that it results from trial and error. The lane line visibility distance has to be assumed to compute its brightness, which in turn affects the visibility distance.

Visibility of the roadway ahead of the driver is reduced because of oncoming vehicle headlight glare. As the volume and density of oncoming vehicles increase, visibility decreases. However, visibility increases as the lateral separation between opposing traffic flows is increased. These facts are reflected in the results of the application of the visibility model to various traffic operational conditions shown in Figure 2. These results were obtained by summing the glare caused by every vehicle in the opposing traffic stream within 1,000 ft (305 m) of the driver. The effects of 500 vehicles were computed. A uniform spacing was assumed in the opposing traffic flow with the first vehicle positioned at half the average spacing in front of the affected motorist.

The oncoming vehicle headlights produce glare in the driver's eyes. Environmental lighting also produces glare. Certainly, the glare caused by different roadside establishments varies widely. But, it seems impractical to require that they be counted or that their effects be measured directly. The objective is to develop a practical method of incorporating roadside lighting into the approach being developed.

If it is assumed that 52.8 ft (16 m) of frontage of an establishment that is lighted at night has a glare equivalent of 1 oncoming vehicle, then a traffic facility that has 100 percent roadside lighted development on 1 side would be equivalent to a vehicle light-source density (as shown in Fig. 2) of 100 vehicles per mile (161 vehicles per km). A 100 percent lighted development on both sides would be equivalent to 200 vehicles per mile (322 vehicles per km).

**Figure 1. Visibility distance of 4-in. (102-mm) lane line as a function of lateral offset and distance of oncoming headlights.**

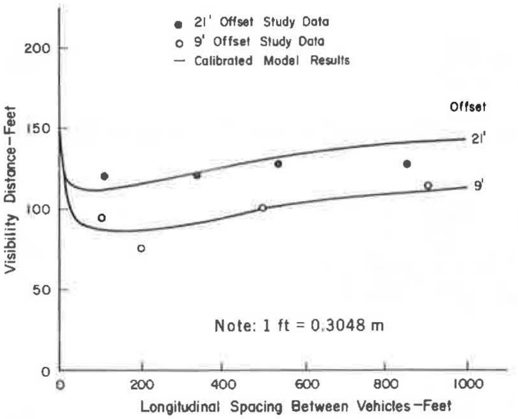



**Figure 2. Low-beam positional visibility distance as a function of oncoming vehicle density and lateral separation.**

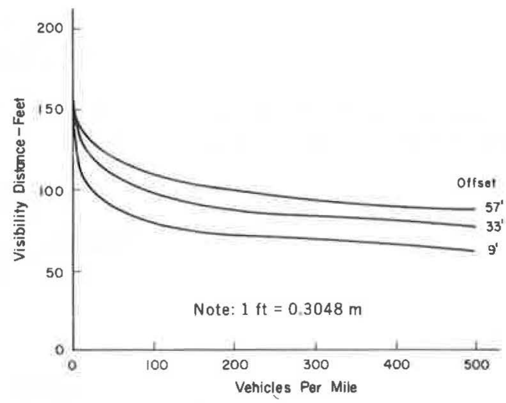
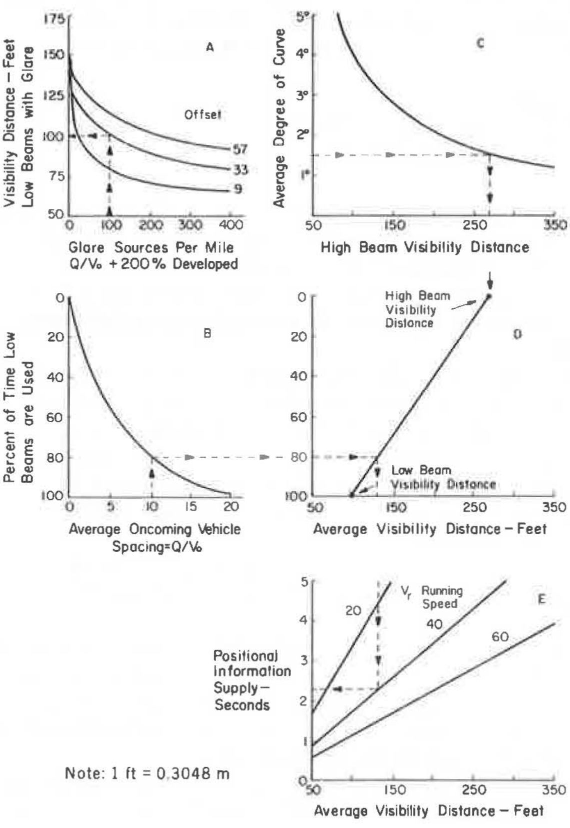



**Figure 3. Information supply.**



This process is simplified by the assumption that roadside lighting is located at the same offset as the oncoming vehicle headlights. Although this assumption may seem unjustified, the principal objective is to include the roadside environmental effects in some reasonable way rather than to neglect them entirely.

Procedure for Computing Positional Information Supply

The following procedure, shown in Figure 3, is presented to compute the positional information supply. The procedure considers general visibility as previously discussed, including glare from oncoming vehicles and roadside development; the percentage of time the driver will be using high and low beams; the average horizontal alignment; and the average speed of the driver.

Step A—The first step is to compute the visibility distance of the lane lines as shown in Figure 3A. Four items of data are required: (a) the opposing traffic stream volume during the night-design hour, Q; (b) the operating speed of the opposing flow for the previous volume, $V_o$; (c) the average lateral offset of the opposing stream flow with respect to the inside lane in the driver's flow; and (d) the average percentage of development along the facility.

Assume that the facility has four 12-ft (3.7-m) lanes and an 18-ft (5.5-m) median. The lateral offset is 3 + 18 + 24/2 = 33 ft (10 m). The directional volume, Q, is assumed to be 300 vehicles per hour during the night-design hour. Because of traffic signals, the operating speed in the opposing flow, $V_o$, which includes delay time, is 30 mph (48 km/h). The flow or speed is assumed to be the same in each direction. The average roadside development that has exterior lighting is 45 percent for both sides.

According to Figure 3A, the number of glare sources per mile is $(Q/V_o) + 200 \times$ development percentage or $(300/30) + 200 \times 45$ percent = 10 + 90 = 100. Using this result and the 33-ft (10-m) lateral offset shown in Figure 3A gives a low-beam visibility distance of 100 ft (30 m). This answer will be used later in the procedure in Figure 3D.

Step B—A driver traveling along a roadway at night generally uses both high- and low-beam headlights. The driver would use mainly high beams on low-volume rural highways, and low beams in urban areas. These facts must be taken into account to estimate the average positional information supply. Figures 3B and 3D were developed to satisfy this requirement.

Figure 3B gives the average percentage of time a driver would use low beams as a function of the traffic volume in the opposite direction, Q, and its average operating speed, $V_o$. This figure is based on Poisson distribution and on the assumption that opposing drivers dim their lights at a 1,000-ft (305-m) longitudinal separation distance. Again, based on the data given, Q = 300, $V_o$ = 30, Figure 3B shows that 80 percent of the time the affected driver would use low beams. This answer will be transferred to Figure 3D.

Step C—The next step is to compute the average high-beam positional visibility distance. The maximum high-beam visibility distance of positional information on a straight roadway is assumed to be 400 ft (122 m) without fixed source roadway lighting. But, as the average degree of curvature of the roadway increases, the visibility of the pavement surface and lane lines decreases because the roadway is curving away from the headlights. The curve shown in Figure 3C is based on the assumption that a vehicle's high-beam headlight pattern will permit lane lines to be visible up to a 2.0-deg angle of divergence with the longitudinal axis of the vehicle.

The average degree of curvature of a roadway is computed by summing the degrees of curvature at each 100-ft (30-m) station and dividing the sum by the number of stations considered. In this example, it is assumed that the average degree of curvature is 1.5 deg. That results in an average high-beam visibility distance of 270 ft (82 m).

Step D—As shown in Figure 3D, after the visibility distances for high beams and low beams are plotted at 0 percent and 100 percent low-beam use, an average positional visibility distance, $\overline{L}$, of 134 ft (41 m) is computed for the 80 percent low-beam operation existing in the example. This figure solves the equation

$\overline{L}$ = percent low beam (L) + (100 percent - percent low beam) ($L_{high\ beam}$)

Step E—The final step is to compute the positional information supply in seconds from the average visibility distance in feet (meters), $\overline{L}$, here 134 ft (41 m), and the average running speed in miles per hour (km/h), $V_r$, here 40 mph (64 km/h). Figure 3E shows that the positional information supply, C, is 2.3 seconds. Figure 3E solves the equation $C = \overline{L}/1.47\ V_r$.

## WARRANTING FIXED ROADWAY LIGHTING AND ESTABLISHING PRIORITIES

The approach used here to warrant fixed roadway lighting is based on the driver's information needs to perform his or her driving task on the facility in question within the driving environment present. From this viewpoint, fixed roadway lighting is warranted along a section of roadway or at interchanges or intersections when the information demand exceeds the information supply without fixed roadway lighting.

The information demand is the time required to fulfill the sequence of positional, situational, navigational, and redundant positional information searches. Demand is given in Eq. 1. The time required by the driver to make a positional update, $P_i$, is computed from Eq. 2. But, 2 positional updates are required, each of the same duration, within a given supply time. The time required to satisfy the situational information needs, $S_i$, for a facility is computed by using Table 1. The time required to make a navigational update is 0.0 second between junctions, 0.4 second where intersections and interchanges do not warrant a higher level, and 0.35 ($\ell/2$ + 1) second where this higher level is warranted as given in Table 2.

Substituting the results from Eq. 2 for both $P_i$ and $P_{i+1}$, determining $S_i$ from Table 1, and evaluating $N_i$ from Table 2, give an information demand of

$$D = 1.5\left(\frac{D^\circ + 2}{W - 7}\right) + S_i + \left[0.0,\ 0.4,\ 0.35\left(\frac{\ell}{2} + 1\right)\right] \qquad (19)$$

where

D = information demand in seconds,
$D^\circ$ = average degree of horizontal curvature in degrees,
W = average lane width [for a 1-lane turning roadway use 5 ft pavement width (1.5 m)],
$S_i$ = situational information time demand, using Table 1, and
$\ell$ = number of facility lanes, using Table 2.

The positional information supply depends on the suitability of the night driving environment without fixed roadway lighting. The positional information supply in seconds, C, is computed from Figure 3.

To check a section of roadway to determine if fixed roadway lighting is warranted, the information index, I, is computed as follows:

$$I = \frac{D\ (\text{information demand})}{C\ (\text{information supply})}$$

Fixed roadway lighting is warranted if the information index, I, is greater than 1. It is recommended that 500-ft (152-m) sections of roadway be analyzed.

### Noncontinuous Warranting

On roadways that do not warrant continuous lighting, the interchanges or intersections should be evaluated without the continuous lighting requirements. Interchanges and intersections will warrant lighting, even though the roadway itself may not warrant continuous lighting. These should be considered for area lighting. Partial interchange lighting might be based on an individual movement analysis.

## Establishing Priorities

The decision-maker, who allocates funds to various competing warranting lighting projects, needs a rational approach to use in allocating funds to maximize benefits to motorists. One such approach is to compute an equivalent priority index, $P_x$, for any warranting lighting project, X, and to compare it to all other competing projects. If all competing priority indexes were ranked in order from highest to lowest, then selections would be made from the top until either all available funds were spent or some minimum acceptable priority spending level was reached based on historical needs. The recommended procedure for computing the priority index for a warranting lighting project is

$$P_x = \frac{\sum_{i=1}^{D} I_i Q_i d_i}{C_i}$$

where

$P_x$ = priority index of warranted lighting project X,
$I_i$ = information index of roadway section i,
$d_i$ = length of roadway section i,
$Q_i$ = ADT on roadway section i,
D = number of sections warranted on roadway, and
C = present cost of lighting, operating, and maintaining the complete project.

## REFERENCES

1. King, G. F., and Lunenfeld, H. Development of Information Requirements and Transmission Techniques for Highway Users. NCHRP Rept. 123, 1971.
2. Walton, N. E., and Rowan, N. J. Warrants for Highway Lighting. Texas Transportation Institute, College Station, Final Rept., 1972.
3. Gordon, D. A. Experimental Isolation of the Driver's Visual Input. Highway Research Record 122, 1966, pp. 19-34.
4. Rockwell, T. H., Ernst, R. L., and Rulon, M. J. Visual Requirements in Night Driving. NCHRP Rept. 99, 1970.
5. Matson, T. M., Smith, W. S., and Hurd, F. W. Traffic Engineering. McGraw-Hill, 1955, p. 14.
6. Mourant, R. R., Rockwell, T. H., and Rackoff, N. J. Drivers' Eye Movements and Visual Workload. Highway Research Record 292, 1969, pp. 1-10.
7. Luckeish, M., and Moss, F. H. Applied Science of Seeing. Illuminating Engineering, Vol. 28, No. 10, 1933.
8. Mitchell, A., and Forbes, T. W. Design of Sign Letter Sizes. ASCE Transactions, Vol. 108, 1943, pp. 233-246.
9. Adrian, W. The Principles of Disability and Discomfort Glare. Presented at Symposium on Visibility in the Driving Task, Texas A&M Univ., 1968.

# EVALUATION OF A THREE-BEAM VEHICLE LIGHTING SYSTEM

Bernard Adler, Computran Systems Corporation; and
Harold Lunenfeld, Federal Highway Administration

One near-term improvement for vehicle forward lighting is a 3-beam 4-head-lamp system. This system, which includes a high and low beam with increased intensities and a moderately high-intensity midbeam, should provide increased seeing distance. This paper describes the results of a 3-phase evaluation of various combinations of beam usages to achieve the 3 modes. A computer program calculated the glare in the rearview mirror as a following vehicle with different headlighting systems approached from the rear. The results show very minor differences in glare among any of the beam configurations on the same mode. Vehicles equipped with the 3-beam systems were driven by a sample of drivers under a representative sample of road and traffic conditions. An evaluation of the subjective responses of the drivers to the system was made, and objective measures of the traffic stream's responses (through dimming requests) were recorded. There were slight differences in the number of dimming requests among the various configurations, and the drivers subjectively favored the use of a midbeam mode but were unable to select 1 high-beam system as superior. The last phase of this program was an empirical determination of seeing distances. The results of this phase showed that a beam configuration using all 4 head lamps in the high-beam mode yielded better seeing distances than others. The high-beam mode using all 4 head lamps appears to be the best configuration of those tested because it does not represent excessive glare and does not yield greater dimming requests, but does yield greater seeing distances.

•THE IMPORTANCE of providing the motor vehicle driver with a clear field of view under varying lighting and other environmental conditions has been pointed out by many investigators. Byrnes (1) indicates that 90 percent of the driver's information is visual. King and Lunenfeld (2) point out that the driver scans a dynamically changing environment searching for information to predict what will occur next. Anything leading to the driver's inability to obtain needed information may lead to missed information and errors. This contributes to the majority of motor vehicle accidents (3). Examination of accident records shows that the majority of fatalities (53 percent) as well as the highest death rate (8.7 per 100 million miles) occur at night (4). Although many factors contribute to this higher night fatality rate (for example, alcohol and fatigue), reduced visibility is the obvious factor according to Schmidt and Connolly (5).

The problem of improving night vision is illuminating the traveled way ahead while minimizing glare effects on the oncoming driver and rearview mirror glare on drivers upstream. Some research has been done in these areas with a diversity of approaches. Research done for the Federal Highway Administration (FHWA) indicates some technical advantages for polarization of headlights (6).

The National Safety Council (NSC) has, over the years, warned U.S. drivers of overdriving their headlights by excessive speed. Because of reduced forward vision at night the driver cannot see the object before it is too late to brake. Of the various schemes of forward lighting presented, most tend to be long range. One short-range program,

Publication of this paper sponsored by Committee on Visibility.

suggested by Hull et al. (7) in a study for the National Highway Traffic Safety Administration (NHTSA), is a recommended 3-beam, 4-head-lamp system to resolve these night vision problems. The NHTSA has called for the development of a 3-beam forward lighting system for a 4-lamp vehicle to be a short-range improvement in night visibility. This system, which represents a new approach in vehicle lighting systems, would provide drivers with 3, rather than 2, beam selections with higher intensities and increased seeing distances in each mode. From a safety point of view, this system must ultimately lead to safer night driving.

This paper describes the results of a threefold series of experiments whose aim was a partial analysis of the efficacy of different 3-beam modes. The first evaluation was done by using a computer program that calculated the glare in the rearview mirror as a following vehicle with different headlight systems approached from the rear. The computer program had flexibility to calculate the glare brightness for many isocandela distributions and numerous vehicular positions, road alignments, and head-lamp configurations. A field experiment was conducted to validate the computer results. The second phase was a subjective series of field evaluation experiments where 6 untrained operators drove different test vehicles for a number of nights. Surveys by questionnaire were conducted before, between, and after the experiments, and an analysis of the human factors associated with the operation of the system was done for subjective evaluation. At the same time, an objective evaluation of the system performance was done by counting the number of dimming requests by the opposing traffic. The third phase of the program was an empirical evaluation based on sight-distance experiments. These experiments had a number of drivers driving vehicles on different beam modes. Their goal was to detect and record the positions of targets randomly arranged on the roadside.

The final project report (8) contains a comprehensive account of the experiments and results that were extracted for this paper.

## EVALUATION METHODOLOGY

The need for increasing light coverage (lamp intensity or road illumination), without increasing the glare to oncoming drivers, leads to improving vehicle headlight systems. Of the various improved systems proposed, 3 configurations incorporating combinations of tungsten-filament head lamps were studied. The 3 configurations, shown in Figure 1, add a third intermediate beam for driving on expressways. The midbeam filament (B, Fig. 1) is a compact directional beam on the driver's side of the vehicle. This head lamp is aimed at the horizontal and adds more light straight ahead and farther down the road. Thus, in cases when high beams are unusable, the additional light from this midbeam reduces the effect of overdriving the headlights. The scope of study in this program was the evaluation of the three 3-beam configurations—2-3-2, 2-3-3, and 2-3-4, as shown in Figure 1.

### Analytical Techniques

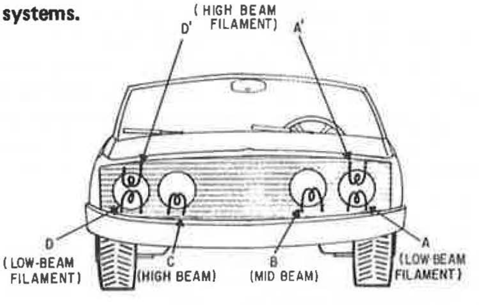
The analytical techniques used in glare computation are similar to techniques previously used in studying the brightness of highway signs (9). The computer program determines the amount of light leaving each head lamp in the direction of the mirror. It then calculates the glare intensity at the mirror and accounts for many variables inserted in the program such as reflectivity of the mirror, and transmission through the rearview mirror.

### Empirical Techniques

Both subjective field evaluation and sight-distance experiments require collection of empirical data. So, a number of cars must be modified for 3-beam headlight systems with new head lamps, wire harnesses, and switches.

Instrumentation—Six leased vehicles—green Plymouth Fury III, 4-door sedans with similar options—were modified for the experiments. Two vehicles were equipped with 2-3-2 configuration, 2 with the 2-3-3 configuration, and 2 with the 2-3-4 configuration.

**Figure 1. Filament use for 3-beam systems.**




| CONFIGURATION | BEAM MODE | | |
|---|---|---|---|
| | LOW | MID | HIGH |
| 2-3-2 | AD | ABD | BC |
| 2-3-3 | AD | ABD | A'CD' |
| 2-3-4 | AD | ABD | A'BCD' |

**Figure 2. Installation in vehicle.**

**switches in passenger compartment**

**relays in engine compartment**

**headlamps and wiring**

The head lamps were supplied to the Airborne Instruments Laboratory (AIL) by Westinghouse Electric Corporation and General Electric Company. Because there were 2 vehicles each with 2-3-2, 2-3-3, and 2-3-4 head-lamp configurations, 1 series of cars was equipped with lamps from 1 company and the other series of cars with lamps from the other. Both manufacturers were requested to supply lamps that conformed to NHTSA HS-800-529 (7).

Figure 2 shows the physical relationships of the components. A small auxiliary panel attached to the dash near the passenger's seat is shown in Figure 2. On this panel is a switch for turning the lights on and off and a 3-position rotary switch for selecting beam mode. Above the switches are 3 panel lights for the individual beam modes. When the selector switch is on low beam, a green light is illuminated; on midbeam an amber light is illuminated; and on high beam a blue light is illuminated. Figure 2 also shows the relays mounted on the inside tire well in the engine compartment and connected to the switches through the car's fire wall. From the relays, a harness of new wires was attached to the head lamps. The present head-lamp system was disconnected by uncoupling the present socket, and the new head lamps were connected to the new harness through new sockets. The head lamps and harness are also shown in Figure 2.

Aiming—The head lamps were aimed with a mechanical aimer and then checked visually on a target 25 ft away according to requirements:

1. Low beam—The upper and left edge of the highest intensity area shall be at the horizontal and vertical axes respectively of the mechanical center of the lamp;
2. Intermediate beam—The upper edge of the high-intensity zone shall be 1½ in. above the horizontal axis and 5 in. to the left of the vertical axis of the lamp; and
3. High beam—The center of the high-intensity zone shall be at the center of the horizontal and vertical axes of the lamp.

## ANALYTIC DETERMINATION OF GLARE BRIGHTNESS

The vehicle's forward lighting system should be changed only if it can aid the driver and if the change can be accomplished without being detrimental to other drivers on the road. Thus, a study of the 3-beam forward lighting system and its effect as a glare-producing source as seen on the rearview mirror of the preceding car was conducted. Configurations, beam modes, and other parameters were varied as the vehicle approached from the rear.

### Analytic Methods

Glare on the rearview mirror is determined by computing the output of each head lamp directed to the mirror, the reduction of light that reaches the mirror as a function of Allard's law ($I/d^2$), transmission through the rear window, and reflectivity of the inside and outside rearview mirrors. A computer program, first developed under NCHRP Research Project 3-12 to determine the brightness of highway signs for many of the same parameters, was adapted to determine rearview mirror glare by substituting mirror for sign.

The program, written in FORTRAN IV for the IBM 360/75 computer, H-level compiler, began the calculation by determining the oblique distance between each headlight and the mirror on the vehicle in front of it. The horizontal and vertical beam angles were then computed trigonometrically from the horizontal and vertical components of the headlight beam. These angles were used as indexes for determining the candela output of each head lamp in the direction of the mirror. These values were entered into an isocandela distribution chart, and linear interpolations were made for intermediate values.

The final illuminance on the mirror is the sum of the individual illuminances from each head lamp and is determined from the following equation:

$$\text{Illuminance} = K\frac{\text{candela output} \times \text{reflectivity}}{(\text{oblique distance})^2}$$

The complete program (REARVU) description and listing can be found in the final report (8).

## Computer Results

The results of more than 300 test cases were analyzed by the computer. The result presented here is the total maximum glare, in footcandles, from both inside and outside rearview mirrors. The graphs were plotted on log-log scales because the response of the eye is logarithmic.

Figure 3 shows a sample plot of low-beam, midbeam, and 3 high-beam configurations for a vehicle on a straight road. The 2-3-4 and 2-3-3 high-beam modes were almost identical and, to the human eye, were imperceptible; both were higher than the 2-3-2 high beam. At maximum values, the 2-3-4 high beam produced about 14 ft-c and the 2-3-2, about 6. These values were extraordinarily high, but they represent high-glare sources from a car following from 50 to 75 ft away. At about 400 ft, these values were approximately 1.0 and 0.6 ft-c respectively, which is more tolerable.

The midbeam mode produced a maximum of about 1.3 ft-c of illuminance from 50 ft. The maximum glare intensity was perceived when the driver looked directly into a rearview mirror. As can be seen by the curve, the values for the midbeam mode were not much more than those of the low-beam mode.

## SUBJECTIVE FIELD EVALUATION

The primary purpose of the 3-beam headlight systems evaluated in this study is to enhance forward night vision to make night driving safer, more comfortable, and more efficient. An evaluation must take into account, in addition to the objective factors pertaining to the physical operation of the system, those subjective human factors associated with its operation by the driver. And, because the driver is a part of the overall highway system of roads, traffic and environments, these subjective human factors must be evaluated in relation to the highway system. The purpose of this phase of the study, a limited on-site evaluation, was to determine how average drivers subjectively evaluate the system to provide an indication of user acceptance and user ratings. The purpose of this phase was also to determine how the traffic stream responds to headlight glare to provide an indication of the interaction of various headlight configurations with opposing and preceding drivers.

These aims required that vehicles equipped with 3-beam systems be driven by a sample of drivers under a representative sample of road and traffic conditions. In the course of these drives, an evaluation of the subjective responses of the drivers to the system was elicited and objective measures of the traffic stream's responses (through dimming requests) were recorded.

### Site and Route Selection

To fulfill the requirements of the subjective field evaluation phase, it was necessary to select a test route that would provide a representative mix of road, traffic, and land use characteristics that would be encountered in normal nighttime driving situations.

A circular intersecting test route incorporating the independent variables was selected. The route, from start to finish, took 2 hours driving time so 2 circuits, 1 in each direction, provided the 4-hour exposure time. A midsession break was also provided so that the drivers could rest and so that subjective data could be taken.

### Subject Selection

Six subjects, each of whom would drive a different test vehicle each of the 3 nights to evaluate all 3 systems, were hired. These drivers were not to be technically oriented and were close to the representative of the medium case driver so that extremes in age, experience, vision, and the like would be controlled. And, selection was based on whether the driver could relate to the situation and be able to talk about it.

The subject driver was an average of 30.7 years of age, had been driving for an average of 13.8 years, and drove an average of 16,000 miles per year. At the beginning of the interviewing session, drivers were given a preevaluation questionnaire to fill out before the new headlight systems were tested. The subjects were assigned to vehicles, systems, sessions, and routes on a random basis to control for order effects.

**Figure 3. Straight road glare intensity.**

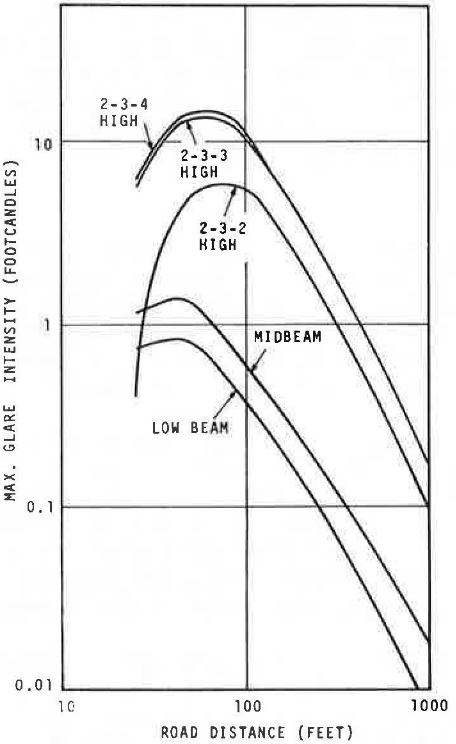



**Figure 4. Systems evaluation profile analysis.**

| LAND USE | ROAD TYPE | TRAFFIC CONDITIONS | ROAD LIGHTS | ROAD GEOMETRY | BEAM USAGE | DIMMING REQUEST FACTOR | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 2-3-2 | 2-3-3 | 2-3-4 |
| 2-LANE | URBAN | LIGHT | MOSTLY LIT | STRAIGHT | LOW | 0.47 | 1.49 | 0.53 |
| | | | | | MID | 0.00 | 0.00 | 0.00 |
| | | | | | HIGH | 0.00 | 0.00 | 0.00 |
| 2-LANE | RURAL | LIGHT | UNLIT | HILLY-CURVED | LOW | 5.68 | 5.09 | 0.00 |
| | | | | | MID | 9.09 | 12.80 | 6.92 |
| | | | | | HIGH | 14.88 | 19.63 | 13.60 |
| 4-LANE | URBAN | LIGHT TO MEDIUM | SOME LIGHTS | STRAIGHT | LOW | 0.00 | 0.00 | 0.00 |
| | | | | | MID | 4.18 | 0.89 | 0.38 |
| | | | | | HIGH | 8.33 | 0.00 | 0.00 |
| 4-LANE | RURAL | LIGHT | UNLIT | STRAIGHT | LOW | 0.00 | 0.00 | 0.00 |
| | | | | | MID | 1.71 | 0.61 | 1.52 |
| | | | | | HIGH | 5.79 | 8.63 | 13.39 |
| >4-LANE | URBAN | LIGHT TO MEDIUM | UNLIT | STRAIGHT | LOW | 0.00 | 0.00 | 0.00 |
| | | | | | MID | 1.07 | 0.00 | 0.00 |
| | | | | | HIGH | 0.00 | 0.00 | 0.00 |
| >4-LANE | RURAL | LIGHT | UNLIT | STRAIGHT | LOW | 0.00 | 0.00 | 0.00 |
| | | | | | MID | 1.34 | 1.51 | 0.00 |
| | | | | | HIGH | 0.00 | 0.00 | 0.00 |

## Observer Indoctrination

Before the experiments began 6 AIL observers were taken on a complete tour of the road to familarize themselves with nodes, choice points, links, and sections of highway. Before the experiment, they were given a complete set of written instructions on the procedures to follow during the experiment. Basically, the role of the observer was to verify the route, operate the headlight selector switch, monitor the safety of the driver, and keep records of time, traffic, dimming requests, and beam usage.

## Experiment Procedure

Evaluation sessions were run on the nights of September 5, 6, and 7, 1972. These midweek evenings were chosen to ensure that traffic composites for each evening would be comparable. There were no weather complications to bar the plans. Before the initial test runs, subjects were told about the session and given a familiarization period to learn the use of the systems and to gain experience driving the test vehicle. The subjects and observers were then assigned to vehicles on a random basis, not knowing what system their vehicles were equipped with.

Evaluation test runs were started at 8:00 p.m. Vehicles were dispatched in opposite directions on the test route at regular headways of 20 min. The headways were structured so that each vehicle would have at least 2 meetings opposite to every other test vehicle in the course of the test run. These meetings were time-phased to occur at different locations for each test run so that each system configuration would oppose each other system configuration on different roads and under different traffic and land use conditions. A series of forms were used in planning and operation—the nightly dispatch, observer, driver, and vehicle logs.

The test began with the observer instructing the driver on the procedures and allowing time for the driver to become acquainted with the vehicle. After driving started, the observer kept the details in the test-run log. At the end of the night's driving, each driver was given the daily evaluation questionnaire to fill out regarding the vehicle driven that night. At the end of the third night of experiments, each driver was given an additional questionnaire to fill out regarding the 3 nights and 3 different vehicles driven. This final debriefing summarized the 3 nights of driving.

## Data Reduction and Analysis

In the head-lamp configuration evaluation, the objective responses generated by the observer and the subjective responses obtained from the drivers were measured.

Objective dependent variables included statistical tabulations of exposure to each independent variable and observed responses by the driver to these conditions. Subjective responses included using subject responses in-transit, ratings on a 7-point opinion scale, and responses to interviews.

Objective Responses—Both the observer's notes and the driver's subjective ratings were tabulated and a systems evaluation profile analysis (SEPA) was constructed. Initially, a set of 36 SEPA profiles—one for each driver's evaluation session—was constructed.

Once the single trial SEPAs had been constructed and compared, they were combined for each driver and for each forward lighting system. This combined SEPA, shown in Figure 4, is divided into the 6 road and land use segments defining the road categories at which the various beams are used. The data were reduced to a dimming request factor by accumulating all the dimming requests and the exposure time for each opportunity to use a beam mode. The utility of the beam configuration, from the SEPA, is thus reduced to comparing the dimming request factors for each beam mode and configuration. This figure is the most valid comparison because it uses the number of measured dimming requests as a function of the number of opportunities that vehicle had in that mode divided by an estimate of the time that beam is on for those circumstances. The dimming request factor is an inverse measure of the utility of each beam mode. The higher the number is, the worse the situation was.

The dimming request factor, however, did not prove to be a conclusive device for measuring efficiency of the beam configurations. In fact, combining the data for the high-beam mode from the 2-lane and 4-lane roads yielded factors of 29.00, 28.26, and 26.99 for dimming requests per vehicle-hour for the 2-3-2, 2-3-3, and 2-3-4 configurations respectively. These numbers indicate that the 3-beam configurations caused a similar number of dimming requests.

When the subject drivers were asked about glare from an approaching test vehicle, again they could not arrive at a consensus. The drivers did not know that there were different configurations of the 3-beam systems on the vehicles. The only thing they were sure of was that 3 headlights were lit on the midbeam mode. Each time they looked for the subject vehicle approaching from the opposite direction they would note if 3 headlights were visible. In no circumstances did they talk about excessive glare from the approaching cars. They were therefore more tuned to 3 headlights approaching than to overly bright lights.

Subjective Responses—A second measure of utility of the beam configuration was measured from the responses that each driver gave to 3 sets of questionnaires. One was given before the tests as a preevaluation questionnaire. One was given at the conclusion of each driving day to measure the effectiveness of that vehicle's beam configuration. A third and final briefing session requested a comparison of systems by each driver. In rating the headlight systems, a 7-point scale was used with numerical values of 1 for inadequate to 7 for excellent.

The results of the preevaluation questionnaire centered on the inadequacy of the headlights, especially on high-speed roads.

The first 4 questions of the daily evaluation questionnaire compared the 3-beam configuration with their present systems. The low beams on all the 3-beam systems were rated better than present systems, but the midbeams, high beams, and the overall headlight systems were rated at least 1 grade higher. The next 6 questions centered on the quality of the beam mode for different types of roads. The composite means of the 3-beam systems for all different road types in each beam mode were as follows:

| Mode | Configuration | | |
|---|---|---|---|
| | 2-3-2 | 2-3-3 | 2-3-4 |
| Low | 4.25 | 3.94 | 3.92 |
| Mid | 5.48 | 5.01 | 4.58 |
| High | 5.17 | 5.62 | 5.67 |

There was a mean of about 4 (adequate) for the low beams, 5 (good) for the midbeams, and about 5½ (between good and very good) for the high beams. There should have been no difference in responses in the low beams and midbeams for any of the configurations because all of the beam patterns were formed by the same type of head lamps. In the high-beam mode, the means of 5.67 and 5.62 were almost identical and were both greater than the 5.17 of the 2-3-2 configuration. This shows a slight preference for either the 2-3-3 or 2-3-4 configuration over the high-beam system composed of only 2 headlights.

The results of the final debriefing were inconclusive. The first question asked of the 6 drivers was whether they felt that a 3-beam system should be installed in all vehicles. Five out of 6 responded affirmatively. The next 3 questions asked the drivers to rank the performance of the low, mid, and high beams of the vehicles they had driven. The rating showed that there was no preference in headlighting systems. The ratings for the high beams (the only difference among the vehicles) were the same as the ratings for midbeams or low beams.

## EMPIRICAL DETERMINATION OF SEEING DISTANCES

In the previous phase, the effectiveness of the system was determined by using subjective motorist and observer opinions. To complete the evaluation required an objective empirical determination of seeing distances. These data augmented and, in a sense, validated the subjective evaluations of the subjects.

## Experiment Design

The procedure used to establish seeing distances was similar to that reported by Hull et al. (7) and Meese and Westlake (10). This procedure entailed setting up targets randomly on the side of the test course. Depending on the conditions (unopposed or with an opposing glare vehicle), the test vehicle was required to accelerate to a steady running speed of 40 mph. The driver would signal each time an obstacle was perceived. The observer in the vehicle recorded the distance.

Six subjects were used for all tests. They were randomly assigned a sequence in the test procedure for each of the test blocks shown in the test conditions. Similarly, the target position was randomly chosen for each block. Each block consisted of 2 trials for each subject, where possible, with the target position changed for each trial. In about 10 percent of the trials, the target was omitted, at random. But, when the target was omitted the subject was retested so that the readings from the trials could be completed within the block.

All seeing distance determinations were made at the Bridgehampton race track in Suffolk County, New York. This race track consists of suitable straight sections to enable simulation of all test conditions and to ensure safe testing. The track, designed for a Grand Prix race, has a straightaway of about 4,000 ft. This allowed enough distance for a vehicle to approach from the opposite direction and meet the test vehicle near the target.

The target selected for these tests was a 16-in. gray square plywood panel with 7 percent reflectivity. This target was selected because of its uniformity in shape and reflectivity and because of the even distribution of light over the whole surface.

The instrumentation for these tests (Fig. 5) was provided by Car and Driver magazine and consisted of a fifth wheel (Teston, model 1625), an electronic counter (Veeder-Root, model 771), and associated controls and wiring to determine the distance in feet. At the starting point, the counter was set at 0 and the driver was given a switch to stop the counter. At the starting signal, the driver accelerated to 40 mph and watched the possible target position. When the car began moving, the counter started reading the distance elapsed. The driver pressed the switch to stop the counter when the target was seen. Knowing the distance from start to the target position and knowing the distance from start to seeing the object, we determined the seeing distance.

## Data Reduction and Analysis

Figure 6 shows the results of the experimentation. The group of bar graphs on the left represents the seeing distances for a case when the test car was driven without an opposing glare car. The group in the center represents the seeing distances when the instrumented car was opposed by a car approaching in the opposite direction with a 12-ft traffic lane separating the 2 vehicles (a 24-ft separation between the center of the cars). In all cases the glare car opposed the test car with the same beam mode and configuration. When the test car was on high beam with a 2-3-2 configuration, the glare car was also. The third group represents the seeing distances when the test car was opposed by the glare car approaching in an adjacent lane (a 12-ft separation between vehicles). Again, the glare car was in the same beam mode and configuration as was the test car. All the unopposed cases had sample sizes of 12 (repeated trial blocks), and the opposed trials had sample sizes of 6.

The first group, the unopposed cases, represents seeing distances on a straight, level, dark road. The low-beam case had a mean seeing distance of 198.9 ft, which was the result of improved low beams. The midbeam head lamp, an additional light on the driver's side of the vehicle, added more light straight ahead and farther down the road and increased the viewing distance to 253.6 ft. The high beam, 2-3-2 configuration, reduced seeing distance to 172 ft, and the high beam, 2-3-3 configuration, reduced seeing distance even lower (to 151.4 ft). This configuration, which had all its beams aimed at horizontal-vertical (0, 0) and none down toward the road, should have added more light farther down the road but not much on the right shoulder. The high beam, 2-3-4 configuration, achieved the greatest seeing distances.

The low beams were aimed down to the right (½ deg vertically and 2 deg horizon-

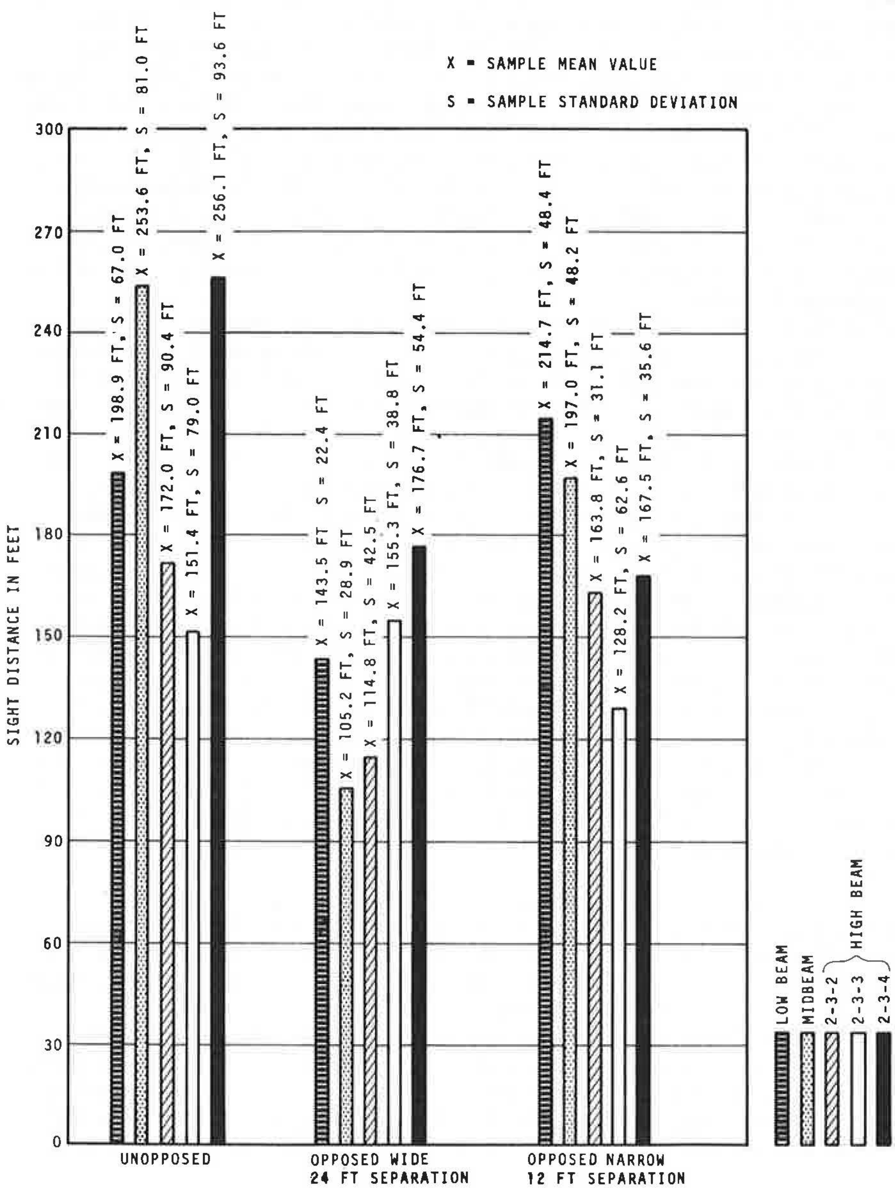
**Figure 5. Sight distance experimentation.**


starting gate and target

test vehicle with fifth wheel

instrumentation inside vehicle

**Figure 6. Sight distance results.**



tally). This sent more light to where the target was placed—5 ft to the right of the pavement edge. Because the midbeam was more concentrated and was also aimed low, the driver should have been further aided. But, the main effect of this beam was in the driver's lane and not off to the right. So, although a gain was noted because some light reached the target, the additional seeing distance was not overwhelming. The 2-3-2 high-beam configuration was the one in which some of the drivers and experts in the field noted a tunnel vision effect. Depth perception and visibility of the outside edges of the road were lost. This may have been the reason for the lower seeing distance in this case. The 3-light high beams should have been an improvement because the outside, low-beam head lamps filled in the picture the driver saw. However, the midbeam head lamp was not used, and this beam was aimed lower to the ground. The 4-light, high-beam configuration added the midbeam head lamp, and the best results in the unopposed category were achieved.

The second group of bars represents viewing distances in the presence of a glare car. This glare car accounted for the lower values of the sight distances for this group (an average of about 140 ft compared to 200 ft for unopposed). In the low-beam case the drivers saw an average of 143.5 ft, which is about 50 ft less than the unopposed low-beam case. This may have been because this was the first time the driver was exposed to an oncoming car in the tests. The unexpected value of these tests was in the midbeam mode (about 40 ft lower than the low beams). This result may also have been due to the unaccustomed driving in the presence of a glare car. Of course, with additional runs of the experiments, a more significant result may have been achieved. The 2-3-2, 2-3-3, and 2-3-4 high beams had seeing distances of 114.8, 155.3, and 176.7 ft respectively. The type 4 beam had little effect on either the midbeam mode or the 2-3-2 high-beam mode. Again, the 2-3-4 configuration had the highest seeing distance. These values may have been lower than the unopposed case because of the glare caused by the car approaching in the opposite direction.

The third group of bars represents viewing the object in the presence of a car approaching in the adjacent lane (12-ft vehicle separation). This group was lower than the unopposed case but higher than the opposed case with a wider separation. (The mean response was about 175 ft compared to 140 ft for the 24-ft separation case.) This group was higher than the previous one because, in general, the effect of the approaching car was to aid viewing of the target by a silhouette effect. The glare car, approaching the target, illuminated the background, gave the driver additional cues, and increased seeing distances. The low beams generated a seeing distance of 214.7 ft, which indicates that the driver was getting more accustomed to the road, the vehicle, the target-sighting switch, and the presence of an opposing glare car. The midbeam mode would have been expected to generate a slightly longer viewing distance than did the low beams, but the presence of a slightly more intense glare source may have caused the reduction. The main purpose of the midbeam head lamp was to add additional light in the center of the lane ahead of the driver. Therefore, even though there may have been additional light on the target, the driver was faced with slightly higher glare and, therefore, a reduced seeing distance. The high beams generated seeing distances of 163.8, 128.2, and 167.5 ft for the 2-3-2, 2-3-3, and 2-3-4 configurations respectively. Although these readings were made with a car approaching with its high beams on and, therefore, with higher glare, the expected results should have yielded longer seeing distances. The 2-3-2 and 2-3-4 configurations are about the same in value and are both larger than the 2-3-3 configuration.

The inconsistencies of the data can be attributed to limited scope and funding. At least 2 nights of trial runs, with and without a glare car and with all the beam configurations and modes, should have been completed before data were taken. And, when the data were taken, at least 3 trials for each task should have been tested, because 1 block (a sample size of 6) is insufficient for the results needed.

In addition, as shown in Figure 6, the unopposed trials have standard deviations varying from 67 to 94 ft. These values are much larger than those in the opposed trials where the deviations are in the 30s and 40s. This is partly due to the silhouette effect of the glare car in the opposed cases and partly because the unopposed trials were run first. That is, as the experiments proceeded, the drivers became more proficient.

## CONCLUSIONS

From the data in the program and by discussions with many experts in the field, the 3-beam headlighting system is desirable and the 2-3-4 configuration is the best of the 3 tested.

Results of the analytic determination of glare brightness showed that the 2-3-4 and 2-3-3 configurations are similar and are both higher as glare producing agents than the 2-3-2 configuration. But, when these values are looked at in proper perspective—from the distances at which they will be used—they are very similar even though the 2-3-3 and 2-3-4 are slightly higher glare producers than the 2-3-2 is.

Subjectively, the drivers were unable to select 1 system as superior. Objectively, there were small differences in dimming requests by the opposing traffic. For the 3 configurations, the 2-3-4 had the fewest number followed by the 2-3-3 and 2-3-2. The last series of tests showed that the 2-3-4 had consistently better seeing distances than the other high-beam modes. So, the 2-3-4 is the proper configuration for a 3-beam headlighting system. (Adding a second filament to the low-beam head lamp is not difficult considering the lack of stringent requirements for this upper beam.) The 2-3-2 system is capable but results in a tunnel effect in the high-beam mode. The 2-3-3 system does not use the midbeam head lamp on its high-beam mode. Even though this beam might not add additional seeing distance in the mode, it does act to fill in the ground plane in front of the driver and again eases the driving task.

## ACKNOWLEDGMENT

This paper is based on a study performed at the Airborne Instruments Laboratory, a division of Cutler-Hammer, for the National Highway Traffic Safety Administration, U.S. Department of Transportation. The opinions, findings, and conclusions are those of the authors and not necessarily those of the NHTSA.

## REFERENCES

1. Byrnes, V.A. Visual Factors in Automobile Driving. American Opthalmological Soc. Trans., 60, 1962, pp. 60-72.
2. King, G. F., and Lunenfeld, H. Development of Information Requirements and Transmission Techniques for Highway Users. NCHRP Rept. 123, 1971.
3. The State of the Art of Traffic Safety. A.D., Little, Inc., Cambridge, Mass., June 1966.
4. Accident Facts. National Safety Council, Chicago, 1971.
5. Schmidt, I., and Connolly, P. L. Visual Considerations of Man, the Vehicle and the Highway. Society of Automotive Engineers, New York, Rept. SP 279, March 1966.
6. Hemion, R.H., Hull, R.W., Cadena, D.G., and Dial, B.C. Development of Plans for Public Evaluation of Polarized Headlights. Federal Highway Administration, 1971.
7. Hull, R.W., Hemion, R.H., Cadena, D.G., and Dial, B.C. Vehicle Forward Lighting Performance and Inspection Requirements. National Highway Traffic Safety Administration, 1971.
8. Adler, B., and Lunenfeld, H. Three-Beam Headlight Evaluation. National Highway Traffic Safety Administration, Rept. No. HS-238-2-411-1, Jan. 1973.
9. Adler, B., and Straub, A. L. Legibility and Brightness in Sign Design. Highway Research Record 366, 1971, pp. 37-47.
10. Meese, G.E., and Westlake, P.E. Key Factors in Evaluating Headlight Systems. Presented at the International Commission on Illumination (CIE), Barcelona, Spain, Sept. 1971.

# SOME OPERATIONAL CONSIDERATIONS AFFECTING THE PERFORMANCE OF CURRENT AND PROPOSED HEAD-LAMP BEAMS

Rudolf G. Mortimer and Judith M. Becker, Highway Safety Research Institute, University of Michigan

A digital computer simulation was used to evaluate some factors that determine the overall effectiveness of current and proposed beams. Specifically, simulation was used to derive predicted visibility distances for a typical U.S. low beam and a proposed midbeam, with correct aim and with 1-deg (0.017-rad) upward or downward misaim. This demonstrated that aiming errors of this amount significantly affect a driver's visibility and the glare intensities to which opposing drivers are exposed. The midbeam offered a 20 percent increase in visibility of a target located at the right edge of the lane on a 2-lane road compared to the present low beam when the beams were correctly aligned. Because the midbeam provides greater visibility than the low beam, it was shown that it is appropriate to dim earlier from high beam to midbeam than to low beam, thereby obtaining better visibility and earlier reduction of high-beam glare. Use of the midbeam as the major meeting beam would make it more feasible to increase the intensity of the high beam. An examination of glare intensities from the beams in rearview mirrors showed the importance of lamp aim and mirror reflectivity to glare discomfort. For the conditions studied, it was concluded that the midbeam offers a satisfactory increase in visibility compared to the low beam and does not significantly increase glare if lamp aim is adequately controlled.

•ALTHOUGH the role of vehicle headlighting in highway crashes has not been determined, it is generally agreed that night visibility needs to be improved on those roads where fixed lighting is not available. To improve visibility in night driving, there has been a continuing evolution in head-lamp performance. Changes have been made recently in both American beams and European beams, where there are significant differences. (For example, the maximum permitted intensity of European high beams is 300 000 cd; in the United States it is 75 000 cd.) The changes have been accomplished by increasing intensities and changing the light distribution. High intensities from head lamps are now possible because of more efficient vehicle generating systems and halogen bulbs. Because inability to produce enough illumination from high beams is no longer a significant problem, the poorer performance of low or meeting beams has been highlighted. The need to improve the visibility distance when opposing vehicles meet has influenced further work to improve the meeting beam. In the United States, this has led to the concept of a 3-beam system consisting of a low, mid, and high beam.

A number of factors determine overall beam performance including visibility, glare effects, aiming effects, and the control switch.

## COMPUTER SIMULATION

A major obstacle in the development of improved headlighting systems has been the lack of methodology to evaluate such systems. Conventionally, this is done by field

Publication of this paper sponsored by Committee on Visibility.

tests in which vehicles are driven toward each other and measures of visibility of certain types of targets are obtained. Although field testing is a necessary part of head-lamp development, it has problems normally associated with experimental techniques. For example, maintenance of head-lamp aim from one test run to another and knowledge of the precise aim used at any time are difficult to achieve. Also, the number of variables that can be studied is limited. For example, the number of beam patterns that can be evaluated depends on the number available in hardware form and on time and cost constraints. For these and other reasons we have developed an analytical technique by which head-lamp performance can be evaluated. The advantages this method has over experimental tests include (a) complete control over all prevailing conditions, (b) precise aim of the lamps, (c) evaluation of beam patterns that are not available in hardware form, (d) low cost, and (e) fast evaluations. But, such a procedure must be validated.

Therefore, a series of field studies were conducted to evaluate the effects of a number of important parameters concerning beam intensity distributions, target location, target reflectance, lateral separation distance between vehicles, and longitudinal distance between the vehicles in a simulated meeting situation (1). The effects were found in terms of target visibility distances. The targets used in these tests are of the type shown in Figure 1. The observers had to detect the target and identify the position of the square with respect to the horizontal line. Target visibility tests, then, emphasized the orientation of the target. A computer simulation model was simultaneously developed to make predictions of the mean visibility of the target before and after the meeting point.

In its present form the computer simulation is limited to straight, level roads having a constant pavement reflectivity. Approaching vehicles move on parallel paths at constant speeds. Each vehicle may carry up to 5 head lamps. A 3-stage model of adaptation and recovery from glare effects is used. The model is described in greater detail by Mortimer and Becker (2, 3).

## Validity of Computer Simulation

The validity of the computer simulation is assessed by how the visibility distances predicted by the model match those obtained in the field experiments. Examples of such comparisons are shown in Figures 2 and 3. Figure 2 shows the comparison between computer simulation and experimentally obtained mean visibility distances for the target having 12 and 54 percent reflectances and positioned on the right of the lane. Both vehicles were equipped with conventional U.S. 6014 low beams. Figure 3 shows the comparison between experimental and computer simulation results for the target having a 12 percent reflectance and positioned on the left side of the lane. Both vehicles were equipped with low and high beams and had a 14-ft (4.27-m) lateral separation. Across the variety of these conditions, there is agreement between the simulation and the experimental results. Therefore, the computer simulation can be used to evaluate the effects on visibility of various head-lamp beams and other conditions, such as the head-lamp aim.

## Effects of Aim on Low-Beam and Midbeam Performance

In a recent study in which the accuracy of aiming head lamps by service outlets was measured, it was found that head lamps were frequently aimed outside the Society of Automotive Engineers (SAE) specification (4). SAE Recommended Practice J-599c states that head lamps should be aimed within ±4 in. at 25 ft (±10 cm at 7.6 m), or approximately ±0.8 deg (±0.014 rad), of nominal aim. The following table gives the percentage of head lamps that were misaimed in the horizontal or vertical or both. Up to 35 percent of head lamps were misaimed by the 24 service stations and 8 automobile dealerships in the Ann Arbor, Michigan, area where the study was conducted.

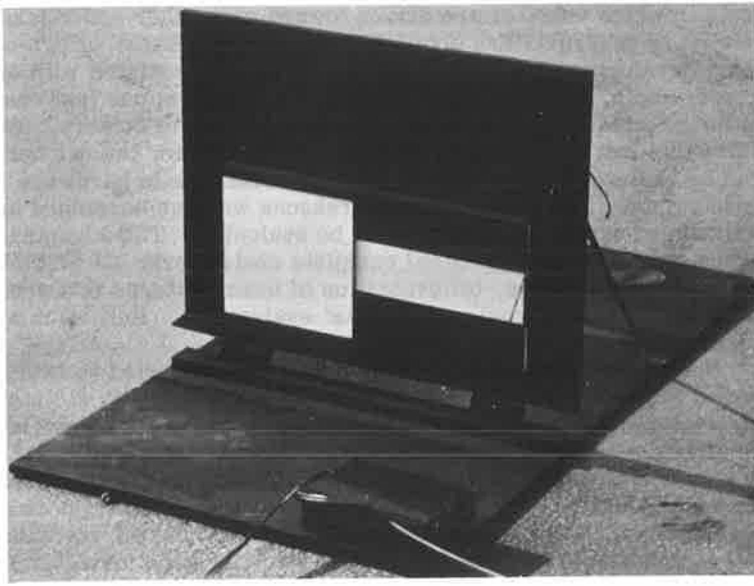


Figure 1. Field experiment target.

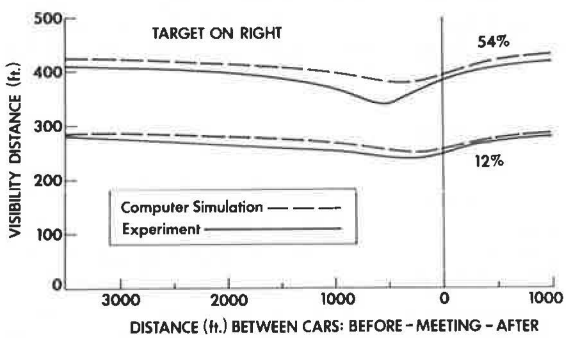



Figure 2. Experiment and simulation reflectance comparison for target on right of lane.

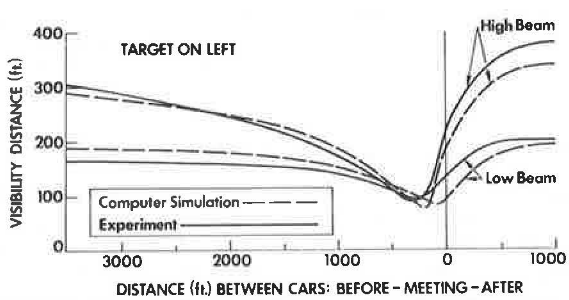



Figure 3. Experiment and simulation reflectance comparison for target on left of lane.

| Direction of Misaim | Percent |
|---|---|
| Horizontal | 18 |
| Vertical | 26 |
| Horizontal and vertical | 35 |

In the same study, the effect of vehicle loading was examined for a number of different automobiles and a pickup truck. The following table gives the change in the vertical aim (inches at 25 ft) of the head lamps that occurred when the vehicles were loaded to full capacity. Initially, the vehicle had a 150-lb (68-kg) driver and a full gas tank. The change in vertical aim exceeded the SAE recommendation in each case.

| Vehicle | Change |
|---|---|
| Compact | +6.5 |
| Sedan | +5.8 |
| Station wagon | +4.3 |
| Pickup truck | +5.8 |

To determine the effect of changes in vehicle aim of 1 deg (0.017 rad) on both visibility and glare, computer simulation analyses were made for low-beam and midbeam performance. Figure 4 shows the predicted visibility distances of a target having a 12 percent reflectance and located on the right side of the lane of a 2-lane road. Both vehicles were equipped with typical U.S. 6014 low-beam head lamps. The photometric test-point values of low beams and midbeams are given in Table 1. The effect of a 1-deg (0.017-rad) upward aim on the low beams of 2 cars meeting each other is to increase visibility. Conversely, the effect of a 1-deg (0.017-rad) downward aim on both vehicles is to substantially reduce visibility.

Figure 5 shows the same computer simulation data involving the midbeam. This composite beam is made up of 2 low-beam lamps and a type 3 lamp mounted on the left of the car, whose high intensity zone is sharply cut off just below the horizontal and its left edge at the vertical (Table 1). In Figure 5 where one midbeam meets another midbeam, there is an increase of approximately 20 percent in visibility compared to low beam meeting low beam. If a midbeam system is introduced, vehicles equipped with midbeams will meet vehicles equipped with low beams. Figure 5 shows that the driver of the vehicle with low beams will not suffer much loss of visibility. Figure 5 also shows the effects on visibility of meetings between vehicles with midbeams that are aimed 1 deg (0.017 rad) up or down, compared to normal aim. The effect of 1 deg (0.017 rad) upward misalignment is a small increase in visibility that is removed close to the meeting point. As with the low beam, a 1-deg (0.017-rad) downward aim is a large loss of visibility.

These data suggest that the midbeam may offer a worthwhile gain in visibility over the low beam. Obviously, this increase in visibility depends on the beam patterns of the composite midbeam and the low beam. Although the data shown here indicate that a 20 percent increase in seeing distance may be expected, other evaluations of various experimental low beams and midbeams found midbeam gains in seeing distance of as little as 10 percent (5).

Comparison of Figures 4 and 5 indicates that if the low beam is aimed 1 deg (0.017 rad) up, substantially the same visibility distances are obtained as in meeting situations between vehicles equipped with correctly aimed midbeams. This might suggest that it is necessary only to increase the intensity of the current low-beam configuration or to change its aim specification or both. However, it is also necessary to examine the effects of discomfort glare during night meeting situations to determine the performance of head-lamp beams.

## Direct Glare Effects of Meeting and High Beams

The computer simulation is a convenient means of determining the glare intensities to which the drivers are exposed. The intensities directed at the driver's eyes from

Figure 4. Simulation visibility distances for low-beam meetings.

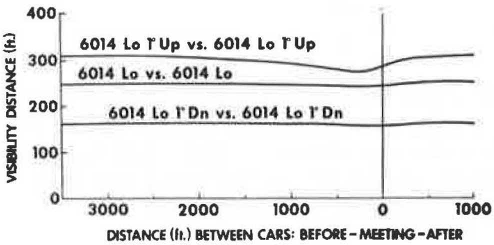



Figure 5. Simulation visibility distances for midbeam meetings.

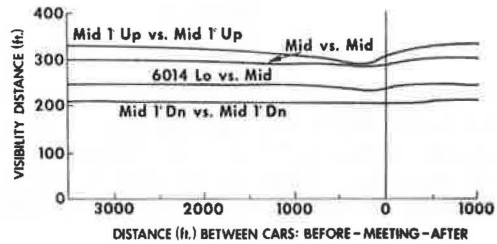



Table 1. Photometric test-point values.

| Test Points (deg) | U.S. 6014 Low Beam (cd) Test | Standard[a] | Experimental Type 3 Beam (cd) |
|---|---|---|---|
| 1 up, 1.5 left | 178 | <700 | 281 |
| 0.5 up, 1.5 left | 333 | <1,000 | 422 |
| 0.5 down, 1.5 left | 1,180 | <2,500 | 722 |
| 1.5 up, 1 right | 412 | <1,400 | 612 |
| 0.5 up, 1.3 right | 1,340 | <2,700 | 11,120 |
| 0.5 down, 1.5 right | 9,000 | 20,000 to 8,000 | 35,760 |
| 1 down, 6 left | 960 | >750 | 631 |
| 1.5 down, 2 right | 26,300 | >15,000 | 28,240 |
| 1.5 down, 9 left | 1,160 | >750 | 766 |
| 1.5 down, 9 right | 3,220 | >750 | 3,256 |
| 4 down, 4 right | 11,830 | <12,500 | 976 |
| 2.5 right, 2 down | 28,000 | | — |
| 4 right, 1 down | — | | |

Note: 1 deg = 0.017 rad.

[a]SAE specification J-579b for low beams.

Table 2. Glare intensity and illumination for low beams, midbeams, and high beams.

| Beam | Aim | Intensity (cd) at Separation Distance 2,400 Ft | 1,200 Ft | 600 Ft | Illumination (ft-c) at Separation Distance 2,400 Ft | 1,200 Ft | 600 Ft |
|---|---|---|---|---|---|---|---|
| 6014 low | Nominal | — | 1 483 | 1 066 | — | 0.001 | 0.003 |
| 6014 low | 1 deg up | — | 4 938 | 3 504 | — | 0.003 | 0.009 |
| Mid | Nominal | — | 2 242 | 1 633 | — | 0.002 | 0.005 |
| Mid | 1 deg up | — | 6 160 | 4 392 | — | 0.004 | 0.012 |
| 6014 high | Nominal | 63 504 | 59 649 | 51 293 | 0.011 | 0.041 | 0.142 |

Note: 1 ft-c = 10.76 lx; 1 ft = 0.3048 m; and 1 deg = 0.017 rad.

Figure 6. Simulation visibility distances for high-beam meetings.

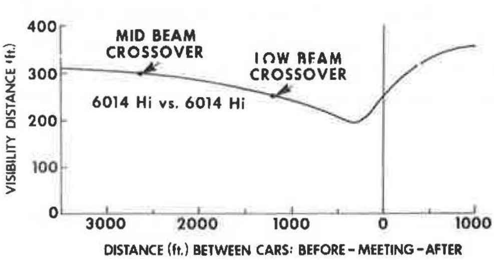



Table 3. Glare intensity and illumination as seen in the interior rearview mirror.

| Beam | Aim | Intensity (cd) | Illumination (ft-c) | Ratio |
|---|---|---|---|---|
| 6014 low | Nominal | 517 | 0.048 | 1.0 |
| 6014 low | 1 deg up | 1 761 | 0.162 | 3.3 |
| Mid | Nominal | 1 158 | 0.107 | 2.2 |
| Mid | 1 deg up | 6 809 | 0.627 | 13.1 |
| 6014 high | Nominal | 18 282 | 1.685 | 35.1 |

Note: 1 ft-c = 10.76 lx; and 1 deg = 0.017 rad.

the opposing vehicle's head lamps are given in Table 2 for selected longitudinal separation distances between the vehicles. For example, in Table 2, at a separation distance of 1,200 ft (366 m), U.S. 6014 low beams provide a glare intensity of 1483 cd at the driver's eyes when the lamps are aimed correctly but 4938 cd when they are aimed 1 deg (0.017 rad) up. Thus, although the visibility was greater in meetings between vehicles whose low beams were aimed 1 deg (0.017 rad) up than when both were aimed to specification, the drivers were exposed to more than 3 times the glare intensities in the former case than in the latter. In meetings between vehicles equipped with correctly aimed midbeams, the glare intensity was 2242 cd at 1,200 ft (366 m), which is 51 percent greater than the glare intensity caused by low beams. However, it is less than half the intensity to which drivers are exposed when meeting a vehicle whose low beams are aimed 1 deg (0.017 rad) up. Therefore, the visibility increase provided by midbeams is obtained with considerably less increase in glare intensity compared to the same visibility increase obtained by aiming the low beams 1 deg (0.017 rad) up. The glare intensity on the driver meeting midbeams aimed up 1 deg (0.017 rad) is only 25 percent greater than meeting low beams aimed up 1 deg (0.017 rad).

Figure 6 shows the computed visibility distances of a target having a 12 percent reflectance and located at the right side of a 2-lane road in meetings between vehicles equipped with U.S. 6014 high beams. The resultant glare intensities, given in Table 2, are far greater than those from low beams or midbeams, aimed correctly or aimed 1 deg (0.017 rad) up. Because the visibility distance curves for high beams cross those for midbeams and low beams (Fig. 6), it is possible to determine the separation distance for switching from high to low beams to maintain maximum visibility. Switching from high beams to low beams should occur at about 1,200 ft (366 m) and from high beams to midbeams at 2,600 ft (792 m).

Another factor that determines switching from high beams is discomfort glare. The Hare and Hemion survey (6) indicates that dimming to low beams from high beams occurs at a mean distance of just over 1,700 ft (518 m), averaged over a number of driving conditions. However, 25 percent of the drivers dimmed their high beams at 2,400 ft (731 m) or more. At this distance, glare illumination is about 0.01 footcandles (0.1076 lx). If this is taken as a criterion for discomfort glare for conditions where the angles between the opposing car's head lamps and the driver's line of sight are small, then a 1-deg (0.017-rad) upward misaim of low beams and midbeams may cause discomfort at about 600 ft (183 m). Further, it can be inferred that high beams, whose maximum intensity is raised to 200 000 cd, will be likely to produce this level of glare illumination at about 4,000 ft (1219 m). Dimming distances for such beams are likely to be increased.

If midbeams replace low beams as meeting beams, the use of higher intensity high beams becomes reasonable because the midbeam visibility curve crosses over the high-beam curve at a separation distance of 1,400 ft (427 m). Thus, switching to midbeams can be done earlier without further loss of visibility and at lower high-beam glare levels.

## Glare From Rearview Mirrors

Another major consideration in developing midbeams is the head-lamp effect on both discomfort and disability glare in rearview mirrors. Preliminary calculations show that, with a following vehicle in the same lane at a distance of 100 ft (30 m), the intensities and illumination values at the driver's eyes from a conventional interior mirror (assuming an interior mirror reflectivity of 0.85 and a rear window transmissivity of 0.88) can be high. Midbeam intensities and illumination values are about double low-beam values for nominal aim of the beam, as given in Table 3. With a 1-deg (0.017-rad) upward misaim, the low-beam values increase by a factor of about 3. Midbeam values at 1 deg (0.017 rad) are about 6 times greater than midbeam values at nominal aim and 13 times greater than low-beam values at nominal aim.

These data show that the aim of midbeams is more critical than that of low beams to avoid discomfort and disability glare to preceding drivers. Glare intensities of head lamps in rearview mirrors can readily exceed those from opposing vehicles (7).

## DISCUSSION

The results of the computer simulation evaluations have shown that midbeams, in meetings with other vehicles, can provide drivers with about 20 percent greater visibility of targets on the right side of the road than do low beams. Midbeams also allow drivers to dim from high beams at greater separation distances, thereby reducing glare and simultaneously retaining better visibility. So, introducing midbeams would make it more feasible to introduce high beams of greater intensity (e.g., 200 000 cd).

Midbeams, when correctly aimed or misaligned 1 deg (0.017 rad) upward, did not increase direct glare levels substantially more than low beams. Correct alignment of midbeams must be maintained, though, particularly to control beam intensities in rear-view mirrors. But, the use of low-reflectance interior and exterior mirrors will reduce this problem (8).

The studies that have been described were limited to those with targets on the right side of the lane. Although this is probably the zone of greatest importance for vehicle control and obstacle detection, the visual task becomes more difficult if the target is on the left of the lane because the disability glare effect will be greater. The visibility and glare performance of the midbeams for other target locations and for roads that have vertical and horizontal curvature must be evaluated.

There is a growing need to better understand the factors that affect discomfort glare from headlights so that modeling of this aspect can be carried out. Analytic methods used to evaluate discomfort glare from fixed luminaires may be partly applicable to the dynamic vehicle meeting case (9).

## REFERENCES


1. Mortimer, R. G., and Olson, P. L. Passenger Car and Truck Headlighting Research: Development of a Field Testing Methodology and Beam Pattern Evaluations. Highway Safety Research Institute, Univ. of Michigan, Rept. UM-HSRI-HF-73-14, 1973.
2. Mortimer, R. G., and Becker, J. M. Passenger Car and Truck Headlighting Research: Development of a Computer Simulation Model to Predict Headlamp Beam Performance. Highway Safety Research Institute, Univ. of Michigan, Rept. UM-HSRI-HF-73-15, 1973.
3. Mortimer, R. G., and Becker, J. M. Computer Simulation to Predict Night Driving Visibility as a Function of Headlamp Beams. Proc. Internat. Drivers' Behavior Res. Assn. Conf., Zurich, 1973.
4. Olson, P. L., and Mortimer, R. G. Passenger Car and Truck Headlighting Research: Investigation of Some Factors Affecting the Aim of Headlamps. Highway Safety Research Institute, Univ. of Michigan, Rept. UM-HSRI-HF-73-13, 1973.
5. Mortimer, R. G., and Becker, J. M. Computer Simulation Evaluation of Visibility Distances Provided by Three Headlamp Systems (C, D, E). Highway Safety Research Institute, Univ. of Michigan, Rept. UM-HSRI-HG-TM-73-3, 1973.
6. Hare, C. T., and Hemion, R. H. Headlamp Beam Usage on U.S. Highways. Southwest Research Institute, Rept. AR-666, 1968.
7. Miller, N. D., and Connolly, P. I. An Evaluation of Glare in Nighttime Driving Caused by Headlights Reflected From Automotive Rearview Mirrors. Donnelly Mirrors, Inc., Holland, Michigan, 1972.
8. Mansour, T. M. Driver Evaluation Study of Rearview Mirror Reflectance Levels. Society of Automotive Engineers, Rept. 710542, 1971.
9. DeBoer, J. B. Public Lighting. Phillips Technical Library, Eindhoven, Netherlands, 1967.

# REFLECTORIZED LICENSE PLATES: DO THEY REDUCE NIGHT REAR-END COLLISIONS?

Charles B. Stoke, Virginia Highway Research Council

In Virginia 100,000 sets of experimental reflectorized and 100,000 sets of control nonreflective 1971 license plates were randomly distributed. Each distribution point in the state received and sold a pro rata number of each type. Plates were distributed evenly throughout each day of the distribution period. Accident data for the vehicles using experimental and control plates were collected for a 12-month period. These data were specifically coded and stored for retrieval by the state police. The reporting format distinguished between the striking vehicle and the vehicle struck. Reflectorized and control comparisons involved statewide data concerning night and daytime accidents. The age of the driver, his or her driving experience, the age of the vehicle, and the weather conditions at the time of the crash were analyzed; accident data were also analyzed. There was no statistically significant difference between the number of night rear-end collisions and crashes of vehicles equipped with reflectorized license plates and those with control nonreflective license plates.

•MANUFACTURERS, researchers, and highway safety enthusiasts, in the United States and abroad, have been interested in reflectorized license plates since at least 1950. The Virginia Highway Research Council has conducted studies on their use. One of these studies, by Stoke and Simpson (1), dealt with legibility and visibility. Field experiments were carried out on an unopened section of Interstate highway, and the plates were attached to the rear of an automobile. The results were similar to those from previous studies (2, 3, 4).

Legislation on reflectorized license plates has been introduced on several occasions in the Virginia General Assembly. The issuance of experimental reflectorized plates was authorized in Va. Code Ann. Sec. 46.1-103.1 (1970). Under this statute 100,000 sets of reflectorized plates and 100,000 sets of control nonreflective plates were issued for research purposes. All plates had black numbers on a white background.

The main question to be answered before adopting the use of reflectorized license plates is whether they provide greater safety by decreasing night rear-end collisions. Several studies have purportedly demonstrated crash reductions attributable to reflectorized plates. A 1959 study (5) conducted in Polk County, Iowa, divided resident vehicle owners into 2 groups: 1 group (60.1 percent of the total) was provided reflectorized plates and the other group (39.9 percent of the total) was given regular steel and enamel plates. The study found that the distributions of night rear-end collisions involving parked cars differed markedly between the 2 groups of plates; 76.7 percent of the struck cars did not have reflectorized plates. But, the Polk County study was deficient in its sampling design because the experimental plates were put on sale first and sold until the supply was exhausted. The possibility exists that persons who purchased their plates early differed in social, psychological, and other demographic characteristics from the later group of purchasers. And, this study did not take into account the number of accidents that occurred in daylight hours or vehicle conditions

Publication of this paper sponsored by Group 3–Operation and Maintenance of Transportation Facilities.

other than parked. It also did not determine whether the accident differences between the 2 groups were statistically significant.

Reflectorized plates were adopted in North Carolina in 1967 with the requirement that they be evaluated for their crash reduction effectiveness. A study on the safety benefits of reflectorized plates was conducted by the Highway Safety Research Center of the University of North Carolina. Researchers studied the occurrences of rear-end collisions for cars with reflectorized plates and those having nonreflective plates during a 6-week grace period when old plates were being replaced. This approach avoided the difficulties of before and after studies, but the design was suspect because a distribution method similar to that of the Polk County study was used and because persons purchasing plates early might have differed in some characteristics from those purchasing late. The authors state, "Circumstances of sample size and unavoidable limitations of study design preclude assertion that the effectiveness of reflectorized plates has been proved in an absolute sense" (6).

## METHODOLOGY

The Virginia study followed a specific method for the distribution of control and experimental license plates for 1971. Data collection and analyses also followed a predetermined format.

### Distribution of Plates

Random distribution of the license plates is important to ensure that the experimental group differed in only 1 measurable respect—reflectorization—from the control group. Random assignment samples the general population. Prior random selection permits the application of statistical logic to assess obtained differences on the experimental variables (rear-end and parked collisions at night) after use of reflectorized plates. A failure to randomize opens the possibility that the experimental and control groups do not represent the same driving population.

The method used by Virginia to distribute 100,000 sets of reflectorized and 100,000 sets of control group 1971 license plates lent itself to statistical analysis. The numbers of reflectorized and control plates sold at each of the distribution points throughout the state in 1971 were prorated for each distribution point by the percentage of plates sold in 1970. For example, a distribution point which had issued 5 percent of the total passenger car license plates during the preceding renewal period received 5 percent of both reflectorized and control plates. During the distribution period from March 15 to April 15 reflectorized and control license plates were sold on a prearranged basis. Neither type was available on request by the purchaser. Equal numbers of both types were sold each day of the renewal period. This method was used to ensure geographical coverage of the entire state, to prevent all the experimental plates from being sold at once, and to ensure everyone an equal opportunity to obtain such plates.

### Data Collection

It was necessary to compare the 1971 accident data of the group that used reflectorized plates with those of the group that used control nonreflective plates on their vehicles to determine whether there was a safety advantage to using reflectorized plates. Rear-end and parked collisions were considered for the safety benefit analysis, because it is in the reduction of these types of accidents that reflectorized license plates are supposed to have their most important benefits.

In determining collision reduction, multivehicle crashes were considered and the reporting scheme distinguished between the striking vehicle and the vehicle struck. Data on the age and experience of the driver, the age of the motor vehicle, weather conditions, and accident data were obtained for both urban and rural locations and were analyzed to determine what role they played in accidents.

The state police furnished computer tapes of accident records to the Virginia Highway Research Council. Enough time was allowed for complete reporting of accidents by individuals and investigating officers and for the processing of the information from the accident report forms by the Division of Motor Vehicles and the state police.

Control and experimental group accident data were obtained to determine whether a safety advantage resulted from the use of reflectorized automobile license plates during nighttime (6:00 p.m. to 6:00 a.m. from October through March, and 9:00 p.m. to 6:00 a.m. from April through September).

Collision data were obtained from 9 state police accident report categories (8). The categories and conditions were as follows for intersection rear-end collisions with both vehicles in the same direction:

1. Both going straight;
2. One turning right, the other going straight;
3. One turning left, the other going straight;
4. One stopped; and
5. All others.

The categories and conditions were as follows for nonintersection rear-end collisions with both vehicles in the same direction:

1. Both going straight;
2. One vehicle parked properly;
3. One vehicle parked improperly; and
4. One vehicle stopped in traffic.

## Data Analyses

Were the reflectorized and control license plate samples comparable groups? Although considerable effort was expended to randomly distribute the plates and thereby have similar groups, the data were tested to determine whether in fact the groups were similar. Statistical tests were applied to the following categories of daytime accidents where crash is any reportable traffic accident and collision is a crash involving 2 or more motor vehicles: crashes by type, collisions by type, age and experience of the drivers involved in the accidents, age of the vehicles involved, and weather conditions when the accidents occurred. Also used were night crashes and collisions (excluding the experimental variables) by type. Data for these analyses were obtained from the state police.

The 50 percent probability test, an extended version of the binomial test for cases in which the known or expected average is 50 percent, is used to compare any 2 things expected to differ from each other only by chance. The test is designed to compare 2 isolated occurrences, such as accidents, if the expected number of occurrences in each sample is the same, such as when both samples have the same duration and are drawn from parent groups of the same size. This test was used to determine whether differences in the number of rear-end collisions of passenger cars with reflectorized license plates and those with control nonreflective license plates occurred by chance.

The conventional way of comparing 2 samples of isolated occurrences is to use the 2-cell chi-square ($X^2$) test with Yates' correction for continuity, but the 50 percent probability test gives identical answers with large samples and more accurate answers with small samples (7). The data required for the 50 percent probability test are

$x$ = number of occurrences in smaller sample,
$y$ = number of occurrences in larger sample, and
$x + y$ = number of occurrences in both samples.

To calculate the value $X^2$, the following formula was used:

$$X^2 = \frac{(|x - y| - 1)^2}{x + y}$$

The critical values of $X^2$ for this test are 3.84 for P.E. < 0.05 and 6.63 for P.E. < 0.01.

If the control license group is not statistically different from the reflectorized license group, we can proceed with the test.

Were there significantly fewer night collisions for vehicles with experimental license plates than for vehicles with control plates? To resolve this question, night data comparisons by collision type, directional analysis, fatal accidents, personal injury accidents (PI), property damage accidents (PD), weather conditions (WC), driver experience (DX), driver age (DA), and vehicle age (VA) were used. The analyses followed this schematic format in making statistical comparisons:

Crashes → Collisions → Rear-End Collisions → 1. Directional Analysis
→ 2. Fatal, PI, PD
→ 3. WC, DX, DA, VA

The standard chi-square test for distribution of data and the 50 percent probability test for sets of data were used to determine whether the collision distributions and individual data sets of the 2 groups differ significantly for accident occurrence or whether the differences could be ascribed to chance. The data for these analyses were furnished by the Virginia state police and contained crash facts for the 1971 license plate year rather than for the 1971 calendar year and were specially developed for this study.

## RESULTS OF ANALYSES

Analyses of the data occurred in 2 stages. First, it was necessary to determine whether the 2 study groups had similar accident experience when reflectorization was not an influencing factor. Then, if the groups were similar, it was necessary to determine the night rear-end and parked collision experience of the 2 groups.

### Are the Experimental and Control Groups Comparable?

In determining the comparability of the 2 study groups, factors representing the influence of the vehicle, the roadway, and the driver on crashes were analyzed. In addition, comparisons were carried out for daytime crashes and collisions and for night crashes and collisions (excluding the experimental variables).

The data given in Tables 1 and 2 include every accident-involved vehicle from the 2 study samples. The data presented in the remainder of this section include only the vehicles involved in the primary collision. The inclusion of all crashes more adequately represents the true picture of vehicle crash involvement. Primary rear-end and parked car collision controls were used for those factors where neither plate type nor other driver, vehicle, or roadway characteristics influence vehicle collision involvement.

Table 1 gives a statistical comparison of daytime and night crashes. The number and distribution of daytime crashes of vehicles equipped with reflectorized license plates were not different from those of vehicles equipped with control nonreflective license plates. In night crashes, these 2 groups (minus rear-end and parked car crashes) also were not statistically different.

Table 2 gives data on the comparisons of daytime and night collisions. The reflectorized and the control license plate groups (again, minus the rear-end and parked car variables for night collisions) did not have a statistically different experience for the total number and distribution of these collisions.

Table 3 gives a summary of chi-square values obtained when the test was applied to the daytime rear-end categories of data. The distribution of daytime rear-end collisions of vehicles equipped with reflectorized plates as influenced by weather, driver, and vehicle variables was not different from the distribution of daytime rear-end collisions of vehicles equipped with control nonreflective license plates. In only 1 category—intersection collisions by vehicle age—were the differences more than chance expectations.

Table 4 gives a summary of the 50 percent probability test results given in Table 5. These are comparisons of individual data sets within each of the distributions of daytime rear-end collisions. Of the total data sets analyzed, 98 daytime sets were not significantly different and 7 daytime sets were significantly different—2 at the 0.01 level and 5 at the 0.05 level. Most were in the vehicle age category. Collision frequency for the 100,000 vehicles with control nonreflective license plates was not different from the collision frequency for the 100,000 vehicles with reflectorized license

**Table 1. Comparisons by crash type.**

| Type | Daytime[a] | | Night[b] | |
|---|---|---|---|---|
| | Reflectorized | Control | Reflectorized | Control |
| With another motor vehicle[c] | 5,447 | 5,401 | 864 | 881 |
| Other noncollision | 13 | 16 | 7 | 5 |
| With fixed object | 80 | 70 | 68 | 75 |
| Overturned in roadway | 14 | 16 | 16 | 24 |
| Ran off roadway | 464 | 478 | 521 | 473 |
| All other and not stated | 124 | 122 | 101 | 83 |
| Total | 6,142 | 6,103 | 1,577 | 1,541 |

[a]Chi-square = 1.727 (not significant at the 0.05 level).
[b]Chi-square = 6.106 (not significant at the 0.05 level).
[c]Rear-end and parked car crashes are not included in the night comparison.

**Table 2. Comparisons by collision type.**

| Type | Daytime[a] | | Night[b] | |
|---|---|---|---|---|
| | Reflectorized | Control | Reflectorized | Control |
| Sideswipe | 1,620 | 1,616 | 392 | 411 |
| Head-on | 591 | 617 | 249 | 245 |
| Rear-end | 1,620 | 1,510 | — | — |
| Parked | 645 | 645 | — | — |
| Not stated and all others | 971 | 1,013 | 223 | 225 |
| Total | 5,447 | 5,401 | 864 | 881 |

[a]Chi-square = 5.113 (not significant at the 0.05 level).
[b]Chi-square = 0.337 (not significant at the 0.05 level).

**Table 3. Chi-square values of daytime collisions.**

| Category | Intersection | | Nonintersection | | Total | |
|---|---|---|---|---|---|---|
| | Chi-Square | Degrees of Freedom | Chi-Square | Degrees of Freedom | Chi-Square | Degrees of Freedom |
| Weather | 5.634 | 5 | 3.206 | 5 | 7.406 | 6 |
| Driver experience | 1.406 | 4 | 5.770 | 4 | 2.792 | 4 |
| Driver age | 2.561 | 9 | 6.447 | 8 | 0.729 | 9 |
| Vehicle age | 17.545[a] | 8 | 14.854 | 8 | 9.896 | 8 |

[a]Significant at 0.05 level.

**Table 4. Summary of 50 percent probability test results for daytime rear-end collisions.**

| Category | Statistically Different | Not Statistically Different | Total |
|---|---|---|---|
| Weather | 2 | 25 | 27 |
| Driving experience | 1 | 17 | 18 |
| Age of driver | 0 | 33 | 33 |
| Age of vehicle | 4 | 23 | 27 |

plates when weather, driver, and vehicle variables were considered.

The overwhelming similarity of these data led to the conclusion that the 2 groups were similar. Having determined this, one could determine whether reflectorization reduced night rear-end collisions.

Are Night Rear-End Collision Results Comparable?

Table 6 gives the 50 percent probability test results for total night rear-end collisions by accident type. Fatal, personal injury, property damage, and total accidents are shown for both study groups. Also included is a calculated number of control nonreflective collisions necessary for statistical significance at the 0.05 level when the number of reflectorized collisions is held constant. Although there were numerical differences between the 2 study groups, these differences were not greater than would be expected because of chance. Therefore, for these categories of night rear-end collisions, it was concluded that automobiles with reflectorized license plates did not have a significantly different collision experience when compared with automobiles with control nonreflective license plates.

Figure 1 shows 50 percent probability test values by accident type. Table 7 gives 50 percent test values for directional analysis. In every night category, there was no statistical difference between the group equipped with reflective license plates and the group equipped with control nonreflective license plates.

For night comparisons by collision type, the data category for parked cars is especially noteworthy because it is the one where the struck vehicle is usually unlighted. Differences for each data set and the distribution of collisions were not greater than could be expected because of chance. Automobiles with reflectorized and control nonreflective license plates did not have a different collision experience for these 2 categories of data as given in the following table where chi-square equals 0.036 (not significant at the 0.05 level):

A Comparison of Night Collisions

| Type | Reflectorized | Control |
|---|---|---|
| Rear-end | 472 | 477 |
| Parked | 416 | 413 |
| Total | 888 | 890 |

Table 8 is a summary of chi-square values obtained for data categories for rear-end collisions. There were no statistical differences from the influences of weather, driver, or vehicle factors on night rear-end collisions. The number of night rear-end collisions of vehicles equipped with reflectorized license plates was not different from the number of night rear-end collisions of vehicles equipped with control nonreflective license plates.

Table 9 gives a summary of the 50 percent probability values for night collisions in Table 10. Vehicles with reflectorized license plates did not have a significantly different night rear-end collision experience than vehicles with control nonreflective license plates.

Figure 2 shows the 50 percent probability test values by directional analysis of night rear-end collisions of the 2 study groups. Vehicles equipped with reflectorized license plates and those with control nonreflective license plates did not have a statistically different rear-end collision experience.

To determine whether reflectorized license plates reduced night rear-end collisions, 4 sets of data were compared. These involved differences in fatal, personal injury, and property damage collisions; rear-end and parked collisions; directional analysis; and driver, vehicle, and weather factors. For all comparisons there were no significant differences between the number of accidents for the reflectorized group and those for the control nonreflective group. It is concluded that the null hypothesis, which states that there is no difference between the reflectorized and control nonreflective groups, cannot be rejected. It is further concluded that the use of reflectorized license plates does not provide a safety advantage by significantly reducing night rear-end collisions.

**Table 5. Fifty percent probability test results for daytime rear-end collisions.**

| Category | Intersection Collision | Non-intersection Collision | Total |
|---|---|---|---|
| Weather | | | |
| Clear | 6.93[a] | 0.18 | 5.56[b] |
| Cloudy | 0.37 | 1.31 | 1.55 |
| Fog | 0.44 | 0.00 | 0.63 |
| Mist | 1.11 | 0.00 | 0.70 |
| Rain | 0.07 | 0.19 | 0.28 |
| Snow | 0.27 | 1.24 | 1.84 |
| Sleet | 0.00 | 0.00 | 0.00 |
| Smoke and dust | — | — | — |
| Not stated | 1.14 | 0.04 | 0.20 |
| Driving experience | | | |
| <3 months | 2.29 | 0.00 | 0.75 |
| 3 to 12 months | 0.32 | 0.00 | 0.26 |
| 1 to 5 years | 0.70 | 0.16 | 0.08 |
| 6 to 10 years | 0.88 | 3.57 | 0.05 |
| >10 years | 3.46 | 0.84 | 4.34[b] |
| Not stated | 0.01 | 0.52 | 0.51 |
| Age of driver, years | | | |
| <16 | 0.00 | — | 0.00 |
| 16 to 17 | 0.12 | 0.00 | 0.01 |
| 18 to 19 | 0.04 | 0.13 | 0.20 |
| 20 to 24 | 2.80 | 1.70 | 0.39 |
| 25 to 34 | 1.63 | 0.14 | 0.71 |
| 35 to 44 | 1.08 | 0.00 | 0.69 |
| 45 to 54 | 0.14 | 1.12 | 0.95 |
| 55 to 64 | 0.14 | 0.61 | 0.67 |
| 65 to 74 | 0.68 | 0.83 | 0.01 |
| >75 | 0.19 | 0.00 | 0.04 |
| Not stated | 0.31 | 0.22 | 0.02 |
| Age of vehicle, years | | | |
| <1 | 6.08[b] | 0.04 | 3.07 |
| 1 | 2.37 | 1.19 | 0.26 |
| 2 | 0.10 | 0.30 | 0.41 |
| 3 | 0.38 | 3.34 | 0.35 |
| 4 | 9.58[a] | 0.37 | 4.13[b] |
| 5 | 0.02 | 5.30[b] | 1.62 |
| 6 to 10 | 0.04 | 2.82 | 0.78 |
| >10 | 0.41 | 0.00 | 0.36 |
| Not stated | 2.04 | 0.10 | 1.88 |

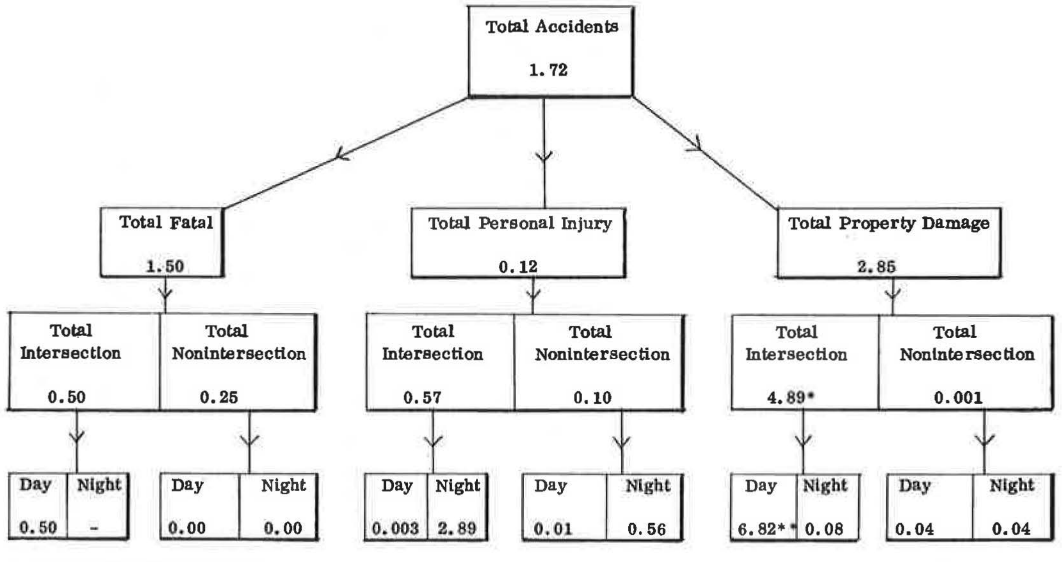
[a]Significant at 0.01 level.
[b]Significant at 0.05 level.

**Table 6. Night rear-end collisions.**

| Category | Reflectorized | Control | 50 Percent Test | Calculated[a] |
|---|---|---|---|---|
| Fatal | 0 | 1 | — | 6 |
| Personal injury | 88 | 98 | 0.44 | 116 |
| Property damage | 387 | 398 | 0.13 | 443 |
| Total | 475 | 497 | 0.45 | 538 |

[a]The number of control collisions necessary for a significant difference at the 0.05 level.

**Figure 1. Fifty percent probability test values by accident type.**




* Significant at the 0.05 level
** Significant at the 0.01 level

**Table 7. Fifty percent probability test values for directional analysis of accidents.**

| Direction | Daytime Fatal | Daytime Personal Injury | Daytime Property Damage | Night Fatal | Night Personal Injury | Night Property Damage |
|---|---|---|---|---|---|---|
| Intersection[a] | | | | | | |
| Both going straight | 0.50 | 0.00 | 0.00 | — | 0.07 | 0.10 |
| One turning right, one straight | — | 0.05 | 3.81 | — | 0.67 | 0.00 |
| One turning left, one straight | — | 1.07 | 0.41 | — | 0.94 | 0.02 |
| One stopped | — | 0.01 | 0.15 | — | 0.31 | 1.19 |
| All others | — | 1.64 | 8.47[b] | — | 0.27 | 0.09 |
| Nonintersection[a] | | | | | | |
| Both going straight | 0.50 | 0.08 | 0.08 | — | 2.78 | 0.07 |
| Parked properly | — | 0.00 | 0.82 | — | 0.03 | 0.21 |
| Parked improperly | — | 0.00 | 0.24 | — | 0.00 | 0.00 |
| One stopped in traffic | 0.00 | 0.00 | 0.002 | 0.00 | 0.00 | 0.00 |

[a]All vehicles are in the same direction.
[b]Significant at the 0.01 level.

**Table 8. Chi-square values of night collisions.**

| Category | Intersection Chi-Square | Intersection Degrees of Freedom | Nonintersection Chi-Square | Nonintersection Degrees of Freedom | Total Chi-Square | Total Degrees of Freedom |
|---|---|---|---|---|---|---|
| Weather conditions | 3.626 | 3 | 1.568 | 3 | 3.269 | 5 |
| Driver experience | 2.318 | 4 | 3.393 | 3 | 0.261 | 4 |
| Driver age | 3.441 | 7 | 5.746 | 6 | 4.585 | 7 |
| Vehicle age | 7.647 | 7 | 14.477 | 8 | 5.260 | 8 |

**Table 9. Summary of 50 percent probability test results for night rear-end collisions.**

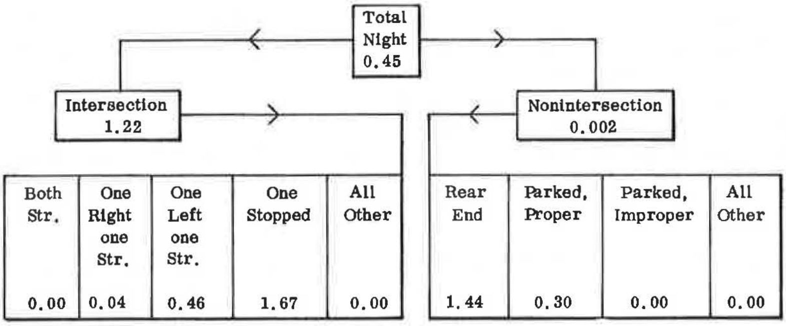
| Category | Statistically Different | Not Statistically Different | Total |
|---|---|---|---|
| Weather | 0 | 27 | 27 |
| Driving experience | 0 | 18 | 18 |
| Age of driver | 0 | 33 | 33 |
| Age of vehicle | 2 | 25 | 27 |

**Table 10. Fifty percent probability test results for night rear-end collisions.**

| Category | Intersection Collision | Non-intersection Collision | Total |
|---|---|---|---|
| Weather | | | |
| Clear | 0.15 | 0.003 | 0.03 |
| Cloudy | 3.74 | 0.00 | 1.69 |
| Fog | 0.00 | 0.36 | 0.64 |
| Mist | 0.56 | 0.27 | 0.00 |
| Rain | 0.02 | 1.73 | 0.60 |
| Snow | — | 0.57 | 0.57 |
| Sleet | 0.00 | 0.00 | 0.00 |
| Smoke and dust | — | 0.00 | 0.00 |
| Not stated | 0.25 | 0.17 | 0.00 |
| Driving experience | | | |
| <3 months | 0.00 | 0.50 | 0.00 |
| 3 to 12 months | 0.00 | 0.00 | 0.00 |
| 1 to 5 years | 0.18 | 0.54 | 0.00 |
| 6 to 10 years | 0.63 | 0.63 | 0.01 |
| >10 years | 1.72 | 1.45 | 0.12 |
| Not stated | 0.00 | 0.49 | 0.37 |
| Age of driver, years | | | |
| <16 | — | — | — |
| 16 to 17 | 0.19 | 0.00 | 0.03 |
| 18 to 19 | 0.52 | 2.12 | 0.02 |
| 20 to 24 | 0.10 | 2.88 | 1.73 |
| 25 to 34 | 1.80 | 0.02 | 0.88 |
| 35 to 44 | 0.35 | 0.41 | 0.00 |
| 45 to 54 | 0.02 | 0.04 | 0.12 |
| 55 to 64 | 0.96 | 0.00 | 0.43 |
| 65 to 74 | 1.50 | 0.00 | 1.78 |
| >75 | — | — | — |
| Not stated | 0.02 | 0.18 | 0.09 |
| Age of vehicle, years | | | |
| <1 | 0.00 | 0.00 | 0.01 |
| 1 | 0.00 | 0.61 | 0.43 |
| 2 | 1.82 | 4.21[a] | 0.37 |
| 3 | 0.57 | 0.79 | 1.56 |
| 4 | 0.02 | 0.00 | 0.01 |
| 5 | 0.31 | 3.21 | 0.72 |
| 6 to 10 | 4.30[a] | 0.18 | 0.83 |
| >10 | 0.13 | 1.56 | 0.38 |
| Not stated | 0.00 | 0.76 | 0.52 |

[a]Significant at 0.05 level.

Figure 2. Fifty percent probability test values by directional analysis.




## INCREASED COST OF REFLECTORIZATION

A recent estimate of the increased costs for reflectorizing license plates has been prepared by the Virginia Division of Motor Vehicles. The increase in costs for the 1974-1975 period is nearly $1.9 million. Virginia is using a multiyear license plate, so the 1976 to 1978 estimate also must be considered. The increase here in costs is over $1.75 million. The 4-year cost increase is over $3.6 million, which represents nearly a 106 percent increase for reflectorizing license plates. A positive benefit-cost ratio does not exist because night collisions have not been reduced for vehicles with reflective plates and the costs to reflectorize plates are high.

## SUMMARY AND CONCLUSIONS

The data and analysis given in Tables 1 through 5 show that the accident experiences of the 2 study groups are comparable in those cases where reflectorization would not play a role in accident reduction. It was concluded that the group of vehicles with reflectorized license plates and the group of vehicles with control nonreflective license plates were statistically similar on vehicle, roadway, and driver characteristics, the total number and distribution of day crashes, the total number and distribution of night crashes (excluding the experimental variables), the total number and distribution of daytime collisions, and the total number and distribution of night collisions (excluding the experimental variables).

After the comparability of the 2 groups was established, analyses were performed to see whether reflectorized license plates reduced night rear-end collisions. Accident type; collision type; directional analysis; and weather, driver, and vehicle factors were analyzed to determine whether night differences occurred. No significant differences were found between the 2 groups. It was concluded that the use of reflectorized license plates did not produce a safety benefit through a statistically significant reduction in night rear-end collisions.

## ACKNOWLEDGMENTS

The author expresses thanks to Jack H. Williams of the Virginia Department of State Police who provided valuable assistance by furnishing computer tapes and data on traffic crashes and who made suggestions for the efficient use of the data contained on the tapes. Thanks are also due Harold R. Sherry of the Virginia Highway Research Council who wrote the computer program for the retrieval of rear-end collision data. Also, researchers from the 3M Company, whose review of an early draft of the report led to the acquisition of additional data, are recognized for their comments on the proposed study methodology.

## REFERENCES

1. Stoke, C. B., and Simpson, C. H., Jr. A Comparison of the Legibility and Visibility of Enamel and Reflectorized 1971 Virginia License Plates. Virginia Highway Research Council, Charlottesville, Dec. 1971.
2. Wortman, R. H. An Evaluation of Reflectorized Annual License Plate Materials. Highway Traffic Safety Center, Urbana, Ill., May 1968.
3. Rumar, K. Reflectorized License Plates. Traffic Engineering and Control, Jan. 1967.
4. Griep, D. J. Reflectorized Registration Plates. Institute for Road Safety Research, Netherlands, 1970.
5. 1959 Motor Vehicle Accident Study: Polk County, Iowa. Cited in Reflective License Plates, 3M Co.
6. Campbell, B. J., and Rouse, W. S. Reflectorized License Plates and Rear-End Collisions at Night. Traffic Safety Research Review, National Safety Council, Vol. 12, No. 2, June 1968.
7. Langley, R. Practical Statistics Simply Explained. Dover Publications, Inc., New York, 1971, p. 255.
8. Crash Facts. Virginia Dept. of State Police, Richmond, 1971.

# DISCUSSION

William L. Sacks, Consultant, Mansfield, Ohio

In his introduction, the author defines the efficacy of reflectorized license plates to depend solely on their ability to reduce night rear-end collisions. To have been fair, he should have acknowledged that reflectorized plates may afford benefits in (a) other safety situations, (b) increased driver comfort at night by aiding the driver in determining the actual vehicle type and position of an oncoming vehicle with one visible headlight, and (c) assistance to night law enforcement efforts.

Furthermore, the author goes to great lengths to ensure an unbiased distribution of reflectorized and control license plates. But he gives no indication that the study groups are indeed representative of statewide accident experience. When I compared overall study group accident experience with that reported in the 1971 issue of Virginia Crash Facts, some differences emerged. First, 62.96 percent of state accident experience occurred during daylight; but, the reflectorized and control groups showed figures of 71.36 percent and 71.51 percent respectively. Second, by conservative estimate, (multiple-vehicle involvements were reduced by 10 percent), the reflectorized and control groups had 7,887 and 7,817 accidents per 100,000 vehicles; statewide, however, the rate was 6,017 accidents per 100,000 registered vehicles. Third, statewide, 71.5 percent of all accidents involved 2 or more vehicles; the figures for the reflectorized and control groups, however, were 82.1 percent and 82.6 percent respectively. These 3 major differences suggest that neither study group truly represented statewide experience and that the results should not be projected.

The discrepancy in the percentage of all accidents that occurred in daylight may be due to the author's use of time periods to define daytime and night involvements rather than encoded illumination data on his source data file. Why this artificial approximation is employed is not explained. However, this approximation for a vital study aspect could have introduced differences in results that could have changed the author's conclusion.

The author cites the capability of his accident reporting system to differentiate between striking and struck vehicles but nowhere in his analysis does he reference or compare such involvements. Table 6, night rear-end collisions, gives greater totals than does the text table on night comparisons by collision type for supposedly the same data. Because Table 6 makes no reference to parked car collisions, the reader is led to believe that this table may be mistitled and, in fact, that it represents the total for struck vehicles in both rear-end and parked car accidents. The analysis should have included a 2-vehicle accident matrix with 4 types of vehicle (reflectorized, control, other Virginia, and all others) and 2 types of involvement (struck and striking). At minimum, the analysis should have pursued the involvement according to light conditions and collision type of study group vehicles as both the striking and struck vehicles.

Review of the study is made difficult by the many tabulations that offer chi-square values rather than actual frequencies. Much of the reader's difficulties could have been avoided had full accident frequency tables for all data subjected to statistical comparison been included.

A major factor weakening the report conclusion is the difference in results presented for daytime and night data. Table 2 shows the reflectorized group to be involved in 1,620 daytime rear-end collisions and the control group in 1,510. Although this difference does not satisfy a 0.05 level test, it comes exceedingly close. In fact, if there had been 1 more daytime rear-end collision in the reflectorized group, the difference would have been significant at better than the 0.05 level. When this is coupled with the night rear-end experience for the 2 groups (472 and 477 involvements for the reflectorized and control groups respectively) it becomes difficult to accept the conclusion that both daytime and night rear-end collision experience are similar for the 2 groups. The data suggest a greater propensity for rear-end collisions in the reflectorized group independent of license plate type. This alone is adequate to invalidate the author's conclusion.

If one accepts the conclusion that there is no significant difference (at the 0.05 level) between the 2 groups in either daytime or night rear-end experience, then one would expect that the numerical difference between daytime and night experience (day minus night) is also statistically insignificant. These differences in day over night experience are 1,148 (1,620 minus 472) and 1,033 (1,510 minus 477) for the reflectorized and control groups respectively. When these are tested by the 50 percent probability test, the resultant chi-square value of 6.06 indicates the differences to be statistically significant at better than the 0.05 level.

Parked car involvements were not included in the previous analysis (although the result would have been the same with a chi-square value of 4.66) because many parked car collisions involve side-to-side or side-to-corner vehicle contacts when the license plate on the parked car is not visible or is of no meaning to the driver, such as in a parking or unparking maneuver or when an out-of-control vehicle sideswipes a parked car.

Other major points that cause me to reject the study conclusion concern

1. The 0.05 statistical significance level used by the author,
2. The discovered differences in accident involvement frequencies, and
3. The difference needed for a break-even investment for reflectorized license plates to be justified solely by night rear-end collision reduction.

Assume an annual extra cost for reflectorized license plates of $0.20 per vehicle. For 100,000 vehicles the total annual investment is $20,000. If an average night rear-end collision has societal costs of $1,850 (computed by weighting U.S. Department of Transportation unit accident severity costs by the severity frequencies offered in Table 6), the required rear-end accident reduction for break-even investment is 11 collisions per year. However, in Table 6 the author calculates a needed difference of 63 rear-end collisions to satisfy a 0.05 significance level. Thus, what the author is really doing through his choice of significance level is demanding that a benefit-cost ratio of 5.7 (63/11) exist before he will acknowledge the value of reflectorized license plates. If a true benefit-cost ratio of, say, 3.0 existed, the author's test would not have the sensitivity to detect the wisdom of the investment.

B. J. Campbell, in his North Carolina work, which is cited by Stoke, cautioned about this sensitivity problem when he wrote

> It would seem in this study a generous significance level is warranted. The consequences of concluding that there is significant improvement when in fact there is not (Type I error) are less serious in a relatively low-cost program such as this. On the other hand, the consequences of concluding

> that the program is ineffective when in fact it *is* effective (Type II error) is more serious. This is because a Type II error could lead to a recommendation that the program be cancelled, thus saving one third million in the state budget; but, this would allow comparable costs to be Incurred in more accidents, death and injury.

Just why the author failed to heed Campbell's advice is not answered in his report.

Attention is now called to the author's quotation from the North Carolina study. As quoted by the author, it reads, "Circumstances of sample size and unavoidable limitations of study design preclude assertion that the effectiveness of reflectorized plates has been proved in an absolute sense." From this quotation it would appear that the North Carolina study recommended against reflectorized plates. However, this is not the case. The full quotation reads as follows:

> While circumstances of sample size and unavoidable limitation of study design preclude assertion that the effectiveness of reflectorized plates has been proved in an absolute sense; nevertheless, we feel that North Carolina is justified in continuing the program since the best evidence indicates that reflectorized license plates can reduce accident costs by an amount that is about twice the added cost of the plates.

In summary, I find it necessary to reject the study conclusion that reflectorized license plates do not reduce night rear-end collisions for the following reasons:

1. The use of arbitrary time periods rather than existing day-night classifications introduces error potential perhaps greater than the real differences being sought;
2. The discovered greater propensity for day rear-end collisions within the reflectorized group was neither recognized nor considered in the analysis; and
3. Statistical test requirements were shown to be far too severe because they precluded finding any economic benefits under a benefit-cost ratio of almost 6 to 1.

R. C. Vanstrum, 3M Company

The author in his acknowledgments states, "... researchers from the 3M Company, whose review of an early draft of the report led to the acquisition of additional data, are recognized for their comments on the proposed study methodology." This might imply 3M's agreement with the actual study methodology and the final report. This is not the case, and the following comments explain why we disagree with the author's methodology and conclusions.

As originally proposed, the study design not only included the 2 study groups, reflective and nonreflective, but also a comparison with the rest of the state. Further, it included a separation of the data into struck and striking car categories. The original study plan that we reviewed was subsequently given up and a more incomplete one substituted.

We studied the rest of the state accident data over the same approximate time period as the study using published state data for 1971 (8). (State data for 1970 and 1972 were also reviewed and the data, reduced to a 100,000-vehicle basis, showed no major trends. Minor adjustments in the figures can be made to convert study vehicle involvements to crashes (a conservative 0.90 factor was used), and the relationship of accident experience for all vehicles to that of passenger cars can be taken into account. [Passenger cars in Virginia account for 83.3 percent vehicle registration and 84.4 percent of vehicle involvement (8).] These adjustments produce greater agreement between study groups and the state data. But, even with the crash data adjusted, the 2 study groups do not agree at all with the rest of the state on a 100,000 vehicle basis. On the average, the study groups are involved in about 28 percent more accidents than for the state as a whole. Other comparisons can be made that show major differences. The question is raised, which data are correct, those of the state of Virginia or those of the license plate study? Is Virginia underreporting total accidents and not correctly reporting subcategories or did the study group statistics get "special treatment"? The type of special treatment given the 2 study groups could decidedly influence the results.

The struck and striking car categories, if they are differentiated in the data at all, are not clearly indicated in the report. In fact, there is virtually no mention of this important consideration except to say, "The reporting format distinguished between the striking vehicle and the vehicle struck." This distinction is not applied to any of the data. In the text table on night comparisons by collision type, the author discusses parked car data especially. It is implied that this table represents struck car data because striking car data or combined data would not directly relate to the effect of reflectorization. In referring to the parked car, the author states, "The data category for parked cars is especially noteworthy because it is the one where the struck vehicle is usually unlighted" (emphasis added). Table 6 is titled night rear-end collisions. According to data we reviewed in an earlier draft, Table 6 contains the struck car data for the entire directional analysis of the study obtained from 9 state police accident report categories, which were described earlier in the paper. Table 6, then, includes struck data for both parked and rear-end collisions although they are not labeled as such. What then is the text table on night comparisons by collision type? If it is struck vehicle only, how does one reconcile the different numbers? If it is struck and striking combined, why is it presented in such a fashion that it implies that it is for struck cars only? If it is struck and striking combined, the author is not justified in making the comparisons which he makes; furthermore, the data do not relate to the questions raised by the study. And, why aren't technical definitions for rear-end accidents used rather than the inconsistent and nontechnical words "parked" and "rear-end"? Most importantly, why doesn't the author clearly label the data?

Another point we objected to in the study methodology was the arbitrary time periods (6:00 p.m. to 6:00 a.m. and 9:00 p.m. to 6:00 a.m.) to describe periods of darkness. Light conditions are encoded in crash reporting data by the state and could have been used. The approximation introduced by using arbitrary time periods introduces over 13 percent error in categorizing accidents by light conditions during the high traffic volume hours of 5:00 to 9:00 p.m., nearly 25 percent error during the hours of 5:00 to 7:00 a.m., and over 10 percent error during the total period of darkness. This is based on an analysis of sunrise and sunset times for 1 locality only (a half hour after sunset to a half hour before sunrise was used for darkness). Even greater variation would be encountered across the entire state. This point alone throws considerable doubt on the accuracy of determining what actually was a day accident or a night accident.

The author provides a number of tables to show that the 2 study groups are identical except for the test variable. In overall statistics they appear quite similar; but, in daytime rear-end accidents in Table 2, a category of special interest to the study, the difference between 1,620 for reflective plates and 1,510 for control lacks only 1 accident to be significant at the 0.05 level. This points to a basic difference between the 2 groups. Table 2 appears to include struck and striking data combined. What about struck car only data? Tables 4 and 5 presumably contain this information although they are not explicitly labeled. They give only the results of the statistical tests. The actual data in the earlier draft show that 7 daytime sets with significant differences in the final report all had reflective plates high. The significant category in Table 3 also has reflective plates high in daytime intersection accidents. Because there is no noticeable visual difference between a reflective plate and a nonreflective plate in the daytime, the idea that a factor other than the license plate visibility was different between the 2 study groups is substantiated. If this different factor exists in the day, what assurance do we have that it does not also exist at night? If the variation was caused, for example, by greater exposure of the reflective plate group in the day producing more daytime rear-end accidents and this same variation was operative at night, then, in the absence of any safety effect from the reflective plate, one would expect more accidents for the reflective plate at night also. This is not the case as given in Table 6 and Table 10, age of vehicle category. The latter contains 2 significant sections (numbers and direction again not noted by the author). The earlier draft reveals they both have reflective plates low with 1 in the 6- to 10-year-old category and the other in the 2-year-old category. The actual numbers show 21 fewer accidents in the 6- to 10-year-old category and 19 fewer in the 2-year-old category. Because they are mutually exclusive they can be added to produce a total of 40 fewer accidents at night for the reflective plate group. This is almost 4 times the accident reduction needed to cost justify the reflective plate program.

Costs can be computed by assigning an additional annual cost of 20 cents (12 cents for initial issue and 8 cents for replacement and other expenses) per vehicle for reflective plates to give a total additional annual cost of \$20,000 for 100,000 vehicles. The cost of a Virginia night rear-end accident can be computed by severity ratios in the appropriate directional categories as given in the state police accident report mentioned previously, by using state and study data coupled with U.S. Department of Transportation accident cost figures. The cost is over \$1,800 for each night rear-end accident. The break-even point for 100,000 vehicles is \$20,000/\$1,800 or approximately 11 fewer accidents. It should be noted that the significance level for rear-end accident reduction in this study is 63 accidents (from Table 6, 538 minus 475) or over 5 times that which cost justifies the program. The "statistical significance" on which the study revolves does not agree with practical significance.

The author adds a brief paragraph on the increased cost of reflectorization. It would have been useful if he had given a full disclosure of actual numbers instead of selected data. For example, it would be germane to indicate that the increased costs of \$3.6 million for 4 years applies to the manufacture of 7,800,000 license plates over this period. These include 3,300,000 annual license plates which the source report indicates have 2.7 times the additional cost for reflectorization as multiyear plates. The additional cost of reflectorization is more accurately represented by the lower cost option, the multiyear plate, which the source report quoted indicates has a 10 cents per plate annual additional cost over a 6-year period. This agrees with the 20 cents additional cost per vehicle.

The author states, "A positive benefit-cost ratio does not exist." It is assumed what was meant was that a benefit-cost ratio of 1 or greater does not exist (the cost-effective break-even point). Nowhere in the data is there justification for this statement. The statistical limitations of the study sample size allow this statement to be considered only at benefit-cost ratios appreciably higher than 1. The author can make no conclusions below a benefit-cost ratio of 3/1 even if the very conservative National Safety Council accident cost figures, which, when combined with severity ratios, show the cost of a 1971 Virginia night rear-end accident to be over \$1,000, are used. (On a 100,000 vehicle, \$1,000 basis, a 20 accident reduction would be needed to equal \$20,000; but there would be no detectable benefit according to the author's criteria of a 63 accident reduction.)

Based on the foregoing, we believe that there are a number of inconsistencies in this study that should prevent anyone objectively reviewing the data from concurring with the author's sweeping generalizations. If anything, a small safety effect from reflective plates does appear in the data. Although small, and one would not expect a large safety effect from a single device of this sort, this safety effect is more than enough to cost justify the program from the safety standpoint alone without considering any other benefits.

## AUTHOR'S CLOSURE

I am indebted to the discussants for reviewing this study. They correctly point out that the study is not explicit on the categories "striking" and "struck" in tabulating the data. I assumed that it would be clear that all data and statistics in the report involved only vehicles that were struck.

I also agree that more definitive titles could have been used for Table 6 and the text table on night comparisons by collision type. The data in Table 6 include both rear-end and parked collisions as defined in the state police accident report, but only for primary collisions—that is, the first vehicle struck. In multiple vehicle collisions, only the vehicle first struck was used for analysis. In the text table on night comparisons by collision type, all experimental and control vehicles involved in a collision were counted and used for the statistical analysis. The significant factor in night multivehicle collisions and night primary collisions is that no differences existed between the 2 groups for the collision experience of the struck vehicles.

Sacks, in his opening remarks, takes exception to the stated purpose of the study. He states that other factors should also be considered. Because the noncollision benefits to which he alludes are without foundation in evaluative research, I chose to investigate whether reflective plates could produce a measurable reduction in night rear-end collisions. The other benefits described by Sacks were not included in the study because this author believed, and still believes, that investigating them would be unlikely to produce quantifiable or meaningful results. On "assisting night law enforcement efforts"—results from a previous report by Stoke and Simpson (1) that studied the legibility distances of reflective and nonreflective license plates showed that the increased legibility distances do not appear to significantly increase the time available to read and record license plate numbers. At a closing speed of 60 mph there is a gain of less than 1/5 second to the rear and 1/3 second for an approaching vehicle. If 2 vehicles are approaching each other at a speed greater than 30 mph, this time is even further reduced.

Sacks calls attention to 1 of the quotes that was used. It was taken from page 40 of the June 1968 Traffic Safety Research Review (6), and was used to show that Campbell and Rouse recognized the limitations of their research and recommended a design similar to the one used for the current study. But, the North Carolina study apparently is viewed differently by its authors and by Sacks about research design, timing of the study (evaluation after initiation), and the encompassing nature of the findings.

Vanstrum, who has been in constant contact with me since the beginning of the study, and at whose suggestion the daytime analysis was added to the study, objects to the use of time periods to delimit periods of light and darkness. (I am not sure why an objection is raised at this time when it was not a concern in June 1972.) Time periods were used because I believed that an investigating officer is rarely able to arrive on the scene of an accident immediately on its occurrence, and therefore he or she cannot reasonably say what the lighting conditions were at the time of the accident. The use of time periods reflects when the accident occurred and not when the investigation of the accident took place.

The discussants made no attempt to account for accidents that occurred during dusk and dawn, and those for which no information was checked. Statewide data including accidents occurring during daylight, dusk, and dawn show that 68.25 percent of the total accident experience involved these categories as opposed to 71.36 percent and 71.51 percent for the study groups.

In his analysis on percent of error using time periods, Vanstrum uses different time periods than were used in the study itself. The point that factors that influence automobiles with reflectorized license plates would also influence automobiles with control nonreflective license plates was overlooked. A 10 percent overcounting of daylight collisions in the study would produce a conservative error in favor of reflectorized license plates. When computations were carried out to modify the data by 10 percent there were no statistical differences for day or night between the 2 study groups.

The mathematical computations and the assumptions made by the discussants warrant comment. First, all data for the study were collected in the normal manner for the state, and it was only when the accident report forms were received by the Virginia Department of State Police that their control or reflectorized status was recorded, thus ensuring unbiased reporting. Second, the study occurred during a registration year, March 15, 1971, through April 15, 1972; the discussants compared these results to 1971 calendar year crash data. Third, the study was concerned only with private passenger vehicles (fleet and commercial vehicles were excluded); Virginia Crash Facts tabulates all passenger vehicle data together. Finally, simply dividing total accidents by registered vehicles assumes that all accidents involved only a single vehicle and that no vehicle was involved in more than 1 accident during the reporting period. The study was based on how many control or reflectorized vehicles were struck; the critiques are concerned with a ratio of total accidents to registered vehicles. There is more than a difference in semantics involved, for the method used by the discussants undercounts accident involvement.

Sacks quotes at length from the North Carolina study in an attempt to show that the current study used too severe a significance level to determine effectiveness. He fails to point out that Campbell's advice (contained in a footnote and referring to his own study) is for studies of "... a small sample and a weak study design..." (6, p. 18). The study under discussion had a large sample and a strong study design; therefore, the advice does not apply. Analyses must set critical statistical limits for the determination of effectiveness. Collision reduction benefits must be real rather than promoted or advertised.

The discussants draw attention to 1 data cell in Table 2, that of daytime rear-end collisions. The report is concerned with night rear-end collision reduction analysis, which includes the parked categories. To have a comparative equivalency during daytime, parked collisions must be combined with rear-end collisions. The computation of the 50 percent probability value for this combined daytime data yields $X^2 = 2.69$, which does not reach the 10 percent level. One additional daytime collision has no effect on the conclusion that there is no difference between the control and experimental groups in cases where reflectorization does not play a role.

The fallacy of treating partial data is exemplified by the head-on collision section of the study. The ratios of the collision figures, although reversed by type of collision for the reflectorized and control groups, are similar for both sets of data. The reflectorized group had fewer daytime but more night head-on collisions, and the control group had fewer daytime but more night rear-end collisions. It is important for the reader to note that in both cases differences in the number of collisions between the reflectorized and control groups were not greater than would be expected by chance. I am not suggesting that this individual cell (Head-On) has more meaning than any other cell; I am showing the pitfalls encountered when individual cells from distributions of data are treated as separate entities. The following are day-night ratio comparisons:

| Collisions | Daytime | | Night | |
|---|---|---|---|---|
| | Number | Percent | Number | Percent |
| Head-On | | | | |
| Reflectorized | 591 | 48.9 | 249 | 50.4 |
| Control | 617 | 51.1 | 245 | 49.6 |
| Rear-End | | | | |
| Reflectorized | 1,620 | 51.8 | 472 | 49.7 |
| Control | 1,510 | 48.2 | 477 | 50.3 |

Vanstrum's comments on the increased costs to reflectorize license plates exemplifies the approach used throughout his discussion of the study. An attempt is made to obscure the report findings by reciting nonessential facts. Cost figures for both painted license plates and for reflectorized license plates were based on identical numerical requirements for the years 1974 to 1978. The issuing of multiyear plates was also included as part of the cost analysis. The Virginia Division of Motor Vehicles estimate of costs (9) for the 4 years under discussion showed painted license plates to have a total cost of $3,415,500 and reflectorized license plates to have a total cost of $7,034,000. Simple arithmetic gives the total increased cost ($3,618,500) for reflectorizing license plates. Vanstrum attempts to decrease the effect of the total increased cost by presenting sheeting costs amortized by single license plate unit costs over a 6-year period. (Virginia does not use and has not proposed to use a 6-year plate.) The use of a pennies per day argument neglects the fact that they accumulate to large sums over time.

In regard to the cost-benefit analysis of a reflectorized license plate program, I computed the average cost of a rear-end accident in 1971 for the state of Virginia to be $907 by using the National Safety Council figures for costs of accidents. According to this figure and the Virginia Division of Motor Vehicles estimated cost for reflectorizing license plates, the needed decrease in passenger vehicle night rear-end collisions must be 1,029 per year for a 2-million passenger-vehicle population. This figure is very different from the discussants' 11 collisions per 100,000 vehicles per year (1,029 versus 220). For all types of crashes in both urban and rural locations, rear-end collisions are the least severe and therefore the least costly accidents (10, 11); head-on collisions are the most costly type of collision in terms of lives lost and injuries suffered.

The discussants have not presented any information that would lead to a conclusion other than that there was no difference in the night rear-end collision experience between the experimental and control groups. The major sales point for reflectorized license plates has been their collision reducing potential, and this purported potential has not been realized. If reflectorization does not reduce night collisions, no other discussion is necessary. Attempting to determine whether the benefits are worth the cost when there are no benefits is a nonsensical exercise.

## REFERENCES

9. Virginia Reflective Safety Plates. Division of Motor Vehicles, Richmond, July 1973.
10. Abramson, P. Accident Evaluation Analysis. Highway Research Record 486, 1974, pp. 33-41.
11. Reinfurt, D. Highway Safety Highlights. Univ. of North Carolina Highway Safety Research Center, Chapel Hill, Vol. 7, No. 11, 1974.

# OBSTACLE VISIBILITY IN RURAL NIGHT DRIVING AS RELATED TO ROAD SURFACE REFLECTIVE QUALITIES

Gabriel Helmers and Kåre Rumar, University of Uppsala, Sweden

Night driving visibility distances were measured in a series of experiments. Road surface was the main independent variable. Two rough and 2 smooth road surfaces with large variations in their retroreflective qualities were used. Reflective qualities were further varied by measuring visibility distances on both dry and wet road surfaces. The size of the obstacles was 0.4 by 0.4 m (1.3 by 1.3 ft). The luminance factor was varied between 2 percent and 26 percent. Visibility distances were obtained in the following full-scale simulated driving situations: (a) low beams without opposing light, (b) low beams opposing low beams, and (c) high beams without opposing light. Safe visibility distances were normally obtained in high-beam situations. Low beams opposing low beams constituted the main safety problem. So, in meeting situations, a low degree of specular reflection (low glare) from the road surface is more important than high retroreflection (high brightness).

• A LARGE number of investigations and discussions on the effects of reflective road surfaces on obstacle visibility at night on illuminated roads have been carried out (3, 4, 5, 6, 13, 14, 15). One finding is that a road surface with a high degree of diffuse reflection has superior visual conditions compared with a road surface with a lower degree of diffuse reflection. In other words, when obstacles are seen as dark silhouettes against a brighter background, an increase of background uniformity and luminance level results in an increase of negative contrast between obstacle and background

Little research, however, has been carried out concerning the effects of reflective road surfaces on roads with no stationary overhead illumination. Rumar (16) reported on field experiments performed on 3 different road surfaces (dry, wet, snow) and compared the results with experiments carried out on different occasions. Frederiksen (6) made an extensive study of the visibility of obstacles in a model situation. Babkov (2) presented some results that indicate that visibility distance to a dark gray obstacle decreases as road surface retroreflection increases. And, Johansson and Rumar (12) reported that a wet road surface does not give silhouette effects to the same extent as does a dry one. Visual conditions in night driving situations on rural roads are quite different from those on roads with overhead illumination. With mobile lighting, the threshold contrast between obstacle and background is usually positive. Silhouette contrasts (negative contrasts) on nonilluminated roads occur only in special situations (12). There are also several variables that interact in a complex way with changing reflective qualities of the road surface. These include the retroreflective luminance of the road surface, the specular reflection of the road surface, the contrast between obstacle and background, and the level of reflected glare from opposing vehicles. Therefore, it is difficult to predict or simulate the effects of changing reflective qualities of the road surface on visibility distance.

## PROBLEM

The purpose of this investigation was to measure rural night driving visibility distances to obstacles on the road as a function of the reflective qualities of the road

Publication of this paper sponsored by Committee on Visibility.

surface. Reflective qualities were divided into retroreflection and specular reflection.

## METHOD

The experiments were carried out on a 2-lane road that had 4 kinds of pavements. The experimental site, shown in Figure 1, was 1 km (3,280 ft) long. Each part of the road covered with 1 pavement was 4.5 m (≈ 15 ft) wide and 500 m (1,640 ft) long. At least 200 m (≈ 650 ft) of each section were completely straight and the rest very slightly curved. Road surfaces and their reflective qualities are given in Table 1.

### Experiments 1 and 2

The experimental setup is shown in Figure 2. A stationary vehicle, A, was situated near the right edge of the road 200 to 300 m (≈ 800 ft) from its end. An obstacle, C, was placed on the left side 0.75 m (2.5 ft) from the front wheel of the stationary vehicle. The obstacle was 0.4 m (1.3 ft) wide and 0.4 m (1.3 ft) high and covered with woolen cloth. Experiment vehicle B approached vehicle A at a speed of 25 km/h (15.5 mph). The lateral position on the lane of vehicle B was identical to that of vehicle A. The vehicle positions and the size of the obstacle were chosen to ensure that the obstacle had an unbroken background of roadway surface.

Four subjects, the driver, and the experiment leader, were seated in vehicle B. The task of the subjects was to press a silent switch as soon as they could see the obstacle. The impulses from the switches were recorded with impulses from a fifth wheel that measured the distance traveled from a fixed starting position. The recorded visibility distances were translated into metres to an accuracy of ±1 m (≈ 3.3 ft). Similar full-scale simulations have been used in earlier studies (10, 11, 17).

The main independent variable was road surface type. To measure effects of interaction between obstacle and background, the luminance factor of the obstacle was varied in 3 steps: 2 percent (black), 7 percent (dark gray), and 26 percent (light gray). The visibility distance was measured both with and without meeting glare from vehicle A's low beams (European continental $H_4$).

A block design was used to adapt the subjects' eyes to the luminance distribution of each pavement. Six trials were made on the same road surface in each block in which the 3 luminance factors of the obstacle and the 2 meeting conditions were rotated. To keep the adaptation level of the subjects constant during each block, the driver reversed the vehicle after each trial and returned to the starting position. The blocks were rotated according to the ABBA principle. As an experimental control, the obstacle was taken away in a number of randomly chosen trials. The experiments were carried out at night in good weather. Two Hella halogen $H_4$ headlights were used on each vehicle. Each headlight was tested by the Swedish Institute for Materials Testing to conform to ECE R 20. The voltage was 13.2 V. The aiming of the dipped headlights was correct and controlled in every road surface condition. The age of the subjects was from 22 to 29 years. Their visual acuity was ≥1.0.

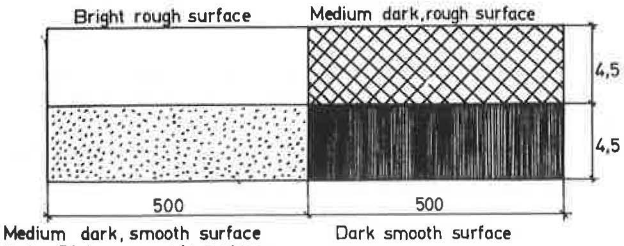
Experiment 1 was carried out under dry road surface conditions. Twenty-four experimental conditions were replicated 4 times. Experiment 2 was a replication of experiment 1 with 2 exceptions: (a) The road surface conditions were wet and (b) 3, rather than 4, replications of experimental conditions were made. Every road surface was flooded with water by a truck equipped with a water tank. The amount of water on the roadway material immediately before each block of 6 trials corresponded to 1 mm (0.04 in.) of heavy rain. The air temperature was 5 C (41 F). Evaporation was low.

### Experiment 3

The purpose of the third experiment was to measure the visibility distances for high beams as a function of road surface and to measure the changes in visibility distance for low beams as a function of the distance to a meeting vehicle, B.

The method used was different from that of experiments 1 and 2. The luminance factor of the obstacle was constant (7 percent, dark gray). Three obstacles were used at the same time on each road surface. The positions of these obstacles, as shown in

**Figure 1. Position and size of the 4 experimental road surfaces.**

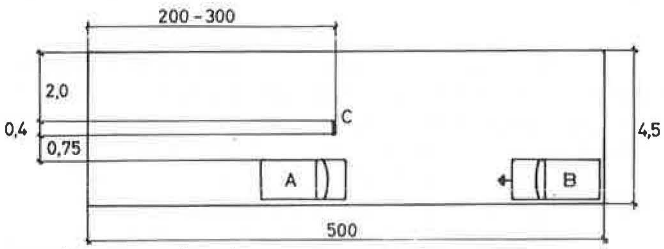



Note: Distances are in metres.

**Table 1. Retroreflection and specular reflection of the 4 experimental road surfaces.**

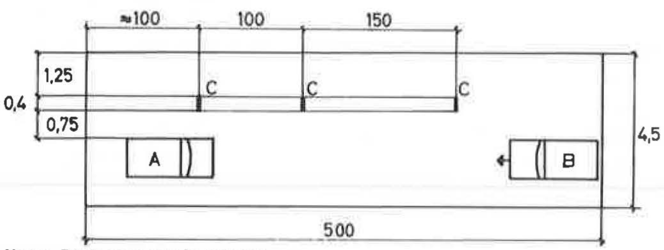
| | Dry | | Wet | |
|---|---|---|---|---|
| Road Surface | Retro-reflection (mcd/m²/lx) | Specular Reflection (mcd/m²/lx) | Retro-reflection (mcd/m²/lx) | Specular Reflection (mcd/m²/lx) |
| Dark, smooth surface (asphalt Ab 8 t) | ≈3 | ≈400 | ≈0.6 | >20 000 |
| Medium dark, smooth surface (asphalt Ab 8 t + Viasole) | ≈15 | ≈550 | ≈1.6 | >20 000 |
| Medium dark, rough surface (diabase Y3) | ≈13 | ≈3 | ≈4 | ≈7 |
| Bright, rough surface (Synopal Y3) | ≈60 | ≈8 | ≈55 | ≈13 |

**Figure 2. Setup for experiments 1 and 2.**




Note: Distances are in metres.

**Figure 3. Setup for experiment 3.**




Note: Distances are in metres.

Figure 3, were 1.25 m (≈ 4 ft) from the left edge of the road at distances of 0, 100, and 250 m (0, ≈ 330, and ≈ 820 ft) in front of the stationary vehicle, A. The lateral distance between vehicle A and the obstacles was identical to the lateral distance in experiments 1 and 2—0.75 m (≈ 2.5 ft). Because the obstacles were positioned near the edges of the 4 roads the top of the obstacle was not always seen against a road surface background. Roadway materials were rotated according to the ABBA principle. The adaptation level of the subjects' eyes was not kept under the same degree of control as in experiments 1 and 2. Three headlight conditions were tested: high beams and low beams without opposing light and low beams opposing low beams. The speed of the experiment vehicle was 50 km/h (31 mph). [The visibility distances presented were corrected for a reaction time of 0.4 s (9)]. And, 4 replications were made for all conditions—2 replications with dry road surfaces and 2 replications with wet road surfaces.

Two independent series of measurements of the reflection qualities of the road surface materials have been carried out. The first was carried out by the National Swedish Road Research Institute. The geometry of each measurement situation, shown in Figure 4, was described by E. Persson in a private communication.

The instrument used was specially constructed for measurements of the retroreflection and specular reflection of road surface materials. In the second series, retroreflection was measured with a Pritchard telephotometer. This series was carried out in full scale using the normal high beams of the vehicle as a light source. The road surface was measured at 25 and 50 m (82 and 164 ft) in front of the vehicle under dry road conditions and at 32.5 m (107 ft) under wet road conditions. The illumination at each point was controlled to be constant. The height of the headlights was 0.75 m (≈ 2.5 ft) and the height of the telephotometer was 1.30 m (≈ 4.3 ft), or normal driver eye height.

A comparison between the results of the 2 measurement series showed consistency for rough road surface conditions. The special instrument, according to E. Persson, tended to give values of retroreflection on surfaces with a high specular reflection that were too high, so the measurement values of Synopal (in $mcd/m^2/lx$) were used as a base to translate the measurement values of the Pritchard telephotometer to $mcd/m^2/lx$. Thus, all specular reflection values given in Table 1 and the retroreflection values of Synopal were obtained with the special instrument. The retroreflection values (means of 4 measurements on dry roads and 2 on wet roads) of the other surfaces came from the Pritchard telephotometer measurements.

## RESULTS OF EXPERIMENTS 1 AND 2

The results were based on group means because the individual results showed the same tendencies and the medians did not depart systematically from the means.

The group means of the 2 meeting and weather conditions were plotted against the retroreflection of the road surface as shown in Figures 5 through 8. The sensitivity of the eye is considered to be logarithmic, so retroreflection was presented along a log scale axis.

Analyses of variance were carried out on each of the 4 road surfaces. The following significant differences refer to those analyses.

Figures 5 and 6 show visibility distances for low beams without opposing light as related to the retroreflection of the road surface. Significant differences in visibility distance existed for both obstacle luminance and road surface retroreflection. In 3 out of 4 cases the interaction between these parameters is significant.

The visibility distances were longest to the light gray and the dark gray obstacles on the road surface with the lowest retroreflection. But, on a dry road, the black obstacle was detected at the farthest distance on the road surface with the highest retroreflection. On a wet road, visibility of the black object seemed to be as dependent on variation in the specular reflection as on variation in the retroreflection of the road surface. These results suggest that the visibility distance with low beams without opposing light depends to a high degree on the luminance contrast between the obstacle and the background (the road surface). Differences in visibility distances between dry and wet road surfaces could not be interpreted because the data were obtained in 2 different experiments and therefore were not directly comparable.

**Figure 4.** Geometrics of the special equipment for measuring reflection.

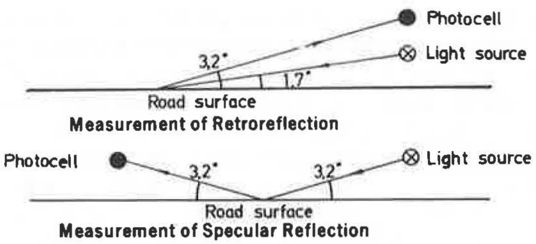



**Figure 5.** Mean visibility distances for low beams without opposing light on dry roads as a function of road surface retroreflection.

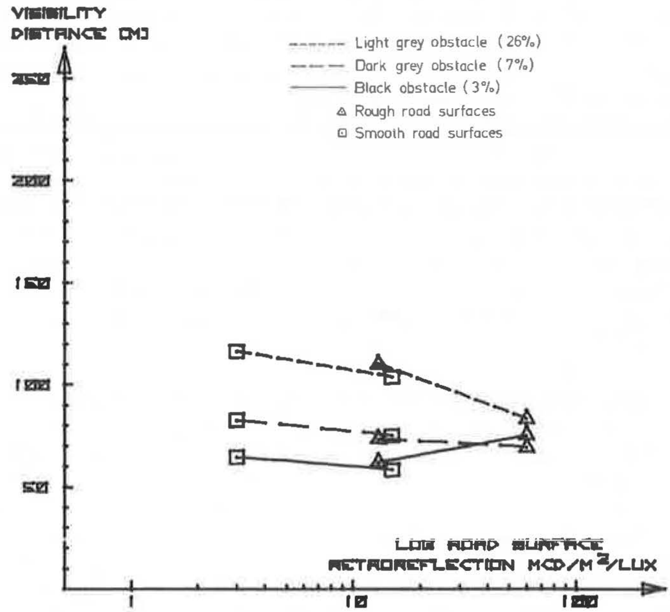



**Figure 6.** Mean visibility distances for low beams without opposing light on wet roads as a function of road surface retroreflection.

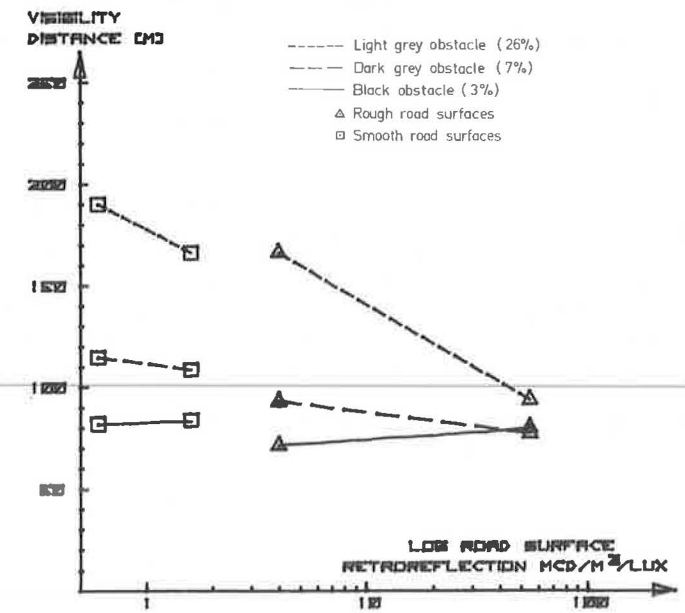


**Figure 7. Mean visibility distances for low beams opposing low beams on dry roads as a function of road surface retroreflection.**

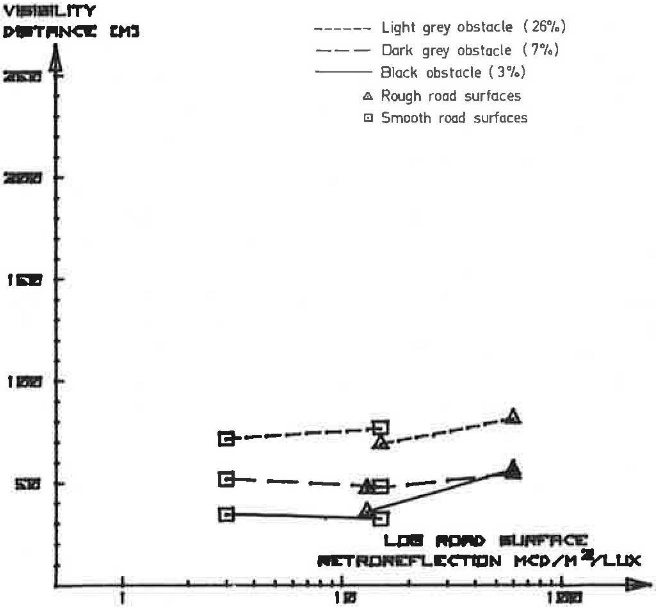
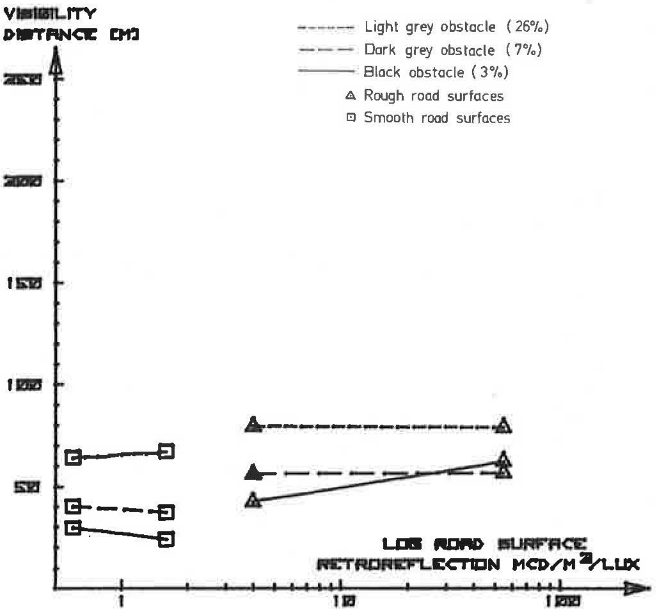



**Figure 8. Mean visibility distances for low beams opposing low beams on wet roads as a function of road surface retroreflection.**



Figures 7 and 8 show visibility distances for low beams opposing low beams as related to the retroreflection of the road surface. This situation is most important for traffic safety on rural roads at night. The dependence of visibility distance on road surface retroreflection was not so pronounced (although it was significant for the rough surfaces) in this situation as in the situation without opposing light. The visibility distance to the black obstacle showed a strong dependence on the retroreflection of the road surface. The dark and light gray obstacles, though, had visibility distances that were relatively constant despite variation in road surface retroreflection. On wet roads the visibility distance to the dark and the light gray obstacles seemed to depend more on specular reflection than on retroreflection of the road surface. These results suggest that, except for the black obstacle, the visibility distance for low beams opposing low beams depends mainly on the luminance factor of the obstacle and is relatively independent of the road surface retroreflection.

Figures 5 through 8 show visibility distances for low beams with and without opposing low beams as related to the specular reflection of the road surface. In comparing the visibility distances of the rough and smooth road surfaces that are most alike in the retroreflection variable, the effect of large differences in specular reflection can be studied. Especially on wet roads, the effect of specular reflection seemed to be pronounced as shown in Figures 6 and 8. Figure 6 shows that a high degree of specular reflection made the visibility distance longer when there was no opposing light. But, with opposing light as shown in Figure 8, a high degree of specular reflection decreased the visibility distance considerably. In this situation the decrease of visibility distance was about 15 percent for the light gray obstacle and 45 percent for the black obstacle when compared to the visibility distances obtained on the road surface with a low degree of specular reflection. On wet roads, significant differences were obtained for specular reflection.

## RESULTS OF EXPERIMENT 3

Because the rankings between the road surface conditions were the same for the 2 experiment nights, the mean visibility distances were computed for all the data. The mean visibility distances to dark gray obstacles for low and high beams without opposing light are shown in Figures 9 and 10. The relationship between visibility distance and road surface reflection was much the same for both headlight conditions. Results were also consistent with the results from experiments 1 and 2. With only 1 exception in all 3 experiments, a smooth road surface resulted in longer visibility distances to a dark gray obstacle than did a rough road surface. Visibility distances decreased as road surface retroreflection increased.

Visibility distance, as related to the reflection qualities of the road surface, decreases as the distance between 2 vehicles in a meeting situation decreases. In Figures 11 and 12 the mean visibility distance to a dark gray obstacle for dry and wet roads is related to the distance between vehicles A and B.

Differences between smooth and rough road surfaces in dry and wet conditions were tested by analysis of variance. On dry roads the decrease in visibility distance as a function of decrease in distance between the vehicles was significant but independent of the texture of the road surfaces (specular reflection). On the other hand, on wet roads, the significant decrease in visibility distance depended on the specular reflection of the road surface and on an interaction between specular reflection of the road surface and the distance between the vehicles.

Visibility distance decreases to a much greater extent on a wet, smooth road than on a wet, rough one because of large differences in the amount of specular glaring light from wet, smooth roads compared with the amount from wet, rough roads.

## DISCUSSION AND CONCLUSIONS

From a safety point of view, some traffic situations are more serious than others. In night driving on rural roads, the low beam opposing low beam situation is the most important because of severely limited visibility. When the driver is alone on the road, high beams should be used to create visibility conditions as favorable as possible. The low beam without opposing low beam situation also was studied to separate the

**Figure 9. Mean visibility distances for low and high beams without opposing light on dry roads as a function of road surface retroreflection.**

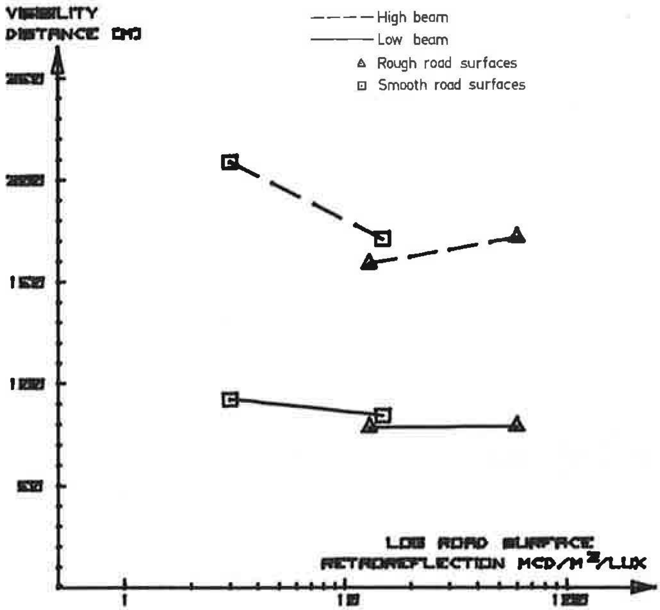



**Figure 10. Mean visibility distances for low and high beams without opposing light on wet roads as a function of road surface retroreflection.**

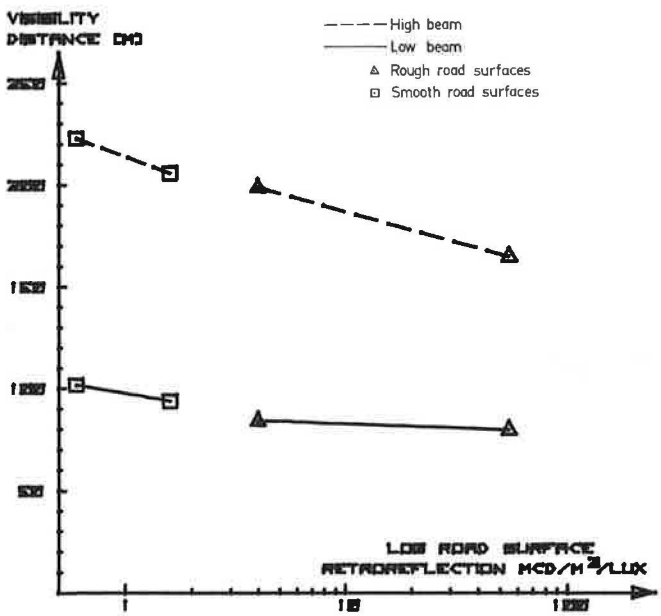


**Figure 11. Mean visibility distances for low beams opposing low beams on dry roads as a function of distance between vehicles.**

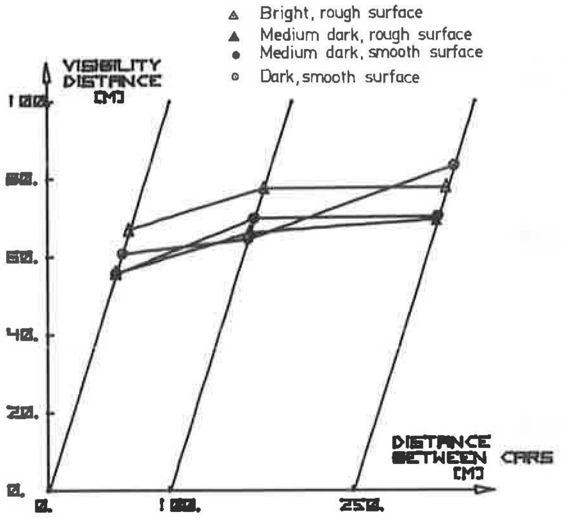
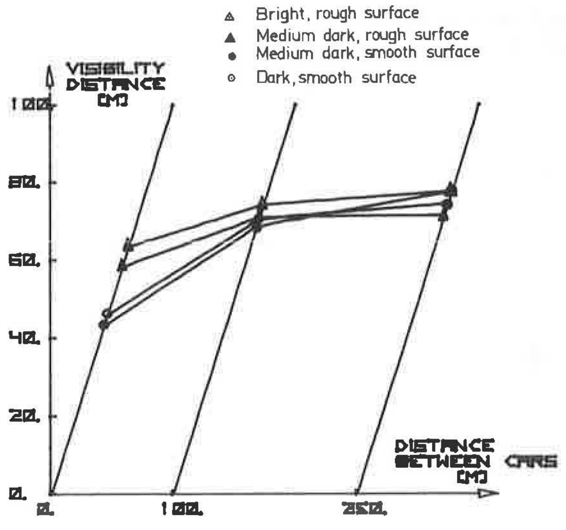



**Figure 12. Mean visibility distances for low beams opposing low beams on wet roads as a function of distance between vehicles.**



effect of glare in the meeting situation. But, conclusions about safety should be drawn from the data obtained in the 2 former situations.

The meeting situation used in these experiments resulted in shorter visibility distances to an obstacle than normal situations in which the stationary vehicle is placed in the adjacent (opposite) lane. Rumar et al. (17) have shown that the decrease of the visibility distance to an obstacle with a luminance factor of 10 percent is about 25 percent when the opposing vehicle is moved from the adjacent lane to the same lane as the car. Judging from the isolux diagrams presented by Rumar et al. (17), the main part of the difference in visibility distance seems to be caused by the decrease in visual angle between the obstacle and the glaring light source (the opposing headlights). A slight increase of light also falls into the subjects' eyes.

Obviously the experimental meeting situation used here is more glaring than the normal meeting situations on the road. In the experimental situation the lateral distances between the obstacle and the 2 opposing headlights were about 1.25 and 2.50 m (4.1 and 8.2 ft) respectively. The corresponding distances in normal car meeting situations are about 4 and 5.5 m ($\approx$ 13 and $\approx$ 18 ft). According to the Holladay formula for veiling luminance ($L_{ekv}$) as presented by Adrian et al. (1), the glare level in the experimental situation would be equivalent to an increase of about 10 times the headlight glare in normal car meeting situations. This corresponds largely to an upward headlight misaiming of about 0.017 rad (1 deg). The purpose of these glare calculations is to give a rough estimate, and the Holladay formula is only one of several ways to calculate veiling glare (8).

The road surfaces used are only representative for new pavement. The rough surfaces were very rough and therefore extreme in their specular reflection qualities. This was a great advantage experimentally, but it makes quantitative generalizations of the results to pavings of less extreme specular characteristics (for example, old rough pavings) difficult.

Because of the very limited width of each experimental road surface—4.5 m ($\approx$15) ft)—the car meeting situation was also extreme. Therefore, generalizations of the results to situations with less glare must be done with care.

The low obstacles that were used in this investigation were chosen to ensure that the road surface was the only background to maximize the visibility effects of the reflective qualities of the road surface. So, visibility distances to taller obstacles are probably less dependent on the reflective qualities of the road surface.

Because knowledge of this area is incomplete, this investigation was, by necessity, exploratory. Further experiments should be made in which road surface reflection parameters and the glare parameter could be varied.

The data obtained were surprisingly consistent. The severe effects of specular glare on the visibility distance in meeting situations on smooth, wet roads were clearly shown. The increase of the visibility distance for high and low beams without opposing glare on smooth, wet roads compared with rough roads was not important because high-beam visibility is generally good enough not to cause severe safety problems (10). These conclusions agree with recent British results that show that night driving accidents on wet roads are overrepresented in road accidents statistics (18).

The results of these experiments agree with those of Rumar (16) and Babkov (2) and also with some of the results published by Frederiksen (7). Rumar (16) showed that a black obstacle had better visibility than a dark gray obstacle on a snowy (very bright) road. Rumar also reported decreased visibility on bright roads and increased visibility on wet roads in conditions without opposing light. Babkov (2) presented results that showed that the visibility distance to a dark gray obstacle decreases as the luminance factor of the road surface increases. One of the results that agrees with the results of Frederiksen (7) is that the difference in visibility distance between bright and dark obstacles decreases with increasing road surface retroreflection. Frederiksen's main results—that the visibility distance to dark obstacles increases as road surface retroreflection increases—is reproduced here only for the black obstacle when road surface retroreflection is varied from medium to high values.

It should be noted also that very bright pavings might constitute a problem, for example, in bright sunshine.

The following conclusions on low-beam visibility distance to obstacles on the road can be drawn:

1. Visibility distance to black objects is longest on road surfaces, such as Synopal, that have very high retroreflection;
2. Except for black obstacles on very bright roads, obstacle visibility is directly dependent on the luminance factor of the obstacle;
3. Visibility distance to obstacles with a luminance factor larger than 5 percent is independent of road surface retroreflection for low beams opposing low beams;
4. Visibility distance on wet road surfaces with opposing vehicles depends more on the roughness of the road surface than on its retroreflection;
5. The decrease in visibility distance on wet road surfaces as a function of distance between 2 opposing vehicles is much less on rough than on smooth pavement; and
6. In low- and high-beam situations without opposing light the visibility distance to a dark gray obstacle increases as retroreflection of the road surface decreases.

Both obstacle visibility distance and road visibility distance (visual guidance) constitute the main safety factors of the road at night. In this investigation, only obstacle visibility distance has been studied systematically in relation to the road surface. The results indicate that in the critical situations rough road surfaces are superior to smooth ones. The same conclusions based on measurements of reflective qualities can be drawn on visual guidance of the road surface. Good visual guidance might also be obtained on dark road surfaces by good retroreflective delineations.

Retroreflection of the road surface is of minor importance for obstacle visibility. However, because of silhouette effects, a bright and rough road surface should be best in critical situations on rural roads at night (12). From a visual guidance point of view, the superiority of bright and rough pavings is evident.

## REFERENCES

1. Adrian, W., Hartman, E., Jainski, P., Pahl, A., and Pfeffer, K. A. Blendung durch Strassenbeleuchtung. Lichttechnik, No. 1, 1968, pp. 1A-5A.
2. Babkov, V. F. The Road in Relation to Traffic Requirements. Report at the 14th World Congress of PIARC, Prague, Czechoslovakia, 1971, pp. 37-39.
3. Blackwell, H. R., Schwab, R. N., and Pritchard, B. S. Visibility and Illumination Variables in Roadway Visual Tasks. Illuminating Engineering, Vol. 59, No. 5, 1964, pp. 277-308.
4. de Boer, J. B., and Vermeulen, J. Simple Luminance Calculations Based on Road Surface Classification P-67.14. International Commission on Illumination (CIE), Washington, D.C., 1967.
5. de Boer, J. B., and Westerman, H. O. Die unterschiedung von Strassenbelägen nach Reflexionskennwerten und deren Bedeutung für die Strassenbeleuchtung. Lichttechnik, Vol. 16, No. 10, 1964, pp. 487-492.
6. Frederiksen, E. An Investigation About Visual Conditions in Nightime Driving on Roads Without Stationary Overhead Illumination. Lysteknisk Laboratorium, Lyngby, Denmark, 1969, 107 pp.
7. Frederiksen, E. Road Illumination and Road Surface. Elektroteknikern, Vol. 2, 1969, pp. 31-40.
8. Frederiksen, E., and Jørgensen, N. O. Glare on Motorways. Rådet før Trafiksikkerhetsforskning, Copenhagen, Rept. 12, 1972, 73 pp.
9. Johansson, G., and Ottander, C. Recovery Time After Glare. Scandinavian Journal of Psychology, Vol. 5, 1964, pp. 17-25.
10. Johansson, G., and Rumar, K. Visible Distances and Safe Approach Speed for Night Driving. Ergonomics, Vol. 11, No. 3, 1968, pp. 275-282.
11. Johansson, G., and Rumar, K. A New Polarized Headlight System. Lighting Research and Technology, Vol 2, No. 1, 1970, pp. 28-32.
12. Johansson, G., and Rumar, K. Silhouette Effects in Night Driving. Scandinavian Journal of Psychology, Vol. 12, 1971, pp. 80-89.

13. Kebschull, W. Leuchtdichtverhältnisse auf feuchten Strassen. Lichttechnik, Vol. 18, No. 9, pp. 109A-114A.
14. Knudsen, B. Bright or Dark Road Surfaces. Dansk Vejtidskrift, Vol. 11, 1968, pp. 205-216.
15. Roch, J., and Smiatek, G. Gesetzmässigkeiten der Lichtreflexion an Strassendecken. Siemens, Vol. 42, No. 7, 1968, pp. 513-520.
16. Rumar, K. Visible Distances in Night Driving: Effect of Various Reflectance Qualities of Road and Object. Department of Psychology, University of Uppsala, Sweden, Rept. 44, 1967, 13 pp.
17. Rumar, K., Helmers, G., and Thorell, M. Obstacle Visibility With European Halogen $H_4$ and American Sealed Beam Headlights. Department of Psychology, University of Uppsala, Sweden, Rept. 133, 1973, 44 pp.
18. Sabey, B. E. Road Accidents in Darkness. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 536, 1973, 22 pp.

# SPONSORSHIP OF THIS RECORD

GROUP 3—OPERATION AND MAINTENANCE OF TRANSPORTATION FACILITIES
Lloyd G. Byrd, Byrd, Tallamy, MacDonald, and Lewis, chairman

Committee on Visibility
Albert Burg, University of California, Los Angeles, chairman
R. Clarke Bennett, Alex J. Castro, Paul L. Connolly, Charles W. Craig, Cazamer L. Crouch, Archibald C. Doty, Warren H. Edman, T. W. Forbes, J. Stuart Franklin, Anthony J. Gioia, S. A. Heenan, Robert L. Henderson, Charles H. Kaehn, Antanas Ketvirtis, Lee Ellis King, W. L. Lammers, Ralph R. Lau, George E. Meese, Nathaniel H. Pulling, Richard N. Schwab, Richard E. Stark, Arthur L. Straub, Ray P. Teele, Frederick E. Vanosdall, Ned E. Walton, Earl C. Williams, Jr., William L. Williams, Henry L. Woltman

K. B. Johns and James K. Williams, Transportation Research Board staff

Sponsorship is indicated by a footnote on the first page of each report. The organizational units and the chairmen and members are as of December 31, 1973.