DRIVER VISUAL NEEDS IN NIGHT DRIVING

Proceedings of a symposium conducted by the Transportation Research Board, September 4-6, 1974, at The Ohio State University, and sponsored by the board, Illuminating Engineering Research Institute, Ohio State University, and Ohio Department of Transportation.

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The members of the committee selected to organize the conference and to supervise the preparation of this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project.

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FOREWORD

The papers and discussions in this Special Report were prepared for and delivered at the Symposium on Driver Visual Needs in Night Driving in Columbus, Ohio, September 4-6, 1974. Sponsored by the TRB Committee on Visibility, the meeting was held in cooperation with The Ohio State University, the Illuminating Engineering Research Institute, and the Ohio Department of Transportation. Its purpose was to focus attention on current research related to driver visual needs in night driving and to discuss ways to implement the findings of such research. Researchers and practitioners in the fields of fixed lighting for streets and roads, vehicle headlighting, and driver vision requirements should find this material useful.

Having studied visibility and illumination on the roadway at night for several years, Blackwell and Blackwell summarize the progress of their research and outline their planned approach to finally arriving at data useful in the practical problems of roadway lighting. The researchers have obtained many values of effective visibility levels for several lighting configurations, two pavement types, and different target reflectances, but conclude that more data must be obtained before they can determine whether there is a luminaire configuration that gives optimal effective visibility levels.

In a laboratory setting, Rinalducci and Beare studied the losses in visibility caused by transient adaptation at low luminance levels. The measured losses are related to time and distance for different vehicle speeds and appear to be more critical as speed increases.

Farber and Bhise present and explain a set of figures developed to show the goals, methods, and status of Ford Motor Company's head lamp evaluation research program. The purpose of the program is to develop a model to evaluate candidate headlight systems in terms of driver visual performance at night. The parameters for human vision capability are based on laboratory studies and need to be validated by field research.

In a real-world street driving situation, Gallagher and Meguire measured the time required for test drivers to perceive targets in the traffic lanes under differing illumination levels and uniformities. Among the conclusions drawn was that, for simple targets, pure contrast ratio is a good predictor of driver visibility.

The work reported by Rockwell and Rackoff was undertaken to develop a reliable, quantitative technique for quickly evaluating effects of illumination design changes on accidents at rural sites with high nighttime accident rates. The studies suggested that the evaluation technique using the eye-marker system could help to identify problem sites and to determine methods of applying illumination to improve driver performance. Corrective actions in signing and marking, as well as in lighting, were also possible.

Mortimer collected field data by using vehicles equipped with varying headlighting configurations to validate a computer simulation model designed to study effects of variables on visibility distances and glare effects. Such things as headlight aim, U.S. versus European low beams, mid beams, glare in rearview mirrors, and others can be studied with the model with reasonable assurance of valid conclusions.

Henderson and Burg examined the literature and made a systematic examination of driving tasks to devise tests for those visual parameters determined to be important to driving. After the tests were devised, they were evaluated by comparing test results with the past accident involvement of those tested. The authors report that there is no clear evidence of a relationship between poor night vision performance and high accident probability. Inadequacy of accident reports contributes greatly to this lack.

Lighting research at the British Transport and Road Research Laboratory is described by Irving and Yerrell. They address relationships between roadway lighting and accidents and also look at conflicts as an indicator of improvement. Photometric studies on all types of road surfaces, wet and dry, are being made to suggest improvements in driving at night on wet roads. A number of vehicle headlighting systems are being studied to determine glare reduction techniques.

A technique for determining visual information needs of drivers at the positional, situational, and navigational performance levels is presented by Walton. The basis for a street lighting design procedure that rationally and effectively satisfies driver visual needs is then suggested.

The papers were reviewed in advance by Baker, Oyler, Stark, and Schwab, who discuss the papers and offer suggestions for implementing the research results reported.

The visibility of objects on the roadway at night has been studied under different conditions of fixed lighting and pavement reflectance in a 15:1-scale model of a divided urban freeway. Visibility was measured in accordance with the quantitative methods described by the International Commission on Illumination, involving psychophysical measurements of equivalent contrast and physical measurements of disability glare and luminance. Initially, three realistic targets were studied at 20-ft (6.1-m) intervals throughout the luminaire cycle down the center of each of eight lanes, under six layouts of model luminaires. Average results indicated that visibility did not increase so much with increases in illuminance as was expected. Also, when the spacing of luminaires was wide, variability in visibility was great. These results were attributed to an anticamouflage effect of roadway luminance nonuniformities. Subsequent research with identical targets of different reflectances confirmed this and indicated that the visibility potential of different pavements and lighting systems should be based on visibility measures of targets of the normal reflectances weighted in proportion to the frequency of their occurrence. The quantity of data needed for this purpose implies need for a physical correlate of target visibility. Target visibility can be predicted reasonably well from roadway luminance and the arithmetic average of the local contrasts of different parts of a target with adjacent portions of the roadway background. It now seems possible to compute indexes of visibility potential for different roadway environments. Further work is needed to assess transient adaptational effects and individual differences in visibility threshold.

NIGHT VISIBILITY UNDER DIFFERENT SYSTEMS OF FIXED ROADWAY LIGHTING: A PROGRESS REPORT

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At the Institute for Research in Vision (IRV), a 1:15 highway visibility simulator was developed (1) and used (2) to study visibility with a special meter known as the Blackwell visual task evaluator (3). Because these data are difficult to interpret in terms of practical recommendations for the design and evaluation of different systems of fixed roadway lighting, the project was continued in the hope of obtaining data of greater practical value. The report represents considerable progress in the direction of practical information.

ASSESSMENTS OF VISIBILITY AND VISUAL PERFORMANCE

The relations between visibility or visual performance and illumination were clarified by the publication of Report 19 (4) of the International Commission on Illumination (CIE). The methods outlined in that report have been used throughout this program. The central ideas are described briefly below.

Visibility of an object varies between bare detection and easy recognition, and illumination is one variable influencing visibility. What is needed is a quantitative metric for describing visibility. Visibility meters are used to reduce the contrast of an object until the object reaches its visibility threshold, the border line between visibility and invisibility. The initial degree of suprathreshold visibility is measured by the inverse of the contrast attenuation required to bring an object to visibility threshold.

Because operators of visibility meters have individual contrast sensitivities, each measurement of initial visibility is referenced to a 4-min luminous disk of variable contrast. This is the visibility reference task. Both object and reference task are presented for $\frac{1}{5}$-sec exposures once a second in a continuous pulse train. The initial visibility of the object is defined by the equivalent contrast $\tilde{C}$, which is the physical contrast of the 4-min disk having equal visibility to that of the object when both are viewed at the same level of general luminance at threshold. Thus, an object of $\tilde{C} = 1$ and a 4-min disk of physical contrast = 1 will simultaneously reach the visibility threshold if both are contrast attenuated by a visibility meter, and this equivalence will be achieved regardless of the contrast sensitivity of the meter operator.

After a value of $\tilde{C}$ is obtained, threshold contrasts obtained on a reference population of 68 normal 20 to 30 year olds are used to describe the degree to which the object exceeds threshold contrast at each value of general luminance. The procedure is shown schematically in Figure 1. The value of C_{eq} is identical to $\tilde{C}$. The value of $\tilde{C}$ (C_{eq}) is obtained with a visibility meter at a known luminance and hence is plotted in Figure 1 as a point. The solid curve is known as the visibility reference function and represents threshold contrast values for the 4-min disk obtained by the reference population at each luminance level. The measure of suprathreshold visibility is

$$VL = \tilde{C}/C_l$$

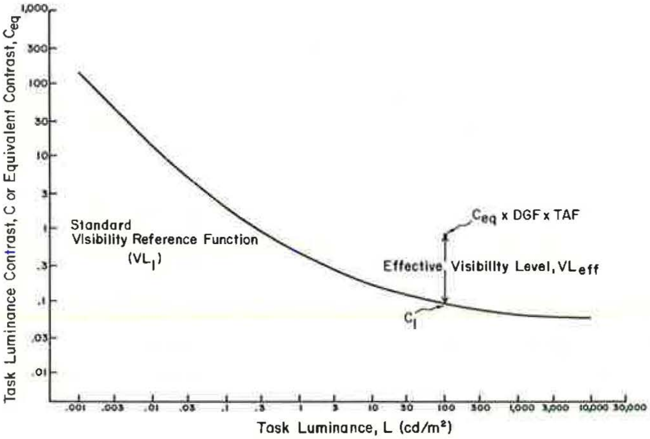
where C_l is the threshold contrast at a given luminance for the reference population. $\tilde{C}$ does not depend on luminance, but of course VL does. VL can be computed for any luminance from the definition.

The CIE system is based on the reference lighting condition produced within a photometric sphere. For all real systems, corrections must be made for effects due to unequal luminance from point to point in the visual environment. For the steady eye, these are described by the disability glare factor (DGF). For the moving eye, they are described by DGF times the transient adaptation factor (TAF). The effective visibility level is

$$\begin{aligned} VL_{eff} &= VL \times DGF \times TAF \\ &= \tilde{C}/C_l \times DGF \times TAF \end{aligned}$$

VL_{eff} measures the degree of suprathreshold visibility in units equal to the threshold contrast for the reference population. VL_{eff} is a linear quality and may be measured

Figure 1. Construction from CIE Report 19 showing the definition of C_{eq} ($\tilde{C}$).



and indeed calculated with some ease and assurance.

In the CIE system, visual performance is defined as the visual work that is required under realistic conditions such as those encountered in night driving. It has been shown (4) that visual performance bears a monotonic though nonlinear relation to VL_{eff}. To date, our work has been mainly concerned with the visibility aspect of the problem and this will be described in some detail. Sets of visibility data obtained with targets of different reflectances are used to define indexes of the degree to which different roadways provide object visibility.

THE IRV HIGHWAY VISIBILITY SIMULATOR

Roadway With Luminaires

Detailed descriptions of the design and construction of the simulator may be found elsewhere (1, 2). The essential details of the simulator are summarized in the following.

The model scale was set at 1:15 so that a 600-ft (183-m) section of roadway and a 200-ft (61-m) viewing distance could be simulated within a 55-ft (16.8-m) room. The roadway is 120 ft (36.6 m) wide and has 12-ft (3.6-m) lanes on either side of a 24-ft (7.3-m) median strip. The surfaces are portland cement concrete on the right and bituminous concrete on the left, the optical properties of which simulate the properties of actual sections of new roadway surfaces constructed in accordance with Interstate standards. The pavements were laid with a crown representing a $^3/_{16}$-in. (4.8-mm) rise per foot in the middle of each four-lane section, simulating an eight-lane urban freeway. The luminance factors of the pavement samples for diffuse illuminance were approximately 0.04 for the bituminous concrete and 0.50 for the portland cement concrete. There is a 32-in.-high (0.8-m) median divider that simulates portland cement concrete dividers in common use.

Luminaires are mounted above the roadway on pendulum poles to simulate different mounting heights. There is a mechanical coupling and an electrical outlet every 20 ft (6.1 m) in each of four stringers running the entire length of the roadway. Two stringers are near the outer edges of the roadway, and two are near the edges of the median strip.

There are locations for luminaires beyond the roadway surface at each end. In all, there are 164 locations for luminaires and an equal number of electrical outlets. Each outlet is supplied with voltage-stabilized 110 Vac, controlled by individual Variacs. A voltage-switching control board makes it possible to monitor the voltage being supplied to each outlet in turn, and the value can be read on a digital meter. This arrangement makes it convenient for the operator to adjust the voltage supplied to each luminaire to a standard value.

Data from only one of the four sets of scale-model luminaires are described in this report: the type BIII medium semi-cutoff (MSC) simulated luminaires. These were mounted 35 ft (10.7 m) high with an overhang of 3 ft (0.9 m) from the edge of the pavement. In addition, data are reported for a system of four longitudinally continuous fluorescent strips mounted 60 ft (18.3 m) high, which provides approximately uniform horizontal illumination at all points over the highway. The four fluorescent strips were adjusted in width, and their positions over the highway were determined on the basis of the requirements for uniform horizontal illumination. Thus, their output was arbitrary, and they represent any system capable of producing approximately uniform horizontal illumination. Therefore output can be scaled to correspond to any realistic lighting system capable of producing approximately uniform horizontal illumination. Simulation of the type III MSC luminaire in general use, however, was an extremely time-consuming and difficult project because of the scale.

Details of design, the measurement procedure, and isoillumination contours of the prototype and the model luminaire were given in earlier reports (1, 2). In general, the isoillumination contours are a little too extended longitudinally and a little too restricted transversely. Because the simulation is not exact, we designated our model luminaire as type BIII MSC to indicate a Blackwell simulation. The simulation was good enough to carry out a realistic study of highway visibility as long as the limitations noted above were recognized.

There are light projectors at the ends of each side of the roadway with separate voltage controls that illuminate pieces of cardboard mounted on the wall at the far end of the simulator. Each projector illuminates half the cardboard roadway extension. Projector output is adjusted so that the luminance of the adjacent roadway extension matches the average luminance of the lane under study. Interchangeable boards with different reflectances were used to cover the range of average roadway luminances obtained with different luminaire layouts. The roadway extensions were wide enough so that visibility targets were always seen against either the roadway or the roadway extension or a combination of the two.

Illumination and Luminance Photometry

The patterns of horizontal and vertical illuminance produced under test conditions were measured with a mobile illumination photometer. The sensor was a barrier-layer photocell whose angular response followed the cosine law approximately. The signal from the photocell was broadcast by an FM transmitter mounted on the photometer carriage, received at the observation station at the rear of the simulator, and used to drive the y-axis of an x-y plotter.

The photocell carriage can be moved back and forth along the roadway just above the surface either horizontally or vertically. The carriage is driven by a chain drive mounted in the median strip divider. An arm extends out from the median strip across the roadway to a protective strip at each edge of the roadway. The photocell can be mounted on this arm at any distance from very close to the median divider to near the outer edge of the roadway on either side. The photocell carriage is driven by a braked variable-speed drive so that it can be stopped at any point along the roadway with an error of less than 1 ft (0.3 m).

There is a continuous circuit board of reed switches running the entire length of the median strip. As the carriage moves along the roadway, its precise position is indicated by the circuit board assembly to within 1 ft (0.3 m). The signal from the circuit board is used both to drive the x-axis of the x-y plotter and to operate a digital meter readout device calibrated in scale feet. The illumination photometer was used to record continuous illumination profiles of both horizontal and vertical illumination in the center of each of the eight lanes. These illumination traces were made for each illumination system described (2).

Luminance photometry was accomplished with a Spectra Pritchard model 1970 photometer. A special elliptical aperture was designed to make a separate measurement of the average road luminance in each lane. Average road luminance $\bar{L}$ is measured in footlamberts (cd/m^2).

Visibility Meter and Glare Lens Measurements

There is an instrument carriage at the observation end of the simulator from which the experimenter views the roadway at the simulated angle appropriate for an automobile driver. The carriage has a precision motor-driven mounting table with two positions. In the first position, the visibility meter is pointed precisely at an object of interest. In the second position, a photometer is pointed precisely at the same object. The observer eye level of 48 in. (1.2 m) above the roadway is preserved. The visibility meter used is the special contrast-reducing model 3 Blackwell visual task evaluator (VTE). This device (3) gives the operator a telescopic view of objects on the roadway surrounded by an annulus whose luminance is set equal to the luminance surrounding the object, either by using the flicker photometer mode of the instrument or, as in this study, by setting it equal to the luminance of a physically measured background. This simultaneously sets the luminance of the light veil produced by the instrument to the same luminance. Then a contrast control gradually reduces the magnitude of focused light reaching the eye of the operator from the object and its background and at the same time increases the magnitude of light veil; the total of focused light and light veil is maintained at a nearly constant value. The object is brought to visibility threshold by means of the contrast attenuation produced by exchanging light veil for focused light. The extent to which contrast attenuation is required provides a quantitative measure of the initial visibility of the object. In this study, the object whose visibility is being measured is presented to the observer's eye in a continuous train of $\frac{1}{5}$-sec exposures in accordance with the standard CIE system of measuring visibility (4). In all the measurements, the contrast of the target was set to the value at which the observer could just barely detect that there was something there to be avoided. This information criterion amounts to a detection criterion of visibility. Each visibility measurement was made five times by an experienced observer. Thus, each value of $\tilde{C}$ reported here represents the average of five independent measurements.

The Spectra Pritchard photometer was mounted in the second position of the observer carriage. By a switch control this is positioned to point at exactly the same object as the VTE and at the correct observer eye position. The target was then removed, and two measurements were made to enable computation of DGF. With a 2-deg aperture in the photometer, we measured the luminance of the area of the roadway or roadway plus extension. Then an optical analog device, the Fry-Pritchard-Blackwell disability glare lens (5), was attached to the front of the photometer, and a second measurement was made. This device integrates all the components of disability glare in the environment, simulating the behavior of the normal 20- to 30-year-old human eye in this regard. Thus a separate DGF was computed for each position of a target under each lighting system. No measurement or calculation of the TAF has been attempted as yet, for no standardized procedure currently exists. Nor have we considered individual differences in sensitivity (6).

RESULTS OF VISIBILITY STUDIES

Studies With Three Realistic Targets

The first study was visibility of three realistic targets under six lighting systems. These consisted of six layouts of the previously described luminaires: 240-ft (73.2-m) opposite, 120-ft (36.6-m) staggered, 120-ft opposite, 60-ft (18.3-m) staggered, 60-ft opposite, and four continuous fluorescent strips providing approximately uniform horizontal illumination. For each layout, the following measurements were made:

1. Vertical and horizontal illumination traces the length of the highway at the center of each of the eight lanes,
2. Average roadway luminance for each lane separately,
3. Five visibility measurements of each of three targets every 20 ft (6.1 m) throughout the luminaire cycle down the center of each of the eight lanes, and
4. Disability glare measurements at each of these positions.

For the uniform illumination, all of these measurements were made for three positions in the center of each lane. The simulated viewing distance was kept at 200 ft (61 m) throughout.

The three realistic targets were agreed on by the various sponsors of the research. One target was a manikin made from wooden circular and cylindrical components to simulate the body proportions of a 6-ft (1.8-m) male. The body had a reflectance of 26 percent, and the body parts were constructed from calculations of proper scale areas. Another target was the rear of a model automobile simulating a clean, newly waxed, dark green sedan with the usual chrome. The third target was a white line marker made to scale by mounting retroreflective tape on supportive strips that were put together to form a continuous line marker along the inside edge of the two inside highway lanes, i.e., those next to the median.

The measurement procedures and tabular data for the type BIII MSC luminaires are reported elsewhere (2), but the data on the continuous strips are reported here.

Data are given in Tables 1 and 2. In Table 1 are given the arithmetic averages of all values obtained with the three targets in all longitudinal locations, in each of the four lanes, with each of the two pavement types. When two luminaire spacings were used with the same number of luminaires per mile, such as 240 opposite and 120 staggered, the two sets of values are shown separately and then averaged. All pertinent quantities are shown; VL_{eff} is computed by assuming TAF = 1. For the continuous-strip lighting, it was assumed that approximately uniform horizontal illumination could be produced by mounting luminaires at 30-ft (9.15-m) opposite spacing. Thus, in computing $\bar{L}$ and VL, we assumed levels of illumination appropriate to a spacing of 30 ft opposite.

VL_{eff} should show a systematic increase as spacing is reduced, for each reduction in spacing doubles the number of luminaires and approximately doubles all values of illumination and luminance. Table 1 shows that, for portland cement concrete pavement, VL_{eff} increased from 17.0 to 20.1 to 31.8 to 53.6 as the number of luminaires was increased by two, four, and eight. These values of VL_{eff} should be compared, however, with values of 17.0, 22.2, 28.3, and 35.2 to be expected from the increases in $\bar{L}$ alone (the value at the widest spacing is used as a base). When the value of VL_{eff} is greater or less than expected, the values of $\tilde{C}$ are either greater or smaller than the

Table 1. Arithmetic averages and average deviations for three realistic targets in four lanes.

		Arithmetic Average						Average Deviation	
Pavement	Spacing (ft)	$\tilde{C}$	$\bar{L}$ (ft-L)	VL	DGF	VL_{eff}	VL_{eff} Expected[a]	$\tilde{C}$	VL_{eff}
Portland cement concrete	240 opposite	4.72	0.794	17.6	0.968	17.0		1.04	3.97
	120 staggered	4.64	0.820	17.6	0.970	17.0		1.18	4.54
	Average	4.68	0.807	17.6	0.969	17.0	17.0		
	120 opposite	3.87	1.46	18.9	0.973	18.4		0.651	3.14
	60 staggered	4.55	1.52	22.4	0.966	21.8		1.06	5.48
	Average	4.21	1.49	20.6	0.970	20.1	22.2		
	60 opposite	5.28	2.88	33.0	0.965	31.8	28.3	0.831	5.06
	30 opposite[b]	6.75	5.76	52.9	1.010	53.6	35.2	0.738	5.71
Bituminous concrete	240 opposite	7.52	0.482	22.4	0.945	21.3		2.76	8.58
	120 staggered	9.55	0.522	29.5	0.942	27.9		3.21	9.97
	Average	8.54	0.502	25.9	0.944	24.6	24.6		
	120 opposite	3.84	0.970	15.6	0.942	14.8		0.684	2.78
	60 staggered	7.45	1.09	28.8	0.937	27.1		1.82	6.80
	Average	5.64	1.03	22.2	0.940	21.0	33.1		
	60 opposite	5.28	1.53	26.6	0.928	25.0	39.1	1.43	7.76
	30 opposite[b]	16.2	3.06	107.0	0.988	104.0	51.3	2.55	16.8

Note: 1 ft = 0.3 m. 1 ft-L = 3.4 cd/m².

[a] Due to $\bar{L}$ alone. [b] Continuous strips.

Table 2. Arithmetic averages and average deviations for three manikin targets.

		Arithmetic Average					Average Deviation	
Pavement	Manikin ρ	$\tilde{C}$	$\bar{L}$ (ft-L)	VL	DGF	VL_{eff}	$\tilde{C}$	VL_{eff}
Portland cement concrete	0.434	2.92	1.05	12.2	0.970	11.9	0.445	1.82
	0.260	3.86	1.05	16.1	0.970	15.7	0.570	2.18
	0.074	4.51	1.05	18.8	0.970	18.3	0.864	3.32
	Average	3.76	1.05	15.7	0.970	15.3	0.626	2.44
Bituminous concrete	0.434	3.29	0.932	13.1	0.961	12.7	0.886	3.46
	0.260	3.44	0.932	13.5	0.961	13.0	0.913	3.64
	0.074	4.92	0.932	19.7	0.961	18.9	0.634	2.43
	Average	3.88	0.932	15.4	0.961	14.9	0.811	3.18

Note: 1 ft-L = 3.4 cd/m²

value obtained with the widest spacing. The data for the portland cement pavement show that $\tilde{C}$ decreased as the number of luminaires was doubled from those used at 240 opposite and 120 staggered, then increased as the number of luminaires was doubled and doubled again. $\tilde{C}$ has a minimum value for the 120 opposite and 60 staggered spacings, being higher for either wider or closer spacings.

The data for bituminous concrete show a similar pattern with respect to $\tilde{C}$ except that the differences are much greater, and the values of VL_{eff} show essentially no improvement as spacing is reduced except for the closest spacing (30 opposite). Values of VL_{eff} fall far below expectations based on the increases in illumination and luminance except for the 30 opposite (continuous strip) layout.

There is one further result of interest. With neither pavement is there an entirely consistent trend for greater values of VL_{eff}, but in three of the four cases VL_{eff} is greater with bituminous than with portland cement pavement.

These effects suggest the existence of what we have called an anticamouflage effect (2). That is, to at least some extent, luminance nonuniformity can be a boon in that it provides such a variety of values of roadway luminance that some part of an object is sure to be seen because an appreciable local contrast exists. Of course, roadway nonuniformity can also conceal objects that resemble luminance nonuniformities, and these two effects can work together to produce good and less good patterns of roadway luminance so far as static visibility goes. This could explain the observed results. Because the bituminous pavement is more specular than portland cement pavement, the effects produced by luminance nonuniformity would be expected to be greater, which was the case.

Table 1 also gives measures of the variability among values of $\tilde{C}$ and VL_{eff} that make up each average. Variability is, of course, due to both errors in measuring $\tilde{C}$ and real differences in $\tilde{C}$ from location to location on the roadway. The data for portland cement concrete pavement under continuous-strip lighting should show little variability due to the second factor and hence give us a measure of the variability due to errors in measuring $\tilde{C}$. We see that the average deviation in this case is 0.738 for a mean of 6.75, representing 10.9 percent. This implies that measurement errors in $\tilde{C}$ are somewhat less than ±10 percent in sets of five measurements, which seems reasonable. Other average deviations are much larger, no doubt because of real differences in visibility among different locations. In general, average deviation values represent larger percentages of the averages the wider the luminaires are spaced. Values of average deviation are consistently larger for the bituminous pavement than for the portland cement pavement because of the greater luminance nonuniformities in the former resulting from its greater specularity.

The apparent significance of the anticamouflage effect made us wonder to what extent the data obtained in this study were influenced by the reflectances of the targets selected. Accordingly, a special study was conducted to investigate sample lighting conditions from among those included in the first study. The three targets were identical except for reflectance.

Studies With Manikins of Three Reflectances

Targets with different reflectances were studied under one lighting condition, 240-ft opposite spacing, which showed the bituminous concrete pavement to be superior to the portland cement pavement. Three identical manikins were painted to have diffuse reflectance, ρ, of 0.434, 0.260, and 0.074. Measurements were made following the same procedures as in the first study except that only the outermost lane (the one under the luminaires) was studied for each pavement.

The results, averaged for all three manikins, are given in Table 2. VL_{eff} is essentially equal for the two pavements: 15.3 for portland cement and 14.9 for bituminous. This differs significantly from results given in Table 1 in which VL_{eff} was higher for bituminous in three cases out of four. It thus appears that the initial data were influenced by target reflectances, inadvertently favoring the bituminous pavement. Table 2 also gives the measures of data variability, confirming that the differences between the two pavements are not statistically significant.

The most rational approach is to study targets of normal reflectances in proportion to their frequency of occurrence in assessing the visibility potential offered by any given roadway. This of course greatly complicates the task of making measurements. For this reason, we decided to investigate use of simplified targets of varying reflectance to determine a physical correlate of $\tilde{C}$ so that we could make physical measurements and calculations of visibility data.

Studies of Two-Dimensional Rectangular Targets of Four Reflectances

We constructed four two-dimensional targets of uniform reflectance, each measuring 12 in. (0.3 m) wide by 32 in. (0.8 m) high. This size was selected so that the targets could be seen entirely against the roadway itself and not against the roadway extension. The diffuse reflectance values ρ for these targets were 0.726, 0.508, 0.317, and 0.0442. Luminance and visibility measurements were made exactly as in the other studies for each of these targets at each target position, except that only the two outermost lanes were studied.

Average results are given in Table 3. As shown in the table, the narrowest spacing (30 opposite) yields higher values of VL_{eff} than the wider spacings for each pavement. Values of VL_{eff} at all spacings are quite similar for the two pavements; portland cement pavement shows a slight advantage as in the previous study. However, values of $\tilde{C}$ are also slightly higher on the average with the portland cement pavement, the reverse of what is shown in Table 2. Apparently, when a variety of target reflectances are used, the two pavements yield about equal average values of VL_{eff} and factors such as luminance nonuniformity show up only for some target reflectances.

A glance at individual values for the different reflectance targets shows that average values of VL_{eff} are somewhat misleading. For example, with each pavement, there is one target that is badly seen under continuous-strip lighting. Inasmuch as this lighting produces uniform roadway luminance, there is indeed a case of fairly good camouflage occurring for each pavement. Camouflage does not occur with the wide luminaire spacing because of the large luminance nonuniformities which are produced. These data suggest the importance of assessing roadway lighting in terms of both average VL_{eff} and a measure of variability in VL_{eff} among different targets, with as large a number included in the data set as possible. Table 3 gives measures of data variability, which show that, the closer the spacing of the luminaires is, the smaller is the percentage of variability in individual values of VL_{eff}. Overall, the percentage of variability is approximately the same for the two pavement surfaces.

It may be useful to consider the smallest value of VL_{eff} occurring with each layout and each pavement for any of the four targets. Using average deviation steps from each average value of VL_{eff}, we find values of 1.6, 5.6, 6.8, and 0.9 as the worst values of VL_{eff} to be expected from the 240 opposite, 120 opposite, 60 opposite, and continuous-strip lighting systems respectively. This index of merit favors first the 60 opposite system and second the 120 opposite system quite strongly. Two of the worst cases appear with portland cement and two with bituminous, suggesting as before that the pavement surfaces are roughly equivalent. We need to extend this analysis to the other six lanes of pavement to provide the complete story of all targets and all locations. This implies the need for a physical calculation system to augment the data we have collected with the visibility meter approach.

PHYSICAL CORRELATES OF $\tilde{C}$

The psychophysical data on simplified targets of varying reflectance presented have been used in a study of different physical correlates of $\tilde{C}$. Additional luminance measurements were made of minute areas of each target and the immediate roadway background. A 2-min photometric aperture was used. Five readings of target luminance

Table 3. Arithmetic averages and average deviations for four rectangular targets.

			Arithmetic Average					Average Deviation	
Pavement	Target ρ	Spacing (ft)	$\tilde{C}$	$\bar{L}$ (ft-L)	VL	DGF	VL_{eff}	$\tilde{C}$	VL_{eff}
Portland cement concrete	0.726	240 opposite	3.76	1.28	17.0	0.970	16.5	1.70	7.46
		120 opposite	2.28	2.30	13.2	0.965	12.8	0.404	2.24
		60 opposite	1.50	3.85	10.4	0.965	10.0	0.240	1.60
		30 opposite[a]	1.04	9.14	7.92	1.010	8.00	0.181	0.977
	0.508	240 opposite	4.84	1.28	22.0	0.970	21.3	1.60	6 93
		120 opposite	3.29	2.30	19.0	0.965	18.3	0.686	3.78
		60 opposite	2.46	3.85	17.1	0.965	16.5	0.612	4.08
		30 opposite[a]	3.31	9.14	29.0	1.010	29.3	0.190	1.63
	0.317	240 opposite	6.06	1.28	27.6	0.970	26.9	1.11	5.06
		120 opposite	4.17	2.30	24.1	0.965	23.3	0.684	3.76
		60 opposite	3.26	3.85	22.6	0.965	21.9	0.362	2.42
		30 opposite[a]	5.57	9.14	49.0	1.010	49.5	0.617	5.50
	0.0442	240 opposite	7.53	1.28	34.1	0.970	33.1	0.921	4.15
		120 opposite	6.46	2.30	37.4	0.965	36.0	1.04	5.77
		60 opposite	4.34	3.85	30.2	0.965	29.1	0.735	4.90
		30 opposite[a]	7.96	9.14	69.7	1.010	70.4	0.390	3.46
	Average	240 opposite	5.55	1.28	25.2	0.970	24.4	1.33	5.90
		120 opposite	4.05	2.30	23.4	0.965	22.6	0.704	3.89
		60 opposite	2.89	3.85	20.1	0.965	19.4	0.487	3.25
		30 opposite[a]	4.47	9.14	38.9	1.010	39.3	0.344	2.89
Bituminous concrete	0.726	240 opposite	4.79	1.20	21.1	0.961	20.3	0.805	3.52
		120 opposite	2.43	2.19	13.8	0.964	13.3	0.710	3.86
		60 opposite	1.50	3.32	9.93	0.957	9.49	0.170	1.01
		30 opposite[a]	3.84	7.31	32.0	0.994	31.8	0.977	8.11
	0.508	240 opposite	5.06	1.20	22.4	0.961	21.5	1.10	4.83
		120 opposite	2.98	2.19	17.0	0.964	16.3	0.788	4.31
		60 opposite	2.50	3.32	16.6	0.957	15.8	0.292	1.95
		30 opposite[a]	0.873	7.31	7.23	0.994	7.18	0.378	3.13
	0.317	240 opposite	5.43	1.20	24.0	0.961	23.0	1.23	5.33
		120 opposite	4.03	2.19	22.9	0.964	22.1	0.927	5.11
		60 opposite	3.32	3.32	22.0	0.957	21.1	0.368	2.32
		30 opposite[a]	3.65	7.31	30.3	0.994	30.1	0.163	1.41
	0.0442	240 opposite	7.22	1.20	31.8	0.961	30.5	0.844	3.73
		120 opposite	5.30	2.19	30.1	0.964	29.0	0.967	5.38
		60 opposite	4.58	3.32	30.4	0.957	29.1	0.895	5.82
		30 opposite[a]	8.12	7.31	67.4	0.994	67.0	0.950	7.89
	Average	240 opposite	5.62	1.20	24.9	0.961	23.8	0.995	4.35
		120 opposite	3.68	2.19	21.0	0.964	20.2	0.848	4.66
		60 opposite	2.98	3.32	19.7	0.957	18.9	0.431	2.78
		30 opposite[a]	4.19	7.31	34.3	0.994	34.1	0.617	5.13

Note: 1 ft = 0.3 m. 1 ft-L = 3.4 cd/m^2.

[a] Continuous strips.

were made in a row down the center of each target. These readings were averaged inasmuch as each target had essentially uniform luminance from top to bottom. The average target luminance was used in all calculations of contrast. Five readings of roadway luminance were also taken along each of the three boundaries each target made with the road, that is, along the left, bottom, and right sides of each target. These 20 luminances were measured for each target in each location under each of the four lighting systems studied. Then, separate formulas were used to compute different measures of target contrast and the correlation between values of $\tilde{C}$ and each measure of contrast was evaluated.

There was a special problem involving the shadow cast by the target on the roadway at its bottom edge. We investigated the effect of including or excluding these values from each definition of contrast.

Three definitions of contrast were used: contrast based on average luminances of target and background; maximum contrast, i.e., the highest contrast of any part of the target with an adjacent portion of the background; and average contrast, i.e., the arithmetic average of the local contrasts of different parts of the targets and adjacent por-

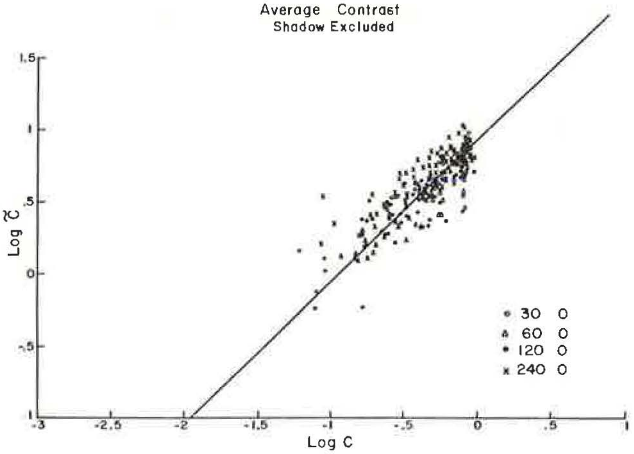


Figure 2. Scatter diagram of individual values of $\tilde{C}$ plotted as a function of average contrast.

tions of the background. In each case, individual values of $\tilde{C}$ obtained were plotted as a function of paired values of each computed contrast. The scales were logarithmic, and a line of unit slope was drawn corresponding to perfect correlation. The lines of unit slope were moved along the abscissa for best fit in each case. Degree of correlation was given by the spread of the points about the line.

It seemed clear that the target shadows should be excluded from any calculation of target contrast, inasmuch as the correlation obtained by excluding these values was significantly better. Of the three measures, contrast based on average luminances shows clearly the least correlation, and average contrast shows somewhat higher correlation than maximum contrast. Figure 2 shows the best of the six sets, using average contrast excluding shadow contrasts. The degree of correlation looks distinctly promising of practical usefulness.

ACKNOWLEDGMENTS

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Transient adaptation refers to the rapid fluctuations in the sensitivity of the eye that result from sudden changes in luminance level. The research reported here examines the effects of transient adaptation and resultant losses in visibility by using luminance levels comparable to nighttime highway lighting conditions. At low luminance levels, sudden increases produce losses in visibility equivalent to those previously found at higher levels. However, at low luminance levels, decreases produce smaller losses than those observed at higher luminance levels. The results also suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold decreases and above which there is a difference. The transition appears to be a gradual one and is complete at about 8 ft-L. The findings of these investigations suggest that visibility loss depends more on the ratio of steady-state thresholds, particularly at low luminance levels, than on the ratio of luminance change as previously supposed. Research has been initiated on the problem of nonuniformities in roadway luminances in the motorist's visual environment. Results indicate that the size of a nonuniformity may have little effect on transient adaptation. However, experiments to examine multiple nonuniformities and the effect of nonuniformities at various distances from the line of sight on transient adaptation are planned.

VISIBILITY LOSSES CAUSED BY TRANSIENT ADAPTATION AT LOW LUMINANCE LEVELS

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Visual adaptation is the process wherein the sensitivity of the eye adjusts to variations in luminance level over time. Some of these changes in sensivity are accomplished in a few hundred milliseconds, but others take several minutes to an hour. The research on transient adaptation is concerned with the faster changes, which are thought to be primarily neural in nature. Adaptation that takes place over a longer period of time, which appears to be more closely related to the concentration of photopigment in the receptors of the eye (1), is not covered here.

When the eye is presented with a sudden increase or decrease in the prevailing level of illumination, a transient burst of neural activity occurs in the retina that is relayed along visual pathways, signaling the change (2, 3). If the individual is asked to perform a visual task at this time, such as the recognition of a test letter, he or she will need greater contrast between the letter and the background if recognition is to take place. This is because the visual system is busy handling information related to the change in luminance level. Thus, the activity produced by the change masks the letter, i.e., makes it less visible. The greater the change in luminance level is, the greater is the additional contrast necessary to recognize the test letter. Eventually, the activity due to the sudden change subsides and reaches a steady state of complete adaptation.

The momentary loss in visibility associated with transient adaptation occurs whenever an individual changes his or her point of regard to surfaces having different luminances, when he or she views a variegated surface, or when natural illumination changes occur in the visual environment. Because variation in the visual field is necessary for vision to exist, the research on transient adaptation has addressed the question of how much variation in luminance should be permitted in the field of view and still allow adequate visibility to be maintained.

A number of experiments have been conducted by Boynton and associates at the University of Rochester (3, 4, 5, 6, 7). These have dealt with luminance levels similar to those encountered in interior lighting conditions. The research presented here was undertaken to provide a similar description of transient adaptational effects at lower luminance levels comparable to those found in nighttime highway lighting conditions.

Transient adaptational phenomena have obvious relevance to the visual problems of driving and highway illumination. Virtually all of the information available to the motorist is in the form of visual signals from the roadway or instrument panel. Anything that impairs his visibility can be detrimental to his overall performance. At night especially, the driver is often confronted with situations in which there are pronounced differences in luminance from one point of fixation to another, for example, when he looks from oncoming headlights or fixed luminaires back to the dark shoulder of the road. Brilliant signs and brightly lighted intersections and rest stops on high-speed throughways pose problems in transient adaptation. Less obvious, but still capable of impairing vision, are the effects of looking from a dark window to a lighted instrument panel or vice versa. Indeed, transient adaptational phenomena may play a disproportionately large role in the visual problems of night driving.

Several laboratory procedures have been used to investigate transient adaptation (3, 4, 5, 6, 7, 8). In one of these, a target to be identified such as a flash-illuminated letter was presented in a fixed location at a particular time relative to the change in the prevailing luminance level. The observer saw the letter superimposed on the changing background. The interval between the beginning of the transition from one background (B_1) to another (B_2) and the onset of the test letter flash is designated by τ. This procedure is shown schematically in Figure 1. An increase in luminance is shown in Figure 1a and a decrease is shown in Figure 1b. The four experiments reported here follow this experimental paradigm.

The results of previous investigations have typically been interpreted in terms of the ratio of the contrast threshold of the target in the transient state of adaptation to the contrast threshold after complete adaptation to the new luminance level. Contrast threshold in the transient state is defined as the luminance required for a test letter target to be just recognizable (B_t) divided by the luminance of the background against which it is presented. In most cases the letter is presented after the change so that the background luminance is B_2. If the contrast threshold for a letter presented against the changing background is divided by the contrast threshold for a letter presented against a steady background, the resulting ratio φ provides an index of visibility loss.

$$\varphi = \frac{B_t/B_2}{B_s/B_2}$$

where

B_t/B_2 = contrast threshold of letter presented at a particular time (τ) following the change from B_1 to B_2 and
B_s/B_2 = contrast threshold of the letter presented against the steady background B_2.

This quantity reduces to the dimensionless ratio

$$\varphi = \frac{B_t}{B_s}$$

where

B_t = increment threshold of letter presented at a particular value of τ during the transient state of adaptation and
B_s = increment threshold of letter presented against the unchanging background B_2 or during the steady state of adaptation.

At $\varphi = 10$, for example, to recognize a test letter requires 10 times as much light in the transient condition as in the steady-state condition. Log φ, the value usually determined, equals 1.0 in this example. Generally speaking, φ can be viewed as a measure of contrast.

METHOD

The first two experiments described are concerned with transient adaptation at luminance levels that approximate moonlight and outdoor lighting conditions. The third experiment is the logical outgrowth of the first two. Whereas the first two experiments have been reported previously (8), the third experiment represents a recently completed extension of the research. The fourth experiment is the first in a series of experiments examining the effects of luminance nonuniformities on transient adaptation and is an effort to simulate a roadway problem.

Apparatus

The apparatus used in this research was essentially a free-viewing system. The subject looked through a pellicle beam splitter at a 14 × 18-deg background field of flashed opal glass. His head was positioned by a chin and forehead rest. The background field was illuminated by two slide projectors. Luminance was increased by adding the luminance of one projector to that of the other; a decrease was effected by occluding one projector. Light from the projectors was presented and cut off by shutter vanes mounted on rotary solenoids placed in front of them. The luminance from each projector was controlled by neutral density filters, and fine regulation was achieved by small variations in lamp voltage. The subject binocularly viewed the transilluminated opal screen and saw by reflection from the pellicle beam splitter a test letter centered within four fixation points as shown in Figure 2. The fixation points defined the location at which the letter would appear and allowed the subject to accommodate his eyes to the proper distance. A slide changer combined with the associated optics projected the test letter in focus in the plane of the subject's pupils.

The test letters were slides of eight equally discriminable Sloan-Snellen letters that were randomly reordered for every experimental session (9). The letters were transilluminated by a microilluminator bulb. The luminance was regulated by neutral density filters, and fine adjustment was achieved by means of a circular neutral density optical wedge that was positioned by a bidirectional digital stepping motor. The axial shaft of the wedge was connected to a linear potentiometer, which allowed the experimenter to read the wedge position on a remote voltmeter. Another rotary-solenoid shutter controlled the presentation of the test flashes, which were 50 msec in duration. The luminance of all light sources was continuously monitored by means of selenium sun batteries and microammeter output.

Procedure

Procedures used in these experiments were similar to those of Boynton, Rinalducci, and Sternheim (7). From a prevailing luminance level, B_1, the background was either increased or decreased by 1 or 2 log units or 10- or 100-fold to a second luminance, B_2, that was maintained for a short period after which the luminance was returned to the B_1 level. For each ratio of change, the threshold was determined for each of 12 values of τ ranging from -100 to +400 msec. Negative τ-values indicate that the test letter was presented before the luminance change, whereas positive τ-values indicate that the letter was presented after the change. Thresholds were also determined against unchanging backgrounds of B_1 and B_2 luminances or steady-state conditions to provide reference points for the computation of φ.

In each experimental session the subject was allowed to adapt to B_1 for 5 to 7 min.

Figure 1. Schematic of sequence of events in stimulus presentation: (a) transition from background luminance B_1 to a higher luminance B_2 and (b) transition from B_1 to a lower B_2 luminance.

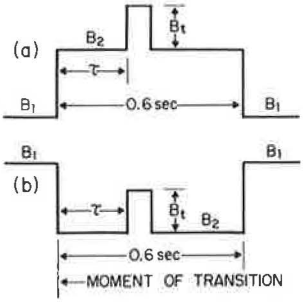


Figure 2. Stimulus configuration as seen by the subject (6).

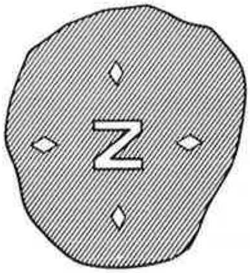


Figure 3. Schematic of the four transient and five steady-state conditions investigated in experiment 1.

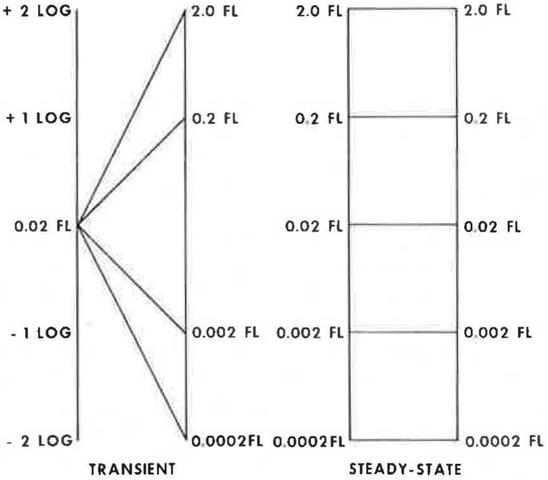
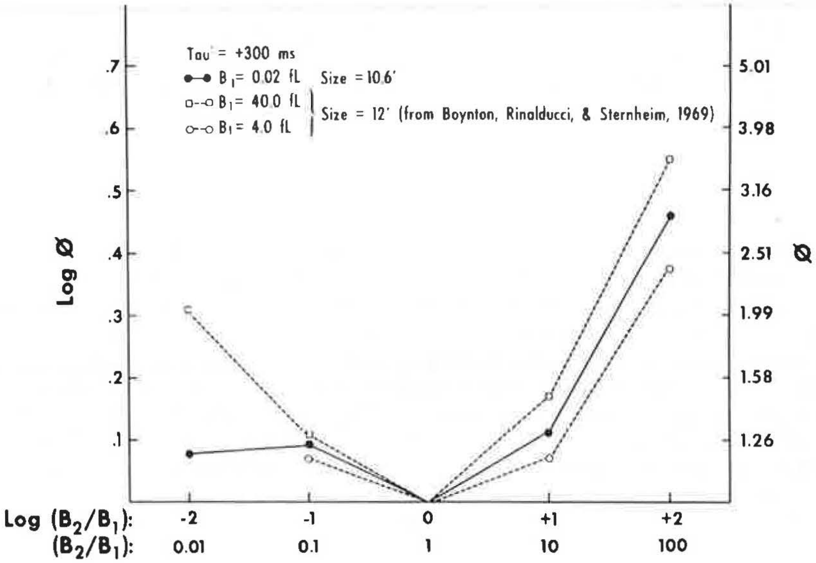


Figure 4. Visibility loss as a function of the ratio of luminance change for experiment 1.



Then began a 15-sec cycle in which the background changed from the B_1 luminance to B_2 for 600 msec and back to B_1 for 14.4 sec. The long recycle times, combined with the brief duration at which the background luminance remained at B_2, ensured that the observer was fully adapted to B_1 at the moment of transition to B_2. Two seconds before the moment of transition from B_1 to B_2 or 2 sec before the presentation of the test letter in the steady-state condition, a warning buzzer sounded. The subject's task was to depress a key corresponding to the letter he believed had been presented. If the subject depressed the correct key, a bell rang and the stepping motor moved the wedge about 0.1 log unit in the direction of increasing density, thus causing the flash on the succeeding trial to be dimmer. If incorrect, the bell did not ring, the wedge was turned in the direction of decreasing density, and the next flash was brighter. Thus, a forced-choice technique giving knowledge of results was combined with the up-and-down psychophysical method (10, 11).

Thirty trials were performed for each threshold determination. Threshold was defined as that luminance at which the letters were correctly identified 50 percent of the time. An Iconix electronic timing system controlled stimulus presentation.

EXPERIMENT 1

Design

Figure 3 shows the transient and steady-state conditions investigated in experiment 1. B_1 was always 0.02 ft-L, which is roughly equivalent to the ambient light provided by the full moon (12). B_2 luminance levels were 0.0002, 0.002, 0.02, and 2.0 ft-L. These provided for a 1- or 2-log-unit decrease or increase. Changes of these magnitudes have been shown to produce significant losses in visibility, at least where higher levels of B_1 have been used (7). In all, there were four transient and five steady-state conditions.

In this experiment, the test letter subtended an angle of 10.6 min at the eye and had a critical detail of 2.12 min. This target size is similar to that used by Boynton et al. (7), who subtended an angle of 12 min with a critical detail of 2.4 min.

Ten subjects, ranging in age from 18 to 32, participated in this experiment. All had a visual acuity of 20/20, either corrected or uncorrected.

Results and Discussion

The results of experiment 1 are shown in Figure 4. In Figure 4, visibility loss in terms of φ for $\tau = +300$ msec (where the test letter flash is presented 300 msec after the moment of transition from B_1 to B_2) is plotted as a function of B_2/B_1 or the ratio of luminance change. In the same slide log φ is also plotted in terms of log (B_2/B_1). $\tau = +300$ msec was chosen for several reasons.

1. It provides a basis for a direct comparison of the data obtained by Boynton and his associates (3, 4, 5, 6, 7), who used $\tau = +300$ msec in much of their work.
2. The +300 msec appears to be a reasonable estimate of the length of a single fixation by a person in an ordinary search or reading task.
3. The threshold at +300 msec is no longer changing rapidly, so that this value is probably more stable and reliable than values obtained at shorter intervals.
4. At +300 msec φ assumes a smaller value than it would at a shorter interval and is therefore a reasonably conservative estimate of the visibility loss under conditions of scanning a nonuniform field.

Although other values of τ were used, the data reported here are restricted to $\tau = +300$ msec.

Figure 4 shows that the largest impairment of visibility was obtained for the 2 log-unit increase in luminance. Selected data from Boynton et al. (7) are also plotted for comparison. Visibility losses resulting from 1- and 2-log-unit increases and the 1-log-unit decrease appear to be comparable in both experiments, even though the preadapting luminance was much lower in the present experiment. However, visibility losses from a 2-log-unit decrease were found to be no greater than those due to a 1-log-unit decrease at the low luminance levels used. That these results at low luminances deviate from previously obtained data at higher luminances is the major finding of experiment 1.

EXPERIMENT 2

Design

In experiment 2 the B_1 luminance level was 0.2 ft-L. This is approximately equivalent to the luminance provided by automobile headlights on asphalt pavement (12). Figure 5 shows the four transient and five steady-state conditions examined. The B_2 levels in this experiment were 0.002, 0.02, 2.0, and 20.0 ft-L, which again provide for 1- and 2-log-unit decreases and increases. As in experiment 1, the test letter subtended an angle of 10.6 min. Ten subjects also participated in this experiment, and their ages ranged from 18 to 33.

Results and Discussion

The results of experiment 2 are shown in Figure 6. The data are plotted as in experiment 1 for values of φ at $\tau = +300$ msec. For ease of comparison this figure also includes the results obtained in experiment 1, which are quite similar. Again, the 2-log-unit decrease fails to produce a greater visibility loss than the 1-log-unit decrease. It should be noted, however, that large decreases in luminance from such low levels (0.02 ft-L, in particular) to even lower levels (such as 0.002 and 0.0002 ft-L) will not usually be experienced in the highway environment. Even so, these visibility losses are on the order of 26 percent.

Previous studies (3, 4, 5, 6, 7) suggested that, to a first approximation, visibility loss was a function of the ratio of the background luminances B_1 and B_2 and that the absolute values of the luminance levels involved played a relatively minor role. Figure 7 (6) shows the value of φ (at $\tau = +300$ msec) as a function of the factor by which the prevailing luminance level is changed. This generalization, however, was inadequate for many conditions where B_1 and B_2 were much greater than 400 ft-L. Boynton has suggested (3) that, just as there is an upper limit to the applicability of this generalization, there is also likely to be a lower limit.

The existence of a lower limit might be attributed to the fact that we are dealing mainly with luminance levels in the mesopic range, near the absolute threshold of the photopic or cone visual system. The cone photoreceptors are primarily involved in the task used to examine visibility loss in these experiments. Within a portion of the photopic range, the eye's sensitivity may be approximated by Weber's law, which states that the smallest difference in luminance that can be detected is roughly proportional to the background luminance. At higher luminances it has been found to be a good approximation under some conditions and a poor one under others. However, it is well known that, at luminances approaching the absolute threshold of cones, Weber's law breaks down. Therefore, varying magnitudes of adapting-field change should not be expected to produce threshold increments different in proportion to the background luminance on which they are superimposed (13).

One explanation for the exaggerated heightening of thresholds observed in transient adaptation is that the luminance change gives rise to a burst of activity in the visual system, and this activity essentially overwhelms or masks activity from a signal superimposed on this change. However, because of a breakdown in Weber's law at low luminance levels the differences in neural activity for a 1- or 2-log-unit decrement

Figure 5. Schematic of the four transient and five steady-state conditions investigated in experiment 2.

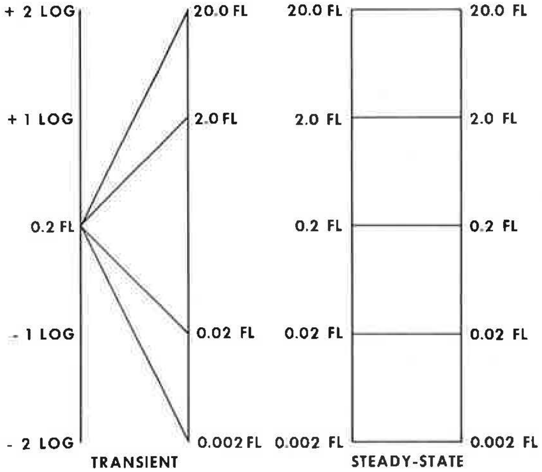


Figure 6. Visibility loss as a function of the ratio of luminance change for experiment 2.

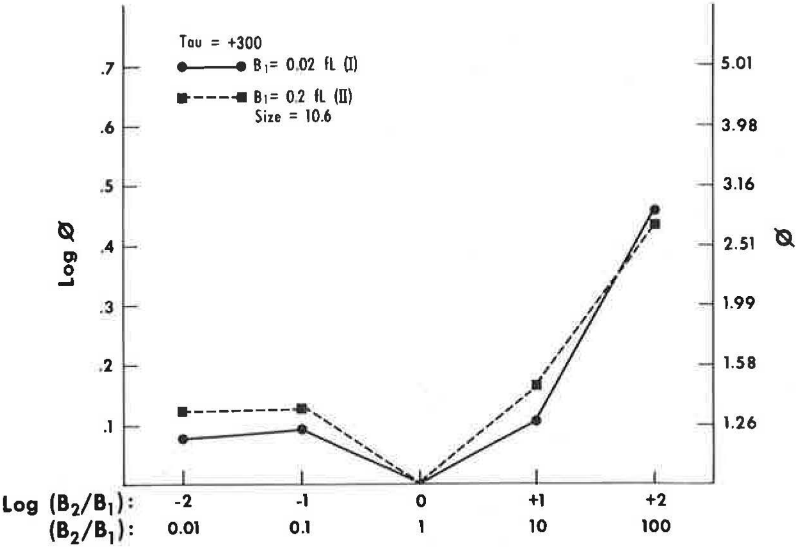


Figure 7. Phi as a function of the factor of change from one luminance to another.

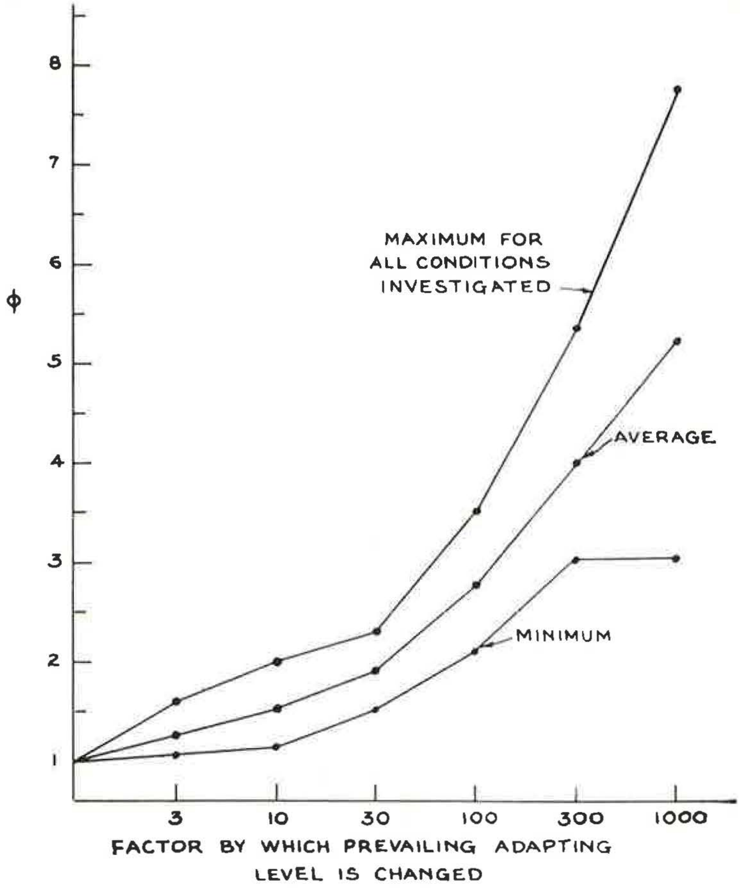
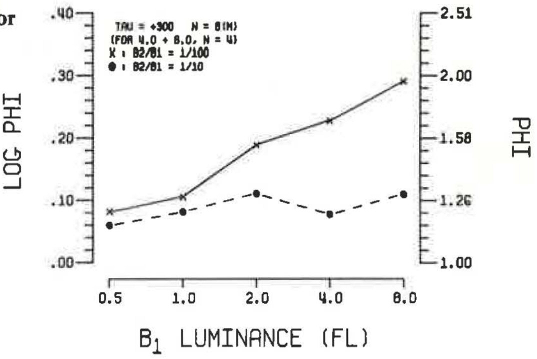


Figure 8. Phi as a function of B_1 luminance level for 10- and 100-fold decreases in luminance.



may not be significant. Both magnitudes of change might be equivalent in their ability to produce visibility loss.

EXPERIMENT 3

Design

The results of experiments 1 and 2 suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold downward changes and above which there is a difference. Experiment 3 was directed at determining where the break-off point is. Visibility losses for 10- and 100-fold decreases were examined for B_1 levels of 0.5, 1.0, 2.0, 4.0, and 8.0 ft-L. Eight subjects were tested at B_1 levels of 0.5 to 2.0 ft-L and four subjects each for 4 and 8 ft-L. The procedures for experiment 3 were basically the same as for experiments 1 and 2 with only minor modifications.

Results and Discussion

Figure 8 shows the combined data for all subjects with φ (and log φ) plotted as a function of B_1 luminance for 10- and 100-fold decreases. The data suggest that the transition from where there is no difference in visibility losses to where there is a difference is a gradual one. Based on previous investigations using much higher B_1 luminance levels (3, 4, 5, 6, 7), the transition appears to be complete at about 8 ft-L (values of φ at +300 msec are approximately the same). Figure 9 shows the data for two subjects who participated in all phases of experiment 3.

Boynton (3) has suggested that visibility loss depends on the ratio of adaptational change (or ratio of background luminances). However, research on transient adaptation at low luminances shows that this relationship breaks down (8, 14). A previous report (8) demonstrated by using data obtained in experiments 1 and 2 that the ratio of the higher steady-state threshold to the lower one shows a high degree of relationship with visibility loss (φ for τ = +300 msec) at low luminances and is equivalent to the ratio of backgrounds at higher luminances. For experiments 1 and 2 the correlation (Pearson product-moment correlation coefficient) between the ratio of steady-state thresholds and φ was found to be high ($r = +0.865$) and statistically significant. For experiment 3 the correlation was also high ($r = +0.792$) and statistically significant. Therefore, we propose that the ratio of steady-state thresholds provides a more adequate basis for predicting and assessing visibility loss in transient adaptation over a wider range of luminance levels.

EXPERIMENT 4

Experiment 4 was the first of a series of experiments to examine the effects of luminance nonuniformities on transient adaptation. Again this is an attempt to simulate a roadway problem. At night a driver's visual field often includes a roadway that is cluttered with variations in luminance and nonuniformities in brightnesses. The first experiments deal with unrestricted or full-area background fields. Later research will examine nonuniformities within a restricted portion of the field by simulating, for example, a ribbon of highway pavement. Initial experimentation on luminance nonuniformities involves examining simple situations before proceeding to the more complex ones.

Design

In this experiment the area of a square patch of light was varied and was seen against

Figure 9. Phi as a function of B_1 luminance level for 10- and 100-fold decreases for experiment 3.

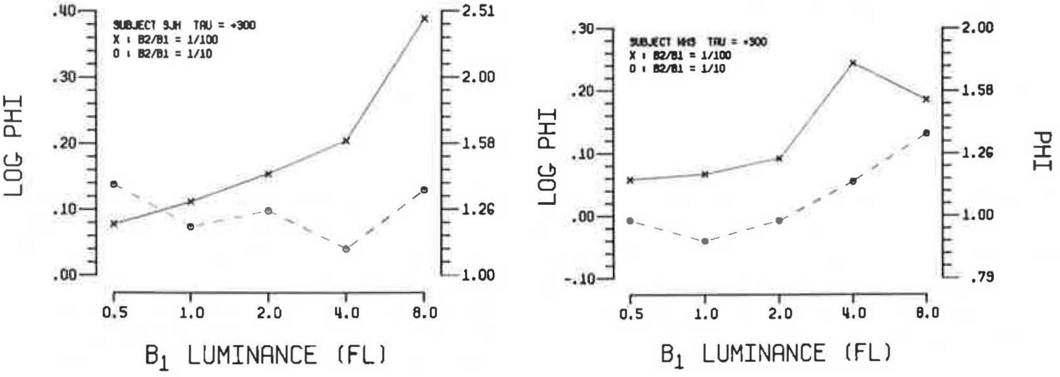


Figure 10. Stimulus configuration for experiment 4.

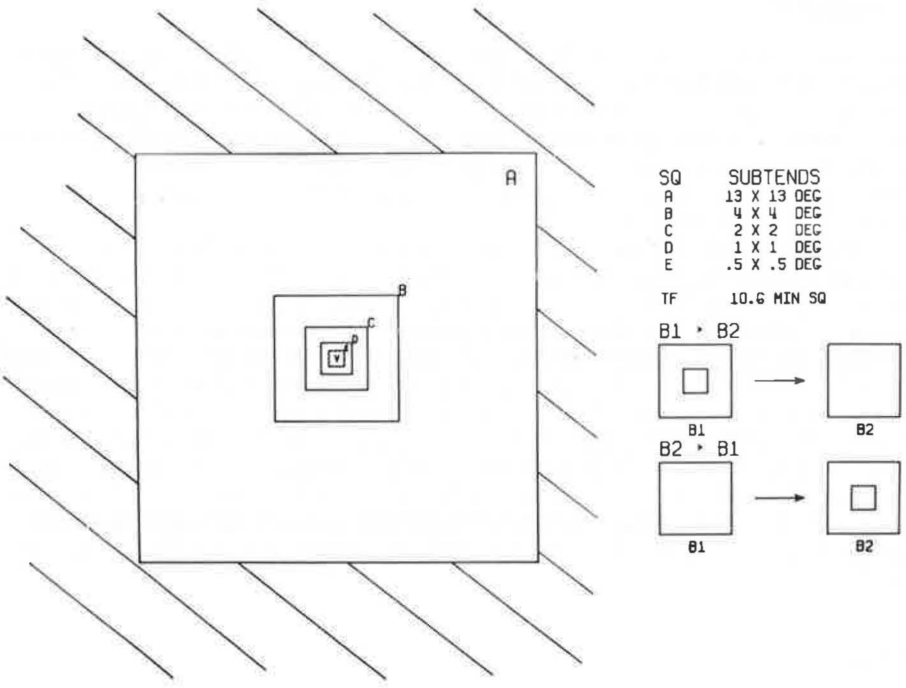
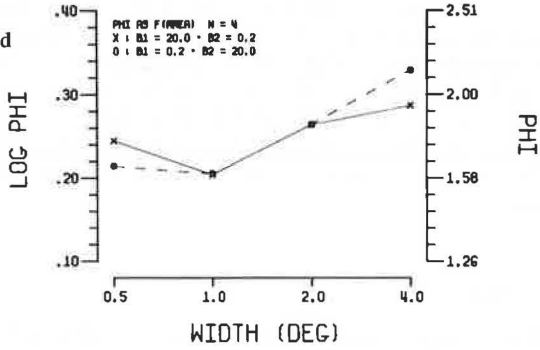


Figure 11. Phi as a function of the area of the square patch superimposed on a background field for 100-fold increases and decreases for experiment 4.



a uniform luminous background field. The luminance of the patch was suddenly increased or decreased by a factor of 100. The width or diameter of the square was varied from 0.5 to 4 deg. Figure 10 shows the stimulus configuration and the relationship between the square patch (nonuniformity) and the background. Figure 10 shows a background square measuring 13 by 13 deg on which one of the square patches or nonuniformities is superimposed (B, C, D, or E). Only one square patch was used at a given time. The test-letter flash, V, which measured 10.6 min, is shown centered within a square patch. In the lower right-hand corner of the figure a schematic representation of the luminance change is shown. In the first case (B_1 to B_2), the bright patch is superimposed on the dim background and the bright patch is then terminated, providing a decrease in luminance. In the second case (B_2 to B_1), the dim background is presented and a bright square patch is then superimposed momentarily on it, providing an increase in luminance.

Thus the observer was confronted with a change from a uniform field to a nonuniform field or vice versa created by square patches of light of a luminance 100-fold higher than their background. The square patches were projected on a uniform background provided by a back-projection screen. For the increase, $B_1 = 0.2$ ft-L and $B_2 = 20$ ft-L and for the decrease, $B_1 = 20$ ft-L and $B_2 = 0.2$ ft-L. Four subjects were used in this study.

Results and Discussion

The results of experiment 4 are shown in Figure 11 where φ and log φ for $\tau = +300$ msec are plotted as a function of the size of the bright patch. Although the effect of area is small there is a general upward trend or loss in visibility with an increase in the size of the bright patch. This is probably the result of an increase in light flux or stray light with an increase in the size of the square patch.

Two subsequent experiments are planned in this series. They will examine the effects of the number of luminance nonuniformities (or number of square patches) and their distance from the line of sight on visibility loss during transient adaptation.

CONCLUSIONS

Several points might be reiterated from the experiments that have been reported here. First, at luminance levels comparable to those found in night driving, sudden increases in luminance produce losses in visibility equivalent to those previously found at higher initial luminance levels. However, for decreases from a low luminance level to an even lower one, smaller losses were observed than those found at higher luminances. Second, the results also suggest that there is a preadapting level or range of levels below which there is little or no difference between visibility losses for 10- and 100-fold decreases and above which there is a difference. The data show that the transition is a gradual one and appears to be complete at about 8 ft-L. Third, the results of the present investigation indicate that at low luminance levels the value of φ depends more directly on the ratio of steady-state thresholds than on the ratio of luminance change. Finally, initial research on luminance nonuniformities indicates that, when the size of a luminance nonuniformity is varied, there is little marked effect on transient adaptation. Subsequent experiments will examine multiple nonuniformities and the effect of nonuniformities at various distances from the line of sight on transient adaptation and visibility losses.

ACKNOWLEDGMENT

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This paper describes a research program in progress whose goal is the development of a head lamp evaluation model. The model will evaluate headlight systems in terms of a single overall figure of merit representing several measures of driver visual performance under night driving conditions. The model simulates relevant aspects of the night highway environment and incorporates a seeing distance model that determines the photometric conditions produced by vehicle lighting and environmental factors and computes glare and seeing distance to pedestrian and pavement delineation targets. The seeing distance and glare calculations used in the seeing distance model are derived from laboratory formulations of human vision capabilities. A program of field research has been initiated to verify the seeing distance model and to provide data for the simulation of those aspects of the nighttime highway environment that determine head lamp illumination of target and pavement and, hence, visual performance.

DEVELOPMENT OF A HEADLIGHT EVALUATION MODEL

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With few exceptions, headlight-seeing distance research has been conducted under structured test situations that represent the least difficult conditions encountered in night driving: straight, level, dry roads; young, alert observers; test vehicles with clean, properly aimed head lamps and clean windshields; and small vertical targets. Often, seeing distance has been measured to targets placed only at the right edge of the driving lane. In general, the visibility of road markings and path delineation elements as a measure of headlight performance has been ignored as a topic for systematic study. These practices reflect the procedural difficulty and cost of representing or working in the whole highway environment rather than a lack of sophistication on the part of the experimenters. Nevertheless, failure to consider a broader range of operating conditions can lead to errors of two types:

1. Because the structured conditions under which most headlight-seeing distance research is performed are ideal, differences between head lamp systems tend to be exaggerated and not necessarily representative of real-world differences; and
2. More important, the performance ranking of a set of head lamp systems may change with the conditions of observation.

Figure 1, which shows seeing distance test results obtained by Adler and Lunenfeld (1), illustrates a case in point. In these tests, a 16-in. square, 7 percent reflectance target was located 5 ft to the right of the driving lane and equidistant longitudinally between the glare and observer vehicles. The glare car, when it was used, had the same head lamp system as the observer car. Of interest is the reversal in low- and mid-beam performance between the no-glare and glare conditions and the fact that seeing distance was greater for both systems when the glare and observer vehicles were in adjacent lanes than when they were separated by an intervening lane, despite the greater glare. An explanation of these findings is suggested by the size and reflectance of the target; it is assumed that the target is darker than the surface immediately behind it and against which it is seen and, hence, is detected in negative contrast. In the absence of opposing headlights, target-background contrast is the same for low and mid beams. However, because the mid beam produces more intense illumination in the direction of the target than the low beam does, it produces longer seeing distances. Opposing headlights in the adjacent lane increase the contrast by backlighting the pavement behind the target; however, because of its beam pattern, the mid beam produces much more glare than the low beam but only slightly more backlighting, which results in a net loss for the mid beam. In the case of an intervening lane, glare is still present but the backlighting is substantially reduced. In fact, because road surface retroreflectance is less at short than at long distances, it is possible that, in the case of an intervening lane, the target was brighter than its background when detected.

Whether or not this explanation is correct for this particular set of findings, it is plausible and illustrates the possibilities for complex interactions among variables such as target size, reflectance, and location; pavement reflectance; beam pattern, and presence or absence of a glare source. Because the relative performance of a set of head lamps may vary with the test conditions, it is difficult to define a meaningful and representative set of test conditions for evaluating and comparing them. Nor, as a practical matter, is it possible to conduct systematic seeing distance and glare tests of head lamp systems under the full range of conditions that obtain in actual driving. Furthermore, even if such an undertaking were feasible, there would still remain the problem of weighting and combining the various performance measures obtained across the range of conditions tested to produce an overall measure of performance.

These considerations led Ford Motor Company to undertake the development of a headlight evaluation model to evaluate and compare existing and proposed headlight systems in terms of several integrated driver performance measures under a wide range of driving conditions. Ultimately, it is hoped that the model can be used to define the characteristics of an optimum system.

The structure of the model, the underlying concepts, and supporting field research are described in the following sections.

DEVELOPMENT OF A COMPREHENSIVE HEADLIGHT EVALUATION MODEL

The Ford headlight evaluation model simulates night driving situations, computes driver visual performance under a variety of situations, and outputs an overall figure of merit or score for each headlight system tested.

Figure of Merit

The figure of merit for a given headlighting system is the total distance traveled on a simulated test route under adequate illumination by a vehicle using that system. Illumination is considered to be adequate when seeing distances to both pedestrian and pavement targets are equal to or greater than some criterion distance and when the discomfort glare experienced by opposing drivers is less than some criterion value.

The computation of the figure of merit is shown in Figure 2. The figure shows the observer vehicle on a section of a standardized test route approaching two pedestrians and two opposing vehicles. The three graphs show seeing distance to delineation features and pedestrians for the driver of the observer vehicle as he proceeds along the test section and the discomfort level of the opposing drivers. Seeing distance to the delineation (shown on the ordinate) is greater than the criterion (CL_1) except when the opposing vehicles are close enough to produce disability glare. Seeing distance to the first pedestrian (shown by the crosshatched segments) is less than the criterion distance (CL_2), but the visibility of the second pedestrian is greater than the criterion level. Discomfort glare (shown on the ordinate) is within limits (CL_3) except when the two opposing vehicles pass. The bottom line shows those parts of the test section in which all three criteria are met. The sum of all the mileage traveled within the criteria levels on all of the test sections constitutes the figure of merit.

The criterion seeing distance for stand-up targets is the stopping distance computed from reaction time, speed, and tire-pavement friction values drawn randomly from appropriate distributions. The criterion seeing distance to pavement delineations is that that will provide the preview a driver needs for lane keeping and path following. The preview value used currently is 2 sec (2), but this is subject to change based on further study of the literature. The discomfort glare criterion applies only to low and mid beams. At present the criterion is set at 110 percent of the glare that current low beams produce in an encounter. However, this too is subject to change depending on the outcome of current Ford field research.

Standardized Test Route

The test route is a computer simulation of a series of highway sections incorporating environmental factors that influence driver visual performance, such as topography, reflectance and ambient brightness of the road and road elements, highway type, traffic characteristics, target characteristics, and weather. The values of the various environmental variables (e.g., pavement reflectance) that characterize a given section are drawn randomly from distributions of these variables as determined by Ford surveys and analyses. Although originally defined by random selection, the same standardized test route will be used to evaluate all headlight systems.

Structure of the Model

Figure 3 shows a flow chart of the evaluation model as it is conceived. Input data consist of the standardized test route; properties of opposing vehicles such as head lamp location, configuration, and misaim; the isocandle diagrams of the test and opposing headlighting systems and driver characteristics, that is, laboratory formulations of human contrast detection and glare susceptibility as validated for highway application by Ford research. An evaluation run with the model will consist of a series of target encounters on the various sections of the test route, each involving a randomly drawn set of environmental, oncoming vehicle, and driver characteristics. In an encounter, traffic density determines whether an oncoming vehicle will be present and, if so, its speed and distance from the observer car at the start of the encounter. Together, environmental factors and the characteristics of the opposing and test headlights determine the driver's visual environment.

The heart of the evaluation model is the Ford seeing distance model. This is represented in the flow chart by the driver's visual environment, visibility and glare computations, and seeing distance to targets. The seeing distance model accepts the environmental, driver vision, vehicular, and head lamp characteristics and computes the relevant aspects of the driver's visual environment: target and background luminance (photometric brightness), glare, adaptation level, and apparent target size. Once the visual environment has been established, driver target detection and glare susceptibility characteristics provide the basis for seeing distance and glare computations. The effect of disability glare in the model is to reduce seeing distances in accordance with veiling glare formulations found in the literature and confirmed or modified by Ford research. In addition, a feedback loop is provided to simulate dimming requests in response to discomfort glare. Excessive discomfort glare produced by mid or high beams will result in a dimming request, as determined by the Ford glare acceptance study, i.e., the glare and/or observer vehicles will switch to low beams. The seeing distance model is discussed more fully below.

On each section of the standardized test route the distance traveled under adequate illumination is computed, and this figure is accumulated over all of the sections of the test route to produce the final figure of merit.

The basic programming for the evaluation model is complete. The seeing distance model will accept head lamp and driver characteristics and environmental data from the files that constitute the standardized test route and will determine for an encounter whether the performance of a head lamp system meets all criterion values. Refinements of the veiling glare and seeing distance formulations may be required, pending further analysis of field data. The data files of environmental characteristics of the standardized test route are only partially complete. Collection and analysis of field

Figure 1. Seeing distance with low and mid beams.

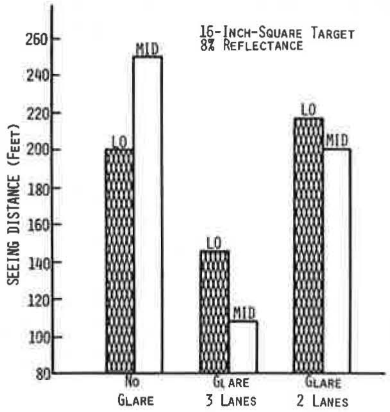


Figure 2. Miles driven under adequate illumination on standardized test route.

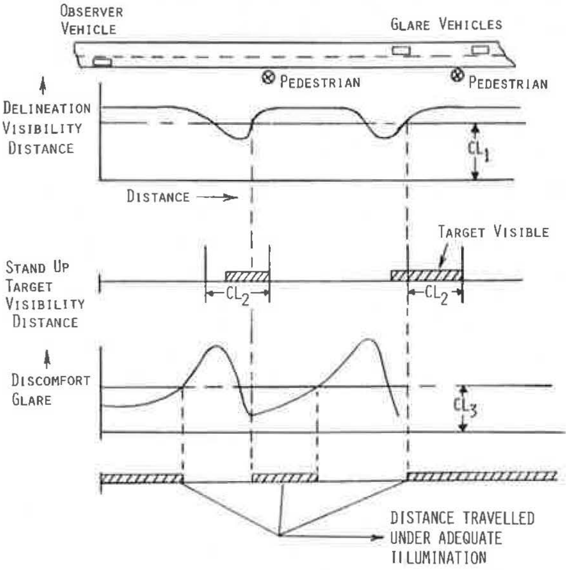


Figure 3. Headlight evaluation model.

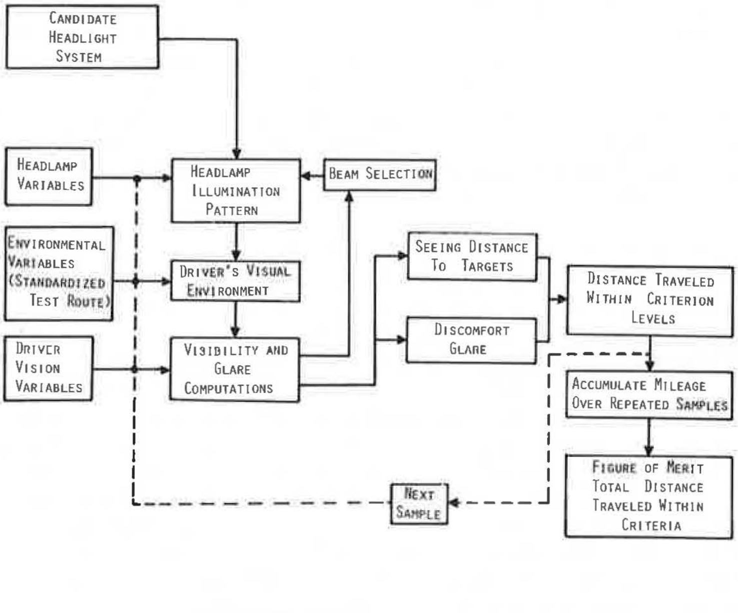
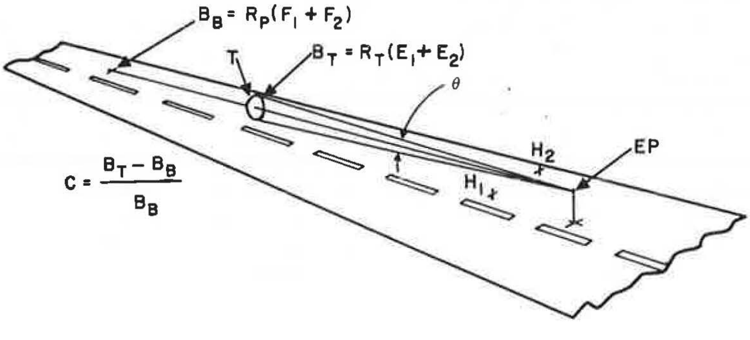


Figure 4. Illustration of target contrast.



survey data are in progress to provide this information.

SEEING DISTANCE MODEL

The visibility and glare calculations in the evaluation model are performed by the Ford seeing distance model. The seeing distance model is based on Blackwell's (3) luminance contrast threshold (minimum contrast required for detection) curves, as modified for highway application by Ford field research. Figure 4 shows the concept of luminance contrast and its application to the highway setting. The target T subtends a visual angle θ at the driver's eye point EP and is illuminated by headlights H_1 and H_2. The target luminance B_T is given by the target reflectance factor R_T times the sum of the incident illumination $(E_1 + E_2)$. The portion of the pavement that serves as the observer's background of the target has luminance B_B, which is the product of the pavement reflectance factor R_P and the illumination falling on the pavement at that point $(F_1 + F_2)$. Contrast is defined as

$$C = \frac{B_T - B_B}{B_B}$$

The form taken by the contrast threshold is shown in Figure 5 (3). Log threshold contrast is plotted as a function of background luminance in foot-lamberts for various target sizes. The contrast threshold increases with decreasing background luminance and target size. The area above a curve represents the region in which a target of size θ is visible to an observer. This particular graph is for a target exposure time of $\frac{1}{30}$ sec, which, according to Blackwell (3), is "appropriate for evaluating visual detection in night driving." Longer or shorter exposures give rise to similar functions: The longer the duration is, the lower the contrast required for detection is. The thresholds for positive and negative contrast are the same except for the sign.

Veiling glare B_V from oncoming vehicles (or any other light source) is computed from an expression developed by Fisher and Christie (4):

$$B_V = (0.2A + 5.8)\,\Pi \sum_{i=1}^{n} E_i\,\theta_i^{-2.2}$$

where

A = observer's age in years,
E_i = illuminance of the i th glare source in foot-candles, and
θ_i = angle to the i th source, measured from the observer's line of sight.

B_V thus computed is added to the denominator of the contrast expression to give

$$C = \frac{B_T - B_B}{B_B + B_V} = \frac{B_T - B_B}{B_B'}$$

and the Blackwell curves are entered with $B_B' = B_B + B_V$ on the abscissa to find the required contrast.

Figure 6 shows contrast threshold data transformed into units appropriate for highway target detection tasks. The solid lines shown the log threshold background luminance required for detection plotted as a function of observer distance from the target.

Figure 5. Liminal contrast as a function of background luminance for various target sizes.

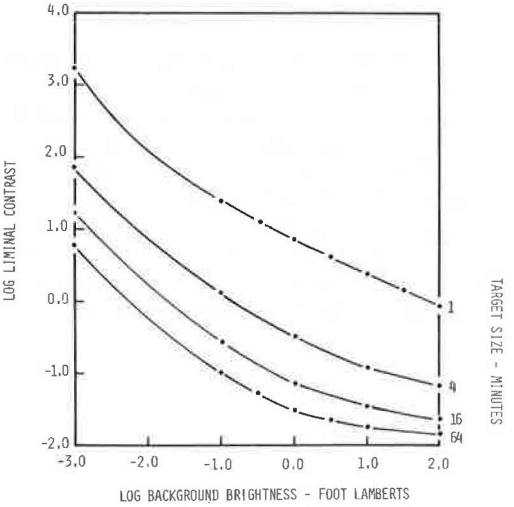


Figure 6. Detection of a pedestrian target with 10 percent reflectance under high and low beams.

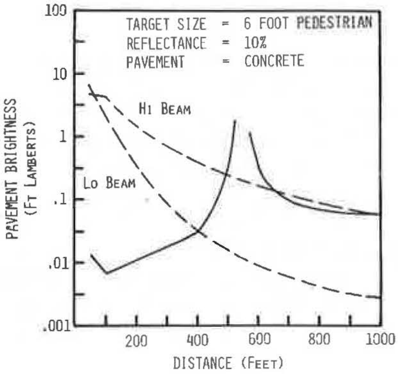


Figure 7. Pavement brightness and probability of target detection.

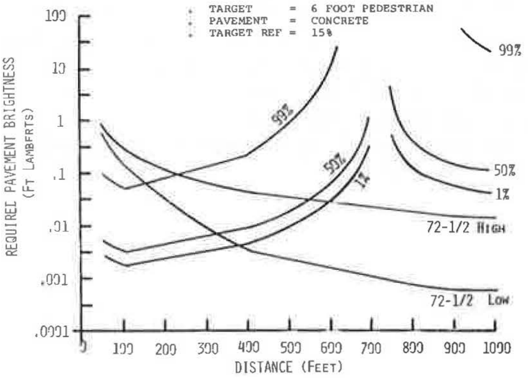


Table 1. Comparison of observed and predicted seeing distances (feet).

Head Lamp	Observed: Pedestrian Target[a] (5)	Observed: Square Target[b] (1)	Predicted: Pedestrian Target	Predicted: Square Target
Low beams	375	199	370	195
Mid beams		253		300
High beams	780	256	775	335

[a] Pedestrian target of 17.5 percent reflectance.

[b] Sixteen-inch square target of 8 percent reflectance.

To generate this curve requires that target size and reflectance and pavement retroreflectance properties be specified. The contrast and angular size of the target can then be computed for any distance, and the required background luminance can be read from Figure 5. If it is assumed that the road surface at the base of the target is the relevant background, contrast is given simply by the difference between target and background reflectance divided by background reflectance, inasmuch as illumination is the same for both (Fig. 4). Performing these operations at each of several distances yields the solid line curve shown in Figure 6. The directional reflectance of the pavement used in the computations to generate the curve increases with distance. At some point between 500 and 600 ft, pavement reflectance is equal to 10 percent, the same as the target, and contrast is zero as shown by the break in the curve. At lesser distances the target is in positive contrast with (brighter than) the pavement, and at larger distances the target is in negative contrast with (darker than) the pavement.

The dotted lines in Figure 6 show the background luminance levels produced at various distances by typical high and low beams. Detection is predicted at the point where a headlight curve crosses the threshold curve. With low beams, the target is detected in positive contrast at about 400 ft. With high beams, the target is detected first in negative contrast at about 950 ft, disappears at about 700 ft, and is detected again in positive contrast at 500 ft.

The formulations shown in Figures 5 and 6 indicate that under certain conditions a target of low reflectance may be seen at a greater distance than a target of somewhat higher reflectance. Further, seeing distances to a target whose reflectance is near the midpoint of the pavement reflectance gradient are likely to be highly variable because of the double threshold; that is, some observers will see the target first in negative contrast and others will detect it only when it is close enough to be in positive contrast.

Figure 7 shows similar information except that, instead of a single contrast threshold detection curve, there are curves for 99th, 50th, and 1st percentile detection. For the conditions specified, a 30-fold increase in background brightness (and hence in candlepower) is required to increase the probability of detection at 300 ft from 50 to 99 percent.

Table 1 gives a comparison of observed (1) and predicted (from the Ford seeing distance model) seeing distances. The predicted seeing distances included analyses of directional reflectance properties of a Ford Proving Ground asphalt surface. Isocandela diagrams for the type of head lamp used in the field tests were used, but there is no way of knowing how closely these agreed with the beam patterns of the head lamp used in field experiments. The predicted seeing distances agree closely with Hemion's field data (5) and with Adler and Lunenfeld's low-beam data (1) but not with the mid- or high-beam data. The poor prediction of the Adler and Lunenfeld mid- and high-beam seeing distances may be due to inaccurate representation of the surface or the mid- and high-beam patterns used in their study.

FIELD EXPERIMENTS, SURVEYS, AND ANALYSES

A program of field studies, literature reviews, and surveys is under way at Ford to (a) validate the seeing distance model for pedestrian and delineation targets, (b) develop formulations for dealing systematically with discomfort glare, and (c) obtain representative data on the night driving environment for the standardized test route.

Seeing Distance Studies

Seeing distance tests were conducted to validate the contrast detection and veiling glare formulations used in the seeing distance model and to determine the effect of increased foreground illumination on down-the-road seeing distance. The second objective was addressed because some controversy exists on how much foreground illumination is desirable, and at least one study (6) has found that high-beam seeing distances are reduced by a bright foreground. Seeing distances to pedestrian silhouette targets and pavement lines were determined for 12 observers under various conditions of illumination, glare, and target reflectance. Trials were conducted with type 5 (government proposed) high beams, with type 2 low beams, and with both to simulate a high beam with a very bright foreground. In these observations, the glare source was stationary. Predicted and actual results for pedestrian and delineation targets in the absence of glare are shown in Figures 8 and 9. Figure 10 shows predicted and actual seeing distances to line targets in the presence of glare plotted as a function of the distance between the target and the glare sources. In all cases, Blackwell's $^1/_{30}$-sec exposure, contrast detection curves (3) were the basis of the predictions. In general, the data conform to the predictions. The fit to the pedestrian target data is very good, but the delineation seeing distance predictions with or without glare differ from the means by as much as 25 percent.

The data shown in Figures 8 and 9 provide no evidence that a bright foreground decreases the visibility of distant targets, i.e., the addition of a low beam had no effect on high-beam seeing distances.

Analysis is under way to resolve the discrepancies between predicted and actual seeing distances to delineation targets and to further evaluate glare data.

Discomfort Glare

A common finding in headlight studies in which glare and observer headlights are the same is that seeing distance remains constant or increases as head lamp intensity increases, despite the increase in glare (5). For example, when opposing cars meet, seeing distances may be greater for high than for low beams (6). The contrast threshold and disability glare formulations used in the Ford model would predict the same outcome. This is because, as head lamp intensity increases, contrast remains the same but the effective background luminance ($B_B + B_V$) increases; and, as Figure 5 shows, the contrast required for detection decreases with increasing background luminance. Low-beam head lamp intensity is thus limited more by discomfort glare than by disability glare. Disability glare has a quantifiable effect on seeing distance, and this effect is incorporated in the model. Discomfort glare is more difficult to quantify but is important because it determines the maximum acceptable intensity of low beams and the conditions under which opposing drivers will request dimming of high or mid beams. Current low beams produce levels of glare that would be rated as unacceptable by models developed to quantify discomfort glare in environments other than night driving. Nevertheless, low beams are tolerated because they represent a reasonable compromise between glare and visibility that has evolved over the years. This is why current low-beam intensity provides the basis for the maximum acceptable discomfort glare level used in the present version of figure of merit in the evaluation model.

The problem of dealing with the discomfort glare produced by mid and high beams is somewhat different because they can be dimmed in response to requests from opposing drivers. High beams are normally dimmed as a matter of course in meeting situations, but the question arises of whether increases in high-beam intensity beyond a certain point produce a net loss in seeing distance because the increased glare results in dimming at greater separation distances.

The potential advantage of mid beams is based on considering them as an augmented low beam rather than a type of high beam; i.e., they need not necessarily be dimmed in meeting situations. In particular, their usefulness will depend on the range of highway conditions under which they can be used in meeting situations. Whether mid beams can be used in a given situation will depend on the level of discomfort glare they produce. At some level of intensity, an opposing driver will request dimming. This intensity will vary from one situation to another depending on distance, highway geometry, ambient brightness, and head lamp misaim.

Determining a maximum acceptable low-beam discomfort level empirically is difficult. Discomfort rating scales are of questionable validity because there is no way to estimate the extent or direction of the bias introduced by the test subjects in a

Figure 8. Observed and predicted seeing distances to pedestrian targets.

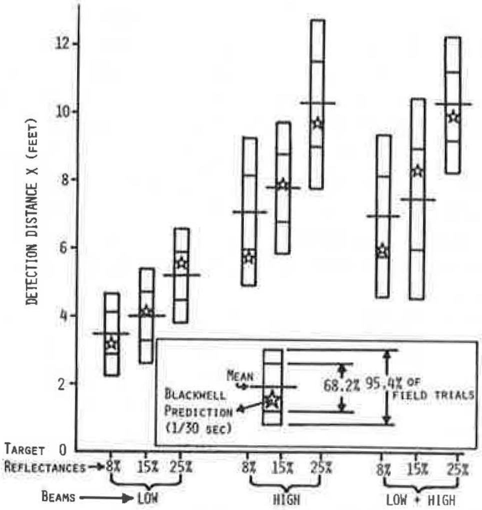


Figure 9. Observed and predicted seeing distances to line targets.

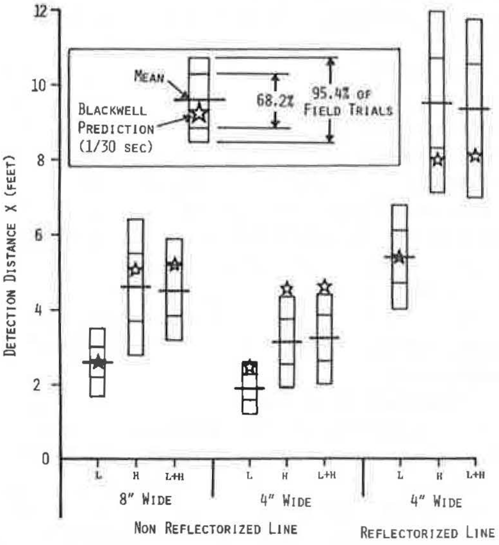
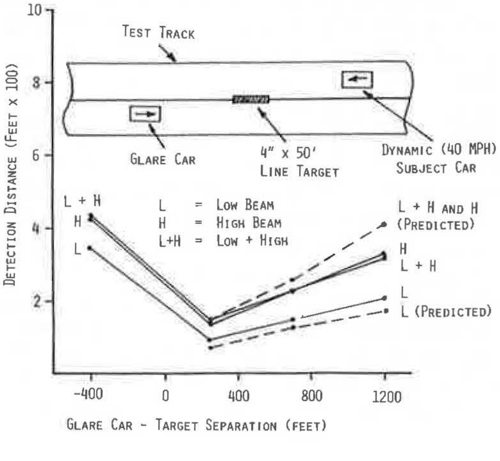


Figure 10. Observed and predicted seeing distances to 4-in. by 50-ft reflectorized line targets.



structured test situation. Counting dimming requests to lamps of varying intensity in actual traffic is also of questionable value in the case of low beams because there is no way of knowing whether opposing drivers are responding to discomfort, brightness, or their estimate of the opposing car's beam type. Further current research by Ford indicates that drivers will tolerate an occasional glare source, without making a dimming request, that is at a far higher level of intensity than would be acceptable on a routine basis. Nevertheless, to the extent that frequency of dimming requests is an index of discomfort, such data can be used to estimate the percentage of drivers discomforted by various levels of glare. Such a formulation might be used as the basis of a somewhat more sophisticated definition of the role of low-beam discomfort glare in the evaluation model.

In the case of high or mid beams, the concern is not with discomfort as such, but with the effect of discomfort, real or anticipated, on beam use. The problem is to determine the conditions under which drivers will permit each other to use mid and high beams. For this purpose, a study of actual dimming requests in response to lamps of various intensities is appropriate.

Glare Acceptance Research

A pilot study was performed to explore some of the factors influencing glare acceptance on public roads. In this study, an instrumented vehicle equipped with three different head lamp systems was driven on a 2½-mile straight section of a lightly traveled non-illuminated public road. The systems were (a) two 7-in. lamps, (b) two 5-in. lamps, and (c) four 5-in. lamps. In system c the intensity relationship between inboard and outboard lamps was as in current four-lamp, two-beam systems. The measure of glare acceptance was the percentage of opposing drivers requesting dimming at various distances. Each head lamp system was exposed to oncoming traffic 30 times under the following three intensity levels: 3,000 cd, equivalent to current low-beam glare; 60,000 cd, equivalent to current high-beam glare; and 105,000 cd, equivalent to a government proposed high-beam system. The candela values are the totals for all the lamps of a system, measured along a vector to an opposing driver's eye point 1,200 ft away. These are, of course, nominal values. Actual illumination levels for each system at the location of an opposing driver's eyes were measured at various distances.

Analysis of the data revealed no effect of total lamp area or number of lamps. However, as expected, the distance at which a given percentage of dimming requests took place was greater for 105,000 than 60,000 cd. None of the 3,000-cd systems resulted in dimming requests. A number of discomfort glare models (7, 8, 9) were investigated to provide a context for organizing the data. The Guth (7) and Linde (8) models were not found to be useful for this purpose. The DeBoer (9) model, however, provides a discomfort scale that is consistent with the Ford dimming request data. Discomfort is scaled by DeBoer as a function of illumination, the observer's line-of-sight angle (the angle between the observer's line of sight and the vector from the observer to the glare source), and adaptation (ambient) brightness. Figure 11 shows isodiscomfort lines plotted according to DeBoer's expression and illustrates the path of the candela levels through DeBoer space as the opposing vehicles close. (Note that the DeBoer index value decreases with increasing discomfort.) The adaptation level assumed was 0.01 ft-L. Also shown are the percentages of dimming request signals by drivers who had not previously signaled for each level of candela and region of DeBoer space. The two high-intensity paths are close to each other in DeBoer space, and the percentages of dimming requests in corresponding discomfort regions are similar for the two intensities. This suggests that the discomfort index accounts, at least in part, for dimming request behavior. However, distance is obviously a factor in that, within about 1,000 ft of the opposing vehicle, drivers who have not yet signaled are less likely to signal as the distance closes, despite the increase in the glare index. Very few dimming requests occur within 250 ft, and a certain percentage of drivers never request dimming in an encounter. Apparently for those drivers who do ultimately signal, the

Figure 11. Relationship of dimming requests to discomfort glare.

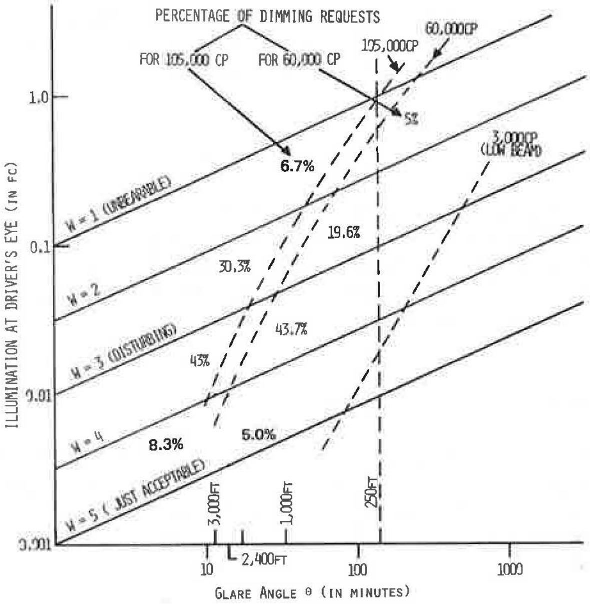
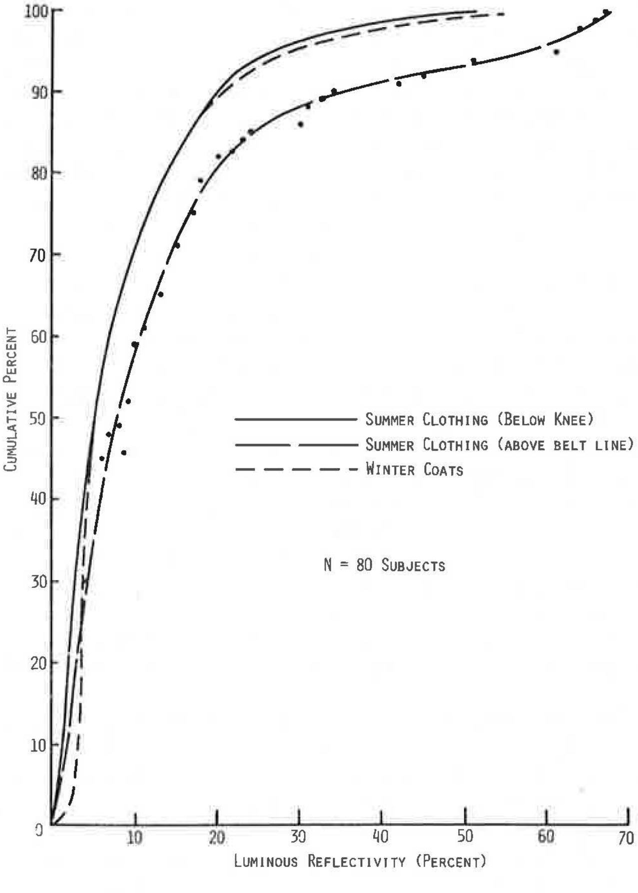


Figure 12. Cumulative distribution of reflectivities.



median discomfort threshold is reached at a discomfort index between 2.5 and 3.5.

Data collection is continuing on this problem to further evaluate the DeBoer model and to determine duration-of-exposure effects associated with highway geometry.

Reflectance and Ambient Brightness Surveys

Target contrast is dependent on the reflectance of both the target and background and the ambient brightness. To provide representative data for the standardized test route, two survey programs have been undertaken, one on pedestrian reflectance and the other on the reflectance of pavement, shoulder, and delineation and the ambient brightness of the highway environment at night.

Pedestrian Reflectance Survey

The pedestrian reflectance survey has been completed (Fig. 12). The data were obtained by measuring the reflectance of the summer and winter clothing of Ford employees. The reflectance of the pedestrian targets represented in the standardized test route will be randomly drawn from these distributions.

Highway Reflectance Survey

Pavement reflectance data will be obtained at sites in a number of states. The reflectance of a surface is defined as the ratio of its luminance to the incident illumination. Two types of reflectance will be considered: retroreflectance, the percentage of head lamp illumination returned by the highway surface to a driver from his own head lamps, and forward reflectance, the percentage reflected by the surface to an observer in an opposing vehicle. Because of the low angles of incidence and reflectance (less than 1 deg beyond 150 to 300 ft), the necessary measurements are tedious and difficult, and there has been only one systematic study of head lamp illumination reflectance (10).

Data collection has been simplified by the development of a photographic technique for measuring reflectance. A calibrated, stabilized light source of known candela distribution is used to illuminate the highway section to be photographed. A telescope fixed to the light source is used to aim the optical axis of the lamp at a precise point on the roadway. The illuminated section is then photographed with Kodak 2475 film. Figure 13 shows a print of such an exposure. Each roll of film is calibrated by photographing a gray scale with known luminance values so that luminance can be scaled in terms of film density. The luminance of the pavement at any point can then be determined by measuring the density of the negative at that point. Luminances measured by the photographic technique are within a tenth of a log unit of the same values measured with a Pritchard photometer. The illumination from the source lamp at that location is obtained from its isocandle diagram. This is determined by finding the azimuth and elevation of the measured point relative to the source lamp's optical axis and reading the candela off that point in the isocandle diagram. The candela so obtained is divided by the square of the distance between the lamp and the measured point to yield illumination. Reflectance is then given by the ratio of luminance to illumination. This procedure is carried out on various points on the paved surface, the shoulder, and the delineation.

Retroreflectance data for several Ford Proving Ground surfaces are given in Figure 14. In general, retroreflectance increases with increasing distance from the source. Based on the limited data available, the retroreflectance of the road surface does not vary significantly with the lateral position of the measured point beyond a distance of 100 ft.

Forward reflectance data (taken with the camera looking toward the light source 800 ft away) are shown in Figure 15. This figure shows contours of equal reflectance on a plan view of the pavement. Forward reflectance values are 10 to 100 times greater

Figure 13. Print of retroreflectivity of pavement and gray scale used for calibration.

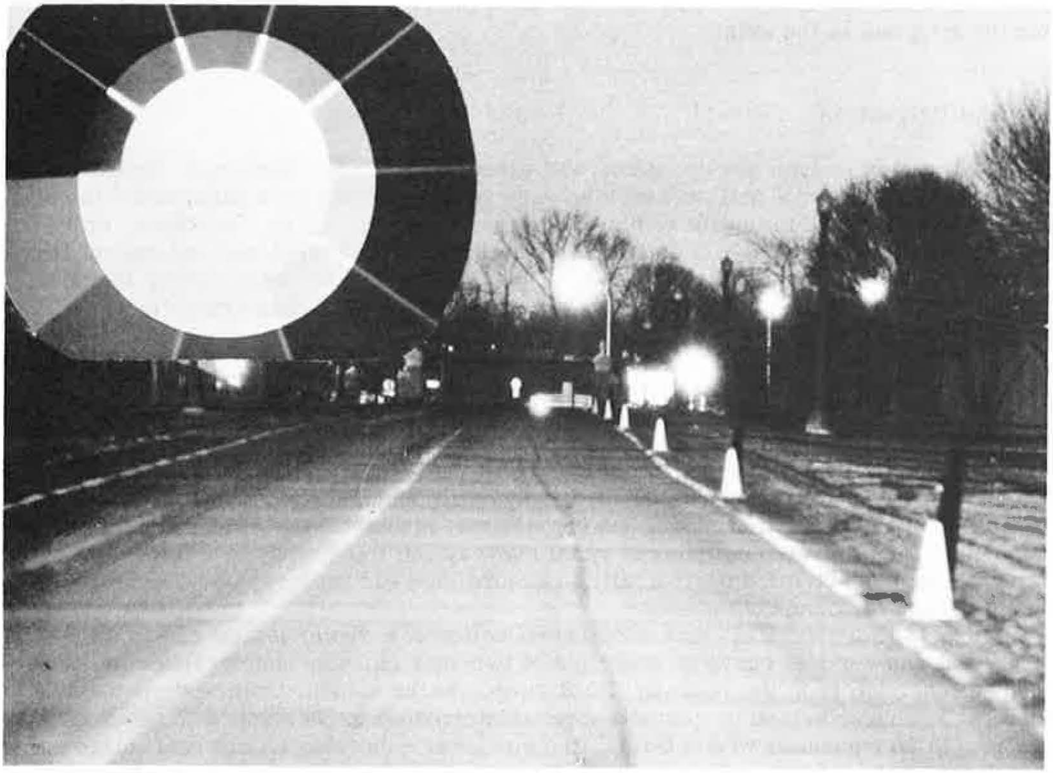
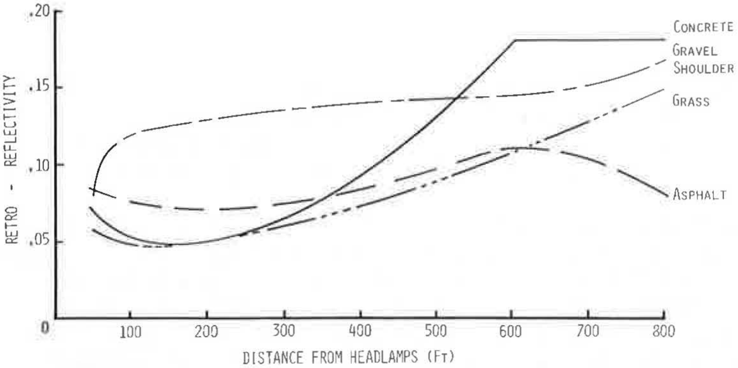


Figure 14. Retroreflectivity coefficients as a function of distance for various road surfaces.



than retroreflectance values because there is a large specular component. Maximum values lie along the source-observer axis and peak at a point that lies between the lamp and the midpoint of the axis.

Ambient Brightness

Path delineation is seen wholly against the pavement surface. However, portions of a pedestrian-sized target will normally be seen against the sky or a background too distant for head lamp illumination to have any effect (Fig. 16). It is, therefore, important to have representative data on the ambient luminance of the night sky and distant backgrounds as well as the nearer surfaces. These values will be measured by the photographic technique at the same time that pavement reflectance data are collected.

Topography Survey

Hills and curves have an important influence on head lamp performance because they displace the beam pattern from the roadway. A photographic survey of road topography has been performed to provide data for the development of the standardized test route to be used in the evaluation model. A camera was mounted in a vehicle driven over a 1,500-mile route of various types of rural highway and topography in a five-state area. The camera was activated periodically to record the road topography. The film was then digitized for computer storage.

Figure 16 is a computer-generated reproduction of a driver's view of a combined horizontal and vertical curve on a section of two-lane highway photographed in the survey; a pedestrian is in the roadway 400 ft away. In the standardized test route each segment is characterized by geometric parameters such as were used to generate Figure 16. In an encounter with a target, the computer generates an internal image similar to that depicted in the figure. The computer then determines the location of the targets and the background with respect to the driver and the optical axis of each working head lamp to permit computation of the photometric quantities, which, in turn, determine seeing distance.

Driver Attention

One of the more important considerations governing visual performance under actual highway conditions at night is the state of alertness of the driver. Headlight-seeing distance tests are typically conducted with an alerted observer who understands that his task is to detect targets as soon as possible. Often the observer knows the exact location of the target.

In 1938 Roper (11) compared the detection distances of alerted and unalerted drivers to a pedestrian dummy placed in the middle of a driving lane on a lightly traveled public road. Roper considered that detection occurred when the unalerted driver lifted his foot from the throttle. The same observer then was allowed a second detection trial with the same target after having been alerted to its presence. On the average, detection distances for alerted observers were two times those of unalerted performance. Cumulative curves of percentage of seeing distance for alerted and unalerted drivers, based on Roper's findings and Blackwell contrast threshold data (representing the alerted driver), are shown in Figure 17.

These curves, generated by the Ford seeing distance model, indicate that the median detection distance for the alerted driver is almost twice that of the unalerted driver. An important consequence of this finding is that differences in seeing distance between head lamp systems as measured in formal seeing distance tests with alerted drivers would, on the average, be twice as great as those expected in the real world. Thus, a 60-ft seeing advantage for a system in a test situation would translate to a 30-ft difference in the real world.

Figure 15. Contour of constant forward reflectivity.

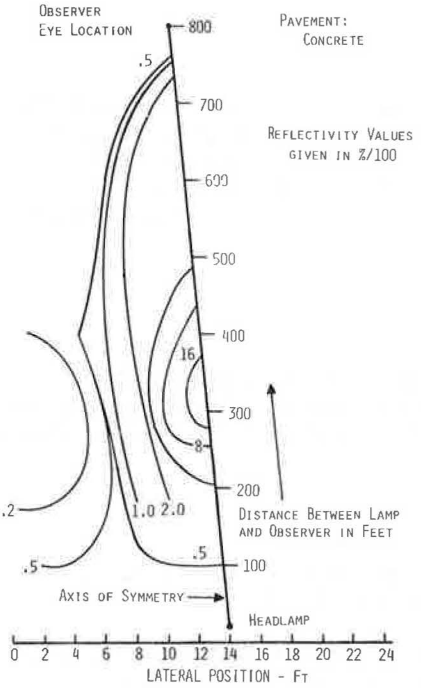


Figure 16. Computer reproduction of highway geometry and pedestrian target.

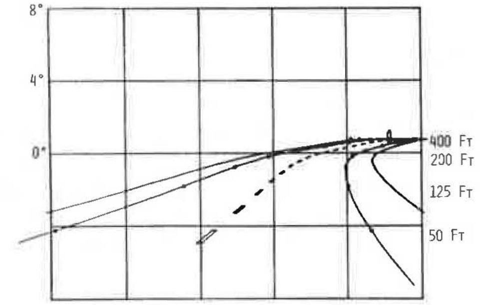


Figure 17. Cumulative probability of detection as a function of target distance.

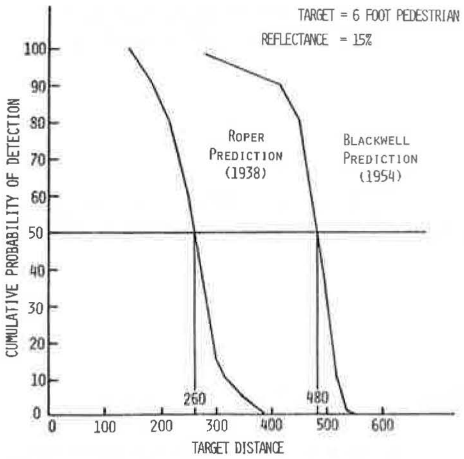
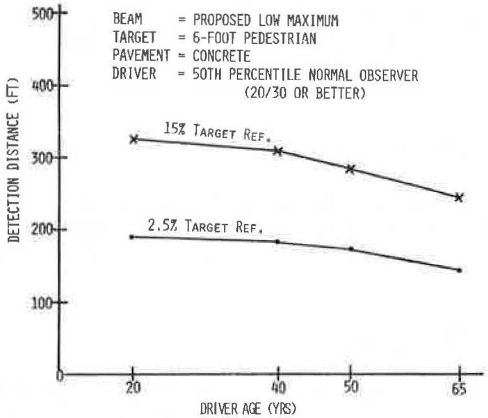


Figure 18. Target detection distance as a function of age of driver.



Roper's findings will be used in the evaluation model to represent driver performance under actual highway conditions rather than formal test conditions.

Driver Age

Figure 18 shows the effect of age on seeing distance and is based on data developed by Blackwell (12). The encounters simulated did not include glare from an opposing vehicle. In glare situations, a further decrement of seeing distance with age would be anticipated because of the greater susceptibility of older people to disability glare. This effect has been modeled by Fisher and Christie (4) and others and is incorporated into the Ford seeing distance model.

Head Lamp Misaim

Head lamp misaim data collected by Hull (13) have been analyzed to provide distributions of misaim in the U.S. vehicle population. These distributions will be used to generate random levels of misaim in the observer and opposing vehicles in the simulations.

CONCLUSIONS

Experience to date from field testing, analysis, and model development has tended to confirm the assumptions under which the program was undertaken.

1. Important measurable aspects of driver visual performance at night (i.e., seeing distance and response to glare) can be predicted from laboratory formulations describing human brightness-contrast detection thresholds and glare susceptibility.
2. The environmental and vehicle factors that determine night driving visibility conditions can be defined and expressed in terms suitable for computer simulation.
3. Because these human and physical factors can be reduced to mathematical expressions, the development of a computer model to evaluate headlight systems in terms of objective measures of driver performance under various conditions is a feasible and worthwhile undertaking.

ACKNOWLEDGMENT

This work was performed in the Environmental and Safety Research Office of the Ford Motor Company. The authors acknowledge the contribution of David E. Naurer, who developed the original Ford seeing distance model.

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This paper addresses the problem of the specification of lighting for the automobile driving operation. The empirical relationship between a measure of driver visual performance and several methods of quantifying visibility is explored in an effort to develop roadway lighting specifications based on visibility needs. Physical contrast, equivalent contrast, relative contrast sensitivity, and glare exposure are discussed. Field measurements of the visual performance of 941 unalerted motorists are analyzed, and a precise method of quantifying visibility is identified. The form of the suggested visibility term uses physical contrast, contrast sensitivity, and a disability glare factor. A method of prescribing visibility in terms of safe stopping requirements is discussed. Follow-up research that will enhance the reliability of the measures, extend the general applicability of the concept, and further develop the prescription approach is outlined.

CONTRAST REQUIREMENTS OF URBAN DRIVING

Vincent P. Gallagher and Patrick G. Meguire,
Franklin Institute Research Laboratories

The purpose of this study was to develop a technique for quantifying and specifying the visibility needs of urban drivers in a manner consistent with state-of-the-art lighting engineering capabilities and practices.

Lighting specifications are typically given as units of average flux with limits of uniformity or dispersion. Warrants are typically related to traffic, geometric, and road use conditions. The specification of lighting has undergone much debate especially as attempts are made to provide international compatibility of standards. There has been much disagreement on the efficacy of specific warranting criteria and on the question of flux units. Many organizations have expressed lighting requirements in terms of pavement luminance. Since the eye requires reflected light to detect objects in space, this approach is clearly related to the needs of drivers. These units present a complex measurement dilemma, however, because pavement luminance cannot be predicted reliably based on the distribution of flux output of luminaires. This is mainly because light reflected off paving surfaces is not uniformly diffuse (1).

The eye responds to small differences in luminous intensity and exposure duration. The limitations of this information processing system must be considered in the context of the human operation under study. Therefore, the problem is addressed in terms of drivers' information and visibility needs. This study assesses the predictive strengths of various visibility concepts and formulations. The experimental conditions have been described in detail by Gallagher and Meguire (2).

EXPERIMENTAL CONDITIONS

Driver Performance Measure

The critical measure of driver visual performance was the time separation between the vehicle and a target when an evasive response was initiated. We measured the point of response as distinguished from the point of perception because the evasive response of a driver to a roadway obstacle of high visibility is largely unconstrained and the driver exercises considerable judgment concerning when he will brake or change lanes. However, when target visibility is lower, the time between perception and response is reduced largely because of the driver's interest in maintaining some personally acceptable comfort level (i.e., with respect to swerving or rapid deceleration). When target visibility is extremely low, drivers respond almost at the point of perception because their time (i.e., distance-velocity) separation is extremely short.

Test Site

The test site was 7th Street between Packer and Pattison Avenues in south Philadelphia. The site is six lanes wide and approximately 1,800 ft (550 m) long.

The lighting system used (Fig. 1) enabled the horizontal and vertical illumination levels and illumination uniformity to be varied. A detailed description of this system can be found elsewhere (3).

Target Placement

The target used was the bottom 18 in. (0.5 m) of a standard traffic cone (the top was cut off) painted to be 6 percent (gray) reflectant.

The targets were spaced at 50-ft (15-m) intervals in the center of the middle southbound lane (Fig. 1). This arrangement provided a full range of representative target placements with respect to the surrounding luminaires. Taken in conjunction with appropriate target visibility measurements (discussed below), these target positions enable determination of the visibility characteristics of the lane under various street lighting configurations. It then becomes possible to predict drivers' behavior in avoiding roadway obstacles of different visibilities based on the placement and reflectance characteristics of the target and roadway visibility.

VISIBILITY MEASURES

The comprehensive study (2) from which this report is derived reported on 10 visibility indexes. Three have been chosen for discussion because of their predictive power and their conceptual importance:

1. Classic contrast (7)

$$C_1 = \frac{\Delta L}{Lb}$$

2. Visibility index (2)

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right] (DGF)$$

3. Effective visibility level (5, 6)

$$VL_1eff = \left[\frac{Ceq(RCS_{Lb})}{5.74}\right] (DGF)$$

Contrast

Visual perception, at least at the threshold level for simple stimuli, is the direct result of perceived differences in background (Lb) and target (Lt) luminances. This difference would be perceived contrast if subjective scales for brightness sensitivity were available. Since they are not, this sensation is approximated by a pure ratio of physically measured stimuli levels (7). This ratio is termed contrast C_1 and is defined as

$$C_1 = \frac{|Lb - Lt|}{Lb} = \frac{\Delta L}{Lb} \qquad (1)$$

This form of the ratio can be used for objects either darker or brighter than the background inasmuch as ΔL represents the numerical difference of the two luminances.

As indicated, this ratio is an approximation of the visibility value of a specific luminance background condition. Because contrast sensitivity is related to background luminance, contrast in its pure form is useful only as a relative comparison of target visibilities under a single background luminance level. For a more universal application of this relationship, some information about contrast sensitivities is required. Blackwell has provided empirical data on relative contrast sensitivity for the low luminance levels typical of roadway lighting (Table 1).

Applying an appropriate relative contrast sensitivity (RCS) value to the calculated C_1 value permits comparison of contrasts calculated for diverse values of driver adaptation luminance.

The Franklin Institute Research Laboratories uses the immediate target surround for background luminance; glare luminance is measured separately and included in some formulations as a separate entity. The terms used were

Lb = background luminance measured at 200-ft (61-m) separation, 43-ft (13-m) photometer elevation, and 30-min photometric aperture

Lv = veiling luminance measured under the same conditions as Lb by using calibrated Fry lens (4)

$\overline{Lb}$ = arithmetic average of Lb along the length of roadway

$$\overline{Lb} = \frac{\Sigma Lb}{N}$$

$\overline{Lb}'$ = arithmetic average of Lb plus Lv at the spot

$$\overline{Lb}' = \frac{\Sigma[(Lb + Lv)/1.074]}{N} \qquad (2)$$

Equation 2 is derived rather loosely from Blackwell's $L' = L + L_v/1.074$ and represents an average value of Lb′ assuming that the Lv of the roadway is not restricted to a single spot. The value 1.074 is a correction for sphere-base glare.

The adjustment of the C_1 ratio can be accomplished most directly by using the RCS value for the luminance most closely approximating the adaptation level of the driver's eye (5). Because the driver is moving through a nonuniform luminance field, only a crude approximation is possible.

The best estimate uses the product of C_1 and the RCS relative to $\overline{Lb}$:

$$C_2 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right) \qquad (3)$$

C_2 may be termed effective contrast or C_2eff. It should be noted that the RCS value increases as $\overline{Lb}$ increases. This is a source of some difficulty, for it is not sensitive to differences in Lv. Lv degrades visibility by reducing contrast. However, as Blackwell has indicated, veiling luminance also contributes somewhat to visibility by raising the level of adaptation. Therefore, the following form is proposed:

Figure 1. Test site.

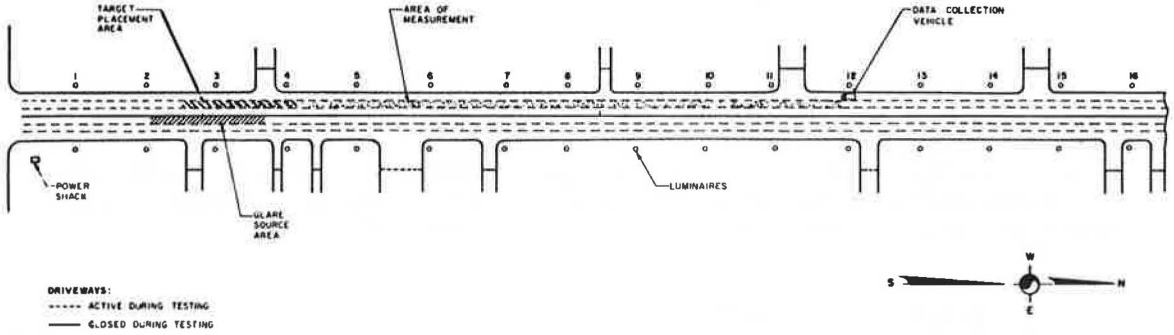


Table 1. Relative contrast sensitivity as a function of luminance for low luminance levels.

RCS	L(ft-L)	RCS	L(ft-L)	RCS	L(ft-L)
17.2	0.473	13.5	0.292	9.9	0.166
17.1	0.467	13.4	0.288	9.8	0.163
17.0	0.461	13.3	0.284	9.7	0.161
16.9	0.456	13.2	0.279	9.6	0.158
16.8	0.450	13.1	0.275	9.5	0.155
16.7	0.444	13.0	0.271	9.4	0.153
16.6	0.438	12.9	0.267	9.3	0.150
16.5	0.432	12.8	0.263	9.2	0.148
16.4	0.429	12.7	0.259	9.1	0.145
16.3	0.423	12.6	0.255	9.0	0.143
16.2	0.418	12.5	0.252	8.9	0.140
16.1	0.412	12.4	0.248	8.8	0.138
16.0	0.409	12.3	0.244	8.7	0.135
15.9	0.403	12.2	0.240	8.6	0.133
15.8	0.397	12.1	0.237	8.5	0.131
15.7	0.394	12.0	0.233	8.4	0.128
15.6	0.388	11.9	0.230	8.3	0.126
15.5	0.383	11.8	0.226	8.2	0.123
15.4	0.380	11.7	0.223	8.1	0.121
15.3	0.374	11.6	0.219	8.0	0.119
15.2	0.368	11.5	0.215	7.9	0.116
15.1	0.365	11.4	0.212	7.8	0.114
15.0	0.359	11.3	0.208	7.7	0.112
14.9	0.353	11.2	0.205	7.6	0.110
14.8	0.347	11.1	0.201	7.5	0.107
14.7	0.345	11.0	0.199	7.4	0.105
14.6	0.338	10.9	0.195	7.3	0.103
14.5	0.336	10.8	0.192	7.2	0.101
14.4	0.330	10.7	0.189	7.1	0.099
14.3	0.327	10.6	0.186	7.0	0.097
14.2	0.321	10.5	0.183	6.9	0.094
14.1	0.318	10.4	0.180	6.8	0.092
14.0	0.312	10.3	0.177	6.7	0.090
13.9	0.310	10.2	0.174	6.6	0.088
13.8	0.304	10.1	0.171	6.5	0.086
13.7	0.301	10.0	0.169	6.4	0.084
13.6	0.295				

Note: 1 ft-L = 3.4 cd/m^2

$$C_3 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right)\left(\frac{Lb}{Lb + Lv}\right) \qquad (4)$$

Equation 4 treats the problem of viewing a certain target-to-background relationship while the eye is adapted to other than simple background luminance and includes a correction for loss of contrast due to glare.

Inasmuch as glare is not restricted to the point of regard (i.e., target location) but is spatially distributed such that a moving observer experiences an adaptational effect with respect to glare, a more general term may be substituted.

$$C_4 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right)\left(\frac{\overline{Lb}}{\overline{Lb}'}\right) \qquad (5)$$

The extension of C_1 to C_4 represents an attempt to account for the exposure of drivers to physical conditions.

Visibility Concepts

Blackwell (5, 6) developed a conceptual framework and instrumentation for measurement of the visibility level. This quantity is measured with a visual task evaluator (VTE), which reduces the perceived contrast of a complex target to threshold and thereby establishes its visibility (for the background luminance under study) relative to laboratory data derived from a large sample (young adults), known target size (4 min), and brief exposure duration (0.2 sec).

As with other instruments requiring subjective matching, especially where color mismatches are expected (e.g., a roadway), a high degree of variability is accepted. Perhaps the most important limitation, however, is the subjective threshold criteria used by the operator, which is applied to the complex target. Whatever informational aspect of the target is chosen must be used consistently. If a nonuniform target is viewed against a nonuniform background, almost any movement of viewer or target will produce markedly different measures. Thus, although large variability is characteristic of the measures to be discussed, the theoretical framework provided by Blackwell is sufficient to extend the derivation of visibility measures to the furthest extent possible.

Effective Visibility Level

Blackwell defines effective visibility level as

$$VL_{eff} = VL \times DGF \times TAF \qquad (6)$$

(Blackwell's original nomenclature refers only to VL_{eff}. We have added subscripts 1, 2, and 3 for clarity while manipulating the various terms. Blackwell also uses a generic L for his background conditions, and we have altered this for clarity.)

The disability glare factor (DGF) accounts for glare produced by the light source as well as other reflective sources in the field of view. DGF has two components.

$$DGF = \frac{Lb}{Lb'} \times \frac{RCS_{Lb'}}{RCS_{Lb}} \qquad (7)$$

where $Lb' = (Lb + Lv)/1.074$.

The DGF has two components because, according to Blackwell, Lv both increases task background luminance (and thus contrast sensitivity) and decreases task contrast. DGF in Eq. 7 is, of course, related to the spot luminance immediately surrounding the target. Because an automobile driver has a more dynamic exposure, this effect may be simulated through use of DGF′.

$$DGF' = \frac{\overline{Lb}}{\overline{Lb'}} \times \frac{RCS_{\overline{Lb}}'}{RCS_{\overline{Lb}}} \qquad (8)$$

This is similar logic to that applied in the development of Eq. 5.

The other component required in the estimation of effective visibility level is VL. This is determined through subjective readings by using the VTE or photometrically by calculating task contrast.

The transient adaptation factor (TAF) (5, 6) compensates for losses in visibility due to exposure to levels of luminance different from that of the fixated region when normal scanning occurs. TAF obviously relates directly to the role of headlighting in the determination of adaptation level. The measurement procedure and data treatment of this parameter are being explored (6).

The classic form of Blackwell's formulation uses the DGF expressed in Eq. 7. The VL component is developed as

$$VL = \frac{Ceq}{C^*} \qquad (9)$$

where $C^* = 5.74/RCS_{Lb}$. The term Ceq is provided by using the VTE and applying known values of the operator's contrast sensitivity thresholds. [We have substituted the nomenclature C^* for Blackwell's term C_1 to avoid confusion. Blackwell defines C_1 as the "numerical values of threshold contrast corresponding to values of the visibility reference function VL_1, at different levels of task luminance" (5).]

A simple substitution into Eq. 9 yields the basic expression for VL_{eff}:

$$VL_1eff = \left[\frac{Ceq(RCS_{Lb})}{5.74}\right] (DGF) \qquad (10)$$

Blackwell has indicated the equivalence of the Ceq term and photometric contrast under certain conditions so that valuable information can be gained through a substitution of C_1 for Ceq in Eq. 10. The expressions using photometric contrast are termed visibility index (VI).

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right] (DGF) \qquad (11)$$

$$VL_2eff = \left[\frac{Ceq(RCS_{\overline{Lb}})}{5.74}\right] (DGF) \qquad (12)$$

$$VI_2 = \left[\frac{C_1(RCS_{\overline{Lb}})}{5.74}\right] (DGF) \qquad (13)$$

$$VL_3eff = \left[\frac{Ceq(RCS_{\overline{Lb}})}{5.74}\right](DGF') \tag{14}$$

$$VI_3 = \left[\frac{C_1(RCS_{\overline{Lb}})}{5.74}\right](DGF') \tag{15}$$

EXPERIMENTAL RESULTS

Figures 2, 3, and 4 show the relationship of visibility measures and driver performance. Table 2 gives the raw data plotted in those figures. Although the regression lines in the figures were calculated from all of the raw performance data points (N = 941), the scattergram in the figures and the performance points (TTT) in Table 2 are the means of the performance points for each measured visibility condition. Standard deviations are also given in Table 2. Statistical measures for nonnormal kurtosis and skewness indicated that all 15 distributions were within the probabilistic limitations of the normal distribution for the sample sizes measured.

The empirical results indicate that local measures of target contrast are the most important and that these vary little over the response distances measured.

The visibility separation distance was 200 ft (61 m). The maximum measured response separation distance was 477 ft (145 m), and the minimum separation distance was (a collision) 0. Given that the mean driver eye height is 43 in. (1.1 m), the following elevation angles are obtained for representative separation distances:

Separation, ft	Elevation Angle
50	4° 5' 43"
200	1° 1' 31"
500	0° 24' 46"

The differences in elevation angle are not great, and, despite the fact that asphalt reflectance is believed to change at shallow vertical angles, the differences are not felt to be important within the range of angles discussed.

Table 3 gives the luminance and glare measures characterizing the test conditions. Table 4 gives detailed descriptions of the various lighting configurations.

Table 5 gives the correlation coefficients for each of the 15 visibility conditions and all performance data points (N = 941).

It is clear from this table that all measures were convincingly significant. Those measures using C_1 provided the strongest predictive expressions. The simplest form of VLeff proved to be the most reasonable of the VL measures.

The factor providing the greatest amoung of information about the visibility is $\Delta L/Lb$.

The factors related to the immediate surround of the target are more meaningful than the average values of either Lb or Lv. These differences are not great, but in the interest of uncovering the most conservative expression we have attempted to discriminate among several equally powerful alternatives. The first choice, of course, is simply $\Delta L/Lb$. However, it is doubtful whether this form would hold up under more disparate conditions.

Blackwell's terms developed in the laboratory under uniform luminance conditions proved to be better estimates of visibility than the time history of luminance exposure of the driver. The reasons for this are not clear, but it may be that the simple arithmetic mean used ($\overline{Lb}$) is not a good estimate of adaptation luminance.

The difference in influence of the twin components of DGF,

Figure 2. Regression line for C_1 and all performance points measured.

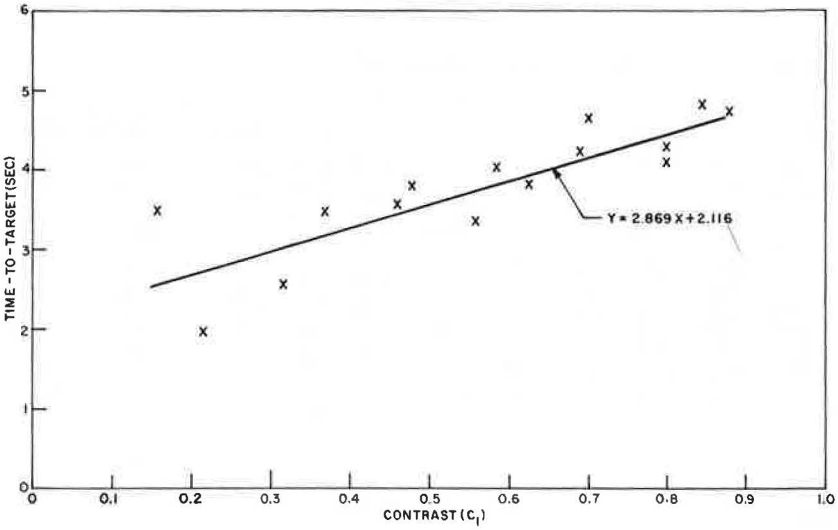


Figure 3. Regression line for VI_1 and all performance points measured.

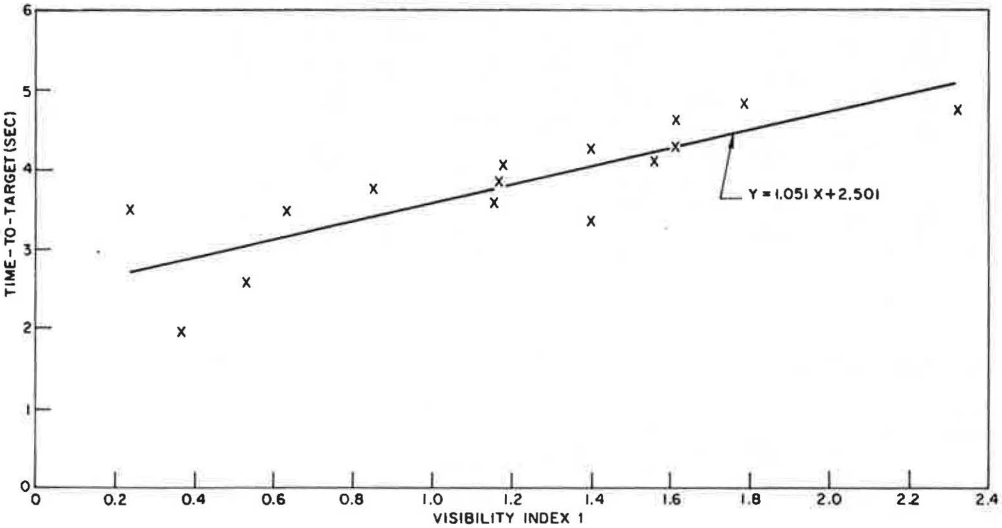


Figure 4. Regression line for VL_1eff and all performance points measured.

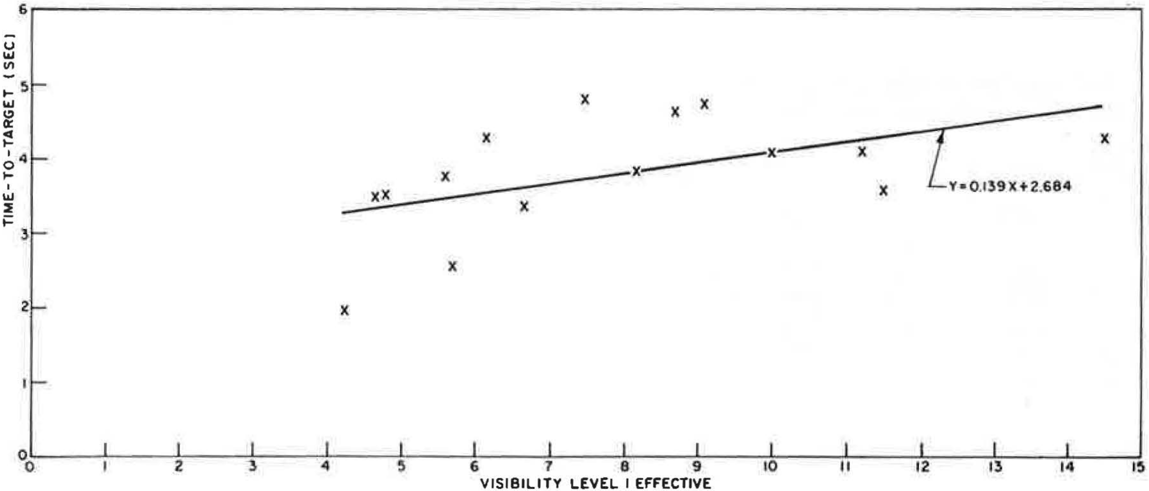


Table 2. Visibility parameters and performance measures for lighting conditions studied.

Lighting Condition	Target Position	VL_1eff	VI_1	VL_2eff	VI_2	VL_3eff	VI_3	C_1	C_2	C_3	C_4	Mean TTT[a]	Standard Deviation	Sample Size
3	5	8.686	1.617	9.164	1.706	9.266	1.725	0.703	11.297	8.531	8.755	4.638	1.936	58
3	6	6.647	1.394	6.578	1.380	6.548	1.374	0.560	8.995	7.028	6.971	3.360	1.631	60
5	5	8.169	1.171	8.880	1.273	9.277	1.330	0.627	8.591	6.157	6.739	3.826	1.615	60
5	6	4.224	0.366	5.098	0.441	5.243	0.450	0.214	2.935	2.148	2.302	1.977	1.845	60
5	8	9.102	2.317	7.585	1.930	7.338	1.868	0.881	12.068	10.239	9.467	4.720	1.720	59
6	5	14.532	1.404	15.322	1.480	15.563	1.503	0.690	9.959	7.196	7.468	4.241	2.346	60
6	6	11.504	1.160	10.835	1.092	10.768	1.085	0.464	7.103	5.574	5.479	3.568	1.367	40
6	11	10.027	1.177	11.401	1.338	11.674	1.370	0.586	8.969	6.535	6.917	4.035	1.622	70
8	3	5.597	0.848	4.728	0.716	4.995	0.756	0.480	5.054	3.308	3.611	3.765	1.724	60
8	4	4.800	0.244	4.708	0.240	4.891	0.249	0.158	1.663	1.105	1.188	3.490	2.386	50
8	6	11.241	1.558	9.213	1.277	9.141	1.267	0.804	8.464	6.297	6.047	4.096	1.891	123
8	8	4.648	0.633	4.188	0.571	4.272	0.582	0.369	3.889	2.715	2.779	3.471	1.752	59
8	9	5.716	0.329	8.684	0.500	8.637	0.498	0.316	3.325	2.209	2.376	2.556	1.909	60
11	4	6.172	1.609	5.514	1.438	5.670	1.478	0.800	9.617	7.050	7.386	4.261	2.259	62
11	8	7.477	1.785	6.680	1.595	6.540	1.561	0.845	10.156	8.218	7.800	4.802	2.149	60

[a] Total sample.

Table 3. Luminance and glare values.

Lighting Condition	Target Position	Lb (ft-L)	$\overline{Lb}$ (ft-L)	Lt (ft-L)	Lv (ft-L)	Lb′ (ft-L)	$\overline{Lb'}$ (ft-L)	Ceq	C_1	DGF	DGF′
3	5	0.370	0.411	0.110	0.120	0.480	0.530	3.774	0.703	0.867	0.876
3	6	0.420	0.411	0.185	0.118	0.538	0.530	2.667	0.560	0.881	0.876
5	5	0.255	0.300	0.095	0.101	0.356	0.383	4.378	0.627	0.850	0.888
5	6	0.210	0.300	0.165	0.077	0.287	0.383	2.474	0.214	0.864	0.888
5	8	0.430	0.300	0.051	0.077	0.507	0.383	3.463	0.881	0.918	0.888
6	5	0.300	0.332[a]	0.093	0.115	0.415	0.442[a]	7.143	0.690	0.853	0.867
6	6	0.420	0.374	0.225	0.115	0.535	0.404	4.006	0.464	0.882	0.877
6	11	0.290	0.374	0.120	0.108	0.398	0.484	4.994	0.586	0.856	0.877
8	3	0.250	0.184	0.130	0.132	0.382	0.257	3.170	0.480	0.813	0.859
8	4	0.190	0.184	0.160	0.096	0.286	0.257	3.104	0.158	0.827	0.859
8	6	0.265	0.184	0.052	0.091	0.356	0.257	5.801	0.804	0.866	0.859
8	8	0.222	0.184	0.140	0.096	0.318	0.257	2.711	0.369	0.842	0.859
8	9	0.095	0.184	0.065	0.048	0.143	0.257	5.481	0.316	0.864	0.859
11	4	0.290	0.234	0.058	0.106	0.396	0.304	3.068	0.800	0.858	0.882
11	8	0.290	0.234	0.045	0.068	0.358	0.304	3.539	0.845	0.901	0.882

Note: 1 ft-L = 3.4 cd/m².

[a] Measurements made after substantial pavement wear.

Table 4. Lighting configurations studied.

Lighting Configuration	Average Horizontal Illumination (ft-c)	Average-Minimum Illumination	$\overline{LB}$ (ft-L)	Average-Minimum Luminance	Luminaires[a]	
					Spacing (ft)	Geometry
3	1.03	1.7:1	0.41	1.4:1	110.5	Opposite
5	0.50	1.7:1	0.30	2.1:1	221	Staggered
6	0.75	1.7:1	0.33	1.8:1	110.5	Single side, near
8	0.38	5.4:1	0.18	1.8:1	221	Single side, near
11	0.44	4.4:1	0.23	3.0:1	221	Opposite

Note: 1 ft-c = 1.07 lx; 1 ft-L = 3.4 cd/m²; 1 ft = 0.3 m.

[a] The luminaires were 400 W mercury vapor and 30 ft (9.1 m) high.

Table 5. Correlation coefficients for visibility indexes and all performance data points.

Visibility Measure	Correlation Coefficient	z Transform	Z	Significance
C_1	0.3104	0.3209	9.828	$>10^{-5}$
VI_1	0.3084	0.3188	9.764	$>10^{-5}$
C_2	0.3019	0.3116	9.544	$>10^{-5}$
VI_3	0.3007	0.3103	9.503	$>10^{-5}$
VI_2	0.3004	0.3100	9.493	$>10^{-5}$
C_3	0.2980	0.3073	9.413	$>10^{-5}$
C_4	0.2959	0.3050	9.342	$>10^{-5}$
VL_1 eff	0.1959	0.1985	6.079	$>10^{-5}$
VL_2 eff	0.1136	0.1141	3.494	$>10^{-3}$
VL_3 eff	0.1089	0.1093	3.349	$>10^{-3}$

$$\frac{Lb}{Lb'} \text{ and } \frac{RCS_{Lb'}}{RCS_{Lb}}$$

is evident. We do know, that the first term is larger in all cases and provides the more meaningful contribution if considered separately. The combined form is, of course, more conservative and is therefore highly desirable. Numerically, however, the term using DGF (VI_2) did not fare so well as the equivalent term without the second DFG component (C_3). These differences have little practical meaning however.

It appears that the RCS terms for $\overline{Lb}$ or Lb have little effect on the performance correlations except that the average values provide correlations somewhat lower than the spot background measure.

Contrast

The correlation of C_1 with driver performance was surprisingly strong. It is apparent that, within the range of variables studied, this represents the most important element in determining visibility. This is a serendipitous finding, of course, and indicates that visibility even in a system as complex as the roadway may be described in these terms. Some caution is warranted, however, for it may be necessary to provide adjustments to the pure form for visual situations of even greater complexity. This is especially true when high glare sources and nonuniform luminance conditions are present.

The range of Lb in this study was relatively limited, 0.095 to 0.430 ft-L (0.32 to 1.47 cd/m^2). Although these conditions are representative of a very large number of urban lighting conditions, the average luminance values and uniformities by no means exhaust even the most commonly encountered designs.

The contribution to the power of the visibility indexes of the correction factors for glare and time-averaged luminance was quite weak. Specifically, the variability of luminances was considerable under some configurations and, although no factor was applied with the intent of correcting for this exposure (except indirectly through the use of $\overline{Lb}$ and $\overline{Lb}'$), it is difficult to envision a meaningful contribution from such an effort. However, because conditions of both high luminance variability and glare can be anticipated in many installations, continued research on the effects of these factors on the adaptation state is needed.

Visibility Level

VL_1, the purest form of VL, proved to be the best predictor. Given the range of luminance under study and the magnitude of the differences of background and average luminance within a lighting configuration, the control for these differences was meaningless. The variability of the Ceq term contributed heavily to this outcome.

The visibility level component Ceq is a subjective measure and consequently is relatively unreliable. The choice of visual criteria for the determination of threshold is difficult and apparently resulted in a higher variance for this term. Hence, as subscripts were added to the VL_1 term, correlations with driver performance tended to decrease.

It should be recognized, however, that the target used was of relatively low internal contrast, and, although detection of a target such as a pedestrian is more complex, it was selected as a photometric expedient. The Ceq is most useful in a scene of greater complexity with a task of greater internal contrast where physical measures are inadequate as measures of visibility.

The VL_1eff expression did result in a highly significant correlation with the performance measures as noted. The substitution of C_1 for Ceq (producing VI_1) resulted in a somewhat more reliable measure in the present context.

DISCUSSION OF RESULTS

Stopping Time Requirements

Figure 5 shows plots of the regression line for the 50th, 15th, 5th, and 1st percentile responders. These target separation gaps are expressed in units of time. The 15th percentile, for instance, represents the upper limit separation time evidenced by the worst 15 percent of the responders. These extreme cases are explored so that we can develop some lighting design concepts related to both visibility and braking time requirements.

It would be speculative to attempt to identify casual factors related to the extreme cases of response performance. However, such extremes are truly representative of the driving public. We have sampled the diversity of scanning habits, acuity, and glare and luminance sensitivities as well as a host of situational factors such as attentional conflict and alcohol or drug use. In addition, some vehicular factors play a role, especially windshield condition (dirt and pitting) as related to glare experience or visual aberrations. Exploration of the extremes of performance although statistically somewhat less reliable is fundamental to the development of a design criterion.

The plot of performance versus VI_1 for the 15th percentile driver, then, provides extremely useful information. Because the ordinate is a time measure of the separation of response point and the target, it is possible to supply a time criterion for roadway operations on these visibility measures. The following are stopping time requirements for several commonly encountered vehicle velocities:

Velocity (fps)	Mean Braking Time (sec)
29.3	1.43
36.7	1.75
44.0	2.09
51.3	2.45
58.7	2.80
66.0	3.15
73.3	3.49
88.0	4.20
102.7	4.89

These requirements are for the response point through 0 velocity [at a uniform deceleration rate equal to ≈ 20 fps^2 (6.1 m/s^2)] for average vehicles (i.e., 50th percentile) and do not include any reaction or (leg) movement time component. This omission is justified because the performance measures are response measures occurring after the cognitive and motor activities of reaction-movement time are completed.

By using Figure 6 we can determine the minimum visibility that must be provided for a target to be seen at a satisfactory separation distance by 85 percent of the driving public. It may be desirable to provide even greater contrast as a design requirement so that adequate visibility is provided for 95 to 99 percent of the drivers at distances sufficient to permit safe braking.

These plots can be used for any of the lower design speeds to determine the required minimum visibility level. The values related to the higher design speeds and probabilities were extrapolated and represented as linear as indicated. Additional research is required for complete confidence in the required VI_1 at high levels.

Figure 5. Regression lines for driver responses and VI_1.

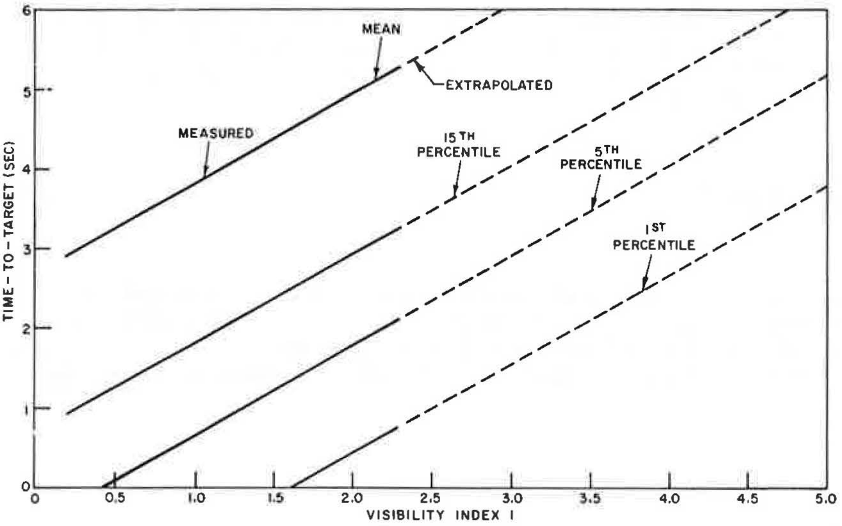
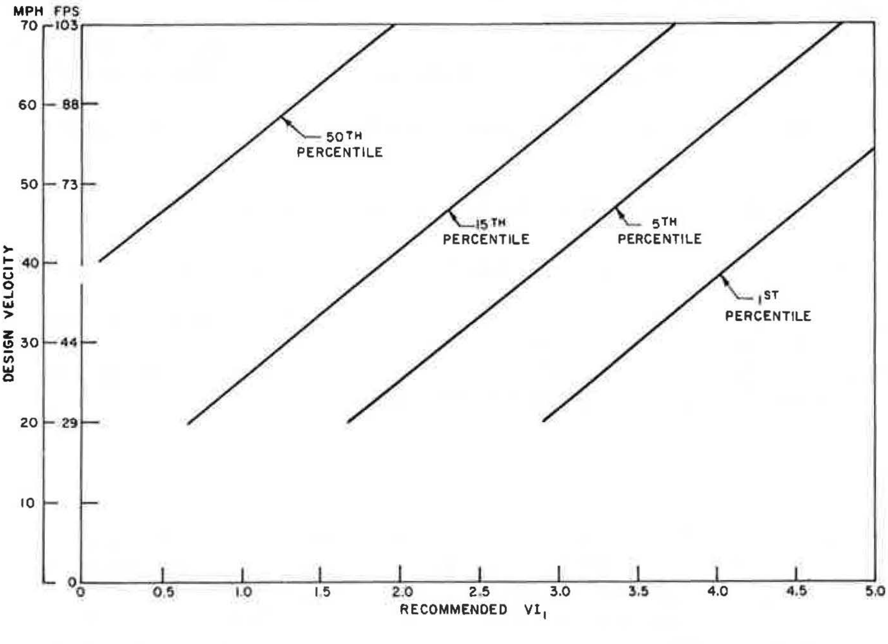


Figure 6. Suggested VI levels for various design speeds and driver populations (extrapolated data).



Field Calculation

As noted, the pure form of contrast proved to be the most reliable predictor. This ignores, however, the known influences of contrast and glare sensitivities. To avoid any situational factors having a bearing on the data reported here we recommend the more general form as represented by

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right](DGF) \qquad (11)$$

Although there is little difference in the forms DGF and DGF′ as they affect the reported data, situations of higher luminance levels are often accompanied by higher glare, and therefore the use of DGF′ may be justified. However, if the target measurement area is unique with respect to the balance of the system in terms of glare, then VI_1 is preferred.

CONCLUSIONS

1. For a simple target, pure contrast ratio predicts driver visibility with considerable accuracy.
2. The influence of glare is largely undifferentiated under the lighting conditions tested.
3. Spot background luminance is a good predictor of adaptation level given the luminance variability reported on here.
4. Visibility index in the form VI_1 proved to be the most reasonable predictor, suggesting that in more variable situations (or as a general form) this measure should be used.
5. Ceq seems relatively sensitive to subjective factors causing this value to be highly variable.

Follow-up research should deal with the following conceptual areas:

1. Validation of the reported findings through the use of visual tasks other than target detection,
2. Extension of the independent variables into higher and lower levels of VI_1 for verification of the extrapolated curves, and
3. Development of a criterion and methodology for the evaluation of current roadway practices in terms of minimum visibility requirements.

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Because the rates of nighttime accidents are higher than daytime accidents, much research has been directed to the unique problems of night driving. Many researchers concur that the driver receives most of his or her information through the visual system. During night driving, the visual cues normally available during daytime are reduced. Whether this paucity of visual information is related to the higher night accident rate is not known. A basic approach to the problem is to identify through visual search patterns the driver's use of night driving cues. Identification of driver visual needs in night driving can eventually lead to improved night driving safety. This paper discusses and presents the results of two studies to investigate drivers' visual search patterns in night driving. The first study compares nighttime visual search behavior to daytime behavior on freeways and rural highways. The second study develops methods of using driver visual search data to evaluate illumination at rural highway intersections, which have high rates of nighttime accidents.

DRIVER SEARCH AND SCAN PATTERNS IN NIGHT DRIVING

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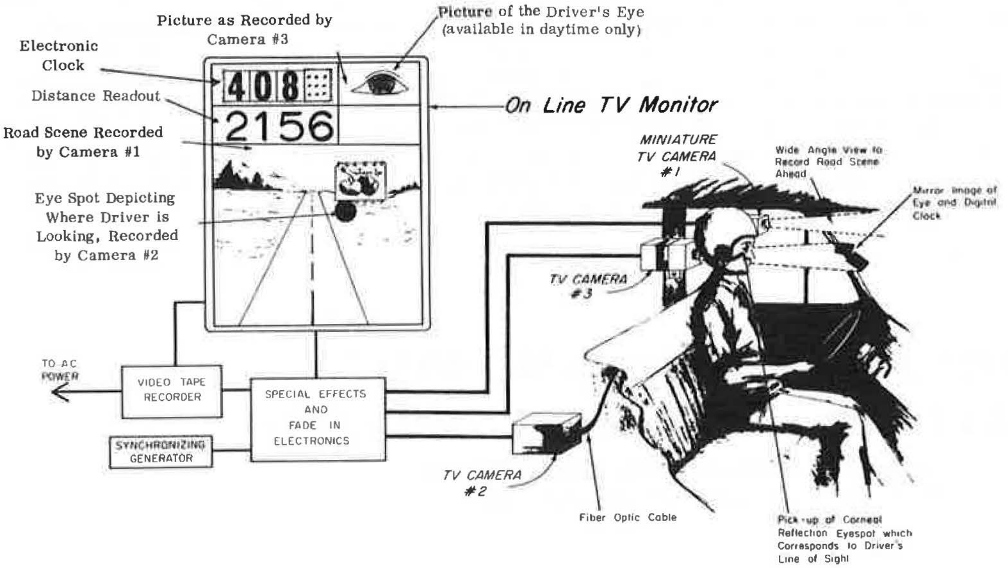
An essential step to the identification of driver visual needs is the understanding of where drivers visually search the environment. With the support of the Ohio Department of Transportation and the Federal Highway Administration, the Driving Performance Laboratory (DPL) of the Ohio State University has developed a method for measuring drivers' visual search behavior during night driving and has conducted several studies of this search behavior at night.

The system developed is a vehicle-based television system that records drivers' eye movements. The system continuously records on video tape the driver's direction of gaze while he is driving an instrumented car. The record contains a small light spot on the moving picture of the driving scene corresponding to the driver's point of fixation. This record and subsequent computer summaries of various measures enable quantitative analyses of visual search behavior (e.g., percentage of time viewing specific areas, fixation times, spatial distribution of fixation locations, eye travel distances).

THE RECORDING SYSTEM

The television system used in this study to record eye movement has been described in detail in another paper (2) and is shown in Figure 1. The driver wears a helmet that is securely located on the head by means of 16 separately adjusted pads on the helmet. In addition, an individually molded bite bar is fitted to the upper teeth and also fastened to the helmet by support brackets. When clamped, the helmet provides a stable unit for supporting the scene camera, light source, and reflection pickup lens. The scene camera provides a 54 by 41-deg view of the road scene ahead. For the night system, this camera was modified to operate at nighttime illumination levels. The light source shines a narrow beam of infrared light onto the driver's cornea, which then reflects from the cornea. As the eye moves this reflection also moves and is received by a pickup lens. This eye spot image is transmitted to a television camera via a high-resolution 3-ft fiber optic cable. The image of the moving eye from this camera is superimposed (faded) onto the driving scene depicted by the camera worn by the driver. The resulting combined image is displayed by a small television monitor in the vehicle, which permits calibration and constant checking of data quality. The resulting picture is recorded on video tape, which provides a permanent record of the data. When prop-

Figure 1. Eye movement recording system.



erly calibrated, the picture provides continuous recording of the driving scene and the driver's fixations (±1 deg) to objects within that scene. A third camera provides a picture of a digital clock, which updates every 20 msec, and a digital readout of distance along the roadway (every 5.28 ft), which is split into the top left of the TV picture to provide an accurate record of event times, durations, and road location.

Eye movement data are reduced by replaying the recorded video tape on a stop-action playback machine in the laboratory. Driver fixations are characterized by a series of discrete dwells in direction of gaze that last at least 200 msec. Each time the eye moves to a new location is a new look event. For data reduction, the tape is advanced to the instant each event begins. The following information is recorded:

1. Beginning time of the event from the digital clock;
2. Location of the vehicle on the roadway from the digital distance readout;
3. Object of fixation (i.e., road surface, road sign, edge line, scenery ahead, headlights of oncoming cars); and
4. Horizontal and vertical position in units of visual degrees (x and y) of the fixation relative to the focus of expansion.

The focus of expansion is that point on the horizon where the road edge lines of a straight road appear to meet. The information in item 4 requires the data reducer to position a transparent grid over the TV monitor screen, which is etched with 1 by 1-visual deg grid squares.

The data are transcribed onto computer coding forms and punched onto computer cards, which are processed by a computer program that provides numerous statistical summaries for each trial. In addition to measures such as mean horizontal position, percentage of time viewing objects, and travel distances, the program derives a set of measures based on the grid coordinates. The program also reduces the visual field to six major areas that appear to have different informational content and different visual cues (i.e., scene ahead 3 by 6 deg around the focus of expansion, scene right, scene left, road surface and road edge right, road left, and sky). The third camera provides data on mirror and speedometer sampling. After the system has been calibrated, registration error is about $\frac{1}{2}$ deg horizontal and 1 deg vertical (18).

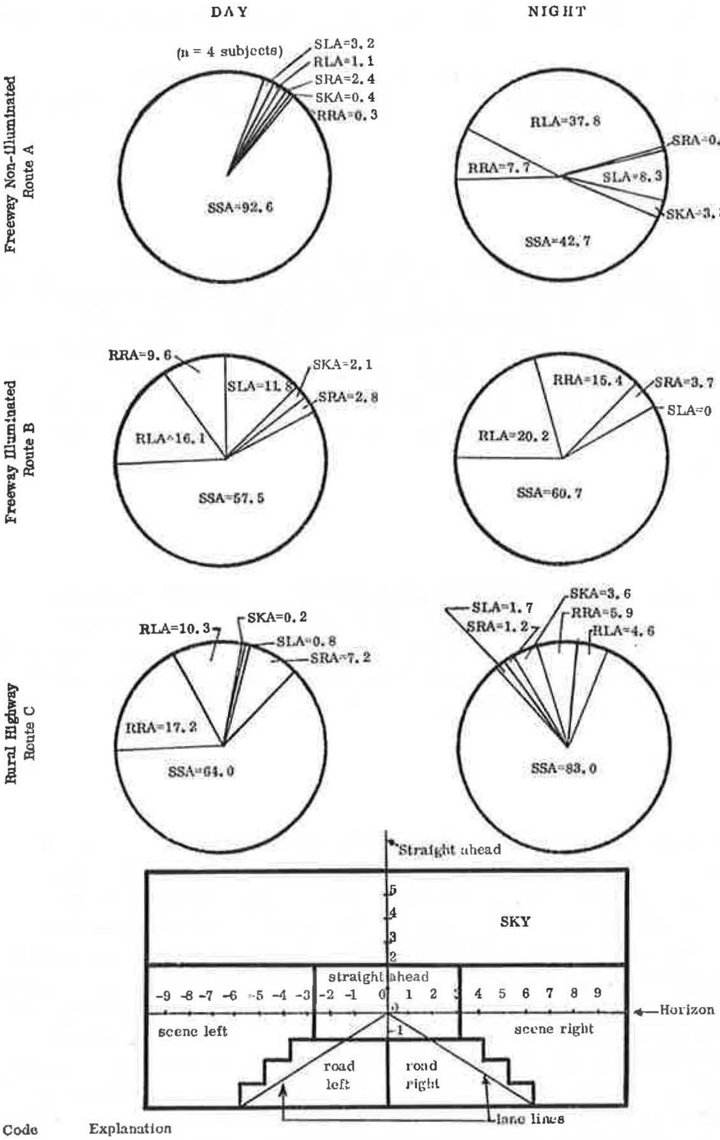
In addition to the eye movement recorder, an oscillograph recorder provides a permanent record of vehicle velocity, steering wheel and brake pedal movements, and

Table 1. Summary of eye movement data.

Route	Time	MVL[a] (deg)	MHL[b] (deg)	CI[c] (percent)	Time Viewing Oncoming Headlights (percent)
Nonilluminated freeway	Day	0.16	0.07	84.0	0.0
	Night	-0.85	-0.98	69.0	16.0
Illuminated freeway	Day	0.07	-0.60	71.1	0.0
	Night	-0.48	0.52	75.4	0.8
Rural two-lane highway	Day	-0.38	0.61	76.0	
	Night	0.41	0.02	78.0	

[a] Above horizon.
[b] To right of straight ahead.
[c] Time spent viewing most populous 3 by 3-deg area.

Figure 2. Average percentage of time viewing spatial areas.



Code	Explanation
RRA	Road Right - Includes right edge lane line and right road surface in front of driver
RLA	Road Left - Includes left edge lane line and left road surface in front of driver
SRA	Scenery right
SLA	Scenery left
SSA	Straight ahead (3° x 6°)
SKA	Sky

vehicle longitudinal position along the roadway. Visual performance measures are given below:

1. Mean horizontal location (MHL) in visual degrees to the right of straight ahead.
2. Mean vertical location (MVL).
3. Mean travel distance between fixations in visual degrees.
4. Two-dimensional concentration index (CI), the percentage of fixation time spent in the most populous 3 × 3-deg grid square.
5. Percentage of time viewing scenery ahead.
6. Percentage of time viewing scenery to the right.
7. Percentage of time viewing scenery to the left.
8. Percentage of time viewing road surface and edge to the right.
9. Percentage of time viewing road surface and edge to the left.
10. Percentage of time viewing sky.
11. Mean look time to the scenery on the left.
12. Percentage of time viewing the combined areas straight ahead and below straight ahead.
13. Mean time per look in the combined areas straight and below straight.
14. Mean time per look away from the combined areas straight and below straight.
15. Mean time per area and out-of-view.

STUDY 1

The purpose of this study was to describe driver eye movement pattern during night driving and to compare those patterns to daytime patterns on freeways and a rural highway. A number of studies by the DPL on daytime driving (2, 20, 22, 23) showed eye movement patterns to be a useful tool in evaluating signing, designing driver information aids, assessing the effects of highway geometry, exploring the effects of instructions, and assessing the effects of alcohol, fatigue, drugs, and age on driver search patterns. A goal of this study was to extend the capability and knowledge gained in the daytime studies to night driving.

Methodology

Four college males drove the experimental vehicle on three routes in both day and night conditions (a divided four-lane rural freeway without illumination, a four-lane urban freeway with illumination, and a rural two-lane highway). The order of conditions was mixed, and subjects drove the routes several times to familiarize themselves. Eye movement data were reduced to 30-sec samples for a total of 24 trials.

Results

The results for several measures are given for the three routes in Table 1 and in Figure 2. The data in Table 2 are based on 30-sec trials and about 150 fixations. Note that, for all routes in both day and night, MVL and MHL are within 1 deg of the zero point. That is, drivers tend to fixate near the focus of expansion (i.e., that point on the scene that appears to remain stationary to the driver and is the direction in which the car is moving; it is also that point in the scene where the lane lines appear to meet). It is also important to note that most of the fixations occur within a narrow visual area. Seventy-five percent of fixations occurred within a visual area measuring about 3 by 3 visual deg. This central tendency and the concentrations shown are similar to results found in previous studies on daytime driver eye movements. Closer examination of Table 1 shows notable differences between day and night. Differences among routes are also pronounced. The major findings for this study are summarized below.

1. On the unlighted freeway, the eye movement pattern shifted down and to the left from day to night by about 1 visual deg. This shift was attributed in part to glances at headlights of oncoming cars across the median, which were viewed about 20 percent of the time at night. Drivers did not fixate on oncoming traffic in the day trials.
2. Eye movement patterns were spatially more disperse at night than during the day on the unlighted freeway.
3. On the unlighted freeway, glances to the road edge lines and road surfaces increased from 1 percent in the day to almost 45 percent at night, whereas glances straight ahead decreased at night.
4. On the illuminated route (which also had light traffic) few differences were noted between the day and night trials. The daytime trials on the illuminated route were similar to the night trials on the unilluminated freeway. Apparently, traffic balances the differences between light conditions. The effect of illumination could not be separated from the differences in traffic conditions or routes.
5. On the rural highway, drivers viewed straight ahead more at night than during the day. They were searching for targets beyond the headlight beam patterns to increase their preview.

Conclusions for Study 1

These results show that nighttime visual search behavior differs from daytime visual behavior. Some of these differences may be due to differences in time spent viewing head lamps of oncoming cars, which are sources of glare. The results for the unilluminated trials support the notion that, in the cue-poor night driving environment, drivers' eye movement patterns concentrate in the area lighted by the head lamp beams for lateral and directional control. Future studies using the night recording system can provide insight on drivers' search and scan patterns at night and the effects of factors such as illumination, traffic load, glare sources, driver aiding, and type of road on those patterns.

STUDY 2

The experiments in study 2 were directed at determining differences in visual search behavior at sites with high and low night accident rates and the effects of illumination on drivers' visual search. Many rural highway sites, particularly intersections, are known to have high rates of night accidents. One method of reducing accidents is to erect lighting. However, few sites are now lighted, and the problem is to determine priorities of which sites to light and how much lighting to erect to best use limited resources of energy and money. An outgrowth of study 2 was to develop a reliable quantitative technique for quickly evaluating the potential effectiveness of illumination design changes in reducing accidents at rural highway sites with high nighttime accident rates. Eye movements were recorded for subjects driving along sites with both high and low night accident rates and with and without illumination during day and night.

Methodology

Six college males drove a total of nine sites. Three intersections with high night accident rates were matched to three sites with low night accident rates. The matching was based on similar geometry (two lanes and no horizontal and vertical curvature), signing and signaling, traffic volume, daytime accident rates, intersection lighting, and surrounding night visual environment. Another three sites were selected that had lighting that could be turned off. Subjects were not informed of the purpose of the study, but drove a specified route that included the experimental intersections. Approximately 1,000 ft prior to the intersections, subjects were instructed to turn left. In all, 128 separate intersection passes were performed.

Three major comparisons of visual search behavior were examined:

1. Nighttime versus daytime,
2. Sites with high night accident rates versus those with low night accident rates, and
3. Illumination versus no illumination.

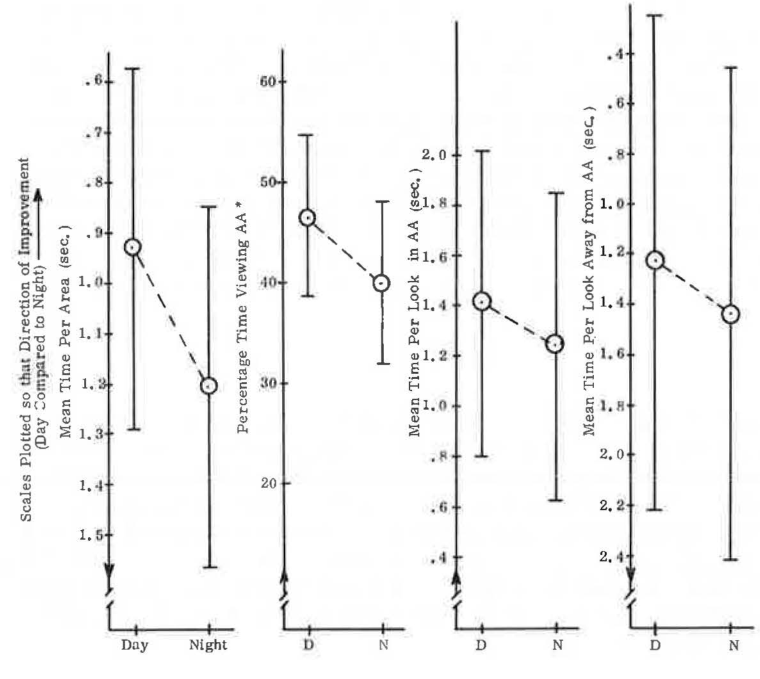
The results that follow are for visual search patterns under the instructions to turn left. Drivers' visual search patterns for left turns (on a two-lane rural highway) shifted to the left, and they spent an increased percentage of time viewing scenery left.

Results

Daytime Versus Nighttime

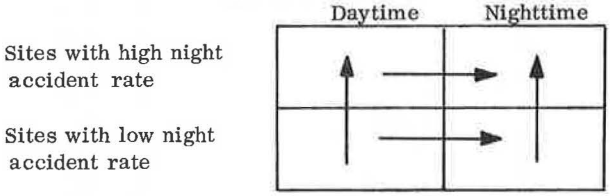
The results for gross differences between day and night for all nine sites are shown in Figure 3. An important difference between the day and night behavior is the greater mean time per look in each area for the night driving (all six areas are combined in this measure). Longer mean times possibly imply longer times on the average needed to acquire or process information. Thus, drivers' mean search time per area is lower during the day than at night; this may be interpreted as an improved search behavior in the daytime inasmuch as time to acquire information is shorter. In the day, drivers also spend more time viewing the combined scene directly ahead of the road right and road left. When looking away from this area, drivers sample in shorter times during the day than at night. Thus, several measures appear to be sensitive to day and night differences, and interpretation of the differences suggests somewhat more efficient visual search behavior in the day than at night.

Figure 3. Significant differences between day and night trials.



Sites With High Night Accident Rates Versus Those With Low Night Accident Rates

The results for the six sites are shown in Figure 4. The data should be compared in the following way:



The first comparison of interest is of sites with low and high night accident rates at night. As shown in Figure 4, only CI showed a statistically significant difference at the p = 0.10 level, and it was a bit higher at the high accident sites. The only other measures with possibly significant trends were (a) MHL, which was more to the right at the high accident sites, and (b) the mean time per area, which was longer at the high accident sites. On the other hand, several differences were noted between sites with low and high accident rates when daytime measures were compared. Drivers at the high night accident sites spent (a) greater percentage of time viewing the scene left, (b) more time when glancing at the scene left, and (c) more time looking away from the scene and road ahead. Thus, the general pattern of visual search results is that sites with different accident rates were very much alike at night but different in the day.

Figure 4 also shows that visual search behavior at the high accident sites was very much the same in the day and night. At the low accident sites, however, most of the measures showed changes from day to night. The results for one measure, percentage of time viewing the scene left, are particularly important, for this area is likely to contain cues for locating the intersection. The results at low accident sites suggest that at night drivers tend to rely on cues from the scene left much as they did in the day, but they require more time in this area and more time to acquire the information. At high accident sites, at night drivers rely less on the scene left; they apparently change the location of search for intersection cues.

An interpretation of the general trends suggests that these differences in the day between high and low accident rate sites indicate that cues are not equally discernible at low and high night accident rate sites in the day. The measures may indicate that visual cues are not so easily obtained even in the day at sites with high night accident rates. At night, the cues at sites with high accident rates are simply not obtained or not obtained in time for a safe smooth maneuver.

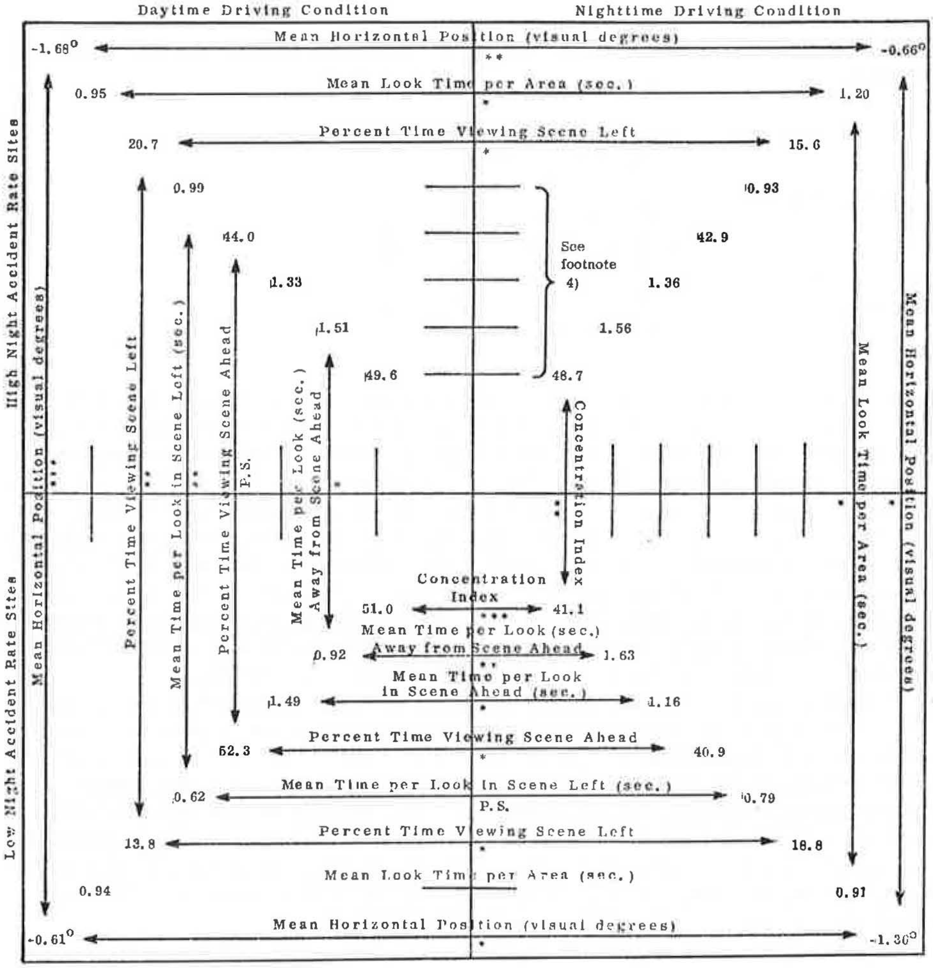
The results may be summarized as follows:

1. During daytime conditions, there are many differences in visual search behavior for sites with low and high night accident rates;
2. There are few differences in visual search patterns at night and during the day; and
3. The lower percentage of time viewing the scene left at night at sites with high night accident rates suggests that drivers search different areas for intersection cues.

In terms of the potential effects of illumination, the results point to the following:

1. Because the nighttime level of performance at high accident sites is not, in the main, different from that at low accident sites, a standard for the effect of illumination would not likely be nighttime performance at low accident sites; and
2. The fact that daytime levels at high accident sites were much different from daytime levels at low accident sites may suggest that the daytime performance level at high

Figure 4. Results of study 2.



NOTE: 1) A line drawn between two numbers indicates that the contrast between those two values was significant (from ANOVA):

*** ⇒ $p < .05$, ** ⇒ $p < .10$, * ⇒ $p < .20$,

P.S. ⇒ not statistically significant but would likely attain statistical significance with a larger sample size (in the judgment of the researchers).

2) Data shown are for six sites and six subjects at each site.

3) These scales are a repeat of the lower scales in inverse order.

accident sites may not be an appropriate standard of illumination effects.

Two possibilities remain as a standard for illumination: (a) the daytime level at low accident rate sites should serve as a standard or (b) the effects of illumination are to modify driver visual search behavior in a manner not suggested by daytime levels at either types of sites or nighttime levels at the low sites. A hint as to this possibility lies in the tendency of drivers to rely less on the scene left at night at the high accident sites than in the day. That is, drivers may be looking elsewhere than the scene left for (but perhaps unable to attain) alternate intersection cues. The role of illumination then might be to highlight these alternate cues.

The potential effect of illumination at sites with high night accident rates, as indicated above, is not clear from the preceding analyses. The experiment described below examined the effect of illumination on visual search at several (not high night accident) sites.

Illuminated Versus Nonilluminated Sites

Three sites (not having high accident rates) both with and without illumination were selected for comparison of nighttime driver behavior in the task of turning left. Figure 5 shows the results of the analyses and the effect of artificial illumination at all sites combined (and, for some measures where signalization was a significant factor, the results are shown separately for signalized sites).

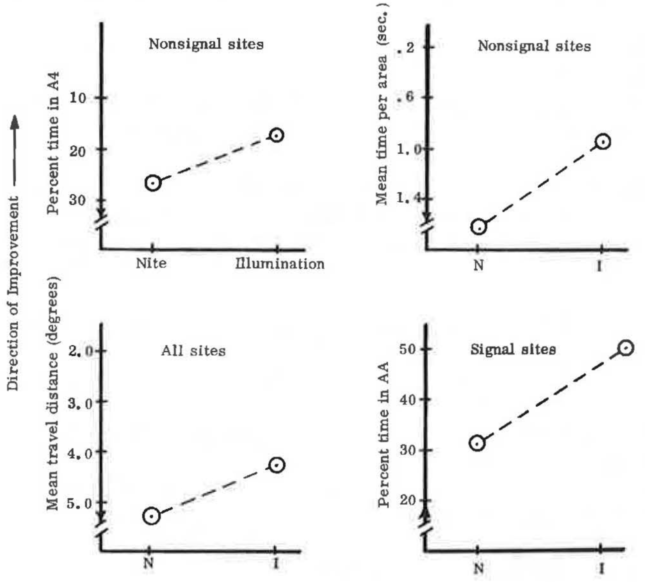
Illumination has an effect on several measures of visual search behavior. At illuminated sites drivers (a) spend less time viewing the scene left (nonsignal sites, 27 to 17 percent), (b) apparently decrease the mean look time per area (nonsignal sites, 1.6 to 0.94 sec), which may indicate shorter times to acquire information, and (c) increase the mean time viewing the scene ahead (signal sites, 31 to 50 percent), the area where guidance control information is concentrated. The mean travel distance was reduced (no differences were found in previous analyses), which indicates a reduction in spatial search activity; this can also be viewed as an improvement when compared to the standard of the lower information load condition in straight road driving (2.5 deg).

In conclusion, the results of this analysis lend encouragement to the notion that illumination can affect driver visual search performance.

Conclusions for Study 2

The results of study 2 indicate that measures of visual search are sensitive at sites with different accident rates and to day and night conditions. The changes in visual search measures due to illumination not only demonstrate that illumination can affect visual search at some sites but also show that visual search behavior can be useful in identifying the specific effects of various illumination designs on driver search patterns.

Figure 5. Significant differences in night behavior at sites with and without illumination.



CONCLUSIONS FOR STUDIES ON NIGHTTIME DRIVER EYE MOVEMENT PATTERNS

The results show that measures of driver visual search patterns are sensitive to day and night differences, to sites with different accident rates, and to illumination. The results from the highway intersections with illumination lend encouragement to using eye movement data to evaluate methods of improving nighttime driving. Illumination, which is generally believed to be of benefit in night driving, was found to affect several measures of driver visual search behavior. The methodologies developed in these studies should be extended to evaluate the effects of illumination at sites with high night accident rates. Another immediate problem to which the methodologies can be applied is evaluation of alternate methods (in lieu of illumination) of improving nighttime driving (e.g., improved pavement markings, signing, signaling, reflectors). This application is particularly relevant because of the energy shortage challenging indiscriminate use of lighting.

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The development of targets for use in field tests to measure visibility distances of drivers and to evaluate head lamp beams is described. The test procedure used appears to have satisfactory statistical reliability. The test provides discriminations in the visibility distances attributable to variations in head lamp beams. In addition, tests that evaluate glare effects to opposing drivers and those due to reflections in mirrors from the head lamps of a following vehicle are described. The development of a computer simulation model that predicts visibility distances and glare effects is described. Model predictions and the results of the field tests are compared and provide a good fit. Some examples of the use of this model to evaluate the effects of head lamp aim and various meeting beam patterns are described.

FIELD AND COMPUTER-SIMULATED EVALUATION OF HEAD LAMP BEAMS

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Before we can evaluate head lamp beams, we must measure those aspects of the driver's visual environment that provide useful information. Studies using eye marker devices (1, 2) have provided valuable information on the visual cues used by drivers, mostly in daytime driving. Such studies are only lately being performed for night driving (3, 4).

One study (4) on night driving tested three head lamp beams. Drivers' eye fixations at night were compared with eye fixations in daytime to determine the extent to which a particular beam provides illumination in those areas of the roadway environment that drivers wish to see. A major finding of that study was that drivers fixated closer to the car at night than in daytime, indicating one of the limitations imposed by vehicle head lamps. Also, the lateral distribution of eye fixations was related to the pattern of the beams.

Although analyses of accident data have not been conclusive in determining the role of vehicle headlighting in nighttime crashes (5), data on eye fixations and subjective impressions clearly show that vehicle headlighting does not provide adequate seeing distances.

To develop improved vehicle headlighting systems requires that the effectiveness of alternative beam patterns be adequately evaluated. There is currently no uniform testing procedure available. In addition to a procedure for testing head lamps, the type of targets to be used must be determined.

A uniform testing procedure would permit better comparisons of the findings of different studies. Among the objectives of the studies reported here were development of procedures for objectively and subjectively measuring performance; development of suitable visibility test targets; and development of a mathematical model to predict the visibility and glare effects of head lamp beams.

DEVELOPMENT OF TEST TARGETS

Three of the targets evaluated, i.e., vertical, up/down, and choice position targets, are shown in Figure 1. The pedestrian target used consisted of a sheet of plywood,

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*The author was with the Highway Safety Research Institute, University of Michigan, when this report was developed.

16 in. (0.4 m) wide and 72 in (1.8 m) high, painted a flat gray for reflectance values of 14 and 22 percent. In the visibility evaluations, the targets were located at the right edge of a flat road and an automobile was driven toward them. There was no opposing traffic. The driver's task was to depress a switch when he detected the target or made the appropriate discrimination, which allowed the visibility distance of the target to be measured.

Results

The mean visibility distances of the vertical target are shown in Figure 2. With low beams, the detection distances did not vary with target reflectance or target size. With high beams, the visibility distance increased as the reflectance and height of the target increased.

The mean visibility distances of the up/down, pedestrian, and choice targets showed more consistent effects of target reflectance, size, and mounting height.

Discussion

The pilot tests showed that each of the targets was at least partly suitable for headlighting tests. However, the vertical target was eliminated because it did not provide a clear-cut effect of reflectance with low beams. In addition, because the vertical target tended to cast a shadow on the road, it was detected on that basis rather than on the basis of illumination.

Visibility distances of the up/down and pedestrian targets increased reasonably consistently with target reflectance. In addition, visibility distances of the up/down target varied with the vertical position of the target face: Visibility distances were greater when the target face was close to the pavement. However, both targets could be seen in silhouette, which showed that the configuration used was undesirable.

Because of these disadvantages, a choice target was developed. The effects of target reflectance and low and high beams on visibility distances were consistent with this target. However, this target did not permit evaluation of the effects of locating the target close to and above the pavement.

The following advantages of the targets evaluated in these studies were incorporated in the target used in the headlighting field test:

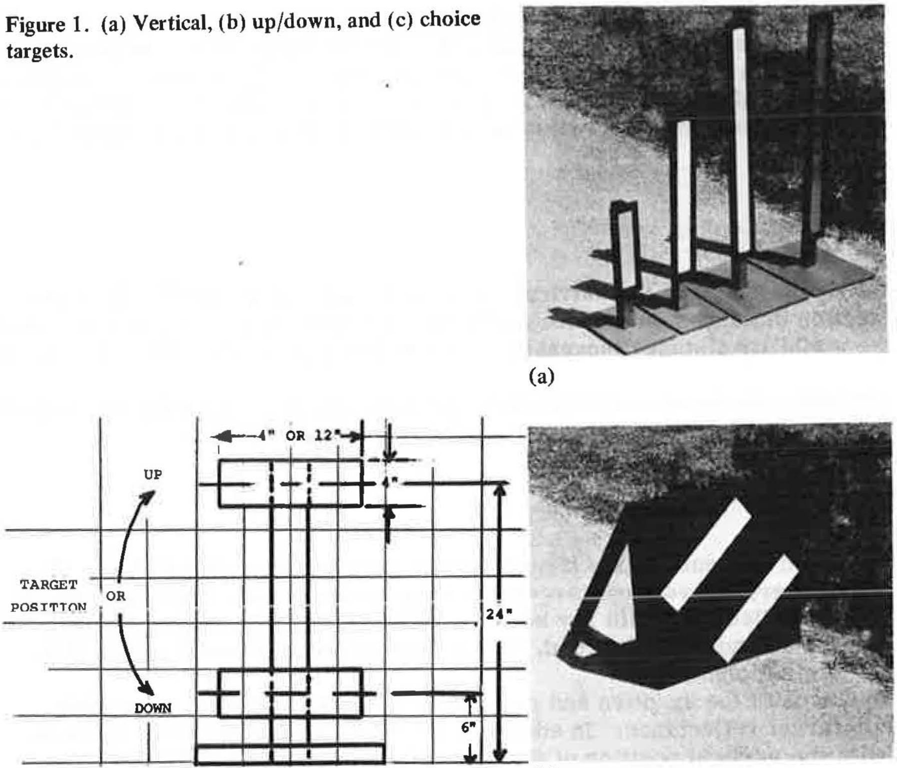
1. A choice target that requires identification of target detail or orientation,
2. Target faces that can be positioned close to the pavement and at some distance above it, and
3. A target that has its own background so that it is not affected by silhouettes or by the contrast of the road or shoulder.

These considerations led to the development of the target shown in Figure 3. After further considerations of the practical visibility requirements of drivers, two other targets that simulate aspects of road and route guidance signs (Fig. 4) were developed.

FIELD TEST PROCEDURE FOR VISIBILITY DISTANCE TEST

In the visibility distance tests, two vehicles were driven toward each other on a straight, flat road that was free of other traffic. Each vehicle was equipped with a special front panel that could accommodate as many as 14 head lamps, which could be selected remotely. The orientation of each test target was controlled so that the subject's responses could be checked against the actual orientation of the target on a given run. The responses of the driver and the passenger, when used, and other pertinent data were recorded on paper strip charts. The subjects pressed push buttons to indicate the orientation of the target. Reflective panels placed behind each target were sensed

Figure 1. (a) Vertical, (b) up/down, and (c) choice targets.

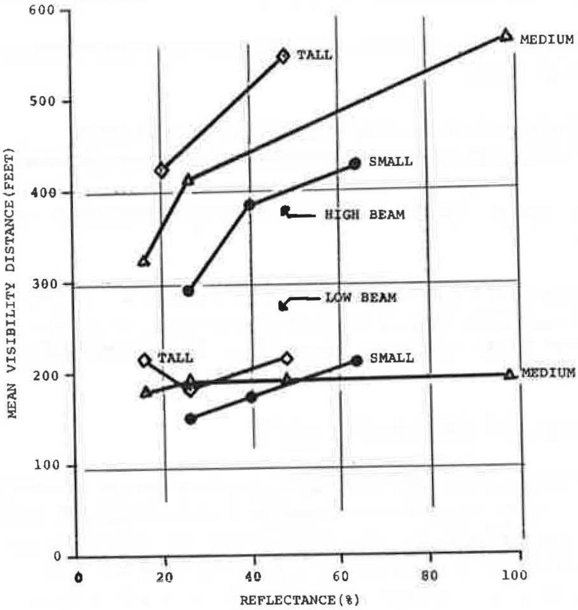


(a)

(b)

(c)

Figure 2. Mean visibility distances of vertical targets.



by a detector device consisting of an infrared source and photocell attached to the rear bumper. Twelve of the type 1 targets were used on each side of the course, either at the right edge of the road, at the left side of the lane, on the centerline, or in the center of the lane. When targets were placed in the center of the lane, tape switches were positioned 80 ft (24 m) in front of each target. A vehicle passing over the tape switch triggered a solenoid that released the support structure of the target, which was hinged at its lower edge, and allowed the target to fall down flat on the road. At the end of each run these targets were repositioned perpendicular to the road.

Each run began with two cars at each end of the course. On signal, each driver accelerated the car to a speed just beyond the lock-in setting of the automatic speed control and then released the accelerator. The subject's task was to indicate the orientation of each of the targets as soon as possible.

Effects of Beams, Target Reflectance, and Target Location

Mean visibility distances of targets with 12 and 54 percent reflectance mounted on the right side of the lane are shown in Figure 5. These distance measurements were made when the lateral separation between the vehicles, which were equipped with type 6014 low beams, was 7 and 36 ft (2.1 and 11 m). The effect of target reflectance on visibility distances is clearly indicated, whereas lateral separation distances between vehicles had a relatively small effect. The trends show the typical initial reduction in visibility during the meeting and an increase in visibility after the meeting and the driver has recovered from glare.

Figure 6 shows the mean visibility distances of targets with 12 and 54 percent reflectance positioned in the center of the lane. The meeting vehicles had low and high beams and a lateral separation of 7 ft (2.1 m). In high beam meetings the minimum visibility is less than in low beam meetings, and the minimum visibility distance was reached further from the meeting point when the targets were located in the center of the lane than when they were at the right of the lane (Fig. 5).

Effect of Test Vehicle Speed

Four of the subjects used to collect the data for targets on the right side of the lane were used to evaluate the effect of vehicle speed on visibility distances. Data were collected when vehicle speed was held constant at either 40 or 70 ft/sec (12.2 or 21.3 m/s). Analysis of variance of the visibility distances obtained in these two tests showed no significant differences in mean visibility distances due to the speeds used, although the mean visibility distances tended to be greater when the test was conducted at the lower speed.

Reliability of Field Test Procedure

Four subjects were exposed twice to a number of tests consisting of meetings of vehicles equipped with type 6014 high and low beams. Targets of 12 and 54 percent reflectance were positioned at the right and left of the lane, and the face of the target was 6 in. (152 mm) above the pavement. Each of the subjects made two replications of a block of eight runs. The means of the visibility distances obtained in the first replication were compared with those in the second replication. The second replication was consistently lower (Fig. 7), but the discrepancy did not exceed 5 percent. The correlation between the mean visibility distances in the two replications was 0.97.

Reliability of Test Sites and Drivers

A subsequent test evaluated a number of beams, including the low and high beams used

Figure 3. Type 1 target selected for use in field tests.

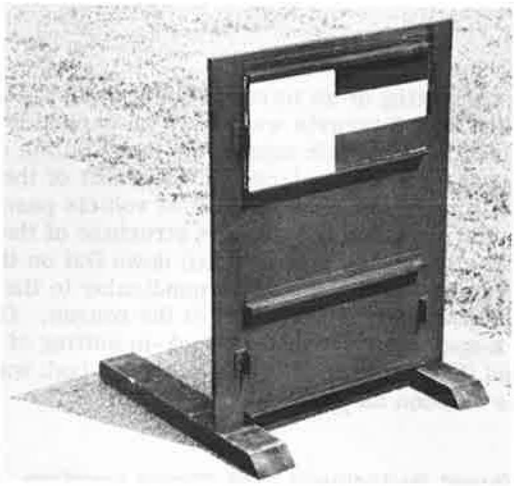
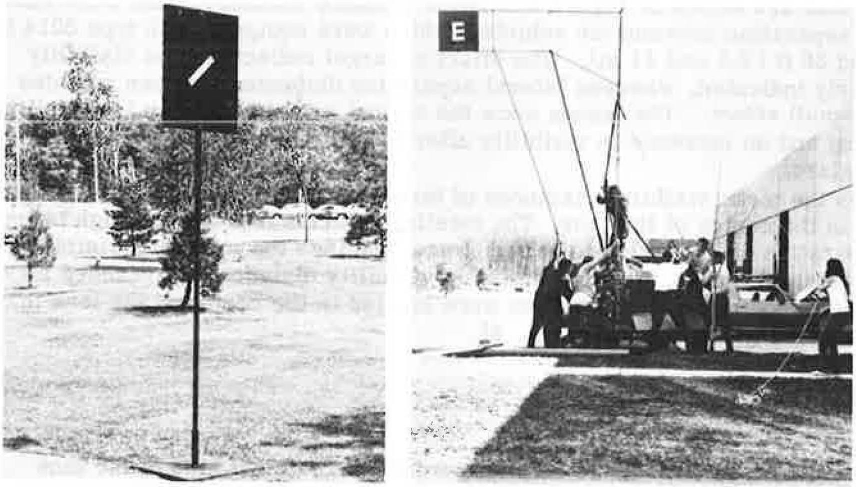


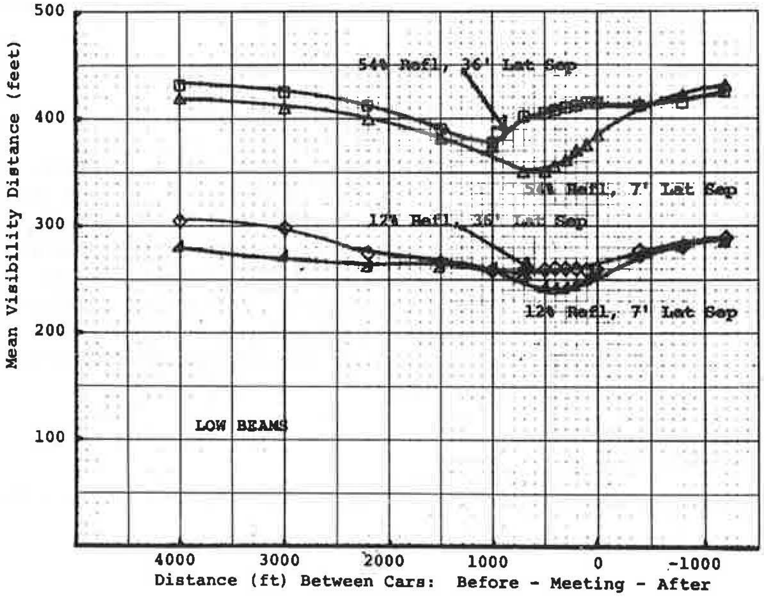
Figure 4. (a) Type 2 (road sign) and (b) type 3 (route guidance) targets.



(a)

(b)

Figure 5. Mean visibility distances of targets in low beam meetings.



in the initial test. The second test was conducted about 12 months after the first one at a private air strip with a usable paved area about 3,500 ft (1.07 km) long. The procedure was modified in that the glare car was kept stationary because of the limited length of the runway. A different group of test subjects was used, and the head lamps were reaimed for the second test. The maximum longitudinal separation between the vehicles at which data could be compared with the first test was 1,500 ft (457 m).

The mean visibility distances of the type 1 targets located at the right side of the road were 10 to 15 percent greater in the second test than in the first in low beam meetings. This difference is partly due to random error and to differences in the vertical alignment of the head lamps used in the two tests. A 0.5-deg difference in vertical aim of the low beam head lamps could easily account for this discrepancy and is believed to be the major cause. The fact that the mean visibility distances obtained in meetings with the high beams were almost identical in the two tests shows that the general procedure used was quite similar. Small variations in vertical alignment of high beam head lamps should not affect mean visibility distances much because the high beam pattern is more uniform than that of low beams. In other respects the correspondence between the shape of the visibility distance curves obtained in the two tests with the low beams is quite similar, indicating that the same effects of glare on visibility were obtained. Product-moment correlations of the mean visibility distances obtained in the first and second tests at various longitudinal separations in low and high beam meetings were 0.96 and 0.97.

Type 2 Sign Target

The mean distances at which the orientation of the reflectorized white line against the low-reflectivity black background was identified were considerably greater than for the type 1 target. In addition, consistently greater visibility distances were obtained with the high beam than with the low beam.

Type 3 Route Guidance Sign Target

In meetings between the vehicles with high and low beams and at a lateral separation of 7 ft (2.1 m), the mean visibility distances at which the orientation of the E was identifiable were considerably less than for the type 2 target. Visibility distances were similar for the high and low beams. Because the high beam provides greater upward scatter of light than the low beam, visibility with the high beam should have been greater. This was not the case, in part probably because relatively few subjects were tested. But a number of subjects reported that they experienced a considerable amount of glare from the target itself, which reduced their ability to determine the orientation of the letter. The green high-intensity sheeting used as the background for the letter had a reflectivity of 80 percent, and the letter E was made of silver high-intensity sheeting, with a reflectivity of 675 percent. The data suggest that the luminosity of route guidance signs made with retroreflective materials may be too great for optimum legibility, at least with high beams.

Road Test of Discomfort Glare

To determine the discomfort glare associated with various head lamp beams, a study was conducted on public highways. The frequency with which opposing drivers flashed their high beam head lamps at the test car equipped with various beams was noted. The beams used were conventional U.S. and ECE low beams; the U.S. low beams augmented by a third lamp aimed in two different ways to provide a type of mid beam; 6014 U.S. and H_4 ECE high beams; and a system of two 6014 U.S. low beams and two H_4 low beams.

The percentage of oncoming drivers who flashed high beams at the test vehicle when it was using the various beams is shown in Figure 8. The test was conducted on two-

Figure 6. Mean visibility distances of type 1 targets in low and high beam meetings.

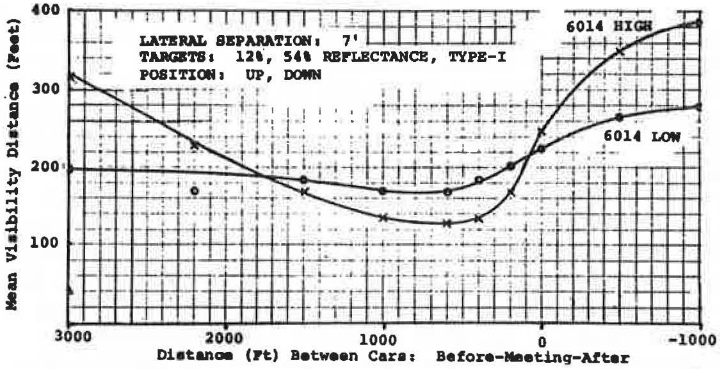


Figure 7. Comparison of mean visibility distances for subjects exposed twice to the same meeting situations.

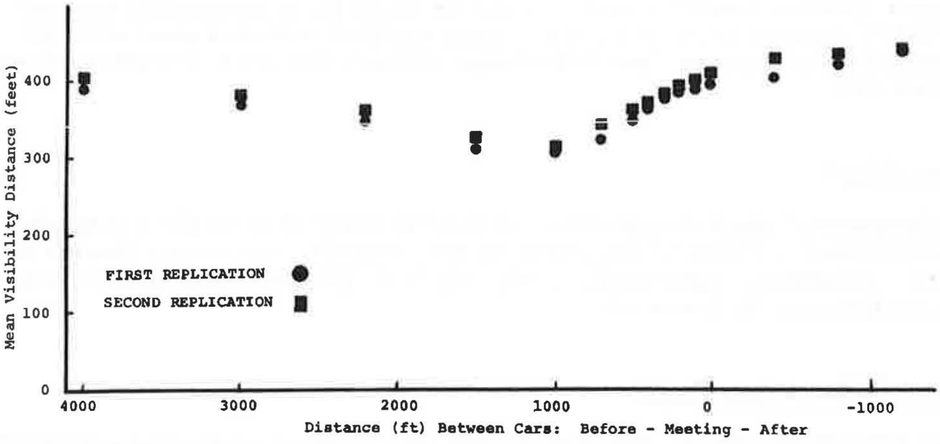
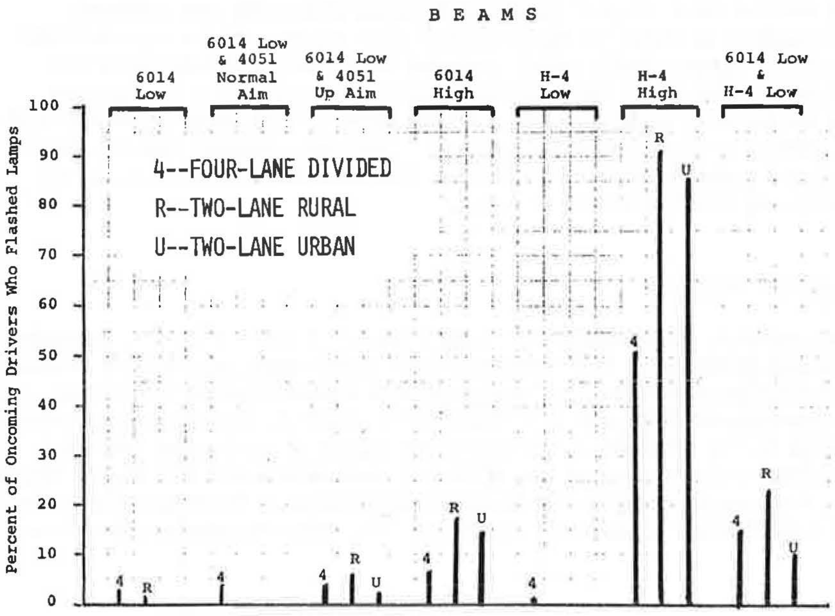


Figure 8. Percentage of oncoming drivers who flashed their lamps when opposed by the indicated beams.



lane urban roads, two-lane rural roads, and a four-lane divided highway. Relatively few responses were made by oncoming drivers when low and mid beams were used. About 18 percent of drivers responded to the 6014 high beam, whereas in the same condition with the H_4 high beam about 92 percent of oncoming drivers responded. Oncoming drivers were also influenced by the number of head lamps on the car: They made more responses when opposed by the four-lamp combination of the U.S. and ECE low beams, although these provided low glare levels, than when opposed by the U.S. high beam.

Glare in Rearview Mirrors

The effects of head lamp glare reflected in rearview mirrors were determined in a subjective evaluation. The subject drove the lead car, which was followed by the car used in the previous test. Tests were conducted on a two-lane rural road, a four-lane unlighted urban road, and a four-lane urban road with fixed lighting. The subject's task was to compare the discomfort glare from the experimental beams with the glare from the standard pair of low beams. He used a 9-point rating scale: -4 denoted no glare; 0 denoted glare as produced by the type 4000 reference low beams; and +4 denoted extremely discomforting glare. Normally, the reference low beam was used on the following car. On command of the experimenter in the lead car, the driver in the following car switched to the desired test beam and then back to the reference beam. The subject then made his judgment, which was recorded by the experimenter. Mirror data were collected in day (78 percent reflectivity) and night (4 percent reflectivity) settings with each of the test beams.

The mean glare ratings were uniformly greater with the mirror in the day than in the night setting. The trends of the mean ratings of the beams are the same on the three types of roads, as well as in the day and night settings. No differences in the ratings were attributable to the road conditions. The results are quite comparable to those found in the test of the glare responses of oncoming drivers to the same beams. The high beams were rated as more glaring in mirror tests than in the meetings. One difference between the two tests was in the response to the combined U.S. and ECE low beams, which was rated the same as the reference beam. Thus drivers responded to the glare illumination and not the total number of lamps lighted.

COMPUTER SIMULATION

A major objective of the field test was to develop empirical data in meetings of vehicles using different beams for development of and comparison with a mathematical model to predict the visibility distances and to compute glare values. The model is described elsewhere (6, 7).

Input data used in the simulation consist of the basic geometry of the situation, such as the location of the head lamps on the vehicles, the eye position of the driver of the main vehicle for whom the visibility and glare effect are to be computed, lateral separation between the vehicles, location of the target, and so on. In addition, a grid defining the intensities radiated by the individual head lamps at angular coordinates is used. The underlying concept of target visibility, as developed by Jehu (8), consists of the relationship between the illumination of a target and the effect of glare in determining the visibility distance. The disability glare effect is computed by using the equation proposed by Fry (9).

A major consideration in the development of the model was to predict visibility both before the vehicles meet and after the meeting point to show recovery from glare. This is accomplished by modeling an adaptation stage to prevailing glare; readaptation, which occurs at the point of maximum equivalent veiling glare; and recovery, which occurs when the veiling glare due to the opposing vehicle's head lamps decreases faster than could be followed by the photochemical process of the eyes.

Figure 9. Comparison of computer simulation and field test in low beam meetings.

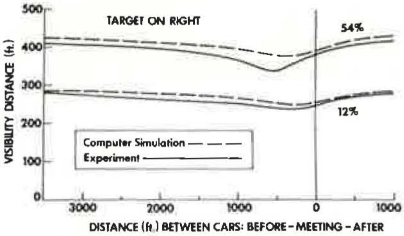


Figure 10. Visibility distances predicted by computer simulation.

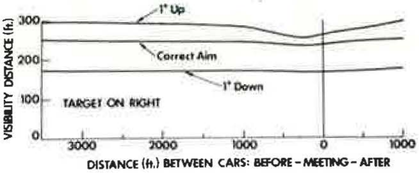


Figure 11. Computed visibility distances with U.S. and European low beams and a mid beam in nominal aim.

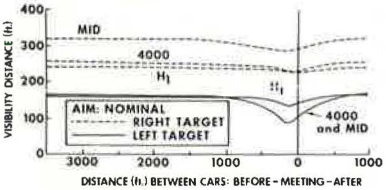


Table 1. Glare intensity and illumination from oncoming beams at 1,200 ft.

Beam	Aim	Intensity (cd)	Illumination (ft-c)	Ratio
H_1 low	Nominal	714	0.0005	0.3
4000 low	Nominal	2,204	0.0015	1.0
Mid	Nominal	2,635	0.0018	1.2
H_1 low	1 deg up	12,716	0.0089	5.8
4000 low	1 deg up	8,588	0.0060	3.9
Mid	1 deg up	8,853	0.0062	4.0

Note: 1 ft = 0.3 m. 1 ft-c = 10.7 lux.

Comparisons Between Computer Simulations and Field Test Data

The validity of the model was established by comparing predictions of the computer simulation with the results of the field tests. For example, Figure 9 shows the results of meetings between vehicles using low beams, with targets of 12 and 54 percent reflectance at the right edge of the road and 7-ft (2.1-m) lateral separation between the cars, as obtained in the field test and computer simulation. A large number of comparisons of this type were made with the many different conditions in which the field test data were collected to show the effect of variables such as lateral separation, beams, target location, and reflectance (6).

Applications of the Model

The model has a variety of applications that can provide insights into the influence of many variables on visibility distances and glare.

Figure 10 shows the effect of vertical alignment of a U.S. low beam head lamp on visibility of a type 1 target of 12 percent reflectance located at the right side of the road in meetings with a similarly equipped vehicle. Headlight misalignment of 1 deg up or down causes substantial changes in the visibility distances (10).

U.S., European, and Mid Beams

The computer simulation was also used to further evaluate the effectiveness of various meeting beams on targets located at the right and left of the lane and at various degrees of head lamp misalignment. Figure 11 shows computed visibility distances with U.S. and European low beams and a mid beam, with all beams in nominal aim condition, for targets located at the right and left of the lane. The mid beam provided greater visibility than the low beams for the target at the right of the lane. For the target at the left of the lane there were no differences between the U.S. low beam and the mid beam, since the mid beam provides little illumination on the left side.

Table 1 gives the glare intensities of oncoming beams on vehicles separated by 1,200 ft (366 m), with the beams in nominal aim and with a misaim of 1 deg up. The table indicates that the ECE low beam produces the lowest glare intensities in nominal aim but also produces the greatest glaring intensities with a misaim of 1 deg up. This confirms the sensitivity of this beam to vertical alignment, which is an important consideration in the selection of meeting beams (11).

Other Computations

The model has now been extended to predict visibility distances in vehicle meetings on roads having horizontal or vertical curvature and the effects on visibility distances of the head lamps of a following car reflected in interior and exterior mirrors. In addition, the discomfort glare model proposed by de Boer (12) has been incorporated, though this must be validated further in dynamic field tests. These capabilities of the simulation have been used (13) to assess the compatibility of headlighting on cars and trucks.

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A thorough review of the relevant literature was combined with a rigorous and systematic examination of the driving task to derive a set of visual functions important to the driving task. The functions included both static and dynamic measures, containing both sensory and perceptual aspects. A device was developed to test performance on these functions, including three measures related to night vision: static acuity under low levels of illumination, in the presence of veiling glare, and under spot glare. The battery of tests was administered to a total of 669 passenger car drivers and 235 truck and bus drivers. Three-year driving records were obtained for all subjects and were examined in relation to performance on the vision tests. Because no data on night accidents were available, an adequate evaluation of the night-vision-related tests was not possible; however, the results showed a high degree of variability in visual acuity performance obtained under conditions similar to those encountered in night driving and also showed that acuity measured under normal light conditions does not adequately predict acuity under typical night driving conditions.

DRIVER SCREENING FOR NIGHT DRIVING

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The importance of vision to driving is well recognized. This recognition has been intuitive, for until recently there has been no evidence that poor vision is associated with increased accident likelihood. All states require driver license applicants to pass some test of visual performance, usually static acuity, at least for their first license. However, there is no standardization of tests, test procedures, minimum standards, or frequency of retesting among the states. In states without renewal examination, there is no assurance that even the minimal level of visual performance originally required is maintained by the driver over the years. When viewed in an international context, the problem is even more complex.

This paper describes a research program conducted to provide some of the information necessary before standards for driver vision screening can be established. The study had several specific objectives:

1. To determine analytically the basic visual requirements of driving by drawing on the existing literature relevant to the problem and by conducting a rigorous and systematic examination of the driving task;
2. To devise tests suitable for use in state driver licensing programs for visual performance parameters determined to be important to driving; and
3. To evaluate the accuracy of the empirical analysis and the adequacy of the devised tests by experimentally determining the relationship between visual capability as measured by tests and past accident involvement of those tested.

Only those tests that demonstrated a relationship between poor performance and high accident involvement would be appropriate for use in screening driver license appli-

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*The research described in this paper was performed while Mr. Henderson was with the System Development Corporation.

cants. (The scope of the study subsequently was expanded to include visual and auditory requirements of driving passenger cars, trucks, buses, and motorcycles. This paper, however, discusses only visual requirements of passenger car and commercial driving, with particular emphasis on night driving.)

GENERAL APPROACH

Identification of the visual requirements for each class of driving (automobile or truck and bus) was based on a three-step procedure:

1. Review of relevant literature;
2. Examination of the driving task, as defined in available task analysis documentation; and
3. Consolidation of the results of the first two activities, identification of common findings, and resolution of differences.

The final output was a list of visual requirements felt to be of sufficient importance to warrant consideration as candidates for inclusion in screening programs. Activities that led to this list of candidates are reported in detail elsewhere (10, 11).

Each requirement identified was then reviewed in terms of how an individual's basic capability to meet the requirement could be measured. Because commercial tests frequently did not exist for this purpose, new tests and test procedures had to be designed and constructed. Once this was accomplished, all tests were administered to a sample of drivers, and their performance on these tests was related to their past accident involvement. Tests found to be of value in predicting accident involvement, i.e., those on which poor performance was related to high accident involvement, were then considered suitable for screening driver license applicants.

SPECIFIC APPROACH

Initially, a list of visual functions potentially important to driving was established. Development of the list relied heavily on the expertise of the project's optometric consultant. This list was not intended to be final and, as expected, was modified as a result of the literature survey and task analysis. The revised list contained 18 visual functions considered potential candidates for inclusion in the vision test device: accommodation amplitude, accommodation facility, adaptation, angular movement, color vision, dynamic visual acuity, field of fixation, fusion, glare sensitivity, movement in depth, phorias, pursuit fixation, saccadic fixation, static acuity, steady fixation, stereopsis, vergences, and visual field. Only two functions in the list appear to be directly related to night driving: adaptation and glare sensitivity. As the following brief review of the literature shows, this is a misleading assumption.

REVIEW OF THE LITERATURE

Adaptation

Adaptation is the change in sensitivity of the eye as a function of change in illumination. Sensitivity increases under reduced illumination (dark adaptation) and decreases under increased illumination (light adaptation).

Although the adaptation process can be an important factor in driving during daylight hours, for example, when a driver enters a long tunnel, the more common concern is with initial dark adaptation at dusk and with perturbations to the state of adaptation that occur during night driving as a result of roadway or roadside lighting and head lamps of other vehicles.

The progress of both light and dark adaptation in the normal eye is well-known and well documented in the physiological and psychological literature and will not be repeated here. Schmidt (19) presents an excellent summary of the pertinent facts and distinguishes among the three levels of adaptation corresponding to photopic (daytime), mesopic (twilight), and scotopic (night) vision. The mesopic range (15), in which the illumination level varies from 0.003 to 4.0 ft-L (1.0 to 13.7 cd/m^2), is of primary interest in night driving.

Schmidt (18), in reviewing the adaptation process, emphasized the magnitude of the individual differences in adaptation facility and pointed out that the greatest variability is found in the mesopic range. Schmidt also discussed the importance of the correlations between dark adaptation and other visual functions in the design of a night vision tester. On the basis of the generally low correlations found, she concluded that it is safer to test the specific function about which information is desired at the specific level of illumination of interest than to rely on correlations with other functions at other levels of illumination. In short, tests for the various visual functions important to driving must be conducted under conditions of illumination actually encountered in night driving if meaningful results are to be obtained.

Domey and McFarland (8) made a detailed study of the relationship between age and adaptation and found a regular decline in adaptation ability with increasing age. The authors showed that the progress of adaptation during the first 10 min allows accurate prediction of the final adaptation level and, although they referred to the 10-min test as a short clinical test of adaptation, it seems prohibitively long for use in a high-volume screening procedure such as driver licensing. Thus, testing for adaptation in screening drivers would appear to be ruled out. However, because the driving task rarely involves scotopic vision, the ultimate level of scotopic adaptation may not be relevant, and adaptation to mesopic levels is essentially complete in 5 min (19). Further, examination of dark adaptation curves indicates that roughly 90 percent of adaptation to mesopic levels occurs during the first 2 min. For screening purposes, therefore, 2 min may be sufficient for testing visual functions at the higher mesopic levels of illumination.

Although no studies that related adaptation ability to driving record were found, it is obvious that the adaptation function is a part of the complex of visual functions required in night driving. Because adaptation ability is known to decline with advancing age, it should at least be considered for inclusion in retesting and screening programs for older drivers. Inasmuch as individual differences in ability tend to be greatest in the range of mesopic vision typically encountered in night driving, some gross test of adaptation might be warranted for all drivers. Further information is required on the magnitude of individual differences and the relationship between adaptation and other visual functions at mesopic levels of illumination before any firm decisions can be made.

Glare Sensitivity

The second function on the list that relates to night driving is glare sensitivity. Relatively bright light that produces unpleasantness or discomfort or that interferes with optimum vision is termed glare. Glare sensitivity refers to the ability to resist (glare resistance) or recover from (glare recovery) the effects of glare.

Any degree of light falling on the retina that does not contribute to clear vision constitutes glare. Vehicle drivers may be subjected to glare during daylight hours either from direct impingement of the sun's rays on the eye or, more commonly, as a result of reflections from shiny surfaces. A dirty or pitted windshield can scatter sunlight so as to create a light veil that tends to obscure objects in the environment. Similarly, reflections of the interior of the vehicle on the inside surfaces of the windshield can also produce veiling glare. Although the importance of glare during daytime driving should not be minimized, the majority of research on glare has been directed toward night driving in which the primary glare sources are headlights of opposing vehicles and light from roadway luminaires, advertising signs, and the like.

The effects of glare in reducing seeing depend on the intensity and position of the glare source relative to the line of sight (16). Glare along the line of sight reduces vision maximally, and the adverse effects fall off rapidly as the angle between the line of sight and the source increases. Connolly (7) states that, when the glare source is more than 10 deg from the line of sight, its effect on visual performance is relatively meaningless.

Burg (4) obtained glare recovery data from almost 18,000 subjects of all ages and reported a progressive deterioration in glare recovery ability with advancing age, but no differences between males and females. Burg's data, as well as those by Wolf (21), show that the rate of deterioration with advancing age is greatly accelerated after age 40. Reading (14) reported that recovery time from headlight glare increases significantly with age and that recovery time is shorter after exposure to white light than to yellow light, particularly in the older age group.

In general, recovery from the effects of glare depends on the retinal area involved, its previous adaptation level, intensity of the glare, exposure time, color of the glare source, accompanying changes in pupil size, and visual health of the individual (16).

The specific effects of glare on driving behavior have not yet been clearly defined; however, experimental data in general support the widely held opinion that in night driving glare degrades visual performance when a glare source, such as an opposing headlight, is encountered and immediately thereafter. Forbes (9) suggests that, in addition to its direct physical effects, discomfort glare encountered in night driving may be an important factor in inducing fatigue and drowsiness, even if the glare is not strong enough to directly reduce visual efficiency.

Burg (5, 6) found a slight but statistically significant relationship between glare recovery and driving record, but reported the relationship to be inconsistent. He points out that the inconsistent results might be attributed to the particular device used to measure glare effects. Allen (1) suggests that the low correlations found by Burg may be attributed to the fact that dirt and scratches on the windshield, plus hygroscopic deposits from tobacco and the like, may create so much glare that the contribution measured in the driver's eyes may not be reflected in accident statistics. In any event, it appears likely that glare sensitivity is an important visual function in driving and, in spite of the low correlation found with driving record, should be a part of any vision screening program for driver licensing including periodic retest in the over-40 age group. Again, however, it is important to test the effects of glare in situations pertinent to driving and on a number of visual functions, not just one, since the effects may be different for different functions. Particularly, the effects of glare on complex visual perceptions should be studied because they depend on a number of cues that may be degraded more seriously by glare than basic sensory responses such as acuity.

Other Visual Functions

Adaptation and glare sensitivity are of direct concern in night driving primarily because of their influence on other visual functions necessary in night driving such as static visual acuity. Many factors influence acuity, but of particular relevance to night driving are luminance, state of adaptation, and contrast.

Luminance

Target luminance is an important controlling factor in visual acuity. Acuity is poorest under low levels of illumination and gradually increases to a limiting value as illumination is increased. It is not generally recognized, however, that the correlation between acuity at high and that at low levels of illumination is rather low. This has significant implications for driver license tests since it points out the inadequacy of current practices in terms of screening out individuals whose visual acuity is unacceptably poor at levels of illumination encountered in night driving.

State of Adaptation

The luminance stimulation in the immediate past has an important influence on acuity largely because of its effect on sensitivity of the eye. If the eye is subjected to a relatively bright stimulus and its sensitivity is then measured in terms of the time required to read a small acuity target at various luminance levels, the resultant data are very similar to the typical dark adaptation curves based on absolute threshold to light stimuli, including the rod-cone discontinuity (2, 3). At the other extreme, the dark-adapted eye exhibits an oscillation of sensitivity and in acuity when subjected to a bright adapting light.

Contrast

The effect of target-background contrast on visual acuity is of primary interest in the context of night driving (17). Stevens and Foxell (20) and Pease and Allen (13) report that maximum visual acuity is achieved when the luminance of the surrounding field is equal to or slightly below that of the central field.

Based on review of the literature, it was concluded that glare sensitivity and overall visual performance under low levels of illumination were among those functions that definitely appeared to be important to driving, whereas the role of adaptation in driving had yet to be established.

EXAMINATION OF DRIVING TASK ANALYSIS

None of the literature on vision and driving has attempted to identify the visual requirements of the driving task. Therefore, available driving task analysis information was examined in an attempt to draw inferences regarding visual requirements. The most comprehensive driving task analysis available was conducted for the U.S. Department of Transportation (12), and this document provided the basis for the systematic evaluation of the visual requirements of driving conducted as part of this study.

Briefly, the analysis identified some 1,500 driving "behaviors" required of the driver. Each of these behaviors was then evaluated in terms of its criticality to safe performance of the total driving task and assigned a criticality rating.

In the current project, each one of these behaviors was examined to determine which, if any, of the 18 visual functions listed were required in normal performance of the behavior. When a visual function was required by a specific driving behavior, the degree to which it was essential to that behavior was judged and a weighting factor assigned.

Once this analytical procedure was accomplished, each of the 18 functions was ranked on two dimensions—the average criticality of the driving behaviors it was involved in and the average degree of essentiality of the function to these behaviors. On the basis of these two rankings, a hierarchy of each function's importance to the driving task was established. However, glare sensitivity and adaptation were not included in this hierarchy because they are not specifically task-related visual functions but can be involved in all tasks under certain conditions. For example, glare sensitivity can conceivably be related to any and all driving behaviors involving visual performance when sufficient glare is present to impair that visual performance. Such glare may take the form of opposing headlights or extremely bright roadside lighting encountered during night driving, or it may occur during daylight hours from the sun shining directly or via reflections into the eyes of the driver. It may also result from the sun striking a pitted and dirty windshield at the right angle to practically obscure all vision. The point is that the presence of glare is determined by environmental conditions and is essentially independent of any specific driving behavior. Because significant individual differences in glare sensitivity are known to exist, it is obvious that glare sensitivity must be considered as a visual function important to driving. However, evaluation of the relative importance must be made on grounds other than analysis of driving behaviors.

Adaptation is another function very similar to glare sensitivity in terms of its relationship to specific driving behaviors. At any time environmental conditions create a situation in which relatively large changes in illumination level occur, then adaptation becomes a pertinent factor in any driving behavior requiring visual performance.

Two other functions, phoria and fixation field, though not necessarily dependent on environmental conditions in the same way as are glare sensitivity and adaptation, are also difficult to evaluate through analysis of driving behaviors. These functions represent difficulties with the muscular control of the eye, which cause the individual to lose fusion and to suffer diplopia under certain conditions, e.g., poor visibility as a result of visual fatigue. Their importance to driving must be ascertained on grounds other than analysis of individual driving behaviors.

SUMMARY OF ANALYTICAL FINDINGS

As a result of both the literature survey and examination of the driving task, the following six functions were judged relatively high in importance to driving:

1. Static acuity,
2. Perception of angular movement,
3. Perception of movement in depth,
4. Dynamic visual acuity,
5. Visual field, and
6. Saccadic fixations.

In addition, the literature review suggests that the following functions also are highly important:

1. Glare sensitivity,
2. Pursuit fixations,
3. Steady fixations, and
4. Overall visual performance under low levels of illumination.

It is not to be inferred from these lists that other visual functions play no role whatsoever in driving. Some, such as color vision, are felt by some investigators to be very important; however, neither the literature nor the analyses of the driving task provide evidence in support of this view. As a consequence, development of the prototype test device concentrated on those functions itemized above, which were felt to have the greatest value in a screening application.

DEVELOPMENT OF A PROTOTYPE TEST DEVICE

Most of the visual functions identified above are not measured by any commercially available test device; therefore, a device was developed specifically for use in the evaluation program. The device consists of three major components:

1. A plywood enclosure approximately 50 in. wide, 24 in. deep, and 24 in. high (1.27 × 0.6 × 0.6 m). Looking through a viewing aperture, the subject is presented stimuli over a field of view of approximately 180 deg laterally and 30 deg vertically. The enclosure houses all test stimuli and excludes ambient illumination.
2. An electronic control box connected to the enclosure by a 3-ft (0.9-m) cable. The control box contains all the electronic circuitry and manual controls required by the experimenter to select and sequence tests and control test parameters.
3. A specialized projector system that includes a standard audio cassette tape playback unit to present standardized verbal instructions to the subject and to control an 8-mm film cassette that presents the stimuli for certain tests.

A photograph of the prototype device is shown in Figure 1. Shown are a side view of

Figure 1. Integrated driver vision testing device.

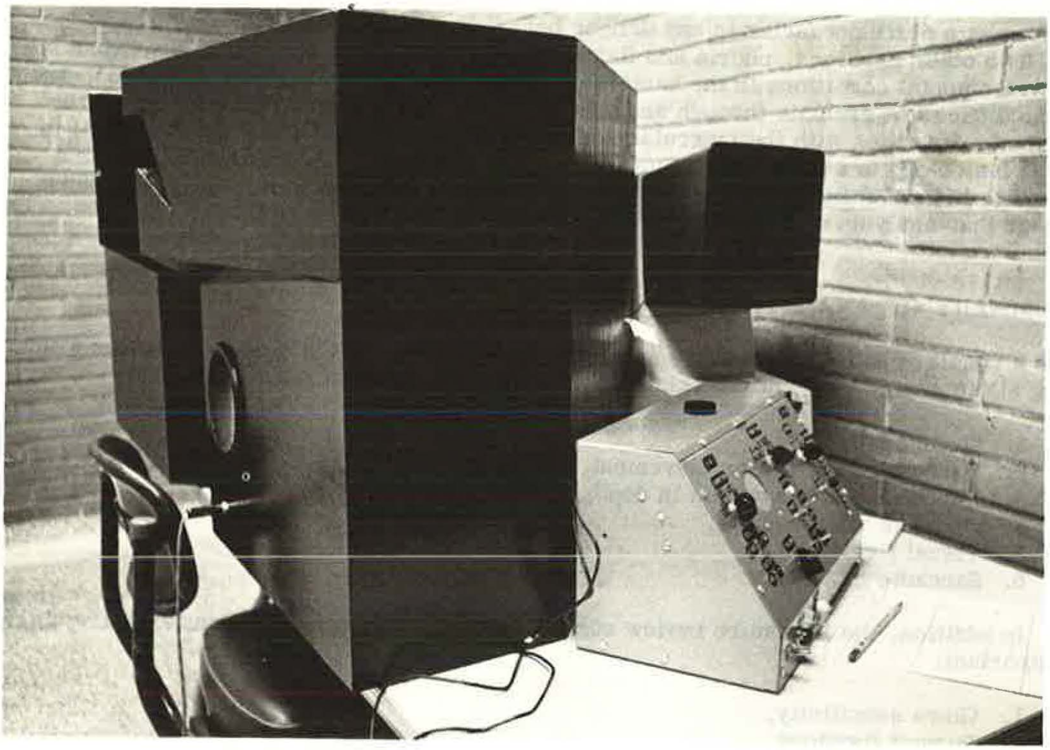
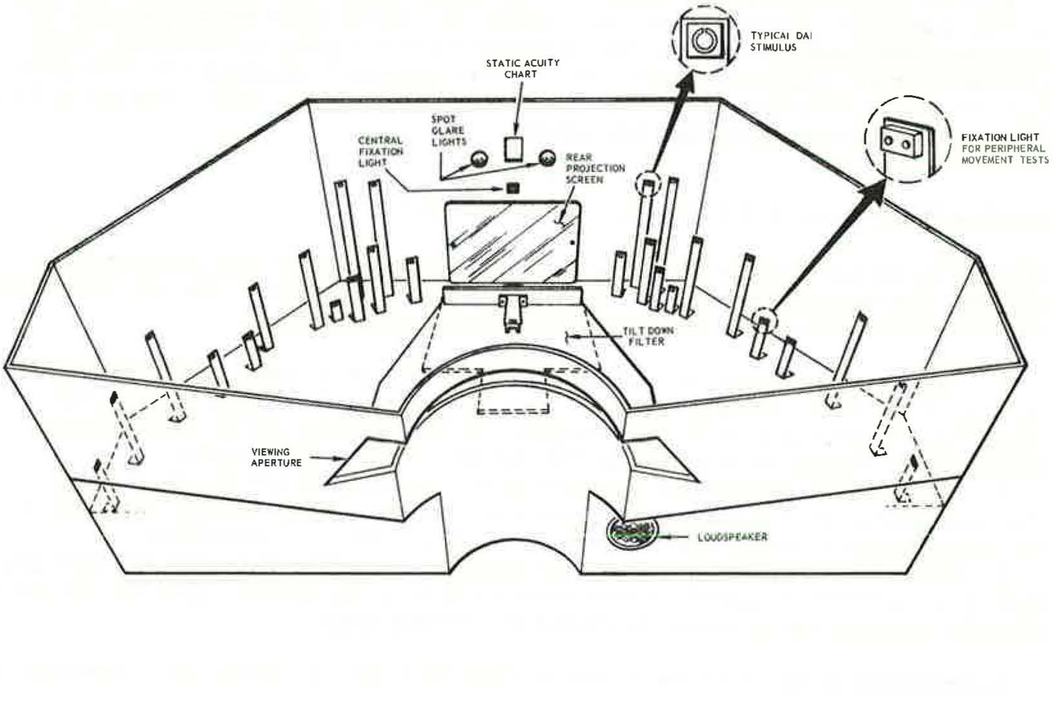


Figure 2. Interior of integrated driver vision testing device.



the enclosure, the electronic control unit, and the rear of the projector unit in the upper right corner of the figure. An artist's drawing of the interior of the enclosure shown in Figure 2 illustrates the basic simplicity of internal design.

The device was designed to provide the following performance measures:

1. Static visual acuity under normal illumination (SA-NORM),
2. Static visual acuity under a low level of illumination (SA-LL),
3. Static visual acuity in the presence of veiling glare (SA-VEIL),
4. Static visual acuity in the presence of spot glare (SA-SPOT),
5. Dynamic visual acuity,
6. Ability to perceive movement in depth (both centrally and peripherally),
7. Ability to perceive angular movement (both centrally and peripherally),
8. Lateral visual field, and
9. Ability to detect, acquire (fixate on), and interpret stimuli presented at random locations in the visual field for brief periods of time.

Except for the tests of movement threshold, the stimuli for all other tests consist of Landolt rings—circles with a break in them.

To keep the overall size of the device within practical limits, we presented all test targets at a nominal 20 in. (0.51 m) from the observer's eyes. To prevent penalizing older drivers who may not be able to focus (accommodate) on an object at that distance and to simulate distances important to the driving task, supplemental lenses are used to make stimuli at 20 in. appear to be at optical infinity [assumed by convention to be 20 ft (approximately 6 m) or more]. This is common practice in all compact vision test devices and is usually accomplished with fixed optics. However, because freedom of head movement is required by some of the tests in this device, these supplemental lenses are provided in conventional eyeglass frames for those who do not normally wear eyeglasses and in clip-on frames for those who do.

The device is flexible enough to permit measurement of performance on any of the tests under varying illumination or glare conditions or both. However, performance measurement on all tests under low levels of illumination and glare obviously was impossible because it would have made testing time prohibitively long. Therefore, the effects of low illumination and glare were measured solely on static acuity, a visual function that is simple to measure and about which much is known. Of the tests listed above, then, only those dealing with static acuity are discussed. The interested reader is referred to Henderson and Burg (11) for a discussion of the other vision tests involved in the research program.

Static Acuity, Normal Illumination (SA-NORM)

The ability of the eye to resolve detail in a stationary object is measured by presenting to the subject a series of Landolt rings, calibrated in size to correspond, in terms of the angular subtense of the break in the circle, to the Snellen system of notation, e.g., 20/20, 20/40, etc. A series of rings of graduated size is presented to the observer who is instructed to call out the location of the break in each circle beginning with the largest (20/175 equivalent) and going toward the smallest (20/20 equivalent). The Snellen equivalent of the smallest circle in which the gap position is correctly identified at least four out of six times is the subject's static acuity score. The test targets used have a brightness of 2.3 ft-L (7.9 cd/m^2) and a background brightness of 0.019 ft-L (0.65 cd/m^2), yielding a contrast of 0.99.

Static Acuity, Low Level Illumination (SA-LL)

A measure of the individual's visual acuity under levels of illumination typically encountered in night driving is obtained by administering the static acuity test again. This time a neutral-density filter is interposed between the subject and the target (and background), which keeps the contrast the same but reduces the Landolt ring target brightness from 2.3 to 0.02 ft-L (7.9 to 0.7 cd/m^2). Although this level of brightness is not in the deep mesopic range and does not represent the worst case in night driving, it was representative of night driving yet not so dim as to require long-term dark adaptation. (Long-term adaptation is not practical for a screening test situation.) In practice, most subjects spend approximately 10 to 15 min in the dark test room viewing test targets no brighter than 2.3 ft-L (7.8 cd/m^2) and, during the 5 to 10 min immediately preceding this test, view moving targets of comparable brightness to those used in this test. The same procedures and scoring criteria are used for this test as for the SA-NORM.

Static Acuity, Veiling Glare (SA-VEIL)

To obtain one measure of an individual's sensitivity to glare, the static acuity test is administered again. In the veiling glare test, the subject is required to view the test targets through a uniform field of reflected white light of 40.25 ft-L (137.9 cd/m^2) brightness. The brightness of the test stimuli is 42.5 ft-L (145.6 cd/m^2), giving a contrast of 0.05.

Static Acuity, Spot Glare (SA-SPOT)

A second measure of glare sensitivity was obtained by presenting the static acuity stimuli to the subject in the presence of two spot glare sources, one on each side of the test targets. Brightness of each bulb, measured directly at the light, is 40,000 ft-L (137 kcd/m^2). Separation between the two lights is approximately 5 in. (127 mm) and, as with the test stimuli, they are approximately 20 in (0.5 m) from the subject's eyes.

The score on each acuity test is the smallest row of acuity targets in which the individual can reliably identify the location of the gap in four out of six targets.

The four tests described above were not administered in the order shown but were worked into a carefully planned sequence that included all the tests listed earlier. All testing was conducted in a dark room.

EVALUATION OF THE PROTOTYPE TEST DEVICE

A full description of the methodology used in collecting vision test data on the prototype device can be found elsewhere (11). Briefly stated, the tests were administered to both passenger car drivers and truck and bus drivers. A total of 669 passenger car drivers were tested, the majority at California Department of Motor Vehicles' field offices. The subjects ranged in age from 16 to 86 and were of both sexes (37 percent female). In addition, a total of 235 male truck and bus drivers were tested at their places of employment. They ranged in age from 25 to 64, with a mean age of 41 years. All subjects were volunteers. Subsequent to testing, 3-year driving record information on each subject was obtained (from DMV files for passenger car drivers and from company records for the truck and bus drivers).

The data collected from both groups of subjects were subjected to three types of analyses: correlational, multiple regression, and graphical. The results of these analyses are summarized below.

RESULTS OF EVALUATION STUDY

The data collected during the evaluation program were analyzed in a number of ways. Because of the known relationship between age and general visual capability and between age and accident involvement, the total passenger car sample was divided into three age groups for most analyses. These age groups were 16 to 24, 25 to 49, and

50 and above. Tables 1 and 2 give selected personal and vision test data for all subject groups.

Correlational and multiple regression analyses were carried out. They revealed that, of the four tests being discussed, only SA-NORM was a significant predictor of accident record and then only for 25 to 49-year-old passenger car drivers.

A graphical analysis was also carried out to evaluate the hypothesis that individuals with poor performance on a given test have a mean accident rate significantly greater than drivers with better visual performance. Used in this fashion, graphical analysis is a more appropriate statistical technique than either correlational or multiple regression analysis for establishing the feasibility of using a particular test in a screening program, for the impact of using various cutoff scores for each test can be assessed.

The results of the graphical analysis show that for the passenger car drivers, even when day and night accidents are grouped together, poor performers on all four static acuity measures have higher accident rates than do good performers. (A similar analysis was not conducted for truck and bus drivers.)

Review of the findings of all the analyses shows that SA-LL, SA-VEIL, and SA-SPOT, which deal with aspects of vision involved in night driving, were not adequately evaluated in this study in that no information was available concerning night accidents to provide an appropriate criterion variable.

What the data do provide is an indication of the degree of variability in visual acuity performance obtained under conditions similar to those encountered in night driving. The data also show that acuity measured under normal light conditions does not adequately predict acuity under conditions typical of night driving. Figures 3 through 7 show cumulative frequency distributions for the various acuity tests and subject groups, and Tables 3 and 4 give intercorrelations among the vision tests and age. Figure 8 shows a comparison of mean performance scores on the tests for the various subject groups.

It is clear from the figures that

1. The effect of age on acuity, regardless of how it is measured, was dramatic;
2. Performance on the spot and veiling glare tests was very much alike within each age group;
3. The range of acuity performance within each age group increased dramatically under low illumination and in the presence of glare (as shown by the relatively low intercorrelations, some individuals are affected much more than others by these adverse viewing conditions); and
4. Truck and bus drivers reacted to the adverse effects of low illumination and glare as did passenger car drivers, in spite of the fact that the acuity test procedure was significantly modified for administration to truck and bus drivers (this modification had the effect of making the test easier at the poor performance end of the scale and at the same time more reliable).

The data given in Table 3 and shown in Figures 3 through 8 are consistent with the literature and clearly suggest that tests of daytime vision do not suffice for the prediction of vision-related nighttime accidents. There is, then, an urgent need for a controlled study of the relationship between night vision performance and night accidents.

PLANS FOR THE FUTURE

The National Highway Traffic Safety Administration is currently sponsoring a program to design and construct an improved vision testing device that incorporates those tests found most promising in this study. Specifically, this program has the objective of constructing a feasibility prototype of a Mark II device that will automatically administer and score tests that measure

1. Static acuity,
2. Static acuity under a low level of illumination,

Table 1. Summary of personal data on drivers tested.

Drivers Tested	Sample Size Number	Sample Size Percent	Average Age	Estimated Average Annual Mileage (thousands)	Number of Accidents in Past 36 Months	Accidents per 100,000 Miles
Passenger car						
16 to 24	155	23.2	20.8	16.1	0.50	2.03
25 to 49	310	46.4	35.9	17.6	0.32	0.69
50 and over	203	30.4	60.0	13.4	0.15	0.80
All ages	668	100	39.7	15.9	0.31	1.03
Truck and bus	235		40.9	69.2	0.64	0.79

Table 2. Summary of vision test data.

Drivers Tested	Normal		Low Level		Veiling Glare		Spot Glare	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Passenger car								
16 to 24	23.4	7.2	129.5	39.7	64.0	32.7	54.3	28.8
25 to 49	23.1	6.0	128.2	41.0	66.7	35.3	60.0	32.4
50 and over	31.6	15.2	149.2	42.4	95.9	50.9	96.1	53.1
All ages	25.8	10.7	134.9	42.1	74.9	42.4	69.5	42.8
Truck and bus	21.5	5.9	73.8	26.0	45.8	21.0	40.2	20.8

Figure 3. Cumulative distribution of static acuity scores for passenger car drivers, both sexes, all ages.

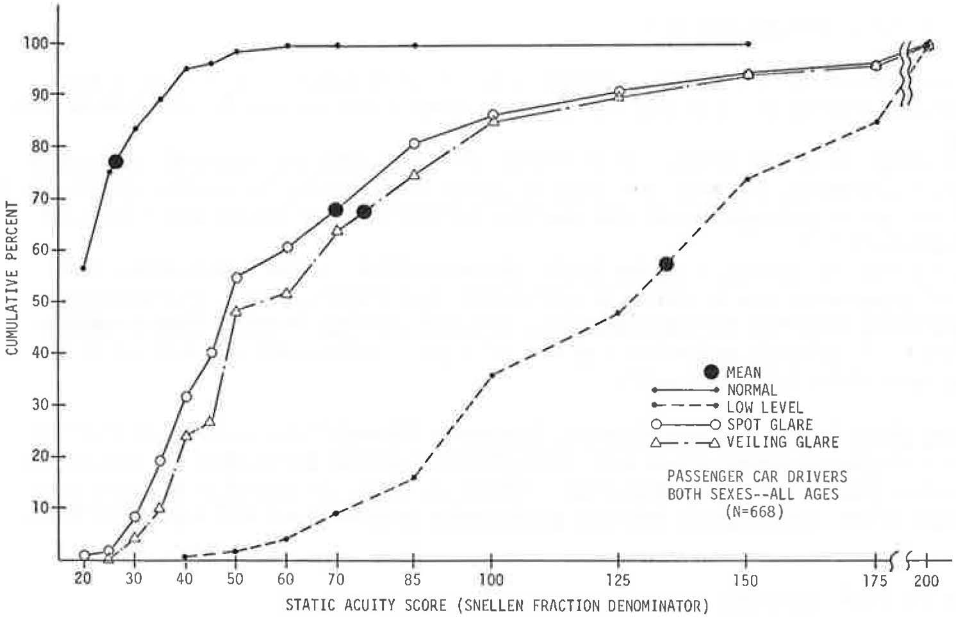


Figure 4. Cumulative distribution of static acuity scores for passenger car drivers, both sexes, ages 16 to 24.

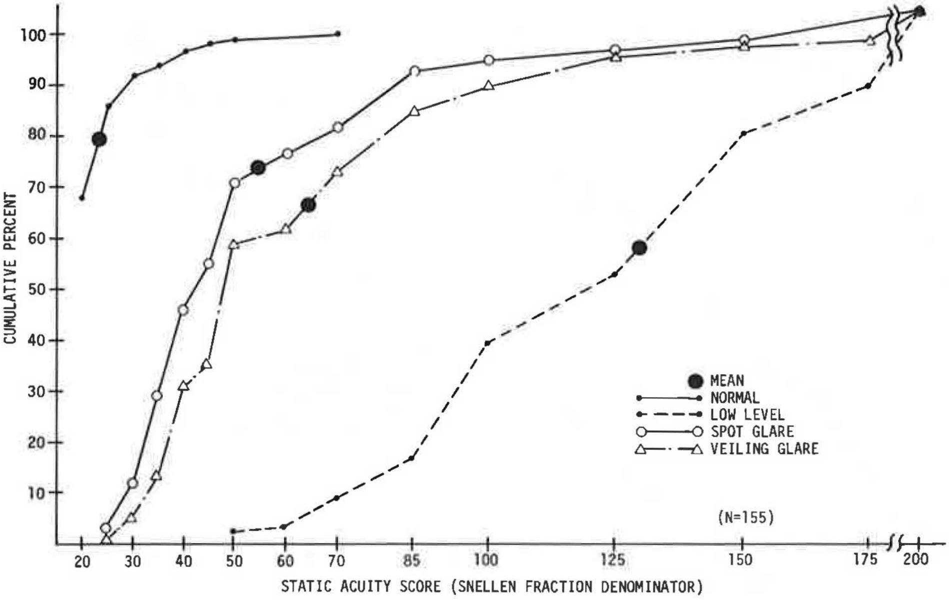


Figure 5. Cumulative distribution of static acuity scores for passenger car drivers, both sexes, ages 25 to 49.

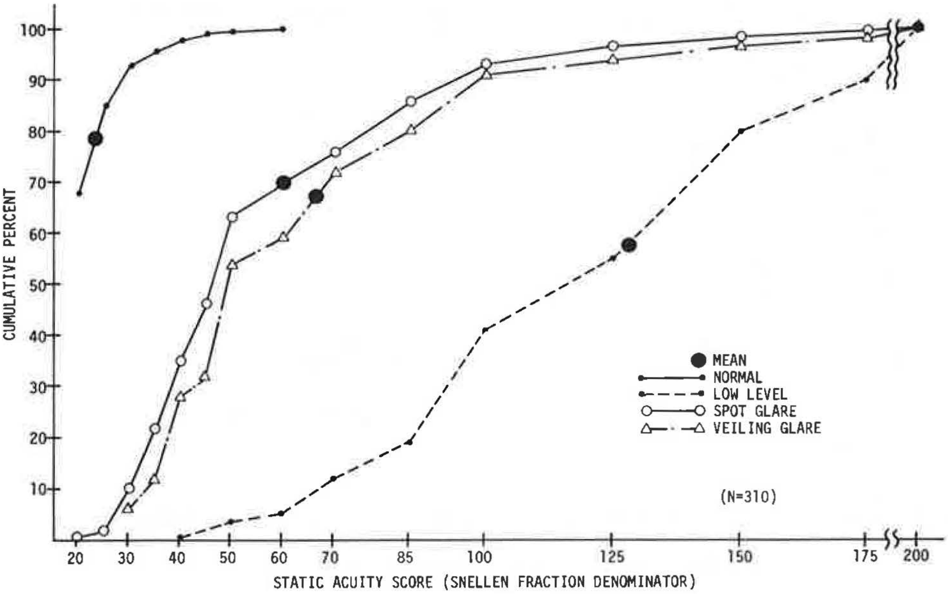


Figure 6. Cumulative distribution of static acuity scores of passenger car drivers, both sexes, ages 50 and over.

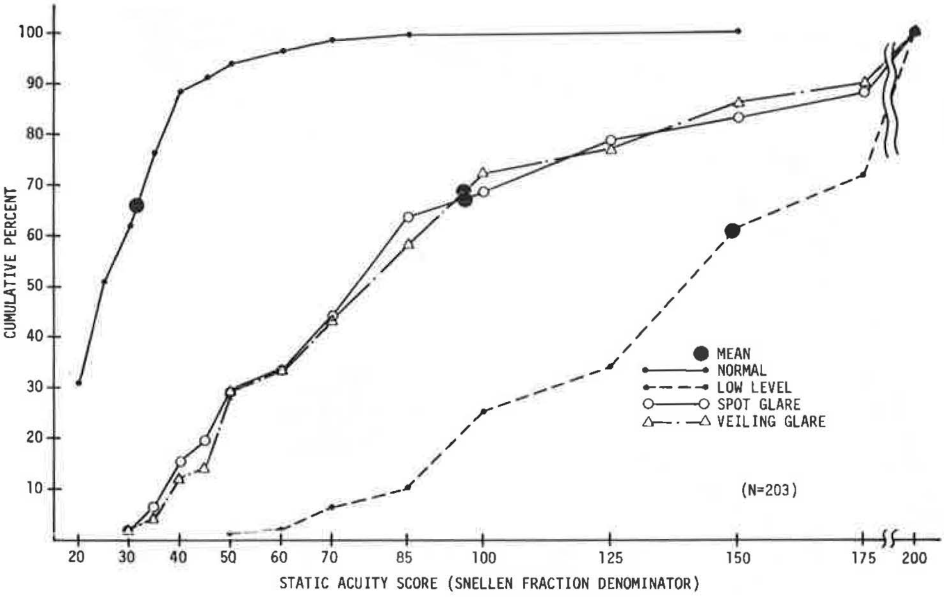


Figure 7. Cumulative distribution of static acuity scores for truck and bus drivers.

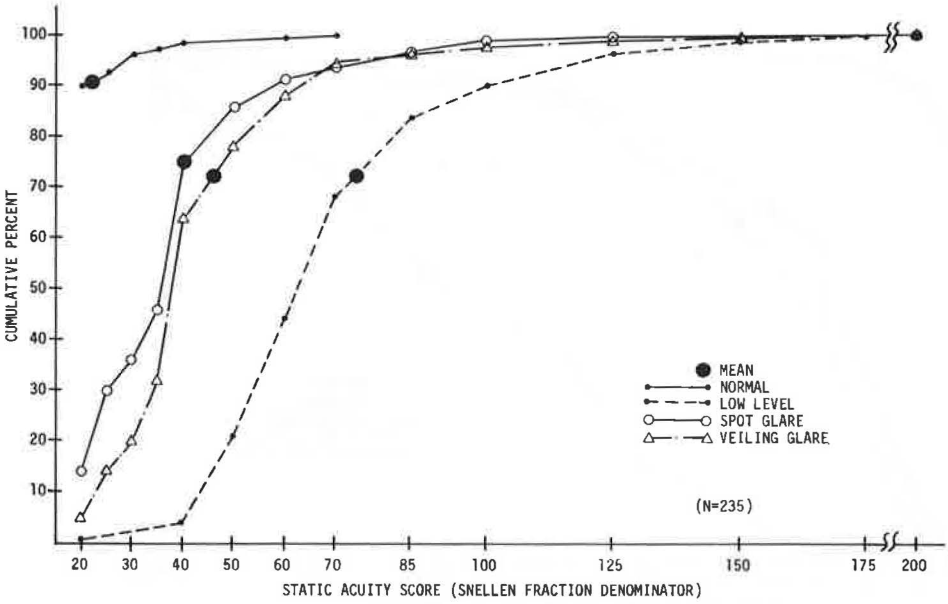


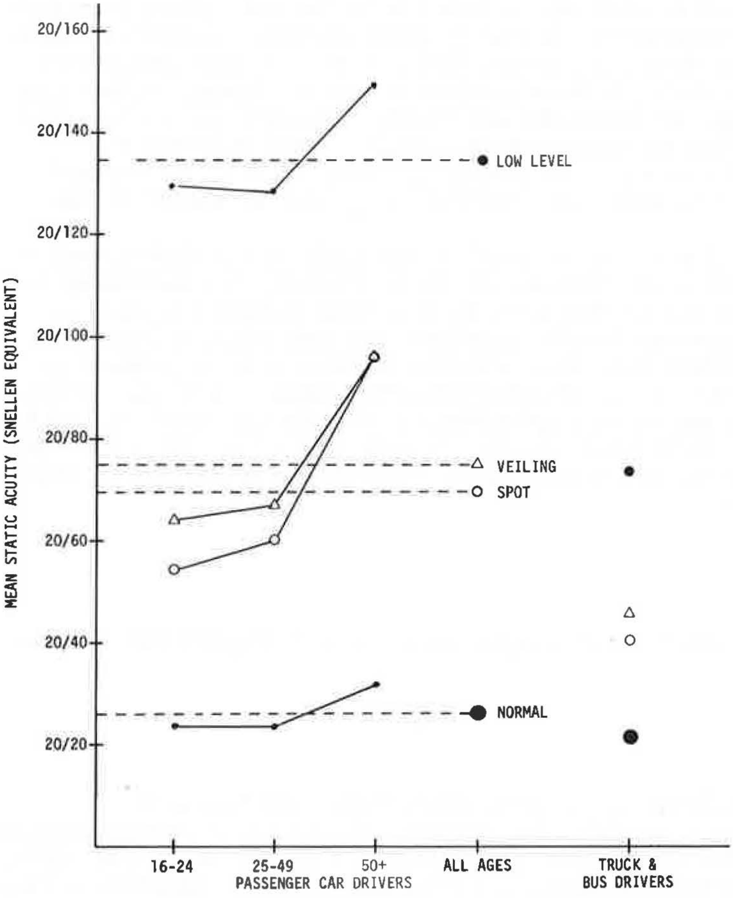
Table 3. Product-moment correlations for automobile drivers significant at P ⩾ 0.90.

Test	16 to 24				25 to 45				50 and Over				All			
	SA-NORM	SA-LL	SA-VEIL	SA-SPOT	SA-NORM	SA-LL	SA-VEIL	SA-SPOT	SA-NORM	SA-LL	SA-VEIL	SA-SPOT	SA-NORM	SA-LL	SA-VEIL	SA-SPOT
SA-LL	0.36	–			0.38	–			0.38	–			0.39	–		
SA-VEIL	0.41	0.32	–		0.37	0.39	–		0.52	0.55	–		0.52	0.47	–	
SA-SPOT	0.54	0.40	0.75	–	0.41	0.42	0.75	–	0.43	0.51	0.79	–	0.51	0.49	0.80	–
AGE	NS	NS	NS	0.17	0.11	NS	NS	NS	0.27	0.27	0.42	0.57	0.37	0.23	0.37	0.48

Table 4. Product-moment correlations for truck drivers significant at P ⩾ 0.90.

Test	Truck and Bus Drivers			
	SA-NORM	SA-LL	SA-VEIL	SA-SPOT
SA-LL	0.21	–		
SA-VEIL	0.36	0.56	–	
SA-SPOT	0.46	0.57	0.86	–
AGE	0.18	NS	NS	0.11

Figure 8. Mean static acuity scores by subject group.



3. Static acuity in the presence of spot glare,
4. Ability to detect, acquire, and interpret acuity targets randomly presented over a field measuring 30 deg laterally by 20 deg vertically,
5. Ability to detect angular movement in the central field,
6. Ability to detect movement in depth in the central field,
7. Ability to detect angular movement in the peripheral field, and
8. Field of vision.

Once this prototype device is built, a series of engineering tests and reliability studies will be conducted. If the results of these tests are satisfactory to NHTSA, a number of these Mark II devices will be constructed for use by various states (and foreign countries) in conducting a large-scale validation study involving 20,000 to 30,000 drivers. Driving record information including data on time of accidents will be used, so that the two measures of night vision can adequately be evaluated and validated.

SUMMARY

In summary, a great deal more research is required before we can adequately answer the question of the importance of night vision screening of driver license applicants. At this point we know that visual performance is seriously degraded under conditions typically encountered in night driving, i.e., low levels of illumination, glare, and low-contrast targets. It may well be that target contrast is the key parameter, since both low levels of illumination and glare tend to reduce target contrast. Further, we know that some individuals are much more severely affected by these factors than others, and as a result the total variability in visual performance of the driving population increases significantly as level of illumination decreases, glare increases, or contrast decreases. We also know that accidents increase at night. What is lacking is clear evidence of a relationship between poor night vision performance and high accident probability. It is hoped that the research under way will provide an answer to this question.

A major problem, not unique to this research, is the quality of accident statistics that may be available for use as the criterion measure. Clearly, the relationship between night vision capability and accident probability must be evaluated relative to nighttime accidents, and more specifically, nighttime accidents where at least some minimal information is available concerning visibility conditions, e.g., presence or absence of fixed lighting, presence or absence of headlight glare, and so on. Obtaining information of this type may be the most difficult part of the total problem, and it is important that both state and federal agencies intensify their efforts toward developing accident data banks that are in a form, both qualitatively and quantitatively, that is most usable for researchers.

ACKNOWLEDGMENT

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At the Transport and Road Research Laboratory, lighting research is concerned with both vehicle and roadway lighting. Work is under way to establish the relationship between road light levels and accidents. The research involves extensive measurements of light levels and detailed recording of accident data. These will be supplemented by the findings of studies of near accidents (conflicts) recorded at specific sites, which should indicate the effectiveness of both conventional and experimental lighting schemes. Nighttime driving is particularly difficult on wet roads, and therefore a photometric evaluation of all types of surfaces both wet and dry is being undertaken to provide physical measurements relating to the problem. Vehicle lighting research is mainly concerned with the investigation of headlight glare-reducing techniques. These include the possible use of dimmed headlight beams as presence indicators in lighted areas, median glare screens, and special low-glare head lamps. A study of the merits of the low-beam head lamp patterns developed in Europe and in the United Kingdom and the United States revealed little overall advantage for either, but showed that there was a considerable problem resulting from head lamp misaim due to vehicle loading. This problem is being tackled by the development of head lamp self-leveling systems.

LIGHTING RESEARCH AT THE U.K. TRANSPORT AND ROAD RESEARCH LABORATORY

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In the United Kingdom, vehicle and roadway lighting is regarded primarily as a safety problem rather than as an aspect of traffic engineering. Thus the priorities in both research and application are dictated by the accident situation.

Some 30 percent of all personal injury accidents take place at night (87,644 out of a total of 264,453 in 1972). Since nighttime traffic is about a quarter of the total, this means an overall night accident rate about 1.3 times that of the day rate. Three-quarters of all night accidents occur on lighted roads, and about three-quarters of these are on roads lighted to the highest standard. An analysis of weather conditions has shown that the combination of wet roads and darkness gives the worst accident figures. Against this background the lighting research at the Transport and Road Research Laboratory (TRRL) falls into the categories discussed below.

EFFECT OF LIGHTING

Overall, studies have shown that installing roadway lighting effects a 30 percent reduction in the number of night accidents and a parallel reduction in accident severity. Some studies have discriminated between road types; for example, a recent British study showed a 50 percent accident reduction on 115-km/h trunk roads, and the current program to light motorways should achieve a comparable reduction. The motorway blanket speed limit is 115 km/h. Studies such as those of Turner (1) and Box (2) have attempted to relate accident rates to lighting levels, an area of vital importance for future lighting policy.

In March 1974 TRRL placed a $442,000 contract with a large commercial lighting firm to collect photometric data from actual roadway installations; those data will then be related to accidents at those locations. The opening phases of the work will use conventional instruments and measuring techniques, but new ways of acquiring and processing the large amounts of data that this sort of work generates will be explored and developed.

An essential part of the research is the development of a mobile laboratory that will travel through the streets and continuously record significant factors such as roadway luminance in the driver's field of view. Initially the lighting quality criteria of the International Commission on Illumination (CIE) will be used (luminance level, uniformity, glare level); the contract is for 4 years and includes the development of both basic measurements and a method of assessing them.

CONFLICT STUDIES

The insensitivity of global accident figures to specific safety measures has led to the search for other objective measures with which to assess safety in particular circumstances. The basic problem can be summed up as a lack of sufficient numbers of accidents occurring at experimental sites. Preliminary laboratory experiments in which driver judgment and behavior were measured demonstrated the difficulties of interpreting specific results as a function of lighting levels or whatever and pointed to the even more difficult task of carrying out similar tests on real roads. A promising method of tackling the problem is to use conflicts (near accidents) observed in real road conditions.

Conflicts can be characterized as sharp, evasive traffic maneuvers. Most conflicts are resolved by one or more of the vehicles involved taking successful evasive action. Conflict recordings enable the frequency of occurrence of accidents to be predicted. Conflict data accrue much more quickly than accident data: Roughly 10 hours of conflict observation will give data comparable to 3 years of accident data. [Conflicts studied at a rural junction showed a spatial and temporal distribution positively correlated with accidents, Spearman rank order coefficients being 0.93 and 0.87 respectively (3)].

The situation leading to the conflict can be studied in detail after it has been recorded with suitable movie or television equipment. Tests have shown that adequate records may be obtained under most roadway lighting levels by using modern low-level films and cameras. In the planned research conflicts at junctions will be observed under different lighting conditions, including experimental lighting.

ROAD SURFACE CHARACTERISTICS

In 1970 a reappraisal of the British Standard Code of Practice for Street Lighting for Traffic Routes (4) was commenced, and particular attention was paid to the relationship of the code specifications to proposals made by the CIE (5). This work sparked a renewed interest by British street lighting engineers in the classification of road surface characteristics to be used in designing lighting installations. As a result, TRRL undertook a survey of the reflection characteristics of British roads.

The work comprised a survey made in cooperation with a Dutch firm to compare British and Dutch techniques for measuring luminance and reflection characteristics by taking sample measurements at a number of sites under various types of installation (6). The main findings are that the installations designed to the present British Code CP1004 gave luminance values that satisfactorily meet the CIE recommendations: The mean luminance levels of 82 percent of measurements were above the lower recommended minimum of 1 cd/m^2, and 43 percent were above the upper recommended minimum of 2 cd/m^2. The uniformity recommendation that the minimum local luminance should be not less than 0.4 of the mean level was met by 71 percent of the installations.

Reflection characteristics were recorded in different areas of the country on different surfaces with different textures at different times of the year. Such variability makes the design of the optimum lighting installations extremely difficult. The survey gave some indication of the problem. However, a more detailed study of surfaces is being made in accordance with current CIE research recommendations. An apparatus is being constructed to record the complete reflection characteristics of a variety of road types; road samples will be subjected to traffic wear and will be examined under both wet and dry conditions. The data will be used for the prediction of the lighting performance of standard and unconventional lighting systems.

The reflection characteristics of wet roads need to be investigated further, and recommendations for surface texture requirements need to be formulated to improve uniformity of luminance. It is fortunate that the requirements for surface texture for all aspects of the wet-weather problem are compatible. For improvements in skid resistance and day and night visibility, all evidence points toward the need for macroscopically rougher textures. Additionally, the requirements for skid resistance demand a degree of harshness on a microscopic scale to maintain an acceptable level of performance. The requirement for road surfaces at night to have suitable texture to reflect light diffusely in wet weather demands both harshness and angularity of projections in the surface.

ROAD LIGHTING HARDWARE

Despite the beneficial effects of lighting, lighting supports are responsible for more than 5,000 personal injury accidents per year. Moving the lighting columns farther back from the road may reduce the risk of collision; however, this can only be done to a limited extent if maximum lighting efficiency is to be maintained. A breakaway lamp column has been designed for use on high-speed rural and semi-urban roads (7). The column breaks away just above the root when struck by a vehicle. The small impact produced by this type of column reduces the severity of injuries to passengers and damage to the vehicle.

The breakaway mechanism (Fig. 1) consists of a special slip joint by which the shaft of the column is attached to the root mechanism. Flanges welded to the shaft and root sections are clamped together by high-tensile steel bolts located in four 60-deg V-shaped notches in the outside edges of the flanges. The bolts are retained in the V-notches by a thin steel gasket between the flanges.

When the column is struck by a vehicle (contact is usually made 0.4 to 0.5 m above ground level), the shaft moves parallel to the root flange causing the bolts to tear the gasket. The bolts on the side away from the impact are carried away by the upper flange, and those on the impact side are retained in the V-slots of the lower flange. The shaft is thus released from the root section, and the lower end is propelled forward by the vehicle.

At collision speeds of more than about 50 km/h the shaft rotates about a point above the vehicle, allowing it to pass underneath. The final position of the shaft is such that it should not cause a hazard to following vehicles. The action is shown in Figure 2. At impact speeds of less than 50 km/h there is a risk that the shaft of the column will fall on the vehicle. To reduce damage to the vehicle and possible injury to passengers in these circumstances requires that the shaft of the column be as light as possible. Lightweight thin steel columns for 10- and 12-m mounting heights have therefore been designed.

Experience in the use of such columns has been gained from installation of 449 columns in five locations for which detailed accident records were kept. From experience to date it appears that the increased initial cost of breakaway lighting columns is more than offset by the savings in accident costs due to the reduction in accident severity.

The installations discussed so far were designed for roadside use. There is, however, a growing use of lighting on motorways and other high-speed roads where conditions are somewhat different. Columns located in medians are cheaper and more effective than those installed on the roadside. Using breakaway columns in such a position could be dangerous, for if struck they would fall into fast moving traffic in the opposite carriageway. The use of hard columns protected by safety fences also presents difficulties because of the lack of space on most median strips.

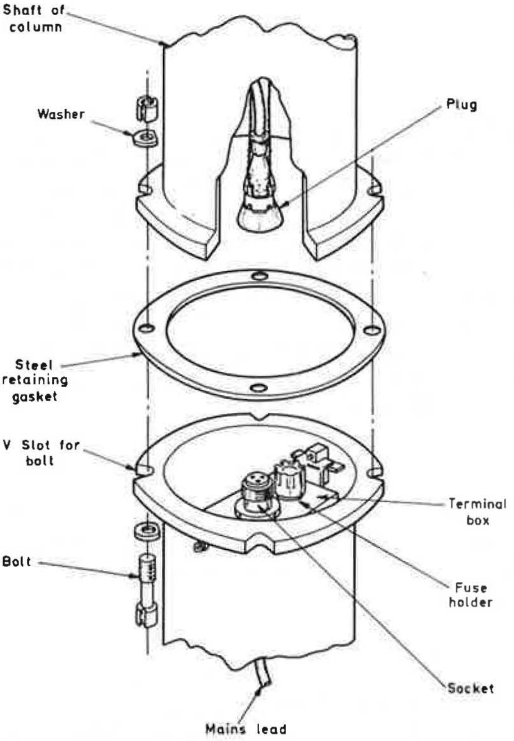


Figure 1. Details of breakaway joint in lighting column.

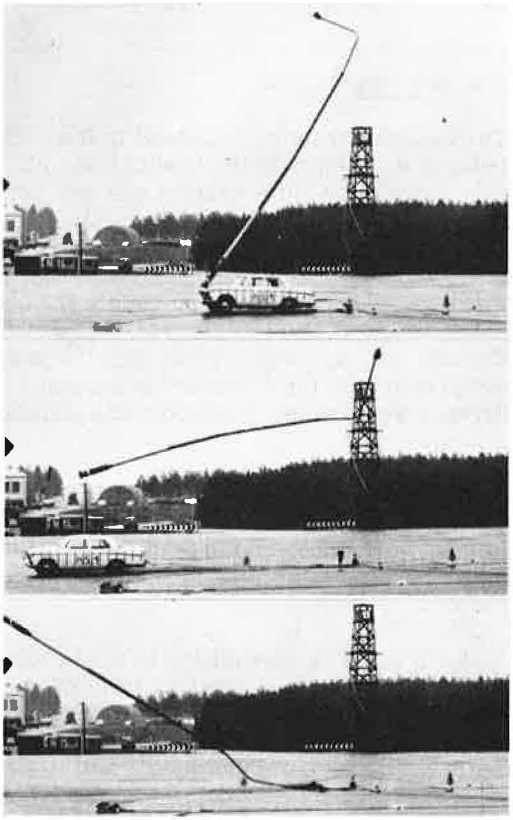


Figure 2. Column breaking away after impact.

The solution developed at TRRL is to site breakaway columns with their bases set inside a double-sided tensioned-beam safety fence that is set on a single line of posts. The important feature of the design is that the tops of the columns are tied together by a wire rope. This prevents the column from falling once the base has sheared but allows it to be pushed aside. Impact tests at 113 km/h and at an angle of 20 deg proved that the system performed adequately.

The system was proved sufficiently to experiment on 1.5 km of two-lane dual carriageway. The columns were 12 m high at 50-m centers, each carrying double 3-m brackets, conventional sodium lanterns, and control gear. The top column connection was made with a 7-mm diameter steel wire rope clamped to the column. At the ends of the complete installation the cable was terminated at rigid columns and tensioned; these hard columns were protected by substantial safety fences. The bases of the breakaway columns were set between a double-sided steel W-section safety fence mounted on wooden posts. So far the experimental section has not been struck, but arrangements have been made to record the details of all accidents involving the installation.

VEHICLE LIGHTING IN LIGHTED AREAS

Like many other countries, the United Kingdom wants to determine the optimum lighting for vehicles traveling in lighted areas. It is generally accepted that dipped headlights are too glaring, and present sidelights are too inconspicuous. What seems to be required is an intermediate or city light. TRRL favors the technique of dimming the dipped beam and, based on experiments using a manual system in 1966, an automatic system has been developed.

The Dim-Dip System

The dim-dip system, proposed in the early 1960s, simply incorporated an additional relay and resistor in the headlighting circuit of the vehicle. When the sidelight switch was operated and the ignition was on, between 6 and 8 V were applied to the low-beam headlights by use of a series resistance in the normal 12-V supply. This gave a dimmed intensity of about 10 percent of the normal beam. Full intensity could be selected by use of the normal switch position. Although the system was trouble-free and simple to use, when and where it should be used were entirely at the discretion of the driver. Inasmuch as use of the system was recommended for certain street lighting conditions, an obvious measure would be to sign the vehicle lighting to be used, but at present this is not practicable for a number of reasons. Thus there would always be a danger that drivers would select inappropriate lighting configurations.

The Fully Automatic System

In view of the shortcomings of the driver-controlled system mentioned above, an automatic headlight dimming system was developed. The system requirements were as follows:

1. It must be insensitive to the headlights of other vehicles;
2. It must give a variable level of dimming ranging from full intensity under very poor or no street lighting to full dimming under highest level street lighting;
3. It must dim at a slow rate but brighten up at a fast rate (e.g., when a driver suddenly enters an unlighted area); and
4. It must not dim the lights under conditions such as daylight fog.

The prototype device satisfies these requirements by responding only to the illumination coming from street lights (8). This is based on the fact that superimposed in all light emanating from street lamps is a fluctuating component due to the main supply frequency. In the United Kingdom, the fundamental frequency is 50 Hz resulting in a 100-Hz component. The device, therefore, detects the amplitude of the 100-Hz component in the light and adjusts the headlight intensity to its inverse magnitude.

The actual equipment comprises the following sections:

1. Photodetector and tuned ac amplifier—A silicon photodetector is coupled to a simple two-stage ac amplifier whose response is tuned to 100 Hz. The amplifier output is substantially zero when the cell receives steady illumination no matter what its strength.
2. Memory circuit—Because the headlight intensity is to be proportional to the amplitude of the ac amplifier output, it is necessary to prevent minor fluctuations of the signal causing a constant flickering of the light. This is achieved by providing a degree of signal integration.
3. Headlight intensity-modulating circuit—The variation in headlight intensity is achieved by using a square wave modulated supply and varying the mark-space ratio of the wave according to the output of the integrator circuit.

Units are being produced so that a controlled trial can be conducted in Central London.

VEHICLE LIGHTING TO REDUCE GLARE

Recent research on vehicle lighting (other than that described above) has been concentrated on vehicle headlights and has not included signaling and presence lights.

The object of any headlight system is to provide adequate illumination of the road scene ahead while creating minimum glare to other road users, particularly oncoming drivers. Thus the intensity pattern of the meeting (low) beams has been designed to emit as little light as possible above the horizontal, particularly on the driver's side of the road. Within this general design two distinctive beam patterns have been evolved. In Britain and North America a light pattern with a graduated cutoff but fairly high intensity on the near side has been adopted (Fig. 3a). In continental Europe, designers have concentrated on reducing glare as much as possible, resulting in a beam pattern that has a sharp cutoff shaped to allow illumination over relatively long distances on the near side (Fig. 3b).

Both beam patterns have their proponents and opponents. However, a series of controlled experiments together with field surveys in Britain and in continental Europe (9) has shown little to recommend one beam over the other.

Field Surveys

Surveys were made of actual head lamp intensities on roads where the two types were in common use. To assess the European beam, surveys were made in Belgium, Holland, Germany, and France. Four sites in Britain were used to record the Anglo-American beams. Intensity measurements were made on dual carriageways (divided highways) (a) toward the near side 60 m in front of the vehicle and (b) in the direction that would have caused glare to an oncoming driver about 60 m away had the road been a typical two-way single carriageway. The measuring equipment was stationed in the median (Fig. 4).

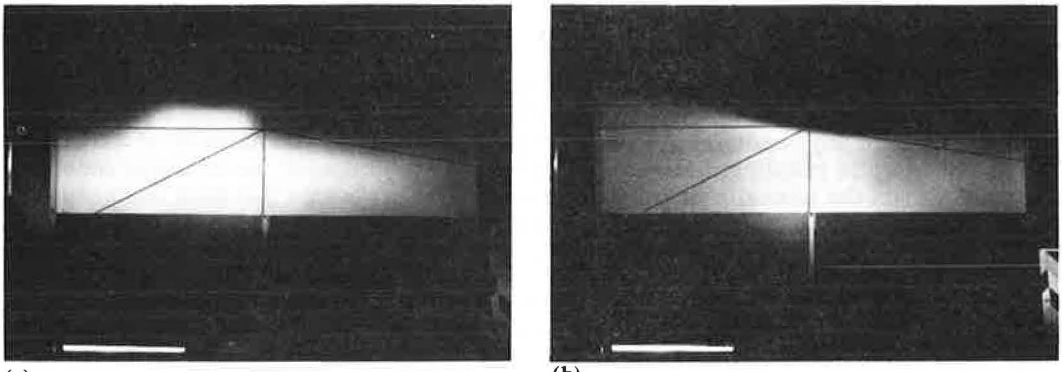
The results shown in Figure 5 indicate that glare intensities from the European beams were typically half those of the Anglo-American beams, but still much higher than expected from the photometric requirements of the beam. The illumination values of the two types were similar, and seeing distances were found to be comparable with the two systems. However, a typical European driver would be at a disadvantage in a population of Anglo-American beams, and, correspondingly, a British driver would have the advantage in a population of European beams.

Seeing Distance Measurements

With opposing cars using low beams in different meeting situations, the distances at which an object could be recognized were recorded. The object had a luminance factor of 0.07, was 0.45 m high, and had a recognizable shape. The speed of approach to the object was always 48 km/h. On lighted roads comparisons were made on straight sections only, whereas on unlighted roads comparisons were made on straight, curved, and undulating layouts. Results given in Table 1 show that the degree to which either beam can reveal an object depends on road layout and transverse location of the object on the road. On unlighted roads Anglo-American beams give greater recognition distances for near-side objects, whereas European beams reveal off-side objects at greater distances. Overall, there is no advantage of one type of beam over the other.

Detailed analysis of the results also showed that the speed of a vehicle bore no relation to the light output of its low beams and that whatever the country drivers were driving well outside the range of their lamps. This confirms the well-recognized view that, despite recent advances in head lamp technology, present low beams are inadequate for safe and comfortable night driving at today's speeds.

Figure 3. (a) Anglo-American and (b) European beam patterns.



(a) (b)

Figure 4. Layout of the test sites.

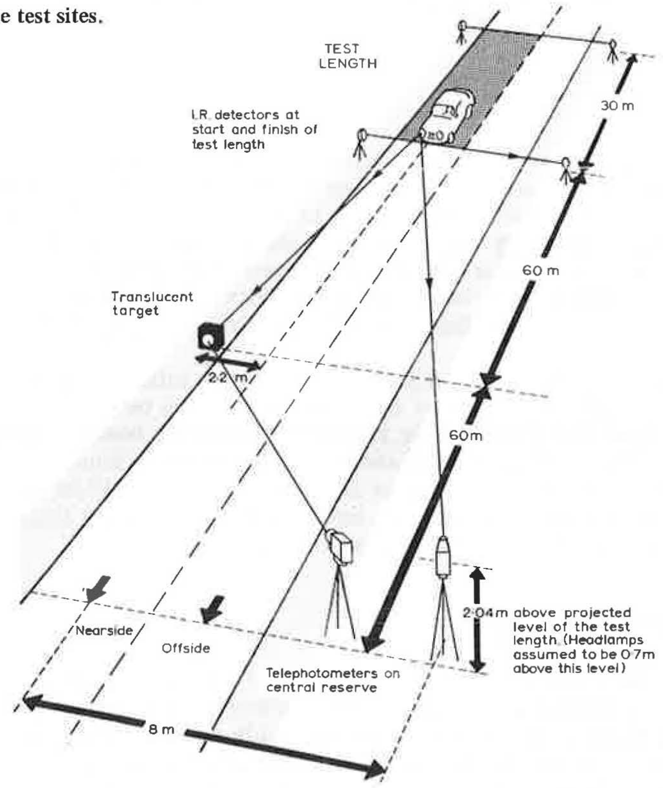
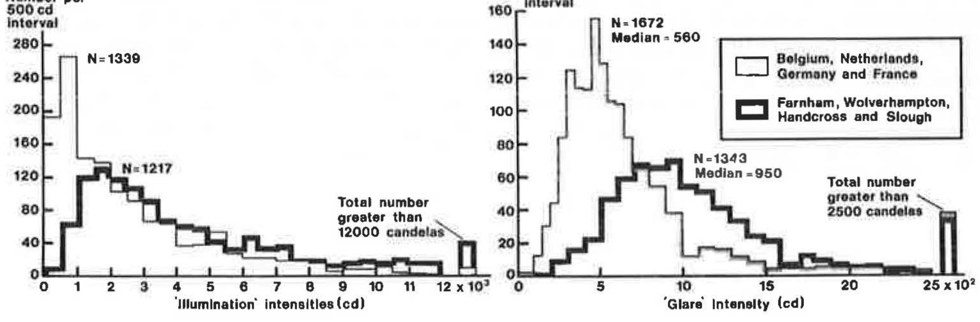


Figure 5. Distribution of headlight intensities in the illumination and glare directions.



SELF-LEVELING HEAD LAMPS

One result of the extensive tests of the Anglo-American and European beam patterns reported above was that the finer points of the beam design tend to be nullified in practice by variations in aim, cleanliness, and so on. A roadside survey (10) in Britian showed that there was a need for some correction of lamp aim to compensate for vehicle loading (30 percent of vehicles were tilted up by more than ½ deg and 7 percent by more than 1 deg), and simple systems have been devised to achieve this (11).

The problem has been solved by pivoting the head lamps in their mountings and making them tilt to compensate for vehicle body movements. The correction signal (and driving force) comes from the movements of the vehicle wheels relative to the body. A French company developed a hydraulic system, and a British organization has developed an even simpler mechanical system. Both systems have been fitted to TRRL vehicles and tested for leveling response to static loads in all positions within the car and the response to movement of the front and rear wheel pairs at various low frequencies.

Both hydraulic and mechanical systems corrected well for static loads. Figure 6 shows the angle through which the head lamp tilted for various angles of body tilt. The 45-deg diagonal represents perfect compensation, and it can be seen that both systems gave good results for rear loading. The poorer results for front loading were simply a matter of the system sensitivity and could be compensated for by adjustments.

The system received some criticism because the head lamp beams seemed to be divorced from the vertical movements of the vehicle. However, such criticism would probably disappear with use. The incorporation of a self-leveling system into mass-produced vehicles at the production stage, used in conjunction with modern high-performance headlights, would contribute to the reduction of glare due to lamp misaim caused by vehicle loading.

POLARIZED LIGHT

In general, reducing glare caused by fixed headlight beams also reduces illumination; the history of head lamp development may be seen as a continual search for adequate road illumination without causing intolerable glare. Polarized headlighting systems, which first became a practical possibility following Land's invention of sheet polarizers in the late 1920s, are once more being investigated. The United Kingdom is participating in a project of the Organisation for Economic Co-operation and Development that could lead to a large cooperative international test. The technical problems are well on the way to a final solution, the unknown areas being those of driver behavior, public opinion, and practical implementation.

OTHER SYSTEMS

The polarized light system is a cooperative system that requires all vehicles to be equipped if the full benefits are to be achieved. There are alternative systems worthy of consideration. The Lucas company in Britain has developed a self-regulating head lamp (12), known as the Autosensa, that provides the user with improved seeing distances without demanding his action to reduce glare to the opposing driver by lowering his beam. This and other devices and ideas on scanning and producing flexible beam patterns are being considered at TRRL. However, all ideas examined so far have been complicated and expensive and have not shown any worthwhile advantage over the modern well-designed sealed-beam head lamp unit.

ANTIGLARE FENCES

On motorways and other divided highways glare problems may be greatly reduced by the

Table 1. Seeing distances (in meters) with Anglo-American and European head lamps.

	Near-Side Object			Off-Side Object		
Road	Anglo-American Beam	European Beam	Percentage Increase	Anglo-American Beam	European Beam	Percentage Increase
Lighted	217.7	225.0	3.3[a]	145.4	152.0	4.5
Unlighted						
Straight	51.4	50.4	-1.9	22.1	24.8	12.7[a]
Left curve	37.5	32.6	-13.0[a]	40.9	40.9	0
Right curve	25.8	27.6	6.5	15.6	21.8	39.7[a]
Bottom of hill	26.5	26.8	1.1	16.8	16.7	-0.6
Top of hill	48.5	42.3	-12.8[a]	23.7	24.6	3.8

[a] Significant change.

Figure 6. Head lamp tilts of self-leveling systems.

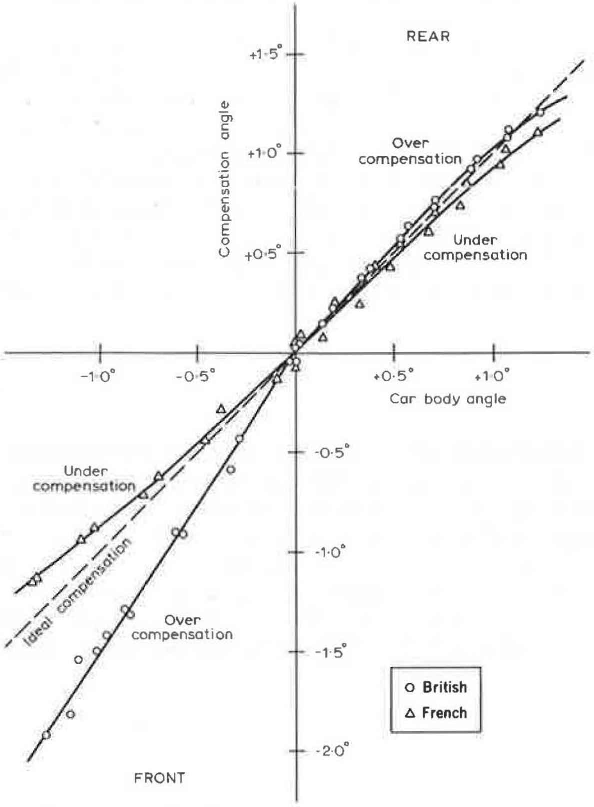


Figure 7. Experimental antiglare fence.

Figure 8. Close-up of attachment of vanes to tensioned safety fence.

provision of a fence or other structure in the median that intercepts light from the opposing headlights. Such a structure need not be solid; it is sufficient if it cuts off the light up to a given angle from the straight ahead direction, leaving the view directly across the road relatively unobscured.

The height of a screening structure above the road need only be 1.75 m above the road in order to provide adequate protection in 98 percent of the meeting situations. Any type of structure that satisfies the particular geometrical requirements will suffice if it also meets the necessary requirements for strength, wind loading, fatigue, cost, and appearance. A wide variety of materials from shrubs to expanded metal panels have been used for antiglare screens.

The benefits of antiglare screens were assessed by installing a fence of the vane type on 19.5 km of the M6 motorway. This particular type of fence was recommended as the most acceptable environmentally by the British Landscape Advisory Committee.

The general appearance of the fence is shown in Figure 7, and Figure 8 shows a close-up of the attachment of the vanes to the tensioned safety fence. Figure 8 also illustrates how the visibility across the motorway is relatively unaffected by the presence of the vanes.

Accident rates recorded on the fenced section will be compared with those occurring on lengths of lighted motorway. The experiment could also be regarded as being a field trial of the effects of glare on accident rate, albeit under the best motorway driving conditions.

REFLECTORIZATION AND EDGE MARKING

Lighting research inevitably spills over into other areas. The effectiveness of reflectorized materials is one example and one that is highly relevant in the United Kingdom now that parking without lights is permitted in lighted urban areas. Another area is the effectiveness of pavement edge markings; a study of accident records is under way to see whether there is a significant safety benefit from edge marking as distinct from a general improvement in driving comfort and amenity.

CONCLUSION

In lighted areas it is possible to achieve technically almost any reasonable level and quality of lighting, at least in dry weather. The debate centers around the economic justification for different levels and thus the need for more evidence on the link between lighting and safety.

In unlighted areas the situation is somewhat different; the technical barriers are still of paramount importance (even a fully polarized headlight system cannot compare in general terms with a lighted highway), and the driving force for improvements in this area may well have to be amenity as much as safety.

ACKNOWLEDGMENT

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Before the need for fixed roadway lighting can be determined, driver visual needs must be identified. This paper first discusses driver performance on the levels of positional, situational, and navigational tasks and relates these levels to visual information needs. Field studies were conducted to refine the visual needs and to determine the pattern and frequency of needs on both controlled- and non-controlled-access facilities. The results of these field studies are presented. The responses of study teams consisting of four professionals and four lay drivers are outlined, and generalizations were drawn from their questionnaire responses.

FIXED ILLUMINATION AS A FUNCTION OF DRIVER NEEDS

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One of the most important characteristics of the twentieth century is the extent to which the automobile has provided mobility. The effect on society created by this mass mobility has yet to be fully understood. One effect, however, is apparent: Highway engineers are faced with the challenge of providing a safe and efficient system of streets and highways.

An analysis of highway accident statistics suggests that the highway engineering profession has not yet met this challenge for nighttime conditions. The night accident rate exceeds the day accident rate, and the fatality rate at night is two to three times that of the daytime fatality rate (23). A number of factors, including differences between the day and night driving population in terms of age, sex, amount of fatigue, and percentage of drinking drivers, contribute to the higher night rates.

It is generally concluded, however, that the absence of a good visual environment at night is one of the primary reasons for the higher rates. This conclusion is supported by research that showed decreases in night accidents and fatality rates after fixed roadway lighting was installed (6, 10, 23).

Fixed roadway lighting probably offers the most comprehensive means of correcting poor night visual environments. When properly applied, roadway lighting can provide quick, accurate, and comfortable seeing conditions for the night driver and can result in an overall improvement in highway accident statistics.

Although the state of the art in roadway lighting has progressed dramatically in the last few decades, shortcomings still exist. Roadway lighting design processes do not fully address themselves to the function that lighting is to serve. Currently there is no process for roadway lighting design that adequately relates to the visual needs of the driver. Lighting needs are specified in terms of traffic volumes, accident experience, and characteristics of abutting property, usually defined as commercial, industrial, or residential. These factors in turn serve as warranting conditions. Design criteria are specified in terms of lighting a roadway surface rather than in terms of providing an environment suitable to the driver. Priorities for lighting installations are normally based on accident experience, traffic volume, or political influences.

Ideally, the design process should be based on requirements of the visual environment. If roadway lighting is to improve the driver's visual environment, a method must be established for determining the driver's needs. When these conditions can be specified, it will be possible to rationally consider requirements for a suitable visual environment that can be provided by fixed roadway lighting. The requirements of the night driving visual environment must also be identified, and these, in turn, must be systematically studied so that design procedures can be developed that will assist the designer in meeting these requirements through roadway lighting.

The objectives of this paper are to present a rational relationship between the driving task and the visual roadway environment and to discuss roadway lighting as it relates to the visual roadway environment.

CONCEPTUAL FRAMEWORK

The conceptual framework on which the objectives are developed consists of visual information needs as related to the driving task and characteristics of traffic facilities that contribute to visual information needs.

Driving Task

Driver visual information needs are a direct function of what is required of the driver in performance of the driving task. Thus, to determine the requirements of a suitable visual environment requires a basic understanding of the driving task.

Previous research by King and Lunenfeld (16) identified three basic levels in the driving task: microperformance, situational, and macroperformance levels. During normal driving, all three are performed simultaneously. As the complexity of the driving task increases, there is a tendency to ignore the higher order levels (macroperformance then situational) and to concentrate on the lower order level. Woods and Rowan (26) restructured the concept to reflect traffic operations and provided the following definitions:

1. Positional level—routine steering or speed adjustments necessary to maintain a desired speed and to remain within the lane,
2. Situational level—change in speed, direction of travel, or position on the roadway required as a result of a change in the geometric, operational, or environmental situation, and
3. Navigational level—selecting and following a route from the origin to the destination of a trip.

These levels of driver performance can be ordered into a hierarchy that describes the organizational content of the driving task (16).

Visual Information Needs

Visual information needs associated with the driving task can be organized along the levels previously described. Although previous research has not made it possible to provide an inventory of visual information needs that take into account all possible trips and situations, types of needs associated with driver performance levels can be suggested.

Positional Information Needs

There are two major subtasks at the positional level, steering control and speed control, and elements of each are involved in all levels of the driving task.

The major information needs of steering control include vehicle response characteristics, vehicle location information, and all related changes. The following types of informational needs, as determined through driver-vehicle task analysis (16), are necessary for steering and speed control.

Steering Control

1. Lateral position with respect to the roadway so that minute steering corrections can be applied and a desired position can be maintained,
2. Spatial orientation with respect to the roadway immediately ahead,
3. Visual feedback of changes in position and orientation,
4. Changes in vehicle response when high demands are placed on the steering task (nonvisual information), and
5. Tactile and kinesthetic perception of accelerator, brake pedal, and vehicle response.

Speed Control

1. Visibility of the roadway at a sufficient distance ahead to maintain a safe speed,
2. Visibility of conditions on the roadway not consistent with the driver's expectancy, and
3. Integration of speed control with steering control requirements.

Situational Information Needs

Situational information indicates a need for a change in speed, direction of travel, or position on the roadway because of a change in the geometric, traffic, or environmental situation. Whereas the positional and associated information needs are very limited, situational information needs are as varied as the number and types of roadway and traffic situations encountered in driving. Information needs at this level include information on all aspects of the highway system, such as other vehicles, road geometrics, obstacles, and weather conditions.

Driver performance depends on the driver's perception of a situation and his ability to respond in an appropriate manner. Therefore, the driver must have a priori knowledge on which to base his control actions as well as an understanding of what the situation demands.

Subtasks at the situational performance level include car following, overtaking and passing, and other situational subtasks (16).

Car Following

In car following, the driver is constantly modifying his speed to maintain a safe gap between his car and the vehicle he is following. Thus, in this situation he is time sharing tracking with speed control activity. The minimal information needs are

1. Speed and changes in speed of the lead car,
2. Speed of the following car and relative distance between the driver and the lead vehicle, and
3. Environmental information.

Overtaking and Passing

Passing involves speed control as well as modifications in the basic tracking activity. In passing, the driver must know control information to maneuver his vehicle most safely. Minimum information necessary includes

1. How fast the lead car is traveling and the acceptance gap,
2. Environmental information, and
3. Information to provide for judgment, estimation, and feedback for maintaining

an area of safe travel relative to the vehicle and other elements of the highway system.

Other Situational Subtasks

Among the situational subtasks that may occur are avoidance of pedestrians or other objects and response to traffic signals, advisory signs, and other information carriers. In all cases, the important point in terms of information needs is that the driver must receive information so that he is able to identify a situation as it occurs.

These subtasks are closely related to roadway lighting. Minimal information needs are

1. Information to maintain a complete appreciation of all events that could affect safe travel,
2. Visual information concerning the relationship of the driver's vehicle to the roadway, to other vehicles, and to the environment, and
3. Information from the environment, a priori knowledge that will provide for appropriate steering and speed control responses, and feedback to indicate the adequacy of the response.

Navigational Information Needs

The navigational performance level takes into account the way in which the driver plans a trip and executes his trip plan. The navigational level consists of trip preparation and planning, which is usually a pretrip activity, and direction finding, which occurs in transit.

Trip Preparation and Planning

Drivers use various means to plan trips depending on experience and the nature of the trip. The means can be as formal as having the trip planned by a touring service or as simple as traveling a route used previously. However minimal the preparation is, it is unlikely that a driver will attempt to reach a destination completely unprepared.

Direction Finding

In direction finding, the driver must find his destination in accordance with his trip plan and the directional information received in transit. He must thus share navigational subtasks with subtasks at the other driving levels. The information needs associated with direction finding are

1. In-trip visual information from guide and service signs and other formal information sources and
2. In-trip visual information regarding landmarks, the environment, and other informal information sources.

Descriptions of the driving task and associated information needs can be used to develop a driver information needs inventory of the night driving visual environment. This inventory should conform to the basic levels discussed previously. In addition, the descriptive informational needs should be structured around conditions or situations that characterize the street and highway system. Below are inventories developed as indicated by the field studies and categorized according to the situations and conditions encountered.

DEVELOPMENT OF VISUAL NEEDS INVENTORIES

Once the types of visual needs associated with the various levels of driver performance were established, field studies were conducted to refine these needs and to determine the pattern and frequency of needs on various types of facilities.

Although the field studies were concerned primarily with the requirements of the night driving environment, some emphasis was placed on the conditions warranting roadway lighting and priorities for the installation of roadway lighting. It is evident that, without visual task problems, roadway lighting is not warranted. Conversely, as visual task problems become apparent, so does the need for fixed illumination.

Studies were conducted in two areas at eight study sites. These eight sites included both controlled- and non-controlled-access facilities. The studies were conducted by interdisciplinary teams consisting of four professionals and four lay drivers.

The study technique was diagnostic study (20, 25, 26). Questionnaires and critique sessions were also used in the studies.

The results of the diagnostic studies are given in Tables 1 through 6. Tables 1 and 4 include all driver responses regardless of whether a serious problem existed.

The questionnaires, which were completed after each run, were tabulated to give general indications of driver attitudes and opinions on informational needs. The following generalizations on non-controlled-access facilities can be drawn from questionnaire responses.

1. The driver's position within a prescribed lane depends on (in descending order) lane lines, edge lines, curbs, position of other vehicles, post-mounted delineation, and roadside objects.
2. Changes in geometry force drivers to slow unexpectedly on unlighted sections, but not so much on lighted sections.
3. Illumination of facilities provides positive identification of roadway direction.
4. Good visibility of curbs and shoulders is necessary on lighted and unlighted facilities.
5. Intersections often have restricted visibility of traffic on that street, especially if unlighted.
6. Visibility of intersecting traffic in advance of the intersection is almost always important and usually very important.
7. The ranking (in descending order) of importance of informational signs is warning, regulatory, route, guide, and informal signs. Route and guide signs are more important for the nonlocal driver.
8. Extraneous lighting interferes with the driving task and more so on the unlighted facilities than on lighted facilities.
9. Roadside signs are considered more visible on lighted facilities than on unlighted facilities.
10. Delineation systems are more effective on lighted facilities than on unlighted facilities.
11. Glare from opposing headlights is more severe on unlighted facilities than on lighted facilities.
12. There were no strong objections to roadside advertising signs, and the informational importance of these devices was considered unimportant.
13. Pedestrians are not expected at midblock, but illumination of pedestrian crosswalks was considered a necessary prerequisite for safety.

Similar generalizations can be drawn from the questionnaires on the freeway sites.

1. The driver's position within a prescribed lane depends on (in descending order) lane lines, edge lines, position of other vehicles, post-mounted delineators, and objects along the roadside.
2. Geometric conditions cause drivers to slow unexpectedly, especially on unlighted freeway sections.
3. Complete loss of roadway direction is seldom encountered on freeways.

Table 1. Summary of responses on the non-controlled-access study site.

Type of Information	Unlighted: Number of Responses	Unlighted: Lighting Would Be Helpful: Number	Unlighted: Lighting Would Be Helpful: Percent	Lighted: Number of Responses	Lighted: More Light Would Be Helpful: Number	Lighted: More Light Would Be Helpful: Percent
Positional	59	3	5.1	27	0	0
Situational	303	112	37.0	211	15	5.7
Navigational	13	2	9.2	2	0	0

Table 2. Significant visual task problems on unlighted, non-controlled-access facilities.

Visual Task Problem	Number of Occurrences	Percentage of Total	Causative Factor: Geometry	Operations	Environment	General Visibility
Roadway	33	25.8	11	2	16	5
Intersections	33	25.8	7	11	10	6
Channelization	11	8.6	1	7		3
Lane markings	11	8.6		8	1	2
Roadside and roadside objects	9	7.0			5	4
Curbs	8	6.3		6	2	1
Access drives	7	5.5		1	4	2
Pedestrians	4	3.1	3	1	1	
Vehicles	4	3.1	1	2	2	
Signs	4	3.1				4
Signals	2	1.6			2	
General visibility	2	1.6	—	1	1	—
Total	128	100	23	39	44	27
Percent			17.3	29.3	33.1	20.3

Table 3. Significant visual task problems on lighted, non-controlled-access facilities.

Visual Task Problem	Number of Occurrences	Percentage of Total	Causative Factor: Geometry	Operations	Environment	General Visibility
Roadway	8	19.0	3	1	2	2
Nonuniform lighting	6	14.3				6
Distraction	5	11.9			5	
Luminaire glare	5	11.9				5
Signal lights	4	9.5	1		1	2
Light to dark transition	3	7.1		1		2
Loss of visibility	3	7.1			2	1
Roadside and roadside objects	3	7.1	1			2
Pavement edge	1	2.4				1
Lane markings	1	2.4				1
Signs	1	2.4				1
Glare	1	2.4			1	
Dark to light transition	1	2.4	—	—	—	1
Total	42	100	5	2	11	24
Percent			11.9	4.8	26.2	57.1

Table 4. Summary of responses on the freeway study sites.

Type of Information	Unlighted: Number of Responses	Unlighted: Lighting Would Be Helpful: Number	Unlighted: Lighting Would Be Helpful: Percent	Lighted: Number of Responses	Lighted: More Light Would Be Helpful: Number	Lighted: More Light Would Be Helpful: Percent
Positional	49	5	10.2	26	0	0
Situational	280	104	37.1	74	12	16.2
Navigational	37	19	51.4	6	2	3.3

Table 5. Significant visual task problems on unlighted freeways.

Visual Task Problem	Number of Occurrences	Percentage of Total	Causative Factor			
			Geometry	Operations	Environment	General Visibility
Roadway	36	26.1	16	12	8	3
Signs	18	13.0	4	3	2	9
Ramp entrances	15	10.9	7	4		6
Ramp exits	13	9.4	10	2	1	1
Merges	12	8.7	5	4		3
Intersections	8	5.8	4	1	1	3
Curbs	7	5.1	1	5		1
Roadside and roadside objects	7	5.1		1		6
Lane markings	4	2.9		1	1	2
On-ramps	4	2.9	2	2		
Off-ramps	3	2.2	2	1		
Vehicles	3	2.2	2	3		
Delineation	2	1.4				2
Light transition	2	1.4				2
Channelization	2	1.4	2			
Roadway objects	1	0.7				1
Glare	1	0.7				1
Total	138	100	55	39	13	40
Percent			37.4	26.5	8.8	27.2

Table 6. Significant visual task problems on lighted freeways.

Visual Task Problem	Number of Occurrences	Percentage of Total	Causative Factor			
			Geometry	Operations	Environment	General Visibility
Glare	4	14.3	1	1	2	2
Ramp exits	4	14.3	4			
Merges	3	10.7		1		2
Signs	2	7.1	1			1
Roadside and roadside objects	2	7.1				2
Pavement edge	2	7.1				2
Roadway	2	7.1	2			
Ramp entrance	2	7.1	2			
Distraction	1	3.6			1	
Light to dark transition	1	3.6				1
Lane markings	1	3.6				1
Off-ramps	1	3.6	1			
On-ramps	1	3.6	1			1
Luminaire glare	1	3.6				1
Nonuniform lighting	1	3.6				1
Total	28	100	12	2	3	14
Percent			38.8	6.5	9.7	45.2

Table 7. Characteristics of traffic facilities that affect visual information needs.

Access and Facility	Characteristic		
	Geometric	Operational	Environmental
Non-controlled-access, highway	Number of lanes, lane width, median openings, curb cuts, curves, grades, sight distance, parking lanes	Signals, left turn signals and lanes, median width, operating speed, pedestrian traffic	Development, type of development, development setback, adjacent lighting, raised curb medians
Non-controlled-access, intersection	Number of legs, approach lane width, channelization, approach sight distance, grades on approach, curvature on approach, parking lanes	Operating speed on approach, type of control, channelization, level of service, pedestrian traffic	Development, type of development, adjacent lighting
Controlled-access, highway	Number of lanes, lane width, median width, shoulders, slopes, curves, grades, interchanges	Level of service	Development, development setback
Controlled-access, interchanges	Ramp types, channelization, frontage roads, lane width, median width, number of freeway lanes, main lane curves, grades, sight distance	Level of service	Development, development setback, crossroad lighting, freeway lighting

4. Good visibility of shoulders is an important prerequisite for safe driving.
5. Good visibility of gore areas of exit ramps is always important regardless of whether an exit is to be made.
6. Ability to see the merge point of an entrance ramp with the freeway is always important.
7. Detection of changes in exit ramp alignment is important before the exit maneuver is begun.
8. Changes in the number of traffic lanes affect drivers, especially on unlighted freeways.
9. Definition of the median edge is important, especially to a driver traveling in the adjacent lane.
10. The ranking (in descending order) of importance of various informational signs is warning, regulatory, guide, route, and informal signs. Guide and route signs are more important to the nonlocal driver.
11. Lighting of adjacent developments interferes with vision less on lighted freeway sections than unlighted freeway sections.
12. Most overhead signs are effective from the visibility standpoint as are roadside signs. They are slightly more effective on lighted freeways than on unlighted freeways.
13. Headlights of opposing traffic create visual problems on unlighted freeways and to some extent on poorly lighted freeways. Headlight glare is least noticeable in median lighting situations.
14. Roadside advertising signs are not especially excessive and their informational value is relatively unimportant.
15. Entrances to on-ramps are seldom visible at an adequate distance on unlighted freeways. It is always important to see the entrance, regardless of whether an entrance is to be made.
16. Exits for off-ramps are seldom visible at an adequate distance on unlighted freeways and sometimes on lighted freeways. It is always important to see the exit, regardless of whether an exit is to be made.

The results of the critique sessions are summarized in the subsequent paragraphs.

The first consensus reached by the study teams involved the necessity of maintaining positional information at all times. Information on lane lines, edge lines, and curb delineation was considered to be the most critical and most necessary information because it held the key to other informational levels. All other tasks at the situational and navigational levels depended on the sufficiency of these visual inputs. The subjects insisted that situational and navigational tasks could be accomplished most effectively when these items were readily available. During the driving runs, it was observed in too many cases that the drivers attended to positional tasks at the sacrifice of the situational and navigational levels. This was due primarily to worn and faded lane lines, absence of edge lines, unpainted curbs, and little contrast between pavement edges and shoulders.

Both study teams also agreed on geometrically induced visual task problems. Even in the interview sessions, the study teams supported the hypothesis that a view of the roadway surface is important at all times. Excessive geometric changes producing restricted longitudinal views of the roadway were considered among the most critical and frequently occurring visual problems.

The study teams also supported the importance of environmental development with regard to informational needs. A strong emphasis was placed on the fact that some environmental lighting has a detrimental effect on performance of the driving task. There was some disagreement, however, on the characteristics of environmental lighting that made it detrimental. This disagreement obviously stemmed from the fact that on several occasions environmental lighting actually assisted in determining roadway direction on unlighted arterials and directed light onto the roadway surface. A final agreement was reached that environmental lighting is detrimental unless a considerable intensity of light actually reaches the pavement surface and unless such sources of light are not in themselves distracting or glaring.

Traffic operations were also considered major determinants to visual information needs. Higher speeds and higher volumes can produce definite visual task problems. First of all, opposing headlights introduce periods of time in which vision is virtually obliterated, and the problem increases as the number of opposing vehicles increases. Lateral separation of vehicles and fixed lighting, especially median-mounted, were considered the best solution to the problems. It was also agreed that accomplishing all driving tasks became more difficult as volumes and speeds increased, mainly because of the competition between the various informational needs.

The final task of the study teams was to develop listings summarizing

1. Visual needs that could be met by fixed roadway lighting,
2. Traffic facility characteristics that affect visual information needs, and
3. Desirable attributes of roadway lighting systems.

On non-controlled-access facilities, fixed roadway lighting can provide information on roadway geometry, roadway surface, roadway objects, roadway edge, roadway markings, signs, signals, delineation, intersection location, channelization outline, access driveways, shoulders, roadside objects, curb locations, vehicles on the facility, pedestrians, pedestrian crosswalks, and sidewalks.

On controlled-access facilities, fixed roadway lighting can provide visual information on roadway geometry, roadway surface, roadway objects, roadway edge, roadway markings, signs, signals on crossroads, delineation, intersection location, channelization outline, curb locations, shoulders, roadside objects, vehicles on the facility, vehicles on interchanging facilities, ramp entrances, ramp exits, merge points, and geometry of on-ramps and off-ramps.

Table 7 gives geometric, operational, and environmental characteristics of traffic facilities that affect visual information needs.

On non-controlled-access facilities, roadway lighting systems should provide uniform lighting on pavement surface, infrequent spacings to reduce glare, high mounting heights to reduce glare, median location to reduce headlight glare, median location to light areas adjacent to roadway, gradual transitions from light to dark areas, and gradual transitions from dark to light areas. On controlled-access facilities, roadway lighting should provide uniform lighting on pavement surface, infrequent spacings to reduce glare, high mounting heights to reduce glare, median location to reduce headlight glare, median location to light areas adjacent to roadway, high-mast lighting in interchange areas, gradual transitions from light to dark areas, and gradual transitions from dark to light areas.

DESIGN PROCEDURE

The design procedure for effective roadway lighting must be responsive to information needs of night drivers. The procedure must identify the information needs that are to be satisfied by roadway lighting, quantify the needs for warranting conditions and design guidelines, and provide a rational method for setting cost-effective priorities. The design procedure should be responsive to these needs.

The design procedure comprises the following elements:

1. Informational needs that are to be satisfied by fixed roadway lighting (requirements for the suitable visual environment),
2. Justification for the lighting (warranting conditions),
3. Design criteria for lighting (providing for the informational needs),
4. Realization of design criteria (illumination design), and
5. Cost-effectiveness priority determination (which lighting designs are most effective and which should be installed first).

Based on these elements, it should be possible to develop a design procedure that is responsive to the goals of lighting and, at the same time, that is compatible with almost any design technique (i.e., illuminance design, luminance design). Suggested procedures have been recommended (27).

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IMPLEMENTING RESEARCH RESULTS

Charles A. Baker,
National Highway Traffic Safety Administration

The importance of appropriate lighting for night driving at intensity levels that provide both safety and comfort has been emphasized, but with a caveat relating to the finite energy resources available to achieve this goal. I share this concern and will temper my comments with the realization that the costs of fuels and emerging national priorities on where and how our energy will be consumed will have a significant impact on the extent and rate of implementation of improved lighting for night driving.

The papers presented at this symposium discussed a variety of problem areas in roadway lighting. Significantly, however, all of the papers dealt with the problems associated with visual glare. For example, the empirical model for headlighting reported by Farber and Bhise and the discussion by Walton on fixed illumination both weighted glare factors significantly. Rinalducci and Beare dealt exclusively with transient adaptation, which, in roadway situations, is frequently the time-ordered consequence of visual glare. When dealing with driver visual screening at night, Henderson and Burg rated glare sensitivity among the top candidate measures from a long list of visual characteristics. Irving and Yerrell presented a list of headlight glare control methods under investigation in the United Kingdom. This list included load levelers, head lamp adjusters, glare fences, automatic dimmers, and polarized lighting. My comments are restricted to some considerations relating to polarized headlighting because it offers a significant potential in reducing glare and may have a significant impact on energy consumption.

During the mid-1940s, the automotive industry devoted considerable study to the feasibility of reducing glare by means of polarized lighting. Subsequently, there have been pockets of interest in this method of glare control. Indeed, several years ago the state of Washington proposed legislation to mandate polarized lighting. Nearly a decade ago the Federal Highway Administration funded research studies on polarized lighting, which have been continued by the National Highway Traffic Safety Administration. The Steering Committee for Road Research of the Organisation of Economic Co-operation and Development appointed an ad hoc subcommittee in 1972 to study and, if appropriate, promote international research on polarized headlighting. This subcommittee is now actively promoting such an international research effort.

Proponents of polarized lighting point out that the nighttime fatal accident rate is nearly three times that of the daytime rate. Although many factors contribute to this increased fatal accident rate, glare is suspected to be a significant contributor. Data from vehicle inspection stations indicate that head lamp misaim is the most frequent cause of rejection. Precise head lamp aim is important because the present-day beams have small vertical angles with abrupt intensity cut-offs. By this means, properly aimed lamps provide adequate headway illumination and, under most conditions, maintain glare at tolerable levels. Slightly misaimed lamps can reduce seeing distance considerably and greatly increase glare. With polarized lighting the beam can be expanded and thus the aim tolerances can be relaxed without compromising either seeing distance or glare.

Glare disability increases with age. Demographic data indicate that the average age of the driver is increasing and is expected to continue at an accelerated rate. Thus, the hazards associated with glare may be expected to increase. Inasmuch as the payoff potential of reducing glare through the use of polarized headlighting is great, its proponents maintain that a concerted research program is justified.

Because of the absorption of light by polarizing filters, the lumen output of the light source must be considerably greater than a nonpolarized light to maintain parity in headway illumination. This increase can, in part, be achieved by using more efficient light sources and reflectors. However, the primary increase will be achieved by more wattage. The increase in wattage will result in greater energy drain on the automobile engine and thus increase fuel consumption. The rough calculations given in Table 1 provide an estimate of what the annual increment in fuel consumption in the United States would be if all vehicles were eventually converted to polarized lighting.

Table 1.

Item	Value
Vehicle miles per year (U.S.)	1.5×10^{12}
Driving hours per year[a]	3.7×10^{10}
Night driving hours per year (⅓ of total)	1.2×10^{10}
Kilowatt-hours[b]	2.4×10^{9}
Horsepower-hours	3.2×10^{9}
Pounds of fuel (0.6 hp-hour)	1.9×10^{9}
Gallons of fuel per year	3.1×10^{8}
Gallons per vehicle per year	2.0

[a] 40 mph avg. [b] At 200-W increments per vehicle.

Based on these rough computations and assumptions, the annual domestic increment in fuel consumption for polarized lighting would be 300 million gallons. This amount represents about ¼ of 1 percent of our road use consumption of fuels. For this typical vehicle, this represents about 2 gallons of fuel per year.

In addition to these fuel penalties, the original polarized lighting equipment will have an incremental cost over conventional headlights. The estimated costs vary with configuration, but range from $15 to $35 per vehicle. The vehicle and fuel consumption costs might well be compensated for by significantly improved driving safety at night. However, comprehensive research programs will be necessary to develop precise safety and public comfort benefits and cost penalty estimates so that a rational decision can be made on whether polarized lighting systems should be implemented and, if so, how they should be configured.

Rex W. Oyler,
General Motors Corporation, Anderson, Indiana

In view of my background, I would be presumptuous indeed if I attempted to comment in depth on the fixed lighting studies. My remarks, therefore, will use as a springboard the studies on automotive lighting.

IMPLEMENTATION RECOMMENDATIONS

The papers by Mortimer and Farber and Bhise cover methodology and might profitably be referred to the Test Methods Subcommittee of the SAE Lighting Committee. Following this route would carry the advantage of further shaking down the techniques proposed and provide the additional benefit of having the work more widely publicized through printing and distribution by SAE after acceptance.

Burg's paper, I suggest, would receive increased consideration if called to the attention of the American Association of Motor Vehicle Administrators' Committee on Driver Licensing.

All this is not to ignore the thought-provoking work done by Rockwell and his associates. Further interpretation, however, may indicate a more accurate direction to implement this research.

IMPLEMENTATION THROUGH STANDARDIZATION

The main thrust of my remarks is to explore the benefits of further performance standardization on channeling and implementation of research. Behind this thinking are three steps: Basic research identifies matters of principle; applied principle shows up in the form of hardware; and hardware normally produces an output designed or manufactured to conform to certain standards. Thus, there is a direct line between research and the number of different standards that bear on application of research results.

A variety of claims have been made for the relative importance of fixed lighting versus automotive lighting. These contentions are commonly dealt with by weighing capital outlay and speed of implementation, leaving many of the claims essentially unresolved.

Two examples may serve to illustrate opportunities for standardization, at least between Europe and the United States; these have been selected from the fields of headlighting and rear lighting.

HEADLIGHTING STANDARDIZATION

For a number of years, controversy has existed on the relative merits of the Anglo-American headlight beam distribution and that obtained from European head lamps. Because these performance differences are rooted in philosophy, there has been more despair than optimism over the prospect of obtaining standardization in any significant sense of the word. Adoption of three-beam headlighting in this country and abroad would resolve a seeming impasse.

It is well grounded in cliché that "all engineering is a compromise." Compromise of the following makeup of a three-beam system, therefore, may be in order.

Upper Beam

Revision of the 75,000-cd maximum output restriction that currently prevails in this country and adoption of 200,000 cd, more or less, as the new maximum would essentially eliminate differences in permissible intensities. When this new level was suggested by NHTSA in a past Notice of Proposed Rule Making, no significant adverse comment resulted. Because the upper beam is a symmetrical one, fixing the details of light distribution should not be a major hurdle. Since a tungsten-halogen light source could optionally be used, that preference (or lack of it) should also occasion no difficulty.

Middle Beam

A middle-beam configuration would habitually be used for driving outside urban areas and would be produced by adding the output of a special unit to that of the lower beam. If careful attention were given to aiming of the special unit, the middle beam could be used even on two-lane roads without objectionable glare to oncoming drivers.

In the case of cars equipped with two-unit headlighting, a third unit could be added to produce a functional benefit and offer various designers the chance to produce a new look.

Based on the specifics of the test setups, this intermediate beam has shown a vision improvement from 85 to 125 ft as compared to a regular low beam. The beam upper cutoff could have a treatment someplace in between the feathered approach used in this country and the sharp black line characteristic of European lower beams.

Lower Beam

In the new system, the lower beam would be used for city driving only; its intensity could be less than the present low beams and greater than that of parking lamps. This should be quite satisfactory in this country, give better results than the European practice of driving with parking lights on in cities, and meet objections concerning too high intensities that dazzle pedestrians and cyclists. Even if this were designed with something approaching the sharp European cutoff, the dancing shadow, which has been one of the major objections here, would be minimized as a result of the contrast reduction due to fixed urban area lighting.

Switching

A must in three-beam lighting is a simple, readily understandable switch arrangement. A three-position, linear motion, column-mounted switch is one configuration that would meet the above-mentioned criteria; this matter also should not be an insurmountable obstacle.

General

Recent experiences in obtaining approvals in Europe on three varieties of head lamps to be manufactured in this country demonstrated friendliness and cooperation from quite a few people. The time and money involved, however, might have been saved had we more resolutely pursued a standardization path in our past interactions.

Perhaps SAE in the United States and such organizations as GTB in Europe can spearhead meaningful efforts to get us all on the track.

REAR LIGHTING

The differences between U.S. and continental approaches to rear lighting and signaling include mandatory amber rear turn signals, stop light intensity requirements, physical location of lighting devices, and use of rear fog lamps. A little give and take on each side could be the basis for zeroing in on research for better rear lighting rather than investigation for better American rear lighting and still more for better European rear lighting.

FIXED LIGHTING

There are substantial differences in thinking and practice regarding intensity of light on a road (produced by fixed lighting) in this country and in Europe. Surely the actual requirements cannot be all that much different. Would not development of improved fixed lighting be aided by having standards that are closer together?

CONCLUSIONS

When automotive lighting research is finally implemented—the production of hardware designed to conform to certain standards—we must evaluate factors over and above those identified by conventional laboratory-proving ground-public road activity. We must additionally consider cost-benefit, contribution to safety, lead time, and operational environment. It is quite possible for a lighting device to appear to have merit within itself; when taken in concert with what we already have, however, it may only add to visual clutter or actually dilute the effectiveness of existing devices.

An effective method of determining net worth—including the public interest—of a device in the past has been to offer it as optional equipment. Some items, as a result, have dropped by the wayside, whereas others have become standard equipment.

It is certainly hoped that future laws and regulations will not be structured to preclude use of this valuable tool. The relationship of industry and government could also be moved from a seemingly adversary position to one of more cooperation by having more effective dialogue prior to issuance of notices of proposed rule making.

More effective research and use of research funds through more carefully coordinated standards—it seems worth a better try than we've been giving it.

Richard E. Stark,
Illinois Department of Transportation

My concern with a symposium on night driving visual needs is to extract from the information presented those concepts and ideas that will help in more effectively serving the public in my capacity as a district lighting engineer in Illinois.

As I review the papers presented, my concern falls into four basic needs:

1. There is need for additional justification of roadway lighting installations,
2. Visibility criteria for fixed roadway lighting must be improved or refined,
3. More sophisticated design techniques for roadway lighting are needed, and
4. New hardware to more effectively implement these techniques and to improve or correct existing deficiencies is required.

ADDITIONAL JUSTIFICATION OF ROADWAY LIGHTING

A solid base for providing roadway lighting is required. Lighting just like other highway projects must be justified. I was encouraged by Irving and Yerrell's report of a 30 percent reduction in nighttime accidents and a parallel reduction in severity when lighting is installed. We have relied heavily on the report by the Illuminating Engineering Research Institute for freeway lighting justification and our own experience of a 40 percent reduction in freeway accidents after lighting. We certainly need more information, better measurements, and controlled studies on the relationship between accident rates and illumination. It will be of great interest to know the outcome of the study being conducted by the British Transport and Road Research Laboratory.

Accident rates related to night illumination are important, but research should explain why these problems occur. Henderson and Burg's paper brings the area to the front: "At this point we know that visual performance is seriously degraded under conditions typically encountered in night driving, i.e., low levels of illumination, glare, and low-contrast targets... Further, we know that some individuals are much more severely affected by these factors than others, and as a result the total variability in visual performance of the driving population increases significantly as the level of illumination decreases, glare increases, or contrast decreases."

Another problem that relates closely to fixed lighting is that of headlight adequacy. I refer now to urban freeways with speeds up to 55 mph where traffic densities are sufficient to warrant fixed lighting. It appears that there are a number of problems with headlights such as misaim, dirt depreciation, changes due to different loadings, and glare production. Thus, whereas the only solution in rural areas is head lamps, in urban areas fixed lighting may be the total solution. Irving and Yerrell's and Mortimer's comments on their problems with head lamp adjustment are of great interest.

Walton expressed the idea that "fixed roadway lighting probably offers the most comprehensive means of correcting poor night visual environments." He also cataloged the night visual requirements of the driver from the standpoint of the three performance levels involved in the driving task. This information will be extremely helpful to the designer in providing the proper illumination to meet driver visual needs. Still there is much work to be done to illuminate those objects that need to be seen.

Rockwell and Rackoff's findings with the eye camera tend to lead to the conclusion that fixed lighting improved driver performance.

This information and continued research and confirmation in these areas will provide administrators with the basis to decide for or against installation of fixed lighting.

IMPROVED OR REFINED VISIBILITY CRITERIA

We desperately need to determine what an adequate night visual environment is as provided by fixed illumination. There is much encouragement in Blackwell's research that indexes of merit of a lighting system will be forthcoming so that present conventional systems may be evaluated.

The research reported by Walton identifies the information the night motorist must have to adequately operate at the three levels described. Perhaps this can be further documented by field studies. Providing the driver with adequate visibility of information sources is an area that needs better definition. There appears to be a need for coordinating the Rockwell and Rackoff findings with those of Walton. Also it would be of great interest to see the results of Rockwell and Rackoff's eye movement technique applied to new concepts of roadway lighting such as high masts. The study of the visibility of some of these objects under existing lighting systems has been reported by the Blackwells.

Certainly Gallagher and Meguire's field experiments verify the concept that contrast ratio is the main criterion for target visibility.

These researchers appear to have solid bases for future formulation of visibility criteria for certain night visual needs.

DESIGN TECHNIQUES FOR ROADWAY LIGHTING

If we are going to provide through fixed lighting the proper night visual environment for the motorist, we need a method of design for such an installation. I am impressed with the work described by Farber and Bhise. Perhaps the techniques they describe can be used to evaluate various lighting designs without the need of constructing the installation.

NEW HARDWARE

The energy crisis has emphasized the need to provide fixed lighting in the most efficient and effective manner. Industry response to this challenge has been outstanding. Lamp improvements and some new luminaires are available, but new designs that provide for light distributions to satisfy revised visual criteria are needed.

In terms of support hardware we are indebted to the Transportation and Road Research Laboratory for its early studies in breakaway light standards. This concept eventually led to the installation of several thousand breakaway or frangible light standards on highways in the Chicago area. These frangible poles have performed extremely satisfactorily in reducing accident severity and cost of replacement.

There is a continued need for practical product development to implement the results of basic research. A number of state and other agencies have installed experimental lighting with some success. These installations, however, generally use equipment currently available rather than new designs based on current research. An effort should be made to implement the results of basic research such that new equipment will be available for field installations.

In summary, I am greatly encouraged by the progress being made in researching the factors that affect drivers' night visual needs. This symposium should be the basis for tying together the efforts of headlighting and fixed lighting researchers. I look forward to the opportunity of installing a system based on these efforts.

Richard N. Schwab,
Federal Highway Administration

These papers have made me appreciate how far we have all come since the first night driving symposium in 1968. We are now using a common basis for evaluation of the driver's nighttime visual needs. Whether we are concerned with vehicular or fixed illumination requirements, driver vision testing, or driver guidance, the evaluative metrics we are using are now based on visibility and required contrast levels for seeing. We are no longer talking solely in terms of the physical illumination output of a particular lighting system.

Such changes in research emphasis will undoubtedly bring a big change in our approach to highway illumination design problems. Eventually we will rewrite design standards toward a performance-based specification aimed at ensuring the driver at least a minimum level of visibility under all common roadway conditions rather than a hardware-based specification. Each highway illumination system will be designed according to the visibility requirements of the driver for the particular driving environment. This is independent of whether the light sources are mounted on the vehicle or along the roadside. It can no longer be blanketly stated that freeway fixed lighting systems should provide 0.6 ft-c to the pavement surface. It will become more of a design job in which, for each roadway situation, the designer will need to define the driver's requirements based on the specific driving situation. The illumination design can then be tailored to meet these requirements.

Walton's paper has started to develop the foundation for such a design approach. He has developed a framework for analyzing the driving task to determine driver visual requirements under different driving conditions. We must now see what parts of these tasks may be affected by changes in the visibility level and the utility for making these changes. At that point it becomes a question of the cost effectiveness of providing the type of illumination system that will alter the visibility to satisfy a given percentage of drivers in the specific driving situation.

The Blackwells and Gallagher and Meguire have started to provide us with the tools to measure driver visual requirements and to design the illumination systems to provide the required visibility. For at least one task, the relationship between driver behavior and visibility is being established. The next step is to expand this relationship to other parts of the night driving task and to relate this to control needs other than the visual complexity of the highway environment that must share the driver's attention. From that point, it should not be too difficult to develop the relationship between the ability of existing lighting systems to meet the visibility needs of drivers and the resulting effects on traffic and pedestrian accidents, traffic flow, crime, and energy consumption.

These factors could all then be related in an economic trade-off analysis to determine what specific aids to driver visibility should be provided for each roadway situation. With a management tool of this nature, administrators will be able to see what the explicit trade-offs are for a particular roadway situation. If we provide a fixed illumination system that gives a certain level of visibility, then we will satisfy the visual requirements of X percent of the night drivers on that facility and we can expect Y accident level, Z crimes, etc. If the level is increased, we can quantify the changes and see whether they are worth the added costs.

Several pieces of the picture are still missing, and work is still required on them. One of the most important questions is the effect of changes on the complexity of the roadside environment. Most of the research to date has been accomplished in very structured situations where the driver does not have much to distract him. As the driver moves into more complex situations where there are pedestrians, visual clutter, and lighted businesses along the street, what happens to his basic requirement for visibility? Can this informational loading be handled as a multiplication factor, or is this too simple a model?

Research on vehicle lighting discussed in the papers appears to be heading toward the same types of visibility measures. Perhaps someday soon we will have the ability to explicitly analyze the trade-offs between vehicular and fixed sources.

The paper on transient adaptation was particularly interesting in what it says about the need for providing transition illumination levels in and out of areas with fixed illumination. It does not appear that this is as major a problem at night driving levels as earlier studies done at higher luminance levels had indicated. There is still a visibility loss, but it is not so large as anticipated.

The paper of Irving and Yerrel demonstrated that the British are facing many of the same problems, and we can learn much from such interchanges. The Transport and Road Research Laboratory study to measure the physical characteristics of large portions of the existing lighting system on British highways and relate this information to accident statistics will be extremely useful. I hope that they will use some of the measures of visibility we have been discussing here.

The paper on driver visual screening gives insight on what the design driver's vision is really like and what can be expected in terms of visual testing in the near future. There are some serious problems in implementing a new vision test that have not yet been addressed by the research. One is the time requirements for any test that obviously must be supported from the taxes or license fees we all pay. Therefore, vision screening should only be going on where it will prove sensitive in the driver licensing process. It, therefore, should not be something that is periodic for all classes of the population, but is probably desirable for certain subclasses of the population, such as older drivers and those with certain types of violation patterns, at regular intervals.

Improved visibility is not going to solve all of the night driving problems. If the problem is the result of a mistake in the geometric design of the roadway, improving the visibility may help alleviate the problem but it will not solve it. There are other techniques that may also help in these cases and we must learn how to determine what is appropriate for each case. Rockwell and Rackoff's research points in this direction. It is hoped that they can demonstrate the explicit trade-offs at the rural intersections they are studying among improvements in delineation, illumination, and signing.

Well, how can all of this be implemented? The method is pretty well known. The first step is to come up with suggested design procedures and warranting conditions. The next step is to develop a procedure for assigning priorities based on some type of economic utility model. Then these procedures should be tried out over some limited geographic area—perhaps a state or two. If the procedures work well and the benefits from using them are positive as compared to the current procedures, then a formal standard can be adopted by IES, AASHTO, AMVA, or SAE as the case may be. The TRB Committee on Visibility can help in this process mainly by seeing that, when research has been completed and it is ready to be tried out, it is brought to the attention of the administrators who have the authority to test and evaluate these results in the real world.

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