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Editorial Staff

FRED BURGGRAF W. N. CAREY, JR. W. J. MILLER

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Normann, O. K., Chief, Section of Traffic Operations, Highway Transport Research Branch,Bureau of Public Roads, U. S. Department of Commerce, Washington 25, D. C.

Ortlieb, Otto P., Engineer of Street Lighting and Traffic, 311 Municipal Building, Trenton, New Jersey

Osterhoudt, E. W., Traffic Engineer, Connecticut State Highway Department, State Office Building, Hartford 15, Connecticut

Post, C. F., Manager, Signal Service Division, American Gas Accumulator Company, 1027 Newark Avenue, Elizabeth, 3, N. J.

Reeder, Earl J., Traffic Engineer, Rader Knappen Tippets Engineering Company, 1615 DuPont Building, Miami, Florida

Reid, Kirk M., General Electric Company, Nela Park, Engineering Division, Cleveland 12, Ohio

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Roper, Val J., Lamp Department, General Electric Company, Nela Park, Cleveland 12, Ohio

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Vey, Arnold H., Director, Bureau of Traffic Safety, Department of Law & Safety, State House, Trenton 7, New Jersey

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Determination of Windshield Levels Requisite for Driving Visibility

WARREN M. HEATH, Automotive Engineer, California Highway Patrol, and DAN M. FINCH, Associate Engineer, Institute of Transportation and Traffic Engineering, University of California

SYNOPSIS

THE 1950 revised American Standard Code for Safety Glazing Materials for Motor Vehicles establishes requirements for glazing materials installed within "levels requisite for driving visibility."

A study to determine the extent of glazed areas necessary for driving visibility is reported upon. Data on current passenger cars are given showing the areas available for seeing by all but the tallest 2½ percent and all but the shortest 2½ percent of California licensed drivers. Visibility angles required for observance of traffic signals are also given.

From the above data and information on human dimensions, a method is suggested for determining the levels requisite for driving visibility applicable to any automobile for various percentages of drivers.

The dimensions and technique for checking windshields to establish a level that will include 85 percent of the drivers is given. This percentage was tentatively agreed upon as a practical value by the Engineering Committee of the American Association of Motor Vehicle Administrators in June 1951.

The American Standards Association on May 16, 1950 approved the revised American Standard Code for Safety Glazing Materials for Glazing Motor Vehicles Operating on Land Highways, Specification Z26.1-1950.(1) Section 4, Items 3, 5, 7, and 9 of the code permit the use of material having less than 70 percent luminous transmittance in certain locations in a vehicle "except at levels requisite for driving visibility."

No definition of these levels is given in the new code. At present, each state must determine the levels that are applicable for the conditions of operation within its boundaries. It is desirable that a definition be adopted which would apply to all states and be made a part of the ASA Code.

Assuming there is for each particular height of driver's eyes some level or angle above or below which it is not necessary to see with maximum efficiency under the driving conditions normally encountered, some method must be devised to determine these levels in each instance. A specification satisfactory for all but a small percentage of the drivers can then be drawn up which will set a reasonable level applicable to each type of vehicle.

Before definite conclusions were reached it was found advisable to make a study of the visibility angles of tall and short drivers in recent models of several makes of automobiles. The results were then compared with angles subtended by objects which must be seen for safe operation of a vehicle.

PROCEDURE

Measurements were taken at the driver's eye position of the angles subtended by solid parts of the vehicle body at points every 10 deg. from 90 deg. left of the driver to 90 deg. right. An arbitrary decision was made to measure the angles above and below which approximately 5 percent of the drivers cannot see due to obstruction by the various parts of the vehicle.

Statistics on adult human dimensions obtained by Pearson and others and reprinted in Moon (2) were assumed to apply to drivers within reasonable limits and were used in determining the eye heights from a sitting position. The standard deviation of the dimensions was used in computing the eye heights that are exceeded by approximately 2½ percent of the driving population and not reached by another 2½ percent. About 270,000 drivers in California would fall outside these limits as calculated from the information available.

Using the dimensions thus obtained, an instrument was constructed for measuring visibility angles from the eye positions of the short and the tall driver. With the facilities available it was not feasible to construct a cylindrical test board upon which the shadows of the vehicle could be projected from a light at the eye position, so the following method was used:

A platform (shown in Fig. 1) was designed to hold the pivot of a small transit at either the tall or the short eye position. The device was placed directly behind the center of the steering wheel and the seat was moved fully back for the tall readings and fully forward for the short readings. Seat depression in each vehicle was measured using a 150- or 180-lb. subject sitting in a relaxed position, and allowance was made for the variations in cushion firmness in setting the eye level for each vehicle.

A shadow diagram was then plotted for each set of data. Traffic signals for various street widths were added to show their position with respect to the driver's eyes.

CALCULATIONS

The following data were used in calculating the dimensions of the test stand shown in Figure 1.

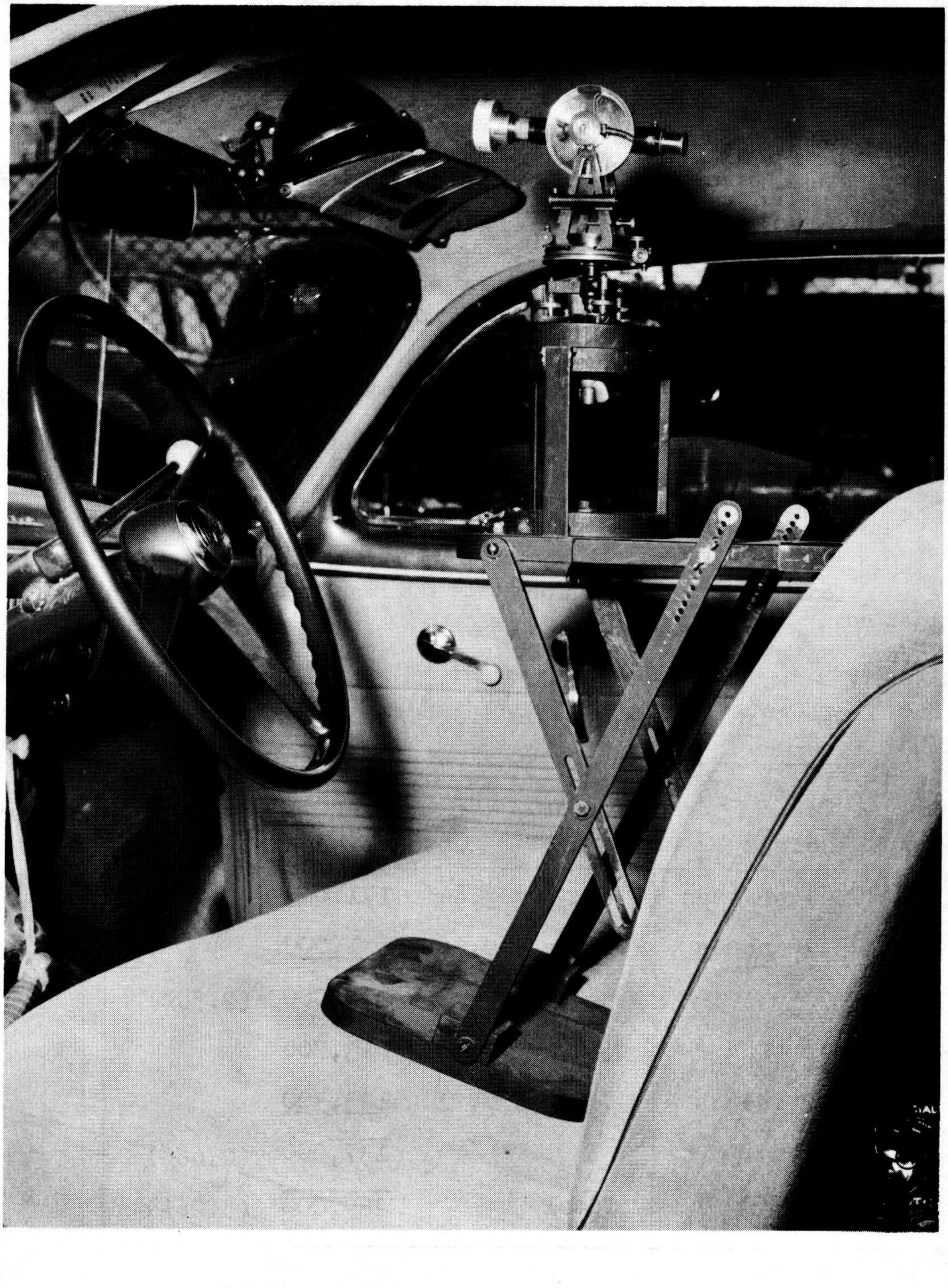


Figure 1(a). Equipment for measuring visibility angles.

The California Department of Motor Vehicles had 5,106,048 operator's and chauffer's licenses in effect as of January 1, 1951. A breakdown of drivers taken from 175,000 driver's license applications submitted in March 1950 indicate the following distributions:

33.48% of applications by women
66.52% of applications by men
100.00% Total

Assuming the same percentages hold true for the whole driving population and neglecting a small duplication of driver's and chauffer's licenses, there are in California:

1,710,000 licensed women drivers
3,400,000 licensed men drivers
5,110,000 licensed total drivers

Figures given in Moon (1) of seat-to-eye height are as follows:

	Mean Seat to Eye Height in.	Standard Deviation in.
Male	31.5	1.24
Female	29.9	1.17

Combining the above information the results shown in Table 1 are obtained.

TABLE 1

SUMMARY OF EYE HEIGHTS, CALIFORNIA DRIVERS

Seat-to-Eye Height	Numbers of Drivers Outside Limits			
Greater than 33.7 inches	Men	3.84%	131,000	
	Women	0.06%	1,000	
			132,000	(2.58%)
Less than 28.2 inches	Men	0.40%	13,700	
	Women	7.21%	123,300	
			137,000	(2.68%)
Both	Total		269,000	(5.26%)

To determine the viewing angles required to observe critical objects, the data contained in the excellent work of W. E. Schwanhausser, Jr., "Visibility of Traffic Signals" (3) was used. A number of driving situations were analyzed in the above reference, but only two of the most important cases are considered in this report. These are typical of California practice and are (a) for right curb mounted signals and (b) for right overhead signals. The plane and elevation sketches for signals at intersections for these two cases are given in Figure 2. The tabulated data on angles are given in Table 2.

TABLE 2

TRAFFIC SIGNAL VIEWING ANGLES

From W. E. Schwanhausser, Jr. (3)

(Refer to Fig. 2 for legend)

FAR RIGHT CURB MOUNTED SIGNALS

W	Y	d (horiz)	8 ft (vert)	10 ft (vert)
30 ft	56 ft	13.1°	6.5°	8.5°
40	66	15.3	5.5	7.2
50	76	16.7	4.7	6.1
60	86	18.1	4.2	5.4
70	96	19.0	3.7	4.8
80	106	19.7	3.3	4.4

FAR RIGHT OVERHEAD SIGNALS

W	Y	d (horiz)	S	15 ft (vert)
30 ft	56 ft	3.1°	8 ft	13.0°
40	66	2.6	13	10.9
50	76	6.3	13	9.5
60	86	5.3	18	8.4
70	96	7.7	18	7.5
80	106	7.0	23	6.7

The angles are based on a road-to-eye height of 4 ft. 6 in.. For the very tall driver this height was found to vary from 4 ft. 6¼ in. to 5 ft. 10 in., depending on the make of car checked. This variation would amount to approximately 1/3 ft. in eye height position. For the 10-ft. mounting heights of the signals used in California this difference would not seriously affect the angles tabulated.

RESULTS

The dimensions shown in Tables 3 and 4 and Figures 1 to 7 were obtained for eight cars and visibility angles are plotted.

TABLE 3

Passenger Car	Weight of Subject, Pounds	Seat Depression, Inches	Road-to-Eye Height	
			Tall	Short
B 1941	180	2½	4' 10"	4'5½"
B 1951	180	3	- - -	4'3"
C 1949	180	2½	4' 9"	4'4½"
C 1951	150	4	4'6¼"	4'3/4"
F 1950	150	3-3/4	4'6½"	4'1¼"
O 1950	150	3½	4'8¼"	4'2¼"
P 1951	180	3	4'9½"	4'4"
S 1950	150	3¼	4'6¼"	4' ½"

DISCUSSION

The visibility of drivers in a motor vehicle is greatly influenced by their height; very short drivers look between the steering wheel and hood with a very restricted view of the highway for a considerable distance ahead; very tall drivers have their view of signs, signals, and portions of nearby vehicles cut off by the top of the car.

Usually the highest objects needed to be seen for driving are traffic lights. In determining the angles required for proper visibility of these lights, the angles subtended at the driver's eye should be considered the controlling factor. The standard mounting height of signals in California is 10 ft. Schwanhausser's data (3) on curb mounted signals at this height were used in plotting the signal light positions with respect to the driver's eyes as shown in Figures 3 to 6.

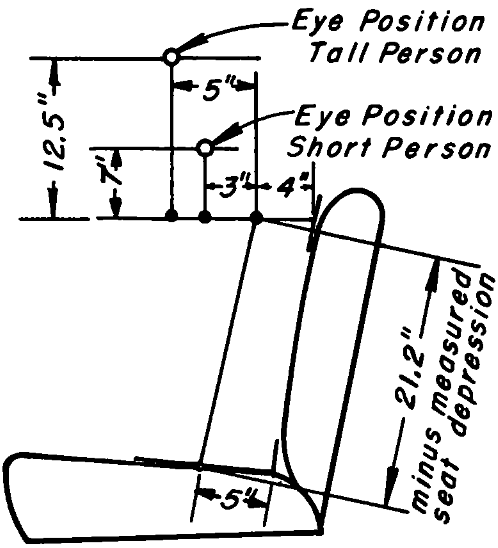


Figure 1(b). Dimensions of measuring equipment.

The diagrams show that the shorter drivers would have little difficulty seeing the signals even though a large portion of the top of the windshield were blocked off. They would have as good upper-angle visibility with the windshield shaded 10 deg. to 18 deg. down from the top as a tall man has with no shading. In the case of the small person, a large part of the upper windshield might be considered as not important for normal driving visibility and could be of low-transmission material.

Since automobiles are not custom made to fit each driver, the upper visibility limits must be determined by the tall person and lower limits by the short person operating the same automobile. If cars were equipped with seats having vertical adjustments as well as the present horizontal adjustments, the restriction on low-transmission or nontransparent areas could be less restrictive. Each driver could then adjust the seat height to fit his particular stature and could improve his visibility.

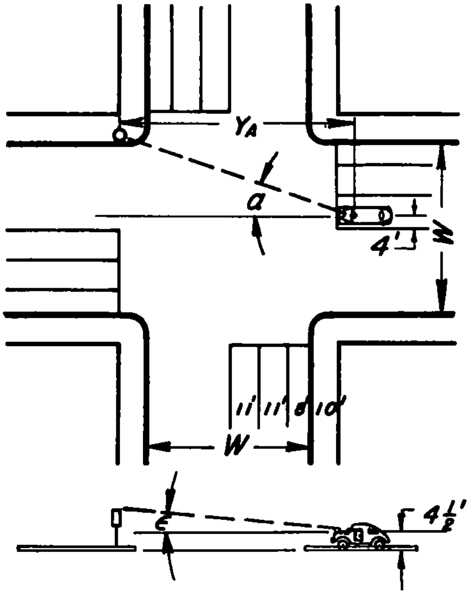


Figure 2(a). Viewing angles for far right curb-mounted signal.

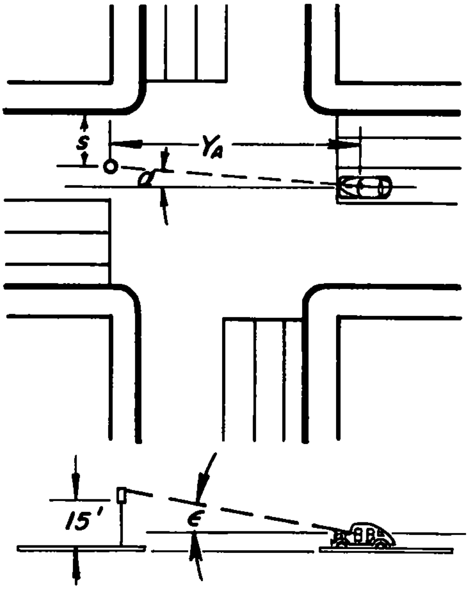
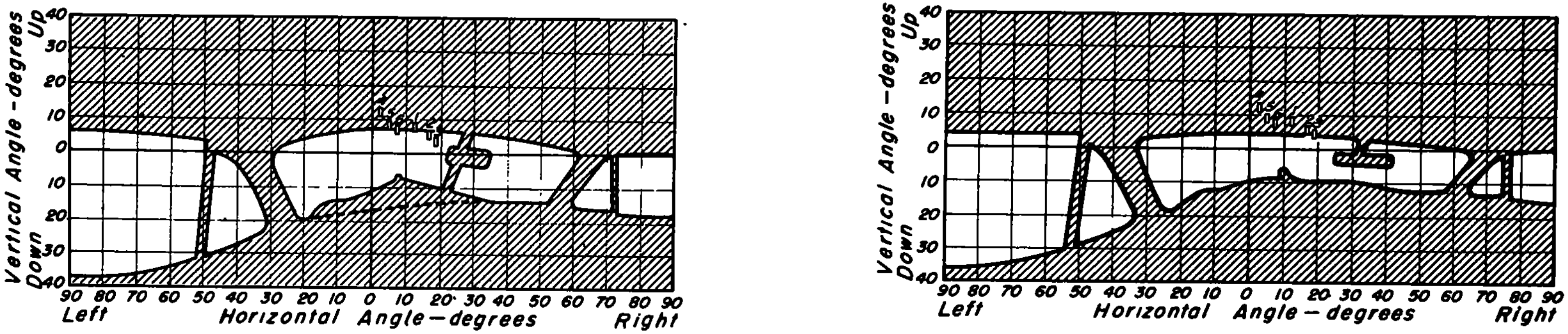


Figure 2(b). Viewing angles for far right overhead signal.

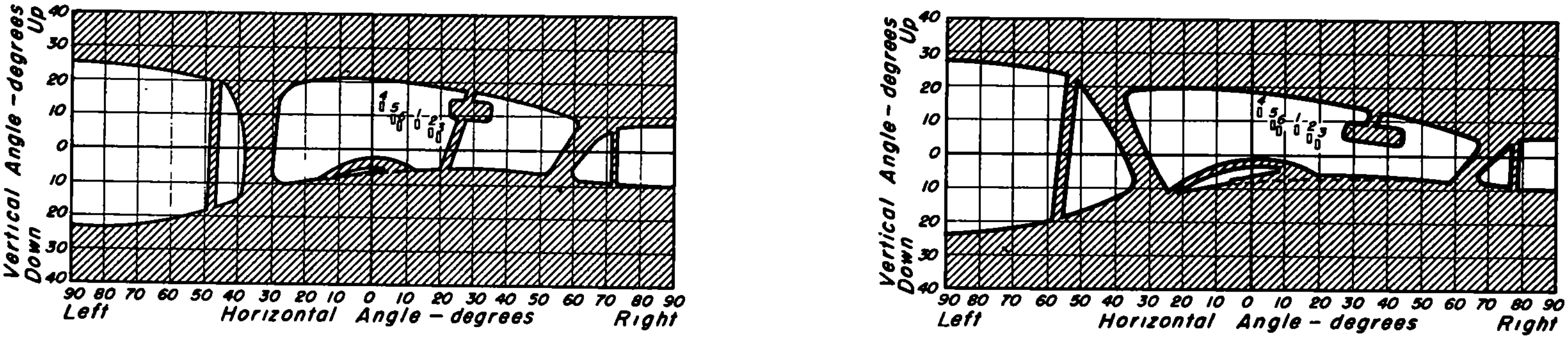
TABLE 4

Standing Height Male (approx.)	California Drivers Taller Than Column 1	Percent Shorter Than Column 1		Passenger Cars			Commercial Vehicles		
		Total	Men	Seat-Eye Height 20° Slant Inches	Seat Depression, Inches	Undepressed Seat-Eye Height Inches	Seat-Eye Height 5° Slant Inches	Seat Depression, Inches	Undepressed Seat-Eye Height Inches
6' ¼"	132,000	97%	96%	32.4	3.4	29	33.7	2.2	31½
5' 11⅛"	252,000	95	93	32.1	3.1	29	33.3	2.3	31
5' 10½"	511,000	90	85	31.6	3.1	28½	32.8	1.8	31
5' 9-3/4"	741,000	85	79	31.3	3.3	28	32.5	2.0	30½
5' 8-3/4"	1,230,000	76	66	30.8	3.3	27½	32.0	2.0	30
5' 6-3/4"	2,532,000	50	34	29.8	3.3	26½	31.0	2.0	29



a. Tall driver, Car B1, 1941.

c. Tall driver, Car B2, 1951.



b. Short driver, Car B1, 1941.

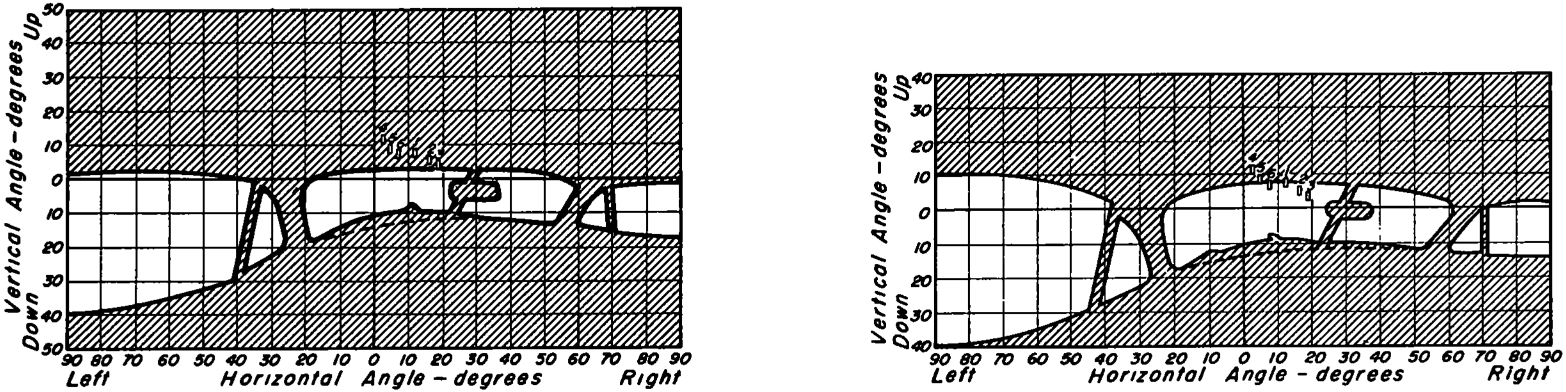
d. Short driver, Car B2, 1951.

Notes: Eye heights at positions shown in Fig. 1.

Signal positions are plotted from data in Table 2.

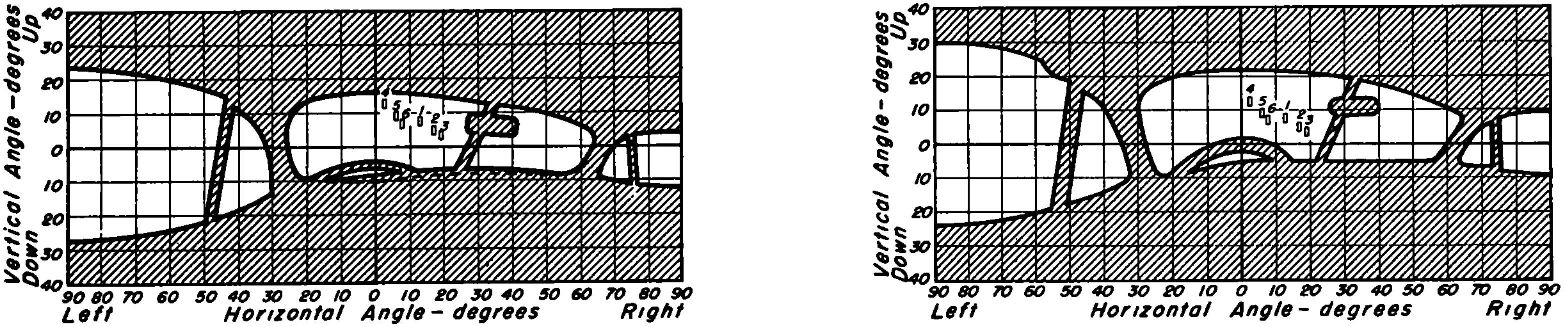
Legend — Signal Positions:
1. 30-ft street, curb-mounted
2. 50-ft " " "
3. 70-ft " " "
4. 30-ft street, overhead-mounted
5. 50-ft " " "
6. 70-ft " " "

Figure 3. Visibility angles from driver's seat.



a. Tall driver, Car C, 1949.

c. Tall driver, Car C, 1951.



b. Short driver, Car C, 1949.

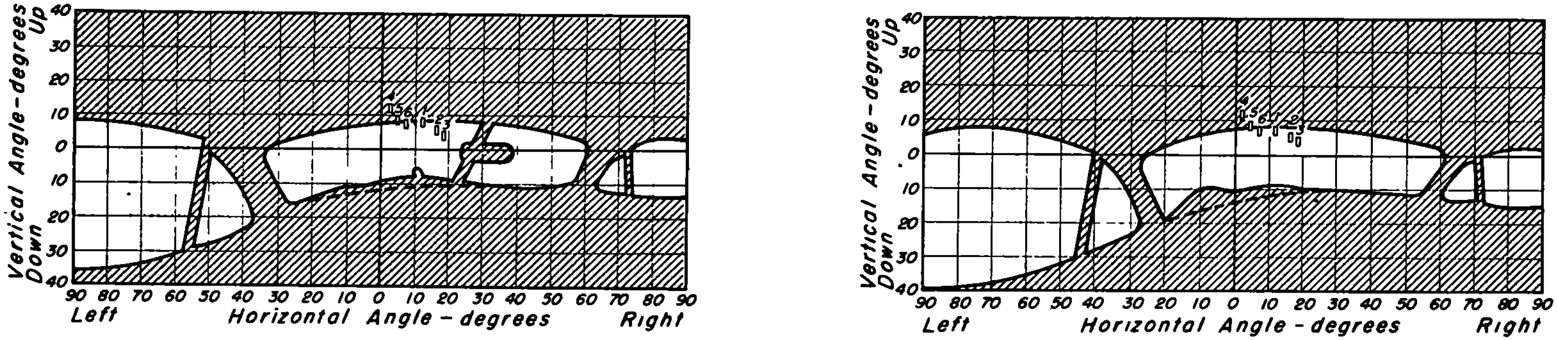
d. Short driver, Car C, 1951.

Notes: Eye heights at positions shown in Fig. 1.

Signal positions are plotted from data in Table 2.

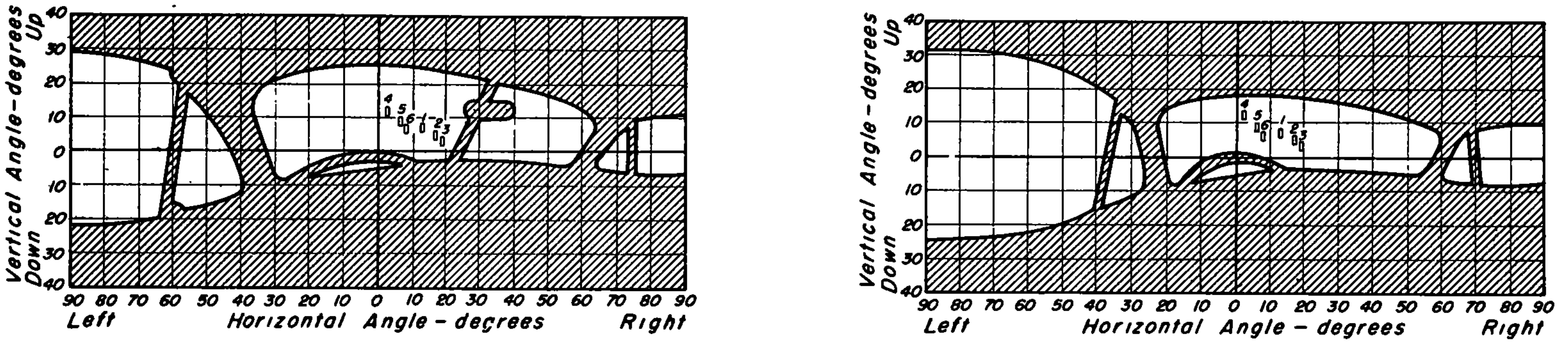
Legend— Signal Positions:
1. 30-ft street, curb-mounted
2. 50-ft " " "
3. 70-ft " " "
4. 30-ft street, overhead-mounted
5. 50-ft " " "
6. 70-ft " " "

Figure 4. Visibility angles from driver's seat (continued).



a. Tall driver, Car F, 1950.

c. Tall driver, Car O, 1950.



b. Short driver, Car F, 1950.

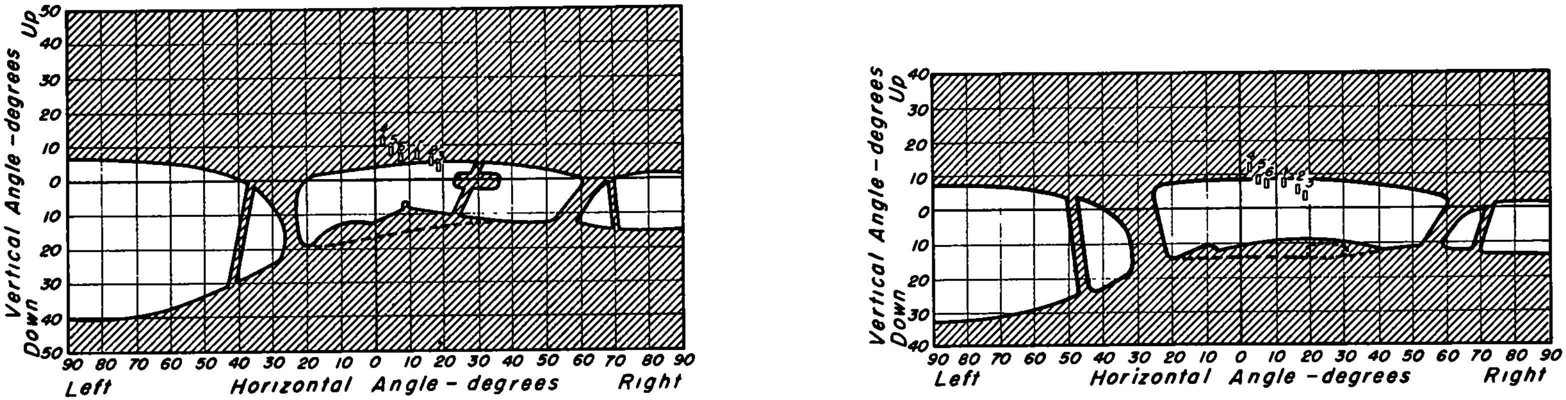
d. Short driver, Car O, 1950.

Notes: Eye heights at positions shown in Fig. 1.

Signal positions are plotted from data in Table 2.

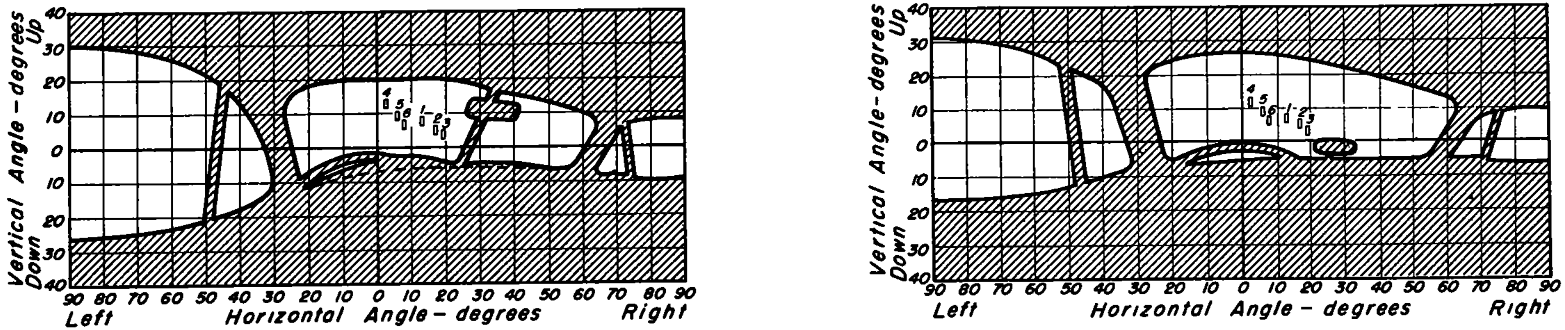
Legend— Signal Positions:
1. 30-ft street, curb-mounted
2. 50-ft " " "
3. 70-ft " " "
4. 30-ft street, overhead-mounted
5. 50-ft " " "
6. 70-ft " " "

Figure 5. Visibility angles from driver's seat (continued)



a. Tall driver, Car P, 1951.

c. Tall driver, Car S, 1950.



b. Short driver, Car P, 1951.

d. Short driver, Car S, 1950.

Notes: Eye heights at positions shown in Fig. 1.

Signal positions are plotted from data in Table 2.

Legend— Signal Positions:
1. 30-ft street, curb-mounted
2. 50-ft " " "
3. 70-ft " " "
4. 30-ft street, overhead-mounted
5. 50-ft " " "
6. 70-ft " " "

Figure 6. Visibility angles from driver's seat (concluded).

At present the only recourse that short drivers have for better visibility of the nearby roadway is the employment of an additional cushion to raise their eye height. The inconvenience of a loose cushion usually precludes its use, as evidenced by the not uncommon sight of a short person peering between the dash and the rim of the steering wheel. Since levels requisite for driving visibility also apply to short drivers, it is necessary to determine levels below which nontransparent material may be located. Figure 7 and the shadow diagrams indicate that all glass below eye level in the vehicles checked is necessary for seeing by short drivers.

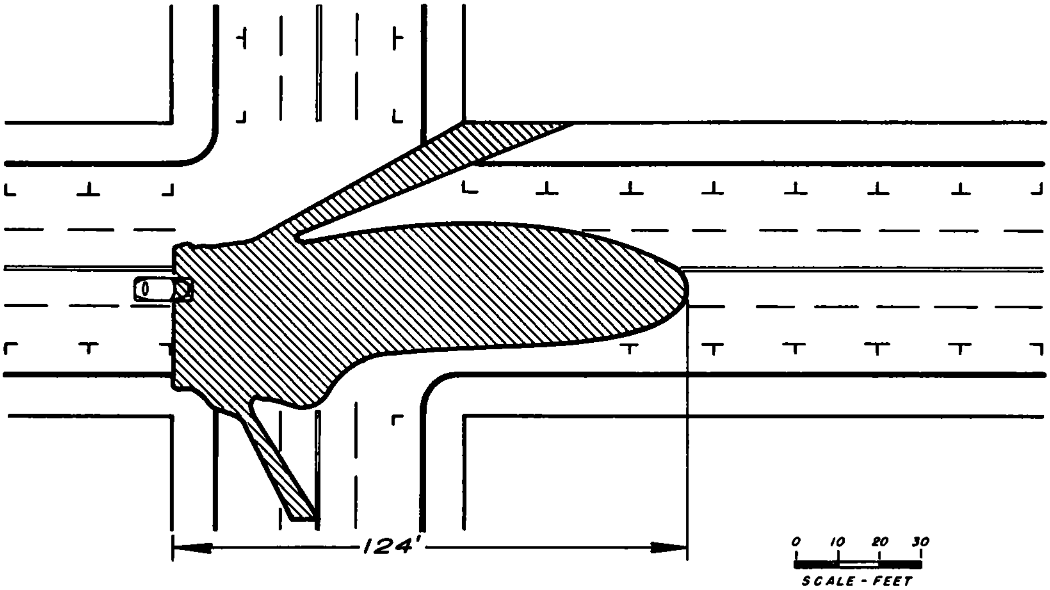


Figure 7. Blind area - - Short driver, Car P, 1951.

It would thus appear that from the viewpoints of both the taller and the shorter driver all transparent areas currently provided in most passenger cars is requisite for good driving visibility. This is especially true for the tall driver, since approximately 49 percent of U.S. total traffic (4) (approximately 55 percent in California) is in cities where upward visibility of signals is of great importance.

Nothing should be done which would decrease the driver's view and understandability of traffic signals, for as Schwanhausser points out:

"...motorists can ill afford to spend more than, or as much as, a fraction of a second to recognize a signal. Tests have indicated that it takes one or more seconds to react to an impulse. Hence, high speeds and dense traffic make it essential that motorists be alert and ready to maneuver their vehicle immediately upon sighting an obstacle or change in signal indication if accidents are to be avoided.

"When we come to contrast, we have a variable over which there is some control. When an object lacks contrast with its background, it is not easily detected. Hence objects such as traffic signals, if placed with some thought towards rapid discernment, should be carefully located against a contrasting, rather than a similar background. Uniformity of the background also helps improve contrast."

Likewise, dark-colored transparent materials on the windshield obscuring view of the signals should be avoided, because of the resulting decrease in brightness difference between the signal light and its background and the change in the color contrast of the signal light.

Viewing angles of curb-mounted traffic-control signals should determine the upper level in terms of angular measure from the driver's eyes. Overhead signals, although at higher angles, are not the limiting condition, since these signals are usually used in conjunction with curb-mounted signals and are intended for the motorist who is 100 ft. or more from the intersection.

The vertical angles for the curb-mounted signals range from 8.5 deg. for the 30-ft. intersection to 4.4 deg. for the 80-ft. intersection. Horizontal angles range from 13.1 deg. to the right for the 30-ft. street to 19.7 deg. to the right for the 80-ft. street. These angles pertain to the vehicle on the inside lane stopped at the crosswalk. The angles would be less for all other vehicles approaching the intersection. Some other forms of signal arrangement would require greater horizontal and vertical viewing angles, but the types shown are representative of those in general use.

The seat-to-eye height of the driver to be used as a standard from which to measure signal angles depends on the seat depression and the percentage of the driving population that should be included within the upper limit. The seat depression was found to vary between 2½ to 4 in. for the 150- and 180-lb. subjects, depending on the make of car. Since the seat depression varies considerably according to the weight and build of the individual, it is difficult to set a value that would correspond with each height of driver.

Reference to the seat depression measurements in Table 3 would indicate that variation between the cars checked is quite small for a given driver. The variation between drivers, however, is fairly large. An average value of 3¼ in. for passenger cars was decided upon, plus or minus a small amount to make the undepressed seat-to-eye height a whole number or easily measured fraction.

Table 4 gives different seat-to-eye heights and corresponding percentages of excluded drivers. The data of this Table assume that human dimensions as given in Moon (2) apply to the driving population. If the height distribution of drivers is not the same as the distribution of the samples used in the statistical survey, then the table may be subject to revision.

As there were no figures at hand on the proportion of miles driven by men and women, the calculations were based on the number of driver's licenses. However, the most representative figures of included driver percentages would be those given for men alone, since the large majority of vehicle-miles can be attributed to male drivers.

CONCLUSIONS

In determining what height is necessary for driving visibility, it must be considered that above this level the ASA Code will allow glazing material having a transmittance ranging from 70 percent down to zero. Under certain conditions objects may be visible through a glazing material even though the transmission is less than 70 percent, but this fact will not permit the approval of the glazing material under the present provisions of the code unless such material is above "the level requisite for driving visibility."

The data on drivers, vehicles, and required visibility angles reported here would lead to the development of the following definition adequate for approximately 97 percent of all drivers:

> Levels requisite for driving visibility in passenger cars include all glazed areas lower than a level of 29 in. above the undepressed driver's seat, measured from an eye position directly above a point 5 in. forward of the junction of seat and back rest and directly in line with the center of the steering wheel. Windshields in addition should have at least 70 percent transmission at all angles included within 8½ deg. above horizontal and between 10 deg. left and 20 deg. right.

A definition using the above figures would be impractical on most cars, for many of the windshields do not extend as high as would be specified. In order to permit low-transmission areas in the upper zone of a windshield, the words "driving visibility" might be interpreted as "roadway visibility", thus assuming that nearby traffic signals are not required for "driving." Under such a modified meaning any glazing material above eye level would not be of prime importance for seeing the roadway or other vehicles but would still be necessary for recognition of traffic signals and in developing a comfortable visual field.

If a more practical attitude toward a definition is taken such that the level would include approximately 85 percent of all drivers (79 percent of male drivers) instead of 97 percent, and if certain manufacturing problems associated with curved windshields are taken into consideration, a definition could be developed as follows:

> The levels requisite for driving visibility are established as all levels below a horizontal plane 28 in. above the undepressed driver's seat for passenger cars and 31½ in. above the undepressed driver's seat for other motor vehicles. Measurements shall be made from a point 5 in. ahead of the bottom of the backrest, and directly behind the center of the steering wheel, with the driver's seat in the rearmost and lowest position and the vehicle on a level surface.
>
> Areas requisite for driving visibility shall include all glazed areas below this plane, except side windows to the rear of the driver and other rear windows not used for

> vision directly to the rear. All windows capable of being moved within the locations specified shall meet the 70-percent-minimum-transmittance requirement over the entire window area.
>
> Corresponding eye heights may be used for specially designed vehicles or vehicles designed for standing drivers. The eye heights are based upon an average seat depression of 3.3 in. for passenger cars and 2.0 in. for other vehicles.
>
> In order to accommodate curved glazing materials and manufacturing procedures for shaded windshields, it may be permissible to reduce the luminous transmittance of the glazing material at each side of the windshield to below 70 percent for a distance from each corner post not to exceed 10 percent of the width of the windshield. This area of reduced transmittance shall not extend more than 1½ in. below the level requisite for driving visibility.

It is recommended that a lower limit of luminous transmittance and color distortion be added to the ASA Code to apply to glazing materials in areas not required for roadway visibility but necessary for signal visibility. The exact value could be found from studies made to determine the minimum acceptable limits of transmission and color for recognition of signals and highway warning signs both day and night. This requirement would help to control the use of opaque areas at the top of the windshield which entirely eliminate upward seeing.

It is also recommended that motor vehicles be manufactured with vertical as well as forward-and-back seat adjustments to enable the shorter and the taller drivers to obtain better roadway visibility.

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5. Report on Levels Requisite for Driving Visibility to AAMVA Engineering Sub-Committee by Special Study Committee for AMA, June 18, 1951.

Effect of Exposure to Sunlight On Night-Driving Visibility

R. H. PECKHAM,
Associate Professor of Research Ophthalmology
Temple University School of Medicine, Philadelphia

SUNGLASSES have been used for about 300 years; yet almost no research has ever been undertaken concerning their usefulness. In fact, these devices have developed almost spontaneously. They are used, because they are comfortable when the wearer is exposed to excessive sunlight. Since persons habitually living on the beach, at sea, or out-of-doors do not use sunglasses, and apparently do not need them, they seem to be devices for city slickers and sissies to wear. They are a luxury item.

During World War II the attitude of the armed services towards sunglasses was shifted from one of considering sunglasses to be a luxury item to the recognition that sunglasses were a necessary part of the uniform allotment. A group consisting of scientists meeting with representatives of the armed services (1) based its conclusions about sunglasses upon the researches of Hecht (2) and of Clark (3). In individual studies, Hecht, and later, Clark demonstrated that the effect of exposure to sunlight during the day resulted in a loss of seeing at night. Hecht demonstrated that about twice the amount of light is necessary for night vision after exposure to sunlight without sunglasses. Clark showed that the use of sunglasses effectively prevented this loss.

Follwing the war, Peckham and Harley (4,5) studied the effect of similar exposures upon civilians, performing their experiments upon life guards of the Atlantic City Beach Patrol. These investigators wished to determine if a comparable effect to that found by Hecht and Clark, could be observed under conditions of moderate photopic illumination (the moderate artificial light used for reading, working, and night driving).

Figure 1 shows the curve of visual response to brightness. It can be shown that at high levels of illumination there is very little or no improvement in vision with increasing illumination, but that at lower levels visual performance decreases rapidly with decrease in brightness (6).

This is a schematic figure designed to compare two subjects whose response to brightness is slightly different, as represented by the constant brightness shift, ΔB. At very low levels, a large difference in response, ΔR_1, is found for the brightness shift. In the middle of the curve, near the cusp of the rod-cone transition, a constant shift of brightness causes a smaller shift in response, ΔR_2. At very high levels of brightness, there is only a negligible change in response, ΔR_3. Peckham and Harley worked near the region shown by ΔR_2. Measurements in this region, of visual acuity or contrast perception, tend to be erratic and undependable. Nevertheless, Peckham and Harley showed that exposure to excessive illumination at the beach resulted in the loss of photopic, or low-level daylight, visual performance, and that this loss can be expressed quite adequately as a factor of reduced effective illumination. The value of this factor was found to closely agree with those previously determined by Hecht and Clark.

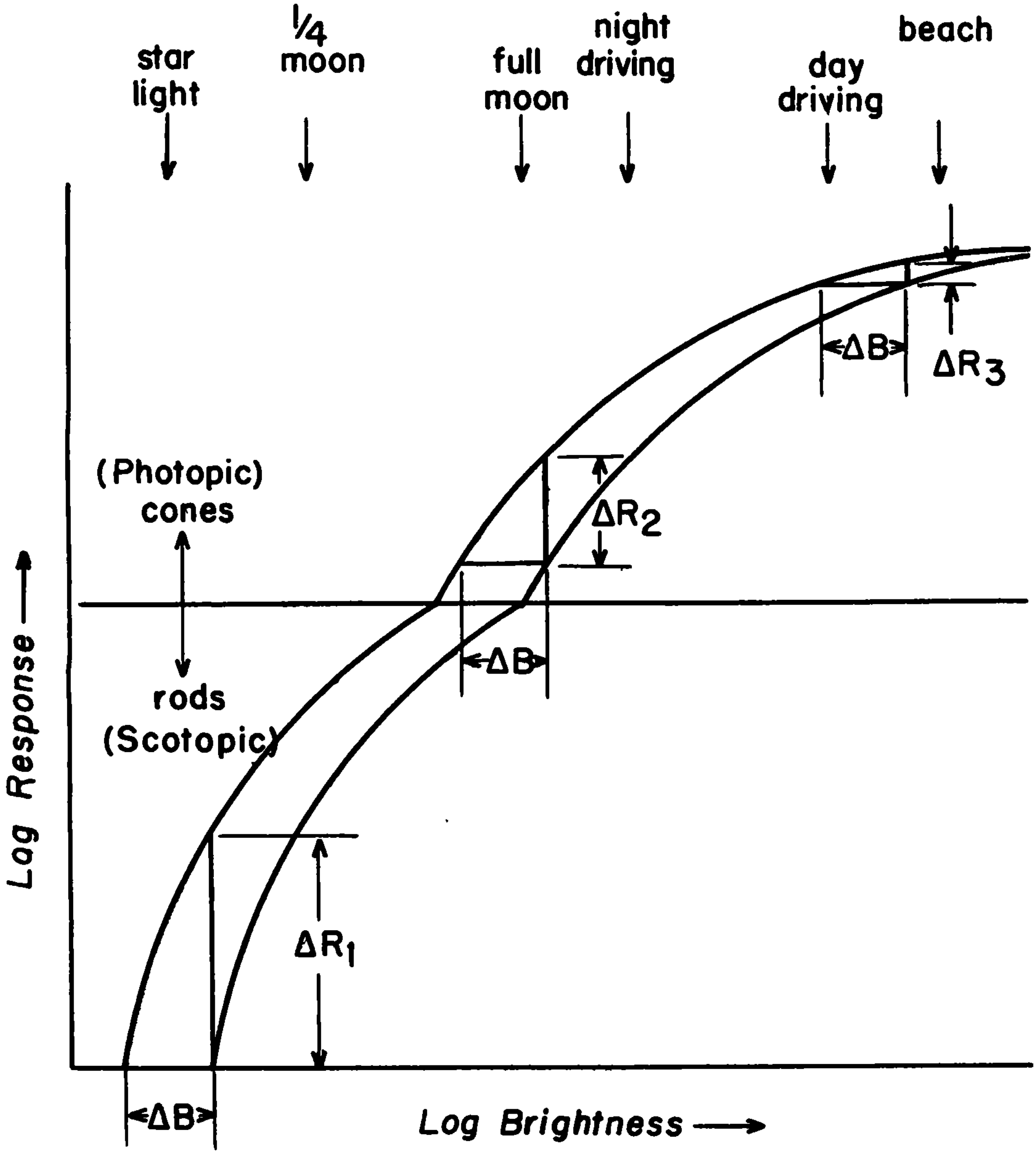

Figure 1. Schematic diagram of visual response: The curves represent the visual response after a constant shift in effective brightness, △ B. The change in response at △ R_1, the threshold, will be greatest. The change, △ R_2, at low brightness is much less. The change at high brightness, △ R_3, may be too small to be reliably measured. Responses below the cusp are scotopic, or night-vision, responses, those above the cusp are photopic, or day-vision, responses.

Since the vagaries of visual acuity at low contrast and low brightness render such measurements extremely difficult, another method of estimating effective visual brightness is needed. Such a function is found in the critical flicker frequency (CFF) at photopic levels. Such flickering objects are frequently found in everyday experience. For instance, in the old motion pictures, and in some home movies, the effects of flicker caused the picture to shimmer and to be very disagreeable. In those parts of the country served by 25-cycle alternating current instead of 60-cycle alternating current, lamps seemed to flicker. In an experimental situation, the flicker can be produced by having a rotating shutter pass rapidly in front of the lamp, thus alternating the light. Or it can be produced by using a gaseous-discharge light source activated in a series of flashes. With such apparatus, if we start it at a low flicker rate, the object will appear to jump, shake, and shimmer. But if the rate of flicker is increased sufficiently, the flickering will disappear. The point at which the flickering disappears is called the critical flicker frequency. It has been shown by several investigators, for instance Hecht (7, 8) and Crozier (9), that a change of brightness results in a change of critical flicker frequency, and that the relation of flicker frequency is linear to the logarithm of the brightness. This means that it would be possible to measure retinal sensitivity directly by determining the critical flicker frequency for a standard brightness.

In Figure 2 the relationship between the critical flicker frequency and the brightness of the flickering object is shown by the line AB. When we change the brightness of the light we will find that the flickering disappears at a low speed with a dim light but will not disappear until a high speed is reached with a bright light. Now suppose that we take a different subject, giving us a series of measurements along the line CD, indicating that this subject responds differently in critical flicker to the variation of brightness. If we compare these two curves at a certain standard brightness, indicated as B_1 in the figure, we notice that subject CD loses the perception of flicker at the rate R_2, which is slower than subject AB, at R_1. If we draw a line parallel to the base from R_2 on CD, it intersects curve AB at the brightness level B_2. Thus, if we wish to compare the first and second subjects, we could say that the brightness B_1 for the second subject was only as effective as the lower brightness B_2 for the first subject. This means that the constant illumination within our apparatus was not as effective for the second as for the first subject. Since this illumination has not changed, we are in effect comparing directly and very accurately the retinal sensitivities of these two subjects. By this means we have conquered an epistemological problem. Although, when using a comparison photometer, both subjects would have reported the same absolute brightness, by means of this visual response to flicker, we can determine individual differences between them. This means of measuring the sensitivity of subjects can be directly applied to the problem of sunglasses. We have here a means of determining the relative sensitivities of a single subject in the morning and again in the evening by comparing his critical flicker frequency for a standard brightness. We could equally well make the same measurement by measuring the brightness required for a standard critical flicker frequency. In either case, our results would be expressed in terms of the logarithm of effective retinal response. This was done upon a group of life guards in Atlantic City (5). It was done again upon a group of automobile drivers in Phoenix, Arizona (12).

In this latter study, a group of 24 young men were required to drive automobiles along country highways for about 6 hours per day for five days without sunglasses. The study was undertaken in the spring of 1951, and illumination measurements show that the brightnesses of the road were no higher than that of country roads in the northern half of the United States during the summer.

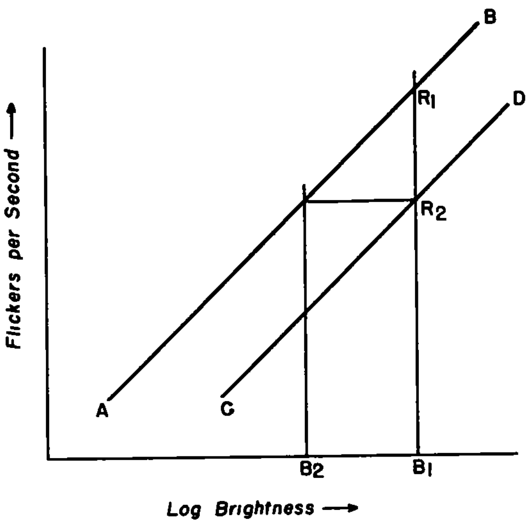

Figure 2. Relationship between critical flicker frequency (CFF) and brightness: CFF varies linearly with the logarithm of brightness. At the fixed brightness, B_1, a normal retina (AB) will yield the CFF at R_1. An exposed retina (CD) will yield the CFF at the depressed value R_2. This would have been shown by the normal retina at the lower brightness B_2. Hence B_1 is only as effective as B_2 for the exposed retina.

The results of the measurements in Phoenix can be expressed as shown in Figure 3 in terms of the accumulated differences between the morning and evening scores of these drivers. These data include 10 measurements each at two levels of brightness, both morning and evening, for 24 subjects for 5 successive days. That is, they represent the results of 4,800 observations. In each case, the average of 10 flicker rates each evening has been subtracted from the average of 10 flicker rates that morning for each subject. These differences are accumulated in units of flickers per second. It will be noticed from the graph, that there was, in a few cases, an actual increase in the evening, so that some subjects seemed to see better in the evening than in the morning. The examination of the figure indicates that 22 percent of the records studied, showed either no change or such an improvement. But 78 percent of the records studied show either no change or a decrease in retinal sensitivity, between evening and morning. Thus, we find that a large majority of the drivers lost some retinal sensitivity during the day. These drivers did not wear sunglasses and drove approximately 6 hours each day, covering about 250 to 300 mi. The average effect of this exposure is indicated by the position of the median point in the figure, that is, the difference of flicker which is halfway between the extremes. We find that half of the group lost a flicker frequency of 2.2 per second to the standard light. This can, in turn, be interpreted as a loss of brightness. It means than the logarithmic decrement of brightness amounts to 0.22. The antilog of this amount is 1.66; the ratio of required brightness for the same visual efficiency is therefore 10 in the morning to about 17 in the evening. The effectiveness of the light in the evening was reduced to about 60 percent of its effectiveness in the morning for half of the drivers. We see further from the figure, that smaller fractions of the population lost even more than this amount. For instance at the 75-percent level we find the remaining 25 percent lost as much as 4 flickers per second, which gives us a ratio of effectiveness of 10 to 25. The light was only 40 percent as effective in the evening as it had been in the morning for this fraction of the drivers. In other words, in one fourth of the group, over half of the light is useless due to the decrease of retinal sensitivity. We find that 10 percent of the population lost about 6 flickers per second or more. This means they require 4 times as much light in the evening as they would have required in the morning for the same visual perception. This group includes the persons most dangerously affected by the loss of retinal sensitivity due to exposure to sunlight during the day's driving. In 1,000 drivers, there are 100 persons so affected.

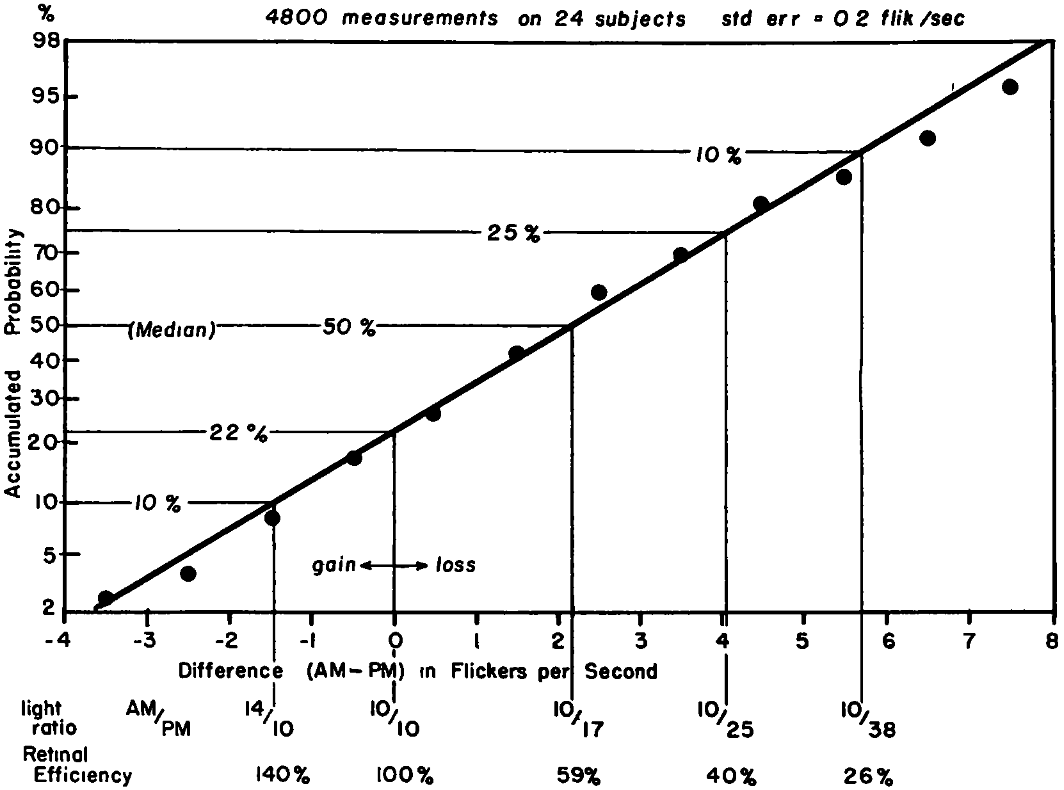

Figure 3. Diurnal loss of retinal sensitivity from exposure during driving: The difference between the averages of each set of ten morning and evening flicker readings at two brightnesses for 5 days on 24 subjects is presented as an accumulated distribution curve on a probability scale. Each change of 10 flickers per sec. represents a change of one $\log_{10}$ unit of effective brightness, hence the ratios of effective illumination between morning and evening can be expressed for any change in critical flicker frequency, as shown.

On the other hand, among those who gained, very little gain is found. At the 22-percent point we find a ratio of no gain or loss. At the 10 percent point the gain was 1.5 flickers per second, amounting to a ratio of 14 to 10, or a gain of 40 percent. Thus, the most gainful 10 percent gained very little compared to the most damaged 10 percent. We can summarize these results as indicating a very significant loss of retinal sensitivity as the result of a moderate day's driving in relatively moderate sunshine. This loss might be attributed to fatigue, or to some function of fatigue, if we had not previously shown that similar loss could be directly correlated with sunlight and could be prevented by the use of sunglasses.

The effect of this change in retinal sensitivity between morning and evening, after driving during the day without sunglasses, can be used to predict safe driving conditions (Fig. 4). Retinal sensitivity can be expressed as retinal efficiency in percent. The division of the group, for various degrees of loss, can be shown at various levels of probability. As a measure of safe driving, we can use the estimates of stopping distances, including reaction time and braking time, for various speeds. In driving at night, obstacles become visible when the illumination from the headlamps reaches a sufficient intensity to make them so. With two upper sealed beams, of 25,000 beam candle power each, the illumination reaches this critical level at a predeterminable distance, depending upon the size, reflectance, and contrast of the obstacle. We can suppose, therefore, that the level is reached at the stopping distance, for a "normal," or unexposed retina, as shown in the diagram. With decreased retinal efficiency, more illumination will be required, depending upon the degree of loss. For each stopping distance this has been computed. For example, at 60 mph. the stopping distance on a dry, level, concrete road is about 260 ft., at which distance the illumination will be 0.7 foot-candles. An obstacle just visible at this distance and brightness can be avoided, under these conditions, with normal retinal sensitivity. But the average reduction of retinal efficiency will require more light for the "normal" response to 0.7 f.c. Such a retina is only 59 percent efficient. Hence, the car must have proceeded to within 200 ft. to provide this illumination. To similarly avoid this obstacle, the driver could not exceed much over 50 mph. The poorest 10 percent, which would include 100 in any group of 1,000 exposed drivers, could not see such an object until the car was within about 140 ft., and could not stop unless the car were travelling below 40 mph. Thus, under identical road conditions, the same degree of safety for one driver at 60 mph. is unsafe for another at 40 mph.

It is not the habit of drivers to accommodate their speed to their retinal efficiency. Rather, a group of cars all travel at about the same speed. This inevitably forces the exposed driver to overdrive his headlamps to keep up with accompanying cars.

At any speed, we can thus predict the effect of retinal efficiency upon safe driving, or upon the probability of an accident. This prediction cannot be considered complete; it is only suggestive. But enough information has been accumulated to show that within the framework of visual sensitivity, a significant cause of accidents can be predicted. It is of great importance that this avenue of approach to accident prevention be fully explored. In the meantime, it is fairly safe to predict that the use of sunglasses during the day is really worthwhile.

As a result of these various researches, the following facts have been determined: (1) the effect of exposure to sunlight is to reduce visual performance during the evening; (2) this reduction can be expressed as a fraction of the measured illuminations provided by artificial light, that is, headlamps; and (3) the effect can be prevented by the use of adequate sunglasses.

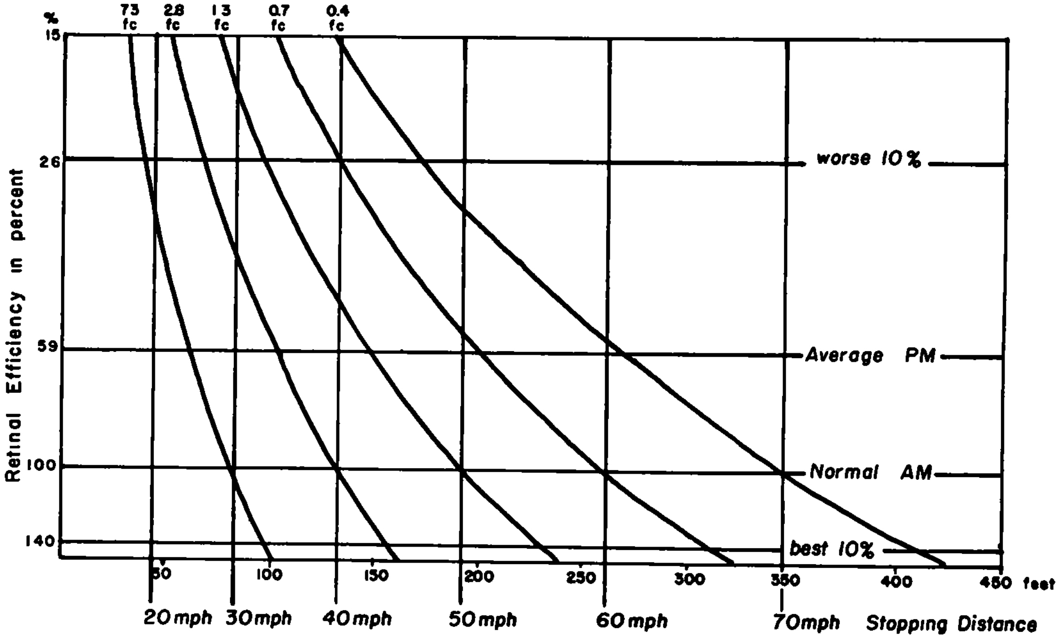

Figure 4. Effect of retinal efficiency on road illumination and stopping distances: Depressed retinal efficiency requires a closer approach of the car to provide equivalent visual response, thus demanding a reduction of safe driving speed. Computed for two upper sealed-beam lamps at 25,000 beam candle power. (Data from General Electric Company and Ford Motor Company).

From our research, we can clearly specify what sunglasses are needed. They should transmit approximately 10 percent, or should transmit from, say, 8 to 18 percent. It may appear that such sunglasses would be abnormally dark and might reduce daytime vision. An examination of the effect of reducing illumination 10 times from 1,000 to 100 foot-candles, or from 100 to 10 f.c., upon visual acuity, shows that the resulting loss of visual performance is so minute as to be practically negligible. Such sunglasses cannot be considered too dark. Certain other research indicates that the color of the glass used is immaterial (10). Finally, the quality of even the least expensive types of sunglasses is not deleterious to vision (11).

Sunglasses of any type, at any price, of any color, will be helpful to automobile drivers if they are worn during the day and thus protect the retina and prepare it for the difficulties of seeing at night with the automobile headlights. Many of the sunglasses on the market, while dark enough to provide comfort, are not dark enough to provide retinal protection. However, if automobile drivers will take the simple precaution of buying the darkest sunglasses they can find, and substituting even darker glasses for those they have already purchased, they can expect a very considerable degree of assistance to their retinal efficiency.

Visual perception is itself an erratic phenomena and the prevention of an accident will require not only visual perception of the situation, but also the psychological and experiential recognition of the danger involved. Visual reduction may be a significant contributory cause to accidents, the primary cause of which may most logically lie in violation of safety rules or bad traffic engineering. Nevertheless, we can logically rationalize that in any accident there is included a visual requirement which might have prevented the accident, and which could have been assisted to a considerable degree by the use of sunglasses. Since driving an automobile is essentially best described as a continual series of avoided accidents, any program of highway safety should recognize this visual factor. It is hoped that this report will assist in disseminating the knowledge of the great usefulness of sunglasses in accident prevention.

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Effect of Pattern Distribution on Perception of Relative Motion in Low Levels of Illumination

HAROLD I. STALDER and A. R. LAUER,
Driving Research Laboratory,
Iowa State College

ONE of the most frequent causes of accidents, as reported by the National Safety Council, is following too closely behind another vehicle. Many interpretations may be placed upon such a general classification but complaints indicate the incidence of one motor vehicle running into the rear of another at night, either moving or stationary, is much too frequent to be assigned to chance.

The exact reason for following too closely is usually not stated. Various reasons of general nature have been given. In some cases poor vision is blamed. Blinding lights, fog, rain or snow, carelessness, or similar conditions are also mentioned. Whatever may be the alleged reason given for front and rear-end contact of two vehicles headed in the same direction, it is axiomatic that a driver in any reasonable condition or state of mind would not deliberately drive into an object or vehicle plainly visible within stopping distance. It should be stated that the driver did not see the obstacle in time and was unable to adjust his stopping distance accordingly. It is also conceivable that the driver was too slow in making a proper judgment.

Hoppe and Lauer (2) found that increased tailgate perceptibility would decrease judgment time, and errors of discrimination of relative motion and change in distance. Likewise relative brightness was found to decrease the difficulty of making judgments according to verbal reports. Their study was made with several types of targets but with speed differentials not to exceed 10 mph.

THE PROBLEM

The present study was designed to test the primary hypothesis that driving speed is a factor in discrimination of relative motion in low illumination. A corollary hypothesis may be stated as follows: The distribution of pattern-detail, well above the threshold of resolution by the retina, has no affect on the perception of relative motion under mesopic vision and other conditions imposed. It was assumed that: (1) variations in the abilities of subjects used affected all experimental conditions in a similar fashion; (2) the absence of manipulation as experienced in driving would tend to place observations and results on the conservative side so far as the margin of safety in distance judgment is concerned; (3) the time required to make an incorrect judgment of direction of movement is the

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best available estimate of the true time required for a correct perception; (4) trials made when distance is decreasing are of more practical value than the reverse; (5) systematic errors are minimized by rotation of stimulus presentations; and (6) subjects were motivated to do a careful job of making judgments.

Due to limitations of time, the design of the experiment was restricted to the use of one control condition and two treatments of tailgate or targets. One color of reflectorized material, a red having a reflection characteristic of 35 as compared with a flat-white surface designated as unity, was used for the overlay pattern.

APPARATUS

The scotometer, as described by Stalder, Hoppe, and Lauer (3) was used to make the measurements. It was adapted to give various equivalent scale-speeds ranging from 10 to 50 mph. by increments of 10 mi., plus or minus 1 mi. per hr.

This apparatus used consists essentially of a dark tunnel approximately 43 ft. long having two moving belts painted neutral gray to resemble a concrete paved roadway. The shoulders and surroundings are painted flat black. The belts may be moved in either direction by a manual control at any desired speed through two Vickers hydraulic transmissions. By attaching miniature cars and panels to the belts the conditions of actual highway operation are simulated more or less realistically. That this is the case was shown empirically (2) by comparison of runs made on the road and in the laboratory with correspondingly scaled distances. The results showed similar parallel and comparable trends with full-sized and miniature apparatus.

By an optical system of periscopic mirrors, the observer viewed an area of the same angular proportions as he would through an average windshield when driving on the highway. Impinging and opposing lights were calibrated to give lighting conditions equivalent to those found from standard headlight illumination on the highway. Three 4- by 5-in. targets were used as shown in Figure 3. A, is a control target painted flat black, having a reflection characteristic of 0.04, and with one taillight as shown. The latter is 3/16 in. in diameter, having a scale value of 4½ in. across the lens. Targets B and C each have 6.25 sq. in. of reflectorized pattern applied as shown. This would be the equivalent of about 25 sq. ft. of surface on a tailgate of actual size. It will be noted that the border was delineated somewhat more in Target B than in the checker-board treatment used for Target C. This target gave a more nearly even distribution of reflectorized pattern. The material used for reflectorization of both targets was 35 times flat-white as stated.

The designs were chosen purely as experimental expedients for comparing concentrated versus distributed areas of reflectorized material. They were not intended as suggestions for actual use on vehicles.

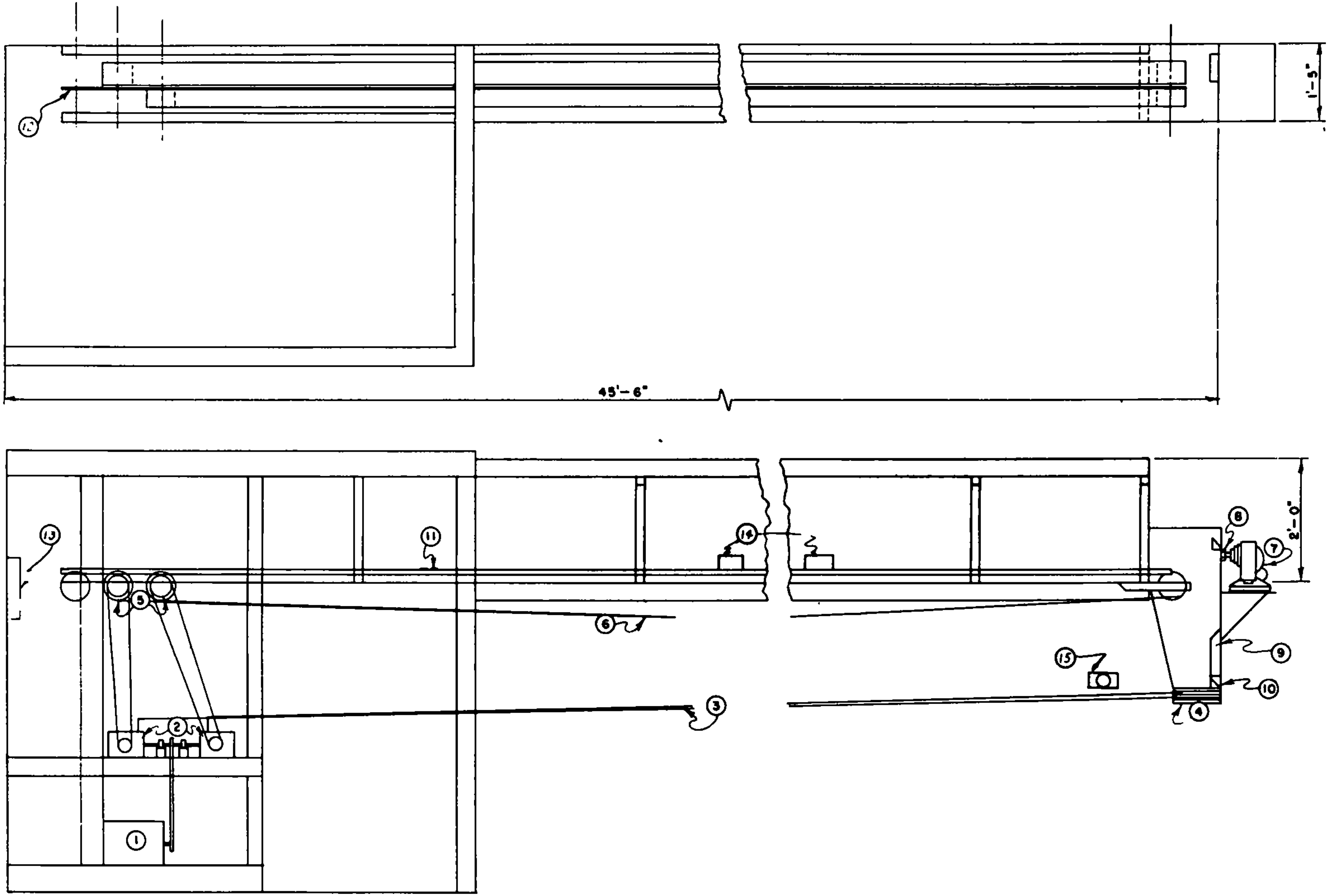

Figure 1. Schematic diagram of the scotometer, or dark tunnel.

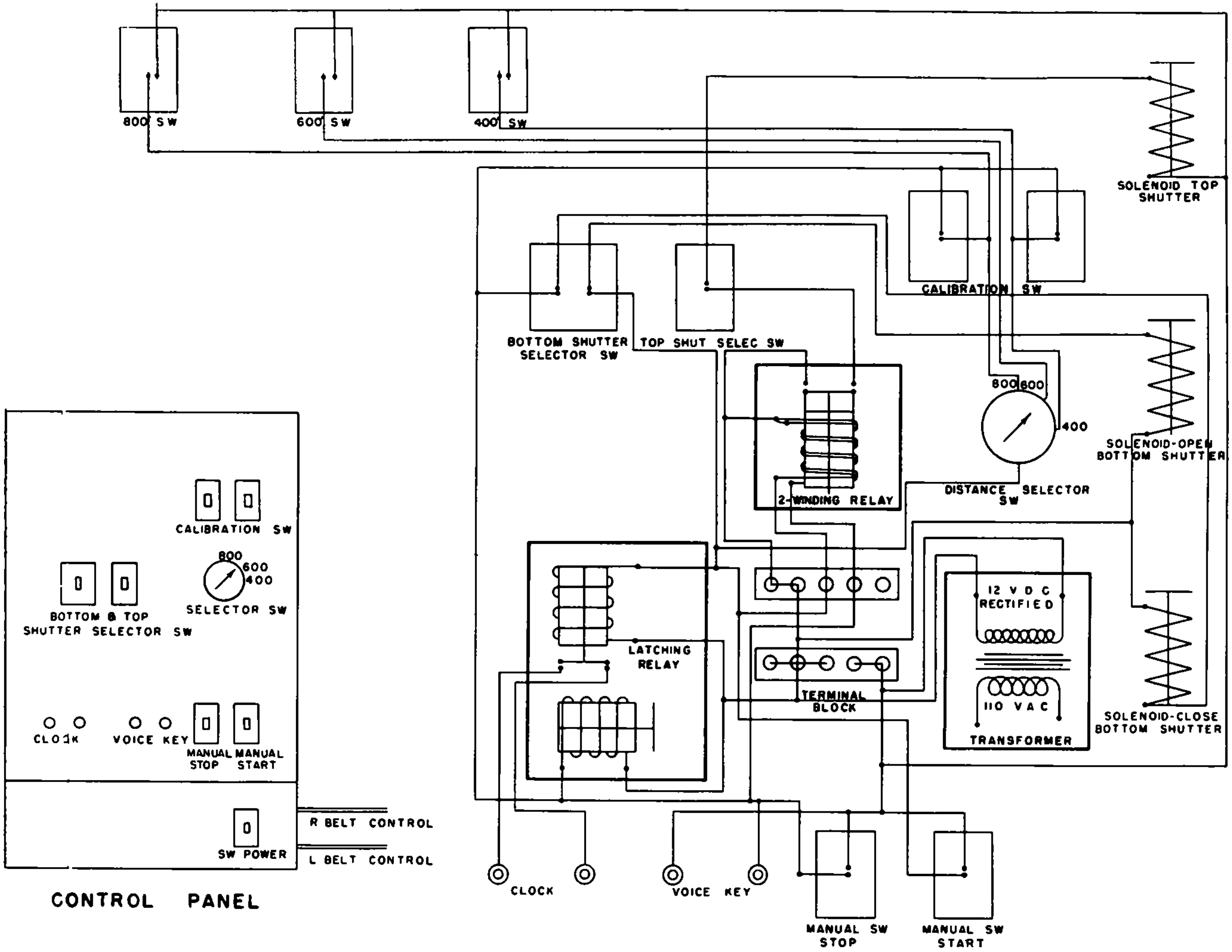

Figure 2. Schematic wiring diagram of control circuits for scotometer.

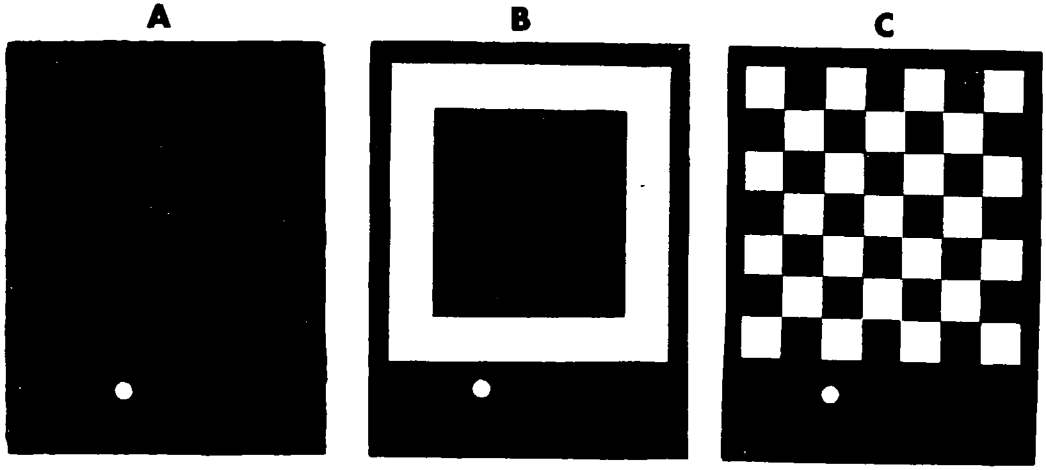

Figure 3. Targets used as stimuli.

METHOD AND PROCEDURE

The observer or subject was first measured for visual acuity since the selection of subjects with near normal vision would tend to reduce variance and thus effect greater economy in time needed for the observations. Next the observer was seated at the scotometer under a black hood with illumination approximately that of the average condition experienced in a car or other vehicle during night driving. The experimental conditions were presented in random and rotation order to reduce the possible effects of systematic error. Each of the three target treatments were presented at 10, 20, 30, 40, and 50 mph. in scale-speed, both with and without opposing lights. In order to keep the length of the experimental period short enough to avoid various fatigue effects and boredom, only two lighting conditions were used: (1) high-beam intensity of impinging lights without opposing light and (2) low-beam intensity of impinging lights with opposing light.

These are usual conditions expected on the roadway, assuming everyone drives with high beams but depresses his beam whenever meeting another vehicle.

The panel of the truck theoretically being overtaken is carried by the right-hand belt as seen from the eye of the observer. At a predetermined point the experimenter opens the shutter which starts a standard 1/100-sec. timer clock. The observer reports verbally the instant he detects whether the target is moving closer to him by saying "slower" and further from him by saying "faster." These responses correspond to the condition of a vehicle ahead moving slower or faster in relation to the driver as experienced in actual driving. An electronic voice-key closes the shutter the instant the sound is emitted, stopping the time clock and measuring the time for each judgment. There is a slight constant error due to lag in the relay. This is of the order of 70.4 milliseconds or about 2 percent of the mean judgment time for all targets.

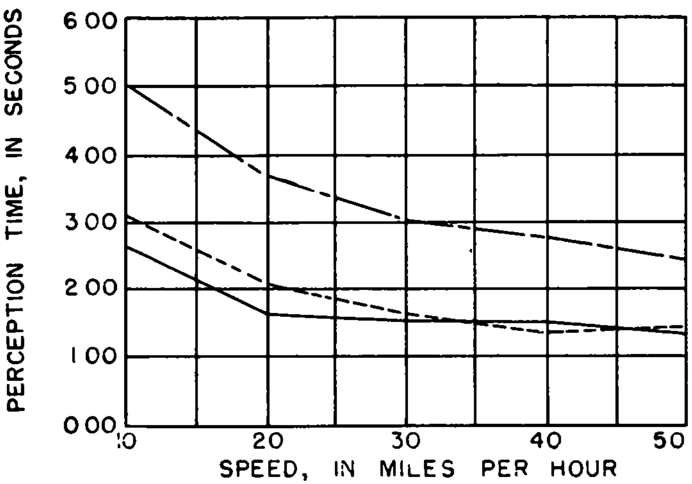

Figure 4. Mean perception time for decreasing distance, no opposing lights.

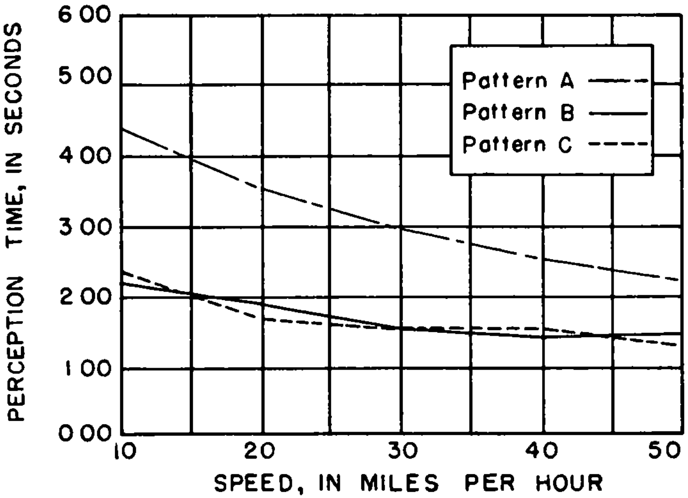

Figure 5. Mean perception time for decreasing distance, low-beam, low opposing lights.

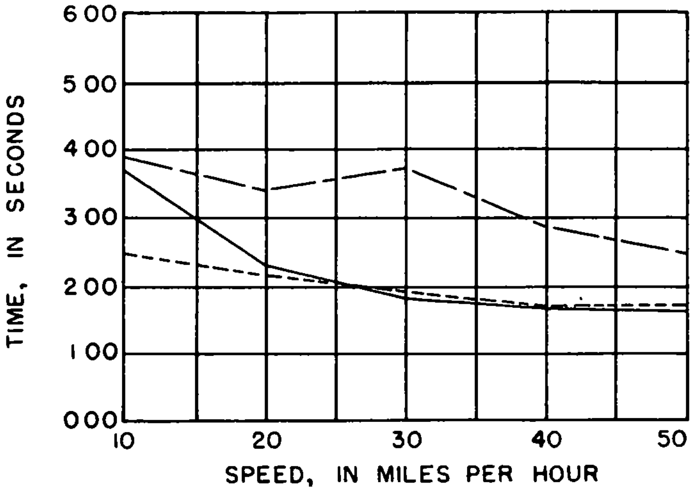

Figure 6. Mean perception time for increasing distance, high-beam, no opposing lights.

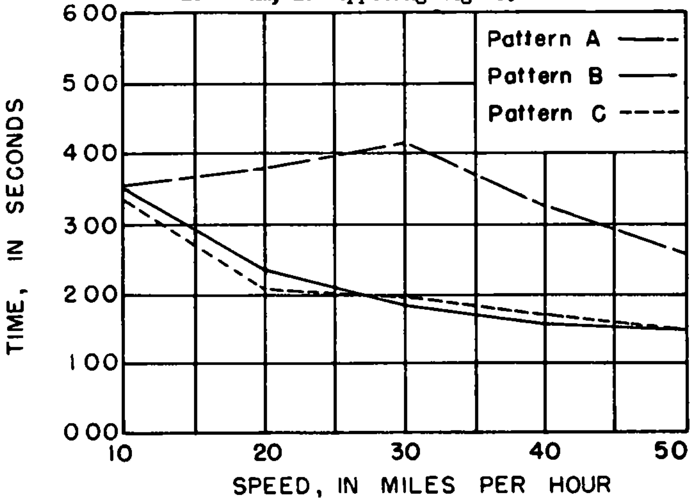

Figure 7. Mean perception time for increasing distance, low-beam, low opposing lights.

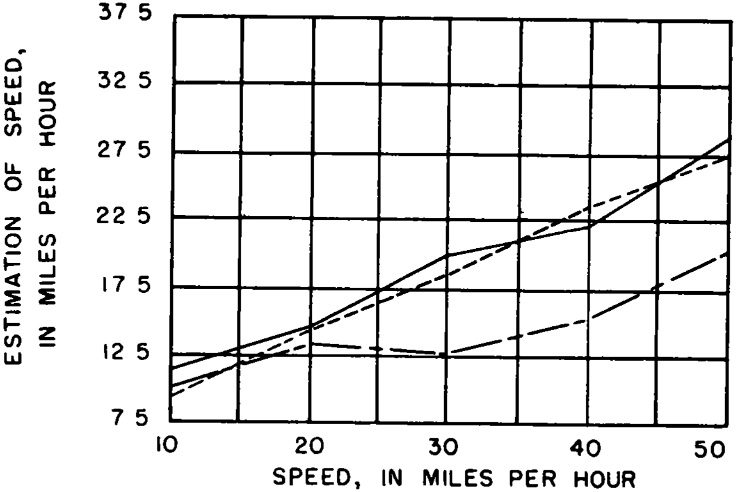

Figure 8. Mean speed differential estimations for high-beam, no opposing lights.

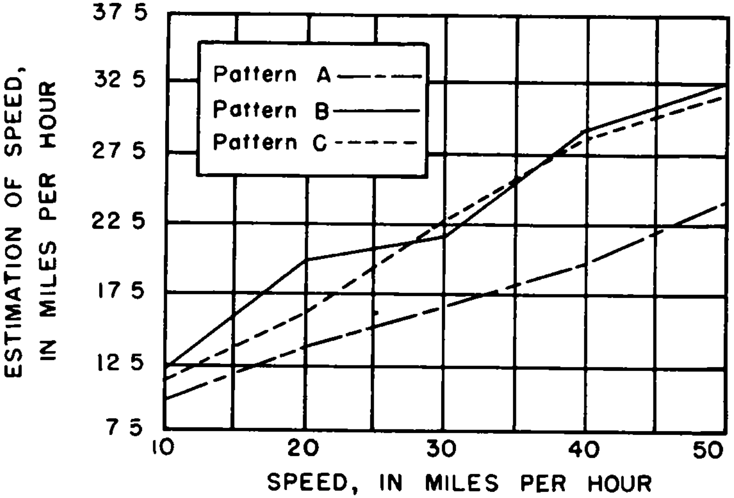

Figure 9. Mean speed differential estimations for low-beam, low opposing lights.

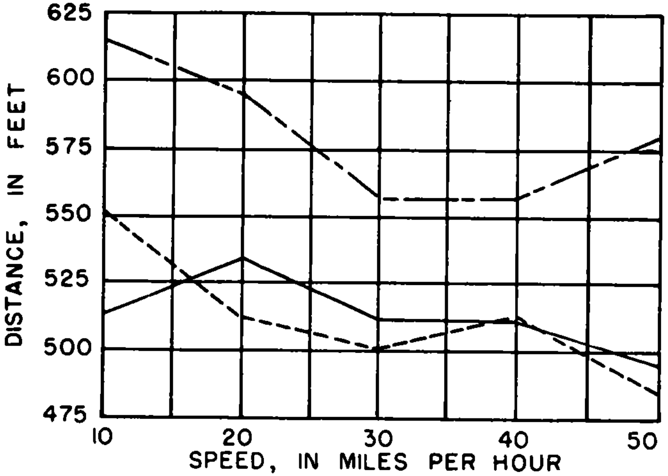

Figure 10. Mean distance judgment estimation for high-beam, no opposing lights.

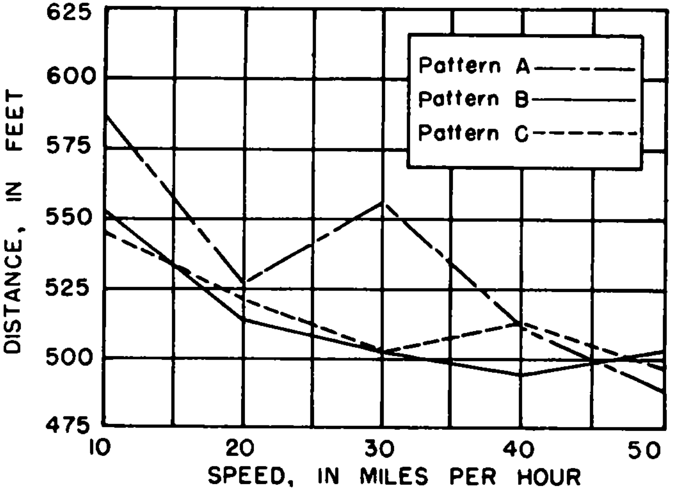

Figure 11. Mean distance judgement estimations for low-beam, low opposing lights.

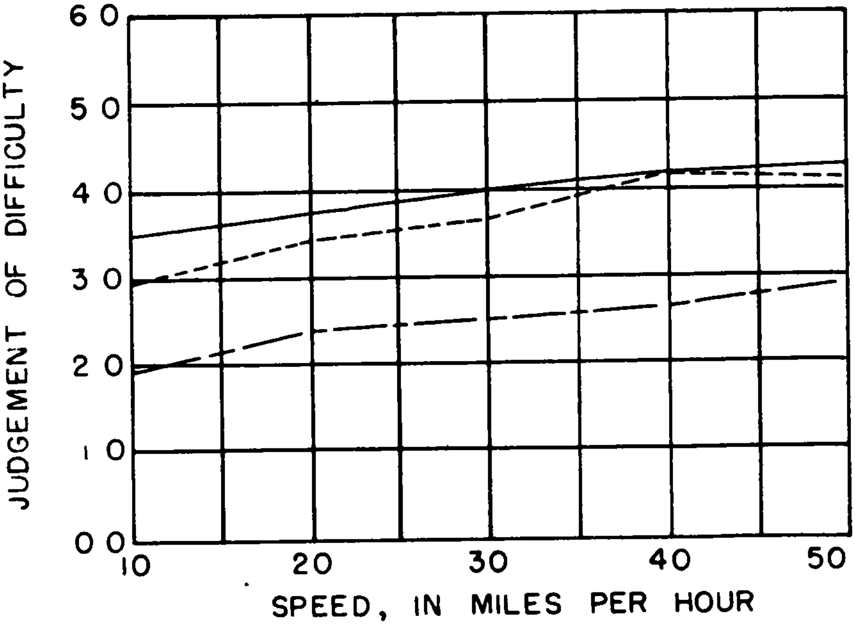

Figure 12. Mean judgements for level of difficulty, for high-beam, no opposing lights.

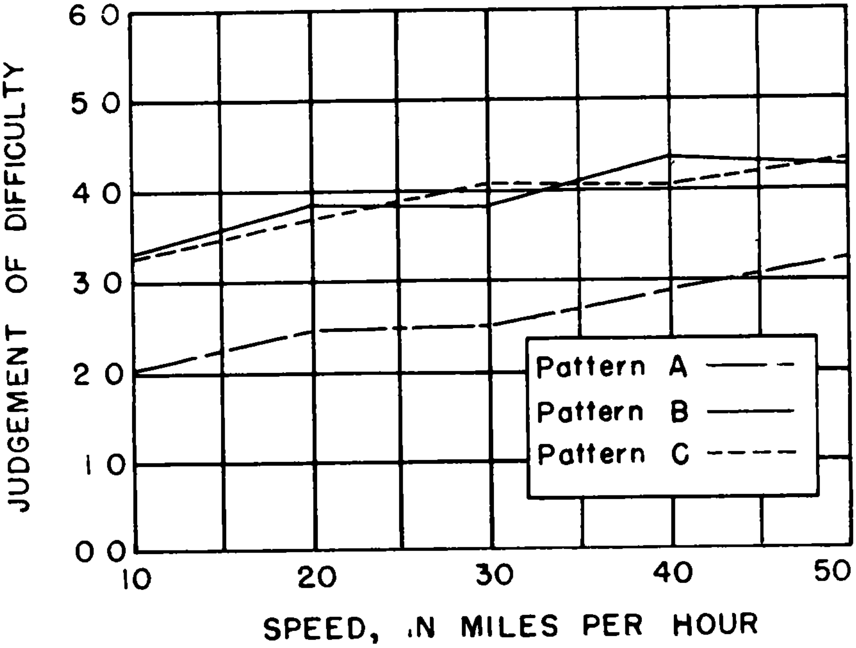

Figure 13. Mean judgements for level of difficulty, for low-beam, low opposing lights.

The subject is then asked to estimate: (1) the difference in speed of the moving vehicle ahead and his own imagined speed, (2) the difficulty of making a judgment, and (3) distance of the vehicle ahead. The request is structured to the extent that he is asked to consider the distances as being between 400 and 800 ft. and to make estimates by increments of 25 ft. Thus the vehicle ahead would be judged as being 400, 425, 450, and so on up to 800 ft. ahead.

Thirty subjects were used ranging in age from 19 to 54 years. Each made 84 separate observations for a total of 2,520 judgments for all subjects. Reliability of observations ranged from 0.67 to 0.94. These are estimates made from the correlation of the sum of two trials using conventional formulas used for this purpose.

RESULTS

The data were analyzed on the basis of the following variables as aspects of the measurements made: (1) perception time, (2) estimation of speed differential, (3) estimation of distance, (4) judgment of difficulty, and (5) errors made in direction of movement.

In order to summarize briefly without going to the trouble of discussing each difference separately, it suffices to say that the mean differences obtained were subjected to the "t" test for significance. Approximately four out of five of the points on the graphs are significant between comparison of Conditions A and B and Conditions A and C. This is roughly equal to about one-line marking distance on the graph for the 1 percent level of confidence and a half line for 5 percent level of confidence as a rule-of-thumb comparison to be applied in studying the graphs.

Although close to the border of significance at times the experimental Condition B was slightly superior to C in the overall comparison.

It is also noteworthy that the errors in direction of movement were much more frequent at scale speeds of 20 mph. and below. Few errors were made at scale speeds above 20 mph. More errors were made when distances were increasing rather than decreasing, for Pattern A as compared with those for Patterns B and C. Differences compared for the latter types of errors were significant at the 1 percent level of confidence. However, it is assumed that decreasing distance is more important than increasing distance so far as discrimination is concerned when driving on the highway. It is more important for a driver to be able to detect the rate at which he is overtaking another vehicle than it is to determine how fast the other vehicle is moving away from him.

A correlation of 0.45 was obtained between visual acuity and perception time, although no one had less than about 67 percent vision. Clason Acuity.[1] This would indicate a marked disadvantage in perceiving relative motion by persons with poor vision. Standards for licensing as low as 27 percent Clason, or about 20/70, have been reported for some states. Vision of 50 percent Clason, or 20/40, is the average lower limit throughout most of the states.

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[1] - Measurement units used by Bausch and Lomb in calibrating the Clason Acuity Meter.

Pattern B required significantly less time for perception of direction of movement at scale-speeds above 20 mph. than Pattern C, indicating an advantage of sharper target border delineation when possible to obtain it. It is hoped that Patterns B and C may be combined in a future study to evaluate additive effects.

Above 30 mph., scale-speed, the advantage of Patterns B and C were significantly superior to Pattern A by the criteria of evaluation used. Targets B and C were significantly judged to be closer than A for all but two conditions of lighting and speed and these two were borderline. Significantly used here in the sense of being at least at the 5 percent level of confidence.

The difficulty of perception and judgment was greatest for all lower speeds. Target A showed much higher average ratings for difficulty of estimation. The results confirmed the general findings of Hoppe and Lauer.

CONCLUSIONS

Considering the conditions of the experiment, the targets used, number of subjects making the observations and other limitations, the following conclusions may be made with a substantial degree of confidence:

1. Increasing visibility of a moving target or vehicle at mesoptic levels of vision will significantly decrease the time for accurate determination of direction and rate of movement, increase the accuracy of estimating or judging actual difference in speeds, increase the safety factor for stopping distance by reducing the apparent distance of the brighter targets, and decrease the errors in judgment of direction of movement.

2. Higher visibility is particularly effective at high differential speeds when the hazards of collision are greatest.

3. Equal areas of reflectorization are slightly more effective, with respect to the conditions used in this experiment, when the target is sharply delineated.

4. Perception time converted to distance travelled before reaching a judgment shows an advantage of 30 ft. or more at lower speeds to 75 ft. at higher speeds for the brighter targets. This conclusion involves the assumption that scale distances correlate highly with actual distance. This was shown to hold for certain targets by actual road tests in earlier experiments.

5. The primary hypothesis set up for investigation, that differential speed is a factor in judgment of relative distance, is confirmed.

6. The corollary hypothesis, that distribution of pattern detail has no effect on perception of movement, is only mildly rejected; further experimentation needs be made with different patterns, colors, and combinations of patterns with delineating borders for definite conclusions on this point.

7. Reflectorization of tailgates greatly increases perceptibility of relative motion over conventional nonreflectorized treatment of tailgates. This is particularly important when vehicles are travelling at higher rates of speed.

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Vision at Levels of Night Road Illumination

OSCAR W. RICHARDS, American Optical Company,
Research Laboratory, Stamford, Connecticut

SYNOPSIS

AUTOMOBILE driving at night is done with illumination of about 3,025 deg. Kelvin and intensities to give a brightness range of about 4 to 0.003 footlamberts. Within this range human visual power decreases in acuity, contrast, form perception, stereoscopic depth perception, the ability to judge size, motion and position and compensation to visual stimuli. Form and silhouette vision become more important than acuity, and mental and perceptual factors change at the lower part of this range. Changes of visual ability with age, specific factors of the eye, aniseikonia, adaptation, and general systematic factors affecting vision are summarized.

Within this illumination range eye changes from photopic (cone) to scotopic (rod) vision, which is important for estimating visual ability and the effect of colored lenses on vision. Positional and specific retinal effects and dark adaptation are considered.

New measurements are given for the effect of yellow glass, for acuity and contrast, and for night myopia obtained under conditions simulating night visibility.

Glare, or dazzle, reduces vision and the eyes should be protected from it, in so far as possible, by selective means which do not reduce the visual field, nor absorb any of the light needed for seeing.

Proper spectacles can improve vision for night driving for some people. When the light is focused exactly on the retina, the image is brighter, glare is reduced and vision is markedly improved. The best correction for after-dark seeing will usually be different from that for daylight use.

Some of the quantitative information on vision can be used in designing road markers for better visibility. After dark, vision on the highway is probably less good than it is in the laboratory and the data and criteria will have to be increased by a proper safety factor when applied to the highways used for night driving.

Visual training has improved night driving performance in the armed services and should be made a part of driving instruction and public education.

To see light, only enough intensity is required for a long enough time to stimulate the retina. To be visible as an object, it must have also sufficient contrast with its surroundings, and what is seen involves the distribution of light as an image on the retina, the sensitivity of the retina, the transformation of light energy to nerve energy, and the integration of the nerve impulses into consciousness in the brain. The spectral quality of the light and of the reflectivity of the object are important. Much is known about these processes at medium to high levels of illumination (25, 26, 38, 46, 96) and there has been considerable investigation of visual processes at very low levels of illumination (23, 42, 65, 75, 83). De Boer and Meulen (27) and Otero and Plaza (70) have summarized information at levels of night driving. Driving by civilians after dark is done with lighting between these levels and this paper will discuss and summarize some of the information pertinent to night driving.

ILLUMINATION RANGE OF NIGHT DRIVING

First must be known the amount of light available for vision while driving at night. It is obvious that it will diminish from daylight values to the very low levels found on a dark, rainy night. Considering the importance of the problem there are relatively few reports with quantitative data. A good example of usable information is Finch's (29) paper giving measurements made with fixed lighting on the East Shore Highway at Berkeley and on a 40-ft.-wide, gray concrete road as illuminated with high-beam and low-beam headlights. The luminance of the road with fixed illumination varied from 0.66 to 0.005 footlambert (ft.-L). With the upper beam the brightness of the road varied from 0.082 to 0.011 ft.-L. and with the lower beam from 0.07 to 0.02 ft.-L. A pedestrian in the outside lane 350 ft. away, dressed in a gray suit (reflectance factor, $\rho = 0.11$) had a brightness of 0.012 ft.-L. Luckiesh and Moss (59) found that highways and roads under moonlight have a brightness of 0.01 ft.-L. Bouma reports that most driving in the Netherlands is done at about 1 ft.-L.

To obtain local values, the author found that a cement section of parkway measured 0.12 ft.-L. with high and 0.2 with low beams and an asphalt section 0.16 and 0.12 ft.-L., respectively. Snow on a Stamford street gave 0.75 to 1.05 ft.-L. when illuminated by street lights of 1,300 ft.-L. brightness. Preliminary measurements are in general agreement with those of Finch and others and indicate the range of luminosity that should be examined.

Two cars were placed 200 ft. apart on the parking lot of the research laboratory on lines about 5 ft. from each other, simulating conditions on a narrow road. The luminosity of the gravelled-oiled surfaces within the beams of light varied from 3.4 to about 0.9 ft.-L. It was a cloudy dark night and the surrounding surface outside the beam was less than 0.01 ft.-L. On the black-top section, 1.2 ft.-L. were measured and the brightest region in both beams on the gravel was 6.3 ft.-L.

Holding the receiver of a Weston No. 603 foot-candle meter (with correcting filter) at the level of the driver's eyes the following amounts of light from the opposing high beam were measured.

Distance (ft.)	200	150	125	100	75	50	25
Foot-candles	0.2	0.2	0.3	0.38	0.4	0.55	0.7

Comparable measurements by Lauer (55) gave somewhat greater values to 2 ft.-L. In the beam from one car the road brightness and the brightness of a person dressed in brown ($\rho = 0.03$) were:

Distance ft.	Road ft.-L.	Person ft.-L.
25	0.34	0.48
50	0.52	0.15
75	0.08	0.03
100	0.025	0.016

This value found for ρ is less than the previously cited values of 0.11 for a gray suit, and Bouma's of 0.09 for clothing. Such low reflections must be considered in evaluating visibility on the highway.

Some of our measurements are higher than those of other investigators. The brightest values, of course, occur only in limited areas, but do contribute to the adaptation level of the eyes. The available data indicate that from 4 to about 0.003 footlamberts includes the average brightness range of night illumination available to automobile drivers. Higher levels give no concern, because seeing will then improve, but lower values will greatly increase the difficulties of seeing.

Knowing the range, we must next define the quality of the light. The 45-watt high beam of the General Electric No. 4030 sealed-beam headlight has a color temperature of 3,050 deg. Kelvin and the 35-wt. low beam is about 3,000 K. at 6.4 volts (1). For our purpose a color temperature of 3,025 K. may be taken as an average value to represent lighting from the automobile itself. In practice this will change with voltage variation. Because of the differential sensitivity of the eye, the color quality of the light must be known for proper experimentation and computation. More information is needed on the quality of road illumination.

Viewing motion pictures is a closely related problem and useful data gathered by their committees should be utilized. The problems of measuring motion-picture-screen brightness and highway brightness have much in common and meet at the outdoor drive-in theater (2).

Comparisons with other conditions of life are not easy. A room with the sun streaming in is bright and pleasant and part of it may be at several hundred footlamberts. At night with good illumination it also appears pleasantly bright; even when the brightness of walls may have only 7 to 10 ft.-L. The reason that both seem bright is due to the adaptability of our eyes. Toward the end of the day workers tend to turn on lights when the natural illumination reaches about 4 ft.-c. (92). For comfortable vision with small details, or with poor contrast, 20 to 100 ft.-c. are recommended by IES (46). White paper reflects about 80 percent, and newsprint 65 percent. Dark cloth may have a reflection of 4 percent, hence the above lighting would yield 4 ft.-L. when the 100 ft.-c. illuminates it. Yet we must see small objects of poor contrast when driving at night that may have a brightness of 0.01 ft.-L. This would be impossible were it not for the unique ability of vision to adapt over a large range of intensities. Seeing at night involves a good many abilities and limitations, some of which will be considered.

DARK ADAPTATION

The outstanding property of the eye is its great ability to adjust its sensitivity in accordance with the light reaching it. This adaptation may be measured as the least brightness perceptible. In the dark, adaptation occurs rapidly for a few minutes and then slowly for well over a half hour, indicating that two processes are involved.

The retina includes two kinds of light sensitive elements, the rods and the cones. Cones alone are concentrated at the optical center of the retina, the thinner fovea, and become less numerous toward the periphery of the retina. Rods are absent at the fovea and become more numerous toward the periphery. Color and best detail vision is mediated by the cones, and is absent at the outside of the visual field on the retina. Rod vision is more sensitive to low illumination. Foveal cones have single direct nerve connections; peripheral cones and rods have grouped connections. Vision is determined both by the composition of the area of the retina involved and the special properties of the light-sensitive elements.

Above a brightness of about 0.01 ft.-L., vision is mediated by cones and involves color. At high intensities the rods probably do not function, or may be inhibited by the cones. The lower level of cone vision is about 0.001 to 0.0001 ft.-L. Below this only rod vision occurs. The mesoptic region, involving both rods and cones, includes from about 1 to 0.001 ft.-L. For night driving we use mesoptic and photopic vision and are concerned with both systems at the critical change-over region.

Since human eyes vary in their sensitivity, it has been necessary to establish an average curve, called a standard observer, for use in problems of vision. At high intensities (more than 5 ft.-L.) the curve represents the cones and maximum sensitivity is found with yellow green light of 555 $m\mu$ wave-length, (Figure 1). At low intensities (0.001 ft.-L. or less) the curve for rod vision has a maximum near 507 $m\mu$ in the blue-green. Vision at the higher levels is called photopic and at lower levels scotopic. Over the interval that both rods and cones are involved, vision is called mesoptic. Between these brightnesses the curves for the sensitivity of the eye are intermediate. The gradual shift in the color sensitivity of the eye toward the blue is called the Purkinje effect. As the light intensity decreases reds appear darker and blues become brighter. At very low illumination color is not seen, merely lighter or darker grays. The curves of Figure 1 may be considered as the apparent brightness of equal amounts of light for the various colors.

Illumination usually does not provide equal amounts of energy for

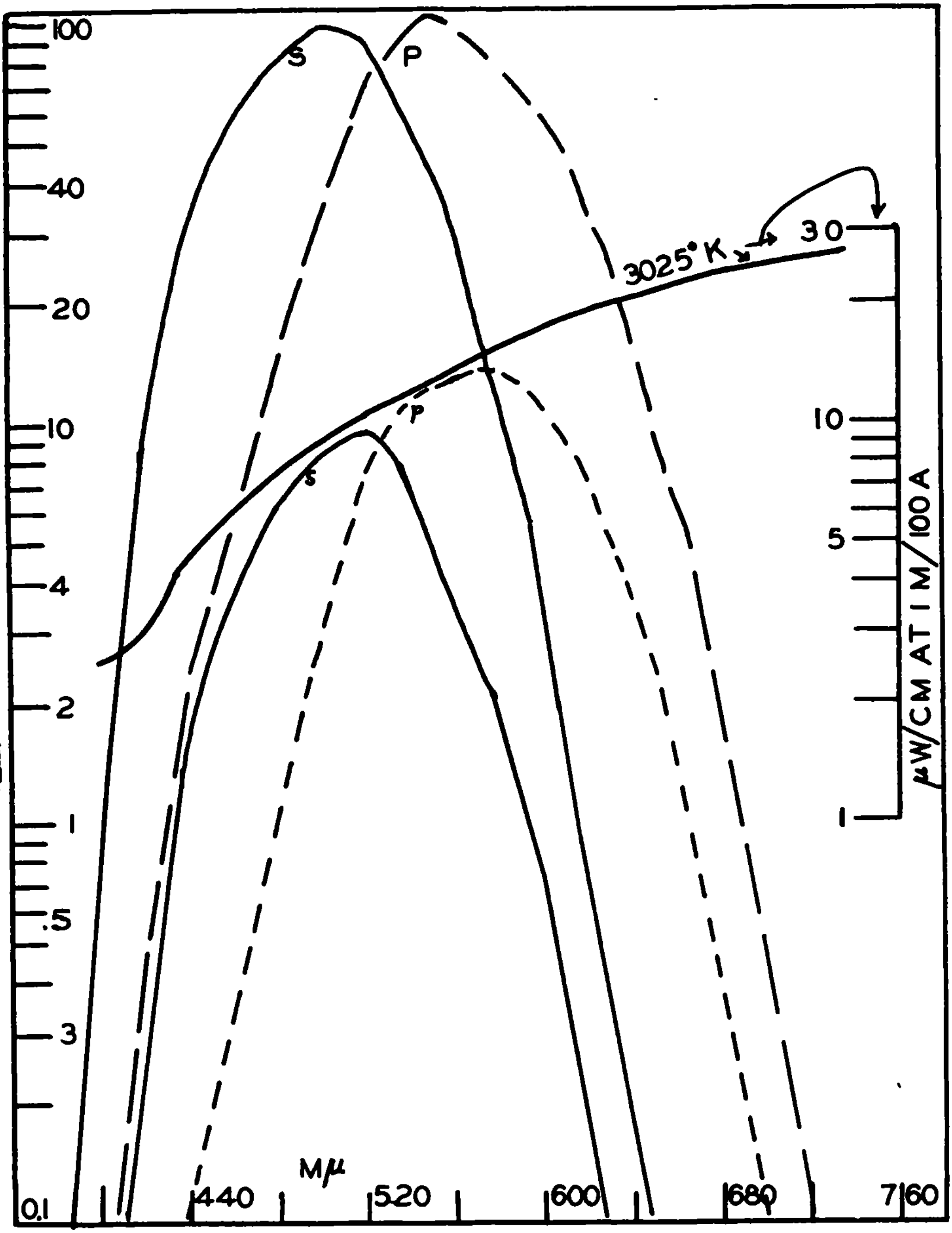

Figure 1. Relative photopic (P) and scotopic (S) visibility curves and their modification (p, s) by 3,025-K. light.

the different colors, e.g., tungsten light is yellower and redder than daylight. The energy distribution curve for tungsten at 3,025-K., representing automobile lighting, was obtained by interpolation from the data of Forsyth and Adams (31). The available energies were multiplied by the corresponding values of the standard observer to obtain the sensitivity curve of the eye with 3,025-K. automobile headlighting. By use of Weaver's tables (90) the sensitivity curves were obtained for the other lumination levels shown in Figure 2.

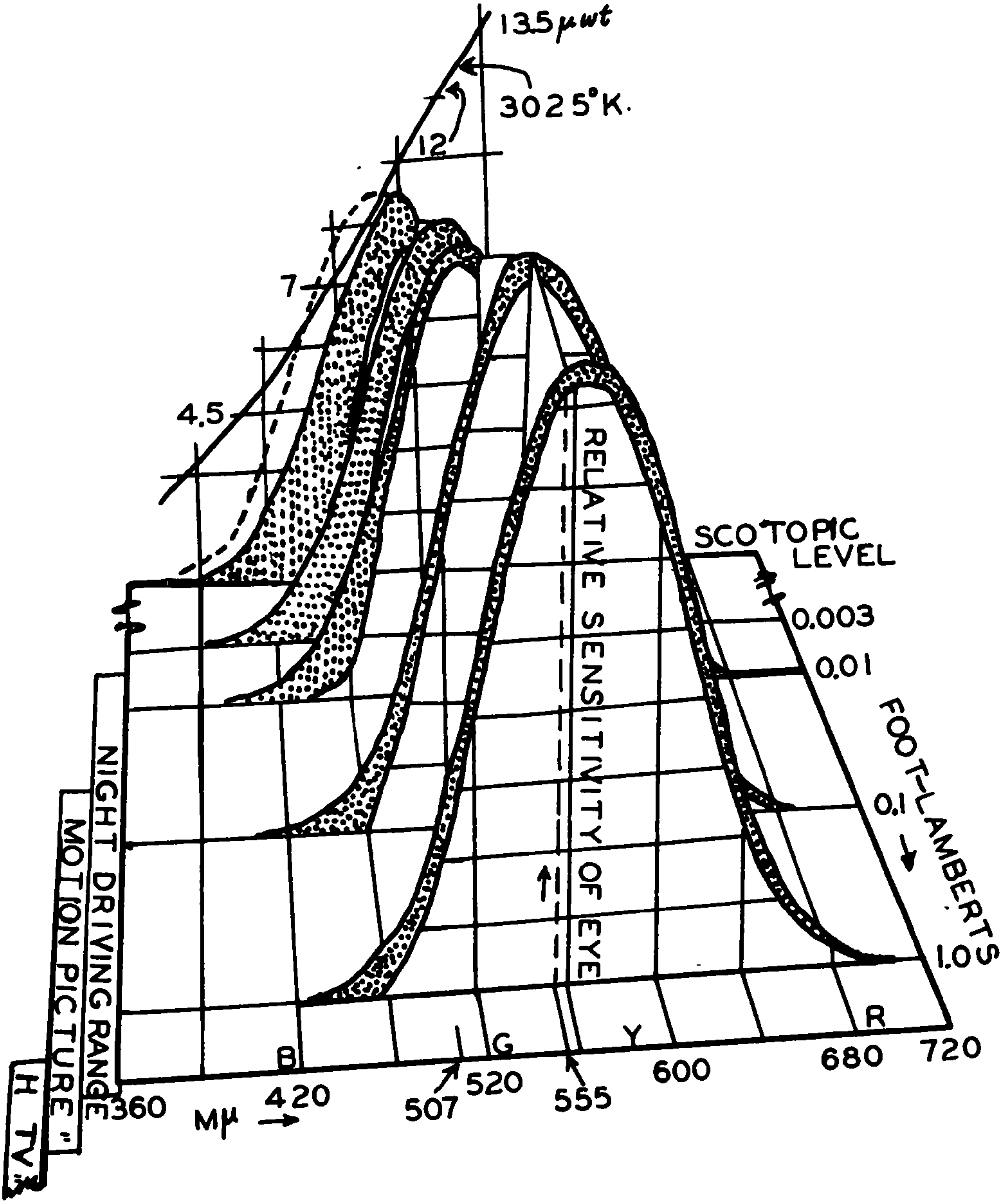

Figure 2. Shift of relative sensitivity of the eye toward blue as illumination decreases and the loss (shaded areas) from Noviol C yellow glass.

The greater amount of longer-wave-length light from tungsten flattens the photopic curve and shifts the sensitivity slightly toward the red. The Purkinje effect is shown by the shift of the maximum sensitivities toward the blue as well as the decrease in visual effectivenss of the light (decreasing area of the curves). Such curves are basic for the examination of many problems of vision. Taking the area under the eye sensitivity curve for 1 ft.-L. as 100, at 0.1 ft.-L. the area is 98 percent, at 0.01 it is 77 percent and at 0.003 ft.-L. it has decreased to 73 percent. The last curve on the model shows only 64 percent for the scotopic standard observer. The lessened sensitivity of the eye reduces the visual effectiveness of the available energy as well as shifting the color sensitivity of the eye.

COLORED GLASSES AND VISION

The model (Figure 2) is helpful for appraising the effects of colored glasses on vision. By multiplying the standard curves by the transmittance for a given filter, and plotting the resulting curve, the relative decrease may be demonstrated. This shows the futility of making comparisons unless the results are based on the radiation distribution being used. The average energy values for noon sunlight (5,400-K.) would have given different curves.

For example, the effect of a yellow glass will be considered. Multiplying the curves of Figure 2 by the transmittance curve of yellow Noviol C, reduces each by the amount indicated by shading on the curves of the model. (In anticipation of this application the standard curves had been reduced for the losses from the two surfaces of the glass to provide comparable data.) Examining the areas under the curves as indicative of overall vision predicts a 6 percent loss at 1 ft.-L.,10 percent at 0.1, 15 percent at 0.001, and about 20 percent at 0.003 ft.-L. Similar computations could be made for any other color. All colored glasses selectively absorb more or less light and the amount vision is affected depends on the radiant energy available, the overall transmission, the color transmitted, and the Purkinje shift. How much loss of vision may be tolerated in night driving remains to be decided.

The sensitivity curve for the eyes of an individual may be different than the average taken for the reference curves and may depart considerably when color deficiency or color blindness is present and such curves illustrate the nature of visual aberrations (94, 96). The standard curves are useful for general appraisal, but for an individual only the individual curve should be used.

Two questions are of interest with respect to the use of a yellow glass for night driving: (1) what is the effect of the yellowness itself, and (2) what difference occurs between wearing yellow glasses and no glasses. These can be investigated using either light from automobile headlights or light adjusted to the same energy distribution with proper color temperature adjusting filters. Such a projector was used in my laboratory to illuminate an acuity test chart (American Optical Company's No. 1930) and a Luckiesh-Moss, calibrated contrast chart (General Electric Company). After a preliminary check with room illumination at 10 ft.-L. for any unusual visual inability, observations were made at 20 ft. distance with 1, 0.1- and 0.01-ft.-L. chart background brightness. Viewing conditions were comparable to driving in that the charts and their surroundings were lighted and the illumination fell off from this region in all directions. Observers wearing spectacles for night driving used them in the tests, otherwise no glasses were worn.

Acuity and contrast were measured at each level of illumination with the Noviol C yellow glasses, without them, and without them at an intensity reduced by 15 percent with a neutral filter, to match the 15 percent overall absorption for the yellow. Comparing the results with the yellow glasses and without them at the same visual intensity of lighting gave the answer to the question as to the effect of yellowness. The other comparison showed the gain or loss between wearing yellow glasses and not wearing them.

The data for the first 30 individuals tested (ages 16 to 56) are shown in Figure 3. For yellowness (yellow versus direct light less 15 percent) we find few gains, more loss and most observers showing no significant differences (greater than ± 3 units) for both acuity and contrast tests. At the lower intensities the loss of visual power was greater. The actual test results support the predictions from the knowledge of vision as expressed in the model of Figure 2.

A large number of the observers could see no better or worse under these conditions with yellow than without yellow glasses. There were more showing less good vision than better vision with yellow. The individuals which gain with yellow may have personal deficiencies in color vision, or a strong liking for yellow, and will be tested further. The comparison of wearing yellow glasses against not wearing glasses demonstrated a much greater loss of acuity and contrast vision from the yellow glasses and the details of this investigation will be reported on its completion. (See also Sections 4 and 7).

Colors affect people differently and these psychological factors must also be considered in night driving evaluation (8). For some, yellow glasses brighten the world, give a sense of euphoria, and they may believe that they are seeing better, even when the test scores show the opposite. Other people cannot tolerate yellow. Roper (3) states that yellow becomes increasingly uncomfortable for some people once the car is in motion. Does the favorable effect of yellow on some extroverts make for more alert, better driving, or does this effect lead to overconfidence and a tendency to take chances? Examination of accident records might provide an answer.

Haus and Cole (44) in a preliminary paper suggest a gain from yellow night glasses in reduced glare, increased comfort and confidence, and reduced fatigue. They used a yellow that transmitted ".1 percent more yellow than ophthalmic crown." Since the transmittance of ophthalmic crown for yellow is limited only by the surface losses, it is difficult to understand their statement unless they used a coating to increase the transmission. Their values of 580 mμ for optimum photopic and 530 mμ for scotopic vision are much higher than generally accepted, and it is believed unlikely that their yellow evades the Purkinje shift as they suggest. It is to be hoped that these discrepancies will be clarified when they present their detailed report.

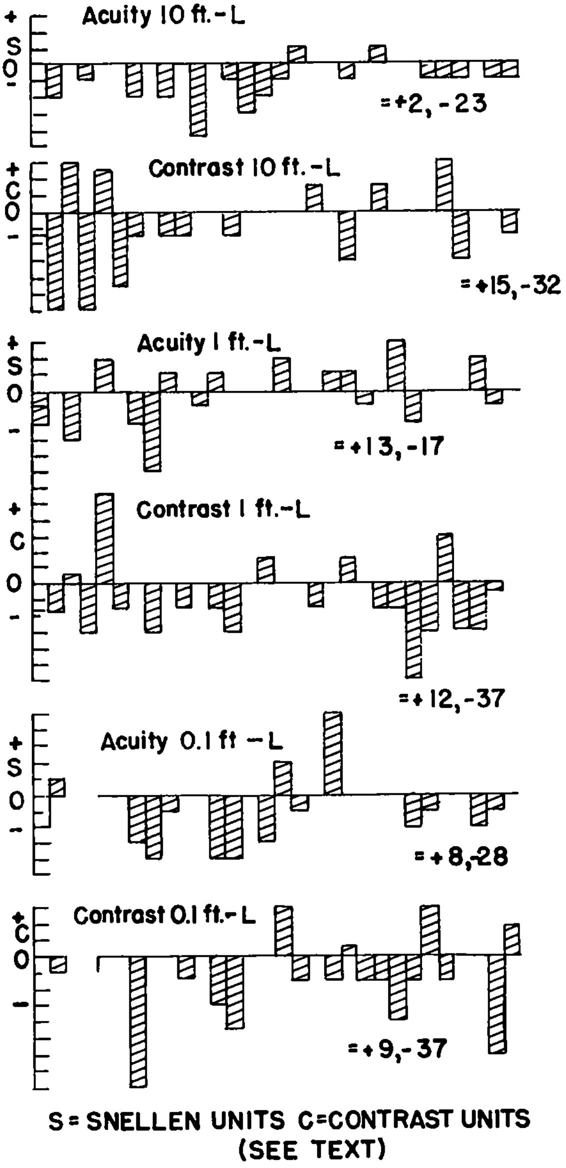

Figure 3. Effect of yellow on the ability to see contrast and detail at different brightness.

Other arguments have been presented in favor of yellow night-driving glasses. Yellow, by absorbing the blue light, is said to reduce the chromatic aberration of the eye, compensate for some of the night myopia, and lessen the effect of haze. Haze scatters light, especially the shorter-wave-length light, but in daylight outdoor tests yellow and other colored glasses have not been found helpful (64A, 87A). Haze and opacities within the eye decrease vision and are especially bad in scattering light as with glare from opposing headlights. Tests with such pathological conditions should be made. Since the eye, in contrast to the photographic plate, is less sensitive to blue, violet, and the long-wave-length ultraviolet, one should not expect a similar gain from a haze filter.

With low illumination, color becomes less important and a corresponding reduction of chromatic aberration may occur. Correcting the chromatic aberration at high intensities has not given greatly improved vision. The eye apparently compensates for these differences, and with considerable limits, to others that may be added, according to Hartridge (38). Changes in apparent brightness with decreased intensity of lighting reported by Bouma (13) for sodium-yellow-lighted roads, fails also to support such a theory as it is a monochromatic light for which there would be no color aberration. Although elsewhere (12A) he states that blue light contributes more to glare and that yellow light is less glaring.

Should yellow compensate for part of the night myopia, less correction should be required and visibility would be correspondingly better at lower levels. The first 30 individuals of the test series reported here gave no evidence to support this premise. Until adequate evidence is forthcoming to support these theories, there seems to be scant use for citing them as possibly favoring yellow vision.

With the exception of such general statements, the author has been unable to find any proof of gain in night vision for any large number of people from yellow glasses. Since such a gain would be contrary to much known visual experience, any proof must be supported by careful, critical experiments. On the other hand, experiments by Lauer (52, 53) and other investigators reveal a loss in vision when colored glasses are worn at the illumination levels of night automobile driving.

ACUITY AND CONTRAST

Other aspects of vision at levels found during night driving are summarized in Figure 4. The amount of increase in brightness to be noticeably brighter (Δ B/B) is a constant over considerable range until the intensity is lowered to about 1 ft.-L., Figure 4A. For lower brightnesses, the Weber fraction (Δ I/I) and the Weber-Fechner law no longer apply and discussions involving them are apt to lead to confusion. The progressively increasing brightness is different for white and colored lights. At the lower levels the illumination has to be considerably increased to appear brighter, and this is another measure of the difficulty of seeing at these levels.

While acuity is sometimes used to summarize the many aspects of vision (51), the physiologist restricts it to the ability to see the least visible, the least separable (resolution), or the least legible. Different tests are necessary and the results obtained depend on the test, the procedure, and the criterion used. Figure 4(c) gives the curve obtained by Lythgoe (61) for acuity as measured by the ability to see the gap in a Landolt C using an end point of 4.5 correct answers in each 8 answers for each test. The reciprocal of angle subtended at the eye by the gap is plotted. Earlier acuity measurements of König are included also. To be seen equally well at 0.01 ft.-L. a test object of high contrast must be about four times larger than it needs to be at 3 ft.-L.

Luckiesh and Moss (59) tested a group of people at 10 and at 0.01 ft.-L. Of 150, they found 117 to have 20/20 vision at 10 ft.-L., but at 0.01 ft.-L. the highest was 20/38 for only 11 individuals, and the median value was about 20/55 for the low contrast test chart used. Lauer, et al (54) demonstrated that some high-contrast test charts are more legible than other charts.

Contrast is the difference in brightness between a specimen and its surroundings. It is expressed numerically as the difference in brightness of background and specimen divided by the brightness of the background, and is often converted into percent, (See Figure 4(c)). The lower the brightness, the greater must be the contrast of the test object for it to be visible. Over the night driving range shown, contrast must be increased from 6 to 20 times to remain visible, depending on the background being lighter or darker than the object. When the contrast is too low, a pedestrian or other obstacle cannot be seen. Unless the contrast of a marker is adequate for its size, it may not be legible long enough to be read by the motorist. Recommendations made for the contrast concerning motion pictures (35, 56) are suggestive for road lighting. Blackwell (11) has published contrast lumens for a test object subtending 24 minutes of arc at four levels of illumination. Information units gathered by the eye also decrease in a comparable manner at corresponding lighting levels (47).

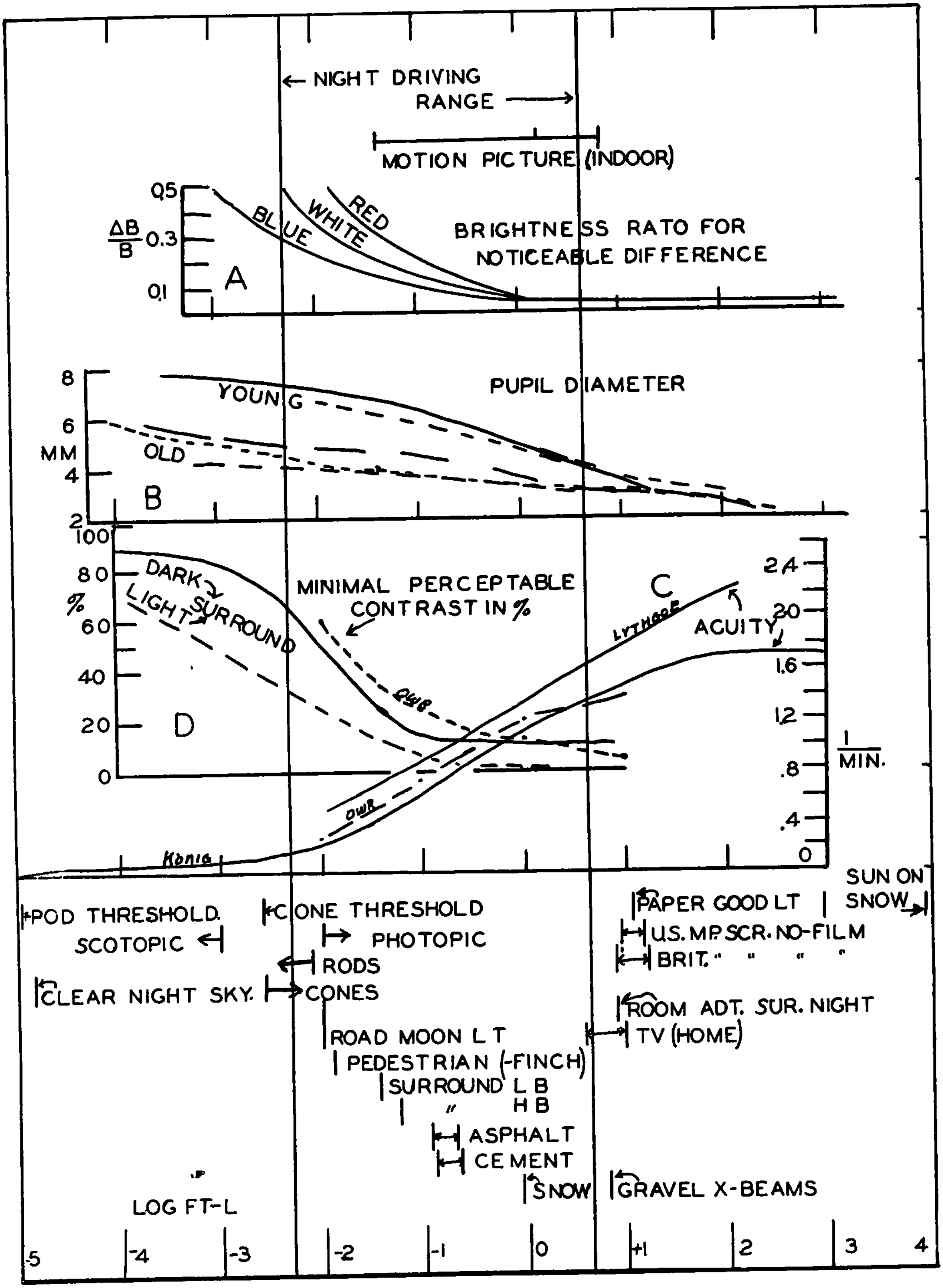

Figure 4. Night-road-illumination values and some aspects of human vision with decreased illumination. Limits of photopic and scotopic vision are located as reported in the literature; although they are actually regions of transition.

Using the equipment that was described briefly above, measurements were made of 30 individuals for acuity on the letter test chart and for contrast with the contrast chart. Taking the averages, gave an acuity (Snellen nomenclature) of 20/15 at 10 ft.-L., 20/18 at 1 ft.-L., 20/29 at 0.1, and 20/84 at 0.01 ft.-L.,which correspond to acuity values of 0.8, 0.9, 1.5, and 4.2 minutes arc subtends. This series has an excess of slightly far-sighted observers and as those needing glasses were well corrected, the average is somewhat better than the usual normal. The minimum contrast seen on the Luckiesh-Moss calibrated contrast chart for the same illumination levels were, respectively, 4.8, 11.3, 25, and 60 percent. The data were obtained in my laboratory under illumination conditions comparable to automobile headlighting, Figure 4, and are consistent with the other curves in emphasizing how vision decreases as the illumination and brightness decrease even over the illumination range of night driving. An increase 5 times in the size and a 12 times increase in contrast is indicated to obtain the same visibility for markers at 0.01 ft.-L. as at 10 ft.-L. When glare is also involved these values may be still greater.

At low intensities the area of the test object affects its visibility as shown by Hanes (37), and Casperson (22). Hoppe and Lauer (45) are measuring this factor with respect to the visibility of autos on a highway. There is evidence that there may be a critical level around 0.02 to 0.05 ft.-L. for visual performances involving more than a yes-or-no response according to Rock (77), and Spragg (87). Seeing at night on a highway depends mainly on silhouette seeing (27, 78), therefore contrast and area become more important than acuity. The visibility with sodium- and mercury-arc lighting of highways has been discussed in terms of contrast and color contrast by Bouma (13, 14).

Both contrast and acuity have been shown to change with the illumination and the measurements can be plotted on three-dimensional figures to give a more complete picture (32, 60). Weston's (91) equation for illumination and contrast might be another point of departure. Older people require more light and even with maximum illumination do not see as well as younger ones (92A). Such information on average visibility can form a basis for design of signs and protective markers, but cannot be used directly as vision is probably less good at night on the road than it is in the laboratory. Some of the differences have been discussed by Bouma, Lauer, and Roper. Appropriate safety factors should be obtained and used. In the meantime Finch's (29) multiplying factors seem reasonable.

SPEED OF VISION

In addition to sufficient light and contrast, the image must last on the retina long enough to initiate nerve action, otherwise vision will not occur. The lower the illumination the longer the light stimulus must act to be effective. The highway marker may not be seen long enough to be understood. Roper and Howard (78) report a loss of 20 ft. in distance vision for an increase of 10 mph. Time factors are important and become more so as the intensity of illumination decreases. The ability to judge motion decreases 66 percent to 75 percent (Hodel-Boos, (40).

A short flash may raise slightly the sensitivity of the entire retina. A second image falling onto the retinal elements during the refractory period after a previous stimulus will not be registered. After-images have a regular time series and a pedestrian cannot be seen when his image occurs on the same region of the retina that has an after-image from a bright sign or has been strongly stimulated by a glaring headlight. A brief summary of these relations can be found in Davson (26). Older drivers see and react less rapidly than younger ones. The threshold for movement discrimination increases logarithmically as illumination decreases linearly.

Less is known about the effect of time at the levels under consideration and this should be a good field for investigation. Either markers should be simple, large, with high contrast and good brightness for parkways permitting fast night driving, or driving rates should be scaled down to within the abilities of the driver.

SPECIFIC FACTORS - THE EYE

External eye. Muscle coordination should be good and the best possible correction for phorias should be given to the person requiring spectacles for night driving. Astigmatism becomes much more important when illumination is less as the distorted retinal image is more difficult to interpret. A cylinder of 0.25 D in the correct axis may improve vision from 6/8 to 6/6 or 25 percent according to Hamburger (36). Convergence is not as well stimulated by dim illumination and stereoscopic vision might well be studied at night-driving levels of illumination, since relative motion, position, and distance judgments are of importance when passing.

When the eyes are blinked, vision is not possible for the 0.3 sec. the eyes are closed and is impaired for part of the closing and opening periods for an average blackout period of about 0.55 sec. (38). The time between blinks averages 2.8 sec. for men and 3.8 for women. Other blink types with longer interblink periods are known and much individual variation is found. The loss of vision in such a blackout period could cover some 60 ft. of travel at 40 mph. to 90 ft. at 60 mph. Should the blink come at a critical time, and blinking cannot be delayed indefinitely, it might cause an accident.

With fatigue, blinking increases and more vision time is lost. Luckiesh earlier suggested that the blink rate might be measure of fatigue, but a quotation by Hausner (39) implies that it may be more of an indication of tenseness or strain.

Internal eye. Changes in the interocular pressure interfere with vision and certain diseases may disqualify a person from night driving. Changes in the absorption and transparency of the components of the eye may reduce night vision proportionally more than day vision.

Age changes in accommodation are important both in focusing and in a diminished reserve, (Figure 5). Duran (28) has demonstrated a decrease in accommodation range with decreased illumination with the midpoints becoming more and more minus until at very low intensities the focusing mechanism fails, leaving the lens focused at about 32 in. according to Otero and his colleagues. There is some question to the exactness of this

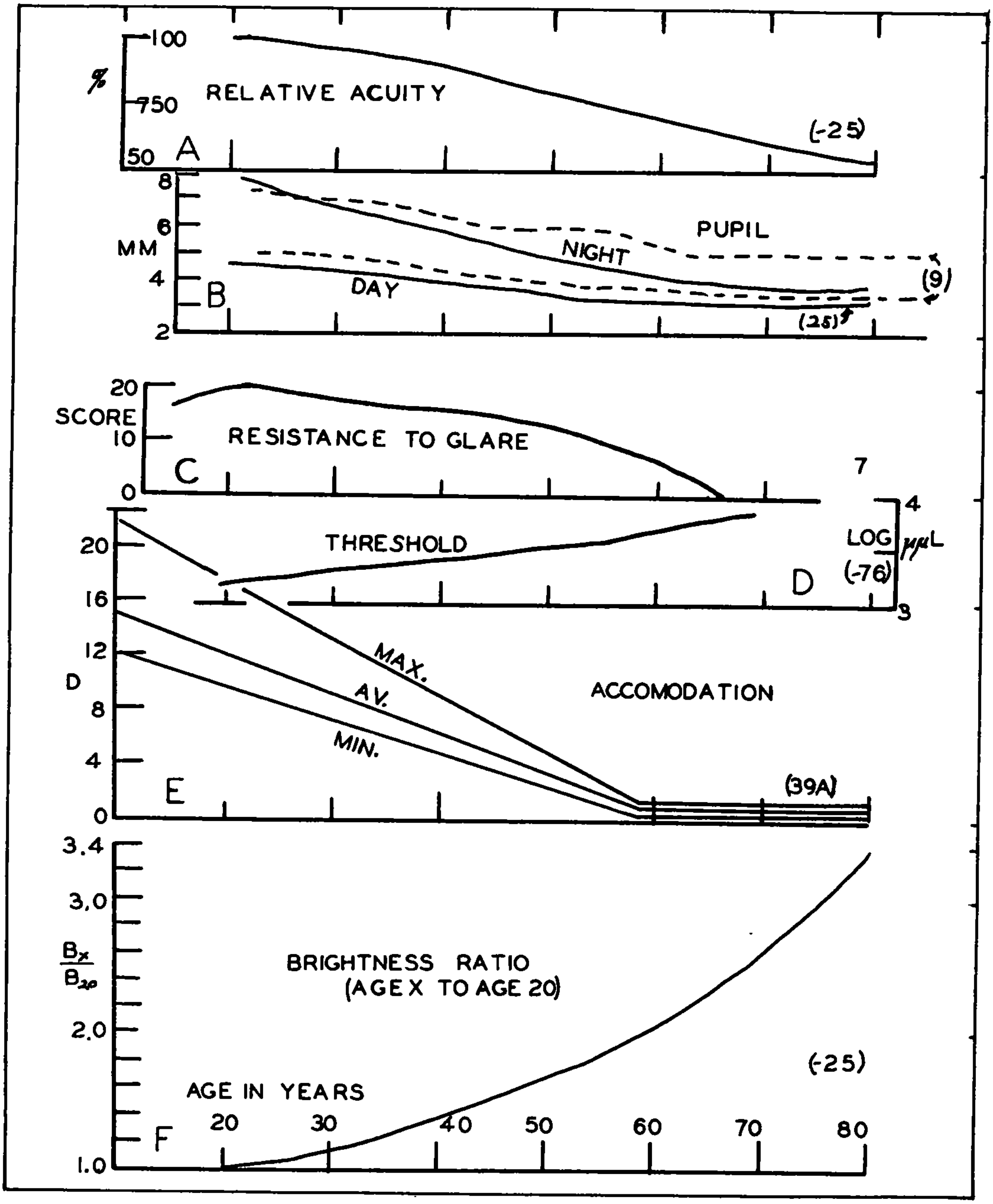

Figure 5. Changes in human vision with age.

conclusion (49), although it is incorporated into the 1950 recommendation of the International Commission of Optics (J.O.S.A. 40:881). This decrease of accommodation may be the source of a considerable part of night myopia.

The pupil diameter increases, as the light intensity decreases, (Figure 5), but the increased diameter becomes progressively less with advancing age. Measurements by Birren (9) show that the pupils of older eyes contract relatively as much as pupils of younger eyes. Some recent study suggests that the pupil does not increase continuously but shows a fast maximum of 5.5 mm at 3.0 to 0.3 ft.-L., a second of about 4.5 mm at 0.5 to 0.03 ft.-L. and then a gradual increase to 8 mm (69). The time relations of these changes as seen on Cabello's (20) curves are of importance in nocturnal vision. The combined effect accounts for the increase in the threshold of vision with age, according to Robertson and Yudkin (76). More illumination is necessary with older eyes to give a just noticeable difference for brightness at a given age to brightness at age 20. Retinal and other changes must be involved as the retinal illumination control by the decreasing pupil expansion does not explain the decreased resistance to glare found in older ages. The increase of the pupil diameter allows more of the edge of the lens to be used and increases spherical aberration; but Otero and others do not believe the small increase (± 0.3 D) in spherical aberration to be very important in night vision. However, the writer believes that it might be more important in naked-eye than in instrumental vision, as it is a cause of unsharp retinal image, equivalent to an appreciable loss of image intensity. Chromatic aberration of the lens is also involved.

Local retinal effects. Vision is partially controlled by the form, the chemical and physical organization, and function of the retina. These factors must be kept in mind in evaluating specific seeing tasks and will now be considered briefly.

Recovery of rods and cones involves bodily metabolism and the greater the bleaching from intense stimulation, the slower will be the recovery. The rods recover more slowly than the cones, which may be one reason for the suppression of rod vision at higher intensities.

Adjacent regions of the retina do affect each other. Juxtaposed surfaces may increase or decrease the apparent contrast of each other, both in color and in brightness from simultaneous contrast. Likewise, areas of equal size, white-and-black-checker pattern, will not appear equal, especially as illumination is decreased due to induction and radiation effects (97). Intense glare may desensitize some of the nearby retina.

Spatial summation depends on how the retinal elements are grouped and interconnected. The rods are connected to the nerve cells in varying-sized patterns and numbers. Thus large fields are prejudicial to acuity, but favor threshold sensitivity and this may explain some of the area effects observed at low brightnesses.

The sensitivity of the retina is highest in the fovea and least at the periphery. Vignetting lessens efficiency for areas beyond about 20 deg. from the fovea. At the night-driving range these factors become important and must be considered. With a one-eyed person a small object may be imaged on the blind spot and not perceived. Objects seen with one eye appear about 60 percent as bright as when seen with two eyes (74). Tests for night vision are discussed by Holmes (42A).

Dark-Adaptation Modifiers. Exposure to sunlight decreases the ability for dark adaptation and Clark et al (24) reported that eyes exposed to strong sunlight, as at a beach, required 90 min. longer to reach the same level of dark adaptation as eyes not so exposed. Protection from sunlight during the day with proper sunglasses improves night vision (98).

Smoking also decreases the ability to dark adapt, presumably from the carbon monoxide rather than from the nicotine content of the smoke, although the evidence is conflicting (63, 84). Lowered oxygen pressure as at altitudes of 8,000 feet or more decrease night vision.

Caffeine, metrazole, strychnine, ephedrin, octin, excessive Vitamin A, muscular exercise, ultrasonic vibrations and stimulation of taste failed to impair or improve night visibility (80). Benzedrine, breathing increased oxygen, or breathing more rapidly and deeply, aid dark adaptation. The lack of drug effects led Mandelbaum (64) to conclude that no central nervous function was involved. Moderate consumption of alcohol can raise the threshold 0.3 log unit, but the gain is offset by the adverse effect of alcohol on judgment and motor response.

Dark adaptation is reduced by a deficiency of Vitamin A, a chemical used in the retina as part of the visual process (30). A deficiency of Vitamin A may be due to: lack of the vitamin or the provitamin in the diet, diseases preventing absorption in the intestine (diarrhea), resulting in a decrease of biliary or liver secretion, of the liver preventing storage or conversion, the capillaries of the chorioid, pigmented epithelium, bacillary layer of the retina, causing high usage of Vitamin A such as fevers and hyperthyroidism, increased basal metabolic rate, chronic alcoholism, or from rapid growth or pregnancy. Stern (87) estimates that two thirds of the Americans in low-income groups are deficient in Vitamin A. Miners have a condition of raised threshold or impaired dark adaptation that Campbell and Jenks (21) could not relate to their nutrition. Deficient rod adaptation is a probable explanation for hereditary night blindness. Fletcher (30) mentions a series where it was traced for ten generations.

Exposure to the ultraviolet from a fluorescent lamp delays the shift to rod vision several minutes and prevents the dark adaptation to reach as low a level of sensitivity by about 0.3 log units as shown in Boeder's summary of Wolf's work (10B, 93). The delay suggests a longer wait outdoors in the dark before driving when one has been exposed to long-wave ultraviolet. To what extent the change in adaptation level affects vision at night-driving levels must be investigated. Tungsten does give off a small amount of ultraviolet radiation at 3,000 K. Windshields are transparent to this radiation (about 75 percent at 365 mμ) as measured by R. D. Hudson. The amount of radiation may be too little to affect night driving, except when the glare is nearly continuous as on roads with nearly constant opposing traffic.

NIGHT MYOPIA

That the eye becomes near-sighted in dim light has been known for about 70 years. Little investigation occurred before World War II, which was followed by considerable literature that has been summarized by Koomen (49) and others (6, 70). The myopia found has ranged from 0.4 to 4 diopters, depending on the illumination levels and methods used.

Two main theories have evolved: Otero and his colleagues attributing part of the effect to spherical aberration (0.25 D), part to chromatic aberration and the rest to decreasing involuntary accommodation; while Koomen's group account for night myopia by the uncorrected spherical and chromatic aberrations of the eye. There is considerable disagreement and more work will be required for a final answer as to its cause.

According to Cabello (20) night myopia increases rapidly for the first 5 minutes to about 1¼ D., remains fairly stationary for 5 minutes and then increases slowly to reach final equilibrium in about 20 minutes.

When night myopia is corrected, both Otero and Salaverri (71) and Wald and Griffin (89) point out that the same degree of vision could be obtained with half the light because of the greater sharpness and efficiency of an infocus image.

Byrnes (19) stated that: "This 'night myopia' does not apply above rod levels of illumination. For this reason the suggestion sometimes made that spectacles for night driving be made 0.5 diopter more minus than the regular distance correction is not justified. The 'night myopia' only occurs in average persons while rod vision is being used when the light is below the level of moonlight."

Schoen (82) demonstrated night myopia by skiascopy and found that at lower illuminations the image was in the vitreous in front of the retina, thus adding objective support for night myopia. He found -0.5 D at 0.01 ft.-L. and -1.62 at 0.0001 ft.-L.

Pratt and Dimmick (73) have analyzed and published Bruger's work on 558 young naval students. The data are grouped by the amount of refraction necessary to give normal vision. They found the eye more myopic at lower levels of lighting and that acuity decreased from 1.0 at 2 ft.-c. to 0.12 at 0.0027 ft.-c., for the group farsighted to the extent of +0.75 at the higher intensity. Daylight acuity tests are adequate for screening the poor night vision group according to him.

Hamburger (36) reported no correlation between night myopia and high myopia at daylight levels of illumination. The increase of night myopia with some very near-sighted people may be related to poorer function of the cones, less active accommodation and possibly a less active pupil function.

Sasian (81) found that a simple hyperopia of +1.8 to +2.0 will neutralize a night myopia of -2 D, but that other types of hyperopia will not do so.

A study is under way in my laboratory to determine the extent and effect of night myopia. Parts of the associated preliminary work on acuity, contrast and yellow have been considered in this paper previously. Using a modified phoropter, the lens additions needed to give best vision were determined subjectively. The differences between the acuity and contrast scores with and without the additional power correction measure the night myopia. The average acuity and contrast were 20/18 at 1 ft.-L. and 11.3 percent. Correcting to best vision with additional minus lenses gave a respectively 20/15 and 8.8 percent. At 0.1 ft.-L. the corresponding values were 20/29 and 25.4 percent, correctable to 20/26 and 20 percent. At 0.01 ft.-L. correction improved acuity from 20/84 to 20/70 and contrast from 60 to 40 percent.

The results indicate that significant improvement in vision may be obtained with additional power corrections of from -0.25 to -1.75 D. Some far sighted people (+0.5 D) without astigmatism see better at night without their spectacles. Loss of any astigmatism correction, however, may be greater than the gain from night myopia and such correction spectacles should not be removed.

Some near-sighted people have greater night myopia, because they lack this plus reserve and may be undercorrected as well, even at daylight levels. Properly determined night glasses (no color) have improved the after-dark driving ability of individuals. The results given are only averages and uncorrected for age effects. As soon as sufficient data are available, a detailed analysis and recommendations will be published. The preliminary results suggest that vision after dark for certain drivers may be markedly improved and that should make for better driving on the highways.

ANISEIKONIA

Binocular vision is impaired for some people because the images have different size and do not fuse to give normal space impressions. The general complex of symptoms: headaches, car sickness, photophobia, blurring of vision and incorrect spatial localization, increases fatigue and lowers efficiency. The specific visual difficulties make driving through narrow spaces, such as narrow roads, garage doors, and traffic jams very difficult and hazardous. Continued scraping of fenders may be due to this kind of faulty vision. Measurement and the proper glasses are known to improve driving ability in close quarters. Aniseikonia may be a greater handicap after dark and it should be investigated as part of the study of people having repeated accidents. Boeder (10A) has described the space problems and their measurement for this abnormality of vision.

GENERAL FACTORS - SYSTEMATIC

Sex. No improtant differences have been discovered in night vision between men and women.

Individual variation. Average day-to-day variation in adaptation levels amounts to 0.2 log units for cone and 0.3 for rod vision. In a healthy individual the variation may be somewhat less; between individuals somewhat more. Lythgoe (61) has discussed variation in visual acuity and precautions necessary for its control.

Diseases have pronounced effects on vision. Some diseases of the eye such as glaucoma, changes in the retina, or detachment of it may decrease vision until blindness occurs. Deficiencies of Vitamin A, riboflavin, thiamine and possibly others diminish vision. Diseases known to affect vision are: urinary calculus, cirrhosis of the liver, and diabetes. Pregnancy causes temporary changes in the retina.

Seasonal. Vision is better in October and poorer in January.

Age. Senescence is a gradual deterioration that starts shortly after fertilization and involves the eyes as well as other parts of our bodies. Some of the more pertinent changes are shown in Figure 5. Accommodation, pupil size, resistance to glare, all decrease the threshold at minimum level increases, and it takes a proportionately greater increase in illumination to give a just noticeable increase in sensation. A pedestrian barely visible to a young eye cannot be seen by an old person. This is an important consideration in evaluating any spectacles of colored glass which would decrease the amount of light to the eye. The transparent media in the eye, especially the lens and vitreous, tend to increase in absorption and may become partially or wholly opaque. Thus any screening program must be capable of discovering such changes. The average curves of Figure 5 must not be used for an individual as some persons have younger eyes in older bodies or vice versa. Proper tolerance ranges will have to be established.

Fatigue. Fatigue occurs with decreased, flickering, unsteady, or varying light. The pulse rate may slow so that less oxygen and nutrients reach the visual mechanism. The blink rate increases giving more blackout periods. Using more than half the accommodation reserve increases fatigue which may be a factor for the older driver whose accommodation is below the needs of the road with night illumination. General bodily fatigue also decreases vision. At night there is little to see other than the small part in the headlight beam. A small region of the retina is used continuously as there is little stimulus to look away and rest the eyes. Also there is less tendency to change bodily position. These may lead to so-called self-hypnosis and loss of consciousness thought to be a factor in single car accidents. Checking the instruments on the dashboard is more difficult than with day illumination and gives added fatigue to the uncorrected presbyope.

Human engineering is concerned with "skill fatigue" with reference to airplanes and MacFarland's (62) summary could cover auto driving as well. The onset of skill fatigue shows: (1) inaccurate timing of control movements, (2) a tendency to require larger changes in stimuli to initiate action and (3) a lessening of the normal span of anticipation. There is an increasing awareness of bodily sensation,hyper-reactivity to machine and people, and small items begin to dominate and prevent reaction to a pattern. The tired night driver thus needs increased stimuli or more light in order to see equally well and a longer warning period before he is required to act (stop, turn, etc.). Since it is not possible to do all this for the tired driver—it should not be surprising that accidents increase. Night warning signs should be placed further from the reference and, if possible, brighter as increasing size beyond an optimum has not been found to increase visibility.

Possibly the only night-driving situation that is not more fatiguing is driving on long stretches of nearly straight road with a minimum of traffic, as may be experienced only in sparsely populated regions.

Psychological factors. Alertness, attitude, and enthusiasm are important in night driving. Anxiety states depress this ability. Roper and Howard (78) have called attention to the more-rapid perception of an obstacle when it was expected than when it was not anticipated. Unusual interest may overcome partial fatigue or delay its onset. Self-hypnosis may be a factor in night driving accidents.

Night blindness. Night blindness with inadequate dark adaptation occurs in a few people who are unable to see well at low levels of illumination. This may be hereditary and permanent, or temporary due to a nutritional deficiency, or to the results of infection or disease. Little can be done for permanent cases, other than restricting their driving to daylight or their speed after dark. The temporary cases are clinical problems, but their existence should be considered in any screening or evaluation program.

All of these systemic factors are vague in the sense of not being quantitative or fitting into a night driving personal equation. However, they are included here to serve as a warning, and a check list for the effectiveness of any program and as problems for investigation.

GLARE

The IES Handbook states: "Disability glare sources, by increasing an observer's adaptation level, reduces his contrast sensitivity as the contrast between a visual task and its background or both.... Disability glare is present whenever a source of higher brightness than that of the task is superimposed on the surround." Various theories are given to account for discomfort glare. Glare has the effect of a veiling brightness, $Bg, = 23E/D^{1.8}$ where E is the illumination at the eye from the glare source, D is the angle it makes with the line of vision, it is equivalent to a change of adaptation to higher level and the eye then cannot distinguish as small differences in intensity.

Marked differences in contrast as 50:1 are unpleasant. Holladay (41) Luckiesh and Holladay (58), Luckiesh and Guth (57) and others, have devised methods for the analysis of glare and the conditions where glare becomes intolerable.

The effect of glare on the retina depends on whether it is diffuse or concentrated within a small area. Even in the latter case there may be some diffuse or scattered lighting of more or less of the retina. When the intensity is considerable, the reserve of materials for regeneration of the sensitive chemicals in the receptors may be depleted and vision greatly reduced for a period of time. A large response in a glare area may inhibit smaller responses of nearby retinal areas due to interactions in the electrical phenomena of the nerve fibers. A concentrated glare area may produce a halo from scattering that will reduce visibility in nearby regions but that will not reduce absolute brightness. Glare causes a change in adaptation, thus tending to reduce its own apparent brightness. Any opacities in the ocular media will scatter light and cause veiling glare (94).

Glare in night driving varies from a quick passing through an opposing light beam to rapid, and successive exposures to the lights of opposing cars on a heavily traveled road, e.g., driving on a narrow parkway in the direction opposite to the main traffic flow. In the latter case the glare causes more fatigue, but is less dangerous as the eyes are kept on a higher adaptation level, than does sudden blinding of nondimmed high beams of a lone car when the eye is adapted to a lower level of illumination. After-images from glare sources may prevent vision in that part of the retina. Glare is not often reported as a cause for accidents (4).

Little study has been made on recovery from glare. Presumably the pupil contracts and then enlarges and such pupil changes are usually fairly rapid. (Contraction to minimum in 5 sec. Increase of 1 log unit above threshold brightness required,88). The rate of recovery depends on the amount of glare (time and intensity). On a trip from Southbridge to Stamford the exposure to passing glare averaged about 2 sec. per car and the brightness of the headlights appeared to average about 500 ft.-L. with extremes of 200 and 3,750 ft.-L. The higher levels were very uncomfortable. As the measurements were made within a moving car, their precision may not be high. Glare is reported to affect the accommodation mechanism (72). Younger subjects are unaffected, but in the older ones, there was a lengthening of the accommodation near point. No effect was found with aphakics. The result was believed by them to be due to the stimulus from heating of the lens by the extra light.

Lauer and Silver (55) investigated vision against opposing lights with a Ferree and Rand acuity meter used as a projector, of 0.25 to 2 ft.-c. and the affect of angle of view as 1 ft.-c. With an opposing beam at 3 deg. of 1 to 2 ft.-c. the required light to see was $y = 0.0556x - 0.1412$, where x is the standard of visibility required. For 100 percent acuity and the opposing light in ft.-c. the light required for seeing is $y = 4.112x - 1.112$, or the light to offset 0-1 ft.-c. of opposing light. The greatest relative effect of opposing light was found at 5 deg. and the greatest absolute effect at 3 deg. from the line of sight, twice as much light is required for observers of 70 percent acuity (20/60) and 1 ft.-c. opposing light requires 10 times as much light to see as well as without the opposing light. Dark objects required 4 times as much light to be seen as do light objects. They reported that the visibility threshold for an 8 percent object is increased 28½ times for opposing light of 1 ft.-c. at 3 deg. Depressing to the low beam decreased the opposing light to 0.2 ft.-c. and the glare about one fourth. Lauer and Silver found further that the color threshold was 75 times greater than the visibility threshold. Fortunately avoiding obstacles in night driving does not require seeing what color they are.

Finch (29) made the only attempt the author has found to evaluate quantitatively night driving lighting. For a low beam the average illumination on the road was 1 ft.-c. and with the reflection for oil-stained concrete taken as 0.10 the adaption field luminosity was computed to be 0.08.L. per sq. ft. Referring to Konig's acuity data, this minimum contrast is 0.035, indicating that the average observer would detect a difference in brightness of 3.5 percent and could correctly identify a brightness difference of 3.5 percent about half of the time. For the upper beam the illumination on the road was 1 ft.-c. at 50 ft., 0.05 at 100 and 0.07 ft.-c. at 200 ft. The adaptation luminosity was 0.042 ft.-L. and minimum contrast 0.05, nearly twice that of the lower beam. For comparison, the adaptation value of an average room lighted with 20 ft.-c. was found to be 7.5 ft.-L. and the minimum contrast was 0.01. Visual acuities then are for the room 1.6 (0.6 ft.) high 0.55(1.8 ft.) and low beam 0.75 (1.3 ft.). A pedestrian 350 ft. ahead in the outside lane in a gray suit would have a contrast of 0.07 which is only slightly above the threshold contrast of 0.05 and the seeing task is very difficult. An empirical equation is developed for evaluating glare and for an example cited a single glare car would reduce visibility by 60 percent. The decrease in visibility is proportioned to the candle power of the opposing glare light. Speed for driving must be greatly decreased to bring the visibility range against the glare within safe limits.

Thus the range between the luminosity of pedestrians and roads and the excess glare is insufficient for good control of vision. Another useful reference (British) is Stiles and Dunbar (86).

An automobkle headlight is an extended rather than a point source and the inverse square law does not apply except at considerable distances. Lens and reflector design scatter considerable light in directions other than straight ahead. Rarely are lights aligned to the best position. These relations may account for our finding of more light at the driver's eyes as the approaching car comes closer. Unless the distribution of light is known, one cannot compute effects of glare on the eye. Scattered light from a dirty windshield covers more of the retina and decreases seeing proportionally more than does limited direct light. An improved lens design has been announced in the Netherlands to lessen glare (27).

Protection from glare becomes a problem of keeping the unwanted light from the driver's eyes and reducing its spread within the eye. Proper correction for after-dark driving with spectacles lessens glare by focusing the glare source sharply on the retina. Screening must be limited to the dazzling light, as it has been shown that the illumination on the road is scarcely adequate for vision and the eye must obtain an unimpeded view of the highway. This requirement eliminates colored spectacles and windshields. Lauer (5) has suggested placing a strip of purple plastic on the windshield for glare protection to one side of the normal line of sight. Covering the upper-left quadrants of night-driving glasses with a pure-red filter takes advantage of the fact that red light does not change the effective level of dark adaptation to any noticeable extent. Rotating the head counterclockwise very slightly puts the filter between the headlights and eyes without otherwise restricting vision. Such mechanical devices are unacceptable to many drivers.

SPECIAL CONDITIONS OF NIGHT DRIVING VISION

Traffic lights are usually bright enough to be identified. Red can usually be recognized as far away as it can be seen. Blue-green may be seen first, at long distance, by its brightness and later by its color. The visibility of warning signs depends on their size, reflectivity, and illumination. Reflector signs depend on the amount and on the angles of the illuminating and reflected beam. Signs need to be placed farther from the obstacles for night vision, in terms of time to see them and likely speed of driving, but no further than necessary, otherwise the lessened illumination would negate the gain.

Atmospheric conditions, extraneous light, and glare may greatly impair night vision and make difficult any visibility studies on actual driving conditions. Rapidly moving objects are less well seen at night than slower moving ones. Stereoscopic vision is poor and there are fewer clues for vision, such as perspective, parallax, and shadows. Chapanis (23) believes that mental and perceptual factors are more important than dark adaptation, because the seeing situation is complex. Distracting factors are more serious in night driving. Some people with good dark-adapting ability have difficulty seeing at night from lack of training, motivation, or psychoneurosis. Form dicrimination is judged more important for night vision than dark adaptation.

According to Kruithof (50) blurring is of little importance in reading X-ray pictures, and sharp line separation is not necessary in photometry. Perhaps this is why some objects are seen better at night than their contrast would warrant.

Roper and Scott (79) have emphasized the role that silhouette plays in seeing at night. A large mass may be seen before a red taillight is seen and Hoppe (45) has determined size effects on the visibility of vehicles both on the road and in the laboratory. The limitation of the oncoming light to specularly reflecting streaks on a wet night largely accounts for the difficulty of seeing. The nonspecular reflection is lacking, and there is no backlighting for silhouette seeing. Traffic on a road may reduce the reflection constant by 8 to 32 percent (15).

Near objects (under 260 ft.) may be brighter than their backgrounds, while far objects may be darker and seen as masses in silhouette. Tall objects may be seen and distances estimated better with one kind of light than another according to de Boer and Vermeulen (27).

Training has improved night seeing for members of the armed services, and a civilian educational program might lessen night-driving accidents appreciably.

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Spherical Lens Optics Applied to Retrodirective Reflection

JAMES H. HAVENS, Research Chemist, and
ALLIE C. PEED, JR., Research Engineer,
Kentucky Department of Highways

SYNOPSIS

THIS paper describes some expedient applications of elementary optical principles to the evaluation of glass-bead reflectorizing systems for highway signs and markers. The optical function of spherical lenses in achieving reflex reflection is illustrated both photographically and diagrammatically. Various optical designs are discussed and analyzed. By simple geometric optics, the efficiency of these systems is correlated with the practical performance criteria for retrodirective reflectorization.

During the past several years various commercial interests have developed or proposed numerous devices as systems for reflectorizing highway signs and markers. Some of them have gained widespread acceptance while others have been rejected or replaced by more recent innovations. The commensurate efforts on the part of highway agencies have been directed toward evaluations, specifications, and performance criteria. As a partial consequence of this, most of the literature on the subject deals more with those particular phases rather than with the theoretical aspects of reflectorization (1, 2, 3).

Perhaps this omission has been due to the fact that most of the basic optical principles of reflectorization can be worked out from information found in any good college physics book. It is, however, the contention here that this knowledge and understanding is essential to the judicious selection of reflective systems. This paper is, then, dedicated to the documentation of some of the theoretical aspects relating spherical lens optics to retrodirective reflectorization.

Performance Criteria -- The performance criteria for reflective highway signs are dictated largely by practical trigonometry. Very simply, the tangent of the angle between the beam of light from an automobile's headlamp and the line of sight of the driver to a distance ahead is equal to the vertical distance between the driver's eyes and the headlamps divided by the distance ahead. If the driver's eyes are 2 ft. above the headlamps and a sign is 400 ft. ahead, the angle is approximately $\frac{1}{4}$ deg., whereas to a distance of 25 ft. ahead, the angle increases to approximately $4\frac{1}{2}$ deg. Only the light reflected back through this conical divergence angle is of any use to the driver.

Due to the fact that signs are set off from the path of the vehicle, the angle between the incident beam and the normal to the surface of the sign may be as little as 1 deg. at 400 ft. and increase to 30 deg. at 25 ft. Thus, the angularity requirements for a retrodirective sign surface are two-fold: it must return a substantial portion of the light backward along the incident beam, and it must preserve that property even through large angles of orientation. The redundant but necessarily descriptive terms "reflex" or "retrodirective" reflection have been ascribed to reflective systems capable of exhibiting those characteristics.

Reflector Categories -- Basically, reflectors are a subclassification of secondary luminous sources which may be defined as "any source that is luminous by virtue of reflection or transmission of luminous flux from or through the surface" (4). Reflection, excluding the reflex type, has been further divided into two general types: diffuse and specular. Accordingly:

> "An ideal diffuse reflecting surface reflects all luminous flux in such a geometric manner that the brightness of the object is constant (with respect to the viewing angle)."
>
> "An ideal specular surface reflects all luminous flux received by it at an angle of reflection equal to the angle of incidence" (4).

Figure 1 gives a somewhat-idealized generalization of the difference in reflection patterns for the three fundamental categories. In both the diffuse and specular types the pattern of reflection is symmetrical about the normal to the surface. In the reflex type, however, the pattern is symmetrical about the line of incidence from the source.

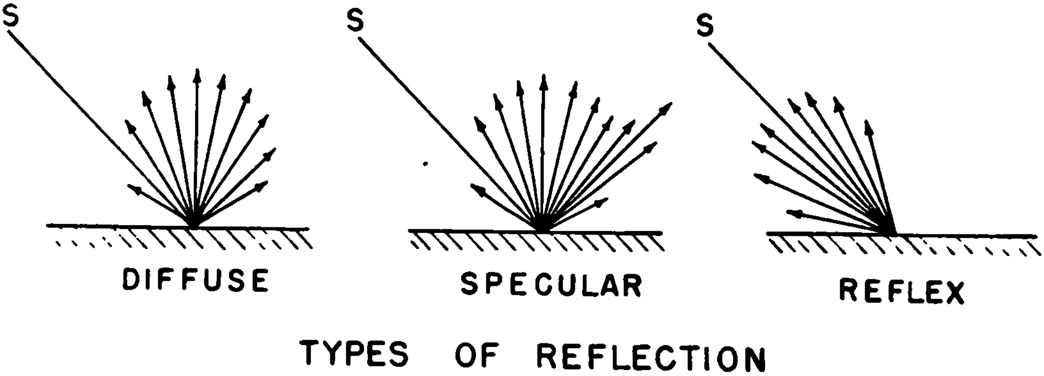

Figure 1. Vectorial illustration of three basic categories of Reflection Characteristics.

One example of a diffusing-type sign is a weathered or chalking painted surface. Since it exhibits a hemispherical pattern of reflection, the intensity of reflection at any distance in front of the sign varies inversely as the square of that distance. Thus the reflection intensity would be about 250 times greater at 25 ft. than it would be at 400 ft.

In the second case, or the specular type, the specular vectors are shown as simply added to, or superimposed upon, the pattern of diffuse reflection. This is a condition approached by a fresh, unweathered enamel surface. By assuming unit illumination at the surface, a fractional relationship must exist between the degree of diffusivity and the degree of specularity in the reflected light. Greater reflection in a particular direction can be achieved only by sacrificing reflection in other directions. The rougher the texture of the surface, the more it scatters the light. The smoother the surface, the more it tends to reflect an image of the source.

Glass-Bead Reflectorization -- Figure 2 shows a photomicrograph of a typical reflecting surface in which minute spherical lenses or glass beads are used to achieve reflex characteristics. These glass beads are in the order of 0.15 mm. to 0.05 mm. in diameter and are imbedded to their equatorial plane in a pigmented resinous or plastic matrix adhering to the sign stock. Each of these minute glass beads acts as a lens which gathers in the incident light, focuses it upon an underlying surface, and returns the reflection back toward the source. Since the sizes of the beads are below the normal resolution of the eye, viewed even at arms length, the surface seems to luminesce when viewed within the cone of reflex reflection. This is particularly advantageous from the standpoint of legibility. The legend is simply painted over the beads giving a large luminous area as the background for dark, nonreflecting letters and design. Other lens systems, such as reflector buttons, are large enough to be resolved individually as points of high glare, even under distant viewing conditions.

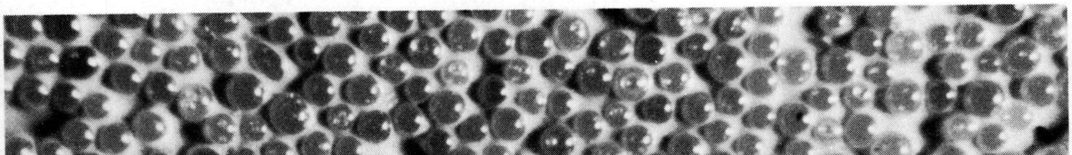

Figure 2. Photomicrograph of a typical glass-bead reflectorising System.

Elementary Optics -- As a practical approach to the theoretical analysis of this optical system, Figure 3 shows an actual photograph of a single glass sphere in the path of a restricted but collimated beam of light incident from the left. It is clearly shown that the light is converged to a focal point behind the sphere. The position of the focal point for a spherical lens is governed by the refractive index of the particular glass. The convention is to express focal lengths in terms of the radius and with respect to the optical center of the lens. Fortunately, for a complete sphere, its optical center is coincident with the center of the sphere. Focal lengths are related to the radius of curvature and refractive index by the simplified equation:

$$f = \frac{u'r}{2(u'-1)}$$

in which f = focal length measured from center of the sphere
u' = refractive index of the glass with respect to air
r = radius of the sphere

Assuming a refractive index of 1.5, which is an approximate value for ordinary glasses, f is calculated to be 3/2 times r or a distance equal to $\frac{1}{2}$ r behind the trailing surface. This is approximately the condition shown photographically in Figure 3.

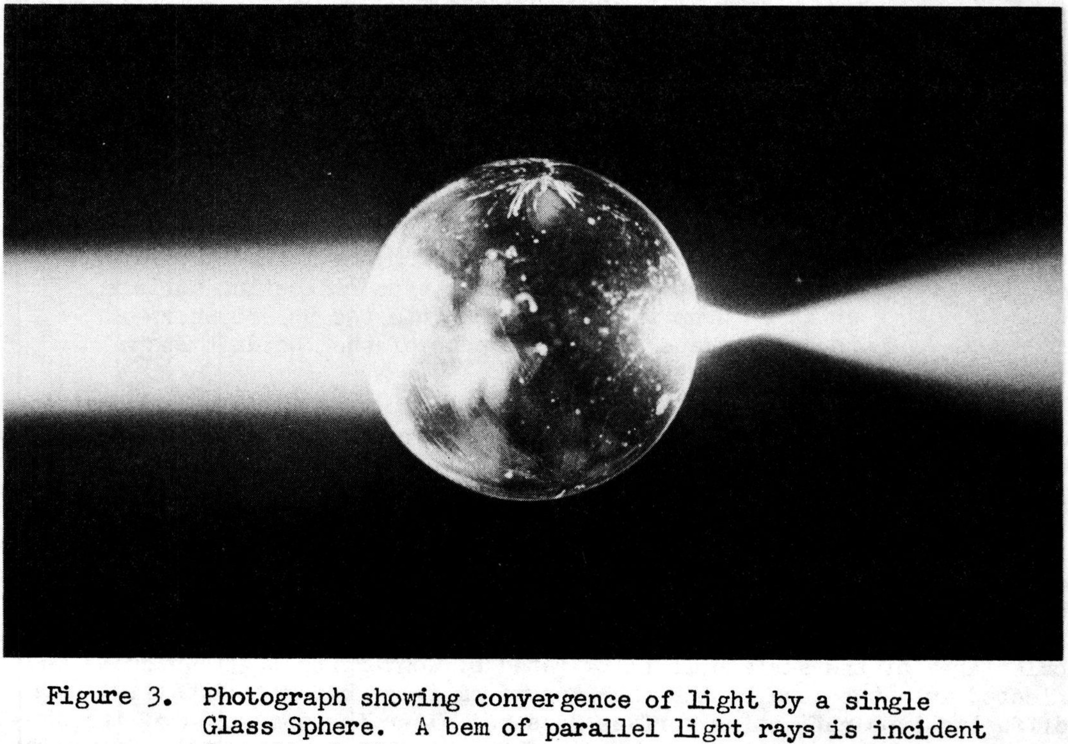

Figure 3. Photograph showing convergence of light by a single Glass Sphere. A bem of parallel light rays is incident from the left.

If a reflecting surface is positioned at the focal point and normal to the incident beam, then the light is reflected back into the sphere and is re-collimated back through the incident beam. This condition is also illustrated photographically in Figure 4. In the photograph, however, the light going into the latter lies inside the boundaries of the incident beam. The reflecting surface used here was a piece of aluminum foil having high specular characteristics. Some scattering or diffusion, however, may be noted at the surface in the photograph.

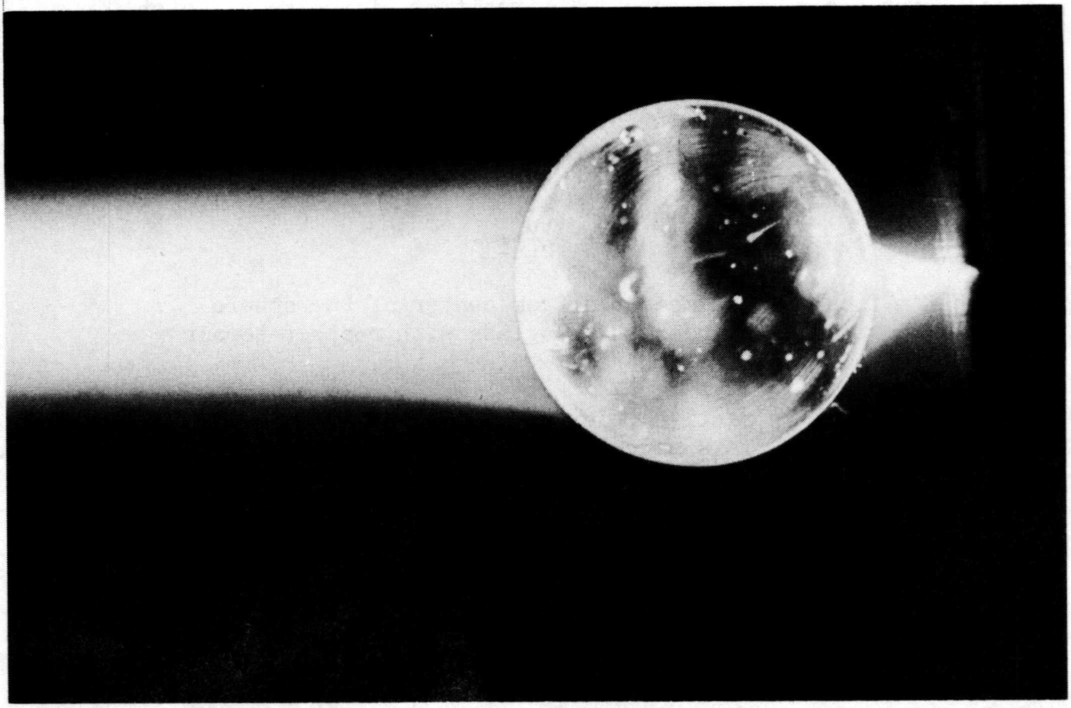

Figure 4. Photograph illustrating the function of a spherical lens in reflex-reflection. Here again, a beam of parallel light rays is incident from the left. The rays are converged onto a specular-type reflecting surface which returns the light back into the sphere where it is recollimated along the path of the incident beam.

If a high degree of retrodirection is to be achieved, the position of the reflector with respect to the focal point is very critical. If positioned behind the focal point, then it receives diverging light from the lens and, due to the greater angle of incidence upon the surface, a large portion of the light reflected may miss the sphere entirely. The system therefore loses part of its former efficiency. Considering the opposite extreme, with the reflecting surface positioned in front of the focal point, converging light strikes the surface and is returned through the sphere in a widely diverging cone, as shown in Figure 5. In this case, a large circular area of the surface is illuminated by converging light which is reflected into the lens rather than away from it as before. Substituting a diffusing-type reflecting surface does not alter the operation of the system appreciably. A greater portion of the light may be lost through scattering, but the mechanics of operation are essentially the same. If the lens is improperly positioned with respect to the reflecting surface, diffusion may compensate to some degree for that imperfection.

With further reference to the relationship between focal lengths and radius of the sphere, in the equation $f = u'r/2(u'-1)$, f increases as r increases. Obviously larger lenses must be spaced at a greater distance from the reflecting surface. Further, as the refractive index of the glass approaches 2.0, f approaches r. If f is equal to r, then the focal point is coincident with the trailing surface of the sphere. As the refractive index increases above 2.0, the focal point moves inside the sphere; which means, of course, that it is impossible to position a reflecting surface there. It also means that all the refraction is produced by the front surface only, and the above equation becomes invalid. A similar equation may be resolved for lenses having front surfaces only; i.e., $f = r/u-1$. Here, also, when $u' = 2.0$, $f = r$.

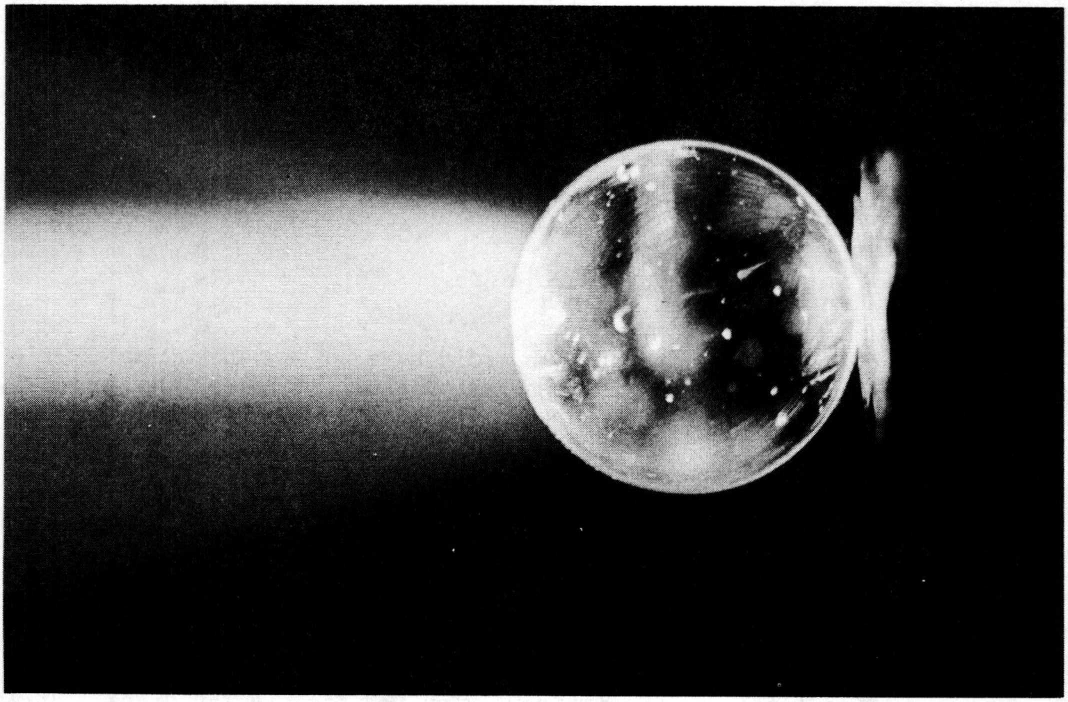

Figure 5. This photograph illustrates the divergent character of light returned through the sphere when the reflecting surface is positioned in front of the focal point.

Geometric Optics -- In the preceeding discussion and in the previous photographs, considerable importance has been attributed to focal-point calculations and the spacing of the reflecting surface. It is important to call attention here to the fact that these focal-length formulas have been resolved for paraxial rays (those which pass undeviated through the center of curvature). They are, therefore, based upon a series of assumptions which introduce appreciable error with the greater obliquity of the rays. In other words, there is no discrete point of convergence for all the rays entering the sphere. This optical imperfection in lenses is called spherical aberration. Consequently the only straight forward method of analyzing the optical systems for reflectorization, to be considered subsequently, is to trace the path of the light through the systems, applying Snell's law of refraction to each surface.

In Figures 3, 4, and 5, both the front and rear surfaces are refracting with respect to air. Actually, they are suspended in air, and only by assigning a refractive index of unity to the air is it possible to resolve the simplified equations above. By using Snell's law any ray of light may be traced through any series of reflecting media by geometric construction, or more specifically, by geometric optics. Snell's law may be written as:

$$\frac{\sin I}{\sin R} = \frac{u'}{u}$$

where I = angle of incidence, with respect to the normal to the boundary-surface

R = angle of refraction, or the angle made with respect to the normal after crossing the boundary

u′ = refractive index of the medium the ray is entering

u = refractive index of the medium the ray is leaving.

Of course, when <u>u</u> is equal to unity, as for air, the equation reduces to its more simple form:

$$\frac{\text{Sin } I}{\text{Sin } R} = u'$$

Refractive indices for unknown media have to be determined experimentally by standard methods. In these theoretical analyses, the appropriate values for refractive indices are assumed and do not represent any specific material.

<u>Optical Design of Reflex Reflectors</u> -- The design of a reflex reflecting system is limited in a practical way by the mechanics involved in actually fabricating the system for use on a sign. Obviously the spheres can not be suspended in front of the sign as they are shown in Figures 3, 4, and 5. It is practical, both optically and mechanically, to imbed them to at least their equatorial plane in a suitable binder, incorporating them as an integral part of the surface. Figure 6 illustrates one of the simplest and most practical designs imminently suited for highway signs. Structurally, at least, this cross-sectional view is comparable to the surface shown by the photomicrograph in Figure 2. Otherwise, it describes a general category of optical designs. The most significant feature in the geometric construction of this optical system is the angle <u>d</u>, which represents the deviation of the returning ray from true parallel reflection. It will be recalled from earlier treatment, based on performance criteria, that only the light returned within a divergence angle of 4½ deg. can be of any use to the driver. In this system that angle is <u>d</u>. Fortunately, due to the simplicity of the system, angle <u>d</u> can be equated in terms of <u>I</u> and <u>u′</u>, and it is otherwise independent of the radius and focal length of the sphere. Accordingly, the efficiency of the system may be tested with respect to the specific property of the glass, <u>u′</u>. From the development shown in Figure 6, where

$$d = 2I - 4\sin^{-1}\left(\frac{\sin I}{u'}\right)$$

<u>d</u> may be calculated for any value of <u>I</u> and u′.

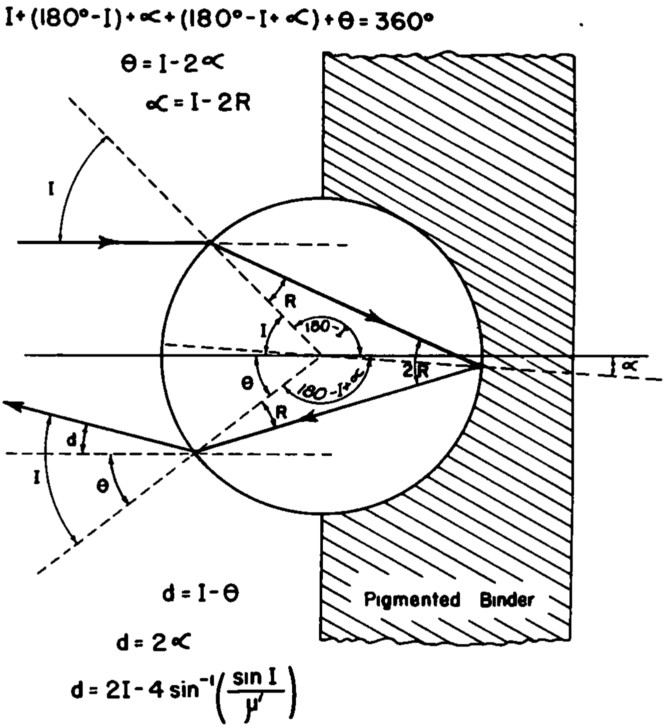

Figure 6. Schematic diagram showing cross-sectional view of a glass sphere imbedded in a pigmented binder and the geometric construction of the path of a single ray of light through the system.

Figure 7 shows a group of theoretically calculated curves relating d to I for selected values of u′ ranging from 1.50 to 2.00. It is significant to note that the angles of incidence contributing useful reflection are those angles corresponding to that portion of the respective curves lying within the bracketed region of 4½ deg. positive or negative divergence. Of course, the sign of the divergence is extraneous to the utility of the light. From further examination of the curves, it seems that minimum divergence is achieved when u′= 2.00 which is favorable to extremely long viewing conditions where the useful divergent angle is ½ deg. or less. However, by sacrificing some of the efficiency for those extreme conditions, a somewhat greater portion of the lens surface becomes useful and the curves cross the zero-divergence line at two angles of incidence.

In this interpretation of the curves, two other features of spherical lenses must be considered. First: 75 percent of the equivalent normal surface of the sphere lies within the 60-deg. angle of incidence. Second: the fraction of incident light reflected without entering the surface of the lens remains fairly constant to 60 deg. incidence but increases sharply at greater angles. Within these boundary angles, even the influence of u, within the range of 1.50 to 2.00, on the fraction of light lost by surficial reflection is less than one tenth of all the light received. These two features establish the boundaries of useful lens surface at approximately 60-deg. incidence. Therefore, those portions of the curves for incidence angles greater than 60 deg. should be disregarded. The angle I in all of the foregoing discussion refers to the angle a ray of light makes with respect to the normal to the surface of the sphere and should not be confused with the angle which the driver's eyes and the headlamps of his car make with the plane of the sign on the highway. That angle is to be discussed in the following paragraph.

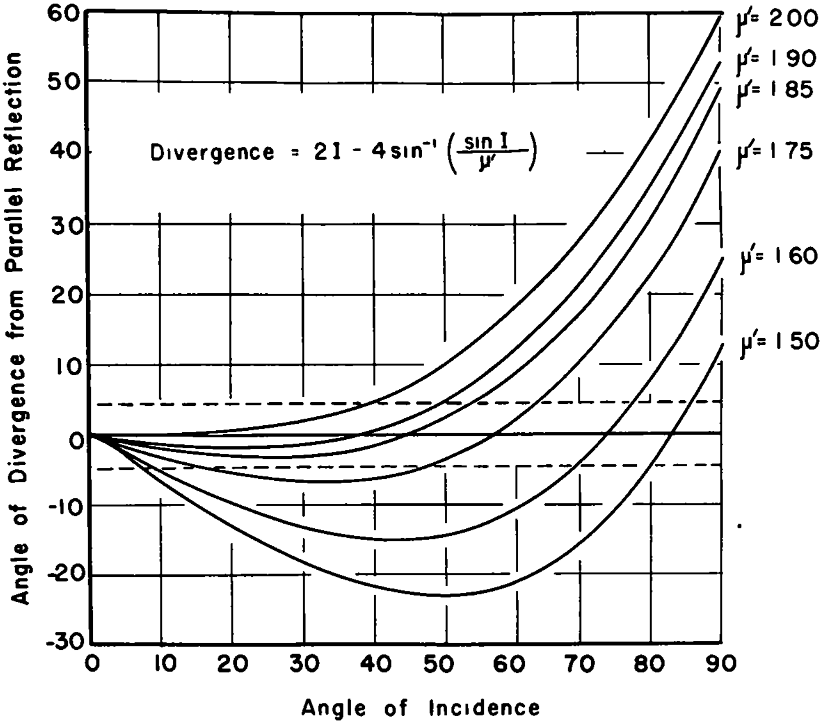

Figure 7. Typical curves showing the relationship between d, I, and u′ for the system illustrated by Figure 6.

From further inspection of the diagram in Figure 6, it may be noted that the central axis, there shown as normal to the plane of the sign, may be rotated about the center of curvature of the sphere until the 60-deg. maximum incidence angle just grazes the binder without impairing the efficiency of the system at all. This means, of course, that the plane of the sign may be rotated through an angle of 30 deg. to the driver and headlamps without sacrificing any of the reflex efficiency of the sign. At angles greater than 30 deg., the binder obscures more and more of the useful aperture of the lens.

In contrast to the system already described, Figure 8 illustrates another system which utilizes the longer focal length lenses and which is functionally comparable to the optical system illustrated by Figure 4. In this diagram, the sphere is envisaged as being imbedded in a transparent medium and properly spaced in front of the reflecting surface shown by the shaded area in the drawing. Here the incident ray is first refracted at the air-glass interface, then at the glass-spacer interface, is reflected and returns in a nonsymmetrical manner back across the two refracting interfaces. This system is complicated by a multiplicity of dependent variables which defy resolution and simplification. When u'for the glass and u" for the spacing medium are known, any incident ray may be traced through the system by geometric construction as shown in the figure, regardless of the inclination of the central axis through the sphere to the reflecting surface which is in the plane of the sign. That is true only for fixed values of r and s. Again from earlier consideration, it will be recalled that, for zero inclination of the central axis, r + s should be approximately equal to the focal length of the sphere. However, due to spherical aberration, greater efficiency is realized for zero inclination when r + s is slightly less than the focal length. Each inclination then introduces an entirely different set of circumstances.

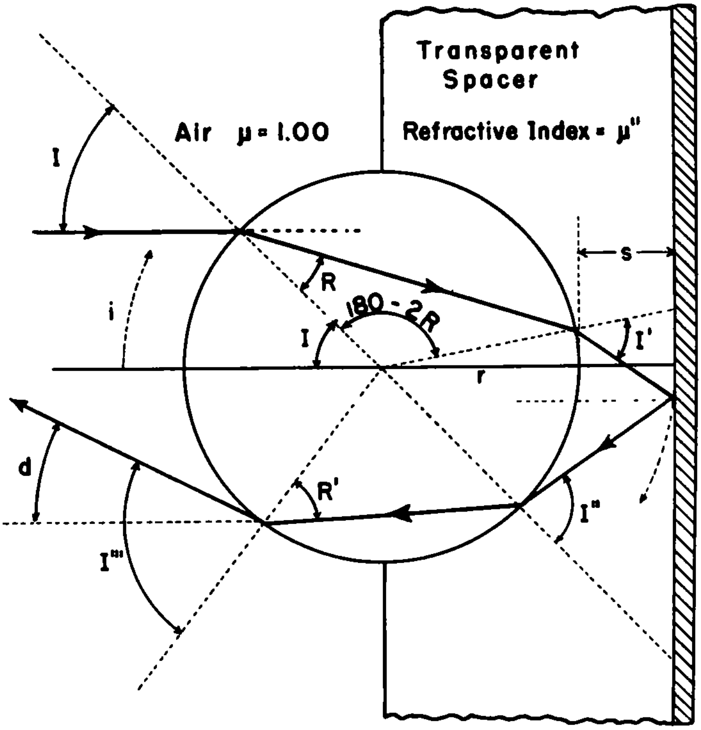

Figure 8. Cross-sectional diagram showing a single glass sphere imbedded in a transparent spacing medium overlying a plane reflecting surface. The geometric construction of the path taken by a single ray of light through the system is also shown.

In general, the design illustrated in Figure 8 seems to be more efficient for near normal orientation of the driver and headlamps with respect to the plane of the sign. Also, it is only by the use of a diffusing-type reflecting surface behind the spheres that it is possible to preserve reflex characteristics through greater angles of inclination. These fundamental imperfections arise from the association of plane and spherical surfaces. In this particular design, the use of the plane reflecting surface is recognized as a construction expediency. It may be regarded, then, as a practical modification of a more fundamental system in which the plane reflecting surface replaces a spherical surface having a radius approximately equal to $r + s$. Accordingly, a similar system having a spherical reflecting surface would be capable of accommodating almost any angle of inclination, i, without disrupting the symmetry of the system. This corresponding fundamental design is illustrated by Figure 9 where it is shown that the former complexity of variables has been eliminated.

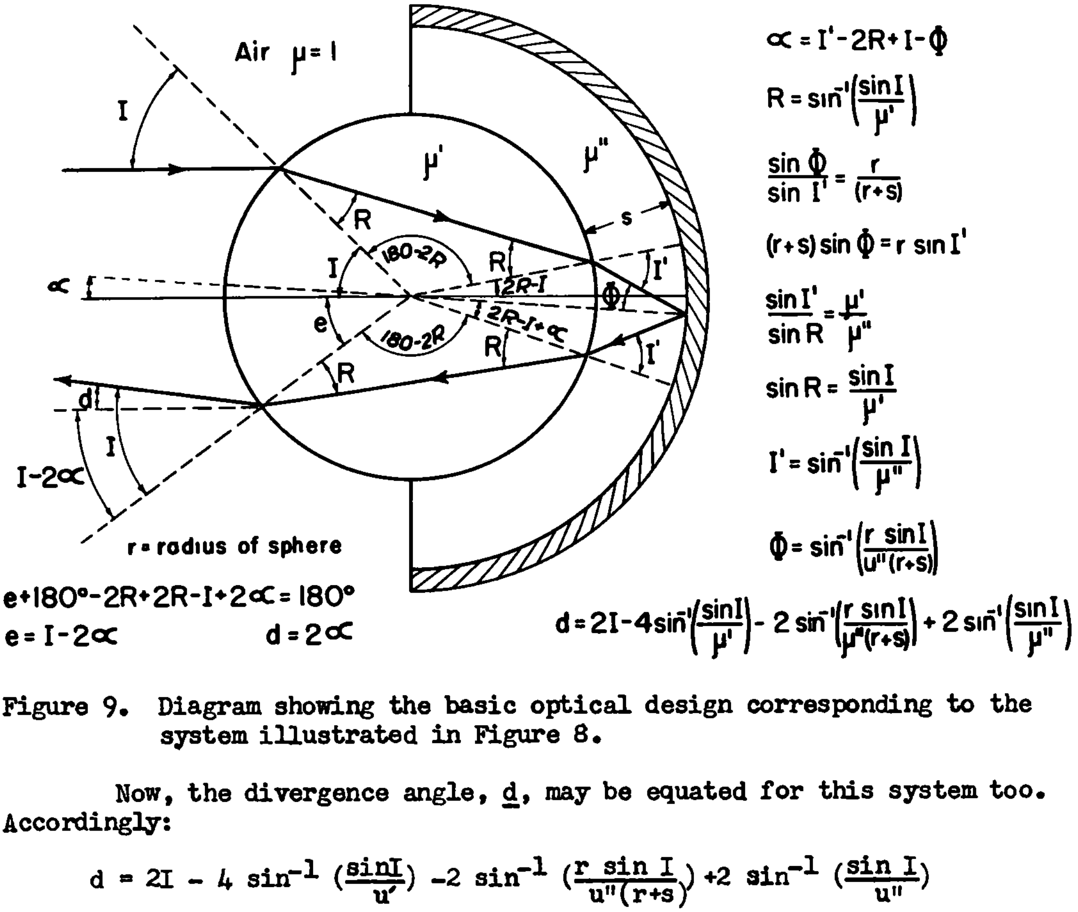

Figure 9. Diagram showing the basic optical design corresponding to the system illustrated in Figure 8.

Now, the divergence angle, d, may be equated for this system too. Accordingly:

$$d = 2I - 4 \sin^{-1} \left(\frac{\sin I}{u'}\right) - 2 \sin^{-1} \left(\frac{r \sin I}{u''(r+s)}\right) + 2 \sin^{-1} \left(\frac{\sin I}{u''}\right)$$

When $u' = u''$

$$d = 2I - 2\sin^{-1} \left(\frac{\sin I}{u'}\right) - 2\sin^{-1} \left(\frac{r \sin I}{u'(r+s)}\right)$$

Also, when $s = 0$

$$d = 2I - 4\sin^{-1} \left(\frac{\sin I}{u'}\right)$$

which is the basic equation for the first design illustrated by Figure 6.

Horizontal Surfaces -- Reflectorization is an effort to compensate for some of the inadequacies connected with night-driving visibility. It is borne out by experience that reflectorized horizontal surfaces such as centerline stripes suffer considerable loss in efficiency during moderate to heavy rains. This loss is unfortunate because it occurs under critical conditions of visibility when drivers need to be compensated the most. The possibility of incorporating additional compensation into the optical design of the reflectorizing systems offers an interesting and practical application of the previously discussed theories.

In Figure 6, the glass sphere is considered to be refracting with respect to air. By imagining such a surface oriented horizontally and the sphere completely inundated by a film of water, the sphere would no longer be refracting with respect to a medium where $\underline{u} = 1$ but where $\underline{u} = 1.33$. In order to preserve the same refractive efficiency of the glass sphere, the ratio the sines of $\underline{I}$ and $\underline{R}$ would have to remain constant.

Suppose, for instance, that the optimum ratio of sin $\underline{I}$ to sin $\underline{R}$ is taken as 1.90; then u'/u must equal 1.90. If $\underline{u}'$ is the refractive index of the glass and $\underline{u}$ the refractive index of the water, 1.33; then $\underline{u}'$ would have to be equal to 2.50.

Contrasting these theoretically ideal conditions with a reflectorizing system using ordinary glass have a refractive index of approximately 1.50 with respect to air; when inundated by water, the ratio of sin $\underline{I}$ to sin $\underline{R}$ is no longer equal to 1.50 but is 1.13 which is little, if any, better than no refraction at all. So, even to preserve a ratio of 1.50 to compensate the system for water inundation, the refractive index of the glass would have to be increased to 2.00.

Theoretically, at least, horizontal surfaces could be compensated for inundation by incorporating some of those more highly refractive glasses with those considered optimum for normal weather conditions; provided, of course, the more highly refractive glasses were available. Such theoretical conjectures as this exemplify the possibilities for further modification and refinement of reflex optical systems.

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